The Total Energy Environment of Severe Storms[1]

Grant L. Darkow

University of Missouri, Columbia

ABSTRACT

The distribution in time and space of the total specific energy $(c_pT+gZ+Lq+V^2/2)$ of the environment of severe storms is examined. Comparison of the total energy profiles of tornado proximity soundings with the closest check soundings show pronounced differences. The tornado proximity sounding has substantially higher total energy values in the lower troposphere and lower values in the mid-troposphere than nearby stations. It is shown that the total specific energy may be approximated with negligible error by the static energy $(c_pT+gZ+Lw)$ and that this parameter is proportional to isobaric equivalent potential temperature and is similarly conservative.

A practical application of these results to severe storm forecasting is given in the form of a "Total Energy Index." This index is readily and objectively determined from routinely transmitted upper air data. Unlike other widely used stability indices, 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. Examples are shown of the Energy Index field on several recent tornado days.

1. Total and static energy conservation

The fields of temperature, moisture, height and velocity have been used both independently and in various combined forms in many convective storm studies and forecast schemes. These parameters can, however, be combined in a physically consistent manner in terms of energy units. The total energy of a unit mass of air may be expressed as

$$E_T=c_pT+gZ+Lq+\frac{V^2}{2}, \qquad (1)$$

the sum of specific enthalpy, potential energy, latent energy and kinetic energy, respectively, where c_p is the specific heat of air at constant pressure, T the temperature, gZ the geopotential, L the latent heat, q the specific humidity, and V the scalar velocity. The kinetic energy term is normally two orders of magnitude smaller than the other terms and may be neglected. The first three terms $(c_pT+gZ+Lq)$ have been called the "Static Energy" by Krietzberg (1964) and the sigma function by Kiefer (1941). This quantity is highly conservative with respect to both unsaturated and saturated adiabatic processes and is directly proportional to the pseudo-equivalent potential temperature and wet-bulb potential temperature.

The normal allowable tolerances in reported upper air humidity values allows the additional approximations $q=w$ and $L=L_0$, where w is the mixing ratio and L_0 a constant latent heat of condensation, yielding

$$E_T\simeq E_S\simeq c_pT+gZ+L_0w. \qquad (2)$$

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Thus, the total energy or static energy may be easily evaluated as known constants times routinely reported upper air data variables. A set of energy equivalent tables for temperatures, heights and mixing ratios (or dew points for specific pressure levels) or a simple slide rule can be constructed to further simplify total energy computations. An example of such a slide rule similar to one suggested by Kreitzberg (1964) is shown in Fig. 1. Dividing by c_p yields an equivalent potential temperature,

$$\theta_E=\frac{E_T}{c_p}=T+\frac{L_0w}{c_p}+\frac{gZ}{c_p}. \qquad (3)$$

Using the values $c_p=0.24$ cal gm^{-1} (°A)$^{-1}$, $L_0=600$ cal gm^{-1}, $g=980$ cm sec^{-2}, yields

$$\theta_E(°\mathrm{A})=\frac{E_T}{c_p}=T(°\mathrm{A})+2.5w+9.8Z, \qquad (4)$$

where w is in gm kg^{-1} and Z in km. The equivalent potential temperature so defined differs from the more commonly used pseudo-equivalent potential temperature in two respects. First, the latent heat is realized and added to the parcel of air during an isobaric process to give an isobaric equivalent temperature, and second, the adiabatic compression proceeds to a reference level of sea level instead of the 1000-mb level. It might be noted that since c_p is 1.004 J gm^{-1} (°A)$^{-1}$ the total energy when expressed in joules per gram is essentially equal to the equivalent potential temperature expressed in degrees absolute.

Since the total energy and its equivalent potential temperature are conservative with respect to both un-

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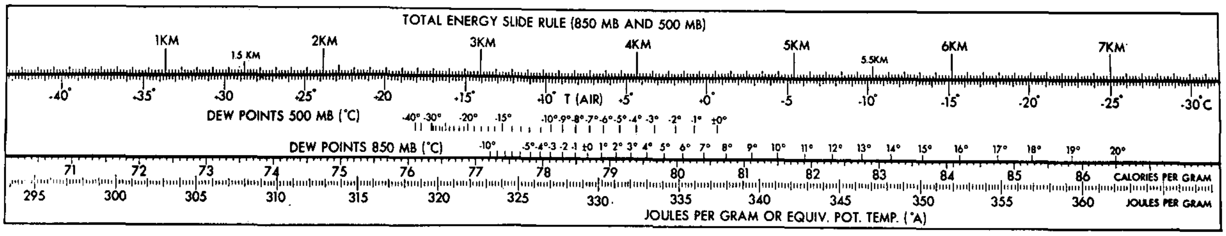

FIG. 1. Total energy slide rule for use with 850- and 500-mb data.

saturated and saturated adiabatic processes, they can be used in the analysis of convective phenomena in the same manner as the more commonly used pseudo-equivalent potential temperature or wet-bulb potential temperature. The total energy related parameters have, however, the distinct practical advantage of ease of numerical computation since they do not involve an exponential dependence on pressure.

2. Total energy profiles and process curves in potentially unstable air

Fig. 2 shows, schematically, the profile of total energy or its equivalent potential temperature typical of afternoon conditions prior the outbreak of severe thunderstorm activity. Riehl and Malkus (1958) have used energy profiles to analyze the role of penetrative convection in the energy budget of the tropics. The lowest 100-mb layer has been assumed to be sufficiently mixed by small-scale convective and mechanical turbulence to produce an essentially uniform value of mixing ratio and potential temperature, and therefore total energy, in the layer. Above this lowest layer there normally occurs a decrease of total energy with height to a broad minimum in the mid-troposphere. The entire layer from the surface to the mid-troposphere is therefore potentially-convectively unstable. Above the mid-tropospheric minimum the total energy increases with height reaching values comparable to surface layer values in the upper troposphere.

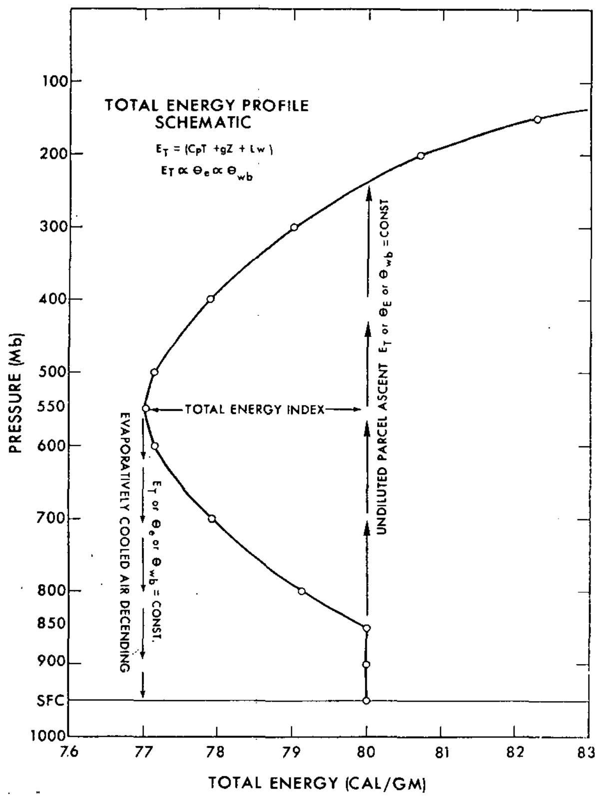

FIG. 2. Schematic total energy profile in late afternoon prior to the outbreak of severe thunderstorm activity. Process curves for non-entraining ascending and descending parcels are indicated by arrows.

In the absence of entrainment effects, parcels of air rising out of the low-level, high energy layer as either buoyant or forcibly lifted elements will conserve their total energy. The process curve for such parcel ascent is shown in Fig. 2. A parcel of low total energy, mid-tropospheric air in descending with negligible entrainment would also conserve its total energy and follow the process curve indicated in Fig. 2. A real atmospheric process which in first approximation will produce such descent is found in the downdraft branch of the circulation of some thunderstorm models. Potentially cold and dry mid-tropospheric air enters the rear of a storm system and is cooled to its wet-bulb temperature by the evaporation of rain drops falling through the air. This air becomes negatively buoyant and descends while conserving its wet-bulb potential temperature and total energy.

Thus, profiles of total energy are useful in a twofold manner related to convective processes. First, the observed total energy profile may be used in connection with "parcel theory" to examine the ascent and descent of elements of air within an undisturbed environment and second, the degree of potential-convective instability of atmospheric layers is indicated by the amount of decrease of total energy in the layers.

3. The energy stability index

Normand (1938, 1946) emphasized the possible contribution of potentially cold air taken into a thunderstorm at upper levels to the total energy conversions and maintenance of cumulonimbus circulations. Recent models of the quasi-steady state, severe thunderstorm systems (Newton, 1950, 1963, 1966; Fujita, 1955; Browning and Ludlam, 1962; Browning, 1964; and

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Ludlam, 1966) have re-emphasized the importance of this downdraft branch of evaporatively cooled air to the intensity and continuity of the severe storm system.

Stability indices widely used in severe weather forecasting such as the Showalter Stability Index (Showalter, 1953) and the Lifted Index (Galway, 1956; Winston, 1956) have, on the other hand, dealt only with the contribution of the ascending, potentially warm, low-level air to the storm energy release. A stability index reflecting the contribution of both the ascending potentially warm air and the descending potentially cold air has not gained widespread operational use. The practical difficulty of rapidly and accurately computing either numerically or graphically the wet-bulb potential temperature may account for this omission. The use of the total energy parameters with their ease of computation overcomes this difficulty.

As in the case of the Showalter Index, the choice of the pressure levels considered as representative of the low-level air and the mid-tropospheric air entering the storm may well be dictated by the routine availability of data at those levels and a desire for complete objectivity. With these considerations in mind it is possible to formulate an Energy Index which is nothing more than the algebraic difference between the total energy of the air at the 500 and 850-mb levels. The difference is shown schematically in Fig. 2 and may be expressed as

$$\text{E.I.} = (E_{T500} - E_{T850}).$$

More realism, at the sacrifice of some objectivity, can be introduced into a modified Energy Index formulation in the same manner in which it is in the Lifted Index. The mean mixing ratio of the lowest 100-mb layer or the first kilometer may be used as more representative of the moisture content of the low-level air than the 850-mb mixing ratio. The forecast afternoon surface temperature or, alternately, the forecast mean potential temperature of the lowest 100 mb can similarly be used as more representative than the 850-mb parcel temperature. These values of mixing ratio and temperature may then be combined in energy units to yield the total energy of the ascending low-level air.

It should be pointed out that a total energy forecast approach has some potential advantage over the usual procedure of forecasting both the low-level temperature and dewpoint or mixing-ratio values. Local diabatic energy additions in the surface layers can be handled without concern as to whether the heating will manifest itself in the form of sensible heat changes or increased dewpoints due to evaporation. Either change is equivalent in terms of total energy units. It is therefore possible to substitute the forecast of the single parameter, total energy, for the forecast of two parameters, temperature and dewpoint. Increasing the dewpoints by evaporation from a heated moist surface rather than increasing only the temperature by heating over a dry

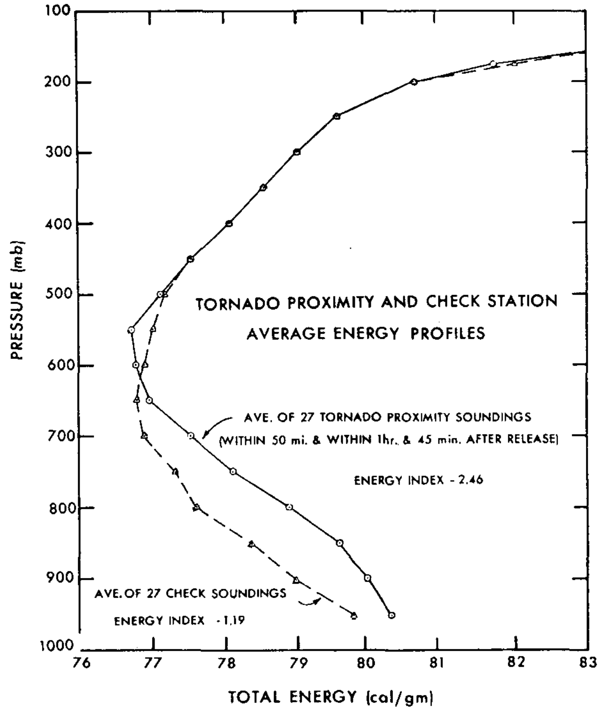

Fig. 3. Average total energy profiles of 27 tornado proximity soundings and corresponding closest check sounding in the same air mass.

surface has the effect, however, of lowering rather than raising the lifting condensation level.

In the interest of complete objectivity, the initial testing of the applicability of the Energy Index as an indicator of the large-scale areas of latent and potential-convective instability has been done using only the 850- and 500-mb data.

4. Energy profiles of tornado proximity soundings

To determine if there does indeed exist a detectable difference in the total energy environment associated with severe tornado-producing storms and non-severe storms, a comparison has been made between total energy profiles derived from tornado proximity soundings and the closest "check" sounding in the same "air mass." For the purposes of this study a tornado proximity sounding is defined as a sounding made within 50 mi of a subsequent tornado reported within one hour and forty-five minutes after the sounding release time.

The results of this comparison are shown in Fig. 3. The average tornado proximity sounding is characterized by markedly higher total energy values than the check soundings from the surface to just above the 650-mb level. In the mid-troposphere the proximity sounding average shows a slightly lower total energy minimum layer centered on the 550-mb level. An analysis of the relative contributions of enthalpy, latent energy and potential energy to these total energy differences shows that the difference is due almost en-

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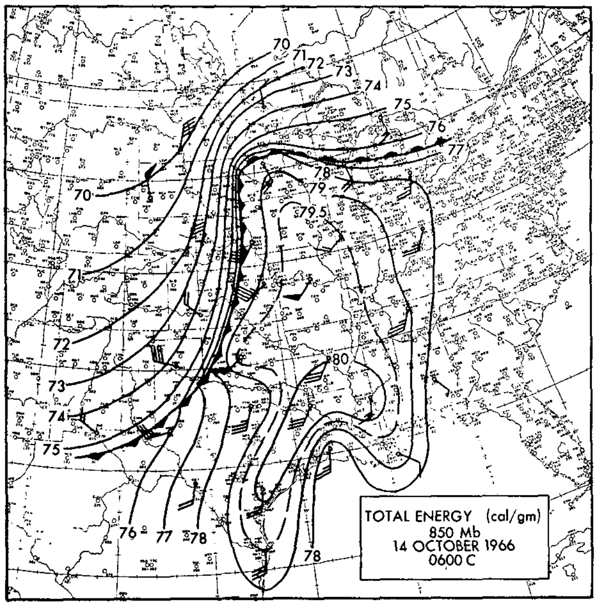
tirely to moisture content and associated latent energy differences. In fact, the average proximity and check soundings have temperature differences of less than 1C at all tropospheric levels with the average proximity sounding consistently cooler at all levels below the 400-mb level. The average Energy Index computations show that although the check sounding displays potential instability, the average proximity sounding is nearly twice as unstable.

5. Total energy distributions in severe storm-producing situations

Energy Index computations have been made for all major severe storm-producing situations in the Midwest during the past year. The experience gained over this period has allowed some tentative quantitative values of the Energy Index to be assigned to various degrees of expected storm intensity. In the range of 0.0 to −1.0, thunderstorms are possible but will not be severe. In the range from −1.0 to −2.0, isolated severe thunderstorm activity is possible, particularly as a continuation of existing severe activity moving into the region. For Energy Index values more negative than −2.0, severe thunderstorms and associated tornado activity are highly probable, providing an adequate triggering mechanism to release the potential instability is present or forecast. Energy Index values as low as −6.0 have been observed. A seasonal variation in the critical



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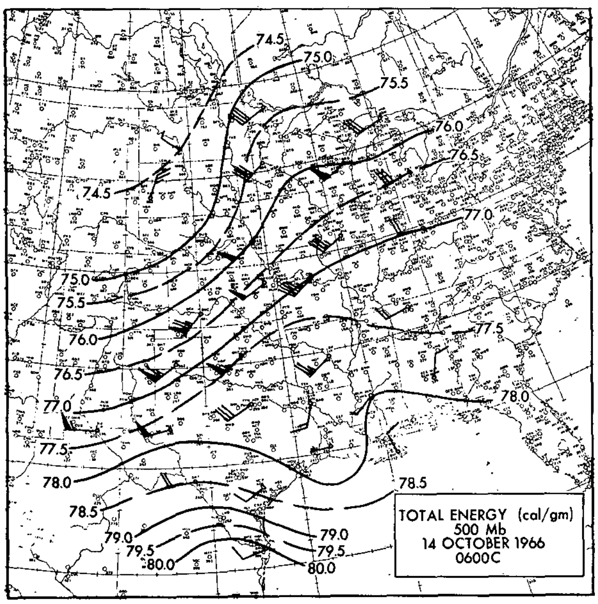

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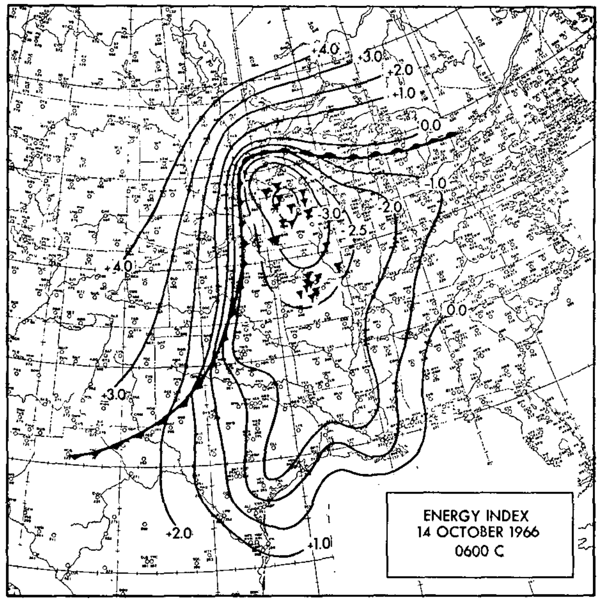

c.

FIG. 4. Total energy distributions at the 850-mb level, a., the 500-mb level, b., and their difference, the Energy Index, c., at 0600 CST 14 October 1966 (Belmond, Iowa, tornado day). Tornadoes were reported at the tip of the funnel shaped figures between 1200 and 2100 CST.

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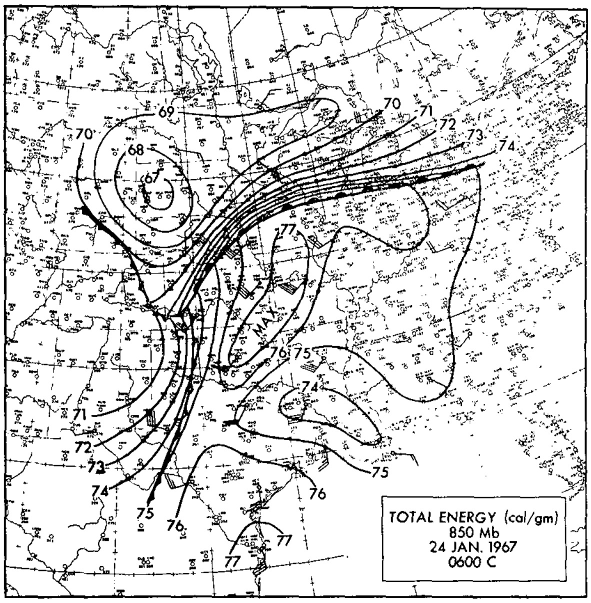
Energy Index values has been observed with values during the middle and late summer being about one unit more negative.

In general, the Energy Index pattern for a given time is similar to the Showalter Index pattern. This is to be expected, since the synoptic-scale gradients of low-level total energy are normally greater than the mid-tropospheric gradients. There is, however, a slight but significant shift of the Energy Index minimum region in the direction of the regions of the injection of cold dry air aloft.

The results of the Energy Index analysis of three noteworthy tornado-producing situations for the past year are shown in Figs. 4–6. The storm systems occurred on 14 October 1966 (Belmond, Iowa tornado day), 24 January 1967 (Orrick and St. Louis, Mo., tornado day), and 21 April 1967 (Belvidere and Oak Lawn, Ill., tornado day).

Figs. 4a, b and c show the total energy distributions at the 500- and 850-mb levels and their difference, the Energy Index pattern at 0600 CST 14 October 1966. Subsequent reported tornado activity occurred at the tip of each funnel shaped symbol. The tornado activity began in southwestern Iowa shortly after noon and within the next three hours spread through central and north central Iowa and into extreme southern Minnesota. A second flurry of tornado activity began in central Missouri about 1430 CST and spread eastward into



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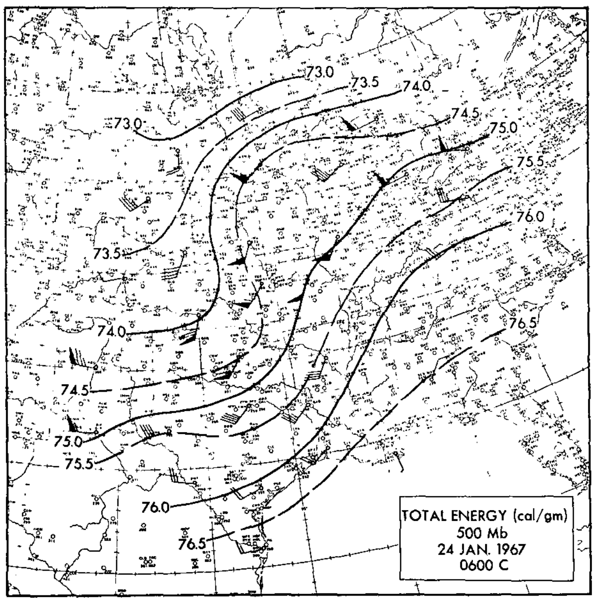

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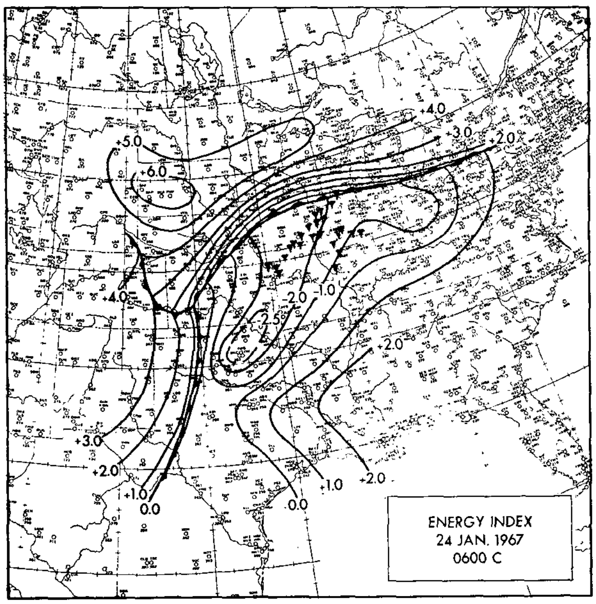

c.

Fig. 5. Total energy distributions at the 850-mb level, a., the 500-mb level, b., and their difference, the Energy Index, c., at 0600 CST 24 January 1967 (Orrick and St. Louis, Mo., tornado day). Tornadoes were reported at the tip of the funnel shaped figures between 1200 and 2100 CST.

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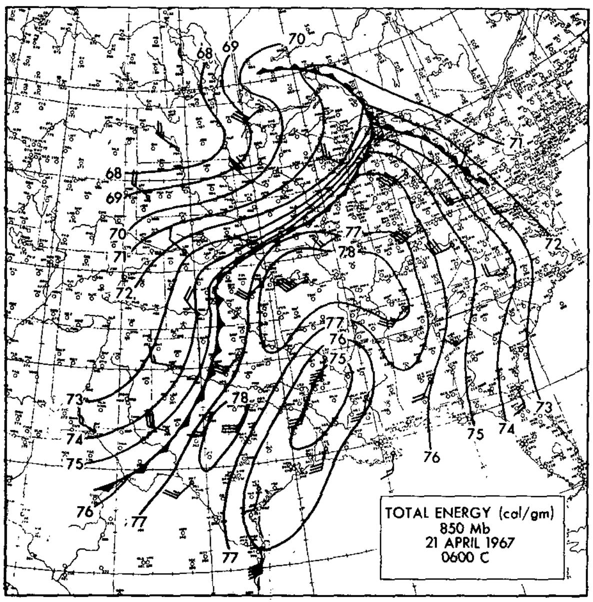
western Illinois by 2000 CST. The −3.5 minimum over north central Iowa was obtained by graphical subtraction of the 850- and 500-mb isolines in that area after the analysis based on values at nearby upper air stations and a surface total energy maximum at Mason City, Iowa, strongly suggested its existence.

Figs. 5a, b and c show the total energy distribution at 850 and 500 mb and the Energy Index pattern at 0600 CST 24 January 1967. The total maximum at low levels from central Oklahoma, across northwestern Missouri to southern Iowa was imbedded in strong southwesterly flow. In the mid-troposphere, the advection of lower total energy values was occurring over eastern Kansas and Nebraska. Severe storm activity broke out in the Kansas City area shortly before noon along the southern end of the north-south oriented squall line. The tornado activity spread northeastward across northern Missouri and into southeastern Iowa by 1500 and across northwestern Illinois and into extreme southern Wisconsin by 1800. A second outbreak of tornado activity began in the St. Louis area and west central Illinois between 1800 and 1900 CST ending in the Champaign, Ill., area about 2100 CST. Severe thunderstorms with damaging winds and hail were common on this date in a fan-shaped area southeast of a line from St. Joseph, Mo., to Green Bay, Wis., and north of a line from Olathe, Kan., to St. Louis, Mo., to Lafayette, Ind.



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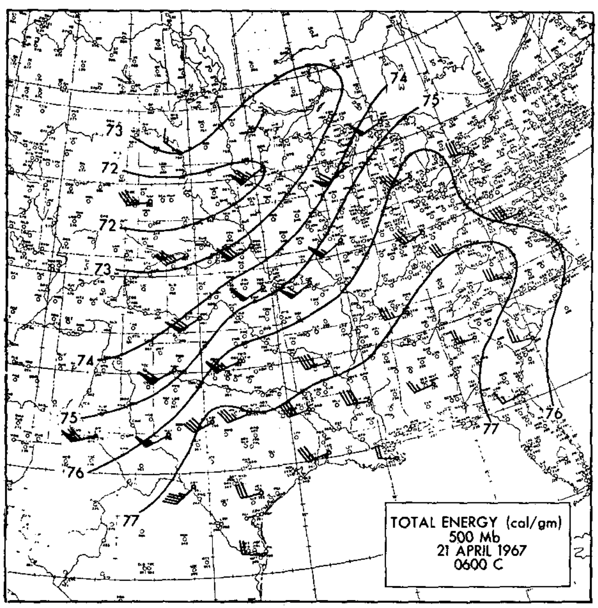

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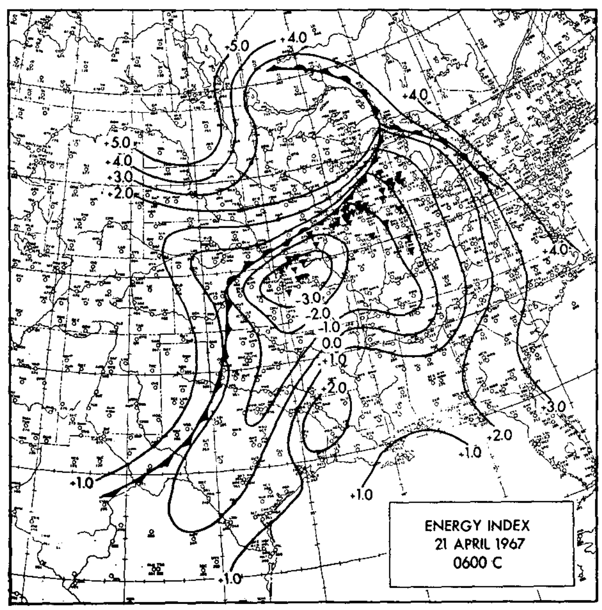

c.

FIG. 6. Total energy distributions at the 850-mb level, a., the 500-mb level, b., and their difference, the Energy Index, c., at 0600 CST 21 April 1967 (Belvidere and Oak Lawn, Ill., tornado day). Tornadoes were reported at the tip of the funnel shaped figures between 0800 and 2330 CST.

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The energy distributions at 850 and 500 mb and the associated Energy Index pattern for 0600 CST 21 April 1967 are shown in Figs. 6a, b, and c. At low levels high total energy air along an axis from Del Rio, Tex., through Columbia, Mo., and from Columbia to Nashville, Tenn., is moving northeastward.

In the mid-troposphere, Fig. 6b, total energy values show a substantial gradient to the northwest of the broad band of relatively high values over the Gulf States. The combined effect of high energy values at low levels and relatively low values aloft over eastern Kansas and Missouri yield an Energy Index minimum in those states (Fig. 6c). A severe thunderstorm produced a tornado in extreme northeastern Missouri and 2-inch hail in extreme southeast Iowa between 0800 and 0830 CST. Severe thunderstorms with associated tornadoes redeveloped about noon in western Missouri north of Kansas City and spread eastward and northeastward across the northern half of Missouri. Severe storm activity crossed southeastern Iowa between 1300 and 1530 and occurred across the northern half of Illinois between 1530 and 1730 and southwestern Michigan and northern Indiana between 1800 and 2000. Forty-five tornadoes occurred in the five-state area between noon and midnight.

6. Conclusions

It has been demonstrated on both theoretical grounds and through application to the real atmosphere that the total energy variations in the vertical and horizontal are useful and meaningful parameters in the analysis of potential-convective instability associated with severe storm activity. The total energy approach combines the temperature, moisture and height fields in a physically logical manner and is easier to compute than its thermodynamic counterparts, wet-bulb potential temperature or pseudo-equivalent potential temperature. The Energy Index pattern has been shown to be a good first indicator of areas of potential severe storm outbreak which must then be combined with other existing severe storm forecast parameters to further define the final forecast. The Energy Index has a slight but significant advantage over the Showalter Stability Index and the Lifted Index since it alone takes into account the possible contribution of potentially cold, mid-tropospheric air to the total energy release of the severe convective storm.

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