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# A REVIEW OF STATIC STABILITY INDICES AND RELATED THERMODYNAMIC PARAMETERS

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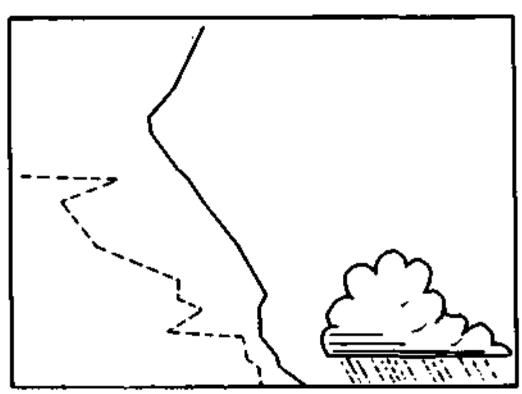

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# CONTENTS

# TABLES

## ABSTRACT

This report describee the findings of a comprehensive literature review concerning the development and application of static stability indices and related thermodynamic parameters (SSITPs). The review was done in support of an effort to determine how to "best" characterize static stability and quantify its importance in relation to growing season (May-August) rainfall affecting central North America (Lamb and Peppier, 1985; Peppier and Lamb, 1988).

Many SSITPs have been developed to estimate the troposphere's state of static stability for forecasting and/or diagnostic purposes, most often in relation to severe weather in the United States. They assimilate various thermal and moisture properties of the lower and middle troposphere into values which then rate the atmosphere's ability to spawn convective phenomena. As will be shown, most SSITPs were developed for specific atmospheric phenomena and/or localized geographic regions. They have been applied, though, to a wide variety of situations and locations, often being chosen for study on the basis of their traditional use rather than on a demonstrated effectiveness for the particular phenomenon or region being examined. In contrast to the climate-oriented studies of Lamb and Peppier (1985) and Peppier and Lamb (1988), many studies concentrated on a limited number of SSITPs, localized geographic regions, and/or relatively short time periods. Certain indices have been found to be especially useful for predicting or diagnosing particular atmospheric phenomena. As specific examples, the K-index and its variants have been useful predictors of precipitation occurrence/amount and non-severe thunderstorm occurrence, while the Total Totals, Lifted, and SWEAT indices (and variants thereof) have been valuable severe weather predictors.

This report first outlines the definitions of tropospheric static stability and describes most of the methods available (i.e., the SSITPs) for its estimation. The document then reviews the past applications of the methods, with particalar emphasis on those which examined summertime, North American rainfall and severe weather.

## SYMBOLS AND CONSTANTS

$T$ = temperature (° C)

$T$ = temperature (° K)

$T_d$ = dewpoint temperature (°C)

$T_p$ = parcel temperature after dry- and/or moist-adiabatic vertical displacement (°C)

$\theta$ = potential temperature (°K)

$\theta_w$ = wet-bulb potential temperature (°K or °C)

$\theta_e$ = equivalent potential temperature (°K)

$p$ = pressure (mb)

$z$ = height (m)

$p$ = density (kg $m^{-3}$)

$a$ = specific volume ($m^3$ $kg^{-1}$)

$q$ = specific humidity (dimensionless)

$c_p$ = specific heat for dry air (.240 cal $g^{-1}$ $deg^{-1}$)

$g$ = acceleration of gravity (9.8 m $s^{-2}$)

$L$ = latent heat of vaporization ( 597.3 cal $g^{-1}$)

Subscripted numbers refer to a constant pressure level (mb), with the abbreviation "sfc" indicating the surface pressure.

# 1. INTRODUCTION

The occurrence, rate and duration of precipitation in a continental region are a function of the existence and strength of several of the atmosphere's physical conditions and processes, and, in particular, the degree to which they are simultaneously favorable. In very general terms, such conditions/processes include the local presence and external supply of water vapor, and the troposphere's predisposition to provide the vertical motion necessary to produce the required condensation rates. One particularly important condition is the troposphere's state of static stability. This is a steady state property of the atmospheric system such that vertical displacements or disturbances introduced into the steady state will be damped, enhanced, or persist unchanged. As part of a comprehensive endeavor to increase our understanding of the conditions/processes contributing to the intraseasonal and interannual variations in growing season (May through August) rainfall that affect central North America (e.g., Richman and Lamb, 1985, 1987; Lamb and Portis, 1986; Portis and Lamb, 1988), an effort was undertaken to determine how to "best" characterize fields of tropospheric static stability in relation to accumulated amounts of rainfall ranging from zero to the maximum recorded (Lamb and Peppier, 1985; Peppier and Lamb, 1988). The information obtained from that study should permit the assessment of the role of this tropospheric condition for central North American summer rainfall on a climatic scale.

Many "indices" for quantitatively estimating tropospheric static stability have been proposed in the literature or applied in weather forecasting schemes during the past 40 years as aids for diagnosing or forecasting convective weather. Most combine measures of the thermal and moisture properties of the low- to mid-troposphere and are purported to rate the atmosphere's ability to produce convective phenomena. Many of the indices were developed to aid in the forecasting of thunderstorms or severe weather (e.g., Showalter, 1953; Galway, 1956; George, 1960; Miller, 1967; Miller et. al., 1971). Some applications, though, have related static stability indices to summertime rainfall (e.g., Curtis and Panofsky, 1958) and to the "yes/no" occurrence of measurable precipitation in the statistical "Model Output Statistics Probability of Precipitation" (MOS PoP) forecasting models of the United States National Weather Service (e.g., Lowry and Glahn, 1976).

In the process of conducting the Lamb and Peppier (1985) and Peppier and Lamb (1988) studies mentioned above, it was found necessary to undertake a comprehensive literature review of the past uses of static stability indices and related thermodynamic parameters, hereafter referred to by the acronym "SSITP". This report summarizes the findings of that survey, which we believe may be of interest and value to other atmospheric scientists. First, definitions of tropospheric static stability and descriptions of many of the SSITPs available for estimating it (those used in Lamb and Peppier, 1985, and Peppier and Lamb, 1988) are given. The report then documents the past applications of these methods in the literature, with particular emphasis on those which have examined summertime, continental rainfall. A brief summary follows.

## 2. THE STATIC STABILITY CONCEPT

Static stability is one of the dimensions of the large-scale atmospheric environment within which rain-producing systems develop. If the atmosphere is unstable with abundant low-level moisture, and a triggering mechanism exists to lift and set the air in motion (thereby releasing instability). convective weather and rainfall can develop. Key air mass characteristics which contribute to such instability are warm. moist low-level air and cool, dry air aloft. For example, Beebe and Bates (1955) hypothesized that low-level moisture, instability and convergence, in conjunction with upper-level divergence, could produce severe weather. Curtis and Panofsky (1958) found the probability of convective precipitation at night over the eastern half of the United States during the first 20 days of July 1955 to be a function of large-scale stability and vertical motion considerations. Wilson and Scoggins (1976), studying a similar region for two days in May 1974. discovered convective activity "to exist in areas where the low and middle troposphere is moist and the air is potentially and convectively unstable and has upward motion, in combination with positive moisture advection, at either the surface or within the boundary layer".

The indices developed to assess the degree of static stability present in the atmosphere have been defined in terms of the concepts of conditional, absolute, latent, and potential/convective instability (definitions not exclusive) and were based on the vertical displacement of a) a hypothetical air "parcel" of very small dimension, and/or b) an entire atmospheric layer of some prescribed isobaric thickness.

The general term static stability is defined (all definitions from Huschke, 1959) as "the stability of an atmosphere in hydrostatic equilibrium with respect to vertical displacements, usually considered by the parcel method". The parcel method is based on displacements introduced to a steady state "under the assumption that only the parcel or parcels displaced are affected, the environment remaining unchanged". The displaced parcel is assumed to undergo adiabatic temperature changes, meaning that it is thermally insulated from its environment, and stability, or lack of it. is determined by a comparison of the parcel's density/temperature with that of the unchanged environment at some new level. For example, an upwardly-displaced air parcel, if lighter (i.e., generally warmer) than its environment at its new level, is said to be "unstable" and will rise freely on its own, while if heavier (cooler) than its environment, it is said to be "stable" and will settle back towards its initial position. However, the parcel method does not allow for compensatory downdrafts or entrainment (the mixing of environmental air into a pre-existing, organized air current), so it oversimplifies this complicated atmospheric process. Adiabatic ascents typically give values of updraft speed, water vapor content, and temperature which are overestimates of those observed, but since these departures are largely systematic, the parcel method can serve as a useful approximation for the vertical displacement of air (USAF, 1969).

Conditional instability (sometimes referred to as the "conditional state") is an application of the above concept which considers both unsaturated and saturated air parcels. It is defined as "the state of a column of air in the atmosphere when its lapse rate of temperature is less than the dry-adiabatic lapse rate but greater than the saturation-adiabatic lapse rate". With respect to an upward-displacement, a parcel is said to be unstable and will rise if saturated but is stable and will return to its initial position if unsaturated. Similarly, <u>absolute instability</u> refers to an environmental lapse rate which is superadiabatic (greater than dry-adiabatic), so that all displaced parcels (saturated or unsaturated) will be unstable, and <u>absolute stability</u> denotes a lapse rate which is less than moist-adiabatic, so that all displaced parcels will be stable.

<u>Latent instability</u> is defined as "the state of that portion of a conditionally unstable air column lying above the level of free convection" (LFC - the point above which a saturated parcel is lighter/warmer than its environment, develops positive buoyancy, and rises freely). "The latent instability is released only if an initial impulse on a parcel gives it sufficient kinetic energy to carry it through the layer below the level of free convection, within which the environment is warmer than the parcel" (i.e., where the parcel is negatively buoyant). The parcel's states of negative and positive buoyancy can be represented on an atmospheric sounding by the negative and positive energy "areas" bounded by the environmental temperature curve and the parcel's adiabatic ascent curve (see further discussion in Section 3.2, pp. 15-16).

<u>Potential</u> or <u>convective instability</u> is defined as "the state of an unsaturated layer or column of air in the atmosphere whose wet-bulb potential temperature ($\theta_w$) or equivalent potential temperature ($\theta_e$) decreases with elevation. If such a column is lifted bodily until completely saturated, it will become unstable (i.e., its temperature lapse rate will exceed the saturation-adiabatic lapse rate) regardless of its initial stratification". Palmen and Newton (1969, p. 395) defined potential instability as a combined state of convective instability ($\theta_w$ decreasing with elevation) and conditional instability when a deep layer is considered, and noted that the terms potential and convective are sometimes used synonymously. Miller (1967, 1972, 1975) used the term potential to "describe all forms of instability that require an activating mechanism for realization", including conditional, latent, and convective instability. Thus, representing the "potential" for a layer to destabilize if lifted as a whole, potential instability is favored when the lower portion of the layer is warm and moist and the remainder of the layer rapidly dries out above.

The modeled-lifting of an entire layer (dynamically-forced by low-level convergence, an approaching weather front, etc. - see Heideman and Fritsch, 1984, for a description of 12 warm-season forcing mechanisms for significant rainfall events in eastern two-thirds of the United States) is based on assumptions similar to those of the parcel method, but with the additional restriction that the vertical pressure difference between the bottom and top of the layer remains constant. On a sounding, this lifting involves the upward displacement of air parcels representative of the thermal and moisture characteristics of key points in the layer (e.g., the bottom and top) to their respective condensation levels, creating a new lapse rate within the layer. Invariably, one of the layer's parcels reaches saturation before the others due to the vertical variation of the layer's moisture content, so that this parcel will begin to cool at the moist-adiabatic lapse rate before the others, altering the thermal structure of the layer. If the lower portion of the layer is moister than the upper portion, lifting and the resultant differential cooling will produce destabilization, and perhaps enhanced convective development. The criterion for the lifted layer becoming unstable (i.e., the original layer being potentially unstable) is that its new lapse rate be greater than moist-adiabatic. This is the same as $\theta_w$ or $\theta_e$ decreasing with height within the original layer, since each is defined by the condensation level temperatures and pressures of the various rising parcels in the layer. Similarly, a potentially stable layer is one in which $\theta_w$ or $\theta_e$ increases with height, while a potentially neutral layer is one in which $\theta_w$ or $\theta_e$ remains constant with height.

## 3. STATIC STABILITY INDICES AND THERMODYNAMIC PARAMETERS (SSITPs)

The SSITPs described below and evaluated by computer in Lamb and Peppier (1985) and Peppier and Lamb (1988) are categorized and listed in Table 1, and an overview of each follows. Each overview contains at least one key reference, a defining equation (if applicable), and a brief discussion of the meteorological motivation behind the development of the SSITP and its application. A condensed version of this survey appears in the Appendix of Peppier and Lamb (1988). Refer to ?age iv of this report for the standard symbols and constants which are used.

### 3.1 SSITPs for Forecasting Non-Severe Convective Showers and Thunderstorms

1. <u>Showalter index</u> (Showalter, 1953)

$$SI = T_{500} - T_{P_{500}},$$

where $T_{P_{500}}$ is the 500 mb temperature which a parcel will achieve if it is lifted dry-adiabatically from 850 mb to its condensation level and then moist-adiabatically to 500 mb.

The Showalter index, designed originally for thunderstorm forecasting in the southwestern United States, estimates the potential instability of the 850 to 500 mb layer by measuring the buoyancy at 500 mb of an air parcel lifted to that level. The index is a function only of the 850 and 500 mb levels. It also provides an estimate of the latent instability of the layer, in that a negative value reveals the existence of positive buoyant energy above the LFC and the possibility of subsequent free convection. Showalter (1953) found values of SI $\leq$ +3 to be indicative of showers and possible thunderstorm activity, while values $\leq$ -3 were associated with severe convective activity. David and Smith (1971) found SI $\leq$ +2 to be a threshold for severe thunderstorms for the eastern two-thirds of the United States during 1966-1969, while Ellrod and Field (1984) also used SI $\leq$ +2 as one guideline for forecasting Gulf Stream area thunderstorms. The Showalter index, as will be shown throughout Section 4, has been one of the most frequently-applied stability indices.

Table 1. Static stability indices and thermodynamic parameters (SSITFs). They are categorized according to their originally-intended or traditional use. Number in parentheses refers to the number of variants of that particular SSITP evaluated in Lamb and Peppier (1985) and Peppier and Lamb (1988).

A. For forecasting non-severe convective showers and thunderstorms:

1. Showalter index
2. Modified Showalter index of Curtis and Panofsky
3. Modified Showalter index of Hovanec and Horn
4. K-index
5. Modified K-index of Charba
6. Rackliff index
7. Jefferson index
8. Adedokun indices (2)

B. For forecasting severe thunderstorms and tornadoes:

1. Lifted index
2. Vertical, Cross, and Total Totals indices
3. Modified Total Totals index of Charba
4. Total Energy index
5. Potential Wet-Bulb index
6. Severe Weather Threat (SWEAT) index
7. Convective Instability index of Reap
8. Convective Instability index of Barber
9. Measures of Parcel Buoyant Energy:
   a. Dynamically-induced lifting of surface air parcels (3)
   b. Heating-induced lifting of surface air parcels (3)

C. For parameterizing static stability in numerical models and diagnostic studies:

1. Thermal measures of static stability (6)

D. For estimating cloud base heights and critical surface convection temperatures:

1. Lifting Condensation Level (3)
2. Convective Condensation Level (3)
3. Convective Temperature (3)

2. Modified Showalter index (Curtis and Panofsky, 1958)

$$SICP = T_{500} - T_{P_{500}}.$$

Because the Showalter index depends only on moisture at the 850 mb level and since "moisture in a thick layer might be important in the formation of convective precipitation", Curtis and Panofsky developed a modified Showalter index in which the mean moisture (mixing ratio) of the 850-500 mb layer is assigned to the initial parcel. Intended for summertime convective precipitation, SICP was a better indicator of the occurrence and intensity of convection than was the Showalter index during 1-6 and 8-15 July 1955 over the eastern two-thirds of the United States. Values of SICP ≤ +5 were found to be indicative of thunderstorms, with convective precipitation uncommon for values above +11. SICP also was a better indicator of convective precipitation at night (0300 GMT sounding values related to 0330-0930 GMT weather) than during the day (1500 GMT values and 1530-2130 GMT weather).

3. Modified Showalter index (Hovanec and Horn, 1975)

$$SIHH = T_{300} - T_{P_{300}}.$$

Hovanec and Horn also developed a slightly modified form of the Showalter index for rawinsonde stations at high elevations in their study of Colorado cyclogenesis. This index, for the 800-300 mb layer, is computed in a manner similar to the Showalter index, and likewise indicates increasing instability as it's values decrease. From their analyses over the conterminous United States for April-May 1964-71, values of this index generally appear to be more positive than those of the Showalter index.

4. K-index (George, 1960)

$$K = (T_{850}-T_{500}) + T_{d_{850}} - (T_{700}-T_{d_{700}}).$$

The K-index arithmetically combines the 850-500 mb temperature difference, the 850 mb dewpoint (a direct measure of low-level moisture content), and the 700 mb dewpoint depression (an indirect measure of the vertical extent of the moist layer) to help forecast continental summertime air mass thunderstorm potential. Air mass thunderstorms were defined by George as "those developing in areas of weak winds without apparent frontal or cyclonic influence". The index was developed from rawinsonde data covering the eastern two-thirds of the United States and portions of extreme southern Canada. The inclusion of the dewpoint depression term reflects the unique emphasis of K on assessing the vertical penetration of low-level moisture, thought to be essential for the formation of air mass storms. Using charts with isoplethed K-index fields and superimposed thunderstorm reports, values of K ≥ +20 were found to indicate an increasing frequency in air mass thunderstorm activity. Hambridge (1967), for the western United States, developed thunderstorm occurrence probabilities for values of the K-index, finding +15 ≤ K ≤ +20 indicative of a less than 20 percent chance of occurrence, with K > +40 indicative of a nearly 100 percent probability of occurrence. David and Smith (1971) found the index to be a relatively poor indicator of severe thunderstorm activity over the the eastern two-thirds of the United States during 1966-1969, but it has been found to be the best or nearly best individual predictor of various characterizations of rainfall and/or non-severe summertime convective activity (e.g., MOS PoP - Lowry and Glahn, 1976; MOS 12-36 hour probability forecasts of thunderstorms - Reap, 1974; Reap and Foster, 1979; Kitzmiller, 1985). Rodgers et al. (1984) applied K-index values ≥ +30 as one tool for forecasting the development of Mesoscale Convective Complexes (MCCs).

5. Modified K-index (Charba, 1977a)

$$KMOD = (T-T_{500}) + T_d - (T_{700}-T_{d_{700}}),$$

where $T = (T_{sfc}+T_{850})/2.$

and $T_d = (T_{d_{sfc}}+T_{d_{850}})/2.$

This modification of the K-index, developed for and evaluated as a candidate predictor in the MOS scheme for operational forecasts of two-to-six hour probabilities of thunderstorms and severe local storms in the United States, was devised as an improvement on the K-index by inclusion of the thermal and moisture characteristics of the surface. The index used by Charba (see Section 4.1.e, pp. 40-41, and Section 4.1.g, pp. 57-59) is slightly different than the purely observational data version of Lamb and Peppier (1985) and Peppier and Lamb (1988), since it averages observed surface data with LFM output forecast 850 mb values. Values of this index indicative of thunderstorm potential should be somewhat larger than those of the K-index unless the surface to 850 mb layer is isothermal or inverted with respect to temperature and/or moisture. The index was found to be the best single predictor for thunderstorms among more than 40 predictor variables for seasons including spring (mid-March to mid-June) and summer (mid-June to mid-September), for forecast periods spanning 1700-0300 GMT, and data grids covering the eastern two-thirds of the United States (Charba, 1977a, 1984).

6. Rackliff index (Rackliff, 1962)

$$RACK = \theta_{w_{900}} - T_{500},$$

where $\theta_w$, the wet-bulb potential temperature, is obtained by raising a parcel dry-adiabatically from its initial level to its Lifting Condensation Level (LCL - defined later), then lowering it moist-adiabatically to 1000 mb. $\theta_w$ is conserved with respect to both dry- and moist-adiabatic processes.

This index, a measure of latent instability, was introduced as a means for forecasting air mass summer thunderstorms over the British Isles and nearby continental areas in western Europe. It combines 900 mb thermal and moisture considerations with 500 mb temperature. 900 mb was selected as the level at which to evaluate $\theta_w$ because it was thought to represent air at low levels that "would not be affected to any degree at night by outgoing terrestrial radiation", while 500 mb was selected not only as "indicative of the thermal structure in the middle troposphere" but also to make the index consistent "physically" with other indices (e.g., Showalter index) that assess instability up to the 500 mb level. For data from May-August 1959. Rackliff found that some showers occurred at values as low as +25, while values ≥ +30 were related to the occurrence of significant showers accompanied by thunderstorms.

7. Jefferson index (Jefferson, 1963a, b, 1966)

$$\text{JEFF} = 1.6\ \theta_{w_{850}} - T_{500} - 0.5(T_{700} - T_{d_{700}}) - 8.$$

Jefferson empirically-amended Rackliff's index to obtain a value "which is independent of temperature and which will still give the same threshold value for thunderstorms over a wide range of temperature". The first variant (Jefferson, 1963a) came in response to the discovery that the Rackliff index gave a higher threshold value for thunderstorms in cold air than in warm air. However, when this variant was tested over the European and Mediterranean regions, it was found to overforecast thunderstorms over the Mediterranean when the 900-500 mb layer was dry. Thus, a second variant (Jefferson, 1963b) evolved which included a weighted measure of the depth of the moist layer (700 mb dewpoint depression - same as the K-index), and the third (Jefferson, 1966 - described by equation above) came about by substituting routinely-reported 850 mb data for those at 900 mb to provide a quicker opeartional calculation. This index is quite similar to the K-index, but is less known. Values ≥ +28 of the final version of the index were found to identify areas where thunderstorms occurred.

8. Adedokun indices (Adedokun. 1981, 1982)

$$\text{ADED1} = \theta_{w_{850}} - \theta_{s_{500}},$$

$$\text{ADED2} = \theta_{w_{sfc}} - \theta_{s_{500}},$$

where $\theta_s$ (°K) is obtained by lowering a 500 mb parcel moist-adiabatically to 1000 mb.

Adedokun developed his indices for indicating potential instability within an intertropical discontinuity (ITD) environment (Adedokun, 1981) and for forecasting precipitation over West Africa (Adedokun, 1982). For the ITD ennvironment, the first index (ADED1) was found to be a better indicator of stability conditions/precipitation non-occurrence, while the second index (ADED2) was better related to instability conditions/precipitation occurrence (Adedokun, 1981). For forecasting precipitation, the second index was again found to be more closely related to precipitation occurrence, but both had a lower percentage of correct forecasts than did the Showalter index (Adedokun, 1982). Values of the indices ≥-1 were defined to be indicative of precipitation occurrence while values < -1 were defined to indicate non-occurrence. The first index was thought to be similar to the Showalter index.

### 3.2 SSITPs for Forecasting Severe Thunderstorms and Tornadoes

1. Lifted index

(Galway, 1956; Prosser and Foster, 1966; Sadowski and Rieck, 1977)

$$LI = T_{500} - T_{P_{500}}.$$

As the original modification of the Showalter index, the Lifted index was developed as a predictor of latent instability to aid in the forecasting of severe local storms over the United States. It has been one of the more frequently-used indices for the analysis and prediction of severe weather (for examples, see Sections 4.1.f and 4.1.g). Stating that "the Lifted Index is similar to the Showlter stability index except for the determination of the level from which the parcel is lifted and the fact that the Lifted Index is a forecast index whereas the Showalter Index is an observed static index", Galway (1956) assigned to the parcel the observed mean mixing ratio of the lowest 3000 ft and the potential temperature corresponding to the dry-adiabat passing through a predicted afternoon maximum temperature. The index was then defined by lifting the parcel adiabatically from the midpoint of the surface layer to 500 mb, where its temperature ($T_p$ at 500 mb), considered the updraft temperature within a developing cloud, was compared to that of the environment. Various other thicknesses have been defined for establishing a surface layer - e.g., Prosser and Foster (1966) and Moore and Elkins (1985) utilized the lowest 100 mb, while Sadowski and Rieck (1977), Lamb and Peppier (1985), and Peppier and Lamb (1988) examined the lowest 50 mb. The predictive form of the index, often applied to morning soundings, has been used for forecasting afternoon thunderstorms (e.g., Galway, 1956; Prosser and Foster, 1966), while the static form, which utilizes just the average potential temperature of the surface layer instead of the forecast maximum, has been used by Sadowski and Rieck (1977), Lamb and Peppier (1985), and Peppier and Lamb (1988). Although no specific LI thresholds were developed, the value -2 was used as an upper bound for severe storm formation in the well-known Miller forecasting scheme (Miller, 1967, 1972, 1975), while David and Smith (1971) found values ≤ 0 of a predictive form to be associated with severe thunderstorms and tornadoes over the eastern two-thirds of the United States during 1966-1969. Ellrod and Field (1984) used values of model-output Lifted index of ≤ +2 as one guideline for Gulf Stream area thunderstorm forecasting. The Lifted index also has been found useful for the synoptic diagnosis of tornado outbreaks (e.g., Ferguson *et al*., 1983, 1985).

2. Vertical. Cross, and Total Totals indices (Miller, 1967)

$$VT = T_{850} - T_{500},$$

$$CT = T_{d_{850}} - T_{500},$$

$$TT = VT + CT = T_{850} + T_{d_{850}} - 2T_{500}.$$

The Vertical Totals (VT: 850-500 mb temperature difference), Cross Totals (CT: the difference between 850 mb dew point and 500 mb temperature), and Total Totals (TT: the arithmetic combination of VT and CT) indices were devised to operationally define a first-guess area for locating potential severe weather development in the United States. Although threshold values were found to vary slightly by geographic location during evaluation studies for the eastern two-thirds of the United States, the values VT = +26, CT = +18, and TT = +44 were found to be the boundaries of the first-guess area, and when related to storm intensity, the lower thresholds for isolated to few lighter thunderstorms (Miller, 1967, 1972, 1975). At the extreme, values of VT ≥ +30, CT ≥ +30, and TT ≥ +60 were found to be indicative of numerous moderate thunderstorms and scattered severe thunderstorms and tornadoes (Miller, 1975). The Total Totals index was among the parameters used in constructing Miller's composite severe storm forecast parameter chart (see Maddox and Doswell, 1982b, for a recent evaluation of this scheme). In the forecasting scheme, TT is considered a to be weak indicator of severe storm development if ≤ +50, moderate if > +50 but ≤ +55, and strong if > +55. TT values ≥ +40 have been applied as one general guideline for Gulf Stream area thunderstorm forecasting (Ellrod and Field, 1984), and TT ≥ +50 have been used in a scheme for forecasting mesoscale convective complexes (MCCs) (Rodgers et al., 1984). The index also has been found to be an important predictor during spring and summer for 12-36 hour probability forecasts of thunderstorms and an even better predictor for conditional probability forecasts of severe local storms (e.g., Reap and Foster, 1979). Since VT and TT can take on large values due to the existence of a strong thermal lapse rate when little supporting low-level moisture is present (small CT), care must be taken when applying the two indices as they may overestimate the potential for convective weather development (Miller, 1967, 1972, 1975).

3. Modified Total Totals index (Charba, 1977a)

$$TTMOD = T + T_d - 2T_{500},$$

where T and $T_d$ are defined in the same manner as for KMOD.

Charba (1977a) devised this modification of the Total Totals index (along the same lines as his previously-described modified K-index - see discussion above) to be a candidate predictor in the MOS scheme for two-to-six hour probability forecasts of thunderstorms and severe local storms in the United States. Values indicative of thunderstorms and severe weather should be somewhat higher than comparable values of the Total Totals index (again, see discussion of modified K-index). During MOS equation development, TTMOD was found to be one of the best predictors of spring and summer thunderstorms

(Charba, 1977a, 1984) and the best single predictor of severe local storms (Charba, 1977b, 1979, 1984).

4. Total Energy index (Darkow, 1968)

$$TEI = E_{T_{500}} - E_{T_{850}},$$

where $E_T$ = static energy
= specific enthalpy + potential energy + latent energy

$= c_p T^* + gz + Lq$ (cal $g^{-1}$ or J $kg^{-1}$)

Darkow (1968) approximated total specific energy by neglecting the kinetic energy term, and used the subsequently-formed static energy as the basis for his Total Energy index, which measures the potential instability of the 850-500 mb layer. Static energy is conserved with respect to both dry- and moist-adiabatic processes. Intended for severe storm and tornado forecasting in the United States, this index indicates instability when static energy decreases with height (i.e., TEI $\leq 0$). From severe storm data over the United States for October 1966 to April 1967, Darkow found the values $0 \leq$ TEI $< -1$ to be indicative of non-severe thunderstorms, while the values $-1 \leq$ TEI $\leq -2$ were associated with isolated severe thunderstorm activity. Values $< -2$ indicated a high probability for severe thunderstorms and associated tornado activity. Spatial patterns of the index were shown to provide a "good first indicator of areas of potential severe storm outbreak" (Darkow, 1968). Unlike indices such as the Showalter and Lifted, "the Energy Index indicates not only the energy release associated with the ascending, potentially warm air but also the possible contribution of the saturated descent of the evaporatively cooled, potentially cold mid-tropospheric air to the total energy release of the storm" (Darkow, 1968).

5. Potential Wet-Bulb index

(David and Smith, 1971; Bradbury, 1977; Pickup, 1982)

$$PWB1 = \theta_{w_{500}} - \theta_{w_{850}}.$$

Independently developed as a predictor of severe thunderstorms and tornadoes in the eastern two-thirds of the United States (David and Smith, 1971) and of summer thunderstorms over the British Isles and Europe (Bradbury, 1977; Pickup, 1982), this index estimates the potential instability of the 850-500 mb layer. David and Smith (1971) found that values $\leq 0$ were associated with severe thunderstorms during 1966-1969, while Pickup (1982) observed that thunderstorm intensity increased as the index value decreased to zero or below during April-September 1980 and that +3 was an upper limit for thunderstorm formation. Bradbury (1977), for 544 thunderstorm day soundings for the British Isles and Europe during 1973-1976, found that the value above which summer thunderstorms were rarely (5 percent chance or less) observed varied as a function of 850 mb 9 , ranging from +6 to -1 as $\theta_w$ increased from 0° to +20°C.

When only non-thunderstorm rainfall was considered, these values ranged from +10 to approximately zero over the same span of 850 mb $\theta_w$. The upper thresholds of -2 and +3 were suggested for the formation of summer and winter thunderstorms, respectively. Cool, dry air at mid-levels overlaying warm, moisture-laden air at low-levels will yield negative/unstable values of PWB1; that is, $\theta_w$ decreasing with height.

6. Severe Weather Threat (SWEAT) index

(Bidner, 1970; Miller, et al., 1971, 1972)

$$\text{SWEAT} = 12T_{d_{850}} + 20(TT-49) + 2f_{850} + f_{500} + 125(S+0.2),$$

where the first term is set to zero if the 850 mb dewpoint temperature (°C) is negative,

TT = Total Totals index (if TT is less than 49, the second term is set to zero),

$f_{850}$ = 850 mb wind speed (knots),

$f_{500}$ = 500 mb wind speed (knots),

and S = sin (500 mb wind direction - 850 mb wind direction). The entire shear term, 125(S+0.2), is set to zero if any of the following conditions are not met: (1) 850 mb wind direction in the range 130-250 degrees, (2) 500 mb wind direction in the range 210-310 degrees, (3) 500 mb wind direction - 850 mb wind direction greater than zero, and (4) both the 850 mb and 500 mb wind speeds greater than or equal to 15 knots.

Realizing the need for a completely objective operational forecast index for specifying and predicting areas with the potential for developing severe weather in the United States, the SWEAT index was created. The version of SWEAT described above (Miller, et al., 1971, 1972) is the second of three that were developed, and is perhaps the most widely known and used. In the first version (Bidner, 1970) no shear term was included, while in the third version (Miller and Maddox, 1975), 900 meter values of dewpoint temperature and wind speed replaced those at 850 mb, and the shear term was replaced by a step function of the veering of the wind direction in the 900 meter to 500 mb layer. The second version of SWEAT, henceforth described, evaluates the thermodynamic and wind structures of the 850-500 mb layer for the sole purpose of evaluating severe storm potential. Using data from 328 case studies of tornadic weather events, plus daily weather forecasting experience, important storm indicators and their relative weights were identified and subsequently combined to form the index. Then, from distributions of SWEAT values for 102 observed severe thunderstorm occurrences and, separately, 57 tornado cases, the value 300 was found to be the lower threshold for the occurrence of severe thunderstorms and the value 400 was found to be the lower threshold for tornadoes. David and Smith (1971) independently found a lower threshold of 250 for the occurrence of severe thunderstorms and for tornadoes in the eastern two-thirds of the United States. Reap and Foster (1979) found SWEAT to be a valuable predictor in the MOS scheme for 12-36 hour forecasts of family tornado outbreaks in the United States. Miller et al., (1972) stated that "The SWEAT index should not be used in the prediction of ordinary thunderstorms", since its inclusion of the wind shear term and minimum values for stability and wind speed were intended to discriminate between non-severe and severe thunderstorms. They also noted that the index was intended only as an indicator of the potential for severe weather development, since a triggering mechanism is necessary to lift the air andd realize the potential.

7. Convective Instability index of Reap

(Reap and Alaka, 1969; Bonner et al., 1971; Reap, 1974)

$$C1IR = \theta_{e_{700}} - (\theta_{e_{sfc}} + \theta_{e_{850}})/2,$$

where 0 , the equivalent potential temperature, is obtained by raising a parcel dry-adiabatically from its initial level to its LCL, then raising it moist-adiabatically until the moist and dry adiabats become parallel (that is, until all moisture has been condensed out of the parcel), then compressing it dry- adiabatically down to 1000 mb. $\theta_e$, like $\theta_w$, is conservative with respect to both dry- and moist- adiabatic processes.

Numerically,

$$\theta_e = T^*(1000/p)^{.286} * \exp(Lw/c_p T^*_c) \ (^oK),$$

where T*, p and w are the temperature, pressure and mixing ratio (g $kg^{-1}$) at the initial parcel level, $T^*_c$ is the parcel's condensation level temperature ( K ) , L is the latent heat of condensation, and c is the specific heat of dry air.

A forerunner of this measure of convective instability was developed by Reap and Alaka (1969), which was then modified by Bonner et al. (1971) to the form above, and subsequently applied by Reap (1974), Reap and Foster (1975) and others, often in combination with a measure of 700 mb 12-hour vertical parcel displacement, as a MOS predictor of thunderstorms and severe weather outbreaks in the eastern two-thirds of the United States. Values of the index ≤ 0 ($\theta_e$ decreasing with height), likely caused by cooler, drier air at 700 mb above warmer, moister low-level air, are indicative of convective instability and perhaps potential storm development. When combined with the parcel vertical displacement term, it was found to be the second-leading predictor of April-September severe local storms (Reap, 1974), and by itself was found to be highly related to 15 March-15 September thunderstorms (Reap and Foster, 1979).

8. Convective Instability index of Barber (Barber, 1975)

$$CUB = \theta_{e_{\text{lowest 100 mb}}} - \theta_{e_{\text{600-500 mb}}}.$$

This index, developed for use in a statistical study relating the distributions of several meteorological parameters to severe storm occurrence in the United States during March-June 1971-1973, is estimated by subtracting the 600-500 mb mean equivalent potential temperature from that of the lowest 100 mb. Values $\geq 0$ (again, $\theta_e$ decreasing with height) indicate the existence of convective instability and perhaps the potential for convective development.

9. Measures of Parcel Buoyant Energy

(e.g., Saucier, 1955; Stackpole, 1967; USAF, 1969)

On thermodynamic charts such as the Skew T-Log p, the areas lying between the environmental temperature sounding curve and an air parcel's hypothetical adiabatic ascent curve are proportional to the amount of energy required by the parcel to force it to ascend and/or the amount of energy released by the parcel during its free ascent. The magnitudes (cal $g^{-1}$ or J $kg^{-1}$) of such areas can be found using the relationship for the change in kinetic energy of a unit mass displaced some vertical distance (see Saucier, pp. 68-70).

a. Dynamically-induced lifting of surface air parcels

Suppose, for example, that the enviromental lapse rate of temperature is in the conditional state. Near the surface, an unsaturated parcel, being cooler/more dense than its surrounding environment ("negatively buoyant"), must be supplied with kinetic energy by some lifting mechanism to force it to rise dry-adiabatically towards its LCL. The lifting mechanism here refers to some type of dynamic forcing (low-level convergence, frontal or orographic lifting, etc.). When/if the parcel reaches saturation, it will ascend moist-adiabatically, whether it is still negatively buoyant and being forced upward or has become "positively buoyant" and is rising freely, releasing latent energy to the environment. For the latter to occur, the parcel will have had to pass its LFC, becoming warmer/less dense than its environment. At yet some higher point during ascent, the parcel may again cool back to the environmental temperature, having reached its Equilibrium Level (EL). By this time, the cloud parcel has achieved its maximum momentum and may continue to rise for some time above the EL (representing an "overshooting" cloud top); but since the parcel has again become cooler/more dense than its environment, it is negatively buoyant and will decelerate to rest or perhaps begin sinking. The amount of low-level kinetic energy required (negative energy to be overcome) by a parcel to force it upward and the existence and strength of some dynamic process to provide the needed uplift are the critical factors for obtaining actual instability from conditional instability. The less the energy required and/or the stronger the forcing mechanism, the more easily instability is achieved. A lower value of negative energy can be caused by the existence of a moist lower layer and/or a thermal lapse rate tending toward dry-adiabatic.

When negative energy is compared with the latent energy released by the parcel during free ascent (positive energy), the degree of conditional instability present is established, allowing an estimate of the amount/strength of subsequent convective activity. This combination is often referred to as "net energy" (sum of negative and positive energies). If positive energy exceeds negative energy (net energy > 0), "real latent instability" is said to exist, indicating the potential for stronger convective activity to form. If negative energy exceeds positive energy (net energy < 0), "pseudo-latent instability" is said to exist, indicating that weaker convective activity may form. The absence of positive energy suggests the existence of "latent stability" and the likelihood that little or no convective activity may form. Lamb and Peppier (1985) and Peppier and Lamb (1988) assessed these energies for an observed surface parcel. Recently, similar measures of negative buoyant energy and positive buoyant energy have been developed: Convective Inhibition - CIN (Colby, 1984), and Convective Available Potential Energy - CAPE (Moncrieff and Miller, 1976), respectively.

b. <u>Heating-induced lifting of surface air parcels</u>

Consider a parcel in an environment similar to the one above. If the parcel is unsaturated, it must again be supplied with kinetic energy to force it to rise dry-adiabatically. If, in this case, the energy is supplied by diurnal heating at or near the surface and is sufficient, the parcel becomes positively buoyant and begins to ascend towards its Convective Condensation Level (CCL - discussed later). The negative energy to be overcome by this parcel represents the amount of low-level heating required by the parcel to warm it to its critical Convective Temperature (CNVT - discussed later) and consequently induce convective overturning. If the parcel does achieve saturation, it buoyantly-rises past the CCL, perhaps as far as its EL. This positive energy again represents the latent energy released by the freely rising parcel. A small value of negative energy, indicative of a moist surface layer, suggests that less low-level heating is required to induce overturning and propel "thermals" past their CCLs into regions where they can rise freely and contribute to the formation of cumulus clouds and perhaps rainfall. Large values of positive energy in relation to negative energy suggest that enhanced convective activity can occur. Lamb and Peppier (1985) and Peppier and Lamb (1988) examined the negative energy component only, but utilized not only the observed surface parcel but also 50 and 100 mb surface layer mean parcels.

### 3.3 SSITPs for Parameterizing Static Stability in Numerical Models and Diagnostic Studies

Thermal measures of static stability (Gates, 1961)

For an atmospheric layer:

$$SS1 = -T^{*}/\theta \ \partial\theta/\partial p \ (\mathrm{deg\ db^{-1}}),$$

$$SS2 = -\partial\theta/\partial p \ (\mathrm{deg\ db^{-1}}),$$

$$SS3 = -1/\theta \ \partial\theta/\partial p \ (10^{-2}\ \mathrm{db^{-1}}),$$

$$SS4 = -\alpha/\theta \ \partial\theta/\partial p \ (10^{-4}\ \mathrm{km^{2}\ s^{-2}\ db^{-2}}),$$

$$SS5 = -p/\theta \ \partial\theta/\partial p \ (10^{-1}\ \mathrm{dimensionless}),$$

and

$$SS6 = -\rho/\theta \ \partial\theta/\partial p \ (10^{2}\ \mathrm{deg\ s^{2}\ km^{-3}}).$$

Compiled by Gates (1961), these six measures of static stability, based on the expression $\gamma_d - \gamma$, where $\gamma_d$ is the dry-adiabatic lapse rate and $\gamma$ is the environmental lapse rate, parameterize static stability for use in numerical models. If $\gamma < \gamma_d$ ($\theta$ increasing with height), static stability is said to exist, while if $\gamma > \gamma_d$ ($\theta$ decreasing with height), static instability exists. Thus, values of these normalized (except SS3) lapse rates of potential temperature decrease with increasing instability. Like the Vertical and Total Totals indices, values indicative of strong thermal instability may occur when the supporting moisture necessary for the formation of convective weather is deficient. Gates (1961) used these measures to climatologically assess the mean vertical and horizontal variations of static stability over the United States. Lamb and Peppier (1985) and Peppier and Lamb (1988) computed these measures for Gates' deep 750-250 mb tropospheric layer.

### 3.4 SSITPs for Estimating Cloud Base Heights and Critical Surface Convection Temperatures

1. Lifting Condensation Level (LCL)

(e.g., Saucier, 1955; Huschke, 1959; Stackpole, 1967; USAF, 1969)

The Lifting Condensation Level (LCL) is the level at which a parcel of air becomes saturated after it has been dynamically-forced upward dry-adiabatically. On a thermodynamic diagram. the LCL is located at the point of intersection of the saturation mixing ratio curve corresponding to the parcel's initial dewpoint temperature and the dry-adiabat representing the parcel's initial temperature. and can be interpreted as the approximate height above the surface of the base of a cumuliform cloud or cloud deck produced by forced lifting. A low LCL/cloud base, indicative of a less-thick unsaturated (subcloud) layer, is associated with air masses having abundant low-level moisture (the thickness of the unsaturated subcloud layer is inversely proportional to the amount of low-level moisture present) and, hence, greater rainfall-producing potential if a sufficient lifting mechanism exists. Parcels characteristic of the surface or of the mean properties of a specified surface layer typically are used for determining cloud base LCLs (Lamb and Peppier, 1985, and Peppier and Lamb, 1988, considered an observed surface parcel as well as 50 and 100 mb surface layer mean parcels). The geopotential height of the LCL above the local surface can be obtained using the hypsometric equation and the characteristics of the parcel at its initial position and at the LCL. This value represents the geopotential thickness or depth of the layer from the surface to the LCL. Though few studies have considered the relation between the height of the LCL and rainfall amounts (e.g., Achtemeier, *et al*. 1978 - see Section 4.1.a, p. 23), the LCL is a routinely-reported sounding parameter. Recently, it has been related to fair-weather cumulus clouds by Stull and Eloranta (1985) and Wilde *et al*. (1985). They found, using 1983 data from Oklahoma, that LCL estimates of cloud base height tended to vary in the horizontal, with deviations from the horizontal average of 15-30 percent occurring over distances of 20 km or more, likely due to local variations in temperature and moisture (Wilde *et al*., 1985). In addition, it was found that LCLs were relatively low in the morning, rose rapidly during the late morning hours into the afternoon, reached a peak approximately three hours before local sunset, and then decreased rapidly into the early evening hours (Stull and Eloranta, 1985). LCLs derived from surface observations were found to provide an adequate measure of the actual local cloud base height and could be used operationally whenever direct observations or pilot reports of cloud base height were missing.

## 2. Convective Condensation Level (CCL) and Convective Temperature (CNVT)

(e.g., Saucier, 1955; Huschke, 1959; Stackpole, 1967; USAF, 1969)

The Convective Condensation Level (CCL) is the level at which a parcel of surface air will begin to condense if it is heated sufficiently at the surface to produce dry-adiabatic ascent. On a thermodynamic diagram, the CCL is located at the point of intersection of the temperature sounding curve and the saturation mixing ratio curve corresponding to the mixing ratio of the inital parcel state. The dry-adiabat through this point extending back to the surface approximates the lowest, critical Convective Temperature to which the surface air must be heated before the parcel, or "thermal", will rise towards its CCL without ever being cooler than its environment. It also represents the ascent curve of the yet unsaturated parcel. The CCL can be interpreted as the height of the base of cumuliform clouds which can be produced by thermally-driven convection, and the convective temperature represents the critical condition for the initiation of cumulus cloud development by heating. A low CCL/cloud base, again indicative of a less-thick unsaturated subcloud layer, is associated with an air mass containing abundant low-level moisture having the potential for spawning cumulus clouds and perhaps rainfall if enough heating is provided. Again, the thickness of the unsaturated layer is inversely proportional to the amount of low-level moisture present. The spread between convective temperature and surface temperature is inversely proportional to the amount of heating that is required to induce convective overturning. The geopotential height of the CCL above the local surface is obtained using the hypsometric equation, and represents the thickness or depth of the layer from the surface to the CCL. When the observed surface temperature reaches the critical convective temperature, the CCL and the LCL are at the same height, but when it is less than this temperature (typically observed), the CCL is above than the LCL. The CCL is also identical to the LFC for a heating-induced lifted parcel. Renne and Sinclair (1969) found the height of the CCL to be related to the occurrence of hail over northeastern Colorado; specifically, a majority of hail occurrences were linked to lower than average CCLs while most non-hail occurrences were associated with higher than average CCLs, reflecting increased low-level moisture content on hail days.

# 4. PAST APPLICATIONS OF STATIC STABILITY INDICES AND THERMODYNAMIC PARAMETERS

We now review the past uses of SSITPs that are documented in the literature. Primary emphasis is given to research which involved some facet of warm-season (e.g., March-September) rainfall or convective activity for all or part of North America. Since SSITPs have been reported on in an uncountable number of sources throughout the years, both in the literature and in operational forecasting, this review is not meant to be exhaustive. However, we have tried to capture the flavor of the past applications of SSITPs. Most of the SSITPs discussed below were defined in Section 3.

It will be shown here that, in contrast to Lamb and Peppier (1985) and Peppier and Lamb (1988), many of the investigations were confined to a limited number of SSITPs, localized geographic regions, and/or relatively short time periods. Many times, the SSITPs selected for analysis were done so on the basis of their traditional or intended use rather than on a demonstrated effectiveness for the particular region or phenomenon being studied.

Regarding the latter, the Air Weather Service (USAF, 1969) some years ago warned forecasters about the perils of haphazardly using stability indices, stating "experience has shown that an index or critical index value which is significant in one region (or season) may not be in another. Hence, the stability-index chart should be more of an experimental or investigative tool than a routine one, unless extensive correlation studies have selected an index significant for the extended general application, and the critical values for various weather conditions have been determined".

With these thoughts in mind, we now commence the literature review.

## 4.1 North America

### 4.1.a. Rainfall

In an early study, Dickey (1956b) related several atmospheric variables to the occurrence of summertime showers at Grand Junction, Colorado (a similar analysis was carried out by Tillotson (1951), for thunderstorms at Denver, Colorado - see Section 4.1.d, p. 32). Among the variables analyzed were three stability measures: the difference between an early morning surface dewpoint temperature and the previous evening's 500 mb temperature; a modified Showalter index in which the expected afternoon maximum temperature and an early morning surface dewpoint temperature were used for the initial parcel; and the pressure difference between the CCL and the freezing level. Data from July-August 1947-1950 were used to determine the degree of shower activity and the values of the various meteorological variables. A shower "day" was defined as the occurrence of at least one of the following: measured rainfall at Grand Junction, including traces; thunder heard at the station but no rainfall measured; or showers in sight but no rainfall recorded. While a "definite" relationship (percentage frequency of occurrence of showers versus class interval values of the particular stability variable) was found between the difference in the morning 0530 MST surface dewpoint temperature and the previous evening's 2000 MST 500 mb temperature, and afternoon and evening shower activity, it was not as pronounced as when the dewpoint was considered alone. When the difference in 0530 MST surface dewpoint and a morning 0800 MST 500 mb temperature was related to the showers, little improvement was found. A somewhat weaker relationship was found between the modified Showalter index and showers. On the other hand, a "fairly strong relationship" between the CCL/freezing level pressure difference and showers was found, likely due to a previously-demonstrated association between 0530 MST surface moisture (a component in the determination of the CCL) and shower activity (the 0530 MST surface dewpoint and 2000 MST sounding from the previous evening were used to find the CCL, while the freezing level was read from the sounding). A joint consideration of the CCL/freezing level difference and 700-500 mb dew point spread proved to be a useful component in the development of a forecasting chart. Similar results of a related study using later 1951-1954 rainfall values were reported in Dickey (1956a).

Sullivan and Severson (1966), in a study of summer showers over the mountains of Colorado, analyzed the Showalter index among other parameters thought important for shower formation. Using data from July 1961-1964 for two triangular areas located in the western half of the state (20 precipitation stations within each triangle) to determine the areal distribution of showers, and 1700 MST facsimile data (afternoon soundings) to compute the Showalter index, more instability was found to occur on days with greater precipitation. However, the instability difference between light and heavy precipitation days was too small to be of significance for forecasting purposes.

Curtis and Panofsky (1958) showed that probabilities of night-time convective precipitation and fair weather over the eastern two-thirds of the United States for 1-6 and 8-15 July 1955 were closely related to large scale static stability, in the form of a modified Showalter index, and vertical motion considerations. Their modified index was found to be a better indicator of convective precipitation than the original Showalter index, but both were found useful for indicating the intensity of convection.

Lyons (1964, as summarized by Dennis et al., 1967), analyzed rainfall data from cloud seeding experiments in western South Dakota during 1964 and found little correlation between the Showalter index and rainfall. He also found little correlation between the Lifted index and 1965 rainfall.

Hollis and Bryan (1965) used rainfall amounts from 74 stations in Arkansas, southeastern Missouri, western Tennessee, northeastern Louisiana, and northern Mississippi to relate areal shower coverage and average rainfall per station to the K-index during the late spring to late fall season. For rainfall during the 24 hour period following the 1200 GMT observation time, they found that for K values less than +20 about 13 percent of the study area was covered with showers and the average rainfall per station was 0.03 inches. For K in the range 20-24, these values rose to 30 percent and 0.08 in., for K from 25 to 29 they rose further to 44 percent and 0.18 in., and for K values of 30 and above, 61 percent of the area had showers and the average rainfall amount per station was 0.20 in. Thus, for this mid-south region of the United States, a definitive relationship was detected between increasing values of the K-index and increasing rainfall amounts for the above warm season period.

Several studies have analyzed stability/rainfall relationships in the south Florida region. Carson (1954), in studying the problem of forecasting summertime air mass showers at Miami, Florida, related the Showalter index to four different categories of upper air soundings. Soundings taken at 0300 and 1500 GMT (treated separately) during July-August 1950 were categorized as either D (total rainfall of zero at Miami within the 12 hour period beginning shortly after the sounding was taken), W (trace through 0.05 in.), WW (0.06-0.99 in.), and WWW (greater than or equal to one inch). For the evening soundings (0300 GMT), average values of the Showalter index for the four sounding types were 2.6 (D), 2.0 (W), 2.0 (WW), and 0.9 (WWW), and for the morning soundings (1500 GMT) were 4.2 (D), 2.3 (W), 2.8 (WW), and 1.6 (WWW). Both data sets thus displayed a good relationship between sounding conditions and rainfall amounts, particularly those at 0300 GMT. The Showalter index was accordingly deemed to have quantitative forecast value at Miami.

Estoque and Fernandez-Partagas (1974) also found the Showalter index taken from morning soundings at Miami to be related to radar-observed summertime convective rainfall over south Florida during July-August 1973. Showalter values less than or equal to zero were found to coincide with greater echo coverage (areal percentage) than values above zero at all times during a 24 hour period. An unspecified negative correlation also was obtained between maximum echo coverage and the index.

Burpee and Lahiff (1984) related several kinematic and thermodynamic parameters, including the K and Showalter indices, to area-averaged rainfall amounts in a study of summertime rainfall variations in south Florida. Area-averaged midnight to midnight (EST) rainfall amounts for seven separate regions were computed from observations at 138 locations in the southern half of the Florida peninsula during June-September 1973-1976. Frequency distributions of the daily values of the all-region-averaged rainfall on sea-breeze days (days with relatively little early morning cloudiness) and disturbed days (days with extensive cloudiness from fronts, upper air disturbances, easterly wave troughs or weak tropical systems) were ultimately correlated to the various kinematic and thermodynamic parameters. Those parameters were evaluated using combined 0700 EST upper air data from four sites in south Florida. The K-index was found to be significantly correlated ($r = +0.32$) to rainfall on sea-breeze days and somewhat less correlated on disturbed days (+0.23). On the other hand, the Showalter index was poorly correlated to rainfall on both types of days (-0.05 and 0.02, respectively).

Watson and Blanchard (1984) analyzed the change in the correlation between total area divergence and convective rainfall in south Florida when other meteorological parameters were varied. Included among those parameters, derived from 1200 GMT Miami soundings, were the K and Showalter indices and a "net positive buoyant energy" that is similar to the net energy parameter described in Section 3.2 (pp. 15-16). Area-averaged rainfall totals were derived from radar data and adjusted using 66 raingages from the Florida Area Cumulus Experiment (FACE) network of July-August 1975. Rain periods were coupled with the closest occurring convergence event in the correlation analysis. The Showalter index was found to be "not well suited for the south Florida environment". Higher correlation magnitudes/more rainfall occurred for convergence events with greater stability than for events with more instability (correlations of -0.68 for $SI > +2$ and -0.49 for $SI \leq +2$). Results were somewhat similar for net positive buoyant energy, as more rainfall occurred during convergence events with less buoyant energy than for events with more energy, but correlation coefficient magnitudes were somewhat larger during the events with greater buoyant energy (-0.63 for buoyant energy > +1000 J/kg and -0.57 for buoyant energy ≤ +1000 J/kg). On the other hand, the K-index fared somewhat better. Correlations grew as the K-index increased up to a certain point (correlations of -0.41 for K < +25, -0.78 for +25 ≤ K ≤ +29, then only -0.60 for K > +29). In addition, the average rainfall was greater for the middle range of K than its lower and upper extremes when all convergence events were considered, but less rainfall occurred, by comparison, in that range of K values for only the events when it rained.

Flueck et al., (1986), as part of a study to assess cloud seeding treatment effects during FACE, computed correlation coefficients between the log transformation of the "total target rainfall as measured by a fixed network of rain gages and interpolated to a regular grid", collected over a fixed six hour period beginning with the time of initial seeding, and potential predictor variables, including the K-index. Nearly 100 raingages in the FACE-2 target area of south Florida during June-August 1978 and July-August 1979 were used to compile this rainfall response variable, and West Palm Beach soundings were used for the computation of the K-index. A correlation of +0.42 was found between the K-index and the rainfall variable for 26 samples, but the index was not selected by a guided linear regression modeling procedure for determining the most important predictors.

Stability/rainfall relationships have also been examined for other diverse sections of North America. In an attempt to improve forecasts of areal summertime shower coverage over the lower Rio Grande River Valley of south Texas, Cimino and Moore (1975) computed correlation coefficients between areal shower coverage and several potential predictor variables, including the K, Showalter, and Lifted indices. Twelve hour (1200 GMT to 0000 GMT and 0000 GMT to 1200 GMT) areal shower coverage was estimated from a combination of three data sources: radar from Brownsville; 24 hour rainfall amounts from an eleven station raingage network; and six hour rainfall amounts from Brownsville and McAllen. These data spanned the period June-August 1971-1973, comprising 188 cases. 1200 GMT and 0000 GMT soundings from Brownsville were used to compute the predictor variables. Correlations of +0.40, -0.23, and +0.13 were found between the rainfall and the K, Showalter, and Lifted indices, respectively. The Showalter index was selected for testing in subsequent development of forecast graphs because the K-index, though more strongly correlated, was highly intercorrelated with mean 800-500 mb relative humidity, an important moisture predictor variable. The Lifted index had the opposite correlation sign to that expected, and had no relationship with areal shower coverage. It was hypothesized that the latter occurred because of the persistent low-level moisture that resides in the region regardless of the moisture content aloft. The Vertical, Cross, and Total Totals indices were also tested and said to give results (not shown by authors) similar to those of the Showalter.

A body of work undertaken at the Illinois State Water Survey during the 1970s addressed the relationships between "environmental covariates" and actual area-averaged convective rainfall amounts for the vicinity of Dodge City, Kansas (Ackerman et al., 1976; Achtemeier et al., 1978; and Achtemeier and Schickedanz, 1979). It was conducted as part of the High Plains

Experiment (HIPLEX) that ultimately involved cloud seeding. Daily natural rainfall totals (0700-0700 CST) from a network of 22 precipitation stations within a 175 km radius of Dodge City were used to compile various rainfall area-averages. In addition, three-hour (0000-0300, 0300-0600, 0600-0900, 0900-1200, 1200-1500, 1500-1800, 1800-2100, and 2100-2400 CST) and six-hour rainfall amounts (1200-1800 CST) were obtained for a smaller number of stations and six-hour (1200-1800 CST) maximum radar echo percent coverages were employed as a quantification of convective activity. All rainfall and radar reports were from June 1958-1970. Covariates were computed from 1200 GMT (0600 CST) soundings for June 1958-1970, in addition to 0600, 1200, and 1500 CST surface data for June 1965-1970. Among the many covariates analyzed were the K, Showalter, Vertical Totals, Cross Totals, Total Totals, Total Energy, and Potential Wet-Bulb indices, and the LCL, CCL, and convective temperature.

No single environmental covariate was able to explain more than about 10 percent of the rainfall variance for any of the rainfall stratifications at Dodge City, with the 0600 CST surface data LCL and the 1200-1800 CST maximum radar echo percentage coverage pairing giving the largest correlation magnitude, -0.32 (Achtemeier et al., 1978). The largest correlation magnitude (0.28) for actual rainfall amounts (24 hour totals) was yielded by the K-index (0600 CST soundings), and separately by the CCL and LCL (0600 CST soundings and 1500 surface observations; Ackerman et al., 1976). See Table 2 for a comprehensive listing of the HIPLEX correlation results. Only correlation magnitudes $\geq$ 0.15 were reported by Achtemeier et al. (1978) for the three-hour rainfall stratifications.

Achtemeier et al. (1978) and Achtemeier and Schickedanz (1979) offered the following suggestions for the relatively low correlation magnitudes found during HIPLEX, and particularly for those covariates derived from morning soundings and observations:

(1) The rainfall-producing environment may have been poorly sampled. Covariates from early morning observations may have little relationship with events that occur later when rainfall is triggered by some type of dynamic mechanism. Stability measures are sensitive to local variations of the thermal and moisture stratifications. The observations from which these covariates were derived reflect these sensitivities and may not be representative of the overall rainfall-producing environment. The Midwest and Great Plains of the United States are often characterized by shower-producing systems that occur on space scales of no larger than 100 km and time scales of a few hours. The advance of these systems may alter the thermodynamic structure of the local atmosphere so greatly that the early morning observations may have little relation to later conditions.

(2) The low density of the raingage network at Dodge City (approximately one gage per 6500 km ) inadequately sampled the rain which fell, producing non-representative area-averages and poor correlations.

(3) Perhaps little or no relationship actually exists between these covariates and convective rainfall at Dodge City.

Table 2. Compilation of HIPLEX correlation coefficient values for various SSlTPs and rainfall stratifications. Region of study was a square 175 km on a side centered at Dodge City, Kansas. All station rainfall was area-averaged within the square. "CCL" and "CNVT" were computed from an initial parcel having the surface temperature and a surface. layer average (below 820 mb) mixing ratio with 2 g $kg^{-1}$ added. "LCL" is the same as the Lamb and Peppier (1985) and Peppier and Lamb (1988) "LCLSFC".

| Reference | Data Period | SSITP data | Rainfall/Proxy | SSITP | Correl |
|---|---|---|---|---|---|
| Ackerman *et al*. (1976) | June 1958-70 | 0600 CST (1200 GMT) soundings | 24-h pre-sounding (0700-0700 CST) rainfall amounts | K | 0.21 |
| | | | | VT | 0.27 |
| | | | | CCL | -0.28 |
| | | | | CNVT | -0.26 |
| " | June 1965-70 | 0600 CST soundings | 24-h post-sounding (0700-0700 CST) rainfall amounts | K | 0.28 |
| | | | | CT | -0.25 |
| " | " | 1500 CST surface data | 24-h (0700-0700 CST) rainfall amounts | LCL | -0.28 |
| Achtemeier *et al*. (1978) | June 1958-70 | 0600 CST soundings | 24-h post-sounding (0700-0700 CST) rainfall amounts | K | 0.24 |
| | | | | SI | -0.16 |
| | | | | VT | 0.05 |
| | | | | CT | -0.23 |
| | | | | TT | 0.14 |
| | | | | TEI | 0.04 |
| | | | | PWBI | 0.07 |
| | | | | CCL | -0.18 |
| | | | | CNVT | 0.11 |
| " | " | " | 0000-0300 CST (3-h amounts) | K | 0.16 |
| | | | | VT | 0.22 |
| " | " | " | 0300-0600 CST | K | 0.15 |
| | | | | VT | 0.20 |
| | | | | CCL | -0.19 |
| | | | | CNVT | -0.17 |
| " | " | " | 0600-0900 CST | CCL | -0.20 |
| | | | | CNVT | -0.18 |
| " | " | " | 0900-1200 CST | CCL | -0.17 |
| | | | | CNVT | -0.24 |
| " | " | " | 1200-1500 CST | K | 0.15 |
| | | | | CT | -0.15 |
| " | " | " | 1500-1800 CST | NONE | |
| " | " | " | 1800-2100 CST | SI | -0.20 |
| | | | | CT | -0.19 |
| | | | | TT | -0.20 |
| | | | | PWBI | -0.15 |

Table 2 (continued)

| Reference | Data Period | SSITP data | Rainfall/Proxy | SSITP | Correl. |
|---|---|---|---|---|---|
| " | " | " | 2100-2400 CST | NONE | |
| " | June 1965-70 | 0600 CST surface data | 24-h (0700-0700 CST) rainfall amounts | LCL | -0.20 |
| | " | " | 6-h (1200-1800 CST) rainfall amounts | LCL | -0.13 |
| | " | " | 6-h (1200-1800 CST) maximum radar echo percent coverage of sampling area | LCL | -0.32 |
| | " | 1200 CST surface data | 6-h (1200-1800 CST) rainfall amounts | LCL | -0.19 |

Several SSITPs were evaluated as potential identifiers of precipitation anomalies at urban and rural locations in the St. Louis metropolitan area as part of METROMEX (Metropolitan Meteorological Experiment), conducted from 1971-1975 (Ackerman, et al., 1978). The SSITPs (K, Showalter, Lifted, Vertical Totals, Cross Totals, and Total Totals indices, and the LCL and CCL) were computed from afternoon (1330, 1400, 1600 CDT) soundings in and around St. Louis for the 1973 and 1975 portions of the experiment during July and August. The Showalter index was found to be a fairly good indicator of rain conditions but overpredicted the probability of showers (30-35 percent of fair weather cases had SI < +4, which was used as a critical value for significant instability). The Lifted index gave results similar to those for SI, while the K-index predicted scattered to widely scattered thundershowers which did not materialize (in 1973). The Totals indices were poor predictors of thunderstorms at both urban and rural locations. It was summarized that the stability indices examined did "not indicate any strong differences between urban and rural locations", but the "urban atmosphere might be slightly less favorable for thunderstorm development than the rural atmosphere". Concerning CCLs and LCLs, the CCLs were lower and warmer on rain days than on non-rain days, and both the CCLs and LCLs were higher and cooler over urban sites, with the CCL difference more pronounced.

Zawadzki and Ro (1978) and Zawadzki et al. (1981) related measures of maximum buoyant parcel energy and daily mean surface parcel energy (among other variables) to (i) 5, 10, and 30 minute rain rate maxima from 14 raingages and radar, and (ii) daily mean rainfall rates from 74 gages, for May-September 1969-1970 in Quebec. Maniwaki upper air soundings both previous in time (Zawadzki and Ro, 1978) and closest in time (Zawadzki et al., 1981) to the maximum rainfall rate periods were utilized to compute the energy parameters. The correlations for 54 cases where the maximum rain rate was detected by the raingage network and the maximum energy corresponded to a parcel originating at the surface, included +0.79 (5 min. rain rate maximum), +0.74 (10 min.), +0.67 (15 min.), and +0.62 (30 min.), all significant at greater than the 99.5 percent level (Zawadzki and Ro, 1978). Thus, the shorter the rainfall averaging period, the larger the correlation. Zawadzki et al. (1981) similarly found a correlation of +0.79 between maximum parcel energy and maximum rain rate for 61 cases when the strongest instabilities again corresponded to a surface parcel, and a value of +0.77 between the daily mean surface parcel energy and daily mean rain rates from 80 storm cases when rainfall occurred in a 24 hour period.

In a related study investigating the influence of vertical wind structure on convective precipitation, Trudeau and Zawadzki (1983) correlated estimates of cloud base (LCL pressure), among other cloud structure variables, to maximum 5 min rainfall rates from storm systems over the Montreal region during the same 1969-1970 period. Using 49 storm cases, the correlation coefficient for the pressure at cloud base was only -0.03, but the correlation for the pressure at the top of the cloud (intersection of the moist-adiabat defined by the surface θ maximum and the environmental temperature sounding) was -0.67, and the correlation for the thickness of the cloud (natural log of the cloud base pressure divided by the cloud top pressure) was +0.76.

Ackerman, (ed., 1982) correlated total area divergence to area rainfall (similar to Watson and Blanchard, 1984, above) over ranges of other parameters such as the K and Showalter indices during the VIN (University of Virginia, Illinois State Water Survey, NOAA) field program carried out from 28 June to 28 August 1979 in central Illinois. A high density network of raingages (260) was used to determine 5 min. area depths, and routine and special rawinsonde releases at Peoria, Salem, and Champaign were used to evaluate the two indices. Correlation coefficients became more negative (-0.04, -0.47, -0.52) and rainfall amounts increased (0.39, 0.81, 4.92 mm) as the Showalter index decreased ($SI > +2$; $-1 \leq SI \leq +2$; $SI \leq -1$, respectively), and likewise became more negative (+0.15, -0.11, -0.50) and rainfall amounts increased (0.02, 1.54, 2.26 mm) as the K-index increased ($K < +22$; $+22 < K < +29$; $K \geq +29$, respectively). Thus, correlations between total area divergence and rainfall were stronger and rainfall was heavier when the Showalter index was moderate or low and the K-index was high, indirectly displaying a positive relationship between rainfall amounts and values of the two indices in central Illinois.

Barnston and Schickedanz (1984), as part of a study of the possible effect of irrigation on warm season (June-July) precipitation over the southern Great Plains (Texas panhandle), analyzed static stability in the form of the Lifted index. Using 1200 and 0000 GMT June soundings from Amarillo from the years 1960, 1965, and 1966, the Lifted index was. found to be 1° C lower over irrigated lands than over non-irrigated lands. It was stated that "the correlation between the lifted index and precipitation amount is not extremely high to begin with", but "the expectation from a slightly reduced lifted index is that occasionally a noticeably greater amount of rain would occur, or some rain would occur which otherwise would not", so that the slightly decreased index "occasionally could spell the difference between light showers and no showers in a synoptically marginal convergence situation".

Carleton (1986) examined the relationships between synoptic "bursts" and "breaks" of monsoon moisture for the southwestern United States summer precipitation anomaly and changes in tropospheric static stability during 1 July-15 September 1980-1982. Twice daily (0000 and 1200 GMT) soundings for five stations in Arizona, southern Nevada, and northern Mexico were used to compute SSITPs, while satellite observations, along with daily rainfall totals for 34 stations in Arizona, were used to identify burst and break situations. Four SSITPs were analyzed: surface-based LCL and CCL, convective temperature, and the K-index. 500 mb temperature was also analyzed in this context. Statistics for each of the SSITPs, stratified by sounding time, occurrence of bursts and breaks, and upper-air station, were compiled. It was found that LCLs were always lower than CCLs with differences more pronounced at 1200 GMT (morning). 0000 GMT (afternoon) condensation levels were usually higher than those in the morning. Both of these results correspond to those observed for most regions of central North America by Lamb and Peppier (1985) and Peppier and Lamb (1988), including Texas in the southwest. In addition, condensation levels were usually higher during monsoon breaks than during bursts with the exception of Empalme in northern Mexico, displaying the inverse relationship between condensation level heights and low level moisture content. The differences in these levels were statistically-significant (two-tailed t-tests) at the three Arizona and Nevada stations (Tucson, Winslow, and Desert Rock). Correspondingly, convective temperatures were higher during breaks than bursts, with differences significant at the three Arizona and Nevada stations and at Chihuahua (1200 GMT) in northern Mexico. Values of the K-index were larger everywhere during bursts, reflecting greater instability, except at Empalme at 0000 GMT. These differences were significant at Winslow, Desert Rock (0000 GMT only), and Chihuahua, but not at Tucson or Empalme. K-index values also were always larger in the afternoon, except at Empalme. This use of the SSITPs thus demonstrated that both moisture content and instability were greater during monsoon bursts than during breaks in the southwestern United States.

#### 4.1.b "Model Output Statistics" (MPS) Precipitation Forecast Modeling

Stability indices have been included as potential predictors in operational MOS "Probability of Precipitation" (PoP) and "Probability of Precipitation Amount" (PoPA) forecasting schemes for the United States. In PoP forecasting, measurable precipitation events have been treated in a "yes/no" occurrence/non-occurrence fashion, with occurrence being a rainfall amount of ≥ 0.01 inch (e.g., Glahn and Lowry, 1972; Klein and Glahn, 1974; Glahn and Bocchieri, 1976; Lowry and Glahn, 1976; Lowry, 1977; Zurndorfer, 1981). Conversely, in PoPA forecasting, measurable precipitation events have been categorized by amount (e.g., Klein and Glahn, 1974; Bermowitz, 1975; Bermowitz and Zurndorfer, 1979; Arritt and Frank, 1985).

Traditionally, PoP equations have been developed for various regionalizations of the United States, with one equation valid for an entire region. Throughout the course of MOS equation development (which is ever-changing), static stability has been found to be of somewhat less importance as a predictor category than either the relative humidity or vertical motion categories (e.g., Lowry, 1977), but the K and Total Totals indices usually have been among the candidate predictors selected from the screening process (e.g., Klein and Glahn, 1974). Individually, these two indices have been valuable predictors (particularly K) in the forecast equations, especially during the warm season of April-September (e.g., Lowry and Glahn, 1976; Zurndorfer, 1981).

Specifically, Lowry and Glahn (1976) and Lowry (1977), for the eastern seaboard region and the 1972-1973 cool season (October-March), found a "binary" form of the K-index (≤ +5) to be the fourth predictor selected in a 12 hour forecast equation based on 0000 GMT data (i.e., model output), while a "binary" Total Totals index (≤ +46) was the twelfth predictor chosen. A "binary" predictor is formed by assigning a value of one to a variable if it is less than or equal to a particular threshold (e.g., K ≤ +5), and a zero otherwise. Both indices were from Primitive Equation (PE) and Trajectory (TJ) model output. Although not documented, Lowry and Glahn (1976) found stability indices to be even more valuable predictors during the warm season.

Glahn and Bocchieri (1976) evaluated PE, TJ, and Limited-area Fine Mesh (LFM) model candidate predictors for PoP equations for the 1973-1974 cold season and the 1974 warm season. The K and Total Total indices were included among the predictors, but no details were given about their performance.

In Lowry's dissertation (1977), correlation coefficients were computed between the occurrence of 12 hour measurable rainfall observed at both 1200 and 0000 GMT and values of the K and Total Totals indices, in addition to the PoP forecast equation development. The indices were derived from the PE and TJ models ("smoothed predictors at hour 24" during daytime hours using 0000 GMT initial data) for the United States during April-September 1973. From national profiles, a maximum correlation magnitude of 0.29 was found for K values ranging from approximately +17 to +20, while a maximum of 0.23 was found for a Total Totals value of about +42. During forecast equation development for the 12-24, 24-36, and 36-48 hour projections and 14 subregions of the United States, the two indices were included as candidate predictors (among 100 total) only for the first two projections. Results for each time projection were given for each of the 14 regions defined during the 1973 warm season, using 0000 and 1200 GMT initial data. A synopsis of these results follows. For the K-index during the first forecast period (12-24 hours), 0000 GMT initial data, and all subregions combined, a binary K ≤ +15 was selected in the forecast equations seven times, K ≤ +20 was chosen four times, K ≤ +25 three times, and K ≤ +30 once. For thi6 forecast period and 1200 GMT data, selection frequencies were 2, 2, 1, and 1, respectively. For the second forecast period (24-36 hours) and 0000 GMT data (K limits of ≤ +5, ≤ +10, ≤ +15, and ≤ +20) they were 1, 2, 3, and 1, respectively; for this forecast period and 1200 GMT data they were 1, 2, 2, and 0, respectively. For the Total Totals index and its limits ≤ +30, ≤ +35, ≤ +40, ≤ +42, ≤ +44, ≤ +46, it was chosen for the first forecast period and 0000 GMT initial data 0, 0, 1, 3, 5, and 8 times, respectively. For first forecast period and 1200 GMT, the frequencies were 0, 0, 1, 5, 6, and 4. For the second forecast period and 0000 GMT they were 0, 0, 0, 6, 3, 3; and for this period and 1200 GMT they were 0, 2, 2, 1, 3, 6, respectively. Thus, the middle-range K-index limits of ≤ +15 and ≤ +20 were most related to the occurrence of measurable rainfall, particularly for 0000 GMT data, while the higher Total Totals limits of ≤ +42, ≤ +44, and ≤ +46 were the most related at either time. The K-index appeared in more equations for the 12-24 hour projection and 0000 GMT data than the other three projections by a factor of two, while the Total Totals index was selected uniformly over the four projections (somewhat more frequently for the two 12-24 hour projections). By region, the K-index was selected more often in the western United States (especially parts of the non-coastal Northwest), the upper Midwest, and the South Central states, while the Total Totals index was uniformly selected across the country, except for the Northeastern seaboard.

Zurndorfer (1981) developed PoP equations for the warm seasons of 1973-1980 in the various PoP regions, valid six-to-twelve hours in advance. Selected results were given for the first six predictors picked for three of the regions in the 0000 GMT 6-12 hour equations. For the northwest Pacific coast, the LFM-based K-index was the fourth predictor selected, while in the upper Midwest a binary LFM K-index ≤ +35 was the fifth selected, and no stability index appeared among the top six in the Northeastern region.

In the development of PoPA forecast schemes, model output stability indices (again, K and Total Totals) were found to be important predictors (and again, particularly K), more so during the warm season than the cool season (Bermowitz and Zurndorfer, 1979). The result for the K-index was in agreement with that found by Reap and Foster (1977b) for general thunderstorm forecasting (see Section 4.1.e, p. 39). Rainfall was categorized into the following amounts: ≥ 0.25, ≥ 0.50, ≥ 1.00, and ≥ 2.00 inches. Equations were developed for each of nine distinct regions for the 6 and 24 hour forecast periods beginning at 0000 and 1200 GMT, with predictors from all three (PE, TJ, LFM) models.

Arritt and Frank (1985), while exploring modifications to the then current MOS quantitative precipitation probability forecasting schemes in the eastern seaboard region of the United States, found that both the LFM-based K and Total Totals indices were extremely valuable predictors, particularly for the two heavier rainfall amount categories (same categories as Bermowitz and Zurndorfer, 1979), during both the warm and cool seasons. Specifically, for simultaneously-derived twelve-term equations for the cool season, the K-index was chosen twice by the regression procedure for the quarter-inch category (binary forms of the index over different thresholds), once for the half-inch category, and twice for the one inch category. The Total Totals index was chosen twice for both the quarter-inch and two inch categories. For individually-derived twelve-term equations for the cool season, and a standard set of predictors (eight categories of parameters), the K-index was among the first six terms chosen once for the quarter-inch category, twice for the half inch category, four times for the one inch category, and three times for the two inch category. It was among the last six chosen terms once, twice, once, and twice, respectively, for the four rainfall categories. The Total Totals index was among the first six terms chosen three times, two times, two times, and three times, respectively, and was among the last six terms two times, three times, zero times, and one time, respectively. Thus, stability indices turned out to be particularly valuable predictors for the heavier amount categories, as either the K-index or the Total Totals index was chosen first in three of the four equations for the two inch category. For an extended set of predictors (six more parameter categories added), the K-index was among the first six predictors once, twice, three times, and three times, respectively, and among the last six predictors three times, zero times, twice, and zero times, respectively. Similarly, the Total Totals was selected among the first six predictors twice, twice, once, and three times, respectively, and among the last six predictors once, twice, once, and once, respectively. For the warm season, little difference was found in a comparison to the cool season equations with respect to both the types of variables selected and/or the physical behavior implied by the regression coefficients.

### 4.1.c. Mesoscale Convective Weather Systems

The existence of a conditionally unstable environment has been found to be an important ingredient for the formation and longevity of rain-producing mesoscale systems that affect much of the eastern two-thirds of the United States - Mesoscale Convective Complexes (MCCs) and Mesoscale Convective Systems (MCSs), also defined by the combined term Mesoscale Convective Weather Systems (MCWSs) (e.g., Maddox, 1980, 1983; Fritsch and Maddox, 1981; Maddox and Fritsch, 1984; Fritsch et al., 1986; Schwartz et al., 1987; Velasco and Fritsch, 1987; Kane et al., 1987). MCWSs are large, rather circularly-shaped, long-lived convective weather systems which are capable of producing widespread areas of significant rainfall and thunderstorms (Fritsch et al., 1986). Often initiating along the eastern slopes of the Rocky Mountains and the adjacent High Plains (shifting northward as the warm season progresses), they become larger and more organized as they drift eastward, frequently undergoing diurnal pulsations which cause them to regenerate over a period of several days, and so affect large portions of the United States (Maddox, 1980). Maddox (1980) surmised that MCCs may "dominate the precipitation and convection climatologies for the growing season over the United States wheat and corn belts". Heideman and Fritsch (1984) found that nearly half of the warm season precipitation over the United States is produced by mesoscale phenomena, and that MCWSs were a prime contributor to the rainfall that occurs over the eastern two-thirds of the country. Fritsch et al., (1986) determined that MCWSs may account for 30-70 percent of the warm season precipitation that falls over the area bounded by the Rockies and the Mississippi River, and that this percentage is higher during the June-August period. As potential producers of widespread precipitation, these systems can be crucial deterrents to drought as well as mechanisms for enhancing midsummer crop development throughout the Midwest (Fritsch et al., 1986).

For MCCs (and presumably MCSs; Fritsch et al., 1986), Maddox (1983) suggested that "the most pronounced features within the genesis environment are the pre-existence of a moist and conditionally unstable environment over the GR (Genesis Region) and MR (MCC Region)", and that decay may begin as "the MCC weather system eventually moves into a more stable and convectively less favorable, environment, apparently initiating its demise". In that regard, the existence/lack of existence of areas of conditional instability as indicated by the Total Totals index (especially values of 50 and above to near 60) and ensuing development/dissipation of the MCC was observed (e.g., Maddox, 1983; Velasco and Fritsch, 1987). Velasco and Fritsch (1987) also noted that Lifted indices of -4 and less (sometimes as low as -7) were observed in the MCC region. Rodgers et al. (1984) used values of Total Totals of $\geq +50$ and K-index values of $\geq +30$ as two forecast parameters in a scheme for predicting MCCs.

### **4.1.d. Non-Severe Thunderstorms/Convection**

Tillotson (1951) related several atmospheric variables to the occurrence of September thunderstorms at Denver, Colorado. Among the stability measures considered were the change in wet-bulb temperature from 850 to 550 mb, the 800 to 500 mb temperature difference, the difference between the surface dewpoint temperature and the 500 mb temperature, and the pressure difference between the CCL and the freezing level. The analysis used 2000 MST soundings and thunderstorm occurrences the following day, for the period 1928-1947. The decrease in wet-bulb temperature from 850 to 550 mb was found to be "closely related" to thunderstorm occurrence; that is, the percentage frequency of thunderstorm occurrence increased as convective instability increased. Also, the frequency of thunderstorms increased as the 800-500 mb temperature difference increased, and as the the difference between surface, dewpoint and 500 mb temperatures increased. The relationship between the CCL-freezing level pressure difference and the frequency of thunderstorm occurrence was stronger for only the thunderstorm cases where both the surface dewpoint-500 mb temperature difference and the Denver-Boise (Idaho) 700 mb height difference were high. Both the surface dewpoint-500 mb temperature difference and the CCL-freezing level difference were used in a six-step forecasting method for afternoon and evening thunderstorms.

Means (1952) developed a thunderstorm climatology for the central third of the United States and identified typical features and synoptic patterns associated with the thunderstorm environment. Parameters found to be important were then used to develop a technique for making 24 hour thunderstorm occurrence forecasts for Chicago. The thunderstorm occurrence day data used to construct the climatology were from May-August 1904-1943. Among the parameters considered for forecasting purposes was the 850-500 mb temperature difference. A scatter diagram relating this temperature difference to the 850 mb mixing ratio was constucted with thunderstorm occurrence/non-occurrence information superimposed for June 1946-1947 and July-August 1945-1947. The thunderstorm information was for the 0030-1230 CST 12-hour period prior to the 1230-1230 CST 24-hour forecast period. Thunderstorm relative frequency "criterion" isopleths (40, 50, 60, and 70 percent) were also drawn. More thunderstorms occurred as both the temperature difference and mixing ratio increased, and all but one thunderstorm occurred for temperature differences and mixing ratios which were greater than or equal to those along the 40 percent relative frequency line. It was found that forecast skill was better if this 40 percent line was used instead of the 50 percent line for categorical thunderstorm forecasts. A test using data from June-August 1948 revealed that all thunderstorms occurred for temperature differences and mixing ratio values greater than or equal to those on the 40 percent line.

Showalter (1953), while developing his famous index for thunderstorm forecasting, found from experience that values of +3 or less were likely to be associated with showers and perhaps some thunderstorms. Thunderstorms were empirically found to have increasing probability as the index fell from +1 to -2, while for values of -3 and less severe thunderstorms occurred. Values of -6 and lower were thought to be associated with tornadoes. Testing of the index at a variety of locations in the United States revealed that it was a "highly significant but not perfect forecast tool".

Madigan (1959) evaluated several potential predictors of summertime (June-August) air mass thunderstorms during the development of an objective scheme for making 6 to 24 hour forecasts of their occurrence at Fort Riley, Kansas. Among the predictors were the LCL, CCL, and two stability indices ("Wet-bulb" and "Dry instability"), all being evaluated from soundings at Dodge City, Kansas, during 1957 and 1958. It was noted that "stability indices, convective and lifting condensation levels, freezing level and wet-bulb freezing level, and many other possible predictors were evaluated with little positive results". Of interest, though, was the fact that thunderstorms over the Plains were found to be mostly nocturnal, occurring between the hours of 1500-0900 CST, with a frequency peak at 0100 CST. Those that occurred during June-August were predominantly of the air mass variety, while those during April-May and September were mostly frontal or pre-frontal in origin.

George (1960) developed the K-index as a means for forecasting the occurrence of air mass thunderstorms over the eastern two-thirds of the United States and extreme southeastern Canada. Using a series of K-index charts with superimposed thunderstorm occurrence information from this region as the testing procedure, no thunderstorm activity was noted for K values less than 20, isolated thunderstorms were detected for values above 20 but less than 25, widely scattered thunderstorms were found for values above 25 but less than 30, scattered thunderstorms were detected for values above 30 but less than 35, and numerous thunderstorms were found for K values above 35. A composite chart containing isopleths of K and contours of arithmetically added 850 and 700 mb heights (the latter taken as confluence/diffluence contours) was found to be a quite useful tool for detecting air mass thunderstorm activity.

Cox (1961a, b) developed a semi-objective graphical technique for forecasting the occurrence of thunderstorms and associated weather in eastern Virginia, and also made a successful attempt to use them to forecast thunderstorm severity. Four thermodynamic measures ("Severe Weather Warning Center Stability Index", the 700 mb dewpoint depression, a "C" stability index, and the surface LCL) were computed from 1200 or 0000 GMT Norfolk (Virginia) soundings (depending on when showers occurred) for June-August 1958 and May-September 1959-1960. The forecast graphs based on these four parameters showed significant skill (via skill score calculations) in detecting the occurrence/non-occurrence of vertical cloud development and showed a high probability for detecting thunderstorm occurrence (Cox, 1961a). The graphs were also used successfully to make categorical yes/no thunderstorm forecasts (Cox, 1961b).

Ardis (1961) developed an objective method for forecasting summertime thunderstorms (mostly of the frontal or pre-frontal variety) at Truax Field (Madison, Wisconsin). The Showalter index and other predictors were evaluated from rawinsonde data collected during portions of June, July and August 1949-1958 (Chicago and Green Bay soundings). Thunderstorm occurrence observations were made at the Madison airport. Although no explicit evaluation of the Showalter index was given, the objective technique (prediction scattergrams), which made 24 hour determinations (beginning at 1200 GMT) of the occurrence (yes/no) of thunderstorms, was found to be a quite dependable forecast tool.

Sly (1966) developed three modifications of the Jefferson index for predicting summertime cumulonimbus activity over Edmonton, Alberta. The data used in the analysis included rawinsonde soundings at 0000 GMT (near the time of maximum heating during summer) and 1200 GMT (near the time of maximum radiational cooling) from 14 May to 31 August, 1962-1964, and corresponding surface weather reports and reports of cumulonimbus during 1100-2300 local time (1800-0600 GMT). All three modifications were found to be well related to the incidence and development of cumulonimbus clouds. The second of the three modifications (using 2100 GMT dewpoint and afternoon maximum temperature to compute G , and 0000 GMT 500 mb temperature) was particularly well related; a "sharp" increase in the incidence of cumulonimbus occurred for values of this index of +31 or higher. This was documented using graphs of the percent frequency of occurrence of a trace (report of distant cumulonimbus or lightning) or more of cumulonimbus development versus values of the indices. Tests for the spring and summer of 1964 showed this modification was accurate enough to be of use in an operational mode.

According to D. Johnson (1982), Bryan (1967) found the K-index to have a high correlation with thunderstorm activity over the mid-south portion of the United States, while Hambridge (1967) detected a similar high correlation between K and thunderstorm activity over the western United States.

Booth (1970) related nine stability indices (Showalter, Lifted, Jefferson (first version), Total Energy, Vertical Totals, Cross Totals, and Total Totals indices, and the "Dry Instability" and "Dew-Point" indices) to radar-observed convective activity in Texas. The analysis used 1200 and 0000 GMT soundings from ten stations and radar data from twelve stations, along with six-hourly synoptic charts, for the period 8-13 April 1969. Three of the nine indices (Showalter, Lifted, Cross Totals) were found to be the best indicators of convective activity, with verification rates (percent forecast convective activity which actually occurred) of 36.7, 37.5, and 37.2 percent, respectively. Other stability index verification rates were: Jefferson, 30.0

percent; Total Energy, 25.8 percent; Vertical Totals, 25.5 percent; Total Totals, 31.6 percent. The following thresholds were identified as indicating the occurrence of convective activity: Showalter ≤ +2; Lifted ≤ +2; Jefferson ≥ +30; Total Energy ≤ +1; Vertical Totals ≥ +24; Cross Totals ≥ +18; Total Totals ≥ +44. When the sign of vertical motion was considered jointly with stability, the verification rates increased sharply to 62.1 percent (Showalter), 65.7 percent (Lifted), and 64.7 percent (Cross Totals). In addition, Booth found the following average stability index values for convective activity: Showalter, +1.14; Lifted, +0.67; Jefferson, +29.5; Total Energy, +0.11.

Scoggins and Wood (1971) analyzed three parameters "essential for the formation of convective clouds and thunderstorms" over the eastern two-thirds of the United States - moisture, conditional instability, and vertical motion. Conditional instability was determined from the 850-500 mb temperature difference; if it existed, convective instability was then assessed from the 850 mb dewpoint depression. Using 1969 data for months representative of the four seasons (March, June, September, December), conditional and convective instability were found to exist in most regions of the United States east of the Rockies where radar echoes were observed. Thus, instability was found to not have been a deterrent to the formation of convection.

Neumann (1971) described methods of forecasting May-September thunderstorm activity at the Kennedy Space Center, Florida. In one technique based on forecast equations derived by non-linear multiple regression, an initial list of 250 sounding predictors (1200 GMT) was reduced to nine siginificant predictors of thunderstorm occurrence (using binomial probabilities), among which was the Showalter index.

Townsend and Younkin (1972) developed an objective method for forecasting summertime (June-September) thunderstorms at Washington, D.C. The method, in the form of a summertime thunderstorm index, which used numerical weather prediction output values comprised of a 24-hour forecast of 1000-500 mb thickness valid at 0000 GMT, an afternoon maximum temperature forecast, and a dewpoint temperature forecast at the time of the temperature maximum, was compared to the K and Lifted indices through use of a skill score based on the number of correct thunderstorm forecasts. Their index, based on independent data tests from 1 June-15 September 1971, was found to have greater skill in detecting thunderstorms than either observed or forecast values of the K and Lifted indices.

Lee (1973) used K-index values and 850 mb temperatures to develop an objective aid for fire weather forecasters. It gave probabilities for the occurrence of afternoon and evening lightning and thunderstorms in Oregon and Washington. Using 1200 GMT soundings from six stations and observations of lightning or thunderstorm occurrence for the period 1 June-30 September 1970-1972, linear and nonlinear (parabolic) regression equations and scatter diagrams were developed for the two predictor variables. Results were evaluated by a series of skill scores. It was found that use of the K-index with the 850 mb temperature was able to produce useful first-guess, short-range, thunderstorm probability forecasts.

Sanders and Garrett (1975) applied a convective plume model to the prediction of summer thunderstorms at Tampa, Florida, and compared it to another model based on a combination of Showalter index values and surface-500 mb precipitable water depth. Regression equations were developed for June-August 1970-1972 for each model using 1200 GMT Tampa soundings and the occurrence of thunder at that station during six hour periods beginning at 1800 GMT. The convective plume model was found to have more skill (via two skill scores) for forecasting thunderstorm occurrence than the Showalter index model, though skill concerned was "modest". The forecast skill was enhanced when a measure of zonal geostrophic flow was included.

Randerson (1977a, b) developed the "Z-index" (derived from discriminant analysis selection of the most significant of various sounding predictors) to determine the relative frequency of occurrence and the spatial variability of summertime (June-September) cumulonimbus and radar echo activity in the Yucca Flat, Nevada, area. Among the sounding parameters considered were the K, Total Totals, and SWEAT indices, though none were among the nine predictors ultimately selected by the discriminant process. A comparison of the forecast skill of the Z-index to the K-index was made (Randerson, 1977a), and the relationship of each to echo occurrence was assessed (Randerson, 1977b). The data used in the studies consisted of 1200 GMT soundings and observations of thunderstorm and cumulonimbus activity for June-September 1962-1971 (dependent sample) and 1972-1973 (independent sample) (Randerson, 1977a), and radar echo data for June-September 1971-1972 (Randerson, 1977b). Randerson (1977a) found that the Z-index explained more of the cumulonimbus activity variance (43 percent) than did the K-index (34 percent) for the dependent sample, and it had somewhat more predictive skill (via a skill score) for the independent sample. Randerson (1977b) found the relative frequency of occurrence of radar echo activity (echo days) to be related to the values of both indices, so that the frequency of occurrence of echo days could be determined from various categories of the indices.

Quiring (1977a, b) also investigated the prediction of cumulonimbus activity in the Yucca Flat, Nevada, area using the Z and K indices. Similar data were used in the two studies - for June-September 1962-1971 in the first and January-December 1962-1975 in the second. Quiring (1977a) found the K-index (via a probabilistic prediction curve) to be a useful guide for predicting the probability of occurrence/non-occurrence of cumulonimbus activity, though again the Z-index had somewhat more skill as a predictor variable. Quiring (1977b) determined that the reliability of the two indices was essentially the same when making cumulonimbus probability forecasts, but both failed to predict occurrence often enough within the higher probability categories.

McNulty (1979, 1981) used multiple discriminant analysis to develop short-term (12 hour) prediction functions for general and severe thunderstorm activity over the eastern two-thirds of the United States during April and July. Four predictors (K and Lifted indices, and mean low-level mixing ratio and mean 200-300 mb divergence) were used to develop and test the prediction equations, using data from 1977 (dependent sample) and 1978 (independent sample). These parameters were selected through experience as to their importance for thunderstorm occurrence. For general thunderstorms (see Section 4.1.f, p. 48, for severe thunderstorm results), the technique was found to be "fairly reliable" for probability of occurrence prediction.

Klazura and Pritchard (1980) analyzed potential predictors of the intensity and coverage of May-July Montana convective activity as estimated by radar. H1FLEX data collected during 1976 (digital radar data and rawinsonde soundings from Miles City, Montana) were used in the analysis to determine ten radar echo characteristic variables and 23 sounding predictor variables, among which were the K, Lifted, and Total Totals indices. The dominant predictor variables were those within the water vapor/stability category, with the Lifted index (from a 100 mb surface layer parcel) and the Total Totals index being among the first three variables selected by a multiple regression procedure for nine of the ten radar echo dependent variables. Individual correlation coefficient magnitudes for the Lifted index ranged from 0.23 to 0.66 for the six radar echo variables for which it was selected, while for the Total Totals they ranged from 0.45 to 0.54 for the three echo variables for which it was selected.

Ellrod and Field (1984), in a detailed analysis of Gulf Stream area thunderstorms, found that most thunderstorm events occurred in areas where the Showalter index was ≤ +2 and the Total Totals index was ≥ +40. Those thresholds, along with specific values of several other variables, were then compiled into a set of guidelines for Gulf Stream area thunderstorm forecasting. 377 convective events (as identified by satellite) were analyzed during the period August 1982 through July 1983 over the Gulf Stream region stretching from south Florida to past Cape Hatteras, North Carolina, along with 160 corresponding soundings from four stations along the Atlantic coast.

Stone (1984) developed a stability index based on the expression for the change in kinetic energy per unit mass of a vertically-moving parcel. Using two "commonplace" 1200 GMT soundings, this index was compared to the K, Showalter, Lifted, and Total Totals indices for its capacity to detect instability. Only Stone's index, via comparison of computed index values, was able to indicate more instability for the unstable sounding than the stable one, as the K and Showalter indices indicated more stability and the Lifted and Total Totals indices showed no difference. The shortcomings of the standard indices were explained by the relatively limited amount of sounding information that each uses in comparison to the energy index. Subjective comparisons between the indices for many soundings during 1983 also indicated that the energy index more correctly characterized stability fields (as represented by radar echo patterns) over the eastern half of the United States.

Bluestein et al. (1987), in an analysis of non-severe mesoscale lines of precipitation in Oklahoma during spring, computed CAPE and CIN, among other parameters, to diagnose the properties of the environment containing the squall lines. Using cases from April 1971 to May 1979, CAPE for non-severe squall lines was significantly smaller than for severe squall lines, while CIN was larger. It was suggested that "the difference between most severe and nonsevere squall lines is that the former are born in an environment of greater CAPE and therefore probably have stronger updrafts".

Djuric (1987), in a study of satellite-detected cloud arches as possible indicators of later thunderstorm development, found that nocturnal thunderstorms in Nebraska on 6 May 1983 formed in an area of instability as indicated by low values of the Lifted index and high values of the K-index.

Colquhoun (1987) devised a decision tree approach to forecasting thunderstorms (and severe thunderstorms and tornadoes - see Section 4.1.f, p. 54), applicable throughout the world, which included several thermodynamic considerations: the state of convective instability via assessment of either the $\theta_e$ lapse rate or the Lifted index; whether or not a parcel would be lifted to its LFC; an evaluation of midtropospheric (600-500 mb) moisture content; and "the presence of a deep, dry layer of near dry adiabatic lapse rate air beneath cloud base". Testing of an early version of this decision tree method by forecasters in eastern Australia found it to be a "helpful" guide.

### 4.1.e MOS Non-Severe Thunderstorm Forecast Modeling

The development of MOS forecast equations for the prediction of "general" (non-severe) thunderstorm probabilities, mostly for the eastern two-thirds of the United States, has involved the substantial use of stability indices. This work can be stratified into two groups, one for somewhat longer-range (e.g., 12-36 hours) forecasting (e.g., Bonner et al., 1971; Derouin and Reap, 1973; Reap, 1974; Reap and Foster, 1975, 1977a, 1977b, 1979; Kitzmiller, 1985), and another for shorter-range (e.g., 2-6 hours) forecasting (e.g., Alaka et al., 1975. 1977; Charba, 1977a, 1981, 1984; Reap, 1986). Also, in a related MOS endeavor, Carter (1979) developed a convective wind gust potential forecasting scheme.

In this work, the potential MOS predictors, which have included the K, Total Totals, Showalter. Lifted, and SWEAT indices, along with Reap's (1974) Convective Instability index and Charba's (1977a) modified K and Total Totals indices, were related to radar-observed convection via linear correlation analysis and/or multiple linear regression.

Within the first of the above groups, Bonner et al. (1971), using PE and TJ model output, found the K-index to be best predictor (from a list of 23 derived MOS predictors) of general convection (echo/no echo) over the eastern two-thirds of the United States for 53 days with widespread thunderstorm activity during summer of 1969 and the spring-summer of 1970. The K-index yielded a correlation magnitude of 0.42, while the SWEAT, Showalter, Total Totals, Lifted, and Convective Instability indices had correlation magnitudes of approximately 0.32, 0.32, 0.30, 0.22, and 0.14, respectively. In a ranking of the derived predictors and 39 basic data field MOS predictors, the K-index was first, while the SWEAT index was fifth, the Showalter index seventh, and the Total Totals index ninth, indicating the importance of instability for general thunderstorm occurrence. In a regression forecast equation for the entire study region, the K-index was the leading predictor.

Derouin and Reap (1973) and Reap (1974), for April-September 1970-1971 and the eastern two-thirds of the United States, found a linear correlation of +0.57 between values of a "truncated" K-index (i.e., $+5 \le K \le +32$) and the occurrence/non-occurrence of radar echo activity. This index, derived from PE and TJ model output, was also selected as the leading predictor in a general thunderstorm probability equation for the entire region (referred to a "generalized operator" equation).

Reap and Foster (1975) developed a new six hour probability equation for the same study region and the occurrence of general thunderstorm activity using manually-digitized radar (MDR) data values ≥ 4 to identify thunderstorm occurrence. The MDR grid area also covered the eastern two-thirds of the United States. Data, and PE and TJ model output from 1 April to 30 September 1974 were used to develop the equation, with the K, Total Totals, and Showalter indices, and Reap's Convective Instability index among the predictors considered. Again, the truncated K-index was the leading predictor in the forecast equation, while the Convective Instability index was third and its combination with the 700 mb 12 hour net vertical displacement (CINVD) sixth. Thus, the existence of a convectively unstable atmosphere below 10,000 ft. (3048 m.) was postulated to be a key ingredient for the occurrence of general thunderstorm activity.

Reap and Foster (1977a) developed six and 24 hour forecast equations for thunderstorm probabilities over the same region for the 1976 warm season, using MDR values ≥ 4 for thunderstorm occurrence and PE and TJ model output for April-September of 1974 and 1975. The truncated K-index was again the leading predictor in both forecast equations, while Reap's Convective Instability index was second in the six hour equation, and a combination of a modified Showalter index (Charba, 1977a) and 700 mb 12-hour net vertical displacement was second in the 24 hour equation. It was summarized that the key predictors for non-severe thunderstorms were the stability and vertical motion fields below 700 mb and the boundary-layer winds. The probability forecasts generated were found to verify quite well for the June-September convective season except for the states bordering the Gulf of Mexico, where the forecast probabilities were too low.

Reap and Foster (1977b, 1979) developed medium-range (12-36 hour) forecast equations for the 1977 season using PE and TJ model output from a three year period (1974-1976) for 15 March to 15 September, again for the eastern two-thirds of the United States. One addition at this stage was the development of an interactive measure (KF) which was to simulate seasonal variations in thunderstorm occurrence. It was computed by multiplying the K-index, previously demonstrated to be the top predictor for general thunderstorms, by daily thunderstorm relative frequencies as obtained from the MDR data. Then, a linear regression predictor ($Y_{i,j}$) was formed by a combination of regression constants representative of a particular MDR grid square and a third-order polynomial linearization of KF. Values of this regression predictor were then treated as a new candidate predictor. In all, 173 predictors (24-hour forecasts based on 0000 GMT initial data) were considered, which also included the full K-index, the Convective Instability index, the Total Totals index, the Showalter index, a modified Showalter index, and the SWEAT index. The new $Y_{i,j}$ predictor produced the largest linear correlation (+0.54) to observed thunderstorm occurrence (MDR ≥ 4 within ± 12 hours of 0000 GMT), while the K-index had the second largest (+0.41), the Showalter index the fourth largest (+0.40), the Total Totals index the sixth largest (+0.33), and the Convective Instability index the seventh largest (+0.33). The forecast equation for 24 hour probabilities (valid 12-36 hours after the 0000 GMT initial time) and the entire study region had as its leading predictor $Y_{i,j}$, while the Total Totals was selected second and the K-index sixth. Verification during the 1977 and 1978 convective seasons indicated that the probability forecasts were reliable for all probability categories (0.00-0.09, 0.10-0.19, etc.) with a slight tendency towards overforecasting. The forecasts were better than any that had been obtained in the past. $Y_{i,j}$ was found to be the key thunderstorm predictor, as it captured "most of the widespread general convective activity associated with deep moist layers in the atmosphere" (Reap and Foster, 1977b).

Kitzmiller (1985) added experimental cumulus model predictors to the list of previously-used operational predictors for MOS convective weather forecasts. All predictors were from 24 hour forecasts based on 0000 GMT initial data. Using MDR data and MOS (from the LFM and TJ models and the Boundary-Layer Model - BLM) for 15 March to 15 September 1980-1983, a linearized K-index from LFM/TJ output gave a correlation of +0.49 with thunderstorm occurrence, while the previously-mentioned KF predictor from the LFM had a correlation of +0.46. Also, a BLM/LFM K-index, "smoothed by 9-point averaging", gave a correlation of +0.43, the Best Lifted index (see Section 4.1.f, p. 42) from BLM/LFM had a correlation of -0.44, and a BLM/LFM linearized K-index smoothed by 9-point averaging gave a value of +0.48. The predictor equation included the linearized K-index from LFM/TJ as its second predictor (a cumulus cloud rainout parameter was first) and KF from the LFM was fourth. Verification using 1982 data showed that experimental forecasts generated by the new model overpredicted thunderstorm occurrence for probabilities below 50 percent and above 80 percent when compared to the current operational model.

Turning now to the shorter term (2-6 hour) forecasting group, Alaka _et al_. (1975) developed an objective scheme for producing forecasts of general thunderstorms at or near FAA airport terminals two to six hours in advance. MDR data, aviation surface observations, and 500 mb temperature forecasts for 80 days during the spring of 1974 from the eastern two-thirds of the United States were used in the analysis. MDR values ≥ 4 again defined the occurrence of a general thunderstorm. The only stability predictor considered was the measure S, defined as the difference between the temperature of a parcel at 500 mb, lifted from the surface, and a forecast 500 mb temperature from the LFM. This index was chosen as the second predictor in a regression equation for the entire region, indicating the importance of stability considerations for short-term thunderstorm forecasting.

Alaka _et al_. (1977) and Charba (1977a) updated the results of the previous study by adding upper air LFM predictors, which included the K-index, Charba's modified K-index, the Total Totals index, Charba's modified Total Totals index, the Showalter index, and a modified Showalter index (surface parcel lifted to 500 mb). Using data from mid-March to mid-June (the spring season) during 1974-1975, prediction equations for the entire region were developed for each of the forecast periods 1700-2100, 2000-0000, and 2300-0300 GMT. From over 40 predictors considered for the 1800 GMT forecast equation (forecast period 2000-0000 GMT), the modified K-index was the first chosen, while the modified Total Totals was third and the Showalter modification thirteenth, again emphasizing the importance of stability considerations for short-term thunderstorm forecasting. Analogous equations (not shown) were apparently developed for 1500 and 2100 GMT. Independent verification for the period 31 March-14 June 1976 showed that the forecasts were 22 percent better than climatology and were reliable up to the 85 percent probability range.

Charba (1981) found a combination of the modified K-index and surface moisture convergence to be the best predictor for two to six hour forecasts of thunderstorms over the Great Plains of the United States. This study was updated by Charba (1984), in which the thunderstorm predictand was defined as the occurrence/non-occurrence of MDR code ≥ 3 within a grid square for a somewhat modified region of the eastern two-thirds of the United States. Predictor variables were derived from objectively analyzed hourly surface observations, the LFM-II model, MDR data, and the climatic frequency of the predictand. Equations were developed for the spring (mid-March to mid-June), summer (mid-June to mid-September), and cool (mid-September to mid-March) seasons, for each of three sub-regions (Northeast, Gulf Coast, Great Plains), using spring and summer data from 1974-197 8 and cool season data for 197 5/1976-1979/1980. Among the stability indices considered were the K-index, modified K-index, Total Totals index, modified Total Totals index, Shovalter index, modified Showalter index, Lifted index, and a modified Lifted index, along with various combinations of some of the indices with other derived (non-stability) parameters. The modified Lifted index wa6 formed by separately averaging observed surface temperature and moisture values with corresponding predicted boundary layer mean values of the two variables. The combination variables included the modified K-index with surface moisture convergence, the modified Lifted index with 850-700 mb mean equivalent potential temperature, the modulated predictand relative frequency with the 500 mb meridional wind component, and the modified Total Totals index with 700 mb vertical velocity. This modulated predictand relative frequency was formed by taking the product of the modified K-index (the single best predictor for thunderstorms) and the relative frequency of the predictand.

Results were given for a probability forecast equation valid for the period 2000-0000 GMT, the spring season, and the Great Plains region, and were said to be typical of the equations for the other forecast periods (1400-1800, 1700-2100, 2300-0300, and 0200-0600 GMT) and seasons. The combination of the modified K-index and surface moisture convergence was again the first predictor selected, while the combination of the modified Total Totals index and 700 mb LFM-I1 vertical velocity was third, the combination the modulated predictand relative frequency and the 500 mb meridional wind component was fifth, the combination of the modified Lifted index and 850-700 mb mean equivalent potential temperature was tenth, and the modified Showalter itself was fourteenth, again underscoring the importance of stability for general thunderstorm forecasting.

Reap (1986) developed six hour thunderstorm probability forecast equations for the western third of the United States, within which convective activity was characterized by the occurrence of cloud-to-ground lightning flashes from the Bureau of Land Management's lightning detection network. Lightning data from 15 June to 15 September 1983-1985 and predictors from the LFM and TJ models were used to develop equations for the periods 0-6, 6-12, 12-18, and 18-24 hours following 0000 GMT. Over 100 basic and derived model predictors were considered, including an interactive KF predictor, which here was a linearized combination of the K-index and the climatic frequency of lightning for each of the four six-hour periods. For the probability of two or more lightning strikes during the 18-24 hour projection period, the KF predictors from 18-24, 0-6, and 12-18 hours, respectively, were the first three chosen by the regression procedure. The 6-12 hour KF was the sixth predictor chosen. The equations for 0-6, 6-12, and 12-18 hour projections contained the same set of twelve predictors as the equation for 18-24 hours. Thus, the interactive predictor was the best indicator of lightning/thunderstorm occurrence in the western United States.

Finally, Carter (197 9) developed forecast equations for the probabilities of convective wind gust potential for 1979 for a 17 station network in the western United States. Data from May-September 1973-197 8 were used to develop equations for the 0000 GMT forecast cycle (with a forecast projection length of 24 hours) and the 1200 GMT forecast cycle (projection of 12 hours). The convective gust potential predictand was defined as the occurrence (within ± 4 hours of 0000 GMT) of a surface wind gust of at least 25 knots in conjunction with an indication of instability such as a thunderstorm, virga, or towering cumulus at or in the vicinity of a station. Among the variables considered were the K-index, Total Totals index, and an "Upper Level Stability index" (formed by raising a 500 mb parcel adiabatically to 400 mb and 300 mb, respectively, taking the difference between the environmental temperature and the parcel temperature at each of the two levels, and then summing the differences). These indices were derived from 0000 and 1200 GMT cycle LFM forecasts and from 1200 GMT soundings. Prediction equations were then developed for three distinct combinations of MOS-derived variables, sounding variables, and surface observation variables. As an example result, the 1200 GMT cycle MOS/sounding/surface observation equation for Salt Lake City was given. The LFM K-index was the first predictor selected, a binary Upper Level Stability index (≤ +9) was the third selected, a binary LFM K-index (≤ +35) was fourth, and a binary LFM Total Totals index (≤ +55) was sixth. Thus, stability indices were found to be important predictors of convective wind gust potential.

### 4.1.f Severe Local Storms

Fawbush et al. (1951) identified important criteria for forecasting tornado development in the United States. The existence of potential instability within the synoptic environment was found to be a necessary condition for tornadoes. This instability was documented by the LFC and the positive area above it. The moist layer LFC pressure was found to be the most significant parameter for assessing the possibility of tornado development and the width of the positive area was indicative of the intensity of the development.

Fawbush and Miller (1954), in an analysis of the types of airmasses in which North American tornadoes form, used the "Stability" and "Dew Point" indices among 14 variables for characterizing the air masses. The tornado forming air masses (three types identified) were found to be convectively and conditionally unstable in the surface to 400 mb layer, although instability was less for the cool, moist, air mass type.

Galway (1956) developed his now famous Lifted index to help in the prediction of severe local storms. It was intended as an improvement on the Showalter index by being "predictive", via a modification of the lapse rate of the lowest 3000 ft. (914.4 m.) by use of the forecast afternoon maximum temperature, to account for daytime heating. Using soundings east of 100° west in the United States, the Lifted index was found to be a better indicator of latent instability than the Showalter index, and was concluded to be a useful forecast tool for the prediction of latent instability later in the day.

According to Dennis et al. (1967), Lyons (1964) found that low values of the Lifted index were related to hail occurrence in western South Dakota during cloud seeding studies. In another study, Musil and Dennis (1968) used the Lifted index and other parameters in a regression equation which was able to predict hailstorms in western Nebraska.

Foster (1964) related air mass stability (in the form of a Showalter-type index in which the parcel is lifted from the surface) and vorticity acceleration to tornadoes in the central and southern Plains of the United States. Few tornadoes formed unless index values were <. -2 and/or positive vorticity acceleration (increasing cyclonic vorticity tendency) was ≥ +0.02 $hr^{-3}$

Fujita and Bradbury (1966) and Fujita et al. (1970), in a detailed analysis of the Palm Sunday tornadoes of 11 April 1965, developed the Best Lifted index as an improvement on the Lifted index for evaluating the stability environment during tornado outbreaks. This index was formed by finding the lowest Lifted index value that occurred within the lower part of a sounding; the procedure used 50 mb layer potential temperature and mixing ratio averages with bases beginning at the surface and moving upward. The motivation for the Best Lifted index came from beliefs that (a) the 850 mb level in the Showalter index often can be higher than the top of the moist layer and (b) the mean potential temperature of the lowest 3000 ft. in the Lifted index can be affected by daytime heating, so that both the Showalter and Lifted indices may misrepresent instability. It was shown that the Best Lifted index predicted instability regions in the afternoon that were associated with the subsequent tornado outbreak, and displayed an advective continuity in time that the Lifted index did not.

David (1967) developed an index for diagnosing and forecasting severe thunderstorm occurrence over the eastern two-thirds of the United States. It was devised as a combination of nine common upper air parameters, among which were the Showalter and Total Totals indices. This combination index had moderate success in delineating severe weather occurrence. Using January-April data, the Showalter index was found to be it6 second-most important component and the Total Totals its least important. For July data, the Total Totals was the third-most important component and the Showalter was fourth.

Miller (1967, 1972, 1975) developed the Totals indices and applied the Total Totals and Lifted indices in his severe storm composite forecasting scheme for the United States. In order to facilitate the use of the Totals indices as predictors, Miller categorized ranges of their values by the frequency and severity of past severe weather events.

Darkow (1968) derived the Total Energy index from the static energy equation to predict severe storms and tornadoes in the United States, and then applied static energy concepts to storm outflow and pre-tornado environments in three subsequent studies (Darkow and Livingston, 1975a, 1975b; Livingston and Darkow, 1979). For the central third of the United States, Darkow (1968) found the index to be a good first indicator of areas of potential severe storm outbreak, and to be more meaningful for severe weather than the Showalter and Lifted indices because it "takes into account the possible contribution of potentially cold, mid-tropospheric air to the total energy release of the severe convective storm". Darkow and Livingston (1975a) successfully used hourly values of surface static energy to identify areas of thunderstorm outflow. Using case studies from portions of the eastern half of the United States, Darkow and Livingston (1975b) and Livingston and Darkow (1979) found a good relationship between high values of surface static energy (which identifies warm, moist low-level air which feeds severe storms) and subsequent tornado activity. Livingston and Darkow (1979) also developed an empirical modification of the LCL and found it to help distinguish areas of subsequent tornado activity three hours before actual tornado development.

Endlich and Mancuso (1968) objectively analyzed atmospheric conditions that preceded or accompanied three severe thunderstorm/tornado outbreaks in Oklahoma, Kansas, Missouri, and Iowa during April, June, and October 1966.

Among the variables examined were 850-400 mb lapse rate and static stability as estimated by the Showalter index. Patterns of that index revealed that it was slightly more unstable than normal in severe storm areas, but that the relationship between instability and storm areas was "not particularly strong". In fact, the most unstable lapse rates and Showalter values were south of the storm areas. The authors determined that low level temperature and moisture fluxes were more related to severe storm activity than either the lapse rates or the stability index.

Renne and Sinclair (1969) related stability and synoptic parameters to hail-producing thunderstorms in northeastern Colorado. It was found that ample low-level moisture, as asssessed by the CCL and surface moisture values, was important for hailstorm formation. A majority of hail occurrences were associated with lower than average CCLs, and non-occurrences were related to higher than average CCLs. The Lifted index was found to indicate more convective instability on days when larger hail fell. No hail fell when the index was greater than -2. A total energy parameter, estimated by the equivalent potential temperature, indicated more potential instability on hail days than on non-hail days.

David (1970) developed an objective aid for estimating the probability of severe thunderstorms in portions of the central United States during May and June. Four parameters (including a 12 hour PE model forecast Lifted index) were used to form two probability tables (Lifted index paired with 24 hour PE model forecast vertical motion, and 0600 CST observed surface wind direction paired with 0600 CST observed sea-level pressure). A combining of the probabilities of these two tables into a third one proved to be a useful aid for giving an early morning indication of the probability of severe thunderstorm occurrence later in the day.

David and Smith (1971) analyzed seven stability indices (Showalter, Potential Wet-Bulb, Total Totals, K, SWEAT, Lifted, and a "total energy index" similar to the net buoyant energy described in Section 3.2, pp. 15-16) as potential predictors of severe thunderstorms and tornadoes over the central and eastern United States. When each of the indices was individually related via linear regression to the occurrence of severe thunderstorms and tornadoes, the SWEAT index was found to give the largest reduction of variance (4.7 percent, translating to a correlation coefficient of 0.22), followed by the total energy, Showalter, Lifted, Potential Wet-Bulb, Total Totals, and K indices, respectively. Values of the top five indices were then converted into binary form and regression equations were developed for each index with the binary limits of each serving as an individual predictor term (similar to the MOS approach). For severe thunderstorms, the Showalter index provided the most reduction of variance (6.16 percent), followed by the Lifted, total energy, Potential Wet-Bulb, and SWEAT indices, respectively. For tornadoes, the SWEAT index gave the most reduction of variance (2.87 percent), followed by the Showalter and Lifted indices. For severe thunderstorms and tornadoes combined, both the Showalter and Lifted indices explained more of the variance than when each event was considered separately (e.g., 6.5 percent for the Showalter). Because of the "good results" the Showalter gave in this evaluation, it was deemed a "valuable stability parameter for any prediction equation".

Harley (1971) developed an index based on static energy and equivalent potential temperature to be used for convective storm diagnosis and prediction over the northern United States and southern Canada during August. The index assessed both latent and potential instability. In concert with other parameters, it was able to identify storm threat areas that later verified.

Whitehead (1971) analyzed two case studies of May-June severe weather activity from the south central United States using two indices of convective activity (SWEAT and Lifted indices) and the vertical transport of moisture from the planetary boundary layer. In the first case study (1200 GMT 31 May-0000 GMT 1 June, 1969), the two stability indices were able to delineate unstable areas having the potential for severe convective activity, and agreed fairly well with observed convection except for the Texas-Oklahoma panhandle area (non-foreca6ted storms occurred) and a portion of northern Texas (instability indicated but storms did not occur). For the second case study (1200 GMT 14 June-0000 GMT 15 June 1970), the patterns of instability coincided better with convective activity at 1200 GMT than at 0000 GMT. A comparison of the indices revealed that "the major portion of all reported activity occurred in areas designated as favorable by each index", with nearly all of the convective activity occurring within areas where the Lifted index was less than +2 and/or the SWEAT index was greater than +200. The simultaneous consideration of the SWEAT index and the vertical moisture transport term (incorporating vertical motion as a "triggering mechanism") significantly refined the severe weather threat areas examined. An evaluation of the terms in the SWEAT index revealed that the Total Totals term was the most important and 850 mb moisture the next-most important.

Miller and David (1971) used regression analysis to select the best predictors for a probability equation to forecast severe thunderstorms and tornadoes over the eastern two-thirds of the United States. Using data from 1967-1969, 41 predictors were evaluated, including binary Showalter and Total Totals indices. For all cases of severe weather, a Showalter index ≤ +2 was the first selected by the screening process, while a Showalter ≤ -2 was second, a Total Totals ≤ +49 was ninth, and a Showalter ≤ -4 was eleventh. For tornadoes only, a Showalter ≤ +2 was the first predictor chosen and a Showalter ≤ -2 wa6 third. However, the overall reduction of variance, 7.98 percent for all severe storms and 2.33 percent for tornadoes, was "disappointing".

Miller et al. (1971, 1972) derived the second of the three SWEAT index versions. The terms in the index were chosen through examination of 328 tornado case studies and personal daily weather forecasting experience. Then, lower threshold values of 300 and 400 were identified for the occurrence of severe thunderstorms and tornadoes, respectively. A tornado outbreak case study from 21 February 1971 verified the utility of the SWEAT index for forecasting storm threat areas.

David (1973, 1974) devised an objective method (via screening regression) for estimating the probability of severe thunderstorms over the central one-third of the United States using predictors derived from surface observations and PE model output. Among the predictors analyzed was the Lifted index. Using data and model output from 1971 and 1972 for equation development, the Lifted index (in the form of various categorized binary limits) was found to be a key predictor of severe thunderstorms 12-24 hours and 24-36 hours in advance, with at least one particular Lifted index limit chosen among the top five predictors for every verification time and data initialization.

Maddox (1973) developed the surface-observation-based "Surface Potential" index (SPOT) as a complement the upper-air-based SWEAT index. Using severe storm cases from the southern and central Plains, the Midwest, and Southeastern portions of the United States, the SPOT index was able to identify areas of severe thunderstorm activity one to four hours in advance. Miller and Maddox (1975) then applied the SWEAT and SPOT indices to two severe storm outbreaks from the eastern half of the United States (10-12 January 1975 and 14 March 1975). Both indices, particularly when considered together, were found to be "valuable forecaster aids".

Barber (1975) compiled a climatology of meteorological parameters thought to be important for severe storm occurrence over the United States, for March-June 1971-1973. Included among the sounding variables analyzed were the Lifted, Showalter, Total Totals, and SWEAT indices, along with various measures of parcel energy and Barber's Convective Instability index. As an example of the mean stability distribution, results for the Lifted index were reported (other indices gave similar results). Minimum stability was found along the Gulf Coast with increasing stability to the north, while a secondary minimum was located over the western mountains. The Gulf coastal minima were found to be related to high mean mixing ratios, while those in the West were due to low-level heating. The greatest percentage of Lifted index values less than zero also occurred along the Gulf with decreasing percentages northward and westward, revealing that significant instability was more related to the availability of moisture than to heating. A comparison of cumulative frequency distributions of 0000 GMT Lifted index at Denver and Topeka showed that, although Denver had a lower mean Lifted index, the significantly higher percentage of negative index values at Topeka and the higher incidence of severe weather there underscored the importance of 6trong instability for severe storm formation. Monthly trends in instability, as determined by an "available updraft energy" parameter, agreed with springtime tornado frequencies, as a northward extension in the instability pattern in late spring corresponded to a northward shift in maximum tornado incidence.

Wilson and Scoggins (1975, 1976) analyzed the K, Lifted, and Total Totals indices, among many other atmospheric variables, at 54 locations in the eastern two-thirds of the United States during the Atmospheric Variability Experiment-II (AVE-II, 11-12 May 1974). They sought to establish the large-scale atmospheric structure and variability within which radar-observed convection was embedded. Convective activity was found to exist "in areas where the low and middle troposphere is moist and the air is potentially and convectively unstable and has upward motion, in combination with positive moisture advection, at either the surface or within the boundary layer" (Wilson and Scoggins, 1976). The probability of convective activity was maximized when the Total Totals was in the range 40-50 and there was upward vertical motion (Wilson and Scoggins, 1975). In the expanded study of Wilson and Scoggins (1976), with the K and Lifted indices also being considered, stability <u>alone</u> was found to be a less accurate indicator of convective activity. However, the K-index (particularly $K \geq +22$) was superior to either the Total Totals or Lifted indices, because of its inclusion of the 700 mb dewpoint depression moisture term (Wilson and Scoggins, 1976). Specifically, joint relative frequency distributions were constructed for each index for convection ($MDR \geq 2$) and no convection. They revealed that the probability of convection for index values for which the relative frequency of convection exceeded no convection was 76.7 percent for K, 64.0 percent for the Lifted, and 61.4 percent for the

Total Totals. In addition, a measure of convective instability (change of $\theta_e$ with height) indicated that while convection occurred in areas with strong convective instability, this parameter was a necessary but not sufficient condition for the occurrence of convective activity. Charts with K ≥ +22, average boundary layer relative humidity ≥ 70 percent, and negative surface or boundary layer convergence superimposed successfully identified areas having MDR ≥ 4; that is, where thunderstorms occurred (Wilson and Scoggins, 1976).

Maddox (1976) evaluated tornado proximity stability and wind data from soundings over the central one-third of the United States during 1958-1972. The Total Totals index, among the parameters examined, had maximum values during April-June, the months of maximum tornado frequency.

David (1976) also analyzed the behavior of selected upper air parameters at the location and time that tornadoes affected the conterminous United States during 1968-1974. Among the static stability parameters considered were the Vertical, Cross, and Total Totals indices, along with the Showalter and SWEAT indices. Little month-to-month variability was noted for any of the indices except SWEAT, which peaked at an average of 395 in June, with a minimum of 116 in February. Spatially, for all months combined, the Total Totals index varied only between +45 and +50, with maxima over the Great Plains, while the Showalter index ranged from -1 to +1 over most of the country, with minima over the Plains. Seasonal averages of the Showalter index revealed it to be more unstable by 2 units in summer than in winter. It was found that when seasonal and/or regional averaging of the index was done, tornadoes occurred for index values which would be categorized in the "weak" class according to Miller's (1972) scheme.

Schroeder (1977) examined 15 years (1961-1975) of Hawaiian waterspout and tornado data in order to compare them with their south Florida counterparts. For one particular tornado proximity sounding and three others which narrowly missed fulfilling proximity requirements, the Showalter, Total Totals, and SWEAT indices were computed. Showalter values ranged from +3 to -3, while values of Total Totals varied from +43 to +52, and those of SWEAT between 319 and 383. The Lifted index was also computed for the sounding which produced the most unstable value for each of the other three indices (18 December 1971), and yielded an unstable -6. A climatology of SWEAT values at Hilo for September 1974-December 1976 showed that nearly 87 percent of the 1666 values computed occurred within the 101-200 range, while only 14 values above 300 were noted.

Mahrt (1977) related early afternoon environmental conditions preceding hail-producing thunderstorms in northeast Colorado to conditions associated with less severe classes of convection. He used soundings taken at Stirling, Colorado, during the 1972-1974 National Hail Research Experiment (NHRE). The parameters examined to represent environmental conditions included the mixed layer depth, the energy required to lift a mixed-layer average parcel to its LCL (i.e., to initiate convection), and the energy required to lift the parcel from its LCL to 300 mb (i.e., to further develop convection). Comparisons were made between the low-level environment preceding the occurrence of hail-producing thunderstorms and that preceding cumulus congestus, non-thunderstorm precipitating convection, and non-hail producing thunderstorms. For hailstorms, mixed layer depths were found to be thin and moist, while the required low-level energy term was larger than normal, and the required above-LCL energy term was significantly less than normal. Various analyses revealed the importance of latent heating for cloud buoyancy and its sensitivity to summer moisture over the High Plains. Mixed-layer depth was found to be a good discriminator between the four above weather types, and the discriminations were more definitive when the parcel energies were partitioned into the below- and above-LCL components.

Fankhauser and Mohr (1977) also related several sounding parameters to hailstorms that occurred in northeast Colorado during the same experiment. Among the parameters examined were the LCL, negative and net parcel energies, and a stability index similar to the non-predictive Lifted index for a parcel with the mean properties of the lowest 50 mb. Hailstorm days were subdivided into three convective categories: (1) weak isolated or scattered storms; (2) moderate to strong multicellular complexes; and (3) large long-lived unicellular storms. LCL height, "a fairly reliable indicator of cloud base altitude" for High Plains hailstorms, was found to be inversely related to storm strength (but decreased only from 3 940 to 3 510 m. from categories 1 to 3) , while negative energy was somewhat greater for the stronger convective categories, and net energy was directly but weakly related to storm strength. Negative buoyancy was seen as a "modulator of storm intensity by inhibiting premature release of potential instability". The stability index was found to be more unstable for the two stronger convective categories.

McNulty (1978) studied the association between upper tropospheric wind maxima and associated divergence fields, and severe weather occurrence in the United States. Various case studies were examined from 1976 and 1977, and fields of Galway's Lifted index were used to quantify low-level instability. Marginal instability (Lifted index values from 0 to +2) was found to be sufficient for producing severe weather if a strong divergence pattern existed in the upper troposphere. However, for several non-occurrence cases, sufficient moisture and instability existed but the necessary upper-level divergence pattern did not. Thus, it was concluded that the "superposition of upper divergence (wind maxima) over low-level moisture, instability and convergence refines the forecast of severe weather in time and space". Further, "marginal low-level instability and strong sources of divergence were found to be as effective in producing severe weather as very unstable low-level air and weak upper tropospheric features".

McNulty (1979, 1981 - previously described in Section 4.1.d, p. 36, for general thunderstorm occurrence) developed forecast equations for severe/non-severe thunderstorm occurrence. Both the K and Lifted indices were included in the forecast equations. The forecasts were found to be encouraging but not as good as those for general thunderstorm occurrence/non-occurrence.

Modahl (1979) analyzed several synoptic-scale parameters in order to test their ability to discriminate between northeast Colorado days of "insignificant" convective activity (no cumulonimbus occurrence) and "significant" convective activity (cumulonimbus occurrence), and between hail and no-hail days. This again used data from the NHRE (see Mahrt, 1977, and Fankhauser and Mohr, 1977, above). Among the parameters studied was a modified K-index for higher elevation stations, which utilized the 700-300 mb temperature difference, and the 500 mb dewpoint depression. A displacement in peak frequencies toward higher index values was found as the strength of convective activity increased. The index was more clearly able to delineate between insignificant/significant convection than between hail/no-hail cases. In fact, this index was the best parameter for discriminating between insignificant/significant convection, due to its 850 mb dewpoint temperature and 500 mb dewpoint depression terms (it was suggested that the 700-300 mb temperature difference term could be dropped from the equation). For hail/no-hail discrimination, the above index was second to the surface mixing ratio. It was concluded that a combination of 850 mb dewpoint temperature and 500 mb dewpoint depression was the best discriminator between insignificant/significant moist convection.

Colby (1980) calculated a "cloud work function" to measure convective instability during the strong 8-9 June 1966 squall line in Oklahoma. This parameter is "an integral between cloud base and cloud top of the difference in virtual dry static energy of the cloud and the environment, modified for water loading", based on a one-dimensional model for an entraining cloud "with variable rainout". The cloud work function analysis showed that the vertical structure of the atmosphere was much more destabilized than any of the soundings had indicated in areas where cells initiated, demonstrating the parameter's usefulness for estimating convective instability.

D. Johnson (1982) conducted a comprehensive stability analysis of AVE-1V severe weather soundings (0000 GMT 24 April-1200 GMT 25 April, 1975). Forty-two rawinsonde stations east of the Rocky Mountains were utilized to develop mean vertical profiles of temperature, dewpoint temperature, mixing ratio, zonal and meridional wind speed, and pressure level height, for each of four convective activity categories: (1) no precipitation, (2) all precipitation, (3) all thunderstorm activity, and (4) all severe thunderstorm activity. These categories corresponded to four classes of MDR data (0, > 0, > 3, > 7, respectively). Two sets of arithmetically-averaged profiles were then analyzed - one from soundings taken at the time of observed convective activity, and the other from soundings taken three hours prior to observed convective activity ("lag" profiles). Fourteen stability indices, chosen on the basis of ease of computation, were examined: SWEAT, Vertical Totals, Cross Totals, Total Totals, Reap's Convective Instability, Showalter, Rackliff, Jefferson (first variant), modified Jefferson (second variant), Boyden, Potential Wet-Bulb, K, and Total Energy indices, and the "Modified Martin" index. The 900 mb level was substituted for the surface in all indices requiring surface data.

For both of the above sets of profiles, all indices except the Vertical Totals and Boyden indicated more instability as convective intensity (category) increased (though the Vertical Totals index indicated increasing instability as intensity increased from categories 2 to 4). For the severe thunderstorm category, the pre-convection profiles gave the most unstable values for all indices except the Vertical Totals, Showalter, Boyden, and K. When index values in the severe thunderstorm category were compared to "approximate threshold index values for severe-type storms", the pre-convection and convection profile values equalled or exceeded the approximate values for all indices except the Showalter and K. Thus, nearly all of the indices were able to indicate more instability for increasing convective intensity type, both for the soundings at the time of convection and those three hours prior to convection. Further testing at Abilene, Texas, confirmed the indices' ability to indicate instability, as the most unstable values were found in soundings taken just before the occurrence of severe weather (the Convective Instability index and the author's Johnson Lag index were the only exceptions to this). The author's index, however, was the only one able to forecast severe weather three to six hours in advance.

Maddox and Doswell (1982a), in an analysis of jet stream configurations, vorticity advection, and low-level thermal advection patterns associated with periods of intense convective activity, identified regions of conditional instability by locating values of the Total Totals index ≥ +50. They found that "when low-level warm advection occurs in regions of strong conditional instability, the resultant lifting may produce important convective events".

Maddox and Doswell (1982b) evaluated Miller's (1967) severe thunderstorm forecasting scheme by diagnosing factors important for severe weather formation during three specific storm events. The scheme's characterization of static stability (Total Totals index) was found to indicate only moderate, weak to moderate, and weak to strong instability from 1200 to 0000 GMT during each of the three outbreaks. The scheme, in general, was found to have shortcomings for "more benign and subtle large-scale environments" (as opposed to those which were strongly baroclinic). Again, a very important factor for storm genesis in these environments was the existence of pronounced low-level warm air advection to trigger the release of conditional instability.

As an application of a stability index for purely diagnostic purposes, Ferguson et al. (e.g., 1983, 1985) have used the Lifted index as one of several "key synoptic parameters" (mostly from Miller's (1972) scheme) with which to diagnose annual tornado occurrences in the United States.

Colby (1984) used AVE-SESAME II data on 19 April 1979 to diagnose thermodynamic conditions prior to the onset of deep convection in western Kansas. Using his "convective inhibition" parameter (CIN) to estimate negative buoyancy and "potential convective energy" to model positive buoyancy, the convective region was found to contain low CIN and substantial potential convective energy above the boundary layer. CIN was found to be a minimum (nearly zero) when the first radar echoes appeared.

Johns (1984) evaluated several meteorological variables in developing a synoptic climatology of northwest-flow severe weather outbreaks that affected the eastern two-thirds of the United States during May-August 1962-1977. The Showalter and Total Totals indices were computed for all 163 cases investigated, both for conditions at least two hours before the beginning of an outbreak, and at the temporal midpoint of each outbreak. Geographical and temporal interpolation of observed data were employed. For the period before outbreaks, the average Showalter and Total Totals values were 0 and +47, respectively, with large variability within the Showalter values. For 26 percent of these cases, Showalter values were greater than +2 (stable). At the temporal midpoint of the outbreaks, the average Showalter and Total Totals values were -4.8 and +54, both indicating increased instability is present during severe weather outbreaks. Over 98 percent of these Showalter values were negative and 77 percent were -3 or less, the latter indicative of extreme instability. In an examination of cases where stable pre-storm Showalter values changed to unstable ones during the outbreak, it was found that either the moist layer deepened to the 850 mb level or nearby moisture was advected into the outbreak area. No distinctive geographic pattern of Showalter values emerged for the pre-storm period, but most instability was particularly evident over the Great Plains during the outbreaks.

Smith et al. (1985) developed a method for displaying satellite-derived sounding and cloud information on a composite image. One of the products of this technique found useful for monitoring severe storm development was the Total Totals index. From imagery products and severe weather reports of two case studies of severe weather over portions of the eastern half of the United States (10 April and 14 May 1984), good correspondence was found between Total Totals values in excess of +60 and afternoon and early evening severe weather reports.

Bluestein and Jain (1985) used CIN and CAPE to help identify four different types of severe mesoscale convective line development (broken-line, back-building, broken-areal, and embedded-areal) in Oklahoma during an 11 year period (April-June 1971-1981). CIN was found to be "statistically identical" (could not reject the hypothesis that the values were the same with high (95 percent) confidence) for the four storm types and for isolated supercells, while CAPE was less (at the 95 percent level) for embedded-areal lines than for broken-line storms and isolated supercells. CAPE values were also statistically identical for back-building and broken-areal storms were statistically identical; they were, in general, one to two orders of magnitude larger than the corresponding CIN values. Composite soundings by storm type revealed that each was conditionally unstable nearly everywhere in the troposphere.

In an analysis of the Kansas City severe weather event of 4 June 1979, Gaza and Bosart (1985) a used 100 mb surface layer average parcel Lifted index and an observed surface parcel Lifted index to diagnose instability, and also evaluated the Total Totals index within Miller's (1972) forecasting scheme. It was found that the most intense cells began to form shortly after a southeastward pushing trough encountered an area of moist, unstable air (as identified by the Lifted index) that had earlier moved in from the southwest. During summer months, moist, unstable air in the southern United States is advected by the low-level southwesterly flow in advance of approaching frontal systems, setting up the possibility for intense convection. The Total Totals index was only classified as weak to moderate in Miller's scheme from 1200 to 0000 GMT on this storm day.

Moore and Elkins (1985) used the Lifted index (100 mb surface layer average parcel) to classify the degree of instability present within the synoptic environment of the 6-7 May 1975 Omaha tornado outbreak. The existence of a narrow band of instability (negative Lifted indices) at 1200 GMT, several hours in advance of the storm outbreak, was found to be one of the key ingredients for storm formation. The minimum Lifted index observed at Omaha was -4. The instability area was formed by warm, dry, mid-level air capping moist, low-level air.

Colquhoun and Shepherd (1985) related tornado intensity to the environment of its parent severe thunderstorm using several parameters, among them the Lifted index. Using the Fujita scale to classify tornadoes, tornado intensity was found to be independent of the Lifted index, as values of the index fluctuated (-5.4, -4.4, -4.7, -5.9, -5.5, and -2.7) while tornado intensity increased (F values of 0, 1, 2, 3, 4, and 5, respectively).

Hillger et al. (1985) used satellite-retrieved soundings to compute Lifted, Total Totals, and K indices, along with water vapor parameters, for the 28 March 1984 tornado outbreak in the Carolinas. It was found that "the primary indicator of the best region of severe weather potential is the lifted index computed from the soundings".

Zubrick and Riese (1985) included the K, Total Totals, and Lifted indices among 30 parameters in an "expert system" (WILLARD) to aid in the forecasting of severe thunderstorms in the central United States. Within the expert system, an index was classified as weak, moderate, or strong according to its current value. A verification of the the model's logic against that of the National Severe Storms Forecast Center's Convective Outlook (NSSFC AC) procedure, using three case studies, showed that "most of the major factors identified by NSSFC as having the most bearing on producing severe thunderstorms were also identified by WILLARD", although more comparisons needed to be made.

Thompson and Lin (1985) evaluated pre-storm stability conditions during AVE-SESAME V (20-21 May 1979) in Oklahoma using the Total Totals, SWEAT, and Showalter indices. The indices were evaluated from special soundings taken at 1200 and 1800 GMT. To evaluate the indices, fields of each were subjectively related to radar summary maps verifying at 1935 and 2135 GMT. Since low-level moisture often did not extend up to the 850 mb level during the early pre-storm period examined, it was hypothesized that the three indices "may not accurately depict the potential instability in the thunderstorm environments", since each samples moisture only at 850 mb and/or above. Moisture at 900 mb was accordingly suggested to be better suited for depicting this instability. In addition, no index was found to be more reliable than any other as a predictor for the convective activity examined, but all of them were capable of identifying general areas where subsequent activity occurred.

In an analysis of nine severe weather producing MCCs in Iowa during 1982-1983, Barlow (1985) computed Lifted indices to assess instability conditions. A composite analysis for six of the events showed that Lifted indices valid at 0000 GMT (3-6 hours before development) were very unstable over the threat area and to the immediate southwest. Values as low as -9 were observed. This instability subsequently fed into the southwest flank of the MCC via surface and 850 mb flow during nighttime hours.

Hirt (1985) attempted to identify synoptic conditions associated with severe weather outbreaks in North Dakota (1976-1983). Among the conditions examined was stability in the form of the Showalter, Lifted, and K indices. For a typical outbreak case (1200 GMT, 15 July 1982 data), the stability indices were "found not to be good predictors. Values of the Showalter, Lifted index and K index were found to be widely variable with little correlation to the amount and extent of severe activity."

Lussky (1985) used surface, sounding, and satellite observations to diagnose conditions associated with a severe weather producing MCC in Montana. The Showalter, Lifted, K, Vertical Totals, Cross Totals, Total Totals, and SWEAT indices were computed from Great Falls and Glasgow soundings taken at 1200 GMT, 21 June 1984. None of the indices at that time indicated a great amount of instability, although a Lifted index of near zero suggested the potential for convective activity later in the day. By 2200 GMT, just before most of the severe weather occurred, derived Lifted indices (based on the current surface temperature and 1200 GMT soundings) had dropped to -7 over southeastern Montana. The author stated "it seems likely that the enhanced moisture convergence, the decrease in convective instability and perhaps the low-level increase in cyclonic vorticity associated with the subsynoptic low center played a significant role in the development of severe weather in this MCC".

Rust and MacGorman (1985) used the Lifted index to diagnose instability conditions in Texas and Oklahoma for storms with unusual cloud-to-ground lightning on 13 May 1983. The morning sounding at Oklahoma City revealed a Lifted index of only -1, but to the west at Amarillo the index was an unstable -6. By 1800 CST, the Lifted index at Oklahoma City dropped to -8, indicating extreme instability had spread eastward. Storms began in the panhandle of Texas around noon and continued throughout the day across Oklahoma.

Maddox and Grice (1986) again used the Lifted index to diagnose the instability environment during the 24 May 1981 Austin, Texas, flash flood, that was produced by a slow-moving, multicelled thunderstorm. The large-scale setting over Texas at 0000 GMT indicated that features conducive to upward motion were present, and that the low-level air was warm, moist, and potentially unstable. During the afternoon the air mass destabilized, as Lifted indices using a 100 mb surface layer average initial parcel for Austin were observed to be -8 at 500 mb and -12 at 300 mb.

In his historical survey of severe thunderstorm forecasting, Schaefer (1986) reviewed the evolution of some stability indices, describing in detail the Showalter and Lifted indices. As quick, simple, yet thermodynamically-sound parameters for assessing the atmosphere's state of instability, these indices were found to be useful for making first-guess decisions on thunderstorm potential over large areas. However, it was emphasized that "no individual stability index gives a perfect evaluation of the severe thunderstorm potential", and that detailed sounding analysis still needs to be done in areas where the potential for convective activity exists.

Sanders (1986) reintroduced and described a "surface lifted index", whereby a surface parcel is lifted adiabatically to a given level and its new temperature, the "surface lifted temperature", is then subtracted from the ambient temperature at that level. He analyzed the characteristics of this index and the surface lifted temperature during periods of deep, and sometimes severe, convection. Negative values of the index at 500 mb were well related to deep convection over the central one-third of the United States on 11 May 1985, when no positive values of the index at 850 mb or 700 mb were observed. In other words, severe convection occurred when the parcel buoyancy at 500 mb was large and no negative buoyancy existed at 850 or 700 mb.

Johns and Hirt (1987), in an analysis of widespread convectively induced windstorms ("Derechos"), utilized Galway's Lifted index in a checklist for forecasting their development. Examination of 70 cases during May-August 1980-1983 revealed "extreme convective instability of the air mass along the derecho tracks". Average values of the Showalter and Lifted indices were -5.9 and -9, respectively. The Lifted index was found to be -6 or less for 84 percent of the cases. Lifted indices more stable than -6 were only associated with strong 500 mb short-wave trough events during May and August. Ninety-three percent of weak 500 mb trough events were associated with values of the index of -8 or less. The high instability found within derechos was found to be partly due to a combined condition of strong diurnal heating and abundant low-level moisture east of the High Plains during the warm season. The increased instability of these events, as compared to northwest-flow events (Johns, 1984), was thought to be due to the warmer and/or moister lower layers in their associated environment. On the checklist, a Lifted index of -8 or less was one of the requirements for derecho development, and values had to extend downwind for a distance of some 250 nautical miles from the observed convective system.

Colquhoun (1987, see Section 4.1.d, p. 37) developed a decision tree method for forecasting severe thunderstorms and tornadoes. It included consideration of the state of convective instability as indicated by either the lapse rate of $\theta_e$ or the Lifted index, whether a parcel would lifted to its LFC, and the vertical extent of the dry adiabatic lapse rate below cloud base.

### 4.1.g MOS Severe Local Storm Forecast Modeling

Stability indices also have played an important role in MOS severe weather probability forecasting. Again, like the effort for general thunderstorm forecasting (Section 4.1.e), this work has been stratified into two groups - that for somewhat longer-range (e.g., 12-36 hours) forecasting (e.g., Reap and Alaka, 1969; Bonner et al., 1971; Derouin and Reap, 1973; Reap, 1974; Reap and Foster, 1975, 1977a, 1977b, 1977c, 1979; Reap, 1984; Kitzmiller, 1985), and that for shorter-range (e.g., 2-6 hours) forecasting (e.g., Charba and Livingston, 1973; Charba, 1975, 1977b, 1977c, 1979, 1984). Another distinction between these two groups is that the former ha6 been for the conditional prediction of severe weather given the occurrence of general thunderstorms, while the latter has been for the non-conditional prediction of severe weather.

Within the longer-range forecasting group, Reap and Alaka (1969) developed an objective quasi-lagrangian index for predicting convective weather outbreaks 24 hours in advance. To this end, 43 severe storm indicators were evaluated for 98 cases during 17 April-31 August 1968. Seven parameters were found to be superior, among which was an early form of Reap's Convective Instability index, along with the arithmetic product of this index with a measure of the net vertical displacement of parcels reaching 500 mb during the last six hours of a forecast period, the latter being from the TJ model. In a subjective rating of the seven parameters versus observed severe weather, the product of the index and vertical displacement was the best indicator, followed by the index itself.

Bonner et al. (1971), described in depth in Section 4.1.e (p. 38), also evaluated PE and TJ model predictors against the non-conditional occurrence of intense line echoes (TRW+ or TRW++) over the eastern two-thirds of the United States. Linear correlation coefficient magnitudes for this predictand were much lower than those for the general convection echo/no echo stratification, with values for the Total Totals, Showalter, SWEAT, Lifted, K, and Convective Instability indices of approximately 0.23, 0.23, 0.19, 0.17, 0.15, and 0.14, respectively. In addition, the correlation for the 850-500 mb temperature difference was 0.17. Among the 23 derived MOS predictors and the 39 basic data field MOS predictors analyzed, the Total Totals index was found to be the best correlated, while the Showalter index was second, the SWEAT index third, the Lifted index fifth, and the K-index ninth, indicating the importance of instability for severe storm occurrence. In the screening regression forecast equation developed, the Total Totals index was also selected as the leading predictor.

Derouin and Reap (1973) and Reap (1974), both described in Section 4.1.e (p. 38), developed probability equations for the conditional occurrence of severe thunderstorms/intense line echoes (TRW+ or stronger), given the occurrence of a general thunderstorm/observed echo. These were derived separately for the spring (April-June) and summer (July-September) seasons for each of two separate regions (East-Midwest and Gulf Coast states), using PE and TJ model predictors. In a regression equation developed for the East-Midwest region for spring, the product of convective instability and 700 mb net vertical displacement (CINVD) was the second predictor selected. The Total Totals index was not selected, in contrast to the non-conditional severe thunderstorm probability equation developed in Bonner et al. (1971). For the Gulf Coast during spring, the only stability predictor selected was the 850-500 mb temperature difference, which was first.

Reap and Foster (1975. see Section 4.1.e, p. 38) developed new severe local storm conditional probability equations for the same spring and summer periods, but for the eastern two-thirds of the United States. These equations predicted the conditional probability of tornadoes, surface hail three quarters of an inch in diameter or larger, or wind gusts at least 50 knots (from surface reports), given the occurrence of a general thunderstorm (MDR $\geq$ 4). Predictors from the PE and TJ models were utilized. For spring, the 850-500 mb temperature difference was the second predictor chosen, while the Convective Instability index was eighth. For summer, the 850-500 mb temperature difference was third and the Total Totals index was fifth. In comparison to the results for general thunderstorms, predictors reflecting atmospheric dynamics had increased importance for severe weather, especially during spring, while stability indices generally assumed less importance.

Reap and Foster (1977a, see Section 4.1.e, p. 39) developed 6 and 24 hour conditional probability forecast equations for 1976 for spring (April-June) and summer (July-September) in the eastern two-thirds of the United States using PE and TJ model predictors. For a six hour spring conditional probability equation for severe local storms (tornadoes, 1.9 cm or larger hail, or wind gusts greater than 93 km/hr and/or wind damage), an 850-500 mb temperature difference < +29° was the second predictor selected and a modified Showalter index < +1 was fourth. For a 24 hour spring equation, an 850-500 mb temperature difference < +29° was the second predictor selected, a modified Showalter < +1 was fourth, a modified Showalter < -2 was ninth, and a 850-500 mb temperature difference < +30 was twelfth. For summer, the six hour probability equation included the Total Totals index < +48 as its third predictor, while the 24 hour equation contained the Total Totals < +46 as its fourth predictor, the Convective Instability index < -6 as its sixth predictor, and the Total Totals < +44 as its twelfth predictor. In general, the summer equation predictors placed more emphasis on thermodynamics than did those in the spring equation when predictors representing large-scale flow and dynamics were found to be more important.

Reap and Foster (1977b, see Section 4.1.e, p. 39) developed 12-36 hour conditional probability forecast equations for (i) severe local storms and (ii) separately for major or family tornado outbreaks for 15 March-15 June 1977 over the eastern two-thirds of the United States (surface reports again used for predictands). Using predictors from the PE and TJ models, a linearized Total Totals index was the second predictor selected in the severe local storms equation, the CINVD was fourth, and the 850-500 mb temperature rate was eighth. Maximal conditional probabilities were found to generally exist in regions where there was large-scale lifting of convectively unstable layers, the lower troposphere had unstable lapse rates, positive temperature advection and strong zonal winds, and the surface pressure wa6 low. For major tornado outbreaks, the leading predictor term was CINVD, while the SWEAT index also was found to be an important predictor term.

Reap and Foster (1977c) developed separate forecast equations (individual terms not specified) for the conditional probability of major tornado outbreaks, damaging winds, and large hail (from surface reports), given the occurrence of a thunderstorm (MDR data), as a supplement to those in Reap and Foster (1977b). Data and output from the PE and TJ models, from 15 March-15 June 1974-1976 for the eastern two-thirds of the United States, were used to develop the equations. Predictand data were stratified by density of occurrence categories (i.e., the number of reports within a 25 grid-block area). A linear correlation analysis indicated that for tornado densities ≥ 6 and wind densities ≥ 9, the single best predictor was CINVD (correlations of approximately 0.25 and 0.21 at a density of 9, respectively). It was the only predictor that displayed a consistent increase in correlation with increasing storm density for all three storm types. Both the SWEAT and Total Totals indices showed a decreasing correlation trend as tornado and damaging wind densities increased, but the SWEAT was the best predictor for tornado densities ≤ 5, with a correlation of approximately 0.27 at a density of 3. For large hail, the Total Totals index was the best predictor for densities ≥ 4 (correlation of about 0.27 at a density of 4), but again showed decreasing correlation as density increased. In general, the best single predictor for severe local storm outbreaks with densities of 9 or more was the CINVD. The above-mentioned results for tornado density were also reported in Reap (1984).

Reap and Foster (1979, see Section 4.1.e, p. 39) also developed equations for the eastern two-thirds of the United States for severe local storm conditional probabilities in spring (15 March-15 June) and summer (16 June-15 September), and for major tornado outbreak conditional probabilities (individual terms specified) for spring. The data and PE and TJ model output used here (15 March-15 September 1974-1976) was expanded over that used in Reap and Foster (1977c) by its inclusion of the summer season. In the spring severe local storm conditional probability equation, the Total Totals index was the second leading predictor, while the CINVD was the fourth predictor, and the 850-500 mb temperature difference was eighth. In the summer equation, the Total Totals was the fourth predictor chosen. Equations for the conditional probabilities of major tornado outbreaks (also reported in Reap, 1984) were developed for the same areal densities of tornado occurrence as Reap and Foster (1977c). For tornado densities ≥ 3, a linearized SWEAT index was the best predictor, a linearized CINVD was selected fourth, and the Total Totals index was sixth, while for densities ≥ 5, the linearized SWEAT index was first, the linearized CINVD was second, and the SWEAT index was sixth. For densities ≥ 7, linearized CINVD was first, linearized SWEAT was third, and SWEAT was fourth, and for densities ≥ 9, linearized CINVD was first and CINVD was fifth. The equation for densities ≥ 7 was used in an operational mode.

Kitzmiller (1985, see Section 4.1.e, p. 39) also evaluated predictors with respect to the conditional probability of severe thunderstorm occurrence. Linear correlations between predictors and severe thunderstorm occurrence for 15 March-15 June 1980-1983 were much lower than for general thunderstorm occurrence, with values of only +0.18 for the LFM/TJ model output Total Totals index, +0.17 for the TJ model CINVD, and -0.08 for the BLM/LFM model Best

Lifted index. For 16 June-15 September 1980-1982 and 16 June-16 August 1983, the correlation for the LFM/TJ Total Totals was only +0.16. In the conditional probability equation for 15 March-15 June, the LFM/TJ Total Totals was the fourth predictor chosen, while the TJ CINVD was fifth and the LFM 500-850 mb temperature difference was sixth. For 16 June-15 September, the LFM/TJ Total Totals was the fifth and last predictor chosen.

Within the shorter-range (i.e., 2-6 hours in advance) forecasting group, Charba and Livingston (1973) analyzed the S stability indicator (see Alaka et al., 1975, in Section 4.1.e, p. 40) among 26 potential predictors for forecasting the probability of occurrence of severe local 6torms for the eastern two-thirds of the United States. Using surface reports from 41 storm days during 20 April-14 July 1972 for the predictand - which was the number of occurrences of severe weather in a grid square during a specified time period, consisting of any one of the following: tornado, funnel cloud, hail greater than 3/4 of an inch in diameter, or wind gust greater than 50 knots - along with corresponding three-hour surface reports and LFM model output for predictors (including S), linear correlation coefficients and screening regression equations were computed for a 15 by 15 degree square covering a portion of the central United States from Texas-Louisiana northward to Nebraska-Iowa-Illinois. For predictor time 1500 GMT and predictand period 1500-1900 GMT, S had a correlation magnitude of only about 0.04 with the predictand and was not selected by the regression process. For 1800 GMT/2000-0000 GMT, the correlation magnitude rose slightly to about 0.09 and S was the fifth predictor selected. For 2100 GMT/2300-0300 GMT, the correlation magnitude was up to approximately 0.13 and S was again the fifth predictor selected. For 0000 GMT/0000-0400 GMT, the correlation magnitude dropped slightly to 0.12, but S was still the fifth predictor selected. Finally for 0300 GMT/0300-0700 GMT, the correlation magnitude was only 0.08 and S was not selected for the prediction equation. Thus, this stability index was only slightly related to severe weather during the late afternoon/early evening period.

Charba (1975) updated the work of Charba and Livingston (1973) for 1975 operational use. Seven spring (15 March-15 June) equations were developed for various combinations of data year (1974 or 1975), predictor/predictand times (1500-2100 GMT range for predictors and 1700-2100 to 2300-0300 GMT range for the predictand), and grid region (eastern two-thirds, central, and southern portions of the United States). A typical order of predictor selection (again, 26 were evaluated) for the seven regression equations indicated that the S stability index was the second-best predictor for two to six hour forecasting of severe local storms.

Charba (1977b) developed new two to six hour severe local storm probability forecast equations for the 1976 season by considering a much-expanded list of candidate predictors (44), particularly within the stability category. The stability indices considered were the K-index, modified K-index, Total Totals index, modified Total Totals index, Showalter index, and a modified Showalter index (parcel lifted from the surface instead of 850 mb). All were based on surface observations and/or LFM model forecasts. Here, the predictand took the value one if one or more tornadoes, hail ≥ 3/4 inch in diameter, or surface wind gusts > 50 knots occurred in a square box approximately 85-90 nautical miles on a side during a four hour period, and assumed the value zero otherwise. An array of these boxes was positioned over the majority of the eastern two-thirds of the United States, divided into two subregions: a Gulf region from Texas to South Carolina and a non-Gulf region extending northward from the Gulf region to the Dakotas in the northern Plains and to New York in the East. Data from 15 March to 15 June 1974-1975 were used to develop primary and backup forecast equations valid for the 1700-2100, 2000-0000, and 2300-0300 GMT periods. Results for the 2000-0000 GMT forecast period (forecast made at 1800 GMT) were reported since they were found to be typical of all those derived, and indicated that the modified Total Totals index was the best predictor in each region. Also, for the non-Gulf region, the Showalter index was the fifth predictor chosen, a binary form of the modified Showalter index was eighth, and the modified Showalter eleventh. For the Gulf region, a binary modified Showalter index was seventh, a binary Showalter index was eleventh, and the modified K-index was fifteenth. The cumulative reduction of variance (explained variance fraction) for the non-Gulf equation was much larger than that for the Gulf region (21.2 percent to 13.0 percent, respectively), though 12 of the 15 parameters selected were common to both equations. This verified a documented operational forecasting problem that severe local storm forecasting was more difficult along the Gulf coastal states than in those states to the north and west, probably due to the fact that large-scale dynamics play a lesser role in storm development near the Gulf.

Charba (1977c) further improved the forecast equations by introducing several more candidate predictors, among which were the Lifted index, a modified Lifted index and a synoptic-modulation of the predictand relative frequency (predictand same as in Charba, 1977b, see above). The modification of the Lifted index involved averaging the observed surface temperature and moisture values with corresponding LFM boundary-layer mean values of the two quantities. The modulation of the predictand relative frequency was developed by taking the product of the modified Total Totals index, found to be the single best predictor of severe local storms, and the predictand relative frequency. Using surface observations and LFM model output from 16 March-15 June 1974-1976 from the Gulf and non-Gulf regions, linear correlation coefficients and screening regressions were computed. For the 2000-0000 GMT forecast period, the following correlations were found with severe weather occurrence (Gulf/Non-Gulf): 0.27/0.36, modified Total Totals index; -0.23/-0.33, modified Lifted index; 0.24/0.28, Total Totals index; 0.15/0.17, modulated predictand relative frequency. In the forecast equations, the modified Total Totals index was the first predictor selected for both the Gulf and non-Gulf regions, the modified Lifted index was not selected for the Gulf but was fifth for the non-Gulf, the Total Totals was not selected for either region, and the modulated predictand relative frequency was selected fourth and seventh, respectively. Again, these stability indices were found to be more effective predictors in the non-Gulf region than in the Gulf region, based both on correlations to severe weather and in the selection positions in the forecast equations.

Charba (1979) presented an expansion of the above work for the 1977 forecast season. Among the list of 37 predictors, again derived from surface observations and LFM model output, were the six indices used in Charba (1977b, see above) and the two indices from Charba (1977c, see above), plus the modulated predictand relative frequency. Prediction equations were developed for the 1700-2100, 2000-0000, 2300-0300, and 0200-0600 GMT forecast periods, for both the Gulf and non-Gulf regions using data from mid-March to mid-June 1974-1976. Results were similar to those of the previous studies, as a correlation analysis for the 2000-0000 GMT period revealed that the modified Total

Totals index was the best individual predictor of severe local storms, while the modified Lifted index was second, the modified Showalter index was third, and the modulated predictand relative frequency was seventh. The prediction equations for the 2000-0000 forecast period again indicated that the modified Total Totals index was the first predictor selected in both the Gulf and non-Gulf regions. Also, in the Gulf region, the modulated predictand relative frequency was the fourth predictor selected. In the non-Gulf region, the modified Lifted index was the fifth predictor selected, the modulated predictand relative frequency was seventh, and the modified Showalter index was ninth. The cumulative reduction of variance for the non-Gulf equation again exceeded that of the Gulf equation, 17.5 percent to 12.4 percent. The modified stability indices were shown to be particularly useful severe storm predictors, especially for the non-Gulf region.

Charba (1984, see Section 4.1.e, p. 40) redeveloped the two to six hour severe local storm probability equations for the 1984 spring season (mid-March to mid-June), and also developed equations for the summer (mid-June to mid-September) and cool (mid-September to mid-March) seasons, using data from 1974-1978 for spring and summer and 1975/1976-1979/1980 for the cool season. Three geographic regions were analyzed: the Gulf region, the Northeast, and the Great Plains (the latter two being a split of the old non-Gulf region). Among the 36 predictors considered (from surface observations and LFM-II model output) were the eight indices used in Charba (1979, see above) and the modulated predictand relative frequency. In addition, several potential predictors were formed by functionally-relating pairs of the existing variables. These included the modified Total Totals combined with surface moisture convergence, the modified Total Totals with 500 mb vorticity advection, the modified Lifted index with 500 mb wind speed, and the Showalter index with a modified boundary layer moisture convergence. All variables were linearized with respect to the predictand relative frequency. Results for the 2000-0000 GMT forecast equation for the Great Plains spring indicated that the functional combination of the modified Total Totals index and surface moisture convergence was the best predictor, while the combination of the modified Lifted index and 500 mb wind speed was second, the modulated predictand relative frequency was fifth, the modified Showalter index eighth, the modified Total Totals index ninth, the combination of the modified Total Totals and 500 mb vorticity advection tenth, and the modified K-index eleventh.

Stability indices, as shown in this section and the previous one (4.1.f), have been extremely important predictors of severe weather in the United States.

### **4.1.h Other Meteorological Phenomena**

Hovanec and Horn (1975) developed a modification of the Showalter index (see Section 3.1, p. 7) and an 800-300 mb temperature difference index for high elevation stations to analyze fields of static stability for 102 cases of Colorado cyclogenesis during April-May 1964-1971 and October-November 1964-1970. From seasonal means of daily values, the 800-300 mb temperature difference was found to be more unstable on the lee side of the southern Rocky Mountains (eastern New Mexico and western Texas) than over the rest of the country, during both spring and fall, with values somewhat larger during spring (maxima of +54) than fall (maxima of +50). During spring, weaker stability also extended northwestward into Utah, while during fall it extended northward into eastern Colorado. Fields of the modified Showalter index for both seasons showed that the region of minimum stability extended east into central Texas (indicative of the effects of Gulf moisture), and that the weaker stability regions were in general displaced slightly eastward as compared to the 800-300 temperature difference. Spring values were less stable than those during fall, with minima of +7 and +11, respectively. For cases of developing cyclogenesis only, the distributions of the two indices were more organized and showed an eastward shift of instability into the Great Plains and a northward shift into the Colorado cyclogenesis region. The least stable index values for cyclogenesis were about the same as the seasonal means except for the modified Showalter during fall, which showed less stability during cyclogenesis (minima dropped from +11 to +8). It was therefore suggested that during spring the weaker stability due to surface heating and adiabatic vertical stretching wa6 sufficient for cyclogenesis, but during fall when heating was less prominent, moist air was the key ingredient. When static stability, as indicated by each of the two above indices, was considered jointly with 300 mb wind fields, it was found that weak stability on the lee side of the southern Rockies was an important ingredient for both developing and non-developing cyclogenesis, but that a strong 300 mb wind maximum was the crucial factor for the developing cases.

Marshment and Horn (1986) further analyzed 39 developing cyclone cases for the April-May season. The Showalter and Lifted indices were used to diagnose "moist" static stability at 1200 GMT on the day preceding, day of, and day after Colorado cyclogenesis. The Showalter index on the day preceding cyclogenesis showed weakest stability from northeastern Mexico northeastward into Oklahoma. By the day of cyclogenesis, this area had become more organized and extended farther northward and eastward, and was located beneath and to the right of the exit region of the 300 mb wind maxima. By the day after cyclogenesis, the weakest stability was still located in southern Texas, but the general area of weak stability was more diffuse and expanded northward and much farther eastward, still ahead of and to the right of the wind maxima. Thus, the existence of an initial area of instability and the subsequent destabilization of the atmosphere in the exit region and right front quadrant of the composite 300 mb jet streak were found to be an important contributors to cyclogenesis. Fields of the Lifted index were found to be similar, except that the minima were located over the Texas Gulf Coast instead of south central Texas.

Stability indices also have been used as potential predictors in MOS forecasting schemes for surface wind (e.g., Carter, 1975; Schwartz and Carter, 1985), cloud amount (e.g., Carter, 1976; Carter and Glahn, 1976), and temperature (e.g., Hammons et al., 1976a, b; Carter et al., 1979; Dallavalle et al., 1980; Dallavalle and Dagostaro, 1982; Dallavalle and Jensenius, 1984; Dallavalle et al., 1985).

For surface wind forecasting, Carter (1975) evaluated the 850-1000 mb temperature difference (from PE model output) as a potential predictor. Separate equations for zonal and meridional wind components and wind speed were developed for each of 233 stations in the United States for 12-48 hour predictions and the warm (April-September) and cool (October-March) seasons. The wind component and speed equations for a given station and prediction were required to have the same ten predictors. Sample results presented included a 12 hour Kansas City forecast equation for 0000 GMT that used 481 days of data during the warm seasons of 1970-1972. This equation had the 850-1000 temperature difference as its tenth predictor. A composite listing of predictors based on their frequency of selection for 0000 GMT (both seasons, all predictions, and all stations) also had this temperature difference parameter as the tenth predictor.

Schwartz and Carter (1985) updated this work by rederiving forecast equations for 267 stations using LFM output from 1977-1982. A stability measure similar to the one used in Carter (1975) was again evaluated as a candidate predictor. A sample cool season equation at Kansas City, valid 12 hours after 0000 GMT, was described. The stability measure did not appear in the list of the 12 predictors chosen, but it was stated that nearly every candidate predictor was selected for one station or another.

For cloud amount forecasting, Carter (1976) and Carter and Glahn (1976) developed objective equations for 233 stations for the probability of occurrence of each of four categories: clear, scattered, broken, and overcast. Among the candidate predictors considered were "various measures of stability", which included the Total Totals index and temperature differences between selected atmospheric levels. From data spanning October 1969 to March 1974, warm and cool season equations were developed for predictions of 12 to 48 hours, with the requirement that the set of four equations for a given station have the same ten predictors. As an example, in the cool season 18 hour forecast equations for 0000 GMT for Oklahoma City (Carter, 1976), stability was an important predictor category, as the TJ model Total Totals index was the third predictor selected and a binary form of that index ($\geq +47$) was the eighth selected. In warm season 12 hour forecast equations for 0000 GMT for the same station (Carter and Glahn, 1976), the LFM 850-1000 mb temperature difference was the second predictor selected, the LFM 700-850 mb difference was the fifth selected, and a binary index of LFM 850-1000 mb temperature difference (threshold of -10 C) was seventh.

For temperature forecasting, Hammons et al. (1976a, b) developed equations to predict maximum and minimum surface temperatures at each of 228 stations 24 to 60 hours in advance of both 0000 and 1200 GMT. Equations were developed for the spring (March-May), summer (June-August), fall (September-November), and winter (December-February) seasons, using data from 1969-1975 for fall and winter and 1970-1974 for spring and summer. Among the predictors evaluated were the K-index from the TJ model and the 700-1000 mb and 500-850 mb temperature differences from the PE Model. Lists of the predictors selected most often in the first three terms of the 0000 GMT equations for each of the seasons and forecast projections did not include any of the above mentioned stability parameters.

Carter et al. (1979) improved surface temperature guidance by developing new 0000 and 1200 GMT maximum/minimum forecast equations valid for 24, 36, 48, and 60 hours in advance, and three-hour temperature forecast equations valid for 6-27, 27-39, and 39-51 hours in advance. Single station and regional equations were developed (single station equations were found to be better). LFM-based 700-1000 mb and 500-850 mb temperature difference predictors were the only stability measures evaluated, and neither appeared in a set of maximum and three-hour temperature equations presented for 0000 GMT at Omaha, Nebraska.

Dallavalle et al. (1980) analyzed errors in the maximum/minimum and three-hour MOS temperature guidance based on the LFM model. The K-index was the only stability parameter still being considered as a candidate predictor in the temperature forecasting procedure.

Dallavalle and Dagostaro (1982) developed forecast equations for predicting temperatures 12 to 80 hours in advance at various levels in the lower and middle troposphere over 10 stations in the northwestern United States and southwestern Canada. Data from October 1972-March 1978 were used for equation development. The LFM model K-index did not appear in a sample equation for 24-hour predictions of temperature from 0000 GMT at various atmospheric levels above Spokane, Washington.

Dallavalle and Jensenius (1984) attempted to improve forecast consistency by requiring that the set of predictors for a particular location be the same in the maximum/minimum and three-hourly forecast equations, but with each having different regression coefficients. The K-index from LFM model output did not appear in 0000 GMT equations for maximum or 24-hour forecast temperatures at Albany, New York.

Finally, Dallavalle et al. (1985) developed equations to predict daytime high temperatures and nighttime low temperatures, in contrast to the previous maximum/minimum forecasting procedures that were valid only for the midnight-to-midnight day. Once, again the LFM model K-index was a candidate predictor, but was not found to be important for temperature forecasting.

### 4.1.i Static Stability Climatologies

Three studies were conducted where the main focus was on the development of a static stability climatology for all or portions of the United States (Gates, 1961; Holzworth, 1964; and H. Johnson, 1982).

Gates (1961) reviewed nine measures of static stability commonly used in numerical modeling, which were derived from fundamental thermodynamic considerations. Six of these measures, in which partial derivatives are taken with respect to pressure (instead of height), were described in Section 3.3 (p. 17). Using average January and July soundings for 1946-55 for 45 stations across the United States, area mean vertical distributions of the parameters were documented in tabular form for 100 mb tropospheric layers, the 750-250 mb layer, and selected stratospheric layers. Geographical distributions of one of the measures ($-T^*/\theta \ \partial\theta/\partial p$) were presented for selected atmospheric layers. For July, lower tropospheric stability (900-800 mb) was extremely cellular across the country. In the middle troposphere (700-400 mb), a large area of instability wa6 found to exist over the Rocky mountains, while in the upper troposphere (300-100 mb), a poleward gradient of stability occurred. Within the 750-250 mb layer, instability over the Rocky mountains was strong but little gradient was observed over the eastern half of the country.

Holzworth (1964), utilizing an extended version of Gates' (1961) data set and 30 year (1921-50) averages of maximum surface temperature, computed monthly mean maximum mixing depths (MMDs). The MMD, representing the "mean maximum depth of vigorous vertical mixing due to convection", assuming dry-adiabatic ascent, is obtained on a thermodynamic chart by extending a dry-adiabat upward from the maximum surface temperature until its intersection with the most recently observed temperature profile. Results for the the four month May-August period indicated that shallow HMDs existed along the Gulf Coast during all months, with another large area of low MMDs extending from the Oklahoma/Arkansas vicinity up through the central Midwest and Great Lakes regions during May and June. A similar area extended from Kansas/Missouri to the Great Lakes during July and August. Comparisons between July MMDs and moi6ture-incorporating LCLs showed that LCLs were higher than MMDs over all of the central third of the United States except along the Gulf Coast, possibly reflecting the higher moisture content of low-level air there.

H. Johnson (1982) constructed a five-year climatology of a large number of stability variables (e.g., Lifted, SWEAT, Total Totals and K indices, Convective Temperature, and the height of the CCL) for the planning of an operational weather modification project on cumulus development over the panhandle, southwestern, and western regions of Oklahoma. Individual soundings were analyzed from 0000 and 1200 GMT at Oklahoma City (Oklahoma) and Amarillo (Texas) for April-September 1976-80 and four sub-seasonal breakdowns (1 April-15 May; 16 May-30 June; 1 July-15 August; 16 August-30 September). Spring-summer air masses over the Oklahoma-Texas area were found to be convectively unstable on a majority of days, and scattered showers or thundershowers were likely to develop somewhere within the region on those days. Convective temperatures were usually low enough to be easily attainable by normal daytime heating (the daily difference between the convective and minimum temperatures was often less than +20 C), and low, warm CCL-derived cloud bases were well-associated with high low-level moisture content. For the above sub-seasons, the Lifted index indicated particularly unstable conditions after mid-May, when the air is typically convectively unstable in the Southwest. The SWEAT index was extremely unstable during the second period, which included the late spring season often characterized by organized severe weather events, while the K-index was especially unstable during the latter two periods when scattered air mass showers are likely. Cloud bases were consistently low and warm during the last three periods.

## 4.2 British Isles/Western Europe

As SSITP development/application was taking place in the United States (described above), a limited amount of similar work was occurring in other locations around the world. Much of this effort concentrated on trying to better predict summertime showers and thunderstorms in Great Britain and western Europe. This work, and that for other locales (Sections 4.3-4.6, pp. 68-70), is now described below.

Hewson (1937) related the degree of potential instability within the warm sectors of 150 western European depressions to the maximum amount of rainfall that the depressions later produced, using cases from 1927-1936. Potential instability was estimated as the fall in 6 in the range of heights within which it was observed to steadily decrease, using a sounding somewhere within the warm sector. The corresponding 12 hour maximum precipitation amount within the warm sector during the 24 hours following the sounding was also determined. The correlation coefficient between the decrease in $\theta_w$ and the subsequent 12 hour maximum rainfall amount was +0.78. When two outliers (decrease in $\theta_w$ was small but the maximum rainfall was large) were omitted, the correlation increased to +0.82. Thus, for forecasting purposes, if a warm sector sounding was available, the strength of this relationship allowed a rough estimate of the amount of precipitation that a depression would later produce.

Rackliff (1962, see Section 3.1, p. 8) developed an index to identify conditions favorable for the development of air mass thunderstorms over the British Isles and extreme western Europe. Rawinsonde data from 13 stations in the region were used to analyze fields of the index, and 29 meteorological stations within a 75 mile radius of Crawley, Sussex, along with press and radio reports, were used to assess shower and thundershower activity, all for May-August 1959. Convective activity directly related to frontal activity was excluded. Using Crawley 2300 GMT soundings and associated convective activity information (89 days), a positive relationship was found between increasing values of the index and both the frequency and severity of convective activity, as categorized by no showers, very slight and isolated showers, slight-moderate showers, showers accompanied by thunderstorms, and heavy thunderstorms. No showers were observed for index values below +25, while showers or thunderstorms occurred for all cases when the index was +32 or higher. For the largest observed value of the index, +35, a heavy thunderstorm occurred. On the five days with heavy thunderstorms, the index values ranged from +31 to +35, which suggested the value +30 as a threshold. Indeed, the days when the index was +30 were evenly divided between no showers and some type of shower activity, so that value was chosen as the threshold for forecasting the possible development of significant showers and thunderstorms.

Jefferson (1963a, b, 1966; see Section 3.1, p. 9) empirically modified Rackliff's index for forecasting thunderstorms over the British Isles, western Europe, and the Mediterranean. A first modification (Jefferson, 1963a) created an index that was independent of temperature (a problem in Rackliff's index), and yielded the same threshold value for thunderstorms over a wide temperature range. Neutral stability was defined as +30 when © was +18°C, a value typical of summer thunderstorms over the British Isles. A second modification (Jefferson, 1963b) was made because the first modification overforecasted thunderstorms over the Mediterranean, an area characterized by dry air in the 900-500 mb layer. This modification consisted of including a weighted measure of the 700 mb dewpoint depression. Tests of the new index suggested that a threshold value of about +28 or +29 was appropriate. A third modification (Jefferson, 1966) replaced the 900 mb wet-bulb potential temperature with that at 850 mb to facilitate faster computation.

Boyden (1963) developed an instability index for forecasting heavy rain and thunderstorms in the North Atlantic/European region (particularly southeastern England). The index consisted of the difference between the 1000-700 mb thickness and the 700 mb temperature, from which 200 was then subtracted to yield values around 100. Using rawindsonde data from May-September 1960-1962 for Crawley (Sussex) and surface weather reports at nine stations in the surrounding region, relationships were obtained between values of the index and various levels of convective activity for both non-frontal and frontal situations. For both types of situations, there was a sharp increase in thunderstorm activity when the index reached +94, a maximum at a value of +95, and a sharp decrease when values increased to +98 and above. It was determined that the value +94 corresponded to mean neutral stability. Probabilities were given for both non-frontal and frontal situations, based on values of +94 and above and +93 and below, for the various levels of convective activity. For non-frontal days, the probability of a day with a thunderstorm in the area was just 10 percent for index values ≤ +93 but was 49 percent for values ≥ +94. The probabilities for a day with heavy showers were 6 percent and 39 percent, respectively. For frontal days, the probabilities of a day with a thunderstorm were 12 percent and 52 percent, respectively, and these probabilities for a day with heavy rain or heavy showers were 30 percent and 60 percent, respectively. Probabilities for the occurrence of these phenomena at a particular station were proportionately much lower. Thus, probabilities were more clearly defined for the frontal cases.

Lowndes (1965, 1966a, b) analyzed shower activity that occurred over southeast England (Lowndes, 1965), southwest England and south Wales (Lowndes, 1966a), and northwest England (Lowndes, 1966b) within airmasses approaching the British Isles from the northwest. Shower activity was classified according to the following: "A", widespread showers with more than 25 percent being moderate to heavy; "B", widespread showers with 25 percent or less moderate or heavy; "C", few showers; "D", no showers. The term "widespread" referred to eight or more showers occurring within a network during a specified daily period, and "few" meant less than eight. For southeast England, the weather data were from an eight station network for the period 0900-2100 GMT during May-September 1952-1964. For southwest England and south Wales, they were from an eight station network for 0900-2100 GMT during May-September 1954-1963, and for northwest England, from a six station network for 0900-2100 GMT during May-September 1953-1960 and 1962-1963. Among the variables examined were the Boyden and Rackliff indices and Jefferson's first two indices.

For southeast England (Lowndes, 1965), 79 percent of the values of the Boyden index of 94 or greater were associated with the widespread shower categories A and B, representing 87 percent of all cases in these categories. For Boyden values of 93 or less, 85 percent were associated with the few and no shower activity categories C and D, representing 77 percent of all cases in these categories. A skill score (number of correct forecasts minus number correct by chance, divided by total number of forecasts minus number correct by chance) of 0.64 was obtained when forecasting widespread showers or few/no showers using the above Boyden values. When the Boyden index was related to rainfall amount, 85 percent of values 94 or higher were associated with an area average rainfall of 0.1 mm or greater, representing 88 percent of all cases of these rainfall amounts, and 85 percent of values less than or equal to 93 were associated with amounts less than 0.1 mm (82 percent of all these cases). For forecasting these two rainfall amount categories, a skill score of 0.70 was found. Somewhat less definitive results were found when rainfall was categorized by amounts above and below 0.5 mm, as the skill score dropped to 0.56. When the index was related to hail or thunder days, 73 percent of values 94 or higher were associated with thunder (96 percent of all thunder cases) and 35 percent were associated with hail (100 percent of those cases). When the index was 93 or less, 96 percent of cases were associated with no thunder (74 percent of all no thunder cases) and 100 percent with no hail (55 percent of those cases). The thunder/no thunder skill score was 0.67 and the hail/no hail score was 0.32. Only skill scores were reported for the other three indices. For widespread showers/few-no showers, the skill scores for the Rackliff, first Jefferson variant, and second Jefferson variant were 0.69, 0.63, and 0.65 (using thresholds suggested by the various authors). For rainfall amounts 0.1 mm and above/less than 0.1 mm, the scores were 0.73, 0.71, 0.69, while for amounts 0.5 mm and above/less than 0.5 mm, they were 0.64, 0.59, and 0.64. For thunder/no thunder, the scores were 0.62, 0.59, and 0.61, and for hail/no hail they were 0.45, 0.45, and 0.47. Overall, the Rackliff index scored highest for the shower activity, and the 0.1 mm and 0.5 mm rainfall amount categories (the latter shared with the second Jefferson index), while the Boyden index scored highest for thunder and the second Jefferson index scored highest for hail.

For southwest England and south Wales (Lowndes, 1966a), the skill scores were systematically lower - on the order of 0.2-0.4 for all indices and categories. The two Jefferson variants scored highest for the shower and 0.1 mm amount classsifications, while the Boyden index scored highest for the three heavier activity categories, including thunder, which it scored highest for in southeast England. Finally, for northwest England (Lowndes, 1966b), skill scores were somewhat lower than those for southeast England but generally higher than those for southwest England and Wales, as the second Jefferson variant scored highest for all categories except hail, when the Rackliff had the highest score.

Saunders (1966, 1967) evaluated various thunderstorm forecasting techniques for the summers (April-September) of 1965 (Saunders, 1966) and 1966 (Saunders, 1967) at locations in the eastern portion of England. Among the stability indices tested were the Showalter index, Lifted index, Rackliff index, Jefferson's second index, Boyden index, and three other indices, including Hanssen's method (see Section 4.3, p. 67). Testing was done for four types of forecasts: overall thunderstorm occurrence/non-occurrence; thunderstorm occurrence/non-occurrence on frontal or trough days; thunderstorm occurrence on frontal or trough days; and thunderstorm non-occurrence on frontal or trough days. Analyses were also made on just those days when thunderstorms occurred, separately for convective days and frontal/trough days. All comparisons were made via percentage of correct forecasts.

For the summer of 1965 and the overall accuracy of forecasts that thunderstorms would or would not occur, although general forecasting "practice" by local forecasters scored higher (79 percent correct) than any stability indices, the Rackliff index scored second-highest (76 percent), and so on, down to the Lifted and Showalter indices, which scored worst (65 percent). For the overall accuracy of forecasts that thunderstorms would or would not occur on frontal/trough days, the Boyden index was best (83 percent), followed by the Hanssen method, general practice, and the Jefferson index (74 percent). The Showalter index again was last at 55 percent. For the accuracy of forecasts that thunderstorms <u>would</u> occur on frontal/trough days, Boyden's index was again first (81 percent) and the Rackliff index was second (70 percent), while the Showalter was last (44 percent). For the accuracy of forecasts that thunderstorms <u>would not</u> occur on frontal/trough days, the Hanssen method was first (87 percent) and Boyden was second (85 percent), while the Showalter was again last (62 percent). Another analysis treated only those days on which thunderstorm actually occurred. On convective days, general practice had the best percentage of correct forecasts (76 percent) and the Boyden index was second (71 percent), while the Showalter and Jefferson indices were next-to-last (54 percent; the "Simila" index was last). On frontal/trough days, the

Hanssen method was first (87 percent), the Boyden and Jefferson indices were second (76 percent), and the Showalter and "Miller/Starrett" indices were last (41 percent). Results suggested that the Rackliff index was best for detecting overall thunderstorm occurrence/non-occurrence, while the Boyden index was best when days were partitioned into those characterized by frontal/trough activity and those dominated by convection.

For thunderstorms in 1966, only the Boyden, Rackliff, and third Jefferson indices were further tested. The Boyden index was found most useful for forecasting in eastern England during summer, with a best threshold of 94/95. For polar maritime air masses, the Rackliff index was suggested as being better. The third Jefferson variant proved to be better than the second one. Forecasts, in general, were al60 better at inland locations than coastal ones.

Bradbury (1977, see Section 3.2, p. 12) used charts of 850 mb $\theta_w$ and the Potential Wet-Bulb index (PWB1) to define areas where significant rains and thunderstorms were likely to occur over the North Atlantic, British Isles, Europe, and Mediterranean regions. Up to 800 soundings taken during the years 1973-1976 were used to compute the PWB1, which was then related to corresponding precipitation and thunderstorm conditions, excluding drizzle. High values of 850 mb 0 (particularly ≥ +16°C) were found to be associated with the development of suimmer thunderstorms. Plots of PWBI versus 830 mb $\theta_w$ for days with thunderstorms revealed that the critical PWBI value for thunderstorm occurrence varied as 0 varied. Specifically, PWBI values above which thunderstorms were rarely observed (5 percent or less of the storms) ranged from +6 when 850 mb 0 was zero (during cool months) to -1 when this temperature was +20 C (during warm months). When only non-thunder precipitation cases were examined, the PWBI value above which 5 percent or less of the storms occurred rose from +10 when 850 mb 0 was zero to +1 when this temperature was +18°C. It was felt that the PWBI was a useful guide for assessing thunderstorm potential when used in conjunction with routine weather charts.

Pickup (1982) compared the PWBI (i.e., Pickup's index) with "established techniques" such as the Boyden, Jefferson, and Rackliff indices as to their ability to forecast summer thunderstorms over the British Isles. A preliminary study for Wales and northwest England for April-September 1968-1970 revealed that the PWBI ≥ +3 was more successful (via several skill scores) at forecasting thunderstorm occurrence than the Jefferson index ≥ +28 or the Boyden index ≥ +94 and ≥ +95. For April-September 1980, the PWBI again scored highest, followed by the Boyden index ≥ +94, the Jefferson index ≥ +28, ≥ +26, and ≥ +27, the Boyden index J> +95, and the Rackliff index ≥ +29 and ≥ +30. For cases limited to cyclonic flow, excluding the PWBI, the Boyden index ≥ +94 scored highest, followed by the Jefferson index ≥ +28 and ≥ +26, the Boyden index ≥ +95, the Jefferson index ≥ +27, and finally the Rackliff index ≥ +29 and ≥ +30. These skill scores were somewhat higher than those when no distinction in flow was made. Thus, the Boyden and Jefferson indices, in addition to the PWBI, were found to be more suited to thunderstorm forecasting than the Rackliff index.

## 4.3 The Netherlands

Hanssen (1965) developed an objective method for forecasting thunderstorms in the Netherlands. It consisted of a combination of midnight (0000 GMT) atmospheric pressure at DeBilt, the characteristic latitude ("lowest(highest) latitude that is reached by the 500 mb isohypse passing DeBilt going upstream"), a thickness difference (1000-700 mb minus 700-500 mb), and a combined saturation deficit (sum of 850 and 700 mb saturation deficits). The Showalter index, evaluated from midnight soundings at DeBilt during the summers of 1949-1959, also was assessed with respect to the probability of thunderstorms over the Netherlands. When the objective method was assessed with respect to thunderstorm occurrence, a "predictive ability" score (Kuipers, 1954) was 0.59. When the Showalter index was $\leq +5$, the probability of thunderstorm occurrence exceeded the climatological probability of 0.27. However, its predictive ability score was only 0.36. When the objective method was assessed with respect to thunderstorm occurrence, the predictive ability score was 0.59, much higher than that of the Showalter index. When independent data (summers of 1960-1962) were used to test the objective method, its predictive ability score dropped to 0.48, but was 2.5 times larger than the score for persistence, 0.18. The Hanssen objective method was concluded to have a good relation to thunderstorm occurrence.

Feteris (1965) conducted a statistical study of thunderstorm occurrence in the Netherlands using data from the years 1960-1962, and related the storms to several atmospheric parameters, including an instability index and the height of the CCL (results not shown). The instability index was formed by raising a 1000 mb level parcel, having the surface wet-bulb potential temperature, along a moist adiabat to the 500 mb level, and then subtracting the environmental temperature there from the parcel's resulting temperature. For the index, updraft penetration into the shearing layer was favored when the index was > 0. Also, it was positively correlated (+0.65) to the surface $\theta_w$, meaning that values of the index were a function of $\theta_w$. Thunderstorms with lightning were found to be more frequent when index values and/or *6* were high. It was suggested that a high index value was necessary to initiate thunderstorms in a warm and moist atmosphere.

## 4.4 West Africa

Adedokun (1981, 1982) related potential instability, in the form of two indices (see Section 3.1, p. 9), to rainfall over West Africa. His first index (ADED1) was thought to be similar to the Showalter index. In the initial study (Adedokun, 1981), over 200 individual soundings from three stations during a wet Sahel year (1958) were used to compute monthly mean values of the indices to assess instability within an intertropical dicontinuity (ITD) environment and to forecast monthly occurrence/non-occurrence of precipitation. In the second study (Adedokun, 1982), 1960-1970 monthly mean soundings at eight stations were used to produce mean single station and area-averaged stability index values which, along with some single station case study values, were then used to compute index values in an attempt to forecast West African precipitation.

In Adedokun (1981), the ADED1 index indicated stability north of the 1TD, while for south of the ITD, where most of the precipitation occurred, it indicated instability. A rough correlation of 0.53 was found between the index and observed precipitation south of the ITD. For forecasting purposes, values of ADED1 and ADED2 ≥ -1 were taken to be indicative of rainfall occurrence, while values < -1 were taken to indicate non-occurrence. For ADED1. the percentage of correct forecasts for the three stations was found to be 7 8 percent. When ADED1 and ADED2 were compared at just one station (Niamey), the percentages were 7 5 percent and 83 percent. respectively, so that ADED2 was a slightly better predictor of precipitation occurrence/non-occurrence. In an analysis where values of each index ≥ +1 were termed "unstable", values between -1 and +1 "neutral", and values ≤ -1 "stable", ADED2 indicated instability for all cases of rainfall occurrence, while ADED1 indicated neutral conditions or stability. For cases of non-occurrence, ADED2 indicated stability for 72 percent of the cases while ADED1 indicated stability for all cases. Thus, ADED2 was a better indicator of instability/rainfall occurrence while ADED1 was more related to stability/non-occurrence.

In Adedokun (1982), the ADED1, ADED2, and Showalter indices were analyzed. The thresholds for each (including Showalter) were defined as ≥ -1 for precipitation occurrence and < -1 for non-occurrence, but the traditional Showalter thresholds were also analyzed. The traditional Showalter index was found to better predict precipitation occurrence than the Showalter with the new thresholds, with the percentages of correct forecasts being 100 percent(58 percent), 7 5 percent(58 percent), and 67 percent(25 percent) for the southern, northern, and entire zones of West Africa, respectively. Likewise, ADED2 was found to perform better than ADED1, as the corresponding percentages were 100 percent(100 percent), 67 percent(58 percent), and 58 percent(50 percent), respectively. Thus, ADED1 and ADED2 were better precipitation indicators than the Showalter index with the new thresholds, but neither was as good as the traditional use of the Showalter index. It was concluded that ADED2 had a proven association to precipitation conditions and that the traditional Showalter index was preferable to the one with the new thresholds.

### 4.5 Australia

Hyson et al. (1964) analyzed the Showalter and Lifted indices in relation to thunderstorms at Darwin, Australia. Using data from November 1962 to January 1963, it was found that the atmosphere was always conditionally unstable so that the two indices added little information for forecasting purposes. The mean Showalter index on thunderstorm days was +0.33 and on non-thunderstorm days was +0.13, and the mean Lifted indices were -1.57 and -1.58, respectively. Thus, neither index was able to differentiate between the two environments.

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## 4.6 India

Subramanian and Jain (1966) examined the Showalter and Lifted indices with respect to summertime (March-June) thunderstorm forecasting for New Dehli, India. Four years of data (1963-1966), composed of the 0000 GMT rawinsonde soundings at New Dehli and subsequent 24 hour thunderstorm occurrence information (as determined by radar) at the station and separately for 50 and 100 mile radii of New Dehli, were used in the study. Visual observation of cumulonimbus at the station was counted as an "occurrence", if supported by radar. The radar criteron to specify an echo as a thunderstorm cell was that the top of the cell had to extend to at least 20,000 ft. (6096 m.) or to the level of the 20°C isotherm, whichever was higher. Percentages of thunderstorm days at New Dehli, within 50 miles of the station, and within 100 miles of the station, were separately plotted as functions of the two indices. These plots revealed that the frequency of thunderstorm days at the station and for both radii increased as the Showalter index decreased, and a similar result was found for the Lifted index. Thus, both were considered to be related to thunderstorm frequency. The 100 mile grouping produced the larger storm frequency percentages, as would be expected. Lower values of the Lifted index better delineated thunderstorm occurrence/non-occurrence than did lower values of the Showalter index, and, in general, the Lifted index was a "better predictor" than the Showalter in the areas of 50 and 100 mile radii around New Dehli, but had a "lower degree of confidence" at the station itself.

Kumar (1972) developed an objective aid for forecasting premonsoon thunderstorm/duststorm activity over the New Dehli region. The objective method consisted of a graphical correlation of the five parameters which were most strongly related to subsequent convective activity. Among the predictors examined were the Showalter index, CCL, and the difference in height between the CCL and freezing level. Data from March-June 1964-1968 were used in the study. A rather strong relationship was found between decreasing values of the Showalter index and the frequency of occurrence of thunderstorms/duststorms, particularly for index values ≤ +1. A similar relationship was found between increasing CCL pressure and storm frequency, especially for pressure values of and exceeding 751 mb. The relationship between the CCL/freezing level difference and storm frequency of occurrence was also good, as thunderstorm frequency increased as this difference grew larger. The Showalter index and CCL both were among the top five predictors of storm occurrence/non-occurrence. A graph of CCL pressure versus Showalter index with plotted cases of thunderstorm occurrence/non-occurrence showed that storm non-occurrence was more prevalent for low CCL pressure/high Showalter values and storm occurrence was more prevalent for high CCL pressure/low Showalter values.

# 5. SUMMARY

As has been shown, static stability indices and thermodynamic parameters (SSlTPs) have been applied to a variety of atmospheric phenomena, at a multitude of locations, for many different time periods. Throughout this past work, some SSITPs have shown a proficiency for indicating or predicting certain phenomena. Using the review in Section 4, an attempt has been made to determine the frequency with which these SSITPs and their variants showed at least some useful association with/predictive ability for certain phenomena. A summary appears below. It should be noted that the indices found to be the "most informative" often were those most frequently applied, generally for a. priori, traditional use reasons.

In the cases of rainfall amounts and rainfall occurrence/non-occurrence, for some portion of North America and for some part of the March-September "warm season" period, the K-index has far and away been found to be the "best" predictor, followed by the Showalter index and its variants, the Total Totals index, and, to a lesser extent, the CCL height or pressure and measures of parcel buoyant energy. One of the key distinguishing characteristics of the K-index is its sampling of the 700 mb dewpoint depression, which affords a rough estimate of the depth of the moist layer. Moisture penetration up to this level, and perhaps beyond, is apparently an important factor for the development of precipitation during the above period.

For North American non-severe thunderstorms, including "air mass" thunderstorms and radar-observed, non-severe convection, the K-index and its variants have again been found to be the best indicators/predictors, followed by the Total Totals index and its variants, the Showalter index and its variants, the Lifted index, and Reap's Convective Instability index. During the Model Output Statistics (MOS) general thunderstorm forecast equation development, work for which a relative large number of atmospheric variables were tested as to their predictive ability, the K-index was found to be the best individual predictor of general thunderstorms 12-36 hours in advance (e.g., Reap and Foster, 1979). For shorter range (2-6 hour) forecasting, the modified K-index was found to be "the best single predictor" for thunderstorms (e.g., Charba, 1984).

For North American severe thunderstorms, including those producing hail, the Lifted index most frequently has been found to be a strong indicator/predictor (and the most often evaluated). However, the Total Totals index and its variants also have been very reliable severe storm predictors, as have been the SWEAT index, Reap's Convective Instability index (usually in combination with 700 mb net vertical displacement), and to a somewhat lesser extent the Showalter index and its variants. These indices, with the exception of the Showalter index, were specifically designed for severe weather prediction. Other measures such as the K-index have shown less applicability to severe weather, and have been less used/evaluated. For 2-6 hour severe local storm prediction, the modified Total Totals index was found to be "the best single predictor" (e.g., Charba, 197 9).

For North American tornadoes, the Total Totals index and its variants, the Lifted index, and the SWEAT index all have been found to be strong indicators/predictors. Again, these indices were intended for severe weather prediction and subsequently were among those most frequently evaluated. In addition, Reap's Convective Instability index, in combination with 700 mb net vertical displacement, was found to be the best MOS predictor of major tornado outbreaks (e.g., Reap and Foster, 1977c; Reap, 1984).

Considering the development/application of SSITPs for other portions of the world, most were for the forecasting of summertime showers and thunderstorms affecting the British Isles and western Europe. For that region, the Jefferson, Boyden, Potential Wet-Bulb, and Rackliff indices have all been found to be related to summertime showers and thunderstorms. In general, the Jefferson and Rackliff indices appeared to be better suited for lighter convection (e.g., showers, lighter rain), while the Boyden and Potential Wet-Bulb indices were more related to heavier convection (heavier showers, thunderstorms, hail). These results parallel those found for the United States, since the Jefferson index, which is derived from the Rackliff index, is quite similar in definition to the K-index, a good indicator of non-severe convection in the United States, while the Potential Wet-Bulb index has been used effectively in the United States as a severe storm predictor.

Often, the Showalter index was evaluated outside of North America, with varying degrees of success. In England, Australia, and The Netherlands, it was found to be poorly related/less strongly related than other indices to thunderstorm activity, while in West Africa and India, the index was found to be well related to showers and/or thunderstorm activity.

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