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A Simplified Surface Analysis for the Detection of Outflow Boundaries from Mesoscale Convective Complexes

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A SIMPLIFIED SURFACE ANALYSIS FOR THE DETECTION OF OUTFLOW BOUNDARIES FROM MESOSCALE CONVECTIVE COMPLEXES

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In Partial Fulfillment
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Master of Science

by
Gregory W. Powell
August 1983

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A SIMPLIFIED SURFACE ANALYSIS FOR THE DETECTION OF OUTFLOW BOUNDARIES FROM MESOSCALE CONVECTIVE COMPLEXES

Recommended 6 Oct. 1983
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Gregory W. Powell 48 pages

Directed by: L. Michael Trapasso, Ronald Dilamarter,
Nicholas Crawford, and Glen Conner

Department of Geography and Geology Western Kentucky University

A simplified surface analysis was developed to detect thunderstorm outflow boundaries that emanate from Mesoscale Convective Complexes (MCCs). The analysis consisted of the interpretation of visible and enhanced infrared satellite imagery, radar observations, and a limited number (10-12) of surface observations. Thirty MCCs were interpreted by the simplified analysis; nine produced identifiable outflow boundaries.

Pre-boundary Cloud Cover (PCC) and radar echo intensities were analyzed to determine if a correlation existed between mean sky cover and thunderstorm intensity. Research established that no correlation exists between PCC and radar echo intensity.

Recommendations were made for future research into outflow boundary identification by the simplified analysis. Specifically, it was recommended that continued work should be conducted on the effect that pre-convective cloud cover has on the intensity of thunderstorms that subsequently develop.

CHAPTER I

INTRODUCTION AND HYPOTHESES

Introduction

The field of mesoscale satellite meteorology is a rapidly evolving area of climatological research. Weather analysis on the mesoscale (250-2500 km) can aid in the interpretation of regional meteorological phenomena and provide an understanding of localized climatic trends. Satellite imagery has enabled the researcher, in real time, to recognize and interpret weather phenomena. An advanced recognition of specific weather phenomena enables the researcher to obtain a greater lead time for predicting forthcoming weather events over a specified geographical area.

The use of satellites for meteorological purposes was first explored with the TIROS series in the 1960s. The Applications Technology Satellite (ATS) was a second generation satellite system of NASA. The ATS was positioned in a geostationary orbit so that full disc images of the western hemisphere could be obtained. The ATS enabled weather forecasters to detect global and mesoscale events as they occurred in the atmosphere; however, ATS did not have night detection capabilities (U.S. Department of Commerce, 1975).

The development of the Geostationary Operational Environmental Satellite/Synchronous Meteorological Satellite (GOES/SMS) provided continuous imagery on both the visible and infrared bands. This system has enabled forecasters to show, in real time, atmospheric disturbances at various scales of motion and size. GOES/SMS is able to view most of the northern, southern, and western hemispheres and is able to produce images detecting mesoscale weather phenomena with the use of various scales and resolution of imagery. The collection of satellite data and rapid distribution techniques have provided a valuable research tool in the study of meteorological phenomena (U.S. Department of Commerce, 1979).

Current research in satellite imagery is being conducted primarily by scientists of the National Oceanic and Atmospheric Administration (NOAA). Specialized studies of mesoscale events (i.e., events that occur over a limited area over a short period of time) are a main focus of recent research using satellite imagery.

The primary purpose of this research is to determine if a simplified surface analysis can be developed to identify thunderstorm outflow boundaries. This analysis is developed through the use of visible and enhanced infrared satellite imagery, radar observations, and a limited number of surface observations. In 1982, Doswell discussed the need to correlate satellite analysis with conventional surface analysis. He indicated that this type of analysis is rapidly being developed and is introducing new research methods to the field of mesoanalysis.

Large predefined thunderstorm complexes or Mesoscale Convective Complexes (MCCs) (Maddox, 1980) were analyzed on enhanced infrared and visible satellite imagery in coordination with radar observations and surface data reports to detect thunderstorm outflow boundaries. A thunderstorm outflow boundary is the leading edge of an outflow downdraft wind from a thunderstorm. The passage of an outflow boundary is usually identified by a wind shift and a rapid rise in pressure. A thunderstorm outflow boundary can initiate new convection at a later time if atmospheric conditions are conducive for convection. Outflow boundaries may be detected on satellite imagery as "arc clouds" (i.e., an arc shaped line of low level cumulus clouds). Arc clouds may not always be detected on satellite imagery because of obscuring high level cloudiness. Though identification of the arc cloud is preferable, it is not necessary, since a surface analysis can detect outflow boundaries. It is the thunderstorm outflow boundary and its possible initiation of new convection which are the primary focus of this study.

Hypotheses

The first hypothesis was that a simplified surface analysis is able to detect outflow boundaries that emanate from Mesoscale Convective Complexes (MCCs). The simplified surface analysis consists of plotted hourly data and incorporates satellite analysis with the surface data. This analysis was developed to be less time consuming than a detailed mesoanalysis, which involves the plotting of hundreds of surface reporting stations. The simplified surface analysis used several (10-12) observation stations to detect the surface signatures associated with outflow boundaries. Satellite imagery was used to identify areas of intense convection, which are the most suspect areas for outflow boundary development. The simplified surface analysis was used with satellite imagery, and surface stations nearest to the most intense convection were analyzed for the detection of outflow boundaries.

The second hypothesis was that mean sky cover prior to convective development influences the intensity of thunderstorms that subsequently develop. This hypothesis tested two theories: (1) Pre-boundary cloud cover (PCC) at a station affects the intensity of thunderstorms that occur at the station and (2) Pre-thunderstorm cloudiness (PTC) at a station not affected by an outflow boundary affects the intensity of thunderstorms that occur at the station. If PTC is minimal then convective intensity will be greater. Additionally, the intensity of thunderstorms that develop along outflow boundaries should be negatively correlated with mean sky cover prior to convective development. An observation station that reports no clouds for the observation period is more likely to experience intense convection than a station that is overcast for the observation period. Clear skies allow a greater amount of daytime heating thus increasing the instability of an air mass. The more unstable the air mass the greater is the intensity of the thunderstorms.

The prediction of where and when an outflow boundary will initiate convection presents an interesting forecast problem. By using satellite imagery, surface reports, and radar observations, a forecasting technique can be developed to locate areas of potential convective development along an outflow boundary. In this research, the author attempts to define outflow boundaries and their potential to initiate new convectional storms.

CHAPTER II

STUDY AREA

The study area for the research encompasses much of the central United States. Maddox, Rodgers, and Howard (1982) found that MCCs primarily affected the region of the United States from the Rocky Mountains to the Appalachian Mountains. Atmospheric moisture necessary to sustain MCCs is present in the central United States due to the frequent influxes of maritime tropical air masses. These air masses advect northward more frequently east of the 100th meridian or 20 inch (508 mm) isohyet.

The topographic barrier created by the Rocky Mountains tends to limit the influence of maritime tropical air masses to the eastern slopes of the Rockies. The mountain barrier created by the Appalachian Mountains on the east also tends to disrupt low level moisture flow that is critical in sustaining the convection associated with MCCs. The central United States is suitable as the study area because a sufficient density of data points (NWS stations) necessary for outflow boundary identification can be found within that area.

To assist in time-space orientation, two types of GOES/SMS image sections were used in the study. They are the 0.9 km resolution and the 1.9 km resolution (Figure 1). High resolution satellite images can be obtained at 30 minute intervals, and provide sufficient detail for the recognition of MCCs and resultant outflow boundaries.

Once an MCC is identified, areas that are likely for the propagation of outflow boundaries can be located, and the area where convection is most likely to develop along an outflow boundary may be identified.

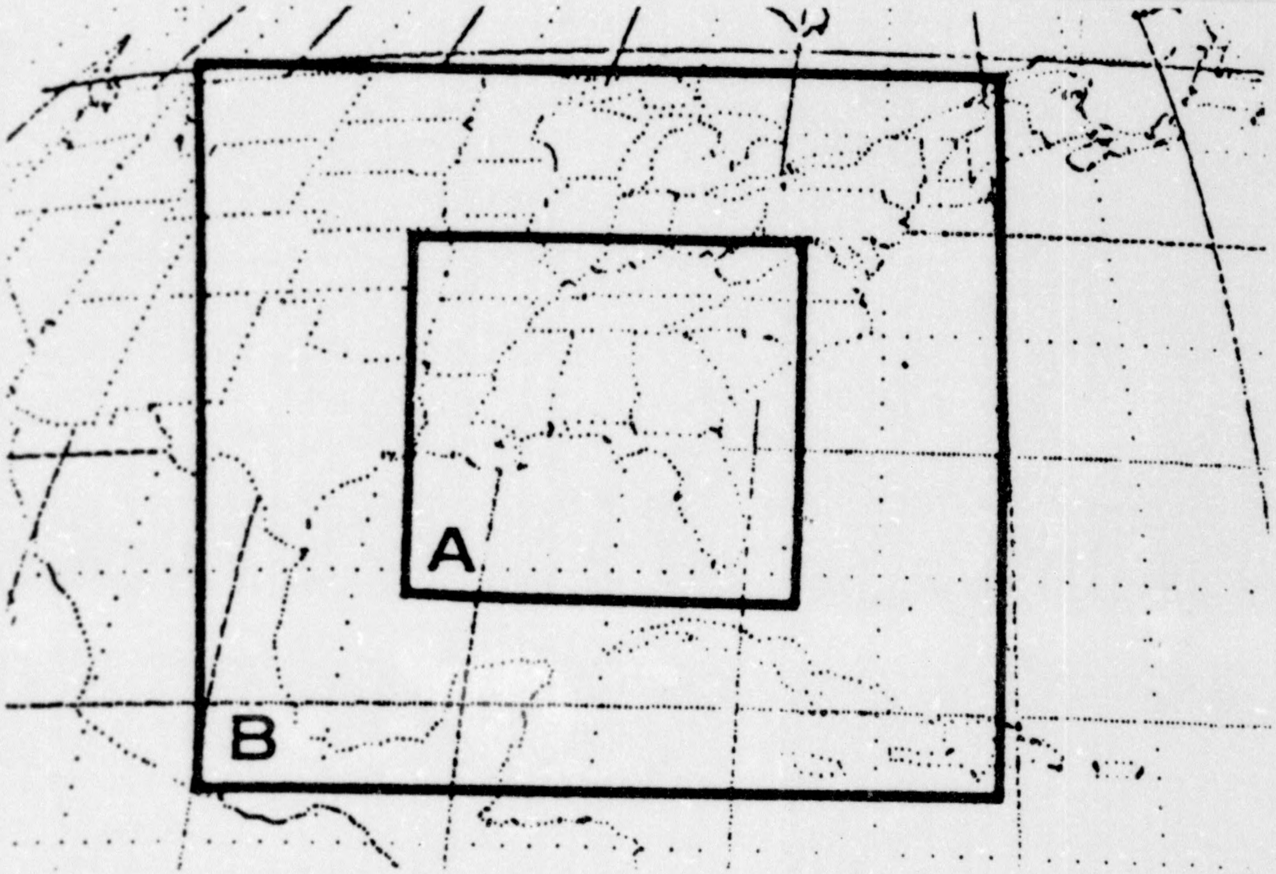


Figure 1. GOES 0.9 km (A) and 1.9 km (B) Image Resolutions (Source: U.S. Department of Commerce, 1979).

CHAPTER III

REVIEW OF LITERATURE

The science of mesoscale weather analysis has been greatly advanced by the use of weather satellite imagery. The importance of satellite imagery to mesoscale weather analysis has long been recognized by weather researchers, for example, Fujita (1963). Researchers have realized that the accurate interpretation of satellite imagery can provide a better understanding of the processes and causes of mesoscale weather events. The ability to view time sequence and real time satellite imagery would provide the researcher with an increased understanding of the atmospheric processes involved in mesoscale weather events.

Prior to the introduction of high resolution satellite imagery, the intermediate processes responsible for the development of convection were observed primarily on the macroscale. The development of GOES-1 km visible imagery has now enabled the forecaster to prepare a mesoscale convective forecast. By using high resolution satellite imagery, the forecaster can more readily detect areas of low level moisture convergence and developing convective lines, which are precursors of thunderstorm development. Their identification is essential in preparing a mesoscale convective forecast (Purdom, 1976).

In 1976, Gurka used visible and infrared satellite imagery and incorporated the data with surface observations to differentiate strong gust fronts from weak gust fronts that emanate from thunderstorms (Gurka, 1976). Gurka felt that the classification of the intensities of the thunderstorm-generated gust fronts would aid in short-range forecasting techniques.

Visible and enhanced infrared GOES imagery has been used to estimate convective rainfall amounts associated with deep convection. High resolution visible and enhanced infrared imagery were used to identify areas of intense convection, overshooting tops, merging areas of convection, and other features (Scofield and Oliver, 1977).

Mesoscale surface analysis is made possible by using both satellite imagery and surface observations. Mesohighs and their outflow boundaries can be identified and their movement plotted. An outflow boundary or "arc cloud" is usually identified by an arc shaped line of low level cumulus clouds. Severe thunderstorms can develop along the outer boundary of a mesohigh if it moves into a convectively favorable environment (Purdom, 1973).

In 1979, Purdom reiterated his ideas and added some new concepts on thunderstorm outflow boundaries. Purdom indicated that outflow boundaries can maintain their characteristics over a hundred miles from where they originated, and the outflow boundary can initiate new deep convection after the outflow-producing thunderstorms have dissipated. Deep convection will develop if an outflow boundary intersects another convectively favorable boundary, but if an outflow boundary intersects a convectively unfavorable air mass convection will not develop (Purdom, 1979).

Thunderstorm outflow boundaries have been an important topic of satellite literature since the early 1970s (Purdom, 1973, 1976, 1979; Smith, 1976; Maddox, 1980, 1982). Research pertaining to outflow boundaries has been focused primarily on the potential of the outflow boundary to enhance new convection. If an outflow boundary encounters a convectively favorable environment new convection will likely develop.

In 1980, Maddox defined a specific set of criteria for the identification of an MCC. These criteria were derived from the analysis of enhanced infrared satellite imagery and are given in Table 1. The set of criteria has enabled observers to easily identify MCCs. These large convective systems are defined on the mesoscale or length scales of 250-2500 km with durations of at least six hours. Because MCCs persist for at least six hours, their circulations and atmospheric effects can be identified by studying surface observations, upper air observations and satellite imagery (Maddox, 1980).

Enhanced infrared satellite signatures are differentiated through the use of the digital enhancement curve or Mb curve (Figure 2). Figure 3 is an example of how the enhancement curve is used to display a thunderstorm system. The enhanced infrared satellite analysis displays convective intensities through varying levels of shading which represent specific cloud top temperature ranges. The colder the convective cloud top temperature the more intense is the convection associated with the cloud. The infrared enhancement thus categorizes cloud top temperatures and their relationship to storm intensity. For example, enhanced imagery that displays the shade white indicates that temperatures within that particular part of the storm are colder than -80.2° C. A white enhancement shade indicates that very intense thunderstorms are located beneath these very high cloud tops. Enhanced infrared imagery can thus indicate thunderstorm intensity and give real

MESOSCALE CONVECTIVE COMPLEX (MCC)

[Based Upon Analyses of Enhanced IR Satellite Imagery]

Physical Characteristics

Size: A - Contiguous cold cloud shield with IR temperature $\leq$ -32 C must have an area $\geq$ 100,000 km^2

B - Interior cold cloud region with temperature $\leq$ -52 C must have an area $\geq$ 50,000 km^2

Initiate: Size definitions A and B are first satisfied

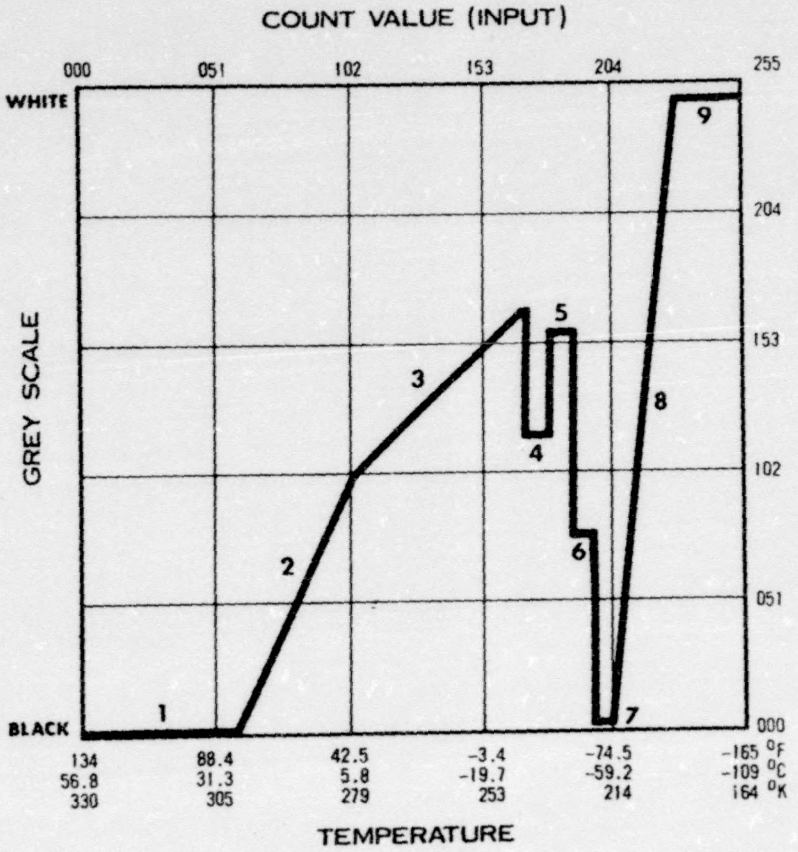
Duration: Size definitions A and B must be met for a period $\geq$ 6 hours

Maximum Extent: Contiguous cold cloud shield (IR temp. $\leq$ -32 C reaches maximum size

Shape: Eccentricity (minor axis major axis) $\geq$ 0.7 at time of maximum extent

Terminate: Size definitions A and B no longer satisfied

Table 1. MCC Identification Criteria (Source: Maddox, 1980).



SEGMENT NUMBER	°C TEMPERATURE ____ TO ____	COMMENTS REASON FOR SEGMENT ENHANCEMENT	
1	+58.8 to +28.2	Little or no useful Met Data (Black)	
2	+28.8 to + 6.8	Low Level/Sea Surface Difference	
3	+ 6.8 to -31.2	Middle Level - No Enhancement	
4	-32.2 to -41.2	First Level Contour	(Med Grey)
5	-42.2 to -52.2	Thunderstorm Enhancement	(Light Grey)
6	-53.2 to -58.2		(Dark Grey)
7	-59.2 to -62.2		(Black)
8	-63.2 to -80.2	Overshooting Tops Enhancement	
9	-80.2 to -109.0		(White)

95

Figure 2. MB Curve (Source: U.S. Department of Commerce, 1979).

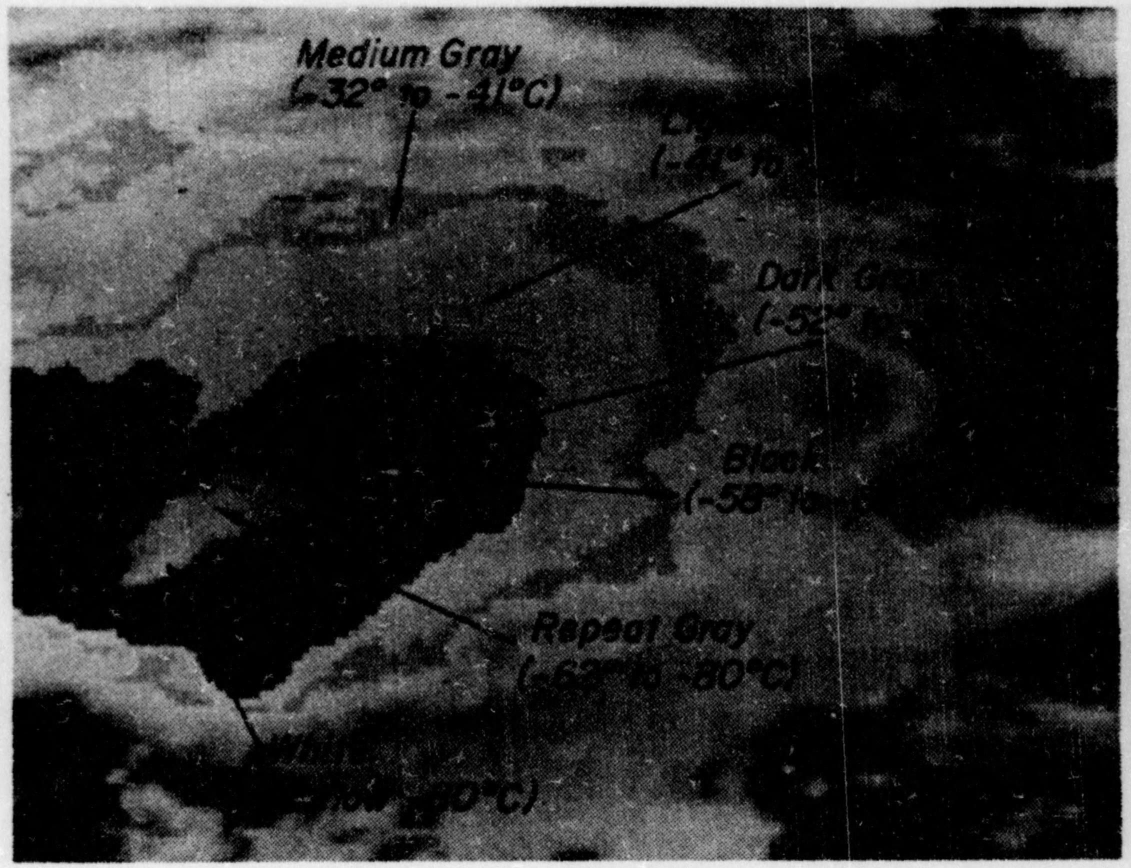


Figure 3. GOES Enhancement Shading (Source: Scofield, Oliver, and Spayd, 1980).

time information for image analysis. Through the use of the Mb curve, the satellite images can identify areas of intense convection, since these areas frequently produce outflow boundaries (Scofield, Oliver, and Spayd, 1980).

Referring to Table 1, Maddox (1980) indicates that a significant area of an MCC cloud shield has a temperature of less than 52°C. This infrared black body temperature (Tbb) indicates that convection is prevalent and precipitation is occurring over a wide area. Linear thunderstorm systems, such as squall lines, are not included in the MCC criteria since they do not meet the specific shape characteristics.

By the use of satellite imagery, the occurrences of MCCs have been recently documented for the warm season of 1981 by Maddox, Rodgers, and Howard (1982) and for 1982 by Rodgers (personal communication, September, 1982) (Tables 2 and 3).

An MCC can have a pronounced effect by changing the characteristics of the atmosphere. Even after an MCC dissipates, the residual atmospheric effects of the MCC can influence the subsequent weather phenomena. For example, afternoon convective activity can be enhanced by MCC-generated outflow boundaries. In addition, precipitation-induced thermal boundaries and remnant cloudiness can have a pronounced effect on the development of afternoon convection (Maddox, 1982).

Outflow boundaries generated by an MCC can greatly increase the probabilities for the development of severe weather when an outflow boundary encounters an unstable air mass (Maddox, 1982). The pronounced thermal boundaries that occur from thunderstorm outflow can maintain their characteristics for a significant time period. Severe

No.	Date	First Storms	Initiate	Maximum Extent	Terminate	Max. Cloud Top Area x 10^3 km^2		Significant Weather
		Time (GMT)/Date				$\leq$-32°C	$\leq$-52°C	
1	31 Mar./1 Apr.	2100/31	0001/1	0400/1	1130/1	412	219	Wind, hail, tornado, 2 deaths
2	10/11 Apr.	2015/10	2315/10	0345/11	0531/11	159	103	Hail
3	13/14 Apr.	1730/13	0145/14	0445/14	1000/14	639	373	Wind, hail, tornadoes
4	27/28 Apr.	2030/27	0245/28	0600/28	1000/28	282	141	None reported
5	8/9 May	2015/08	0115/09	0445/09	1015/09	267	160	Wind, hail, tornadoes
6	13 May	0530/13	0700/13	1030/13	1615/13	310	188	Wind, hail
7	15/16 May	2000/15	0445/16	0815/16	1315/16	276	169	Hail, wind, tornado
8	26/27 May	2130/26	0515/27	1130/27	1400/27	272	150	Wind, hail
9	28/29 May	0100/28	1330/28	1730/28	0145/29	318	190	Hail
10	28/29 May	1800/28	2130/28	0145/29	0800/29	419	276	Hail, heavy rains, wind
11	5 Jun	0300/05	1000/05	1545/05	1715/05	280	140	Heavy rain
12	7/8 Jun	1930/07	2315/07	0445/08	0745/08	239	188	Tornadoes, wind, hail, hvy. rain, 1 inj.
13	10 Jun	0445/10	0615/10	1130/10	1900/10	207	160	None reported
14	11 Jun	0530/11	1030/11	1400/11	1630/11	328	211	Heavy rain, 3 deaths
15	20/21 Jun	1700/20	1245/21	1530/21	1900/21	245	188	Hail
16	22/23 Jun	0545/22	1100/22	1545/22	0415/23	445	318	Hail, hvy. rain 6-8", flooding
17	22/23 Jun	2315/22	0445/23	0700/23	1000/23	304	210	None reported
18	23/24 Jun	1230/23	0145/24	0515/24	1000/24	367	270	Hail, hvy. rain 5-6", tornadoes
19	2/3 Jul	1930/02	0000/03	0400/03	0630/03	338	265	Tornado, flash flooding 6"
20	12 Jul	0200/12	0800/12	1030/12	1530/12	236	123	Hail, wind, heavy rain
21	23 Jul	0600/23	0930/23	1200/23	1530/23	282	92	Wind, hail, flooding, hvy. rain
22	4/5 Aug	1600/04	0400/05	0645/05	0945/05	309	186	Wind, hail
23	29 Sep	0600/29	1100/29	1330/29	1700/29	187	93	None reported
	Mean	2240	0515	0905	1345	310	192	

Table 2. 1981 Mesoscale Convective Complexes (Source: Maddox, Rodgers, and Howard, 1982).

Date	Time GMT				Cloud Top Area At Maximum Extent x 10^3 km^2		Case Number
	First Storms	Initiate	Maximum Extent	Terminate	$\leq -32°C$	$\leq -52°C$	
19 Mar	0000	0600	0800	1300	467	279	1
17 Apr	0000	0600	0900	1500	400	349	2
19-20	1415/19	2200/19	0200/20	1000/20	288	224	3
20-21	1230/20	1500/20	2030/20	0330/21	385	313	4
10-11 May	2045/10	0145/11	0415/11	1130/11	198	99	5
11-12	1930/11	0600/12	0915/12	1315/12	210	189	6
16	0100	0630/16	1415/16	2100/16	286	196	7
16-17	2000/16	0030/17	0430/17	0730/17	435	242	8
07 Jun	0500	0830	1200	1901	328	201	9
08	0545	1015	1431	2200	235	188	10
08-09	1201/08	1845/08	0100/09	1000/09	294	216	11
09-10	2045/09	0100/10	0330/10	0730/10	268	188	12
10-11	1601/10	2030/10	0115/11	0415/11	243	133	13
10-11	1901/10	2245/10	0830/11	1531/11	439	240	14
14	0200	0800/14	0930/14	1700/14	252	196	15
14-15	1801/14	0300/15	0430/15	1030/15	434	303	16
15-16	1930/15	0130/16	0530/16	0800/16	321	193	17
26-27	1900/26	0800/27	1231/27	1400/27	188	113	18
28-29	1230/28	2231/28	0215/29	0430/29	179	122	19
29-30	2031/29	0031/30	0430/30	0800/30	275	201	20
01-02 Jul	2015/01	0115/02	0345/02	0830/02	158	106	21
04-05	2200/04	0045/05	0745/05	1201/05	450	329	22
06-07	2215/06	0530/07	1100/07	1300/07	279	172	23
13-14	2130/13	0145/14	0515/14	0945/14	194	118	24
18	0330	0630	0800	1630	289	145	25
18-19	2300/18	0400/19	0800/19	1130/19	189	106	26
24-25	2215/24	0245/25	0415/25	1115/25	168	86	27
04-05 Aug	2200/04	0300/05	0700/05	1017/05	279	177	28
12-13	2330/12	0330/13	0830/13	1430/13	356	235	29
13-14	2230/13	0700/14	1100/14	1330/14	243	105	30
15	0430	0830/15	1101/15	1501/15	193	115	31
26-27	2230/26	0400/27	0730/27	1101/27	385	197	32
29-30	2130/29	0330/30	0600/30	0930/30	169	74	33
30-31	2100/30	0200/31	0645/31	0900/31	212	92	34
31-01 Sep	2000/31	2300/31	0230/01	0530/01	166	94	35
02	0300/02	0545/02	0815/02	1145/02	199	145	36
05	0545/05	1015/05	1345/05	1715/05	340	217	37

Table 3. 1982 Mesoscale Convective Complexes (Source: Rodgers, Personal Communication, 1982).

thunderstorms may often occur in conjunction with outflow-induced thermal boundaries as a trigger mechanism (Maddox, Hoxit, and Chappell, 1980).

Maddox and Doswell (1982) indicated that severe thunderstorm forecast guidelines are not completely applicable within weak synoptic settings. The results of their study suggested that emphasis should be placed on detecting pronounced east/west thermal boundaries and areas of vertical motion forced by lower-tropospheric warm advection, because these are essential tools for forecasting convection in an otherwise weak synoptic setting.

In 1982, Weaver and Nelson discussed thunderstorm-derived gust fronts. They found that gust fronts in conjunction with cold frontal boundaries have a varied influence on the development and duration of new convection. In one example, Weaver and Nelson found that gust front interaction between two convective cells initiated rapid convective development and probable tornado genesis at the intersection of the two gust fronts. Their study also suggested the need for better methods of detecting outflow boundaries so that nowcasting techniques could be improved.

In a recent study from the Illinois State Water Survey (Scott and Ackerman, 1983) the authors discussed the identification of dry nocturnal gust fronts that were detected within a densely instrumented research area. The Illinois State Water survey network was more densely instrumented than the hourly weather observation reporting network that exists over the central United States.

Since a densely spaced observation network does not exist over the rest of the United States, alternate observation methods must be developed to detect outflow boundaries. The simplified surface analysis was designed as an alternate method for detecting outflow boundaries.

CHAPTER IV

DERIVATION OF DATA

Introduction

Thirty MCC occurrences were selected to determine if convection occurs in conjunction with MCC induced outflow boundaries (Table 4). Surface observations were collected for the stations that were likely to be affected by an outflow boundary. These stations were chosen by observing satellite imagery and thus determining the areas where outflow boundaries were most likely to emanate from MCCs. The MCC locations were obtained from Maddox et al. (1982) and from Rodgers (personal communication, September, 1982).

The simplified surface analysis can identify a potential outflow boundary using hourly surface plots (which can be retrieved from the National Weather Services AFOS computer system) and can be completed by the following procedure: (1) Frontal systems are plotted on the surface analysis to differentiate frontal windshifts from outflow boundary related windshifts. The surface plot should enable the forecaster to locate outflow boundaries by their characteristic rapid pressure rises and windshifts upon passage; (2) surface stations situated near the area of the most intense convection associated with an MCC should be analyzed closely for outflow boundary identification; (3) if an outflow boundary is identified, hourly surface plots can be requested so that the movement of the outflow boundary can be plotted; (4) the outflow

MCC DATA LIST

DATE	MCC#	TERMINATE
1).8/30/82	34	0930/30
2).8/13/82	29	1430/13
3).8/5/82	28	1017/5
4).7/25/82	27	1115/25
5).7/19/82	26	1130/19
6).7/18/82	25	1630/18
7).7/7/82	23	1300/7
8).7/5/82	22	1201/5
9).7/2/82	21	0830/2
10).6/27/82	18	1400/27
11).6/15/82	16	1030/15
12).6/14/82	15	1700/14
13).6/11/82	14	1531/11
14).6/10/82	12	0730/10
15).6/9/82	11	1000/9
16).6/7/82	9	1901/7
17).5/17/82	8	0730/17
18).5/16/82	7	2100/16
19).5/11/82	5	1130/11
20).4/20/82	3	1000/20
21).9/29/81	23	1700/29
22).8/5/81	22	0945/5
23).7/23/81	21	1530/23
24).7/12/81	20	1530/12
25).7/3/81	19	0630/3
26).6/24/81	18	1000/24
27).6/11/81	14	1630/11
28).6/10/81	13	1900/10
29).6/8/81	12	0745/8
30).5/27/81	8	1400/27

Table 4. MCC Data List (Source: Maddox, Rodgers, and Howard, 1982) and (Rodgers, Personal Communication, 1982).

boundary is a prime area for convective development, and should be watched closely for the development of thunderstorms.

Two types of data were collected to calculate a statistical relationship between (1) the intensity of convective development along an outflow boundary and (2) Pre-boundary Cloud Cover (PCC). The first data type consists of the mean sky cover for a six hour period prior to convective development over a station. The second type is the ranking of radar echo intensity that develops along the outflow boundary (Table 5). The six hour observation time period is an arbitrary limit but was chosen because the effect that an outflow boundary has on a station is limited to a few hours.

In the 30 MCC cases that were studied, it was decided that if convection occurred at a station without detection of an outflow boundary, then the statistical test would be used to relate the intensity of thunderstorms that develop and the Pre-thunderstorm cloud cover (PTC) at the station.

Mean Sky Cover

PCC was obtained from surface observations, and is defined as the mean sky cover over a station determined prior to any convective development (Table 5).

Certain criteria have been developed to ascertain mean sky cover in situations where obscurities limit reporting values. A thin sky cover (for example, 250-BKN or 100-OVC) will not serve as a ceiling since it is not opaque. A ceiling is designated by greater than one-half of the sky being opaque. A thin sky cover layer will be ranked as a scattered layer, since a thin sky cover is not as effective in reducing insolation as an opaque sky cover. If an obscurity occurs

Table 5

Derivation of Data

Ranking of Mean Sky Cover	Ranking of Radar Echo Intensity
1 = Clear	1 = Moderate
2 = Few (Less Than 1/10)	2 = Strong
3 = Scattered (1/10-5/10)	3 = Very Strong
4 = Broken (6/10-9/10)	4 = Intense
5 = Overcast (10/10)	5 = Extreme

during the six hour observation period, then the potential effect of the obscurity on the insolation must be taken into account. If the obscurity is due to dense fog for five of the six hours of the observation period, then the sky cover will be recorded as overcast. Fog allows little insolation to heat the surface; and as dense fog dissipates, daytime heating may be slow to recover. If dense fog obscures for less than five hours of the observation period, then the mean reportable sky cover for the six hour observation period will be taken. It would be unusual for fog to persist past the early morning hours during the warm season months because of the rapid temperature recovery caused by strong daytime heating. If the obscurity is due to dust or haze then the sky cover will be reported as scattered, since insolation is generally not severely limited by this obscuring phenomenon. If reportable sky cover is possible through the dust or haze layers then that sky cover will be used and not the arbitrary scattered layer.

Radar Echo Intensity

Satellite imagery can be used to identify the area along an outflow boundary where convection develops. Corresponding hourly radar observations are then interpreted to establish the maximum echo intensities along the outflow boundary (Table 5). The maximum echo intensity of thunderstorms is obtained from National Weather Service Manually Digitized Radar (MDR) observations. The MDR report provides echo intensities from moderate to extreme, and lists the strongest echos within predetermined grids (Figure 4). Each MDR grid box encompasses an area of 1600 square miles. MDR has primarily been used to estimate the areal distribution of precipitation. In this research

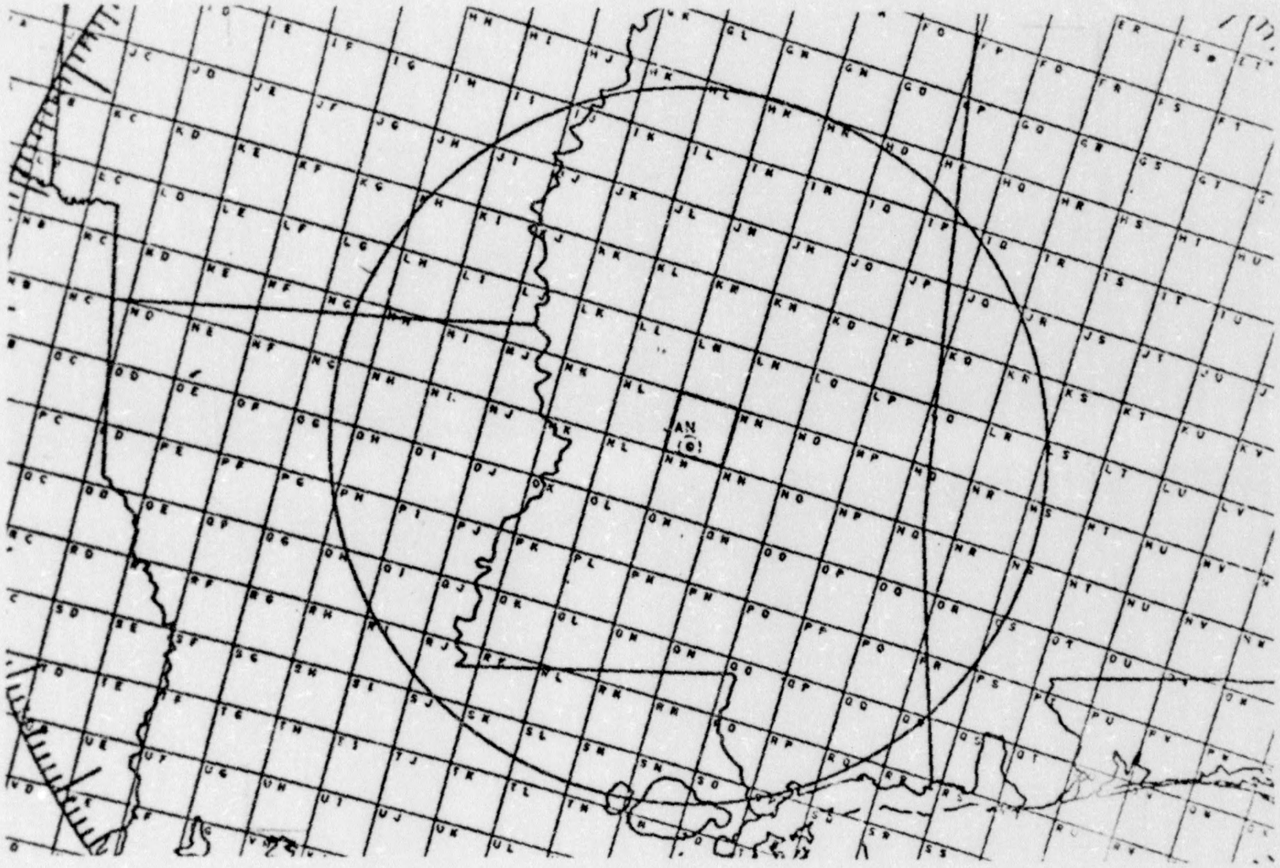


Figure 4. MDR 125 nmi Grid (Source: U.S. Department of Commerce, 1982).

the MDR was used to determine spatial distribution of convective intensities. The MDR report provided a detailed observation of echo locations and intensities (U.S. Department of Commerce, 1978).

Radar observations are reported according to intensity levels. Radar reflectivity levels of two through six, or moderate to extreme, were used in this research. These intensity levels of precipitation are determined by the reflectivity of a radar echo. The greater the echo reflectivity, the more intense is the precipitation and the more severe the thunderstorm. The lowest echo intensity level was eliminated because it is generally associated with stratiform rainfall. Convective precipitation is associated with the intensity levels of two through six.

The radar data were obtained from the National Weather Service WSR-57 radar network. The network radar data that were used are those whose sites cover a 125 nautical mile (nmi.) range in the area where outflow convection was likely to occur. Satellite imagery was used to aid in determining the areas of likely outflow convection. Radar observations were recorded every hour with special observations taken as needed. All radar observations report echo intensity levels and maximum echo tops. Each station fell within a predetermined grid and the corresponding maximum echo top was plotted for that grid.

Statistical Methodology and Analysis

The statistical test that was used is the Spearman's coefficient of rank correlation (ρ).

$$\rho = 1 - \frac{6 \Sigma d^2}{N(N^2-1)}$$

Where: N = the number of paired ranks

d = the difference between a ranked pair

The Spearman values range between -1.0 (when paired ranks are in reverse order), 0.0 (when ranks are random), and +1.0 (when paired ranks are in the same order). This is a nonparametric statistical method and is most valid when the data are applied in the form of ranks. Surface reporting stations that were located within an MCC outflow boundary's projected path were chosen as data points. The surface data were ranked according to the mean sky cover or (PCC) at a station affected by an outflow boundary prior to and up to the onset of convective development. The radar echo intensities were ranked (Steel and Torrie, 1960) for the convection that developed at or near a station affected by an outflow boundary. The rankings for sky cover mean and radar echo intensity are given in Table 5. In this method, there are five possible ranks for each category. The information used to establish these ranks was obtained from government radar weather reporting stations. Only stations where some degree of convection occurred were included in the data sample.

CHAPTER V

ANALYSIS OF DATA

The first hypothesis was established to determine if a thunderstorm outflow boundary could be identified using a new and less complex surface analysis. Since a detailed mesoanalysis is impractical to analyze for outflow boundaries on an hourly basis, the less time-consuming simplified analysis was developed.

In the simplified analysis, satellite imagery was analyzed to determine the areas where outflow boundaries were most likely to emanate from MCCs. Areas of intense convection associated with an MCC were closely observed, since intense thunderstorms frequently produce outflow boundaries. Once an outflow boundary was identified the simplified surface analysis was completed to determine if this boundary could be detected at the surface. The simplified surface analysis consisted of analyzing observations from several (10-12) surface reporting stations located along the projected path of the outflow boundary. An outflow boundary was identified by a windshift and a rapid rise in pressure at a station. The pressure rise and windshift caused by the outflow passage was confirmed if followed by a return to pre-boundary passage wind direction in later observations at the station.

It should be added that occasionally outflow boundaries can be detected by weather radar. The radar signature of an outflow boundary is indicated by a thin line of convective echoes. This fine line echo delineates the leading edge of an outflow boundary. In this research, fine lines were not recorded on any radar data, therefore this technique was not utilized as a tool for identifying outflow boundaries. Only surface observations and satellite imagery were used as tools to identify outflow boundaries.

The 0.9 km (KA5) and 1.9 km (KB8) satellite images provided the visual analysis for outflow boundary identification (Figures 5 and 6). National Weather Service observation forms 10A and 10B were used to extract surface observations from stations associated with possible outflow boundaries (Figures 7 and 8). The National Weather Service weather radar observation from MF 7-60 (Figure 9) supplied digital radar information of convective activity for the target stations included in the simplified surface analysis.

Case Example: 10 June, 1981

To clarify the new surface analysis procedure, an example is provided. On 10 June, 1981, intense thunderstorms developed in the central Mississippi River Valley along an eastward progressing MCC-induced outflow boundary. The simplified analysis was utilized to identify and plot the boundary as it moved from northwest Arkansas to eastern Arkansas and Missouri where thunderstorms developed.

At 1200 GMT, a cold front extended through central Missouri into the Ohio River Valley (Figure 10). Stations south of the cold front were analyzed for outflow boundaries since the most intense convection associated with the MCC occurred south of the front. Additionally, anticyclonic flow and frontal-related pressure rises north of the cold

CORRECTION

★ ★

PRECEDING IMAGE HAS BEEN REFILMED TO ASSURE LEGIBILITY OR TO CORRECT A POSSIBLE ERROR

Figure 5. KA5 Image Section (Source: National Weather Service).

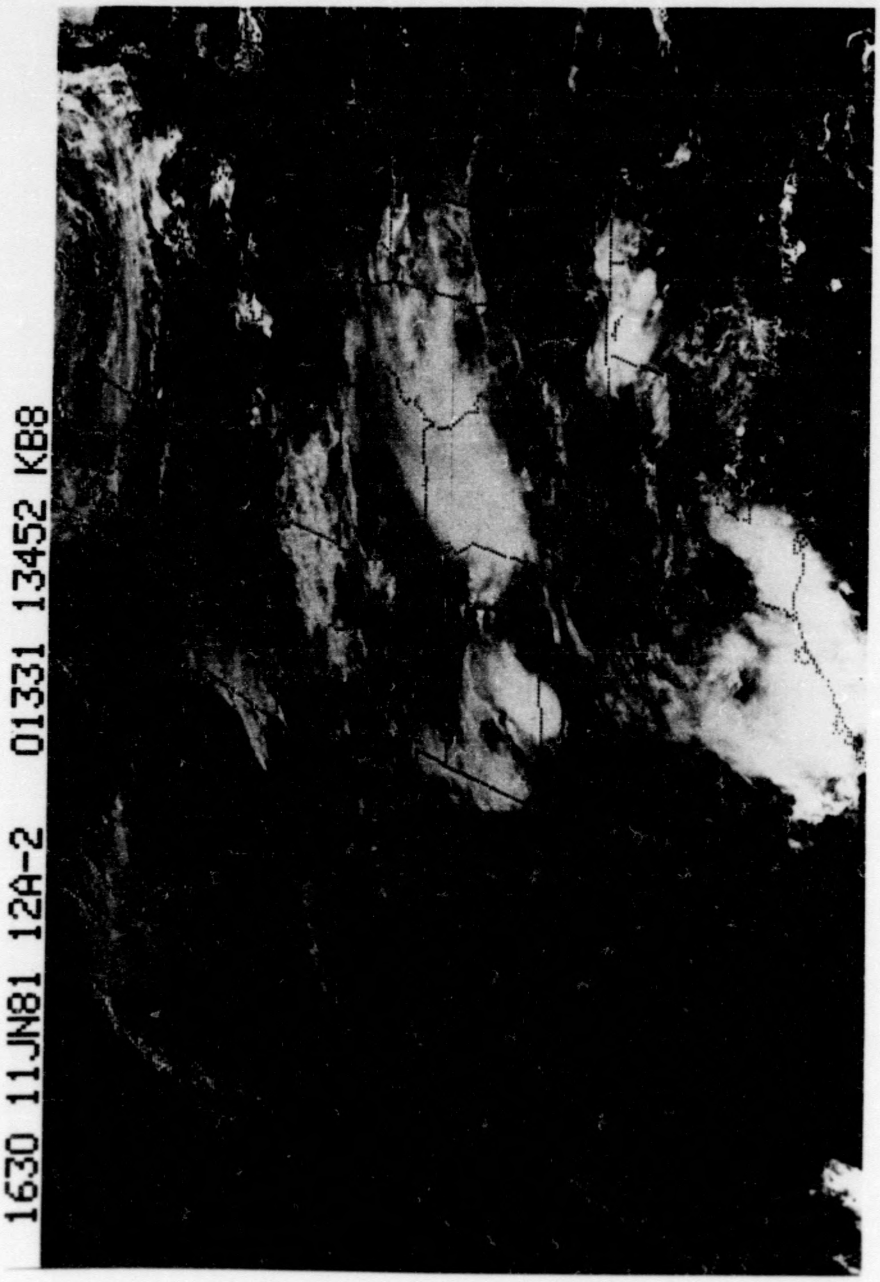
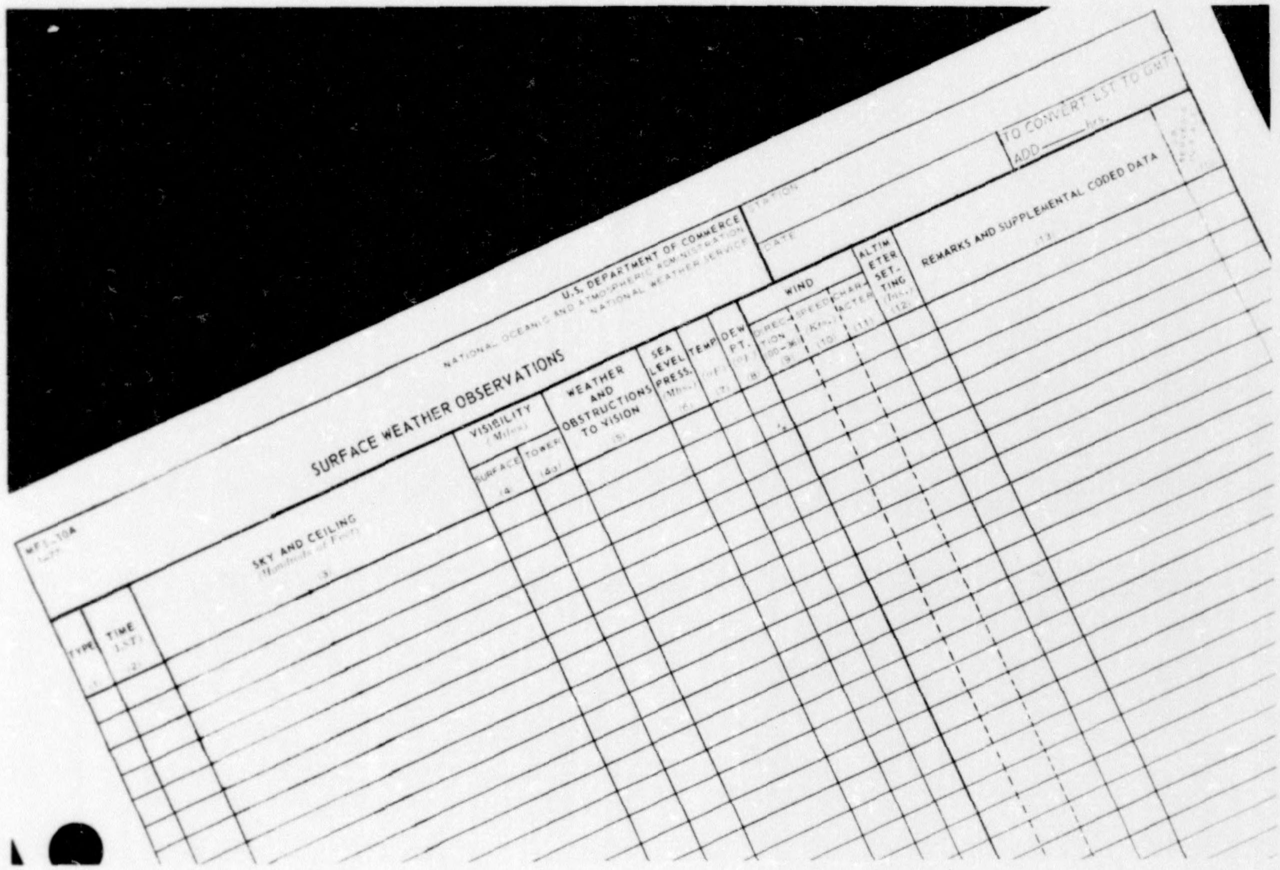


Figure 6. KB8 Image Section (Source: National Weather Service).



WBAN 10A

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE

SURFACE WEATHER OBSERVATIONS

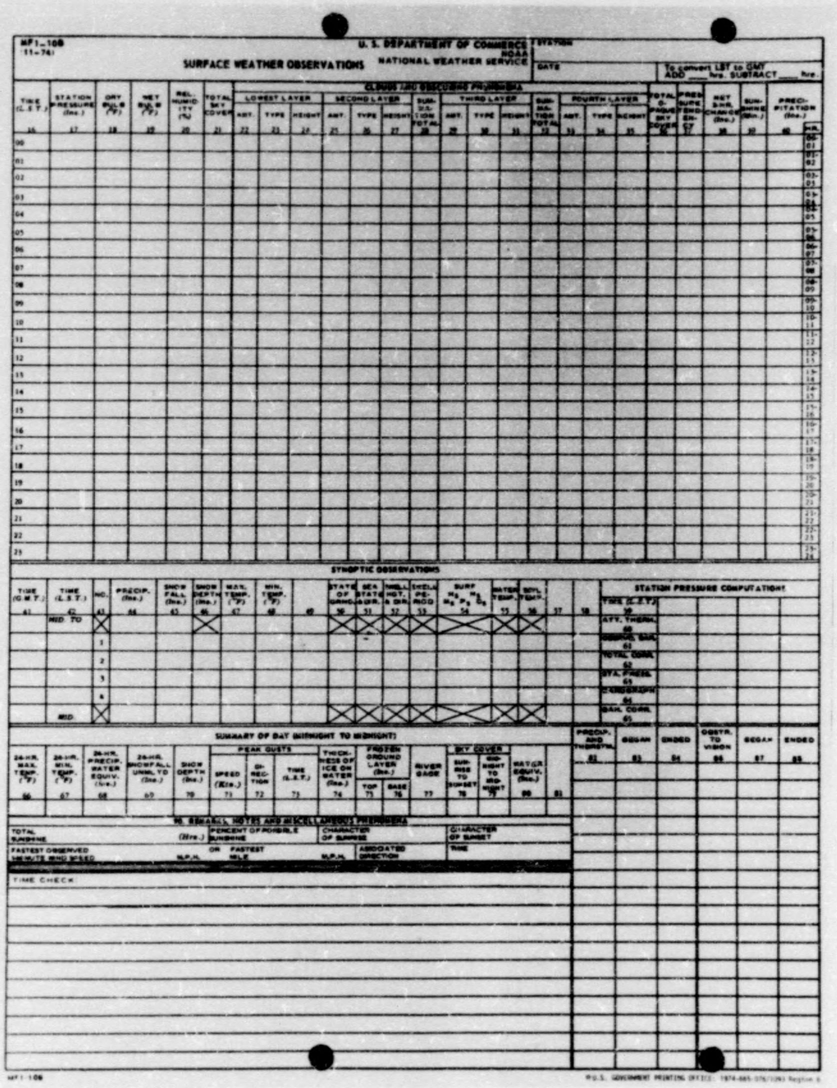
STATION

DATE

TO CONVERT LST TO GMT
ADD ______ hrs.

TYPE (1)	TIME (LST) (2)	SKY AND CEILING (Hundreds of Feet) (3)	VISIBILITY (Miles) SURFACE (4)	VISIBILITY (Miles) TOWER (4a)	WEATHER AND OBSTRUCTIONS TO VISION (5)	SEA LEVEL PRESS. (Mbs.) (6)	TEMP (°F) (7)	DEW PT. (°F) (8)	WIND DIREC-TION (00–36) (9)	WIND SPEED (Kts.) (10)	WIND CHAR-ACTER (11)	ALTIM-ETER SET-TING (Ins.) (12)	REMARKS AND SUPPLEMENTAL CODED DATA (13)

Figure 7. Weather Service Observation Form 10-A (Source: National Weather Service).



MF1-10B
(11-74)

U. S. DEPARTMENT OF COMMERCE
NOAA
NATIONAL WEATHER SERVICE

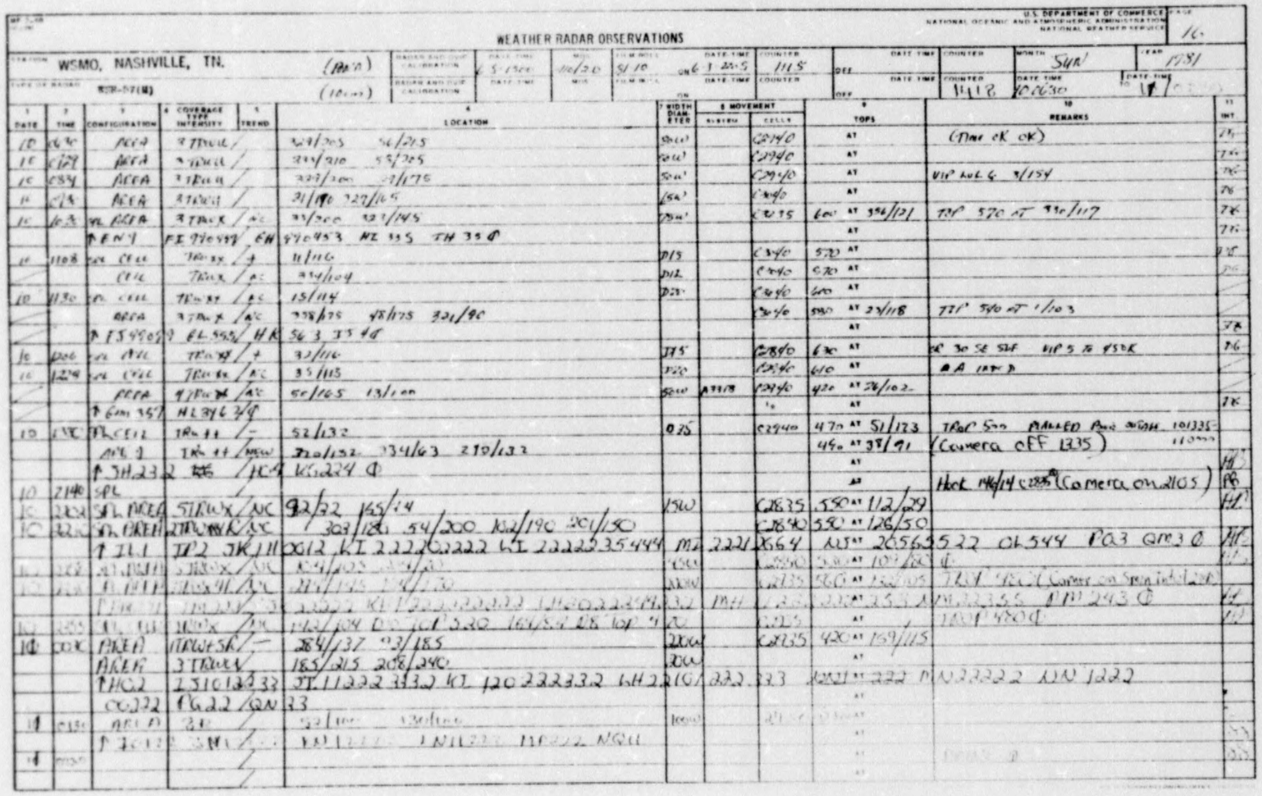
SURFACE WEATHER OBSERVATIONS

STATION

DATE

To convert LST to GMT
ADD ___ hrs. SUBTRACT ___ hrs.

Figure 8. Weather Service Observation Form 10-B
(Source: National Weather Service).



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NATIONAL WEATHER SERVICE

PAGE 16

WEATHER RADAR OBSERVATIONS

STATION WSMO, NASHVILLE, TN.

YEAR 1981

1 DATE	2 TIME	3 CONFIGURATION	4 COVERAGE TYPE INTENSITY	5 TREND	6 LOCATION	7 WIDTH DIAMETER	8 MOVEMENT SYSTEM	8 MOVEMENT CELLS	9 TOPS	10 REMARKS	11 INT

Figure 9. Weather Radar Observation Form MF7-60
(Source: National Weather Service).

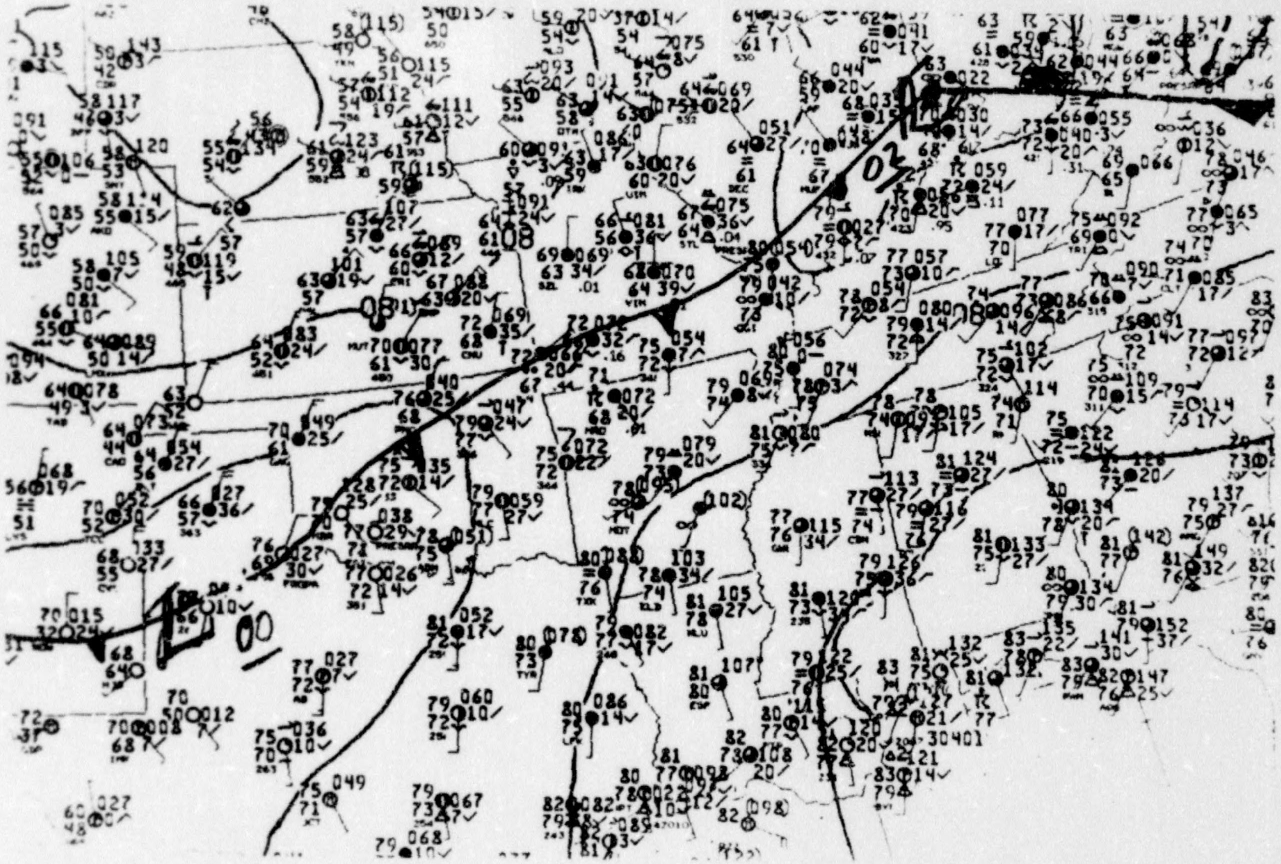

Figure 10. 1200 GMT Surface Analysis (Source: National Weather Service).

front would mask any outflow boundaries. Thirteen reporting stations south of the front were analyzed hourly to identify the passage of the outflow boundary in conjunction with the predefined MCC over southwestern Missouri (Maddox et al., 1982). The observation stations were selected from the area most likely to encounter an MCC-generated outflow boundary and correlated with the location of the most intense convection indicated on the enhanced infrared satellite imagery.

An outflow boundary at 1200 GMT was located by surface analysis in northwest Arkansas. This outflow boundary was associated with the MCC that was situated over southwestern Missouri. As the outflow boundary moved east-southeast, it retained its identifiable surface characteristics through 1800 GMT.

By 1700 GMT, the outflow boundary had progressed eastward and was approaching the Missouri Bootheel and northeast Arkansas (Figure 11). The satellite image in Figure 12 indicates an outflow boundary from A to A'. Part of the outflow boundary is obscured by convective debris associated with the MCC in northwest Arkansas. At the same time, a second outflow boundary had emanated from the MCC and was moving through northwest Arkansas.

The 1735 GMT Radar Summary Chart (Figure 13) indicated that thunderstorms had begun to develop in southeast Missouri along with an eastward progressing outflow boundary. The 1800 GMT visible satellite image failed to clearly identify the outflow boundary (Figure 14); however, the series of simplified surface analyses had successfully tracked the boundary since 1200 GMT. By 1835 GMT, intense thunderstorms had developed along the outflow boundary (Figure 15). These thunderstorms produced no less than four severe storms which

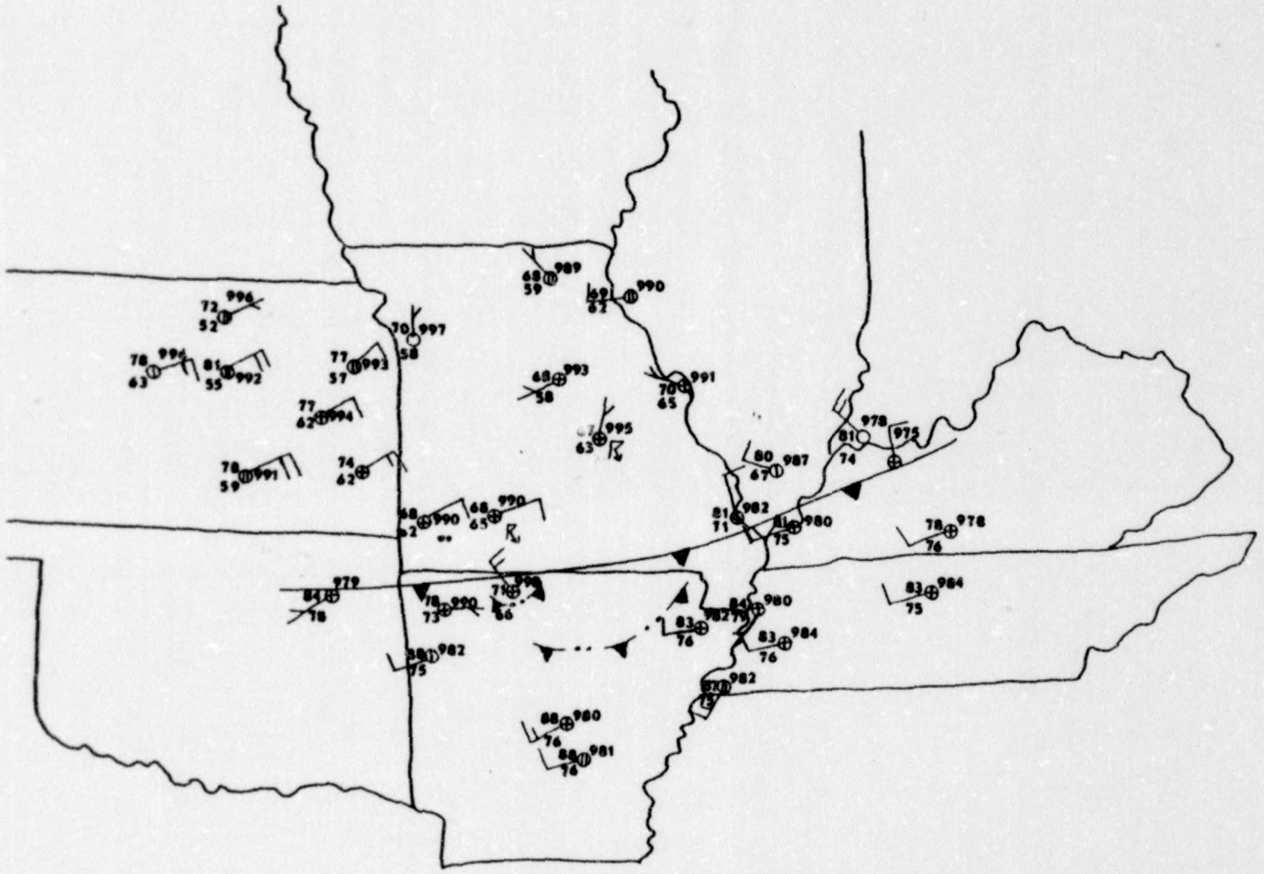

Figure 11. 1700 GMT Surface Analysis.

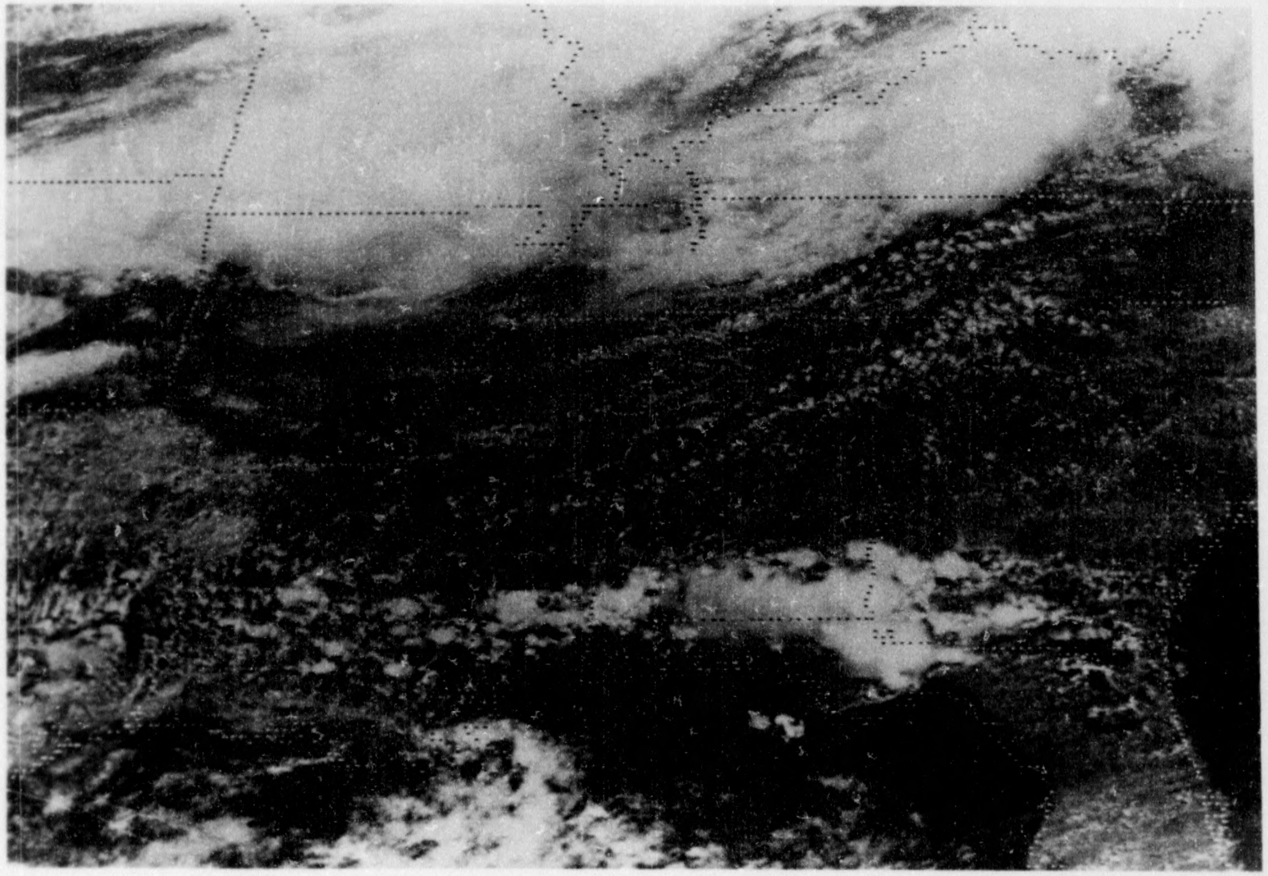

Figure 12. 1700 GMT Satellite Image (Source: National Weather Service).

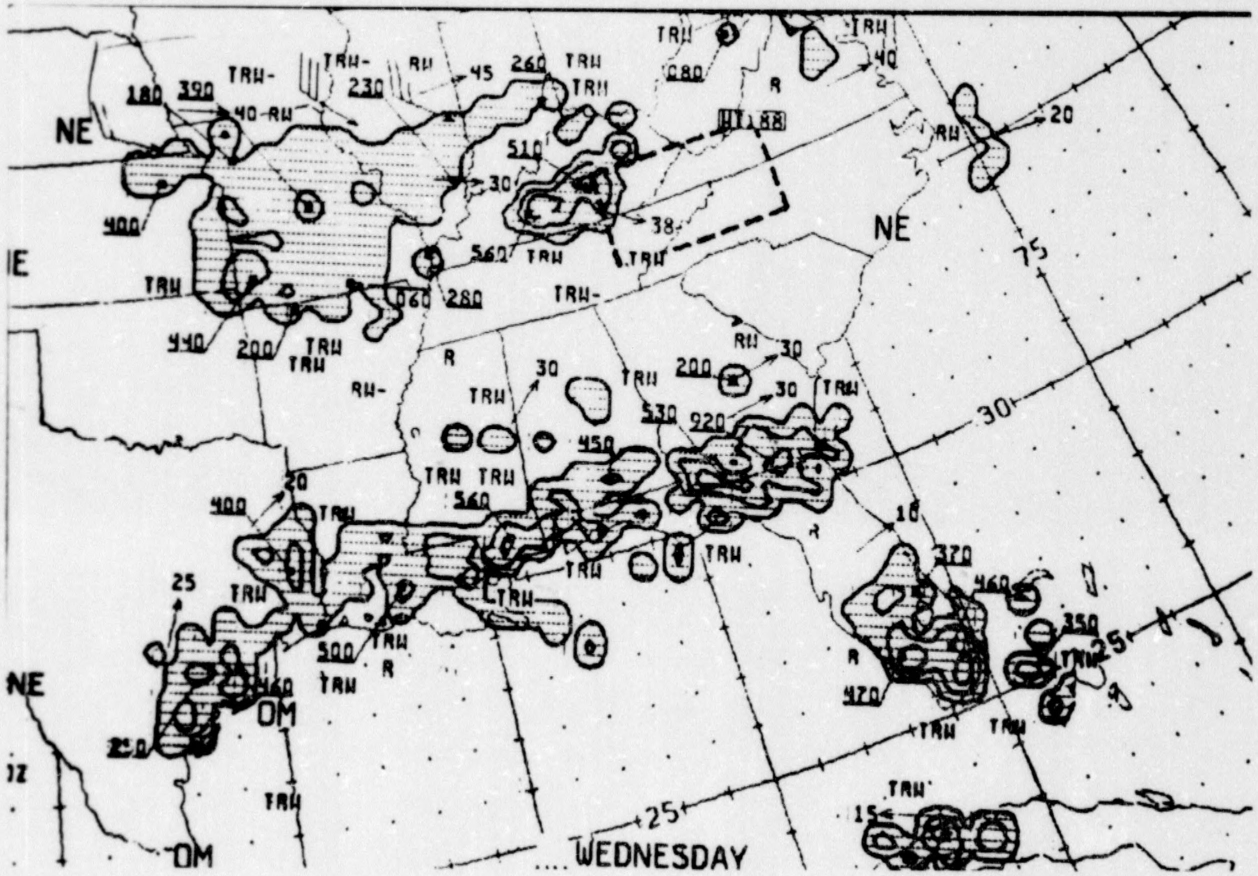

Figure 13. 1735 GMT Radar Summary Chart (Source: National Weather Service).

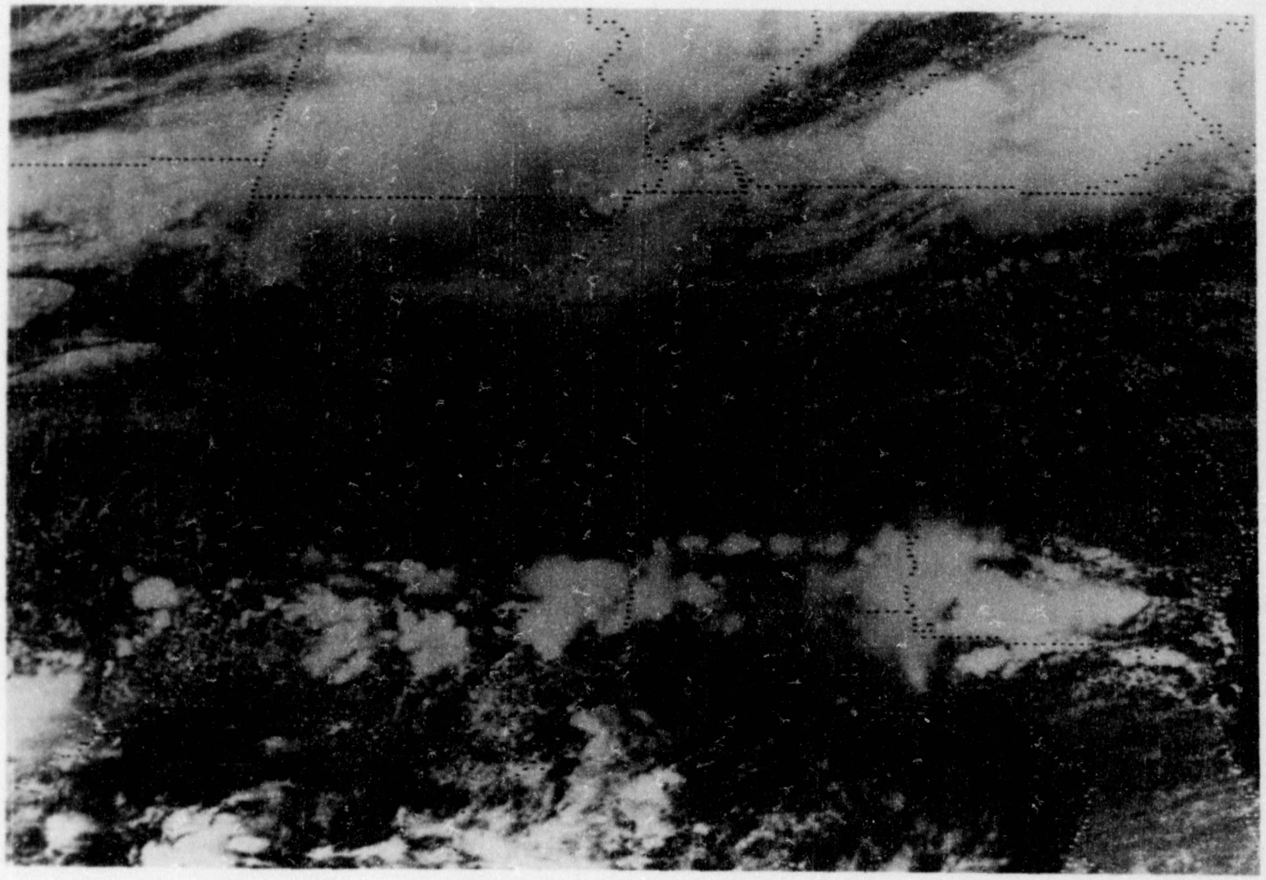

Figure 14. 1800 GMT Satellite Image (Source: National Weather Service).

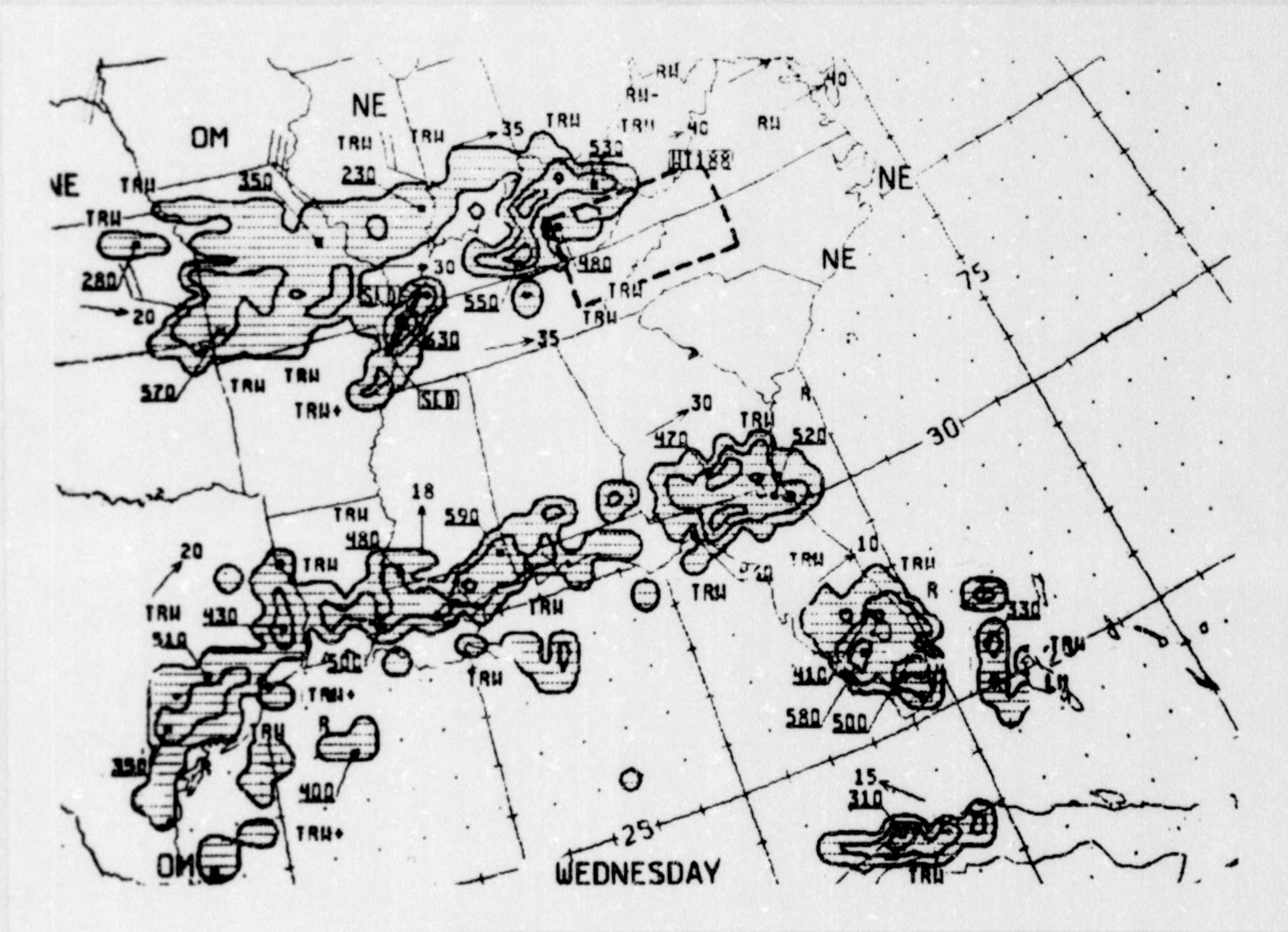

Figure 15. 1835 GMT Radar Summary Chart (Source: National Weather Service).

moved through western Tennessee (U.S. Department of Commerce, 1981).

To summarize, a limited number of surface observations in conjunction with a simplified surface analysis were used to detect an MCC-derived outflow boundary hours before the development of intense convection. Satellite imagery was correlated with the simplified surface analysis to track the outflow boundary until the thunderstorms developed. The simplified analysis enabled this researcher to quickly plot an hourly surface analysis of the outflow boundary's movement and direction. This method of rapid interpolation of the location of the boundary permits forecasters to designate areas that are likely to experience convective activity. Though the simplified surface analysis is not as detailed and time consuming as a complete mesoanalysis, it verified the first hypothesis, proving that outflow boundaries can be detected by this new technique.

Pre-boundary Cloud Cover and Convective Intensity

The second hypothesis was established to test the relationship between the intensity of thunderstorms that develop along outflow boundaries and the mean six hour sky cover at a station prior to convective development. Statistical analysis was used to determine if there was a significant correlation between Pre-boundary Cloud Cover (PCC) at a station, and the intensity of thunderstorms that affect the station. If a strong inverse relationship appears between mean sky cover and corresponding convective intensity, then the hypothesis can be accepted.

In 1981 and 1982, sixty documented MCCs occurred (Maddox et al., 1982; Rodgers, personal communication, 1982). Satellite imagery of the documented MCCs was analyzed to detect outflow boundaries. Of the 60

MCCs studied, 30 were chosen for the statistical testing because these cases displayed favorable image sections of potential outflow boundaries. In the analysis of the 30 MCCs approximately 3,000 satellite images, 10,800 surface observations, and 800 radar observations were studied to detect MCC-induced outflow boundaries.

Of the 30 MCCs analyzed, it was determined that nine MCCs produced identifiable outflow boundaries. Twenty-three surface stations reported convection induced by the outflow boundaries. The Spearman Rank Correlation Coefficients (ρ) were calculated for the 23 stations that experienced outflow convection. Application of the test yielded a value of 0.01038. This value indicates that the rankings are near random; that is, no correlation exists between Pre-boundary Cloud Cover and intensities of outflow induced thunderstorms.

Pre-thunderstorm Cloud Cover (PTC) and Convective Intensity

The Spearman coefficients were used again to determine if a correlation exists between the intensity of thunderstorms and the PTC at stations that were unaffected by an outflow boundary. According to the second hypothesis, if PTC is minimal then convective intensity will be greater. Conversely, overcast conditions should result in weaker intensity thunderstorms. In order for the second hypothesis to be accepted, a strong inverse relationship must appear between mean sky cover and thunderstorm intensity. Eighty-three stations that reported thunderstorms were ranked to determine if there was an inverse relationship between PTC and thunderstorm intensity. The ρ value equalled 0.096989 and showed no correlation between PTC and thunderstorm intensity.

CHAPTER VI

CONCLUSIONS

This research was designed to address two specific questions: (1) Can MCC-generated outflow boundaries be identified through the interpretation of satellite imagery, radar observations, and a newly developed simplified surface analysis and (2) Can Pre-boundary Cloud Cover (PCC) at a station influence the intensity of thunderstorms that develop at that station?

The results of the research show that the simplified surface analysis can be successfully used to identify MCC-generated outflow boundaries and enable forecasters to pinpoint areas where convection is likely to develop. In addition, the research demonstrates that Pre-boundary Cloud Cover (PCC) and Pre-thunderstorm Cloudiness (PTC) at a station are not well correlated with the intensity of thunderstorms that subsequently affect the station.

Purdom (1979) indicated that outflow boundaries that move into clear regions are not likely to enhance convection. He felt that clear regions suggest stabilization within an air mass indicating that the air mass is not favorable for intense convection. However, convection will result when an outflow boundary moves into an area of cumulus clouds. Cumulus clouds were thought to indicate areas of instability and, thus when the outflow boundaries encounter areas of cumulus clouds, convection is enhanced.

As opposed to Purdom's rationale, this author anticipated that extensive PCC can help to cool the surface (during daylight hours) thus causing the air mass in that region to remain stable. Conversely, areas free of PCC that are more efficiently warmed by incoming solar radiation are more likely to initiate intense convection. Purdom based his arguments primarily on the analysis of visible satellite imagery. Well defined outflow boundaries were identified as arc clouds on visible satellite imagery and their effects were analyzed as they encountered areas of varying amounts of cloud cover. Because the analysis relied on visible satellite analysis, outflow boundaries could not be identified if they were masked by high level cloudiness. Using only visible observation of outflow boundaries, Purdom could not analyze the potential for outflow boundaries to induce convection in cloud covered areas.

The simple surface analysis used in this thesis detected even those outflow boundaries obscured by convective debris (i.e., high level cloudiness). The results of this study determined that PCC has no effect on the intensity of thunderstorms that develop along an outflow boundary (ρ=0.01038). These findings show discrepancies in the rationale set forth both by Purdom and this author. Correlations show that, when outflow boundaries are detected either by visual methods or by the simplified surface analysis, there is no relationship between pre-existing cloud cover and convective intensity.

This author recommends that research continue to seek the atmospheric causes for the occurrence of convection along some outflow boundaries while other outflow boundaries yield no thunderstorm activity. Additional work should be conducted on the influence of pre-convective cloud cover on the intensities of subsequent thunderstorm activity.

Finally, the new simplified surface analysis introduced in this research should be further tested to find its full utility and geographical application. With new initiative and techniques (such as this one) forecasters may better define the spatial distribution and intensity of thunderstorm activity.

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