P1.12 **METEOROLOGICAL ASPECTS OF HIGH-IMPACT TORNADO OUTBREAKS**

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1. INTRODUCTION

What are the worst tornado outbreaks on record? Were there one or more common meteorological patterns associated with them? These are the questions that have motivated this study.

Answering the above questions first requires defining what is meant by "worst." While the number of tornadoes in an outbreak is one attribute for consideration, it is not a very reliable measure. The reporting of these tornadoes has increased tremendously over the years, suggesting that these tornadoes were seriously underreported in the past (e.g., McCarthy and Schaefer, 2004). The use of this attribute will require some type of normalization scheme to intercompare recent with historical outbreaks.

Another aspect of the challenge in defining the "worst" tornado outbreak is the recognition that some outbreaks have many low-impact weak (F0 and F1) tornadoes. It is typically the wide, long-track, and high intensity (on the Fujita Scale) tornadoes that cause most of the injuries, deaths and extensive damage. To reflect the impact of an outbreak, weight must be given to these injury, death and damage attributes. However, both deaths and damage also pose normalization challenges. Death rates from tornadoes have declined due to improved warnings and greater awareness. Damage amounts have increased due to inflation.

Yet deaths and damage amounts are dependent to some extent on population density and to a certain amount of chance in the paths taken by the tornadoes relative to the populated locations. Should we weight an equally intense tornado less just because it happened to miss a community by a mile? Thus, while the goal in this paper is to rank tornado outbreaks on their actual impact, rather than potential impact, outbreaks with many large, strong, and long-track tornadoes merit consideration in light of that "chance" factor. Section 2 gives details of the parameters and normalization procedures used in defining and ranking the impact of tornado outbreaks.

Once tornado outbreaks were ranked by their impact, large-scale weather patterns were examined for the 19 highest-impact and largest tornado outbreaks. Results are presented in section 4.

2. PROCEDURE FOR DEFINING HIGH-IMPACT OUTBREAKS

A tornado outbreak was first defined as one with a substantial number of tornadoes (1) occurring within adjoining states and (2) with no tornado-free gap during the outbreak of six hours or longer.

Tornado outbreaks with at least 45 tornado reports were then examined in greater detail to assess their impact. In addition, smaller outbreaks with high Destruction Potential Index (Thompson and Vescio, 1998) were examined based upon a list compiled by Hart (2003), and for selected other tornado outbreaks with large death tolls.

Brooks and Doswell (2001) went through a similar procedure in seeking to intercompare major tornadoes in the period 1890-1999, as did Edwards et. al (2004) for tornado outbreaks.

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In this paper, eleven tornado outbreak attributes were used to compute a Forbes Impact Index, with 100-point maximum value. In most (9) instances, the attribute was assigned a value of 10 points, with two attributes assigned half-value (maximum 5 points). The outbreak having top value of an attribute was assigned the maximum value (normally 10 points) for that attribute, with other outbreaks assigned points based upon the ratio of their value for the attribute to the maximum. For example, an outbreak with half the tornadoes of the largest outbreak would get 5 points (out of 10) for the tornado count attribute.

Outbreak attributes were:

(1) Tornado count (10 point maximum) – normalized by converting to the percentage of a year's average number of tornadoes, using a centered 11-year running mean
(2) Number of deaths (10 point maximum) – normalized by converting to the percentage of a year's average number of tornado deaths, using a centered 11-year running mean
(3) Number of injuries (10 point maximum)
(4) Number of killer tornadoes (5 point maximum)
(5) Number of significant (F2 or stronger) tornadoes (10 point maximum)
(6) Number of violent (F4 or stronger) tornadoes (10 point maximum)
(7) Number of wide-path (400 yards or greater) tornadoes (10 point maximum)
(8) Total path length (10 point maximum)
(9) Total damage (10 point maximum) – normalized by multiplying by the ratio: 2005 consumer price index divided by that year's consumer price index
(10) Tornado rate density (10 point maximum) – tornado count divided by duration of the outbreak
(11) Number of states affected (5 point maximum)

3. TORNADO OUTBREAKS WITH LARGEST IMPACT

Based upon the Forbes Impact Index described above, Table 1 is a listing of the top-impact tornado outbreaks. Maximum index value would be 100 if the outbreak had the top value of each of the 11 attributes.

For comparison, Table 2 is the list of tornado outbreaks ranked by reported number of tornadoes.

The effects of the normalizations of the tornado count, death, and damage attributes are incorporated into the multi-attribute Forbes Impact Index rankings. One interesting result from Table 2 is that the two largest tropical cyclone tornado outbreaks rank far down on the impact rating, due primarily to their tornadoes being weaker and less deadly and their paths shorter and narrower than many other outbreaks. Note also that not all of a hurricane's tornadoes qualified as part of the outbreak because of the time gap or adjoining-state criteria for an outbreak, described in Section 2. Table 3 shows a few interesting results of the normalization process.

It should be noted that the only tornado outbreak included prior to 1950 in the Forbes Impact Index computations is the 1925 Tri-State Tornado outbreak. The tornado outbreaks with the second and third largest death counts (March 21-22, 1932 and April 23-25, 1908) have not yet been included in the Forbes Impact Index calculations because the number of tornadoes and other attribute values are not fully known. Likewise, several other large-death outbreaks prior to 1950 have not yet been examined for the same reasons.

Rank	Index	Date	Comments
1	92.56	April 3-4, 1974	Superoutbreak; tops in 9 of the 11 attributes
2	56.01	April 11-12, 1965	Palm Sunday 1965; tops in normalized damage
3	40.50	Nov 21-23, 1992	largest November tornado outbreak
4	32.76	May 3-4, 1999	Moore/Oklahoma City outbreak
5	30.99	May 26-29, 1973	tornadoes in 17 states
6	27.99	April 2-3, 1982	includes Broken Bow OK F5
7	27.51	March 21-22, 1952	deadliest Arkansas tornado outbreak
8	27.41	March 28, 1984	Carolinas tornado outbreak
9	27.00	May 31, 1985	Wheatland, PA F5 tornado outbreak
10	26.98	Jan 21-22, 1999	largest January tornado outbreak
11	26.69	Nov 9-11, 2002	outbreak included Van Wert, OH F4
12	26.32	May 4-5, 2003	largest outbreak in record month
13	25.95	May 29-31, 2004	largest outbreak in raw tornado count
14	24.29	June 2, 1990	largest outbreak in record June
15	24.01	March 18, 1925	includes deadliest, longest Tri-State tornado
16	23.28	March 13-14, 1990	Hesston/Goessel KS outbreak
17	21.45	April 26-27, 1991	Andover KS F5 outbreak
18	21.08	March 20-21, 1976	largest outbreak in record March
19	19.46	June 24, 2003	biggest SD outbreak; Manchester SD
20	19.18	June 7-8, 1984	includes Barneveld, WI F5

Table 1. Tornado outbreaks with largest values of Forbes Outbreak Impact Index.

Rank	Count	Date	Forbes Impact Index Rank
1	170	May 29-31, 2004	13
2	147	April 3-4, 1974	1
3	138	Jan 21-22, 1999	10
4	119	May 3-4, 1999	4
5	110	May 6-8, 2003	22
6	105	Nov 21-23, 1992	3
7	102	May 4-5, 2003	12
8	101	Sept 5-8, 2004	38 (Hurricane Ivan)
9	99	May 26-29, 1973	5
10	95	June 24, 2003	19
11	93	Nov 23-24, 2004	24
12	92	May 9-11, 2003	26
13	89	Sept 20-21, 1967	40 (Hurricane Beulah)
14	87	May 15-16, 2003	37
15	82	Nov 9-11, 2002	11
16	78	Apr 19-20, 1996	23
17	76	May 18-19, 1995	28
18	71	June 2, 1990	14
19	71	May 11-12, 1982	33
20	69	April 2-3, 1982	6

Table 2. Tornado outbreaks ranked by reported number of tornadoes.

Normalized Tornado Count Rank	Date	Raw Tornado Count Rank
1	April 3-4, 1974	2
2	Sept 20-21, 1967	13
3	May 29-31, 2004	1

Normalized Damage Rank	Date	Raw Damage Rank
1	April 11-12, 1965	4
2	April 3-4, 1974	2
3	May 3-4, 1999	1

Normalized Death Rank	Date	Raw Death Rank
1	April 3-4, 1974	4
2	March 18, 1925	1

Table 3. Interesting results of the normalization process on values of tornado count, damage, and death attributes used in computing the Forbes Impact Index.

4. METEOROLOGICAL PATTERNS OF THE LARGEST AND LARGEST-IMPACT OUTBREAKS

The meteorological patterns were examined for (1) the 15 outbreaks since 1950 ranked highest by the Forbes Impact Index and (2) additional tornado outbreaks ranked among the twelve largest by raw tornado count, excluding those from tropical cyclones. This comprised a sample of 19 outbreaks.

Meteorological parameters were examined of the large-scale type that have long been recognized as favorable for tornado outbreaks (e.g., Miller, 1972). Large-scale meteorological conditions for the various tornado outbreaks were examined using 6-hourly NCAR/NCEP reanalysis data, obtained from the NOAA/CIRES Climate Diagnostic Center: http://www.cdc.noaa.gov.

These studies showed that:
(1) All of the outbreaks were ahead of a 500 mb trough or closed low.
(2) All were associated with a trough of surface low pressure, closed low, or frontal wave – but usually ahead of it.
(3) All of the outbreaks occurred in the exit region of an upper-level jet streak. Some were in the left exit, some in the right exit, and some in both quadrants.
(4) All were associated with an 850 moist flow, sometimes in the form of a low-level jet. The angle between the 850 mb flow and the 500-300 mb flow varied from 90 degrees to nearly 0 degrees. Several cases had westerly low-level jets.

In addition to these parameters, additional factors were examined. Of the 19 largest and highest-impact tornado outbreaks since 1950, 10 occurred during an El Nino, 4 during La Nina, and 5 during neutral conditions. Seven occurred during a positive phase of the Madden-Julian Oscillation, 2 in a negative phase, 6 near a neutral phase, and 4 were unknown, using data from the Climate Prediction Center, (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/new.mjo3.shtml).

The large-scale weather patterns were categorized into seven types based upon the nature of their sea-level pressure patterns, 500 mb height patterns, and 300 mb jet stream patterns.

A. Superoutbreak-Type Pattern (classic cyclogenesis pattern with large amplitude trough, strong surface low, upper jet surging toward the warm sector)

April 3-4, 1974 (See Figure 1)
May 26-29, 1973
March 28, 1984

B. Palm Sunday 1965-Type Pattern (strong surface low, but associated with smaller 500 mb trough mainly as short wave with a more west-east jet stream; 850 flow mainly from west)

April 11-12, 1965 (See Figure 2)
June 2, 1990
May 31, 1985

C. Mobile Cutoff Pattern (strong surface low, but associated with a cutoff 500 mb low, usually in base of a full-latitude trough)

Nov 21-23, 1992 (See Figure 3)
April 2-3, 1982
Nov 23-24, 2004

D. Progressive Trough Pattern (surface low somewhat elongated north-south and mobile large 500 mb trough)

Nov 9-11, 2002 (See Figure 4)
May 4-5, 2003

E. North-South SLP Trough Pattern (full-latitude surface trough with large 500 mb progressive trough)

May 29-31, 2004 (See Figure 5)
May 3-4, 1999

F. Along Stagnant Trough Pattern (large 500 mb stagnant trough with wave of low pressure or trough of low pressure elongating north ahead of it)

June 24, 2003 (See Figure 6)
March 13-14, 1990

G. Stagnant Trough with Mobile Short Wave Pattern (stagnant broad long-wave trough with short waves running east through it; compact surface low or lows)

May 6-8, 2003 (See Figure 7)
May 9-11, 2003
March 21-22, 1952
Jan 21-22, 1999

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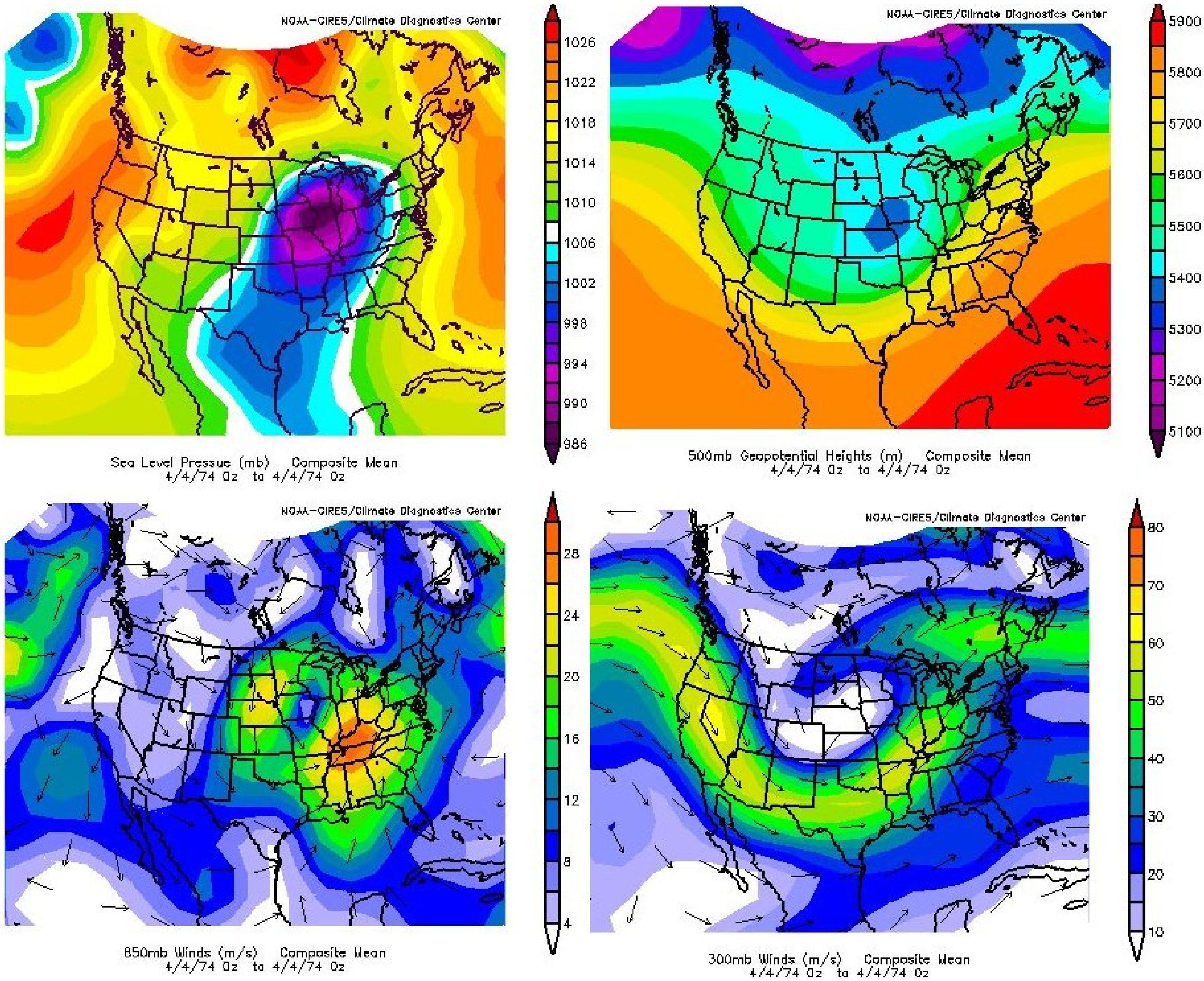

Figure 1. Large-scale maps from 0000 UTC 4 April 1974 during the 3-4 April 1974 Superoutbreak, courtesy of NOAA-CIRES/Climate Diagnostics Center, an example of the “Superoutbreak-Type” pattern. Tornadoes developed mainly in IL, IN, MI, OH, KY, TN, MS, AL, GA, NC, VA, WV.
Top left: sea-level pressure at 2mb intervals from 986 to 1028 mb
Top right: 500 mb geopotential heights at 50 m intervals from 5100 to 5900m
Bottom left: 850 mb winds at 2 m/s intervals from 4 to 30 m/s
Bottom right: 300 mb winds at 5 m/s intervals from 10 to 80 m/s

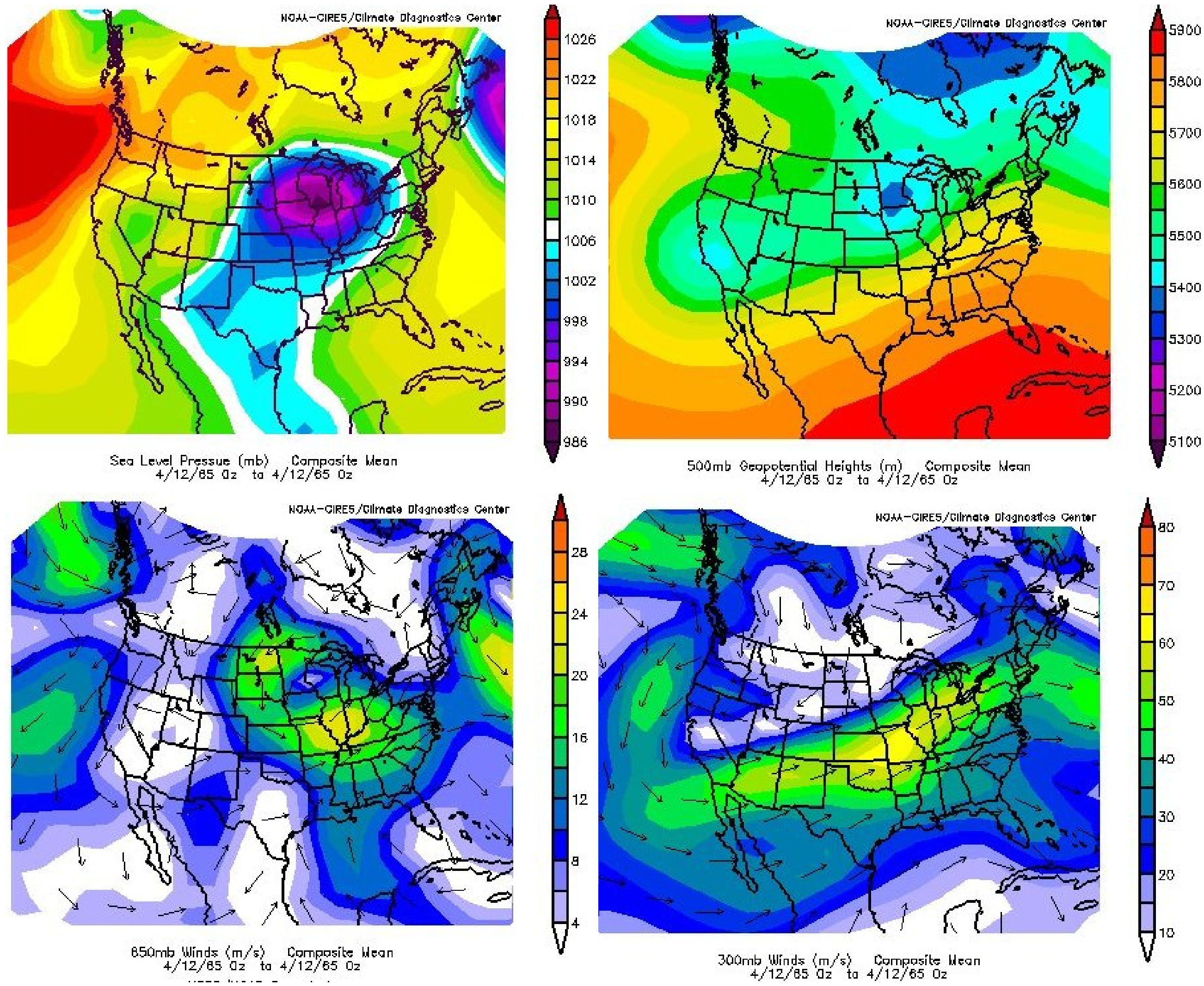

Figure 2. Large-scale maps from 0000 UTC 12 April 1965 during the 11-12 April 1965 Palm Sunday tornado outbreak, an example of the “Palm Sunday 1965 Type” patern. Layout as in Fig. 1. Tornadoes developed mainly in WI, IL, IN, MI, OH.

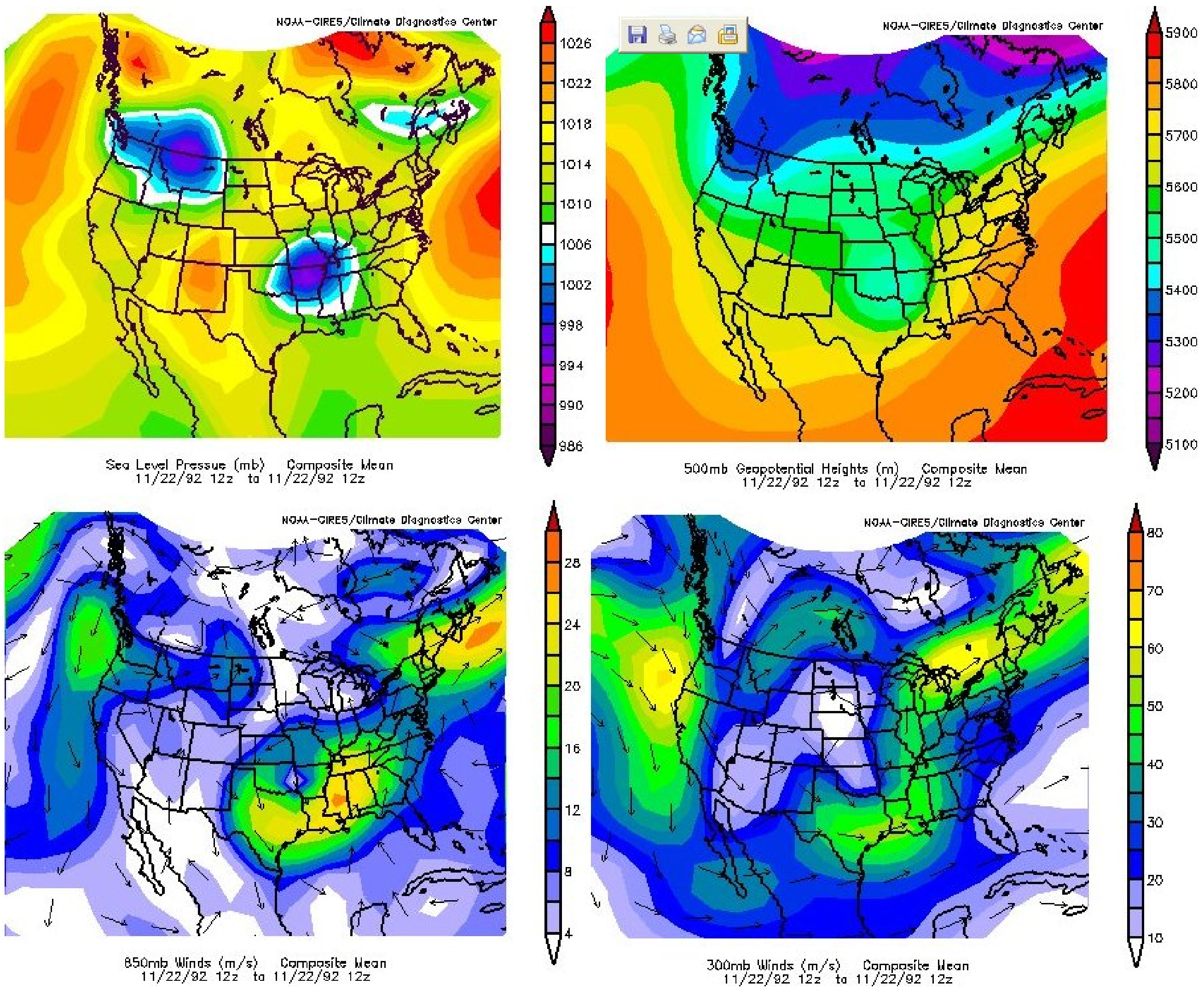

Figure 3. Large-scale maps from 0000 UTC 22 November 1992 during the 21-23 November 1992 tornado outbreak, an example of the “Mobile Cutoff” pattern. Layout as in Fig. 1. Tornadoes developed mainly in TX, LA, MS, AL, GA, SC, NC, TN, KY, IN, OH, VA.

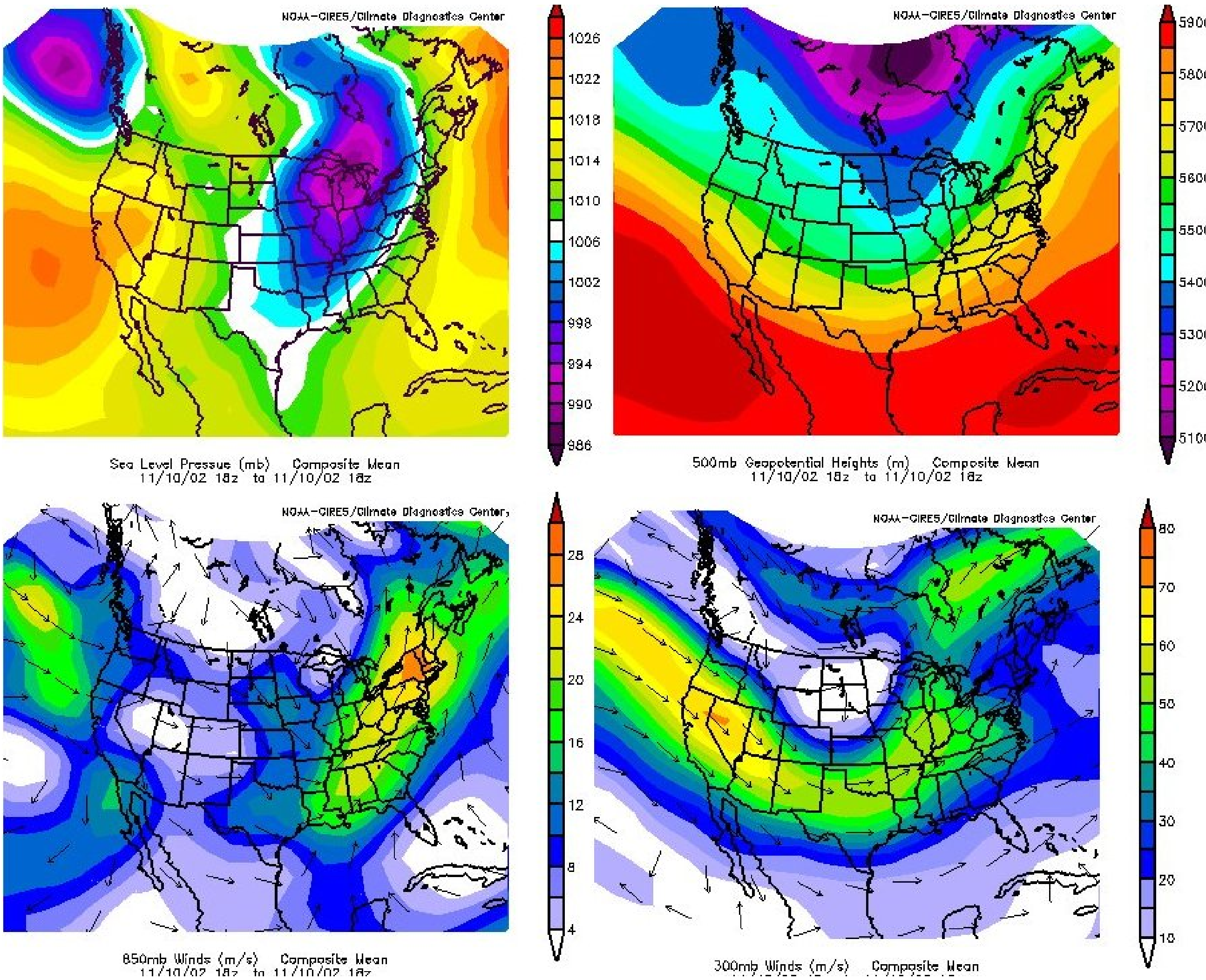

Figure 4. Large-scale maps from 1800 UTC 10 November 1992 during the 9-11 November 2002 tornado outbreak, an example of the “Progressive Trough” pattern. Layout as in Fig. 1. Tornadoes developed mainly in TN, KY, IL, IN, OH, MS, AL, GA.

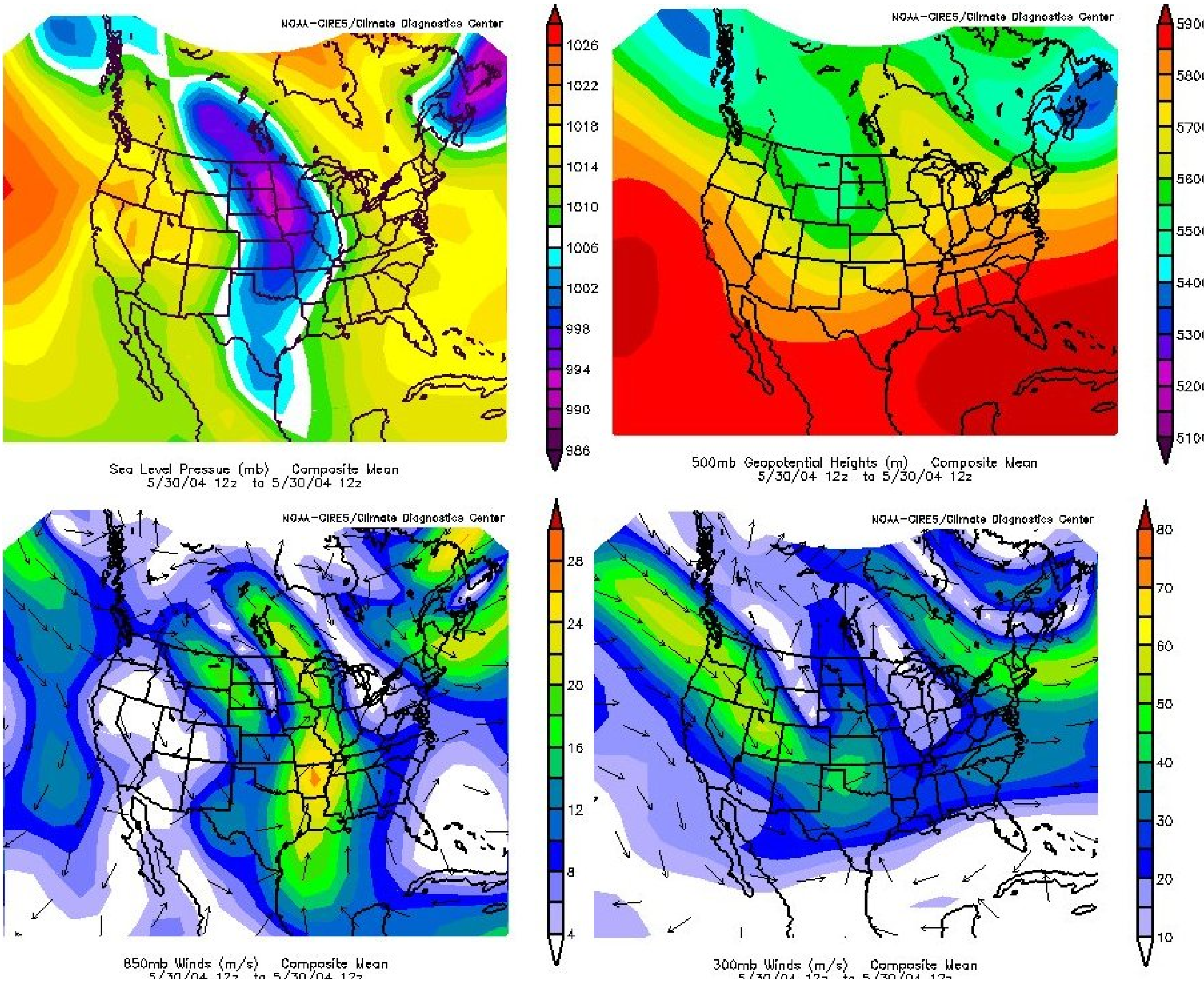

Figure 5. Large-scale maps from 1200 UTC 30 May 2004 during the 29-31 May 2004 tornado outbreak, an example of the "North-South Sea-Level Pressure Trough" pattern. Layout as in Fig. 1. Tornadoes developed mainly in OK, KS, NE, SD, MN, MO, IL, AR, IN, KY, TN, AL.

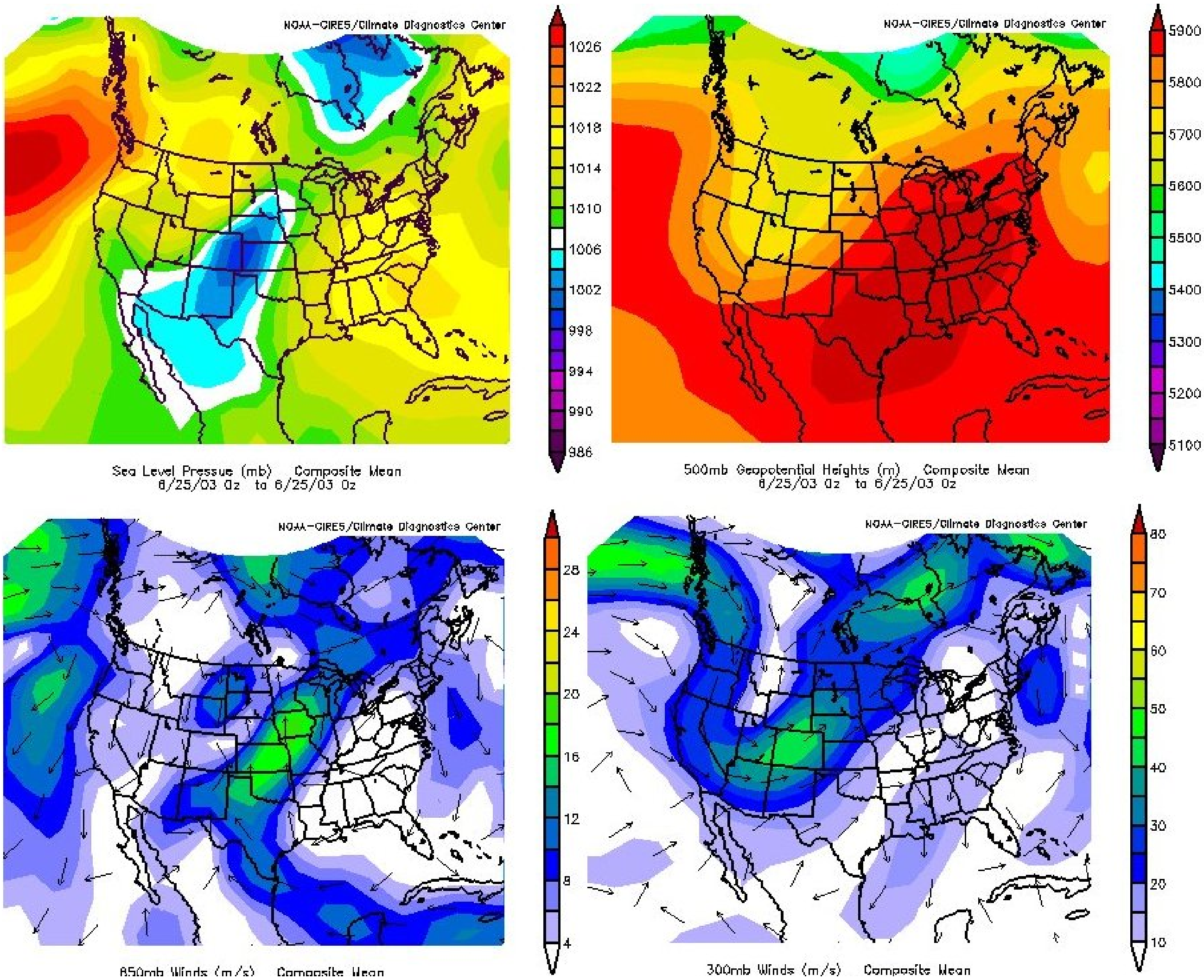

Figure 6. Large-scale maps from 0000 UTC 25 June 2003 during the 24 June 2003 tornado outbreak, an example of the "Along Stagnant Trough" pattern. Layout as in Fig. 1. Tornadoes developed mainly in NE, SD, MN, IA.

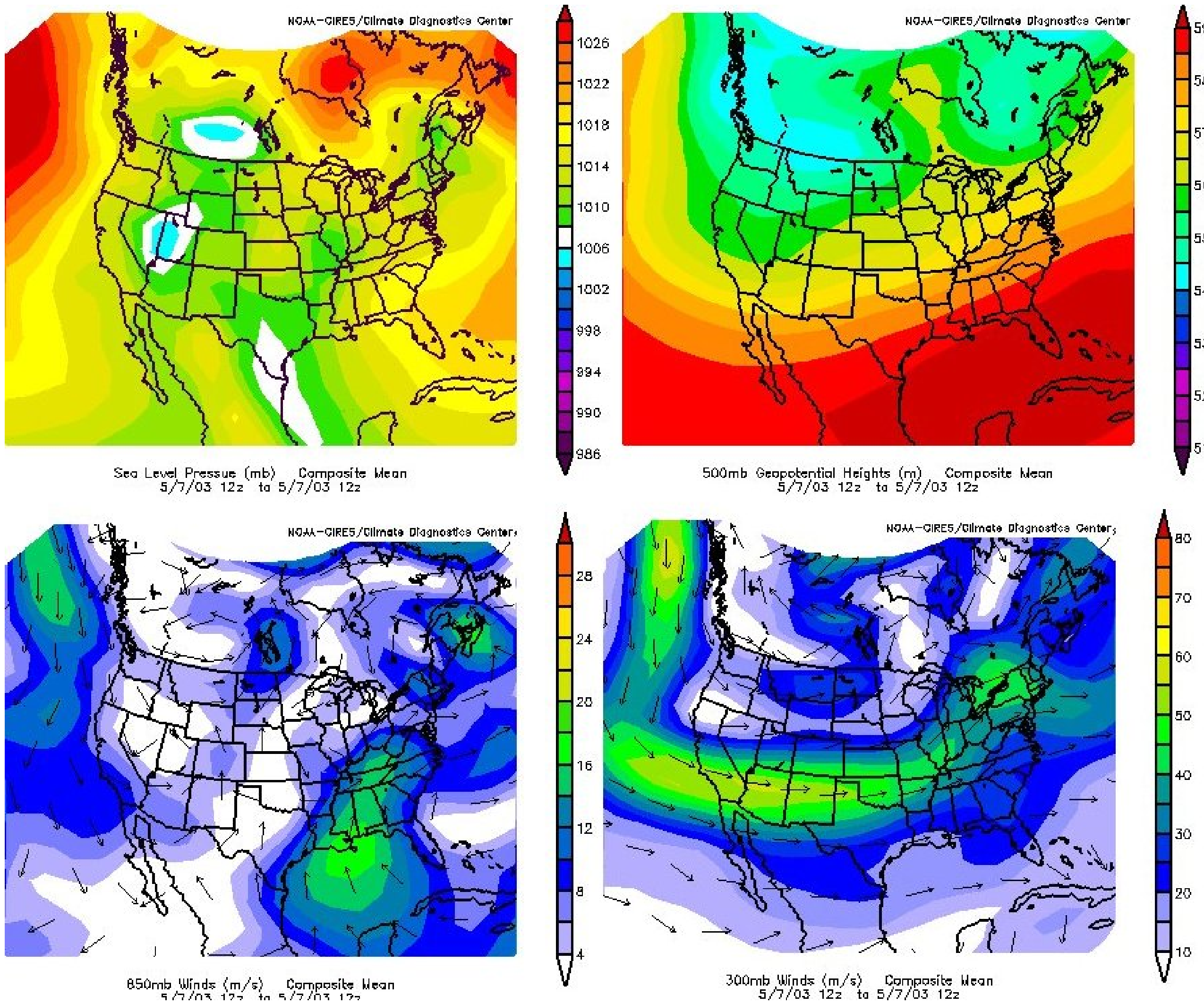

Figure 7. Large-scale maps from 1200 UTC 7 May 2003 during the 6-8 May 2003 tornado outbreak, an example of the "Stagnant Trough with Mobile Short Wave" pattern. Layout as in Fig. 1. Tornadoes developed mainly in TX, OK, KS, MO, AR, LA, IL, TN, MS, AL, GA, SC.