Storm Prediction Center Forecasting Issues Related to the 3 May 1999 Tornado Outbreak

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ABSTRACT

Forecasters at the Storm Prediction Center (SPC) were faced with many challenges during the 3 May 1999 tornado outbreak. Operational numerical forecast models valid during the outbreak gave inaccurate, inconsistent, and/or ambiguous guidance to forecasters, most notably with varying convective precipitation forecasts and underforecast wind speeds in the middle and upper troposphere, which led forecasters (in the early convective outlooks) to expect a substantially reduced tornado threat as compared with what was observed. That, combined with relatively weak forecast and observed low-level convergence along a dryline, contributed to much uncertainty regarding timing and location of convective initiation. As a consequence, as the event approached, observational diagnosis and analysis became more important and were critical in identification of the evolution of the outbreak. Tornadic supercells ultimately developed earlier, were more numerous, and produced more significant tornadoes than anticipated. As forecasters addressed the meteorological facets of the tornadic storms on the evening of 3 May 1999, there were other areas of simultaneous severe-storm development, and one of the tornadoes posed a threat to the facility and family members of the forecast staff. These uncertainties and challenges are discussed in the context of SPC convective outlooks and watches for this outbreak. Recommendations are made for continued research aimed at improving forecasts of convective initiation and mode.

1. Introduction

From the late afternoon into the nocturnal hours of 3–4 May 1999, a violent tornado outbreak affected portions of central and northern Oklahoma and southern Kansas, with 10 tornadic supercells responsible for over 60 tornado reports (Speheger et al. 2002). Long-lived, violent (F4–F5 damage) tornadoes occurred in the Oklahoma City, Oklahoma, and Wichita, Kansas, metropolitan areas, as well as in the small towns of Mulhall and Dover, Oklahoma, to the north and northwest of Oklahoma City. [For mapping of the supercells and tornadoes, and a postmortem overview of the meteorological conditions of the event, refer to Thompson and Edwards (2000, hereinafter TE00).]

The Storm Prediction Center (SPC) in Norman, Oklahoma, has nationwide responsibility for forecasting organized severe local storm threats. SPC was actively involved in providing synoptic-scale outlook guidance, mesoscale discussions (MDs), and severe-weather watches (WWs) for the 3 May 1999 event [see Ostby (1992, 1999) for an overview of SPC's forecast products and services]. Except for the addition of two more convective outlooks to the daily product schedule (issued at 0100 and 1300 UTC), the basic suite of products discussed by Ostby (1992) is the same as that which was available on 3 May 1999 (see Table 1 for the 1999 SPC outlook schedule). In addition, the 1300 and 2000 UTC day-1 convective outlooks were accompanied by a set of experimental probabilistic forecasts (Kay and Brooks 2000) for tornadoes, severe hail, and severe thunderstorm wind—products that were extended to all day-1 and day-2 outlooks in 2000 and that became fully operational in January of 2001. Also, during this event, watch status reports routinely contained short discussions about the degree or location of the greatest threat within a WW area. However, starting in 2000, more frequent MD products within WWs have taken the place of status narratives; and, as of this writing, the status report is primarily a set of points representing the ending of the severe weather threat within a WW area.[1]

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[1] The current (at the time of writing) SPC product suite is described online at http://www.spc.noaa.gov.

TABLE 1. Schedule for transmission of SPC national convective outlooks, as valid on 3 May 1999.

Time (UTC) and date issued (type)	Range valid, time (UTC) and date
0730 2 May (day-2)	1200 3 May–1159 4 May
1730 2 May (day-2)	1200 3 May–1159 4 May
0600 3 May (day-1)	1200 3 May–1159 4 May
1300 3 May (day-1)	1300 3 May–1159 4 May
1630 3 May (day-1)	1630 3 May–1159 4 May
2000 3 May (day-1)	2000 3 May–1159 4 May
0100 4 May (day-1)	0100 4 May–1159 4 May

Many meteorological parameters associated with this outbreak were characteristic of other severe-weather outbreaks in the southern plains; however, the preconvective evolution of this event presented substantial challenges to SPC forecasters in large part because of *ambiguous* and often *conflicting* diagnostic and prognostic information available before the event. The resulting uncertainties delayed recognition of the magnitude of the impending outbreak and, in particular, delayed upgrade of the categorical convective outlook from ''slight'' to ''moderate'' risk until 1630 UTC 3 May. These uncertainties arose from two primary factors: 1) occasionally inaccurate synoptic-scale guidance by operational numerical weather prediction models, especially with regard to several critical parameters, from 2 days in advance through the afternoon of the event and 2) model and observational difficulties regarding convective initiation and evolution.

The purpose of this article is to focus operational and research attention on these critical forecast issues by documenting their influence on SPC's handling of the 3 May event and to discuss some of the lessons learned. Also, the unique operational environment of SPC is briefly discussed as applied to the 3 May 1999 outbreak.

2. Synoptic- and subsynoptic-scale numerical model guidance

A large suite of operational and experimental numerical model guidance was available to the SPC at the time of the outbreak, with the most commonly used output being that from the Eta (Black 1994), Rapid Update Cycle 2 (RUC2; Smith et al. 2000), and Aviation (Kanamitsu 1989) Model runs. In the initial forecasts for this event, the day-2 outlooks, the Eta and Aviation Model runs were most thoroughly examined. During the day-1 outlook periods, the Eta was the model most intensively utilized because of both 1) its timeliness relative to product deadlines, and 2) the SPC's operational perception of the Eta as being the most reliable short-range model for forecasting environmental conditions conducive to severe thunderstorms. The hourly RUC2, valid for no more than 12 h after initialization, was also examined frequently during the morning, afternoon, and evening of 3 May 1999.

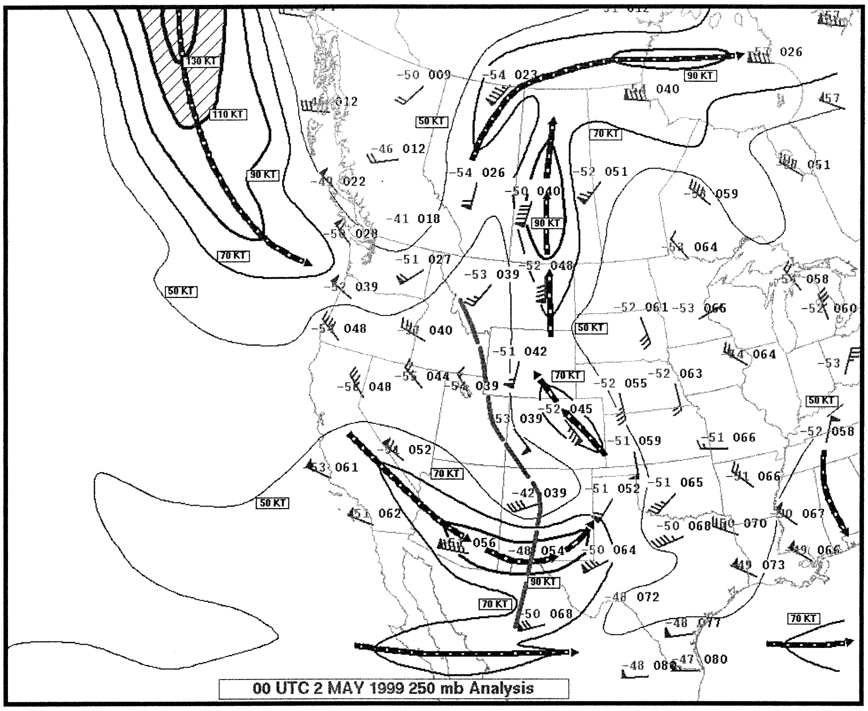

FIG. 1. Isotach analysis (kt) and geopotential height plot for the 250-hPa pressure level, 0000 UTC 2 May 1999, over conventional station plots. Axes of speed maxima are denoted by thick black lines with arrows. Geopotential height trough is represented by the thick, dashed gray line.

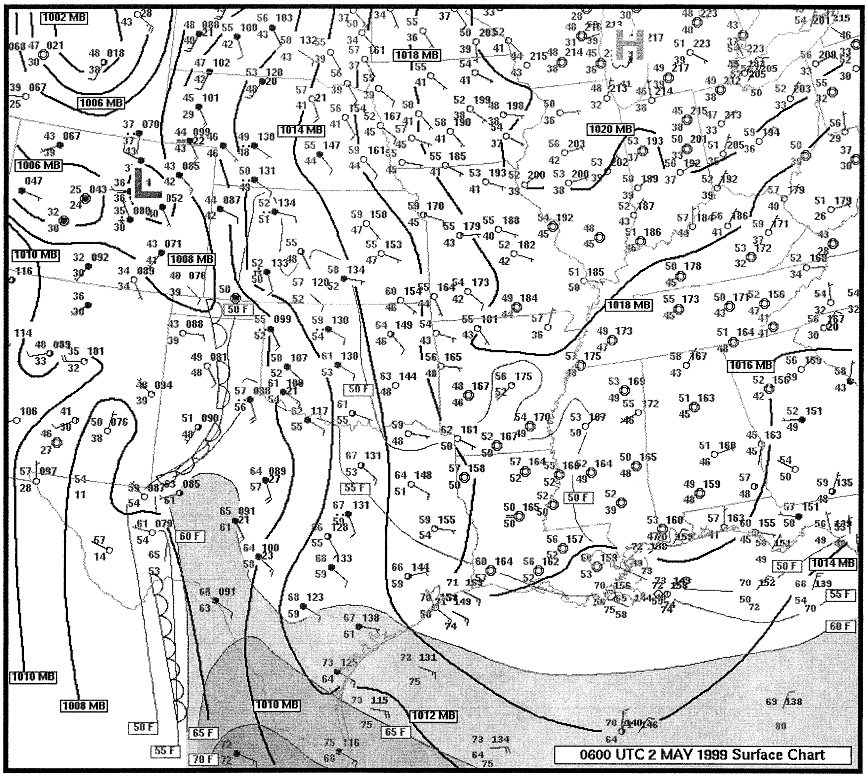

FIG. 2. Subjective surface analysis for 0600 UTC 2 May 1999. Station plots and analyzed features are operationally conventional, with isodrosotherms (°F) in light, isobars (hPa) in dark, and wind barbs plotted in knots. Isodrosotherms >60°F are filled with progressively darker shading.

In the day-2 and early day-1 forecasting time frames, a concern for SPC forecasters was model performance with respect to the character and evolution of the synoptic-scale pattern, as depicted by forecasts of upper-level winds and geopotential heights on mandatory pressure levels (e.g., 500 and 250 hPa). Data at these mandatory pressure levels are often used by SPC forecasters as a component of ‘‘pattern-recognition’’ forecasting typically invoked in the day-2 and initial day-1 outlooks (e.g., Johns and Doswell 1992). Beginning early in the day-1 forecast period, forecaster assessment of the forecast large-scale pattern and smaller-scale details was hindered somewhat by Eta Model forecast errors detected through subjective examination of 500- and 250-hPa geopotential heights and wind speeds. The forecast valid at 1200 UTC 3 May from the 0000 UTC 3 May 1999 Eta run appeared to be underestimating wind speeds in the middle and upper troposphere, thus casting uncertainty upon associated forecasts of vertical wind shear and the timing and position of troughs in the height patterns. The distribution and magnitude of vertical shear, along with the location and intensity of a middle- to upper-tropospheric speed maximum, were each considered important factors in determining the mode and coverage of deep convection. These concerns were conveyed to the later forecasting shifts (namely the day shift on 3 May), thereby encouraging the day-shift forecasters to rely more heavily on observational data than on the explicit model forecasts. Inconsistent Eta and RUC2 forecasts of precipitation similarly introduced considerable uncertainty not only for that field, but also for critical parameters incorporating moisture and instability. This includes convective available potential energy (CAPE), which can be acutely sensitive to whether a model turns its convective parameterization on (e.g., Baldwin et al. 2000). Despite the noted model forecast problems with the operational models in the 3 May 1999 case, general forecasts of vertical wind shear and CAPE appeared generally supportive of supercells in a relatively broad area from Texas to Kansas.

a. Antecedent synoptic conditions and day-2 outlooks

The upper-tropospheric jet pattern during the predawn hours of 2 May 1999, as the initial day-2 forecast was prepared, featured a large-scale, negatively tilted trough, the axis of which was oriented from north-northwest to south-southeast over the Rockies, with an embedded jet streak over southern New Mexico (Fig. 1). In association with the jet streak, a lee trough over the High Plains had induced southeasterly low-level flow that had brought deep moisture northward over southern and western Texas (Fig. 2). Forecast passage of the New Mexico jet streak in a cyclonically curving, northeastward to northward

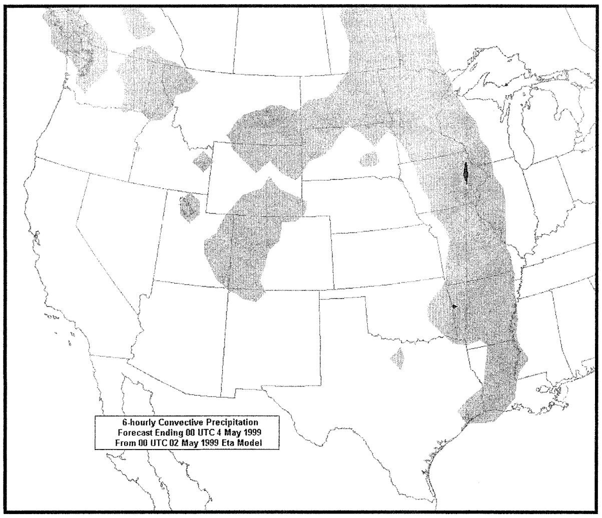

FIG. 3. Forecast of accumulated convective precipitation from the 0000 UTC 2 May 1999 Eta Model run, valid during the 6-h period ending 0000 UTC 4 May 1999. Light gray shading represents ≥0.01 in. (0.025 cm); dark gray shading represents ≥0.10 in. (0.25 cm).

path across the High Plains on 2 May was expected 1) to maintain low-level southerly flow over most of the southern plains, boosting confidence that substantial northward moisture transport would continue through the afternoon of 3 May, and 2) to veer flow above the boundary layer over the south-central United States. This, in turn, was expected to contribute to low-level air being diabatically heated and vertically mixed on higher terrain [an elevated mixed layer, after Carlson et al. (1983) and Lanicci and Warner (1991)]. The elevated mixed layer then would be advected northeastward atop the moistening boundary layer over the southern plains, leading to large CAPE. SPC forecasters generally consider lapse rates approaching dry adiabatic (e.g., $>9°\mathrm{C\ km^{-1}}$ in the 700–500-hPa layer) as extreme, and Eta forecast lapse rates were substantially less—generally around 7.5°C $\mathrm{km^{-1}}$. Still, it was recognized that such values could support severe convection given the presence of low-level moisture already observed across Texas and the Gulf of Mexico, as well as sufficient moisture and low-level lift to initiate deep convection.

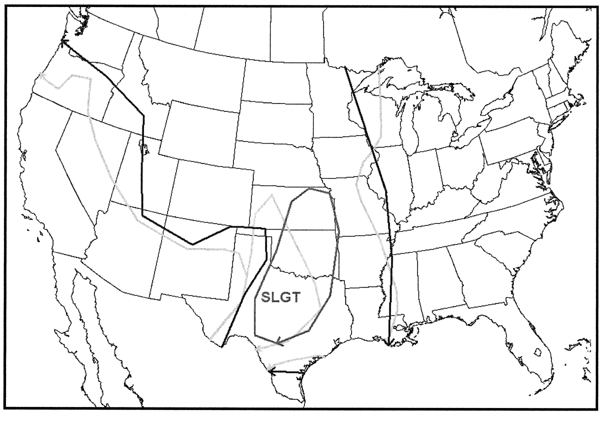

FIG. 4. Maps of SPC day-2 categorical convective outlook risk areas valid from 1200 UTC 3 May through 1200 UTC 4 May 1999, beginning at the following issuance times (UTC) on 2 May: 0730 (light lines) and 1730 (dark lines). Unlabeled lines denote general thunderstorm forecast bounds, and the SLGT label is located in the overlap region for both slight risks.

Even as early as the period in which the day-2 outlook was being prepared, forecasters questioned the strength of low-level ascent, which could potentially lead to convective initiation. Pressure falls over the Dakotas were expected to maintain a large southerly surface flow component on both sides of a dryline, which was expected to become more sharply defined as moisture increased to its east. Nevertheless, confidence was strong that vertical wind shear, storm-relative flows (Thompson 1998), and instability would be at least adequate for a supercell and tornado threat, given convective initiation. For example, 48-h forecasts from the 0000 UTC 2 May Eta[2] run showed 1000–500-hPa velocity differences of greater than or equal to 35 kt (18 $\mathrm{m\ s^{-1}}$) over most of Oklahoma and northern Texas, with values approaching 50 kt (25 $\mathrm{m\ s^{-1}}$) beneath the southern jet branch in southern Texas, and most-unstable-parcel CAPE (MUCAPE) of greater than 2500 J $\mathrm{kg^{-1}}$ over a broad swath of the plains from Nebraska through Texas.

Despite the large forecast area of favorable CAPE and shear, the absence of both a significant low-level forcing mechanism for upward motion east of the dryline and a well-defined trough in the mid- and upper troposphere forecast by the Eta and Aviation Models, along with a prominent lack of Eta convective precipitation from Nebraska southward over Texas (Fig. 3), diminished confidence in development of a widespread or unusually intense severe thunderstorm threat. Therefore, the potential for organized severe thunderstorms on 3 May was deemed a ‘‘slight risk’’[3] in the 0730 UTC 2 May issuance of the SPC categorical day-2 outlook (Fig. 4).

This reasoning was continued through the 1730 UTC 2 May update of the day-2 outlook (Fig. 4), largely because of the close resemblance of patterns in shear, instability, and lift in the 1200 UTC 2 May Eta (not shown) to those from previous runs. The newer model run did, however, produce precipitation in the moist sector from central Texas to southern and eastern Kansas after 0000 UTC 4 May. (Because the operational Eta did not extend

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[2] In 1999, the Eta Model forecast output extended through 48 h, corresponding to only the first half of the initial day-2 outlook period. Out of necessity, the initial day-2 outlook relied on a blend of Eta and Aviation Model guidance to cover the entire 24-h forecast period.

[3] The term slight risk means that severe thunderstorms are expected to develop, but not with widespread coverage. It is not meant to be interpreted in the same way as, for example, a local precipitation forecast. The inherent ambiguity in categorical severe-thunderstorm risk terminology led to development of the probabilistic outlooks (Kay and Brooks 2000), which the SPC was issuing experimentally on 3 May 1999.

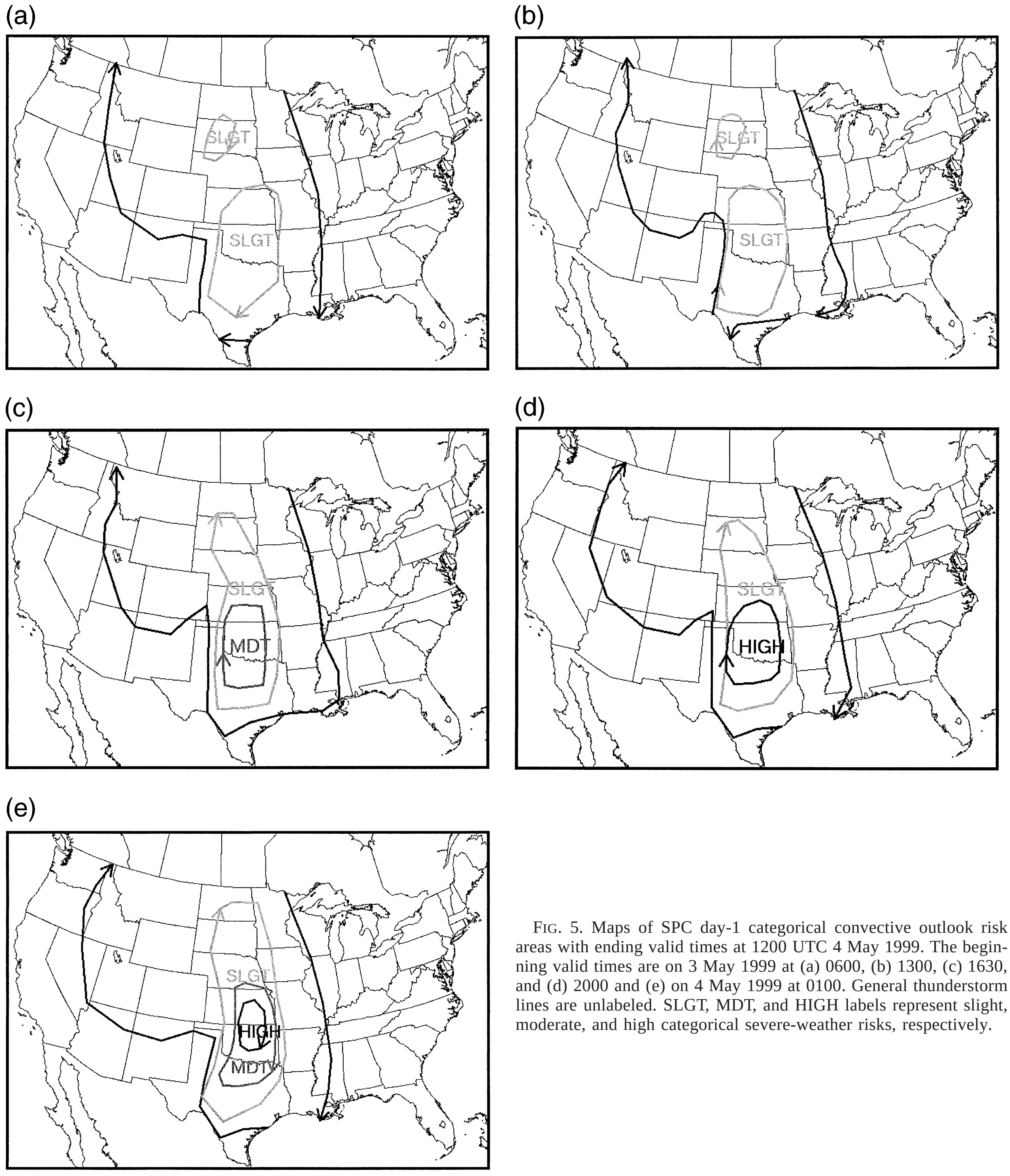

FIG. 5. Maps of SPC day-1 categorical convective outlook risk areas with ending valid times at 1200 UTC 4 May 1999. The beginning valid times are on 3 May 1999 at (a) 0600, (b) 1300, (c) 1630, and (d) 2000 and (e) on 4 May 1999 at 0100. General thunderstorm lines are unlabeled. SLGT, MDT, and HIGH labels represent slight, moderate, and high categorical severe-weather risks, respectively.

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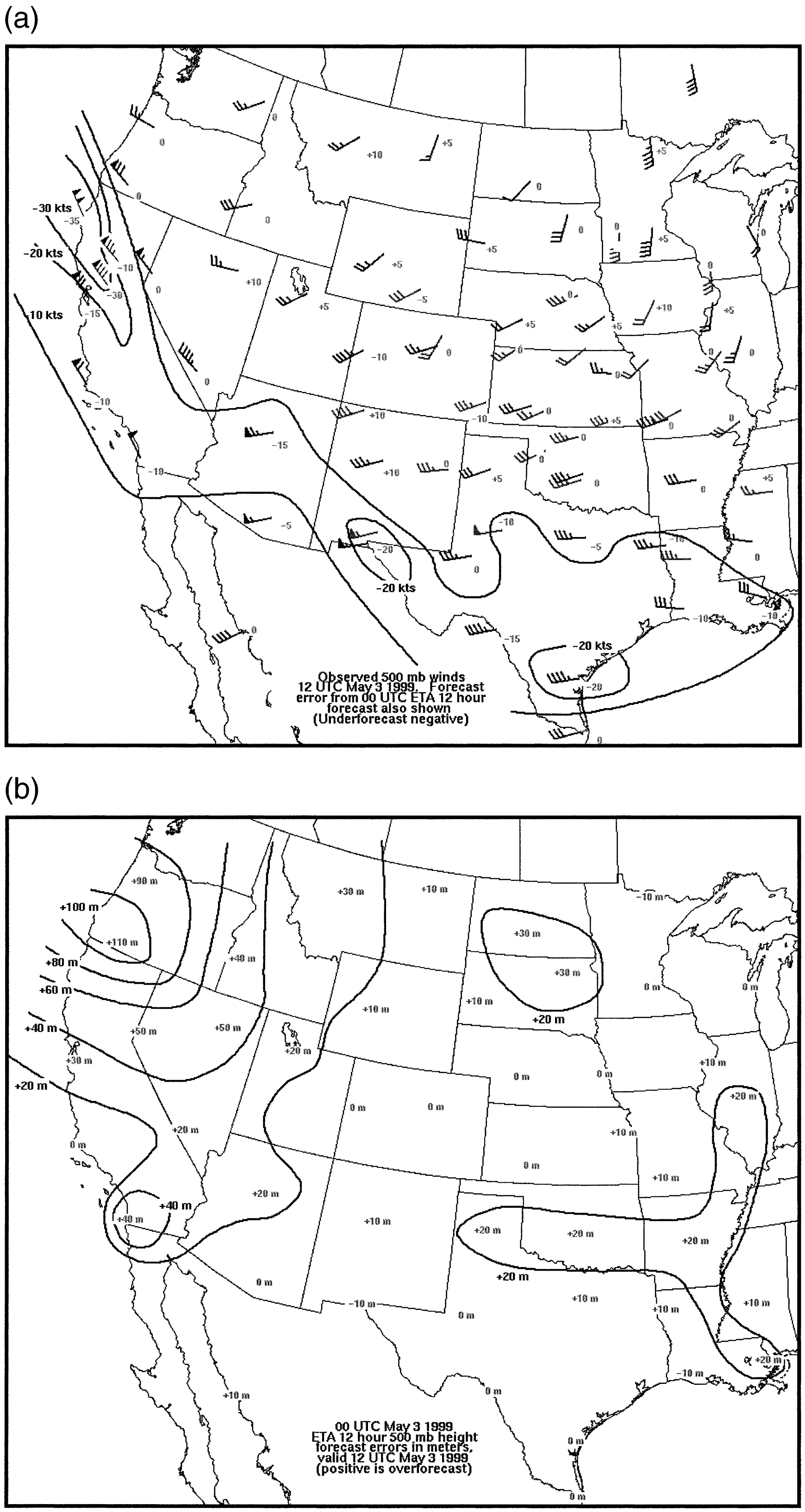
FIG. 6. (a) Observed 500-hPa winds (kt) at 1200 UTC 3 May. Isotachs represent the subjectively analyzed difference field between observations and 12-h Eta forecast winds from the 0000 UTC (3 May) model run. (b) Subjectively analyzed differences (m) between observed 500-hPa heights at 1200 UTC 3 May and the 12-h Eta forecast from the 0000 UTC (3 May) model run. (c) As in (a) but valid at 0000 UTC 4 May. (d) As in (b) but valid at 0000 UTC 4 May.


(a)
-30 kts
-20 kts
10 kts
-20 kts
-20 kts
Observed 500 mb winds
12 UTC May 3 1999. Forecast
error from 00 UTC ETA 12 hour
forecast also shown
(Underforecast negative)
(b)
+100 m
+110 m
+90 m
+80 m
+60 m
+40 m
+20 m
+40 m
+20 m
+20 m
+30 m
00 UTC May 3 1999
ETA 12 hour 500 mb height
forecast errors in meters,
valid 12 UTC May 3 1999
(positive is overforecast)

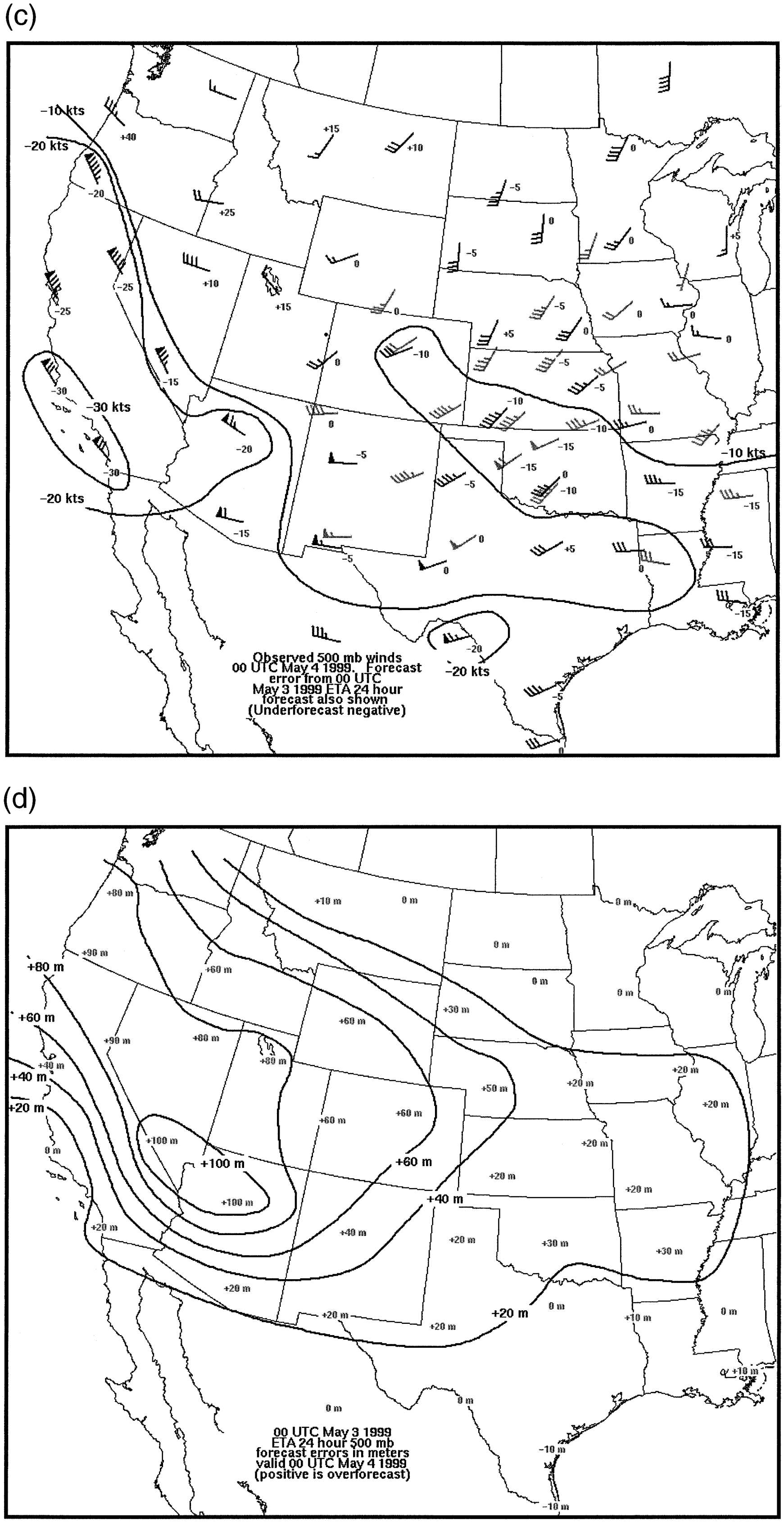


FIG. 6. (*Continued*)

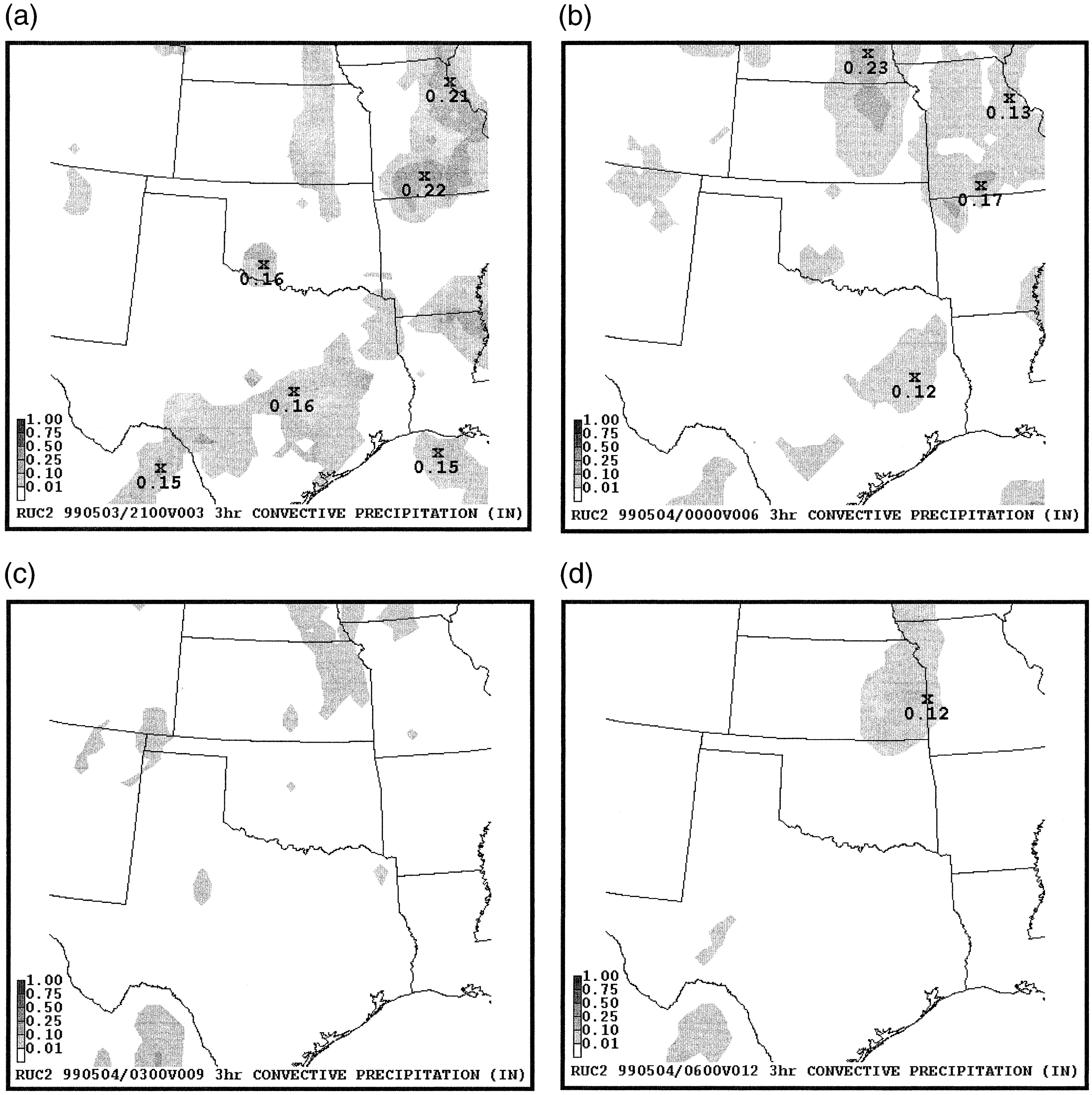


FIG. 7. Precipitation forecasts (in., 1 in. = 25.4 mm) from the 1800 UTC RUC2 model run, valid at (a) 2100 UTC 3 May, (b) 0000 UTC 4 May, (c) 0300 UTC 4 May, and (d) 0600 UTC 4 May. Lightest gray shade corresponds to the 0.01–0.10-in. (0.25–2.54 mm) range bin.

beyond the 48-h forecast period at the time, corresponding model forecasts from the 0000 UTC run were unavailable for comparison.) The patchy, erratic spatial distribution of forecast precipitation in this run was further evidence that forcing for convective development would be subtle, and that meso- to storm-scale processes would strongly influence convective mode.

b. Numerical guidance and the early day-1 outlooks

The day-1 outlooks issued at 0600 and 1300 UTC 3 May incorporated observed trends of both the low-level thermodynamic fields and the position and movement of upper-tropospheric features evident in water vapor channel satellite imagery. That far in advance of the potential event, though, each forecast was still greatly dependent upon numerical model predictions of fields critical for severe-weather prediction, including vertical shear, CAPE, storm-relative flows, and precipitation. Major uncertainties remained regarding the degree of severe weather risk over the region, including these considerations: *where* within the relatively broad slight risk area (e.g., Figs. 5a,b) the greatest threat existed (i.e., the potential moderate risk), *when* severe convection would develop, and *what* convective mode (e.g., supercellular, multicellular, or linear) would predominate.

Model forecast kinematic and instability parameters—including bulk Richardson number shear and CAPE (e.g., Weisman and Klemp 1986), 0–6-km shear above ground level, and storm-relative winds—appeared to support development of supercells and some potential for tornadoes. However, given the continuing uncertainties regarding model guidance, convective initiation, and convective mode, the decision was made to maintain the severe thunderstorm risk as slight. The general consensus, in telephone coordination with the National Weather Service (NWS) Forecast Office in Norman, was that an upgrade to moderate risk category could be required during the day and would include some portion of Oklahoma, Kansas, and/or northern Texas, once analytic evidence made foci and potential morphology of convection clearer.

The 0000 UTC 3 May Eta Model run predicted deepening of the middle- and upper-tropospheric trough and intensification of wind flow over the Rockies and Four Corners regions by 0000 UTC 4 May. However, it was apparent from rawinsonde and profiler winds at 1200 UTC 3 May that the 0000 UTC 3 May Eta was underforecasting the strength of these fields (Figs. 6a,b). Forecast errors of 500-hPa heights from the 0000 UTC model run ultimately exceeded 100 m over the southwestern United States by 0000 UTC 4 May, and wind speeds were 10–15 kt stronger than forecast over the outbreak region[4] (Figs. 6c,d).

Thermodynamic support for severe weather was clearly evident, with surface dewpoints expected to increase through the middle and upper 60s°F (roughly 18°–20°C). These values would contribute to forecast surface-based CAPE (SBCAPE) of greater than 2500 J kg^{-1} in the moist sector from Kansas to Texas. In conjunction with strong boundary layer mixing over the High Plains, the increasing moist-sector dewpoints would help to establish a dryline roughly from south-central Nebraska across western portions of Oklahoma and over west-central Texas. There was a disturbing lack of boundaries to focus convective initiation away from the forecast dryline as well, which was apparent from observations and numerical forecasts through the day. In the absence of significant low-level boundaries, subtle boundary layer processes become critical for convective initiation, and forecasts of storm-scale phenomena intrinsically will have large uncertainty (Crook 1996).

Most of the thunderstorms were expected to form around 0000 UTC 4 May. By that time, the mid- and upper-tropospheric trough was expected to approach the area from the west, along with an increase in model-forecast boundary layer moisture flux convergence near the dryline. The 0000 UTC 3 May Eta Model forecasts produced precipitation within the warm sector across north-central and northeastern Texas and southern Oklahoma before 0000 UTC 4 May (not shown)—east of the dryline and near no apparent boundary. Forecasters generally disregarded that precipitation guidance because this aspect of the Eta forecast was inconsistent with the two previous run. The model's convective precipitation also led to a pronounced underforecast of CAPE (Weiss 1996; Stensrud and Weiss 2002), which was likewise disregarded in the modeled precipitation areas. In addition, modified Eta forecast soundings from 18 to 24 h prior to the outbreak (not shown) indicated a probability that any supercells that formed during late afternoon could become characterized by excessive outflow because of forecasts of relatively weak (8 m s^{-1}) storm-relative winds in the middle troposphere, limiting the tornado threat (Thompson 1998). These same forecast soundings also showed relatively weak storm-relative winds in the upper troposphere (12 m s^{-1}), which have been shown to contribute to heavy-precipitation supercell character (Rasmussen and Straka 1998).

3. Mesoscale guidance, convective initiation, and mode

In the transition from the initial convective outlooks (made during the previous evening and overnight) to the daylight hours of 3 May, forecaster attention shifted from model wind and vertical shear forecasts to observed data. Water vapor satellite imagery suggested the presence of an upper-tropospheric speed maximum moving eastward into New Mexico during mid- to late morning (roughly 1400–1700 UTC). The inferred presence of this speed maximum was confirmed during the late morning and early afternoon hours by a time series of profiler winds[5] from New Mexico, western Texas, and western Oklahoma (see TE00 for details). These increasingly ominous synoptic- and meso-α-scale (Orlanski 1975) clues for strengthening vertical shear, in combination with strong instability, led to an upgrade of the categorical outlook to moderate risk at 1630 UTC (Fig. 5c), and an additional upgrade to ''high'' risk followed in the 2000 and 0100 UTC outlooks (Figs. 5d,e). Despite these factors, which appeared to support an increasing supercell and tornado threat from Texas to Kansas, substantial uncertainties remained regarding the character, timing, and location of convective development during the late morning and afternoon of 3 May.

Eta Model precipitation fields from the 1200 UTC 3 May run (not shown) revealed a cluster of thunderstorms

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[4] The information contained in Figs. 6c,d was available neither at the time of these early day-1 outlooks nor until after the outbreak was in progress.

[5] Profiler winds were not incorporated into the operational RUC2 on 3 May 1999.

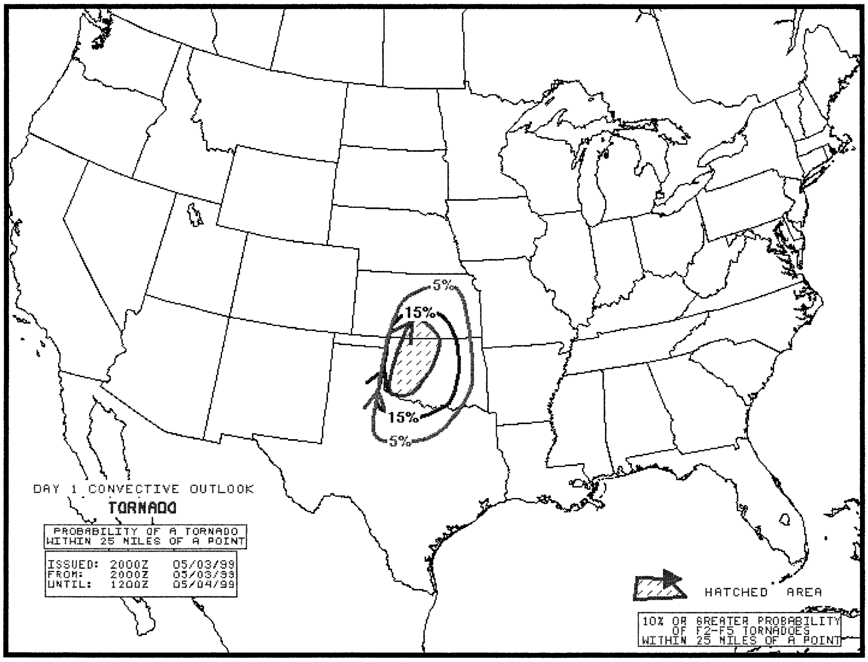

FIG. 8. SPC probabilistic tornado forecast graphic from the 2000 UTC 3 May day-1 outlook, valid until 1200 UTC 4 May. Isopleths represent probability of any tornado occurrence within a 25 n mi (46.25 km) radius of a point within the area, exclusive of areas enclosed by isopleths of greater values. Hatched areas signify ≥10% probability of F2–F5 tornadoes within the same radius of an included point.

by 1800 UTC over portions of northern and northeastern Texas and an accompanying surface trough along the Red River. This guidance was a substantial change from the 0000 UTC 3 May Eta run and was disregarded in light of contradictory observational trends, including a lack of well-defined kinematic or baroclinic boundaries east of the dryline upon which convection could develop. The RUC2, in contrast, showed a tendency to generate very little precipitation in the warm sector over Texas and Oklahoma from morning through late afternoon. The 1800 UTC run predicted a small area of convective precipitation in southwestern Oklahoma by 2100 UTC (Fig. 7a), but it consisted of minimal accumulations and was forecast to dissipate by the 0000–0300 UTC 4 May period (Figs. 7b–d). There was a warm and dry bias[6] in the RUC2 forecasts that was unknown to SPC forecasters on 3 May 1999. (Forecast Systems Laboratory 40-km-resolution reruns[7] of the 3 May case produced a more realistic precipitation forecast across north Texas and southern Oklahoma but did not necessarily capture the location or intensity of the actual deep convection.)

Consecutive categorical risk upgrades were made in the 1630 and 2000 UTC day-1 outlooks. Thermodynamic fields and upper-level flow patterns were becoming progressively more favorable for a major severe-weather event. Observed 1200 UTC soundings and model soundings from the 1200 UTC runs, modified for expected late afternoon surface thermodynamic conditions, yielded weak convective inhibition (negative buoyancy) of less than 50 J kg^{-1} and SBCAPE values increasing to greater than 4000 J kg^{-1}. The buoyancy was trending into the climatologically extreme range for strong to violent tornado situations[8] (Johns et al. 1993), given the forecast of storm-relative helicity above 200 m^2 s^{-2}. As the day progressed, those favorable factors more convincingly overcame lingering contradictory evidence, including 1) mixed signals from more recent numerical guidance, 2) concerns about limited insolation under a cirriform cloud deck (TE00), and 3) continued observational and forecast weakness of low-level convergence. It was accordingly recognized by mid-morning that the potential for strong to violent tornadoes was increasing, given afternoon and/or evening con-

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[6] The operational RUC2 carried a warm and dry bias at the surface caused by a vegetation fraction erroneously set to zero (Smith et al. 2000).

[7] These reruns, unlike the operational RUC, included wind profiler data, used different cloud microphysics and convective parameterization, and were run at 40-, 20-, and 10-km grid spacing. See Smith et al. (2000) for details.

[8] The Johns et al. study only examined conditions for times at which strong and violent tornadoes occurred. The frequency of those same conditions without significant tornadoes was not considered. Doswell and Rasmussen (1994) give a national CAPE condition description for a year without regard to the presence of significant tornadoes and showed that 4000 J kg^{-1} is a rarely achieved value.

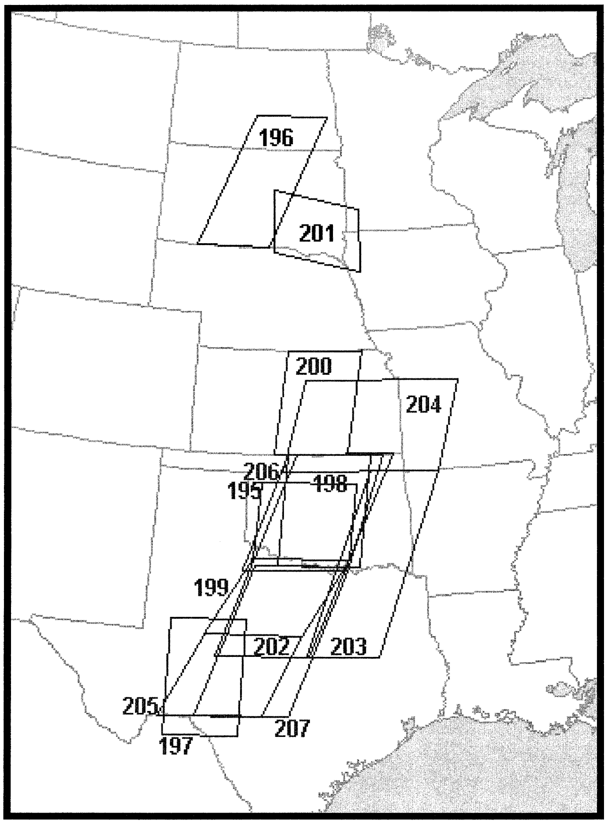

FIG. 9. Severe-weather watches issued by the SPC during the period 2100 UTC 3 May to 1000 UTC 4 May and valid as late at 1600 UTC 4 May. Watch areas are annotated with their respective issuance numbers. Parallelograms in SD and NE represent severe-thunderstorm watches: all others are tornado watches.

vective development, as conveyed in the following 1630 UTC day-1 outlook text:

> . . .N central TX/OK/SRN KS. . .
> Low level jet will maintain significant inflow of low level moisture with surface dewpoints around 65F. Clearing skies evident on visible images will further contribute to strong destabilization over region with late afternoon MUCAPEs forecasted from 3500 to 4500 J/KG over MDT risk area. As short wave approaches WRN OK/TX border. . .lifting will deepen near/along dryline with thunderstorms increasing as they move EWD into instability axis. 50 KT mid level SWLY flow spreading over low level jet axis will provide sufficient shear for a few strong or violent tornadic supercells given the abundant low level moisture and the high instability.

As trends in instability (based on 1800 UTC observed and model forecast soundings) and shear reinforced the possibility of a significant severe-weather episode, the 2000 UTC categorical outlook was upgraded to a high risk (Fig. 5d), and the accompanying experimental tornado probability outlook included a significant tornado area across western Oklahoma (Fig. 8). Shortly after 2000 UTC, the mesoscale forecaster issued an MD that highlighted an area east of the dryline in southwestern Oklahoma and northwestern Texas where the most intense juxtaposition of moisture, instability, and vertical wind shear was located. The MD text follows:

> SPC mesoscale discussion #0345 for. . .SW OK/NW TX. . .
> concerning. . .severe thunderstorm potential. . .
> Water vapor imagery shows a lead mid level shortwave trough moving ENEWD over E/NE NM this afternoon. . .and this is confirmed by profiler time series from AZC/GDA/TCC/JTN. Mid/upper 60 dewpoints and temperatures near 80 are contributing to surface-based CAPE values of 3500-5000 J/KG over WRN OK and NW TX to the E of the dryline. Convergence on the dryline is not strong and a cirrus shield over the TX Panhandle/NW TX/WRN OK should limit additional surface heating. . .but visible/radar imagery has shown the first attempts at TCU over far NW TX as of 20Z within a break in the cirrus. Mid level flow and vertical shear will increase over NW TX and WRN OK through late afternoon. . .with an increasing threat of supercells near the dryline from 00-03Z. This area is being monitored for a possible tornado watch later this afternoon.

Between 2000 and 2015 UTC, the initial towering cumuli and brief cumulonimbi in northwestern Texas dissipated. Additional development followed from 2030 to 2100 UTC over southwestern Oklahoma. By 2200 UTC, the first two supercells were present; these would become the two most prolific tornado producers in the outbreak [storms A and B, after TE00 and Speheger et al. (2002)]. Though forecasters had begun to suspect a supercell and tornado threat before dark, development occurred 2–3 h sooner than forecast. Thunderstorm initiation along such subtle features as an apparent horizontal convective roll (HCR; Edwards et al. 2000) was not anticipated, nor were major strengthening trends in supercells and tornadoes associated with a confluence line detectable in mesonet wind plots (TE00).

4. SPC forecasting logistics during the outbreak

Initial forecaster concerns during the evening shift (which began at 2100 UTC) regarded whether the isolated deep convection in southwestern Oklahoma (early stages of storm A) would persist much longer than the recently failed convection in northwestern Texas. Observations available at the beginning of the evening shift did not yet reveal the strong increase in low-level wind shear in the region in which cumulonimbi were forming. This shear increase did not become apparent in profiler wind plots until approximately 2300 UTC. The first WW, tornado watch 195 for central and southwestern Oklahoma, was issued at 2130 UTC (after a coordination call to the Norman NWS office) when satellite and radar imagery revealed intensification of storm A and explosive development of a second storm in south-

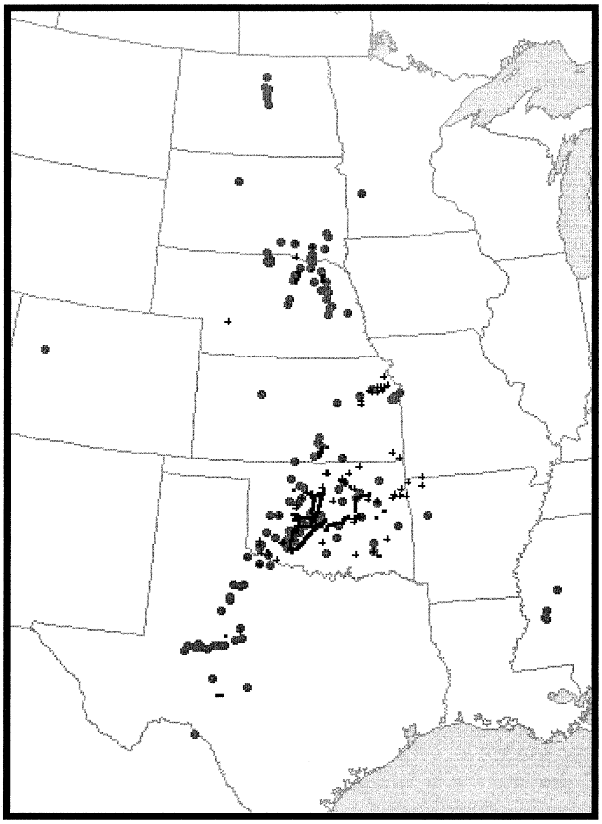

FIG. 10. All severe-weather reports [derived from NCDC (1999)] occurring during the period 2100 UTC 3 May–1600 UTC 4 May—matching the time covered by weather watches in Fig. 9. Tornado reports in close proximity (black) are blended because of the large spatial scale. Severe-thunderstorm wind (light gray filled circles) and hail (dark gray crosses) are also plotted.

western Oklahoma (storm B). This watch became effective more than 0.5 h before the first significant tornado (≥F2 damage), and preceded the F5 tornado by over 2.5 h. It was relatively small in size by design 1) to allow SPC more time to monitor convective evolution before further WW issuance and 2) to expedite issuance of the WW by minimizing the time required for NWS interoffice telephone coordination (only the Norman NWS office jurisdiction was affected). Nine additional WWs were subsequently issued throughout the remainder of the afternoon and evening as numerous tornadic supercells formed over Oklahoma and as severe thunderstorms formed from the Dakotas to southwestern Texas (Fig. 9).

Adjacent areas of severe-weather concern were evident throughout the process of providing forecasts for this event—starting with the day-2 outlook and continuing through the MD and WW issuances on the evening of 3–4 May. SPC severe-weather outlooks and WWs extended across much of the central United States (Fig. 9), and severe weather was reported throughout much of the plains (Fig. 10). Some attention was necessarily devoted to those areas throughout the outlook process and into the time frame of the southern plains outbreak, even though the highest priority was given to the more potentially life-threatening events over Oklahoma and Kansas.

As is standard practice at SPC, subjective, mesoscale surface map analyses were performed for all severe-weather threat areas, and MDs were issued for heavy rainfall both within and outside the primary tornado outbreak region of Kansas and Oklahoma. The 0100 UTC (4 May) outlook update (Fig. 5e) drew continued attention to the outlying convective threats while maintaining a high risk over the Oklahoma–Kansas outbreak area. Also, telephone calls were made to numerous NWS offices for coordination of WWs and discussion of severe-weather threats. By 2254 UTC, for example, tornado watch 197 was required for southwest Texas as convection was developing along the dryline west of San Angelo, with another isolated supercell north of Del Rio. The occurrence of multiple severe-weather threats and heavy rain potential, all requiring SPC forecasting guidance and NWS interoffice coordination, is very common from midspring through summer. Beginning with the preparation of the 1300 UTC (3 May 1999) day-1 outlook and becoming much more frequent during the outbreak that afternoon and evening, telephone coordination was undertaken with NWS offices in the region for watch issuances, threat clearance lines, and mesoscale nowcasting.

One critical element in operational forecasting is shift-to-shift continuity, meteorological conditions permitting. During potential or actual severe-weather events at SPC, this is done through detailed shift-change briefings at all forecast desks. These briefings use subjective, national map analyses to maintain synoptic perspective, followed by focusing on the mesoscale and smaller environments. On this day, convective initiation around the 2100 UTC shift change allowed the evening shift very little time to analyze and to diagnose the situation before numerous WWs were required. The watch issuance strategy was complicated greatly by thunderstorm initiation occurring somewhat sooner than expected and just minutes before the arrival of the evening shift for briefing. Because the cumulonimbus that would become storm A was developing away from all known surface boundaries, there remained great uncertainty as to where subsequent convection would occur. The watch layout was deferred to the evening-shift lead forecaster. Despite the problems posed by the timing of the shift change, continuity provided by the briefing allowed the evening shift meteorologists to assess the situation as quickly as possible. A watch was soon issued for Oklahoma that covered the initiation region of most of the subsequent supercells, as well as recently initiated storms A and B. This shift change highlighted the importance of maintaining a continuous meteorological surveillance, using thorough subjective analysis to minimize familiarization time required by succeeding shifts.

Last, a unique logistic threat was posed for what is believed to be the first time in the history of SPC (and its predecessor, the Severe Local Storms Unit of the National Severe Storms Forecast Center): the distinct possibility of the operational facility and/or families of on-duty employees being in the path of a tornado known to be very large and destructive. By 2330 UTC, local television news video showed a wide, long-lived tornado moving toward the southern portion of the Oklahoma City area from the southwest. SPC forecasters became concerned that the tornado could persist and strike parts of northwestern Norman—perhaps even the SPC facility. At 2355 UTC SPC notified the U.S. Air Force Weather Agency, at Offutt Air Force Base near Omaha, Nebraska, that they may have to assume backup responsibility if the SPC were to be struck or otherwise incapacitated by the tornado. Duty staff also called family members—many of whom resided closer than the SPC site was to the eventual damage path—to advise them on preparing for the approaching storm. The tornado persisted with F4–F5 damage across the southern and eastern portions of the Oklahoma City area and missed the SPC by 8 mi (13 km), though it was faintly visible from the facility's roof. It was fortunate that no forecasters' families or homes were directly affected.

5. Summary and discussion

Unlike many ''synoptically evident'' severe-weather outbreaks (after Doswell et al. 1993), the 3 May 1999 tornado event was strongly dependent upon convective initiation by *weak, subtle, and/or heretofore unknown mesoscale processes.* Similar but less well publicized situations had been recognized operationally for several years—such as an outbreak containing killer tornadoes in Arkansas earlier the same year. Like the 3 May event, the 21 January 1999 tornadic supercells over Arkansas appeared to develop in a favorably unstable and strongly sheared warm sector, with only subtle kinematic and thermodynamic foci for convective development. Some of these features, such as HCRs, do not appear in mesoanalytic conventions. Unlike 3 May, the 21 January outbreak was preceded by consistent and accurate Eta Model precipitation forecasts, which led to greater forecaster confidence and a much earlier upgrade of the categorical convective outlook to the high risk category. Despite the differences in model precipitation forecasts for each event, the 3 May outbreak brought forth the idea that *weak low-level lift can be beneficial for supercell development and maintenance* in situations in which capping is also small (TE00). This idea represents an amendment to the well-established synoptically evident severe-local-storms forecasting paradigm—a shift that, in effect, argues, ''weaker forcing can be more favorable.'' Cases such as 21 January and 3 May 1999 suggest that there is a delicate balance between the convective mode extremes of no thunderstorms, multiple tornadic supercells, and numerous thunderstorms in clusters or squall lines. Events of this nature bring up the question, Where do the critical distinctions lie with regard to convective initiation and storm character? Because of the great difference in public danger represented by these convective modes across a potentially small adjustment in the environment (e.g., Brooks et al. 1993), much research effort is warranted into observing and simulating differing storm morphologies in weakly convergent air masses.

Successful forecasting of tornado outbreaks, and severe weather in general, requires *careful, detailed diagnoses of real-time observational data and trends,* regardless of the frequency, resolution, or accuracy of numerical guidance. This diagnosis is crucial when important yet subtle mesoscale and storm-scale processes cannot be resolved by model input data and/or develop after model initialization, such as on 3 May 1999. Such real-time analyses of kinematic and thermodynamic trends, surface and aloft, were aided greatly by the presence of profiler wind data; visible, infrared, and water vapor satellite imagery; Weather Surveillance Radar-1988 Doppler (WSR-88D)–derived winds; and surface observations from the Oklahoma Mesonet (Brock et al. 1995). Ready availability of observational data and meticulous attention to detail also allow forecasters to ''ramp up'' a weather hazard forecast just ahead of an event that may have been unforecast or underforecast in earlier decades, when some diagnostic data were either coarser in resolution (satellite imagery) or altogether unavailable (e.g., surface mesonets, wind profilers, and WSR-88D winds). Convective forecasting capabilities could be improved further in the future by increased operational awareness and availability of supplemental and/or experimental observational data sources of high spatial and temporal density, such as the atmospheric emitted radiance interferometers (Mecikalski and Feltz 2000), that were running on 3 May 1999.

Greater scientific knowledge and situational awareness on the part of severe-storms forecasters (e.g., Ostby 1999) also play a major role in adjusting outlooks and other guidance to rapidly evolving, highly challenging events such as the 3 May outbreak. Operationally valuable work has been published related to this area since the outbreak, but much more is needed. For example, Weckwerth (2000) has documented the sensitivity of deep moist convective development to moisture distribution, which may become exceptionally important to nowcasting thunderstorm formation in the absence of strong baroclinic boundaries such as fronts or outflows. Weaver and Avissar (2001) simulated mesoscale vertical circulations and surface heat fluxes conducive to convective cloud development, caused by landscape inhomogeneities of human origin in Oklahoma and Kansas; they found that the circulations were not necessarily mitigated by increasing ambient winds. Mesoscale model simulations by Roebber et al. (2002) indicate that 1) insolation beneath the cirrus gap documented by TE00 was strong enough to lead to convective initiation and 2) the potential vorticity filament (jet streak) moving overhead during the outbreak was sufficiently deep to strengthen low-level convergence, further enhancing convective development. Detection of subtle mechanisms that influence initiation—in the case of 3 May 1999, HCRs, confluence lines, vertically deep jet streaks, and cloud layer edges—can be crucial because of the uncertainty they can impart to the convective forecast (Crook 1996). Thus, mesoscale prediction of their development, location, and strength can also be a critical factor in improving convective forecasts. It is in the convective initiation forecasting problem where ready availability (and ease of use) of mesoscale models and high-density observational sampling may provide the greatest operational benefit.

Forecasters at SPC routinely examine the various model precipitation forecasts to aid in delineating areas of thunderstorm potential, especially in situations of subtle low-level forcing such as the 3 May 1999 outbreak. Confidence that storms will form in a given area is boosted if one or more models generate precipitation in the area of concern, particularly with run-to-run consistency. This was not the case here as operational models failed to predict correctly or consistently the convective initiation timing and location. Further, observed trends in kinematic fields and geopotential heights revealed substantial model errors. SPC forecasters, though faced with some important uncertainties as discussed above, were able to disregard or modify such model guidance using analytic and physical reasoning. However, this event serves to alert forecasters that excessive reliance on model guidance in such situations, at the expense of examining real-time observations, not only increases the potential for inaccuracy, but can be dangerous when the quality of watches and warnings for deadly events is affected.

Numerical model guidance can be helpful in anticipating synoptic- to meso-α-scale developments relevant to the smaller scales. There is some promise in the development of short-range ensemble techniques for reducing uncertainty in convective forecasts (Stensrud and Weiss 2002). However, given the meso-β:- to storm-scale detail and nonlinearity of features and processes associated with convective development, severe-weather threat assessment will always require both objective and subjective analyses of real-time observational data. For numerical models to become ‘‘perfect’’ severe-storms predictors, they may require not only complete and theoretically infallible physics packages, but also perfect initial analysis fields. The latter cannot be achieved given meso-β-scale and larger data voids in the surface and upper-air observational input, both over land and upstream oceans, because perturbations on smaller scales can heavily influence convective initiation and mode. However, continued improvements in model physics, parameterization, resolution, and in the *density* and *quality* of observational input, are expected to reduce the risk of ‘‘surprise’’ severe-weather outbreaks further and to lengthen the advance notice of their potential occurrence. The trends in numerical modeling toward more dense spatial resolution, more complicated physics, and ensemble systems each pose challenges for forecasters in effectively utilizing such guidance (e.g., Brooks and Doswell 1993), particularly when faced with a proliferation of other prognostic and diagnostic information sources to examine within operational time constraints.

Last, during severe-weather outbreaks, NWS forecasters are faced with short-fuse decisions amid a work environment of 1) routine products with required deadlines; 2) increased distraction in the form of telephone calls, event documentation, and other nonscheduled tasks; and 3) less time to diagnose and to predict the situation given an increasing volume of prognostic and diagnostic information as discussed above. Forecasters must prioritize tasks and weather threats, ‘‘load shedding’’ some of them within the constraints of deadlines and duties. This task is done with a nontrivial risk of mistakes. Operational data processing and analysis efforts must consider the ability of forecasters to absorb and to process broad arrays of information in a timely, well-prioritized manner during extreme weather situations. This consideration likely will require cross-discipline cooperation across the fields of meteorology, psychology, and computer science to balance forecaster workload and performance optimally.

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