Hourly Surface Static Energy Analysis as a Delineator of Thunderstorm Outflow Areas

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(Manuscript received 18 June 1974; in revised form 27 May 1975)

ABSTRACT

The advantages and potential for the use of hourly surface static energy \( (e_pT + gz + Lw) \) analysis to readily detect and monitor areas affected by thunderstorm outflow air are presented. A comparison between the delineation of thunderstorm-produced meso- or bubble highs by conventional pressure analysis and static energy analysis is made using the 15 May 1968 severe storm day as an example.

1. Introduction

The detection and subsequent monitoring of surface outflow air from thunderstorms or thunderstorm complexes such as squall lines can play a critical role in operational mesoscale and severe storm forecasting. At times, the mesoscale outflow air from a number of thunderstorms in an area may merge and have a pronounced impact on subsequent synoptic scale developments (see for example Fujita, 1955; Zipser, 1969).

The detailed analysis of thunderstorm outflow areas and their associated meso- or bubble highs has been largely in the domain of post storm research efforts. These efforts, as reviewed by Fujita (1963), rely quite heavily on input from special mesoscale observational networks or on data laboriously gleaned from microbarograph and thermograph traces. Many of the meso-meteorological research analysis techniques are, unfortunately, too involved and time consuming to be readily adaptable to real time analysis and forecast requirements. However, some operational success in the detection and tracking of thunderstorm-produced meso- or bubble highs has been demonstrated by forecast personnel at the Severe Local Storms Unit of the National Severe Storm Forecast Center (Magor, 1959) and the Air Force Global Weather Central of the Air Weather Service (Miller, 1972) through very careful attention to hourly changes in pressure and/or altimeter setting, wind, temperature, and dewpoint. Prosser (1970) and Hamilton (1970) have demonstrated potential operational mesoscale analysis techniques by incorporating real time radar data. Purdom (1973, 1974) has shown the potential for incorporation of geosynchronous satellite imagery in real time mesoscale analysis.

It is the purpose of this paper to call attention to the potential for and advantages in the use of hourly surface static energy \( (e_pT + gz + Lw) \) analysis to readily delineate thunderstorm outflow areas.

2. Static energy and its conservation

The term "static energy" was introduced by Kreitzberg (1964) to describe the thermodynamic parameter \( (e_pT + gz + Lq) \), the sum of specific enthalpy, potential energy, and latent energy. Riehl and Mankus (1958) referred to the same quantity as "total heat content" in the application to penetrative convection in the tropics. Considering the normal allowable tolerances in reported upper air humidity values, Darkow (1968) used the approximation \( E_s \approx e_pT + gz + Lq + w \), where \( w \) is water vapor mixing ratio and \( L_0 \) a constant latent heat of condensation, to study the structure of the severe storm producing environment. Using the values of \( e_p \approx 1.00 \text{[g}^{-1}\text{K}^{-1}], \quad L_0 \approx 2500 \text{[g}^{-1}], \quad g \approx 980 \text{[cm s}^{-2}], \) yields \( E_s ([J g^{-1}] \approx T(K) + 9.8 \times 10^{-2} z(m) + 2.5 w(g kg^{-1}) \). Although, as discussed by Madden and Robitaille (1970), static energy is not exactly proportional to its more familiar thermodynamic counterparts, equivalent potential temperature and/or wet bulb potential temperature, from an applied standpoint, it may be considered to be similarly conservative. Thus, non-training parcels of air will essentially preserve their static energy values during either saturated or unsaturated adiabatic ascent or descent or during evaporative cooling due to falling rain.

3. Practical advantages of surface static energy analysis

In addition to the analysis advantages which result directly from the conservative nature of static energy discussed in the previous section, there are two addi-
Table 1. Conversion of temperature (°F) to equivalent energy values (J g⁻¹).

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Table 2. Conversion of dew point temperature (°F) to equivalent energy values (J g⁻¹) based on psychrometric calculator used by stations with elevations from 120 m to 409 m mean sea level.

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The conversion of dew point temperature (°F) to equivalent energy values (J g⁻¹) is important for practical applications to the delineation of thunderstorm outflow areas.

1. Surface static energy values can be readily determined for any network of stations reporting nothing more than temperature and dew points. This assumes, of course, that station elevations are known. A simple direct tabular conversion of temperatures and dew points in °F to their respective energy equivalents c_pT and L_wv can be made. Sample tables to convert surface temperatures and dew points to their equivalent energy values are shown in Tables 1 and 2.

2. Surface static energy values of maritime tropical air over land typically range from about 320 J g⁻¹ to 360 J g⁻¹ depending on the time of year and time of day. At any particular observation time during the late morning and afternoon, however, the warm air sector displays considerable homogeneity in surface static energy values. The order of magnitude of synoptic scale gradients in static energy is 10⁻² J g⁻¹ m⁻², upon which is superimposed a random noise level of the order of ±2 J g⁻¹. The static energy values of thunderstorm outflow air are observed typically to be 10 J g⁻¹ to 30 J g⁻¹ less than the pre-thunderstorm air which it replaces. As a consequence then, thunderstorm outflow air frequently appears as a well-defined closed center in the surface static energy field with values 3 to 10% lower than the surrounding air values.

By way of contrast, meso- or bubble highs typically superimpose a 2 to 10 mb pressure excess on a background sea-level pressure field of the order of 1000 mb containing a random noise level of the order of ±0.2 mb and synoptic scale gradients of the order of 10⁻¹ mb m⁻¹. The mesohigh is therefore frequently masked in the large scale pressure field as a perturbation of only 0.3% to 1.0% of background pressure values. Delineation of the thunderstorm-induced high frequently requires judicious subjective analysis or some objective filtering of the mesoscale disturbance from the background pressure field.

Figure 1 and 2 are an example of these effects. In Fig. 1, a 2 to 3 mb mesohigh over Illinois and Indiana produces only a ridging effect on the large scale pressure field. The spatial extent and the location of the center of the mesohigh are not readily apparent. By contrast, the surface static energy analysis for the same time shown in Fig. 2 reveals the thunderstorm outflow air as well-defined centers with values 15 J g⁻¹ to 20 J g⁻¹ below ambient values.

4. The mesohigh of 15 May 1968

On 15 May 1968 severe storm activity affected 12 states in the Midwest. Thirty-five tornadoes killed 73 people and injured more than a thousand. Particularly devastating tornadoes hit Charles City, Iowa, and Jonesboro, Ark. For the purposes of this paper we will focus our attention on a mesohigh system that was initiated by thunderstorm activity which first reached severe limits in extreme west central Illinois between 0500 and 0600 CST. This mesohigh, nurtured by the composite outflow from numerous storms, not only spread eastward and northward during the entire day to cover large portions of Illinois, Indiana, and Ohio by evening, but was instrumental in triggering a resurgence of even more severe activity across central Illinois during the afternoon. Changnon and Wilson (1971) have made a detailed study of the extensive heavy rain, hail, and tornado activity in central Illinois on this date.
By noon the impact of the large mesohigh was quite evident in the surface pressure field over the northern half of Illinois. A surface pressure analysis for 1200 CST based on altimeter setting reports from all available stations is shown in Fig. 1. (The rather “amateurish” appearance of the analysis due to the irregular wiggles and spacing in the isobars is quite intentional and results from a conscious effort not to smooth to some preconceived level of significance.) Particularly evident at this hour is the pronounced trough along the southern and southwestern edges of the mesohigh from southeast Iowa across south central Illinois and into Indiana. The National Meteorological Center surface analysis for this same time, based on approximately one third of the number of reporting stations, gave no indication of either the mesohigh or the trough.

Figure 2 shows the surface static energy field over the same area at the same time. The regions of static energy values less than 325 J g⁻¹ in Illinois and eastern Iowa are associated with thunderstorm outflow air and stand in sharp contrast with the higher values of static energy (335 to 350 J g⁻¹) in the surrounding warm moist air. (The analysis over Lake Michigan is speculative but guided by static energy values of lake shore stations with a lake breeze.)

5. Objective-numerical analysis of the mesohigh

The comparison of the appearance of the mesosystem in terms of pressure and static energy in Figs. 1 and 2 has some unavoidable impact of subjectively inherent with conventional manual analysis. In an attempt to increase the objectivity in the analysis and comparison of the pressure and static energy fields, the technique for maximizing details in numerical weather map analysis by Barnes (1964) was applied in slightly modified form. A 10×11 grid with 11 km spacing was centered on north central Illinois. A portion of this grid is shown in Fig. 3. The data from the surface stations shown in Fig. 3 were interpolated to the grid points by the exponential weighting function suggested by Barnes using a radius of influence of 1.5 grid lengths. The slight modification to the Barnes’ technique consisted of interpolating the “first guess” values from the four grid points surrounding each station back to each station location using the same exponential weighting function. An error value at each station was determined by comparing the interpolated first guess value to the

![Figure 3](image3.png)

Fig. 3. Objective-numerical analysis of pressure field for 1200 CST 15 May 1968 based on altimeter setting reports from station locations indicated by open circles.
observed value. This error field was then interpolated back to the grid points and added to the first guess field. Three interactions of this technique produced rapid convergence towards observed data values.

The objective-numerical analysis of the original altimeter setting field (expressed in mb) is shown in Fig. 3. The ridging and troughing associated with the superposition of the mesohigh on the background pressure field of the warm air sector is again apparent. To objectively filter the mesoscale pressure disturbances from the background pressure field a numerically smoothed pressure field was determined by 20 passes over the grid of a nine-point smoothing function (Shuman, 1957).

The resulting smoothed pressure field is shown in Fig. 4. Disturbances in the pressure field less than two grid lengths (222 km) have been filtered out completely and disturbances greater than four grid lengths remain essentially unchanged. To recover the "mesoscale" pattern the smoothed pressure field of Fig. 4 was subtracted from the original pressure field in Fig. 3. The resulting "mesoscale" pressure field is shown in Fig. 5. The mesohigh with pressure excesses greater than 1 mb over the smoothed background pressures is now much more apparent than in the original pressure field. The mesoscale troughing on the southern and southwestern edges of the mesohigh is also evident.

6. Objective analysis of the static energy field

A numerical analysis of the original static energy field is shown in Fig. 6. The agreement with the manual-
subjective analysis in Fig. 2 is striking and gratifying. The objective analyses of the original data produced a slightly more intense center of low static energy in the region of maximum outflow in east central Illinois. The mesoscale disturbance pattern in static energy was also determined by subtracting a numerically smoothed field from the original field and the results are shown in Fig. 7. Also shown in Fig. 7 are 1200 CST positions of the radar echoes as extracted from WSR-57 radar film for CHI, STL, EVV, and DSM. Once again the agreement with the original subjective analyses of the surface static field is striking. The low static energy values of the thunderstorm outflow air are producing a region of surface station energy ranging from 5 to almost 20 J g⁻¹ below the surrounding air. The mesoscale static energy deficit field appears to show good spatial relationship with the radar echoes.

If one accepts the objective determinations of the mesoscale disturbance fields in pressure (Fig. 5) and static energy (Fig. 6) as valid and meaningful, the following observations may be made.

![Diagram](image)

**Fig. 8.** Thunderstorm outflow air mesosystem continuity chart.

1) Mesoscale regions of thunderstorm outflow air can at times be clearly and adequately defined by a subjective analysis of the original surface static energy field (an analysis which can be accomplished in real time from hourly airways data).

![Image](image)

**Fig. 9.** ESSA 5 satellite view at 1519 CST 15 May 1968.
2) Regions of thunderstorm outflow air as manifest in the mesohigh formation may be masked within the large scale pressure field and require some form of filtering for adequate definition.

3) Static energy analysis of hourly surface reports may be used operationally to complement other subynoptic and mesoscale analyses techniques such as pressure, wind, radar, and satellite analyses and thereby enhance the detection and monitoring of thunderstorm outflow air.

7. The mesosystem viewed in static energy analysis

The continuity of the core of the main mesosystem of thunderstorm outflow air with values less than 328 J g⁻¹ based on hourly manual analysis is shown in Fig. 8. Inferred minima in the static energy of the mesosystem are also shown. The secondary growth in central Illinois after 1400 CST was associated with the redevelopment of severe activity in this area discussed earlier.

This mesosystem became the dominant feature in the flow and weather patterns over a three-state area during the afternoon and evening of 15 May 1968. It was not only mesoscale in its origins but served to trigger significant additional mesoscale and severe storm activity during its lifetime of over 12 h. The impact of the system as viewed from the ESSA 5 satellite at 1519 CST is shown in Fig. 9. The redevelopment of severe storm activity in north central Illinois, which began about 90 min before this picture, and the squall line at the leading edge of the mesosystem entering western Ohio and southern Indiana dominate the view from this vantage point also.

The only possible source of the air with the low values of static energy observed in the core of this mesosystem was shown by Aizu (1971) on the basis of static energy cross-sectional analysis for this same day to be in the lower midtroposphere between 700 and 500 mb. This is entirely consistent with the earlier conclusions of others based on wet bulb potential temperature analysis of aircraft and sounding data (see for example Fankhauser, 1971; Newton, 1963). The near equality in the static energy values of the thunderstorm outflow air at the surface and at its midtropospheric level of origin suggests a surprisingly small impact of entrainment on the thermodynamic properties of the core of the downdraft.

8. Concluding remarks

There are times when the differences between the static energy values of the thunderstorm outflow air and the prethunderstorm air are not as large as in the example presented in this paper. Thunderstorm outflow air reaching the surface after appreciable local nocturnal cooling has taken place or on the cold air side of a front in association with overrunning type thunderstorm activity may result in such small changes in surface temperature and dew point as to preclude easy detection by static energy analysis. It is hoped, however, that the discussion and examples presented in this paper will stimulate others, particularly those with operational forecast responsibility, to explore and exploit the advantages and potential of hourly static energy analysis as an additional subynoptic and mesoscale analyses tool.

REFERENCES


Fujita, T. T., 1955: Results of detailed synoptic studies of squall lines. Tellus, 1, 405-436.


