NOTES AND CORRESPONDENCE

Standardized Anomalies Applied to Significant Cold Season Weather Events: Preliminary Findings

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ABSTRACT

Forecasting significant weather events, such as floods, heat waves, arctic outbreaks, ice storms, large severe weather outbreaks, and major winter storms, is a critical function for all weather services. However, conventional pressure level geopotential and temperature fields often are insufficient to determine whether an event represents a large departure from normal. This is largely due to the variability that exists throughout the year and regionally throughout the world. What represents an unusual departure from average conditions in fall may not be as unusual in winter. What is an unusual departure from average conditions in California may be normal in New England. This paper presents a method, normalized field departures from local climatology, that gives forecasters guidance on the relative rarity of events. Thus, in this paper a method is presented to help forecasters identify potentially significant weather events. The focus of this paper is on significant winter storms. However, a record winter warmth event is shown to demonstrate the broad potential use of this method.

The results suggest that many record snowstorms in the literature were associated with storms that departed significantly from normal. Using model data, it is demonstrated that models can successfully forecast events that represent a significant departure from normal. In fact, the results suggest that the models are quite successful at forecasting unusually strong weather systems in the short range (2–3 days) and show some success out to 6 days.

1. Introduction

Forecasting significant weather events, such as floods, heat waves, arctic outbreaks, ice storms, large severe weather outbreaks, and major winter storms, is a critical function for all weather services. Extreme weather events have the greatest economic and human impact due to either their intensity or areal coverage. Therefore, it is of the utmost importance that these events are forecast accurately. However, the traditional statistical forecast guidance tools, such as model output statistics (Glahn and Lowry 1972; Klein and Glahn 1974; Bocchieri 1979), available to forecasters today do not readily provide information on how much a particular forecast deviates from normal. In order to quickly visualize a potentially significant weather event, forecasters need the ability to readily visualize the departures from normal.

Previous works have emphasized patterns that produce significant weather and the anomalies associated with events of these types. Lackmann and Gyakum (1999) showed the anomaly patterns associated with heavy rain in the Pacific Northwest, Bell and Janowiak (1995) showed the anomalies associated with the Midwest floods of 1993, and Anderson and Arrit (1998) showed the anomalies associated with persistent and elongated mesoscale convective systems. In each case, the anomalies were displayed as the departure of the field, for example, 500-hPa heights, from normal along with the base field. These graphics were then used to explain the associated weather based on the pattern of the base field and the associated departure of this field from normal. In an attempt to evaluate the anomalies objectively, in this paper all departures from normal were standardized by determining the number of *standard deviations* the anomaly departed from normal. The hypothesis being tested is that *standardized anomalies* may provide important meteorological insight to the forecaster.

The purpose of this paper is to offer *a forecast approach* that integrates operational model data with cli-

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matological data to facilitate the identification of potentially significant weather events. Forecast tools are provided to assist the forecaster in identifying events that will be ordinary from events that have the potential to be extraordinary. To prove the potential utility of the tool, past events are shown and compared to the climatological fields to determine how much these storms departed from the 30-yr climatology. A case study is presented, using these standardized fields, to show forecasters how they can use this approach to quickly determine what regions of the country are likely to experience an unseasonable or significant weather event. A detailed description of the methodology used is given in Section 2, followed by demonstration of the methodology on a few cases in section 3. A discussion is given in section 4, with a concluding summary in section 5.

2. Method

a. Gridded datasets and analysis

The National Centers for Environmental Protection (NCEP) reanalysis dataset (Kalnay et al. 1996) was used for this analysis. The dataset has a 2.5° × 2.5° resolution at 17 pressure levels, extends from 1948 through August 2000, and is updated monthly. For this analysis, three basic meteorological variables from that dataset were used including mean sea level pressure (MSLP), geopotential heights, and temperatures at 12-h intervals. The latter two variables were available over the range of 1000–300 hPa. The local climatology (for each 2.5° × 2.5° grid point) and 21-day centered means and standard deviations were based upon the fixed 30-yr period of record (POR) from 1961 to 1990. This 30-yr sample was chosen because of data availability and the National Climatic Data Center (NCDC) and National Weather Service use of a 30-yr POR.

The Grid Analysis and Display System (GrADS) software (available online at http://grads.iges.org/grads/) was used to compute and display the means and standard deviations of 500-, 700-, and 1000-hPa heights; 850-hPa temperatures; and mean sea level pressure fields. GrADS was also used to compute derived fields, such as thickness values and their related climatologies. Only a limited amount of these data are shown in this paper. Sample output of the 500-hPa mean height and standard deviation fields (m) and the 850-hPa mean temperature and standard deviation fields (°C) for January are shown in Fig. 1. *These relative coarse resolution data will likely smooth away the observed locally extreme values.* For example, note the large (~180 m) standard deviation in the Gulf of Alaska and over the North Atlantic, the impacts of the Aleutian and Icelandic lows, respectively. Both of these features show an axis down the coasts of North America. In the temperature field (Fig. 1b) the impacts of the ocean moderating the temperatures are quite evident. Over North America, the largest

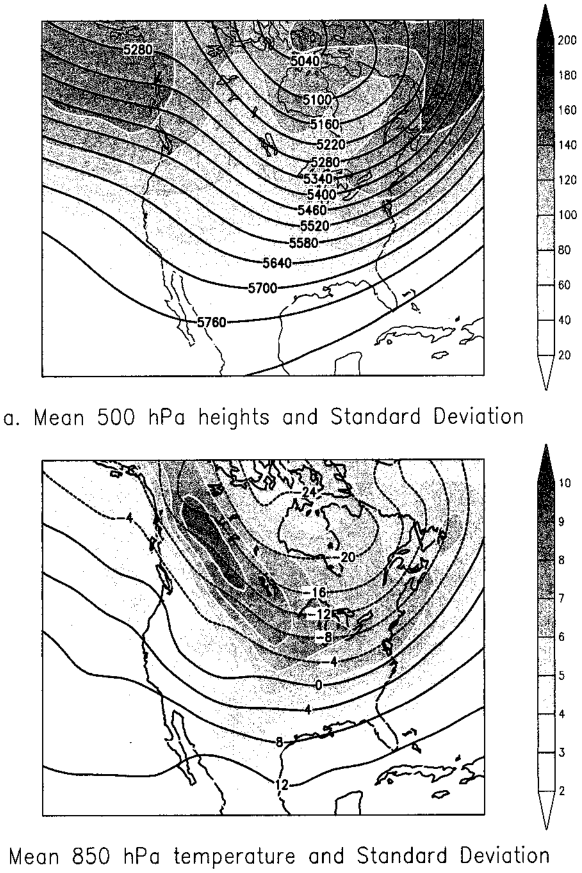

FIG. 1. Mean and standard deviations of (a) 500-hPa heights (m) and standard deviation (m) and (b) 850-hPa temperatures (°C) and standard deviations (°C) for Jan. Data are for the 30-yr period 1 Jan 1961–31 Dec 1990. Height contours are every 60 m and standard deviation contours (white) and shading is every 20 m. Temperature contours are every 4°C and standard deviations are every 1°C.

standard deviations are present over Canada (7°–8°C) with the axis of strongest variability extending into the western plains of the United States and a secondary axis extending into the Great Basin. These data suggest some regional variability is linked to the variability of synoptic weather systems. These data imply, for example, that a departure of 850-hPa temperatures of 8°C over northwestern Canada and a departure of 5°C over Virginia are both within about 1 standard deviation of normal.

For each case 500- and 700-hPa heights, 850-hPa temperatures, and sea level pressure were plotted. In addition to this, the deviation of these fields was computed from the *21-day running mean values* and then divided by their respective *21-day running standard deviations.* Thus, the fields were normalized with respect to the regional climatology by

$$N = (X - \mu)/\sigma, \tag{1}$$

where X is a gridpoint value, μ is the gridpoint 21-day running mean, and σ is the 21-day running standard

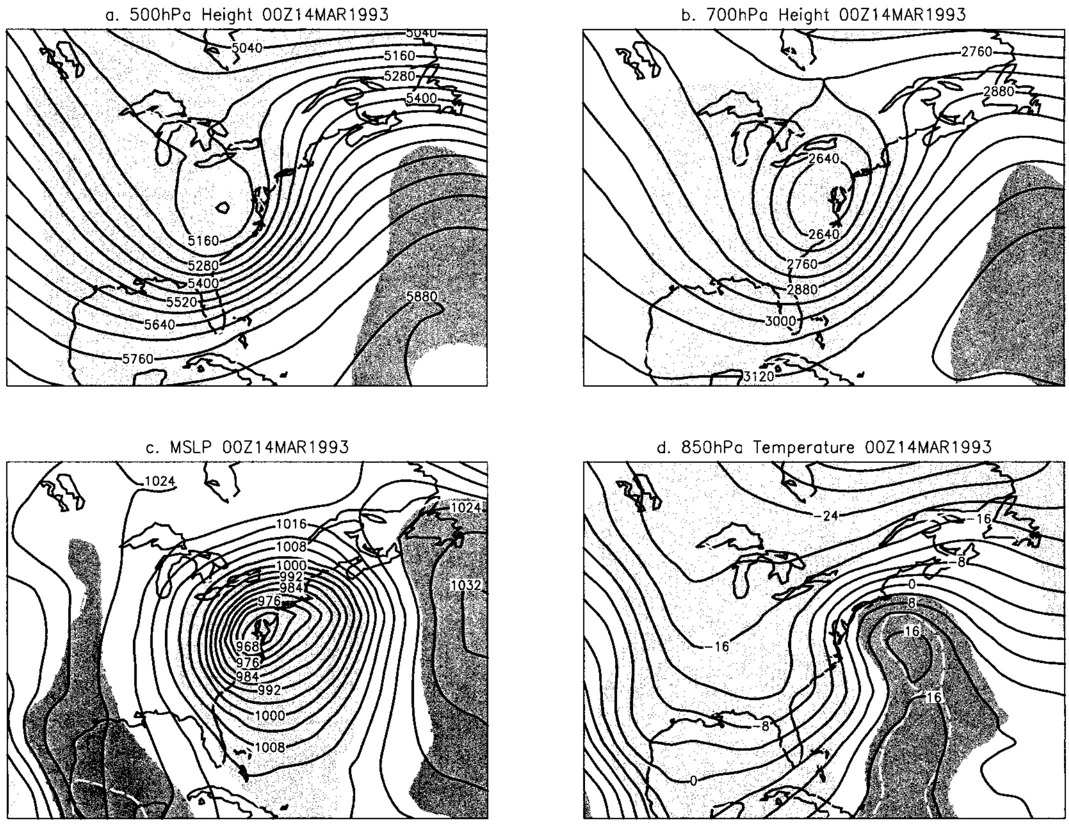

FIG. 2. Standard meteorological fields for the Superstorm of Mar 1993 valid at 0000 UTC 14 Mar 1993 including (a) 500-hPa heights (m) and standardized anomalies, (b) 700-hPa heights (m) and standardized anomalies, (c) surface pressure (hPa) and standardized anomalies, and (d) 850-hPa temperatures (°C) and standardized anomalies. Height contours are every 60 m, isotherms every 4°C, isobars every 4 hPa. Standardized anomalies are dashed white contours with a contour interval of 1 standard deviation. The light shading denotes negative anomalies equal to or less then −1 and darker shading denotes positive anomalies greater then or equal to +1.

deviation for that field at each grid point. This normalization process is an attempt to convert the distribution toward a standard normal distribution. The magnitude of the anomaly, or departure from normal, is given by N. A value of −3 for N means that the field is three standard deviations below normal for that location and month. The resulting *standardized anomalies* (N) were then plotted in each panel (e.g., Fig. 2).

The frequency of occurrence and the return period of departures from normal of 850-hPa temperatures from a grid point near State College, Pennsylvania, are shown in Figs. 3a and 3b, respectively. These data include all available 0000 and 1200 UTC periods from 1 January 1948 through 31 August 2000. These data show that the distribution of 850-hPa temperatures was skewed to the right of the mean. The mean and skewness were 278 K (5.3°C) and −1.93, respectively. The return period data (Fig. 3b) show that departures of +/−2 standard deviations from normal occur approximately once every 3 months. However, departures of −3 and +3 standard deviations occur once every 48 and 120 months, respectively. From a forecast perspective, an 850-hPa temperature anomaly of −3 (+3) standard deviations over a point, such as State College, would be a singularly rare event occurring about once every 2 (10) yr. The +3 standard deviation departure would actually be an even rarer event.

These data show that intrusions of extremely warm air occurs less frequently then intrusions of extremely cold air. Examining the 850-hPa temperature data over the eastern United States shows a bimodal distribution (not shown). Similar results were found at other locations and parameters, including 850- and 500-hPa heights and winds, in the eastern United States (not shown).

Based on these data, the term anomalous throughout this paper refers to fields that depart by more than *2.5 standard deviations* from the 30-yr means. This value was arrived at based on the confidence limits determined using the Chebyshev theorem (Blaisdell 1993) as an upper limit and those of the normal distribution as a lower limit (Table 1). In an absolute sense, a departure of 2.5 standard deviations from normal implies that the anomalous field occurs between 16% and 5% of the time at any given location. Based on the return periods and an examination of the largest events in the dataset (Hart

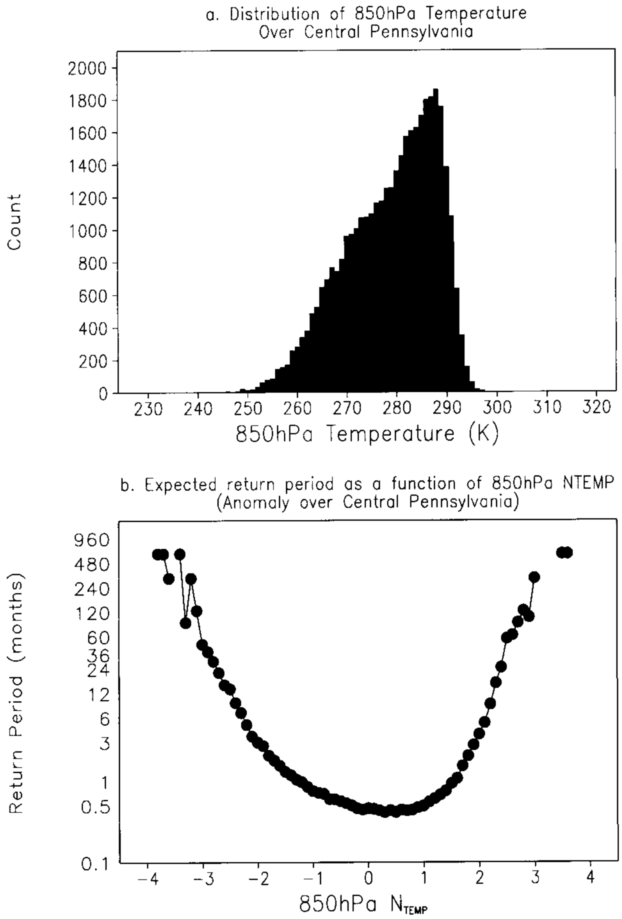

FIG. 3. Distribution of (a) 850-hPa temperatures (K) and (b) the return period of departures from normal (standard deviations) of 850-hPA temperatures at a grid point near State College, PA. The return period is shown as months, temperatures are shown as to the number of occurrence (count) per 1-K temperature range. Data span the period of 1 Jan 1948–31 Aug 2000. Departures are taken as the values departure from a 30-yr climatology as defined in the text.

and Grumm 2001b), the actual confidence limits are probably closer to those of the normal distribution.

b. Gridded forecast data

Gridded forecast data used for comparing operational weather prediction data to the climatology were obtained from the NCEP stepped-terrain Eta Model, Global Spectral Model (GSM), and the NCEP GSM ensemble forecasts. Cases were selected to show how these data could be used operationally to add value to real forecast problems. The reader should be aware of data resolution differences between the reanalysis data and the model data. The finer-resolution model data will likely produce slightly larger departures from normal compared to the coarser reanalysis data used to compute the climatological means and standard deviations.

TABLE 1. Significance levels based on the standard deviations from normal. Significance levels are shown for both a normal distribution and using the Chebyshev inequality for non-normal distribution. For skewed data the table provides upper and lower confidence limits.

Standard deviations from normal	Chebyshev's inequality (%)	Normal distribution (%)
1	0	68
1.5	56	86
2	75	95
2.5	*84*	*98.8*
3	89	99.9
4	94	100
5	96	100

c. Case study selection

The selection of historic case studies was based on case type and was confined to events that affected Pennsylvania over the period from 1964 to 2000. *Storm Data* (NOAA 1959–2000) was used to identify heavy rain events (Hart and Grumm 2001a) and local climatological data were used to identify heavy snow events, record heat waves, and record cold waves. Only winter events are presented in this study. For each case, the reanalysis data were compared to the 30-yr POR to determine if the event represented a significant departure from normal.

To demonstrate that this approach may be applicable to the rest of the country, a search was made to identify extreme weather events from the literature. Cases were gathered from studies documented in *Weather and Forecasting*, *Monthly Weather Review,* and the *National Weather Digest* to test the utility of the technique beyond Pennsylvania.

Snowstorms that impacted the East Coast were readily identified (Kocin and Uccellini 1990, hereafter KU). Other events, such as the Cleveland superbomb (Gaza and Bosart 1990; Hakim et al. 1995), and the ''Superstorm'' of 1993 (Kocin et al. 1995) were analyzed. The goal was to identify storms that had a significant impact on populated areas and determine if these storms were statistical outliers and, if so, by how much. These extreme events provide the forecaster with a quantitative measure of the ''range'' of atmospheric extremity. *The examples in this study emphasize snowstorms because such events have been examined in the published literature. However, the forecast approach presented here for identifying extreme weather events need not be limited to snowstorms.*

In addition to analyzing storms of historical significance, recent events were compared to short-term model forecasts. The goal was to determine if significant weather events provided a characteristic signal relative to the climatology that could be used to anticipate the potential intensity of the event.

TABLE 2. List of major snowstorms used in this study. The majority of storms examined were retrieved from local climatological data and Kocin and Uccellini (1990). Other storms were gleaned from case studies in the literature, specifically for large storms. Data include the day, month, and year of the event; and the number of standard deviations that the 500 and 700-hPa troughs, 850-hPa cold pocket, and surface low pressure system departed from the 30-yr climatology. Qualitative information relative to other anomalies or unique names attached to an event are included in the notes column.

East Coast and Pennsylvania snowstorms						
Date	Source	500-hPa heights	700-hPa heights	850-hPa temp	MSLP	Notes
13 Jan 1964	KU	−3.69	−3.30	−3.87	−2.57	Anomalous ridge in Canada +3 std dev MSLP
25 Dec 1966	KU	−2.75	−2.56	−2.43	−3.16	Anomalous ridge northern Canada; surface low peaked 1200 UTC 25 Dec
30 Jan 1966	KU	−3.77	−3.77	−3.87	−3.39	Anomalous ridge Canadian Maritimes +3 std dev
7 Feb 1967	KU	−2.11	−2.06	−1.96	−2.76	+1 std dev anticyclone in Canada
9 Feb 1969	KU	−2.14	−2.50	−1.02	−3.88	Deep low
18–24 Feb 1969	KU	—	—	—	—	Anomalous ridging at 500- and 700-hPa and surface near Hudson Bay, +3 std dev; main low offshore
26 Dec 1969	KU	−3.15	−3.30	−1.85	−3.56	Anomalous anticyclone Canadian Maritimes, +2 std dev
20 Feb 1972	KU	−3.75	−3.40	−3.41	−3.65	Strong storm
17 Dec 1973	A	−4.33	−3.76	−3.79	−3.47	Anomalous 500-mb ridge over N Atlantic; anomalous negative tilted trough over United States; anomalous surface low and high couplets
20 Jan 1978	KU	−1.40	−2.01	−2.28	−2.36	Deeper and stronger in southern stream wave at early stages; large surface anticyclone over central North America
26 Jan 1978	HBK	−3.72	−4.52	−3.31	−6.04	Cleveland superbomb; strong Great Lakes cyclone
6 Feb 1978	KU	−2.74	−2.72	−3.16	−2.72	Anticyclone +3.5 std dev in Hudson Bay area
6 Apr 1982	KU	−2.94	−3.54	−2.79	−4.74	Anticyclone +2 std dev; deep surface low developed
23 Jan 1987	KU	−3.76	−3.43	−3.17	−3.82	Rapidly developing cyclone
27 Jan 1987	KU	−3.53	−2.33	−2.48	−1.62	Rapidly developing cyclone
11 Feb 1983	KU	−1.86	−1.36	−0.89	−1.42	Large Canadian anticyclone, +3 std dev
11 Nov 1987	A	−2.76	−2.71	−3.28	−2.75	Mesoscale short-wave; Veterans' Day, Washington, DC, snow
16 Dec 1987	S	−1.81	−2.66	−2.14	−3.34	Midwest storm 1987
10–11 Dec 1992	A	−3.09	−3.13	−2.09	−3.50	Anomalous 500-mb trough; anomalous 500-mb ridge over eastern Canada
13 Mar 1993	KSMU	−5.47	−5.77	−4.46	−6.22	Anomalous 500-mb ridge over western Atlantic (2.5) std dev, superstorm 1993; Anomalous negative tilted trough over southeastern United States (3.5 std dev); anomalous surface low and high couplets; anomalous cold–warm couplet at 850 mb over eastern United States and western Atlantic
4–5 Jan 1994	A	−3.33	−3.40	−1.75	−4.24	Anomalous 500-mb ridge over western Atlantic; anomalous negative tilted trough over United States; anomalous cold–warm couplet at 850 mb over United States and western Atlantic

TABLE 2. (*Continued*)

East Coast and Pennsylvania snowstorms						
Date	Source	500-hPa heights	700-hPa heights	850-hPa temp	MSLP	Notes
15 Nov 1995	A	−4.26	−3.47	−3.02	−2.89	Inland early snow WV to NY
20 Dec 1995	A	−1.64	−2.35	−1.50	−3.33	Major East Coast storm
25 Jan 2000	A	−3.55	−3.81	−2.29	−4.23	Major East Coast storm NC to NY

KU: Kocin and Uccellini (1990). A: author contributed. HBK: Hakim et al. (1995, 1996). S: Schnieder (1990). KMSU: Kocin et al. (1995).

3. Results

a. Analyzed historic events

1) EAST COAST SNOWSTORMS

Table 2 lists several snowstorms used to compare against the 30-yr climatology. The list includes several storms, which brought heavy snow to Pennsylvania, as well as several storms from the recent literature. The Superstorm of 1993, also known as the ''Storm of the Century'' (Kocin et al. 1995) and the megalopolitan storm of 1983 (Bosart and Sanders 1986) are included in the study. A brief summary of normalized departures from average of the 500-, 700-, and 850-hPa, and mean sea level pressure fields is included in Table 2. These departures show the depth of the 500- and 700-hPa troughs, 850-hPa cold air, and depth of the surface low pressure center. References to other features, such as the relative strength of the anticyclone north and east of the surface cyclone, are included in the remarks. These data were tabulated because of the importance of the magnitude, spatial extent, and geographic location of the features that depart significantly from normal. The majority of the events selected showed anomalous features at one or more pressure levels. Based on the data in Table 2, one could conclude that storms representing large departures from normal are ones most often studied by the meteorological community.

For example, the Storm of the Century meteorological fields, valid at 0000 UTC 14 March 1993, are shown in Fig. 2. Key features for this event are summarized in Table 2. Note the large area of −3 standard deviation departures from normal of the 500- and 700-hPa heights,

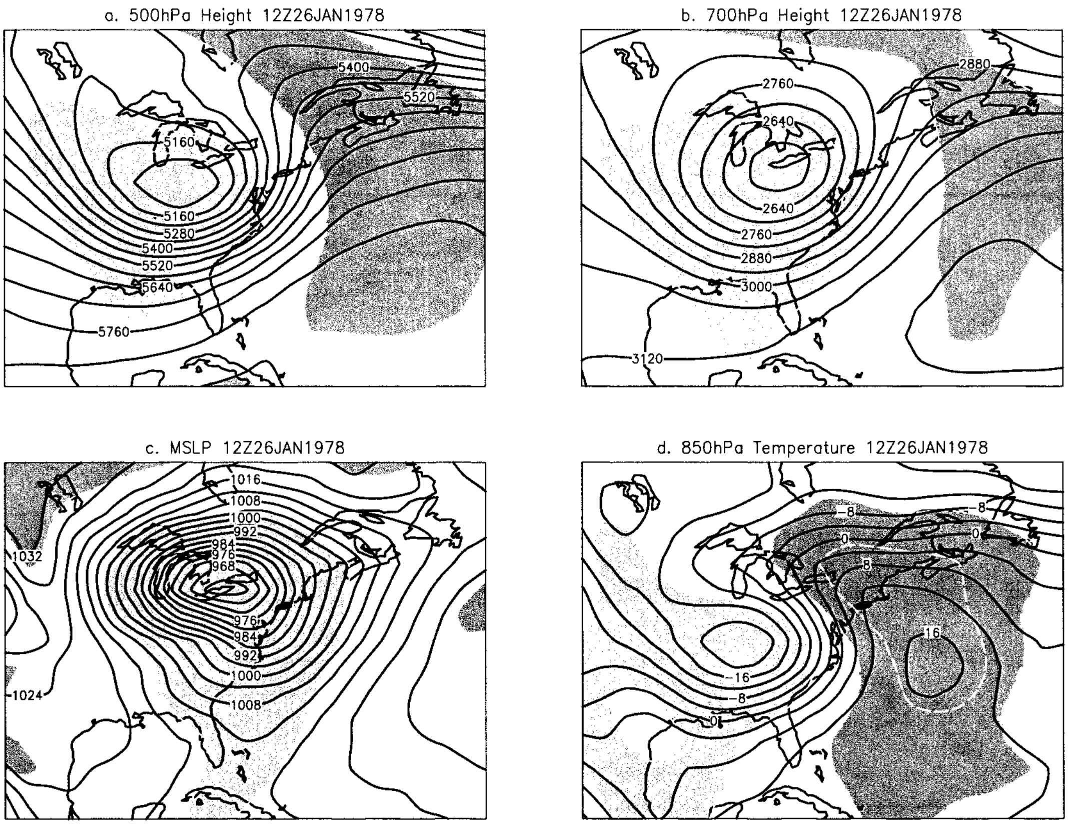

FIG. 4. As in Fig. 2 except for the Cleveland superbomb, valid at 1200 UTC 26 Jan 1978.

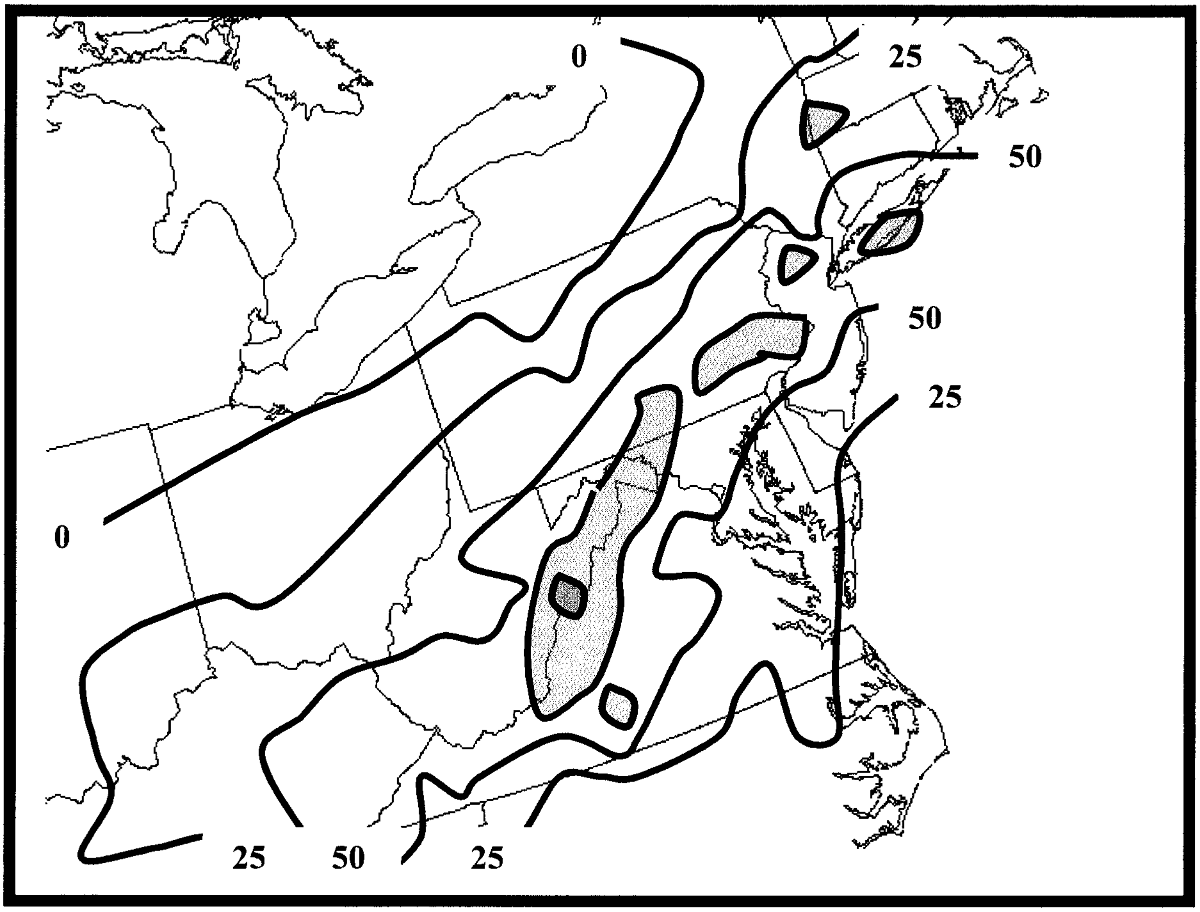

FIG. 5. Total snowfall ending 1200 UTC 8 Jan 1996. Contours are every 25 cm with shading showing values greater then 75 cm. Darker shading shows regions in excess of 100 cm of total snowfall.

and 850-hPa temperatures over the southeastern United States. These data show that an anomalously cold and deep upper-level trough was present over the region, with an anomalously deep low pressure system over North Carolina. Other significant features relative to this storm would include the unseasonably high 500- and 700-hPa heights over the western Atlantic and the surge of anomalously warm air at 850 hPa over the western Atlantic moving into southern New England. All these data suggest that this storm was associated with an anomalously strong midtropospheric trough, an anomalously cold pool of air on the cold side of the storm, and an anomalously strong surface cyclone. All this pointed toward a major late season winter storm farther south than normal. Based on the departures from normal, it should be no surprise that this storm produced record snowfalls at many locations along the East Coast.

The Storm of the Century clearly represented a rare event when compared to the other storms listed in Table 2. This event was the third most anomalous event in the reanalysis dataset between 1948 and 1 August 2000 (Hart and Grumm 2001b). In terms of societal impact, this may have been the winter storm of the century for the eastern United States. The data in Table 2 suggest that, with few exceptions, significant winter storms are composed of events that show distinct departures from normal in the 500-, 700-, and 850-hPa, and surface fields. This suggests there are detectable signals, allowing forecasters to anticipate and perhaps to quantify these events.

2) THE CLEVELAND SUPERBOMB OF 25–26 JANUARY 1978

The Cleveland superbomb (Hakim et al. 1995) was identified as another statistical outlier, ranking as the 18th most significantly anomalous event in the dataset (Hart and Grumm 2001b). This storm produced record low pressure (955 hPa) over the Great Lakes. The standard meteorological data for this event are shown in Fig. 4. These data show a deep surface low over the Great Lakes, which was 4.5 standard deviations below normal. There were significant departures in the 500- and 700-hPa heights and 850-hPa temperatures as shown in Table 2.

These data were compared to the 15 December 1987

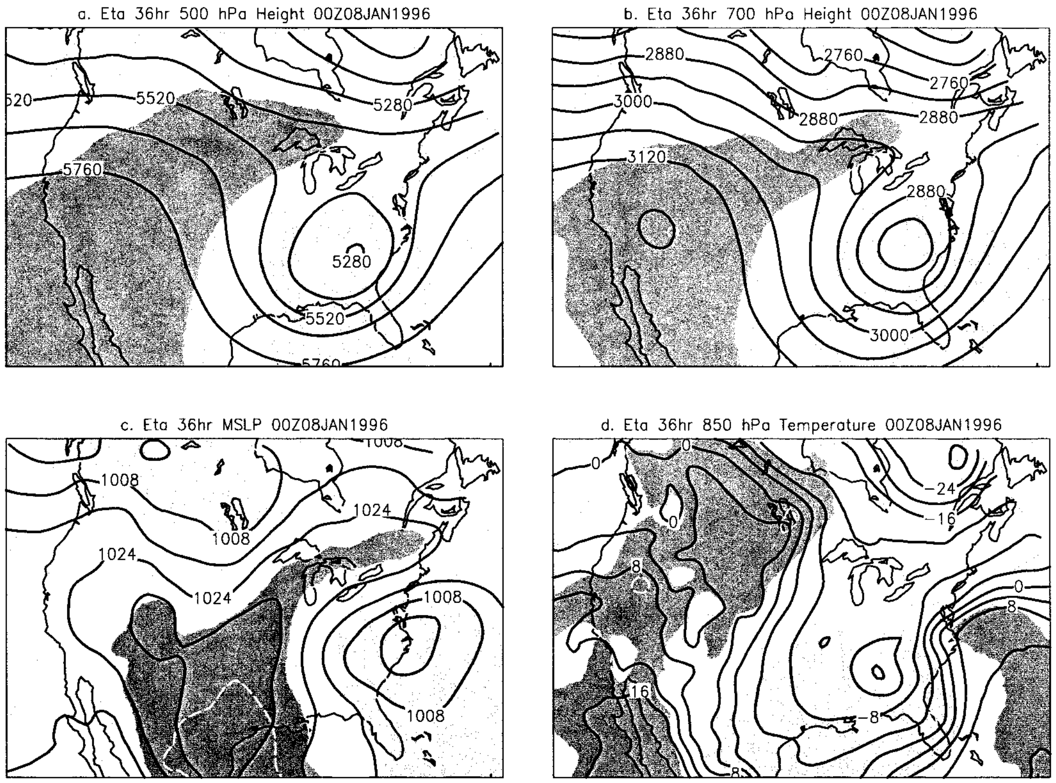

FIG. 6. As in Fig. 2 except for Eta 36-h forecast from 1200 UTC 6 Jan 1996, valid 0000 UTC 8 Jan 1996.

storm (Schnieder 1990) and the *Edmund Fitzgerald* storm (10 Nov 1975). These latter two storms were not as strong as the Cleveland superbomb. In fact, the *Edmund Fitzgerald* storm is not shown because the departures from normal associated with this event were less then two standard deviations from normal. For the limited cases we have examined, the Cleveland superbomb stands out as the most anomalous storm since 1948 in the Great Lakes region (Hart and Grumm 2001b).

b. *Using model guidance to forecast significant weather events*

In this section, operationally available model forecast grids are compared to the fixed 30-yr POR. The goal here is to demonstrate that operational models can and do forecast potentially significant weather events. Providing the model forecasts and the *forecast standardized anomalies* of fields, such as 850-hPa temperatures and 500-hPa heights, may allow forecasters to better anticipate significant weather events. This approach allows forecasters to quickly identify areas where these parameters significantly depart from normal. However, the forecaster must then determine the type and location of the potentially significant weather hazard based on the anomalous mass and thermal fields. The forecaster is warned that these anomalies will capture synoptic-scale features and may show the conditions favoring the development mesoscale features (such as mesoscale convective systems). Additionally, when these data are applied to mesoscale model output, the finer-scale model may show stronger anomalies due to the stronger mesoscale gradients produced by these models.

1) 8 JANUARY 1996

On 7–8 January 1996, a large snowstorm moved up the East Coast producing heavy snow from Richmond, Virginia, into New England (Fig. 5). Several locations measured record snowfalls for the date (*Storm Data*). This was one of the largest snowstorms to impact the large cities of the northeastern United States since the 13–14 March 1993 storm (section 3a). NCEP 48-km Eta Model forecasts from 6 to 8 January were used to determine if this storm, in addition to having characteristics often associated with major snowstorms along the East Coast (Kocin and Uccellini 1990), contained evidence suggesting the potential that this storm would produce record to near-record snowfall over the eastern United States.

The 36-h forecast from the 1200 UTC 6 January 1996 Eta Model is shown in Fig. 6. Significant upper air features included the anomalously deep 500- and 700-hPa trough moving across the southeastern United States and the downstream confluent zone often associated

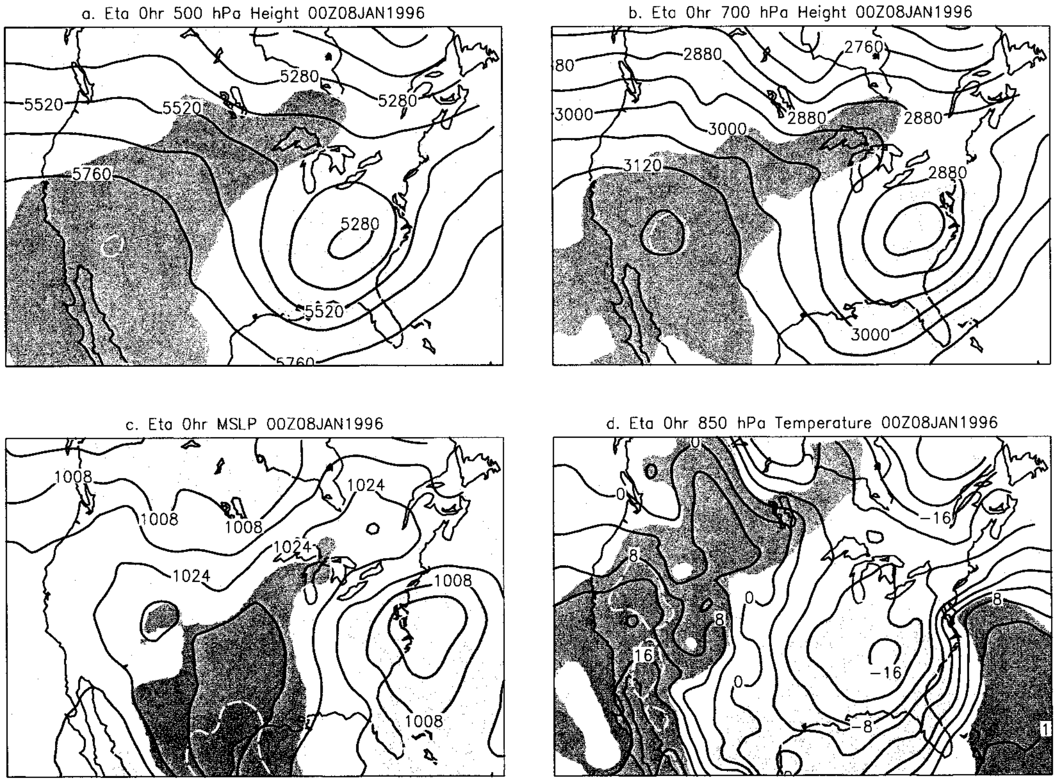

FIG. 7. As in Fig. 6 except for the verifying Eta analysis valid at 0000 UTC 8 Jan 1996.

with large snowstorms along the eastern seaboard (Kocin and Uccellini 1990). The 500- and 700-hPa heights were forecast to be 4 and 3.5 standard deviations below normal over the eastern Gulf states (Figs. 6a,b), respectively.

At the surface, the model forecasts, compared to the climatology, suggested that this was not going to be an ordinary East Coast winter storm (Fig. 6c). However, the most significant features were the anomalous surface anticyclone over the western Gulf states and the anomalous cyclone along the Carolina coast. Surface pressures along the Carolina coast were forecast to be 3–3.5 standard deviations below normal (Fig. 6c). The 48-h forecast (not shown) predicted a 3 standard deviation below normal surface cyclone over the Delmarva Peninsula by 1200 UTC 8 January 1996.

At 850 hPa, the Eta forecast anomalously cold air over the entire Gulf region. Temperatures were forecast to be 3–4 standard deviations below normal over most of the region. The model also forecast a surge of slightly above normal 850 hPa temperatures in the warm sector ahead of this surface cyclone.

The 24- and 36-h Eta forecasts from the 0000 UTC 7 January 1996 run were similar to those produced for the 1200 UTC 6 January 1996 run (not shown). The only notable exception was the stronger forecast of a +3 standard deviation surface pressure anomaly over northern Mexico and southern Texas and a large area of −4 to −4.5 standard deviations of 850-hPa temperatures over the eastern Gulf states.

The 0000 UTC 8 January 1996 verifying 48-km Eta initial analyses are shown in Fig. 7. These data show that the 48-km Eta did a credible job forecasting the anomalously strong upper-level and lower-level features associated with this event. A minor error appeared to be that earlier forecasts deepened the upper-level wave faster than observed.

2) 15 NOVEMBER 1995

This case represented an early season winter storm that produced widespread record heavy snow across central Pennsylvania and New York (Fig. 8). Coastal regions and lower-elevation inland regions received mainly rain from this storm. In Pennsylvania, heavy snow was observed mainly in the elevated terrain to the west of Blue Mountain (Fig. 8). This storm represented an unusually successful medium-range forecast and the long-range forecast aspects of this storm have been published by Toth et al. (1997). In this study, the focus is on how well the models forecast the anomalies associated with this event. Forecasts from the 0000 UTC Aviation Model (AVN) from 12, 13, and 14 November 1995 along with an Eta forecast from 1200 UTC 14 November 1995 are shown (Figs. 9–11). Both models showed the same overall trends; therefore, selective

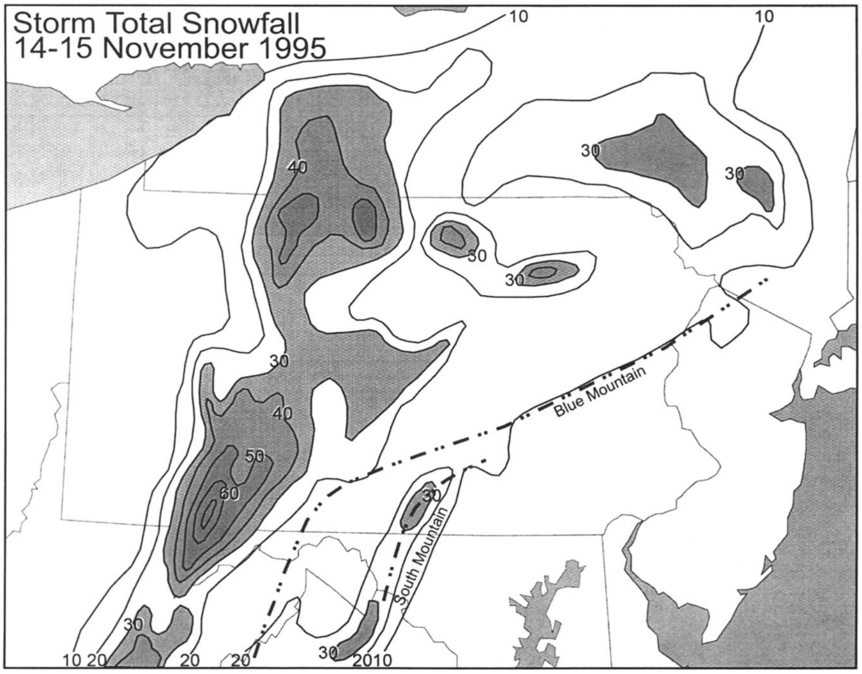

FIG. 8. Total snowfall ending 1200 UTC 15 Nov 1995. Contours are every 10 cm with shading showing values greater then 30 cm. Darker shading shows regions in excess of 40 cm of total snowfall. Thick-dashed and double-dotted lines denote the positions of Blue and South Mountains.

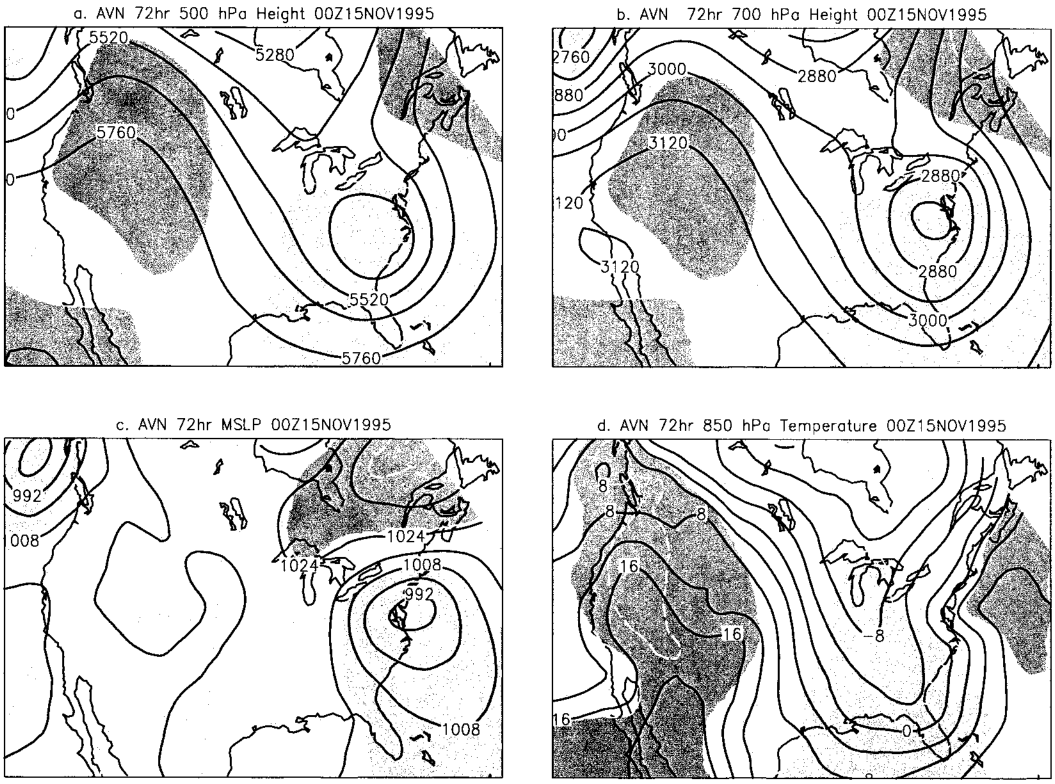

FIG. 9. As in Fig. 6 except for the AVN 72-h forecast from 0000 UTC 12 Nov 1995, valid at 0000 UTC 15 Nov 1995.

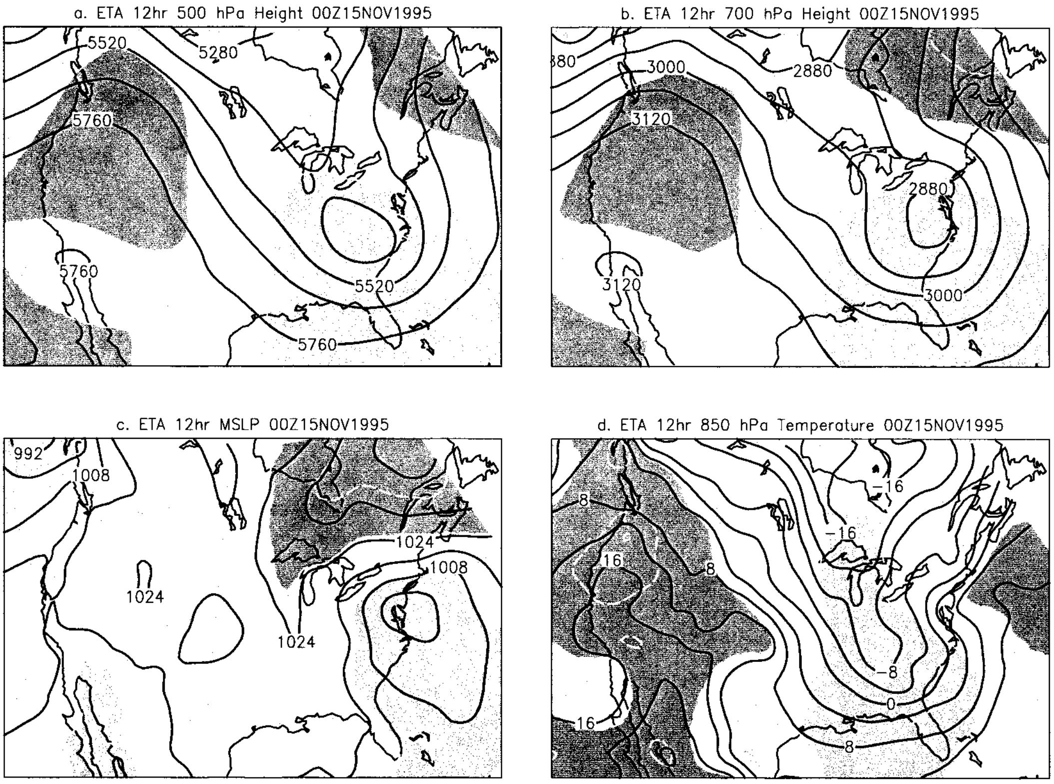

FIG. 10. As in Fig. 6 except for Eta 12-h forecast from 1200 UTC 14 Nov 1995, valid at 0000 UTC 15 Nov 1995.

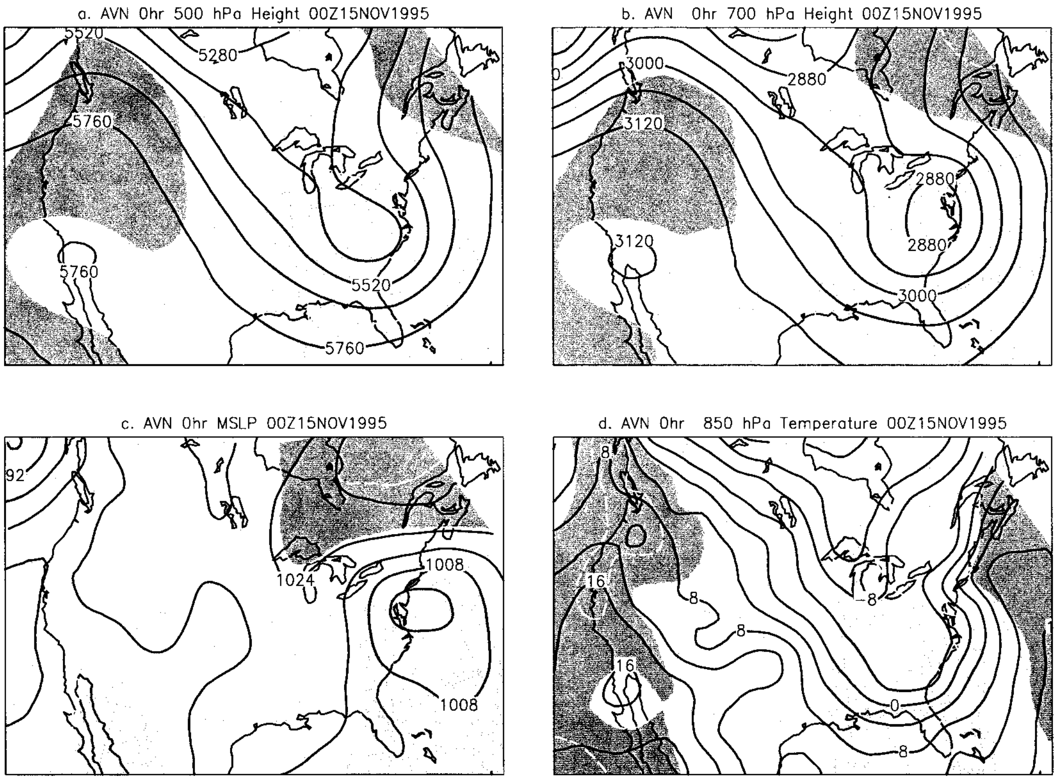

FIG. 11. As in Fig. 9 except the verifying AVN 0-h analysis from 0000 UTC 15 Nov 1995.

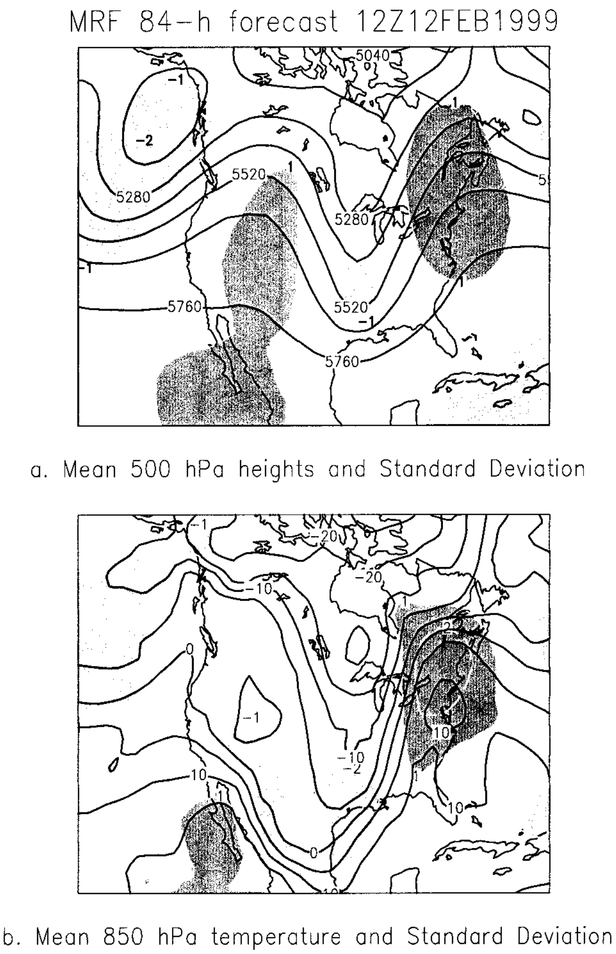

FIG. 12. MRF 84-h forecasts of (a) 500-hPa heights and departures from normal and (b) 850-hPa temperatures and departures from normal from the 0000 UTC 9 Feb 1999 forecast cycle valid at 1200 UTC 12 Feb 1999. Contours and shading are as in Fig. 2.

forecasts from the AVN and Eta are shown to emphasize that the technique works with either model.

The 72-h AVN forecast from the 0000 UTC 12 November 1995 run is shown in Fig. 9. This forecast showed an intense upper-level disturbance moving across the southeastern United States. At 500 and 700 hPa, the AVN forecast heights are shown to be -4.5 standard deviations below the 30-yr climatological values. At the surface, the model forecast an unseasonably strong surface cyclone, which was to be accompanied by unseasonably cold low-level temperatures. The 850-hPa temperatures were forecast to be below normal over most of the southern United States. Other features of interest, which are often associated with snowstorms along the east coast of the United States, include the large 500-hPa ridge over the western United States and the strong surface anticyclone ($+2$ standard deviations above normal) over eastern Canada.

The AVN continued to forecast a strong surface cyclone along the East Coast in subsequent runs. The 60-h AVN forecast from 0000 UTC 13 November 1995 (not shown) continued to forecast a strong surface anticyclone over Canada, the strong upper-level ridge over the western United States, and the intense surface low along the East Coast. Despite some minor differences with exact position and intensity, this forecast was consistent with the forecast from 12 (not shown) and 24 h earlier.

The 48-h AVN forecasts from the 0000 UTC 14 November 1995 run (not shown) continued to forecast the above trend and the significant features remained unchanged in this forecast compared with previous forecasts. The biggest change was the decrease in the intensity of the surface cyclone along the mid-Atlantic region.

The 12-h forecasts from the 48-km Eta run for 1200 UTC 14 November 1995 are shown in Fig. 10. These data appear to be similar to those shown in Fig. 9 despite the 60-h difference in time and the fact that the data in Fig. 9 are from the AVN model. The three key features, including the ridge over the western United States, the surface anticyclone over eastern Canada, and the surface cyclone and upper-level wave over the eastern United States, are in the same relative positions and of comparable strength. All model runs shown were relatively consistent and all four forecast an anomalously strong surface cyclone, associated with anomalously low 500- and 700-hPa heights and 850-hPa temperatures.

The verifying AVN 0-h analysis from 0000 UTC 15 November 1995 (Fig. 11) showed that these forecasts were relatively consistent and accurate. There were minor differences in the timing and track of the surface cyclone. These latter errors are significant on the local scale for forecasting the onset, amounts, and type of precipitation. Similar to the 8 January storm, slightly above normal temperatures were forecast at 850 hPa in the warm sector.

3) 12 FEBRUARY 1999

During the early afternoon hours of 12 February 1999, many locations in the mid-Atlantic region set record high temperatures for the date and the month. Harrisburg, Pennsylvania, set a monthly record high of 24.4°C (76°F) around 2000 UTC. Shortly afterward, a strong cold front moved across the region. The focus is on the model output statistics (MOS: Glahn and Lowry 1972; Klein and Glahn 1974; Bocchieri 1979) and their high temperature forecasts for 12 February 1999.

This case represents the forecast of a surge of anomalously warm air ahead of an approaching cold front during the winter. The 84-h forecasts of the 500-hPa heights and 850-hPa temperature from the Medium-Range Forecast Model (MRF) for 0000 UTC 9 February 1999 valid at 1200 UTC 12 February 1999 are shown in Fig. 12. The features associated with this event provide a good example of how the forecast anomalies can be used to improve upon MOS forecasts during times

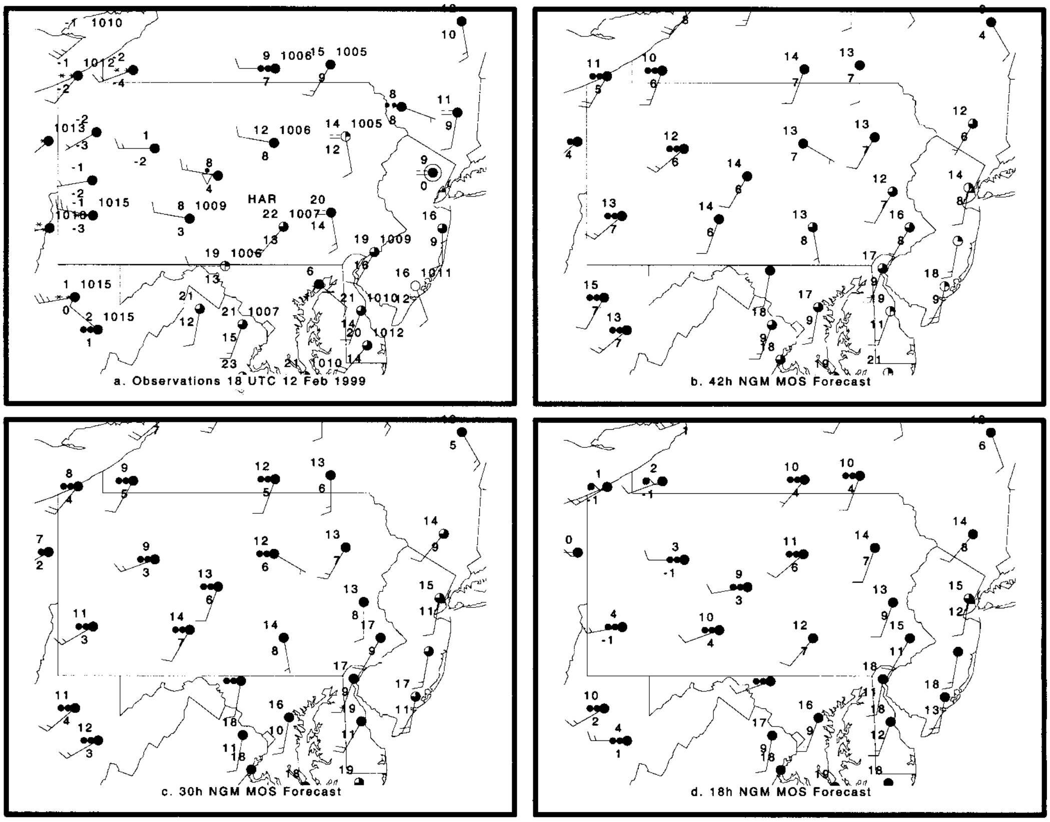

FIG. 13. The (a) observed temperatures and NGM MOS forecast temperatures valid at 1800 UTC 12 Feb 1999 from the (b) 0000 UTC 11 Feb, (c) 1200 UTC 11 Feb, and (d) 0000 UTC 12 Feb NGM forecasts. The location of Harrisburg is denoted in upper-left panel by the letters HAR above the observation point.

when forecast fields depart significantly from normal. Unlike previously mentioned cases, this was not a large disruptive storm. This case was selected because it represented a widespread record high temperature event and it demonstrates how forecasters can apply 30-yr climatologically data to improve upon MOS forecasts.

The observed temperature at 1800 UTC 12 February 1999 (Fig. 13a) and the Nested Grid Model (NGM) based MOS forecasts valid at the same time are shown in Fig. 13. The forecast minimum and maximum temperatures are shown in Table 3. These data show that the NGM MOS severely underforecast the observed high temperature at Harrisburg of 24°C (76°F). At Harrisburg at 1800 UTC, around the time the maximum temperature was observed (although not drawn, a sharp cold front was halfway across Pennsylvania at this time), the MOS temperature was forecast to be 8°–10°C too cold. On this date many high temperature records for the date and month were set across Pennsylvania, Maryland, and Virginia (not shown) prior to the passage of a sharp cold front.

By examining short- and medium-range forecast anomalies (MRF 84-h forecast, Fig. 12; Eta and NGM 24–48-h forecasts, not shown), forecasters could anticipate that the forecast MOS predictors would be over 2 standard deviations above normal. Using this knowledge, and the time of year, forecasters could anticipate that MOS forecast temperatures (even though high) might *still* be too low for the coming event. The anomaly contours thus added important information that could not easily be obtained from examining the basic upper-air height and temperature forecast fields alone.

The corresponding forecasts from the MRF MOS (Table 3) revealed a similar pattern of underforecasting the high temperatures. Longer-range MRF-based MOS forecasts had extremely large errors due in part to the timing of the frontal passage. For example, the MRF MOS high temperature forecasts made on 7–9 February valid for 12 February 1999 were in the single-digit (°C) (30s °F) range. These large errors were partially due to the MRF forecasting the frontal passage 12–24 h earlier than observed (not shown). Both the MRF MOS guidance and the anomaly forecasts would have been similarly impacted as a result of these timing errors.

The MRF verifying analysis of 500-hPa heights and 850-hPa temperatures valid at 0000 UTC 12 February 2000 are shown in Fig. 14. These data show that the model forecast a strong, but short lived, surge of unseasonably warm air into the mid-Atlantic region ahead of the surface cold front. The anomaly was stronger and

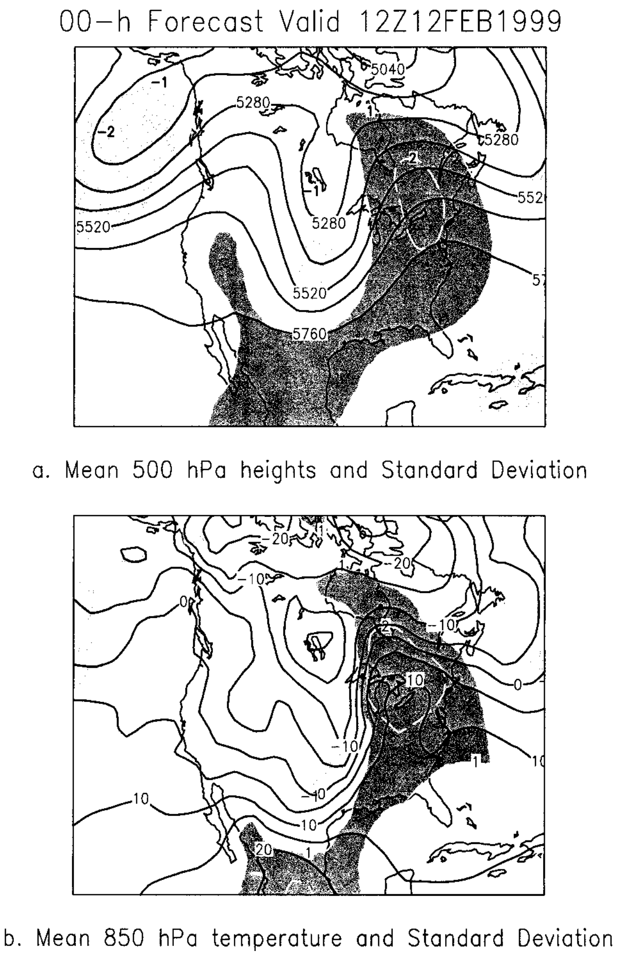

FIG. 14. As in Fig. 12 except MRF verification's at 0000 UTC 12 Feb 1999.

farther west than forecast by earlier MRF runs. Short-term anomaly fields from the Eta (not shown) revealed slightly stronger positive 500-hPa height and 850-hPa temperature anomalies.

4) 7–10 OCTOBER 2000

An unusually strong early season arctic air mass moved southward into the United States between 6 and 10 October 2000. As this air mass moved southward, it brought record low temperatures to much of the southern plains and southeastern United States. By 8 October, record lows were being set as far south as the Mexican border. The temperature fell to 13°C (55°F) at Brownsville, Texas, just before midnight on 7 October, tying the previous record set in 1915. The 13°C reading would be the high temperature on 8 October, nearly 7°C lower than the previous record low (67°F), which was the lowest high temperature ever recorded so early in the season. The low temperature on 8 October was 7.2°C (45°F), setting both the record low for the date and coldest low ever so early in the season.

TABLE 3. Temperature forecasts valid for 12 Feb 1999 from the MRF and NGM MOS valid at Harrisburg, PA. Cycle shows the day and the hour (UTC) that the model was initialized. Minimum (min) and maximum (max) temperatures are in °C with Fahrenheit values in parentheses. Min and max are the forecast low and high temperatures for the periods ending 1200 UTC 12 Feb and 0000 UTC 13 Feb, respectively.

Model	Cycle Day/Time (UTC)	Min	Max
MRF	08/0000	3.9 (39)	6.7 (44)
MRF	09/0000	7.8 (46)	10.6 (51)
MRF	10/0000	7.8 (46)	15.0 (59)
NGM	10/1200	5.6 (42)	12.8 (55)
MRF	11/0000	7.8 (46)	15.0 (59)
NGM	11/0000	3.3 (38)	15.0 (59)
NGM	11/1200	5.6 (42)	16.7 (62)
MRF	12/0000	—	12.8 (55)
NGM	12/0000	—	13.9 (57)

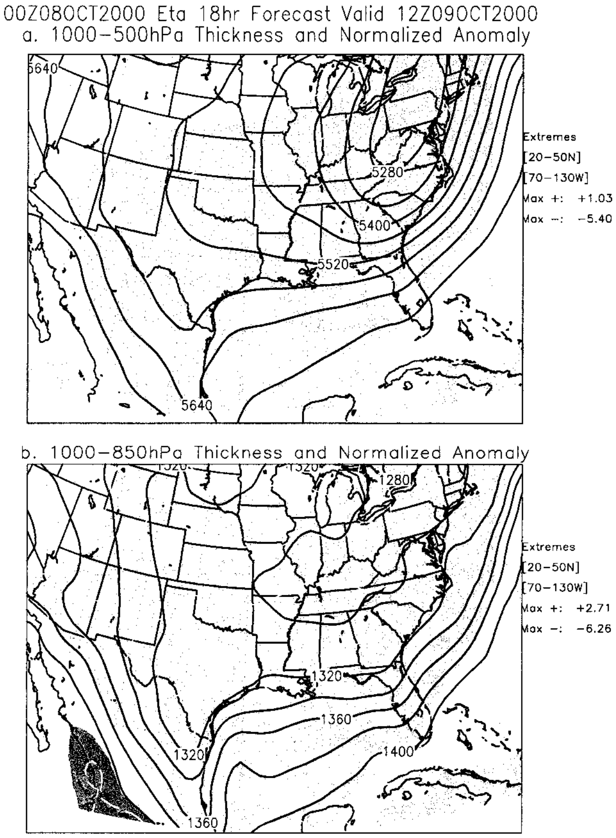

FIG. 15. NCEP Eta Model forecasts of (a) 1000–500-hPa thickness (m) and (b) 1000–850-hPa thickness (m). Shading in both panels shows the standardized anomalies of both fields. The 1000–500-hPa thickness contours are every 60 m and the 1000–850-hPa thickness contours are every 20 m. Light shading denotes negative anomalies and dark shading denotes areas of positive anomalies. Light dashed contours are every 1 standard deviation.

TABLE 4. Record temperatures set during the arctic outbreak of 7–9 Oct 2000. These data represent a few locations. Many sites in Texas broke records that stood for up to 100 yr. Source: National Climatic Data Center.

Location	Date	Record [°C (°F)]	Notes
Brownsville, TX	8 Oct	Low: 7.2 (45)	Record low for so early in the month
		High: 12.8 (55)	Record low high for the date
Del Rio, TX	8 Oct	High: 8.3 (47)	Record low high previous of 8.8°C (48°F) on 23 Oct 1936
		Low: 5.6 (42)	
Charleston, SC	8 Oct	Low: 9.4 (49)	Record low
Atlantic, IA	9 Oct	Low: −10 (14)	Record low for so early in the month
Jacksonville, FL	9 Oct	Low: 7.8 (46)	Record low
Barltesville, OK	9 Oct	Low: −13.8 (17)	Record low
Brownsville, TX	9 Oct	Low: 6.6 (44)	Broke 100-y-old record of 8.8°C (48°F).
		High: 10 (50)	Record low high so early broke previous value of 11.1°C (52°F) set on 30 Oct 1925
Gilbert, AR	9 Oct	Low: −1.6 (29)	Earliest observed freezing temperature, previous 20 Oct 1964
Del Rio, TX	9 Oct	Low: 4.4 (40)	Record low
		High: 6.6 (44)	Record low high was 21°C (70°F) set in 1970
Wichita Falls, KS	9 Oct	Low: −0.8 (31)	Earliest freeze on record
San Antonio, TX	9 Oct	High: 7.8 (46)	Broke 100-y-old record for record low high of 21°C (70°F) set in 1900

As the record cold air mass spread eastward, record lows were reported from Iowa to Florida. New records included a low of −8.3°C (17°F) at Bartlesville, Oklahoma, on the morning of 9 October 2000. A brief summary of some of these and other records, obtained from NCDC, is shown in Table 4. Many locations in Texas broke records that had stood for over 100 yr. Clearly, this outbreak represented a significant departure from normal.

The record cold air mass was exceptionally well forecast by NCEP's models. There was evidence of a significant thermal anomaly in the NCEP ensembles as far as 7 days in advance of this historic event (not shown). However, to demonstrate the utility of examining model forecasts and the departures of forecast fields to identify these types of events, a 36-h forecast from the NCEP Eta Model is shown in Fig. 15. These data show that 36 h prior to the event, the Eta forecast 1000–500- and 1000–850-hPa thickness anomalies on the order of −5.40 and −6.26 standard deviations below normal, respectively. The deepest cold air was focused over the southeastern United States (Fig. 15a) while the intense shallow cold air was focused over the southern plains. The coldest 1000–850-hPa thickness anomaly was located over northeastern Mexico (Fig. 15b). The implication being that the coldest air was a shallow feature, with the larger anomaly present in the 1000–850-hPa layer. The 850-hPa thermal anomalies were similar to the 1000–850-hPa thickness anomalies and are not shown. A computation from the 52-yr data revealed a return period of −6 standard deviations from normal occurs about once every 52 yr over the entire United States east of the Mississippi River. It is likely that the distributions are similar west of the Mississippi River; therefore, these thermal anomalies, on the order of −6 to −6.5 standard deviations from normal, have return periods on the order of decades.

Nested Grid Model based MOS forecasts showed mixed results in predicting these records over the southern United States. These large negative thermal anomalies forecast by the Eta and AVN (not shown) should have provided forecasters a clear signal that a record event was about to unfold. These anomaly forecasts provided confidence of MOS forecasts of near-record lows. The MOS forecasts and the observed high and low temperatures valid at 1200 UTC 9 October and 0000 UTC 10 October 2000 are shown in Fig. 16. An examination of these MOS forecasts showed that the 24-h low temperature forecasts (Fig. 16c) were too cold over southern Texas and too warm over Oklahoma. The warm bias over Oklahoma occurred under clear skies with a surface anticyclone observed in the hourly surface data (not shown) over eastern Oklahoma from 0000 through 1500 UTC 9 October. Clouds persisted over most of Texas overnight and light rain fell across the southernmost parts of Texas through 1200 UTC. The observed clouds and rain may have precluded temperatures from falling during the night. Additionally, many locations in southern Texas reached their lowest temperatures after 1200 UTC.

The MOS high temperature forecasts (Fig. 16c) showed a tendency of the forecast being too warm over most of Texas. High temperature forecast errors on the order of +10°C were observed at many locations in southern Texas. The persistent clouds may have contributed to the anomalously low high temperatures (Fig. 16b and Table 4) observed across southern Texas. The departures of the 850-hPa temperatures and 1000–850-hPa thickness, predictors in MOS high temperature forecasts (Jacks et al. 1990), may have provided forecasters

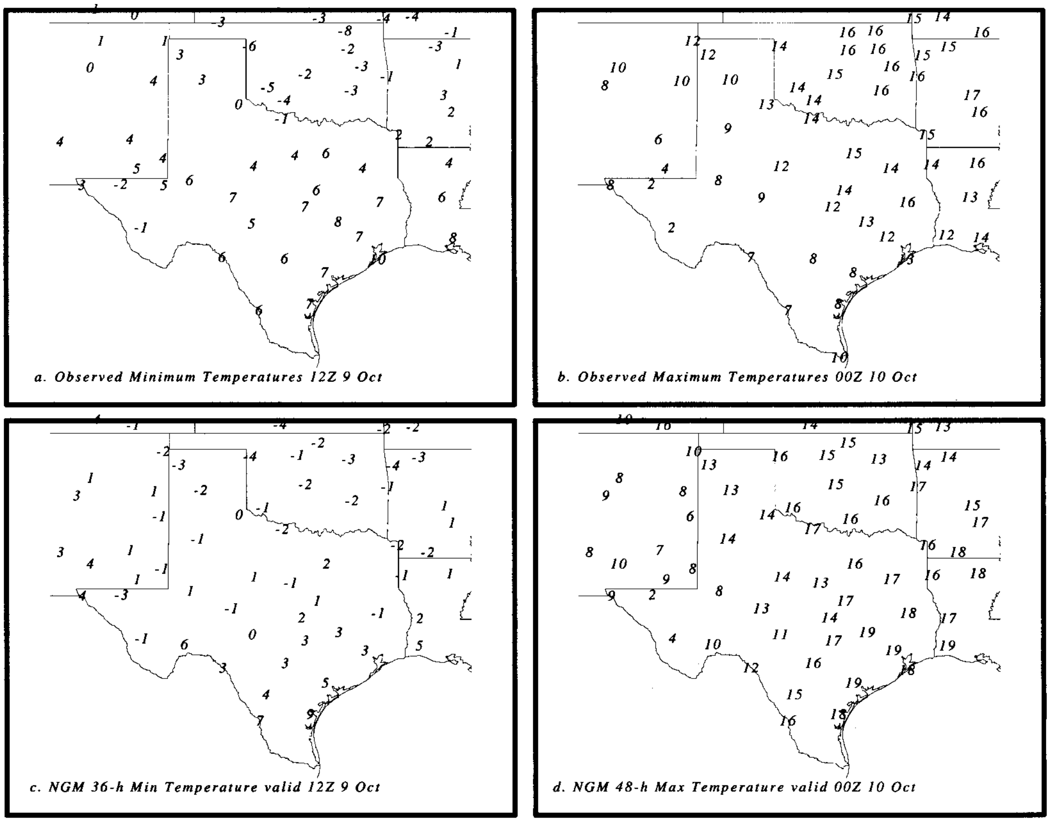

FIG. 16. The observed (a) low temperatures valid 1200 UTC 9 Oct 2000 and (b) high temperatures valid 0000 UTC 10 Oct 2000, and the MOS (c) 36-h low-temperature forecasts valid at 1200 UTC 9 Oct 2000 and (d) 48-h high-temperature forecasts valid 1000 UTC 9 Oct 2000 (in °C).

some clue that MOS forecasts in Texas might be too warm.

4. Discussion

The preliminary results shown here suggest that significant weather, including large snowstorms, winter warm spells, and early season arctic outbreaks are often associated with significant departures from normal. This implies that if forecasters recognize the magnitude, location, and spatial extent of anomalies associated with a particular type of event, they may be able to anticipate its potential severity relative to average. Another important aspect of this approach is that forecasters must be aware of both the rarity and the return period of anomalous features, which may impact the forecast.

Two winter storms were presented to show how the 30-yr climatological data can be used to add value to model forecast data. In both cases, the models forecast large-scale patterns that are often associated with intense surface cyclogenesis and heavy snow. The 30-yr climatological data could then be applied to see if any of the features associated with the pattern departed significantly from normal. For example, strong upper-level 500-hPa troughs and surface cyclones are often associated with significant snows along the East Coast (Kocin and Uccellini 1990). If the operational models forecast both features, and they depart from normal at the desired level of significance (~2.5 standard deviations), a forecaster should have high confidence that this storm could produce a record event for the date.

In both cases shown, the model forecast the surface cyclone and the upper-level trough to depart significantly from normal. The models were capable of forecasting these strong and persistent anomalous features 72–84 h in advance. This implies that the models are capable of forecasting anomalous features quite accurately at least 3–5 days in advance and in some cases at even longer ranges.

It is critical to consider both the strength of the anomalies and the type of weather associated with these anomalies. Both snow cases exhibited characteristics often associated with major East Coast snowstorms (Kocin and Uccellini 1990). The majority of the major snowstorms in KU had anomalies that were on the order of -2 to -3 standard deviations from the 30-yr mean. Once the forecaster establishes that the forecast pattern favors a certain event type, such as a snowstorm, the strength of the anomalies can be evaluated, allowing the forecaster to determine if the storm is likely to be ex-

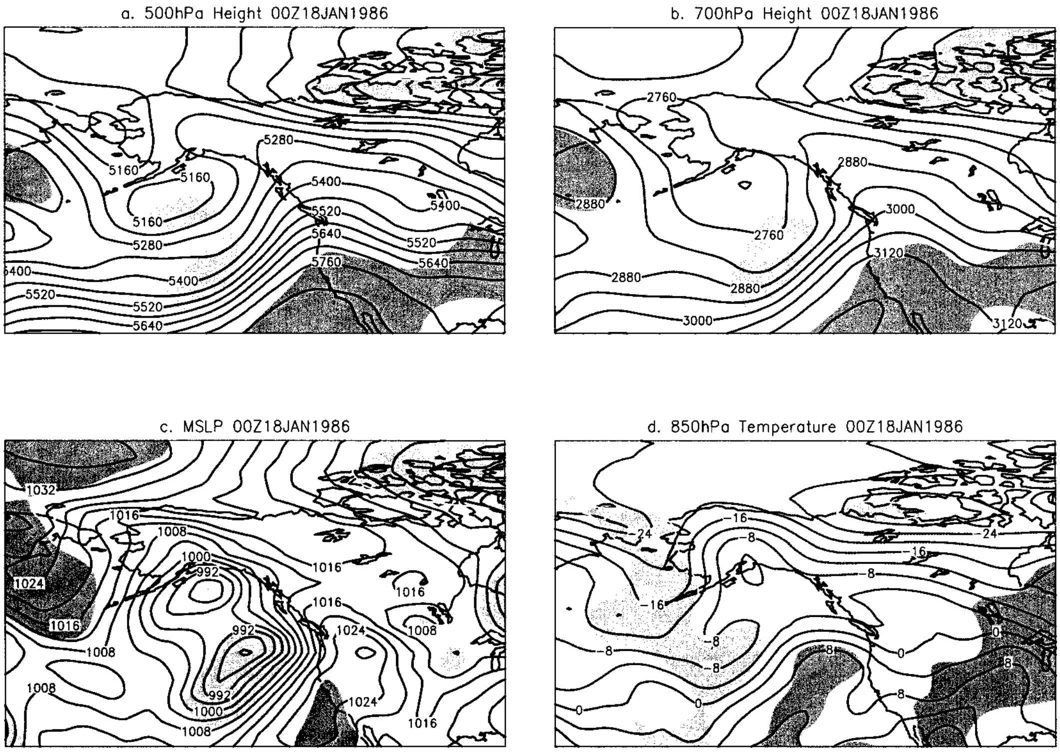

FIG. 17. As in Fig. 2 except for 0000 UTC 18 Jan 1986 showing the standardized anomalies over the eastern Pacific similar to those shown by Lackmann and Gyakum (1999).

traordinary or not. This method applies to large-scale conditions and does not consider locally heavy precipitation, which often occurs on the mesoscale.

Lackmann and Gyakum (1999) showed the climatological mean 500-hPa heights, 850-hPa temperatures, and mean sea level temperatures associated with heavy cold season precipitation events in the northwestern United States. Lackman and Gyakum (1999) identified a large-scale pattern conducive for heavy rains and flooding in the Pacific Northwest. Their study determined the relative position of height anomalies to these events. An attempt was made to see if the case study in Lackman and Gyakum (1999) represented an anomalous event. The data for this case are shown in Table 5 and in Fig. 17. These data show that the 17–18 January event was more anomalous than the mean for all 46 events of this type. However, with the exception of the surface pressure anomaly on 17 January, none of the anomaly centers departed significantly from normal when compared to the 30-yr climatology. All values were within 1 standard deviation of normal. At its deepest, the surface low was −2 standard deviations from the 30-yr mean. The Lackman and Gyakum (1999) study may reveal the importance of the magnitude, the spatial extent, and the geographic location of the meteorological variables associated with important weather events. An examination of moisture variables during substantial heavy rain events may be a course of future study.

TABLE 5. Departures from normal of features associated with the trough moving toward the west coast of the United States during 1986. Values represent maximum number of standard deviations the parameters depart from normal.

Date	500-hPa height	700-hPa height	850-hPa temp	MSLP
15 Jan	−1.5	−1.5	−0.5	−1.5
16 Jan	−1.5	−1.5	−1.0	−2.0
17 Jan	−1.5	−1.5	−1.0	−2.5
18 Jan	−1.5	−1.5	−1.0	−2.5

5. Conclusions

The role of weather forecasters will slowly shift from providing routine daily forecasts to interpreting data to identify significant weather events. In order to correctly anticipate significant weather events, the forecaster must be familiar with the features associated with these events and whether the parameters associated with these features are within the range of normal during the event. Ultimately, routine daily weather forecasts, when no significant mesoscale features are present, within a standard deviation of normal should be heavily biased toward MOS or a MOS blend. *Forecasters will have to focus on recognizing the potential for significant weather events based on patterns and anomalies, which MOS may not handle as well.*

Determining what an extreme event is, or might be, is a difficult task. It is unlikely that the forecaster *quantitatively* knows what a normal 500-hPa height is, and what values are within 1 standard deviation of normal. This requires that model output of specified fields be displayed showing departures from normal. Significant events would likely include those that depart 2–3 standard deviations from normal. *The combination of model continuity, and the convergence of solutions toward large departures from normal, should provide forecasters confidence in a significant weather event.* For example, if 850-hPa temperatures are forecast to be 2–3 standard deviations above normal, forecasters should have a high confidence in forecasting temperatures significantly above normal (and possibly above MOS forecasts). In a case such as the 7–9 October 2000 arctic outbreak, thermal anomalies on the order of 6 standard deviations below normal should alert forecasters to the potential for a rare event. In order to know this, future work will require building a database showing the return period of important parameters to assist forecasters in quickly identifying model forecasts of significant and historic events.

The results shown here suggest that many record snowstorms in the literature were associated with storms, which departed significantly from normal. Using model data, it has been demonstrated that models can successfully forecast both the patterns associated with these events and significant departures from normal in extreme events. In fact, the results shown here suggest the models are quite skillful at forecasting unusually strong weather systems in the short range (1–3 days).

Future work will include anomaly composites of heavy rain (2 in. or more) events, major tornado outbreaks such as the April 1974 event, large-scale severe weather events, ice storms, arctic outbreaks, and snowstorms for central Pennsylvania and the mid-Atlantic region. One goal would be to see if there are specific large-scale patterns and anomalies associated with these weather events. Additionally, anomalies of specific parameters (Junker et al. 1999) will be analyzed to see if they may offer some skill in anticipating heavy rainfall events. Ultimately, it may prove harder to forecast locally heavy rains associated with mesoscale forcing when synoptic-scale conditions are closer to normal. Preliminary examination of moisture variables compared to 30-yr climatological values appears to show great promise in identifying some heavy rainfall events (Grumm and Hart 2001).

While examining the anomalies associated with storms of note in the literature, it became apparent that we could find most synoptic-scale meteorologically significant storms from our existing database. A follow-on study to examine these events has already begun.

These results suggest that learning algorithms could be developed to interpret model guidance and identify significant weather events. These artificial intelligence (AI) applications could be used to adjust MOS outputs and forecast potential record events. Furthermore, parameters traditionally used to identify heavy rain, severe weather, and heavy snow events could be added to these AI applications and probabilities of significant events could be determined.

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