The Great Basin Derecho of 31 May 1994

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ABSTRACT

A significant, convectively induced windstorm known as a derecho occurred over parts of Utah, Wyoming, Idaho, and Colorado on 31 May 1994. The event was unusual in that it occurred not only in an environment of relatively limited moisture, but also one with a thermodynamic profile favorable for dry microbursts in the presence of moderate midtropospheric flow. The development and evolution of the severe wind-producing convective system is described, with emphasis on the synoptic and mesoscale features that may have contributed to its strength and maintenance. A very similar derecho that affected much the same region on 1 June 2002 is more briefly introduced. Questions are raised regarding the unique nature of these events and their potential utility in achieving an increased understanding of the mechanics of derecho-producing convective systems in more moisture-rich environments.

1. Introduction

Widespread convective windstorms, known as derechos, have been well documented since the 1980s over that portion of the United States east of the Rocky Mountains (e.g., Johns and Hirt 1987; Evans and Doswell 2001; Bentley and Sparks 2003; Coniglio and Stensrud 2004). Derechos account for a significant percentage of the casualties and damage associated with convectively induced, nontornadic winds in the central and eastern United States (Ashley and Mote 2005). These events are produced by rapidly moving thunderstorms, typically in the form of bow echoes (Fujita 1978) that propagate downshear along the progressive part of an elongating cold pool (Corfidi 2003). By definition (Johns and Hirt 1987), the damage swath produced by a derecho must extend continuously at least 400 km (approximately 250 mi) and include several "significant" wind gusts (those at or above 33.4 m s^{-1} or 65 kt) An updated and more dynamically based definition of "derecho" proposed by Corfidi et al. (2016) increased the minimal damage swath length to 650 km (400 mi) while eliminating the significant gust criterion. Damaging surface winds associated with microbursts or downbursts (Fujita 1978) accompany many bow echo convective systems, and derechos consist of groups or "families" of downburst clusters (Fujita and Wakimoto 1981) produced by long-lived convective systems. Such systems may contain multiple bow echoes of various scales, with the bow echoes themselves often containing smaller vortices that locally enhance the convective winds (e.g., Weisman and Davis 1998; Weisman 1993; Weisman and Trapp 2003; Wakimoto et al. 2006; Atkins and St. Laurent 2009). Operational experience suggests that derecho-producing convective systems are not nearly as common as individual bow-echo events.

Bow or "spearhead" echoes over the central and eastern United States and Canada have been studied in considerable detail since the late 1970s (e.g., Fujita and Caracena 1977; Leduc and Joe 1993; Przybylinski 1995; Wakimoto 2001). Increased availability of animated

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radar imagery has facilitated documentation of bow echoes outside North America in more recent years. For example, bow echoes have been observed over Europe (e.g., Schmid et al. 2000), Australia (e.g., Holland and May 1996), Africa (e.g., de Coning et al. 2000), and the mid-Pacific (e.g., Businger et al. 1998). It appears that bow echoes, often of small spatial and temporal scales, are a fairly common feature of multicellular, deep convection in environments of moderate to strong shear over much of the world.

Despite their comparatively infrequent nature, a number of derechos outside central and eastern North America also have appeared in the literature. Strongly forced or ''serial type'' derechos (Johns and Hirt 1987), for example, have been documented in Cuba (Alfonso and Naranjo 1996) and Germany (Gatzen 2004). At least three other European derechos also have been described in the formal literature, including one in Finland (Punkka et al. 2006), one in Spain and France (Lopez 2007), and another in Bulgaria (Gospodinov et al. 2014). The Finland case was the first documented event to have occurred poleward of 60° latitude. Closer to the equator, it appears that the ''nor'wester'' storms of Bangladesh and adjacent regions (Peterson and Dewan 2002) might be derechos, most likely of the ''progressive'' type (Johns and Hirt 1987).

In contrast, documentation of bow echoes and derechos over the western United States and Canada thus far has been limited. This partly reflects the relatively low frequency of organized, deep convection over that area owing to the comparatively dry mixed layers that typically exist during periods of moderate-to-strong vertical shear. The lack of documentation also, however, reflects the fact that most of the western United States remained outside the National Weather Service's radar surveillance network until the mid-1990s. Once the WSR-88D radar network was established, occasional bow echo events began to be observed (e.g., Staudenmaier and Cunningham 1996; Ladue 2002).

Derechos are especially uncommon over western North America because such events require the development of a long-lived cold pool to continuously regenerate deep convection over a long distance. Given the limited potential buoyant energy over much of that region and the mountainous terrain, most convective systems with bow echoes do not last sufficiently long to satisfy the derecho length criteria established by Johns and Hirt (1987) or Corfidi et al. (2016).

Nevertheless, in May 1994, a severe wind-producing convective system occurred over parts of Utah, Wyoming, Idaho, and Colorado that met the length criteria for both the Johns and Hirt (1987) and Corfidi et al. (2016) definitions of a derecho. The 31 May 1994 derecho also crossed significant mountains without dissipating. The event was included in a study (Corfidi et al. 2006) of severe wind-producing convective systems that occurred in environments of limited low-level moisture, where general features of the storm were discussed. The purpose of the present paper is to document the 31 May 1994 Great Basin derecho in greater detail, noting especially those characteristics that distinguish it from more typical derechos over the central and eastern United States. The derecho's winds are presented in section 2, and section 3 describes the evolution of the associated convective system. Synoptic-scale aspects of the event are provided in section 4, while sections 5 and 6 present the system's thermodynamic and wind characteristics. Additional thoughts on the 31 May 1994 derecho, as well as a brief look at a similar storm that affected the same region in June 2002, follow in section 7.

2. Areas affected and observed winds

A convective system intensified over far eastern Nevada and far western Utah during the late morning of 31 May 1994. The system moved rapidly northeast across central and northern Utah, southeast Idaho, northwest Colorado, and southwest Wyoming during the remainder of the day before dissipating in central Wyoming. The resulting derecho was over 700 km in length and caused considerable damage to trees and buildings. Many measured gusts near and above severe limits (25.7 $\mathrm{m\,s^{-1}}$ or 50 kt) occurred (Fig. 1 and Tables 1 and 2).

The strongest wind gust, 62.6 $\mathrm{m\,s^{-1}}$ (122 kt), was recorded at an elevation of approximately 1665 m (5460 ft) MSL on Camelback Mountain in the Dugway Proving Ground in north-central Utah (location D in Fig. 1). The gust occurred at approximately 1820 UTC [1120 local standard time (LST)]. At the nearby Tooele Army Depot, estimated 36.2 $\mathrm{m\,s^{-1}}$ (70 kt) gusts blew trailers off railroad cars and caused structural damage. But the most extensive damage occurred about 30 min later in the Provo, Utah, area, where thousands of trees were blown down, many homes and cars were damaged, and 16 people were injured (P in Fig. 1). Surface winds reached 46.8 $\mathrm{m\,s^{-1}}$ (91 kt), and a gust of 54.0 $\mathrm{m\,s^{-1}}$ (105 kt) was measured on the top of a 12-story building at Brigham Young University. Farther north, airplanes were damaged at Salt Lake International Airport, and part of the roof of the Saltair Pavillion on the southeast shore of Great Salt Lake was removed. A photograph showing the shelf cloud along the storm's gust front overspreading the Salt Lake City area around 1930 UTC (1230 LST) appears in Fig. 2.

After crossing the Wasatch Mountains (a north–south band of elevated terrain immediately east and south of

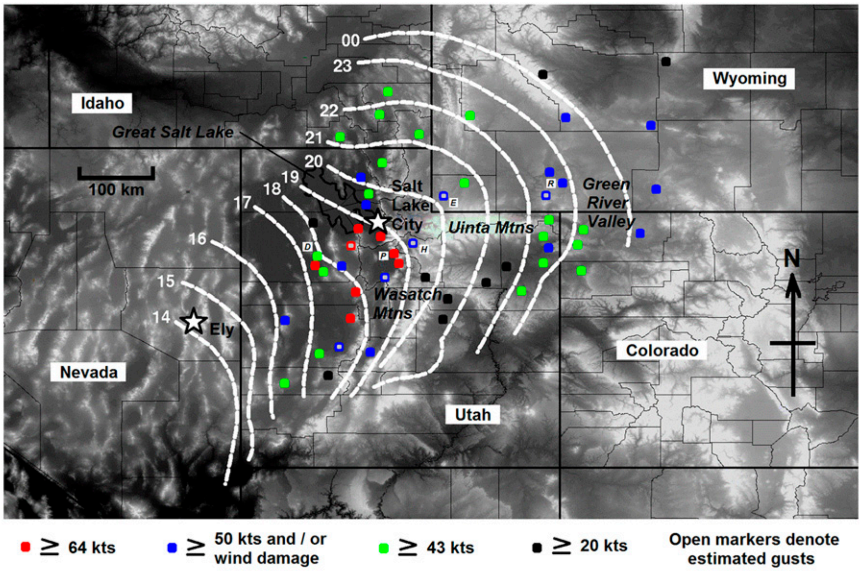

FIG. 1. Path of the 31 May 1994 derecho and associated severe weather reports. White dashed lines depict approximate hourly (UTC; LST = UTC − 7 h) progression of the derecho-producing convective system's gust front. Positions during the earlier hours (i.e., before 1600 UTC) mark the leading edge of the developing convective band in satellite imagery. Red dots denote "significant" [greater than 33 m s^{-1} (64 kt)] wind gusts; blue dots, "severe" [from 26 m s^{-1} (50 kt) to 33 m s^{-1} (64 kt)] gusts and/or wind damage; green dots, "near severe" [from 22 m s^{-1} (43 kt) to 25 m s^{-1} (49 kt)] wind gusts; and black dots, gusts from 10 m s^{-1} (20 kt) to 21 m s^{-1} (42 kt). Estimated winds indicated by open markers. Background shading shows topography, with altitudes at or below 1200 m MSL (e.g., the Great Salt Lake) in medium gray, and areas above 3000 m (e.g., the Uinta Mountains east of Salt Lake City) in very light gray. Ely and Salt Lake City, locations of the soundings shown in Figs. 7–9, are depicted by white stars; other observing sites mentioned in text are indicated by small black letters.

the Great Salt Lake), the convective system's surface winds somewhat weakened. However, severe wind gusts were recorded at both Heber City [31.4 m s^{-1} (61 kt)] in northeast Utah and at Evanston [26.8 m s^{-1} (52 kt)] in southwest Wyoming (H and E, respectively, in Fig. 1). The observed surface gusts increased again as the convective system entered the Green River valley. Near-severe and stronger wind gusts were recorded on both sides of the Uinta Mountains in far eastern Utah and southwest Wyoming. The most damaging winds occurred in Wyoming, where roofs were blown off houses and windows were blown out of cars at Rock Springs (R in Fig. 1). At Flaming Gorge Reservoir southwest of Rock Springs, boat docks were blown ashore, and winds remained above severe levels for nearly 1 h.

3. Satellite evolution of the derecho-producing convective system

In 1994, the WSR-88D radar network was not yet complete over the interior western United States, so composite radar observations are not available for the event. However, visible satellite imagery (Fig. 3; for an animated version, see http://www.spc.noaa.gov/misc/AbtDerechos/images/94may31loopviswidereversemed) provide a regional overview of the derecho-producing convective system. The images show the convective system's arc-shaped, composite gust front moving rapidly northeastward from the Nevada–Utah border into southwest Wyoming, while cirrus-level outflow clouds (derived from cumulonimbus towers along the gust front) are left behind. At least on the system scale, the overall motion and bowed shape of the gust front do not appear to have been much affected by the mountainous terrain, despite the considerable variation in elevation (between 1000 and 4000 m) across the region (Fig. 1).

The trailing high-level clouds and the fact that the leading edge of the convective system throughout its life was marked by new, sharply outlined cumulonimbus buildups suggest that the system moved faster than both the mean wind and the mid- to upper-tropospheric flow. Johns and Hirt (1987) were the first to note that some derecho-producing convective systems move faster than the mean wind. More recently, Corfidi (2003) observed

TABLE 1. Maximum surface wind gusts reported during the 31 May 1994 Great Basin derecho from National Weather Service and RAWS data. Observations include "significant" gusts [exceeding 32.9 m s^{-1} (64 kt)], "severe" gusts [25.7–32.9 m s^{-1} (50–64 kt)], and "near severe" gusts [22.0–25.6 m s^{-1} (43–49 kt)] that occurred in the derecho path. The reports are listed in approximate chronological order. Times are LST, where LST = UTC − 7 h. Times for most RAWS sites are the ending hours during which the observed gusts occurred, with RAWS sites indicated by R in the left column. Estimated maximum gusts and times are indicated by E; elevations are with respect to sea level. The gust at Brigham Young University was recorded on the roof of a 12-story building; the elevation is estimated.

Obs location	Max gust [m s^{-1} (kt)]	Time (LST)	Lat (°N)	Lon (°W)	Elev [m (ft)]
Tule Valley, UT (R)	25.5 (50)	1000	39.35	113.39	1585 (5200)
Fillmore, UT (11 km S)	E 26.8 (52)	E 1015	38.90	112.34	1495 (4900)
Delta, UT	36.0 (70)	1051	39.35	112.58	1410 (4630)
Lost Creek, UT (R)	26.4 (51)	1200	38.77	111.86	2285 (7490)
Mud Spring, UT (R)	30.8 (60)	1200	39.80	112.27	1755 (5760)
Simpson Springs, UT (R)	24.1 (47)	1200	40.09	112.73	1495 (4900)
Dugway Proving Ground (Camel Back Ridge), UT	62.6 (122)	E 1120	40.13	112.96	1665 (5460)
Dugway Proving Ground (valley NE of Camel Back Ridge)	24.1 (47)	E 1125	40.19	112.89	1330 (4360)
Dugway Proving Ground (airport)	44.3 (86)	E 1130	40.23	112.75	1495 (4900)
Cedar Mountains, UT (R)	22.4 (43)	1200	40.30	112.78	1220 (4000)
Vernon, UT (R)	25.0 (49)	1200	40.10	112.43	1675 (5500)
Santaquin, UT	E 26.8 (52)	1140	39.98	111.78	1520 (4990)
Tooele, UT (4 km SW)	E 36.2 (70)	1140	40.52	112.34	1475 (4840)
Provo, UT (airport)	46.8 (91)	1150	40.22	111.72	1370 (4490)
Provo (Brigham Young University)	54.0 (105)	1153	40.25	111.65	1435 (4710)
Cottonwood Heights, UT (8 km SE)	32.6 (63)	1213	40.57	111.75	1770 (5800)
Heber City, UT	E 31.3 (61)	1227	40.51	111.41	1715 (5620)
SaltAir Pavilion, UT	36.2 (70)	E 1225	40.75	112.14	1285 (4215)
SLC (airport)	27.7 (54)	1228	40.78	111.97	1285 (4220)
Hill Air Force Base, UT	25.9 (50)	E 1255	41.13	111.98	1455 (4780)
Lewiston, UT	25.9 (50)	1258	41.95	111.86	1370 (4500)
Ogden, UT (airport)	23.2 (45)	1300	41.20	112.01	1355 (4440)
Brigham City, UT (airport)	25.9 (50)	1330	41.55	112.06	1285 (4220)
Logan, UT (airport)	23.3 (45)	E 1340	41.79	111.85	1355 (4440)
Evanston, WY	E 26.8 (52)	1400	41.27	110.97	2055 (6750)
Rangely, CO (R)	22.8 (44)	1435	40.09	108.77	1975 (6480)
Buckboard Marina, WY	E 31.3 (61)	1438	41.25	109.60	1845 (6060)
Hansel Mountain, ID (R)	21.9 (43)	1500	42.17	110.12	1690 (5550)
Grace, ID (R)	23.3 (45)	1500	42.54	111.86	1895 (6210)
Chausse, ID (R)	22.8 (44)	1500	42.18	111.08	1975 (6480)
Muddy Creek, WY (R)	24.1 (47)	1500	41.40	110.55	2125 (6970)
Pole Canyon, ID (R)	22.8 (44)	1600	42.90	111.83	2040 (6700)
Yampa Plateau, UT (R)	23.3 (45)	1600	40.28	109.29	2135 (7000)
Diamond Rim, UT (R)	22.8 (44)	1600	40.62	109.24	1675 (5500)
Miner's Draw, UT (R)	26.8 (52)	1600	40.38	109.09	2480 (8130)
King's Point, UT (R)	24.6 (48)	1600	40.86	109.10	1730 (5670)
White Rocks, WY (R)	29.5 (57)	1600	41.60	109.25	1965 (6450)
Snow Springs Creek, WY (R)	27.3 (53)	1600	41.42	109.04	2300 (7550)
Anderson Ridge, WY (R)	29.1 (57)	1700	42.44	108.94	2475 (8120)
Great Divide, CO (R)	28.6 (56)	1700	40.76	107.85	2195 (7200)
Cow Creek, WY (R)	25.9 (50)	1700	41.31	107.55	2205 (7230)
Camp Creek, WY (R)	25.5 (49)	1800	42.34	107.57	2250 (7380)

that such movement occurs when the advective and propagational components of system movement are additive, in other words, in the presence of substantial "forward" or downshear propagation. The propagation component of system motion in this case was marked by the persistent redevelopment of new thunderstorms on the downshear (northeast) side of the convective system's elongating cold pool; this redevelopment outpaced the upper-level flow, as seen in the satellite imagery (Fig. 3).[1] Comparison of the average forward speed of the convective system [23.1 m s^{-1} (45 kt) toward the northeast] with the 850–300-mb mean wind

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[1] Low ambient humidity, and the related absence of accessory cloud cover, can make forward propagation within mesoscale convective systems over arid regions like Utah more readily apparent in satellite imagery than with systems occurring in more humid environments.

TABLE 2. Reported convective wind damage where measured or estimated wind gusts were not recorded during the 31 May 1994 Great Basin derecho. The reports are listed in the approximate chronological order; time in some cases is approximate.

Damage location	Damage	Time (LST)	Lat (°N)	Lon (°W)	Elev [m (ft)]
Sugarville, UT	Trees uprooted and blown onto a house	1020	39.47	112.65	1400 (4590)
Elberta, UT	Grain elevator blown down	1128	39.95	111.96	1435 (4700)
Lakeview, UT	Structural damage to chicken farm	1145	40.12	111.73	1380 (4520)
Orem, UT	Shingles blown off; many tree limbs downed	1220	40.30	111.69	1450 (4760)
Salt Lake Valley, UT	Trees and power lines downed at numerous locations	1230–1315	40.67	111.89	1310 (4300)
Murray, UT	Large trees downed; one on a house	1320	40.65	111.88	1310 (4300)
Green River, WY	Numerous tree limbs downed	1440	41.53	109.47	1860 (6110)
Rock Springs, WY	Tree limbs downed; roofs blown off homes	1542	41.59	109.22	1910 (6270)

[south-southwesterly at 16.5 m s^{-1} (32 kt), based on the 1200 UTC Ely, Nevada, radiosonde data, and using the averaging technique of Fankhauser (1964) and Corfidi et al. (1996)] shows that this was indeed the case. The system's forward speed increased during the life of the event, ranging from about 16.5 m s^{-1} (32 kt) during its initial development over west-central Utah to approximately 26.8 m s^{-1} (52 kt) later in the day over southwest Wyoming.

Surface observations were used to estimate hourly positions of the convective system gust front. Satellite and cloud-to-ground lightning data (not shown) assisted in determining gust front location in areas lacking surface data. Like satellite, the lightning data also indicate that the convective system moved generally northeastward. Comparison of the three data sources shows that the gust front was located just behind the leading edge of the arcing clouds depicted by satellite, but ahead of the associated band of lightning. This relationship remained consistent along the length of the derecho and helped refine the estimated hourly gust front positions shown in Fig. 1. The displacement of the lightning and, presumably, the deepest convection somewhat behind the gust front is consistent with the notion of upshear-tilted convective towers being undercut by the fast-moving cold pool of the larger-scale, forward-propagating convective system.

Frame and Markowski (2006) present the results of numerical simulations involving squall lines traversing sinusoidal mountain ridges using the Advanced Regional Prediction System (ARPS) cloud model (Xue et al. 2000). In their simulations, convective bands initially tend to strengthen upon encountering a topographic barrier, only to undergo subsequent weakening and then later restrengthening downstream of the barrier. This behavior is attributed to the interaction of the convective system's cold pool with the sloping terrain. The most rapidly moving part of the 31 May 1994 squall

FIG. 2. Wide-angle photograph of the gust front cloud associated with the 31 May 1994 derecho as seen from the William Browning building on the campus of the University of Utah, Salt Lake City, at approximately 1930 UTC (1230 LST). The view is toward the south, with the University of Utah campus in the foreground, and part of the Wasatch Mountains at left. (Courtesy of Dr. S. Krueger.)

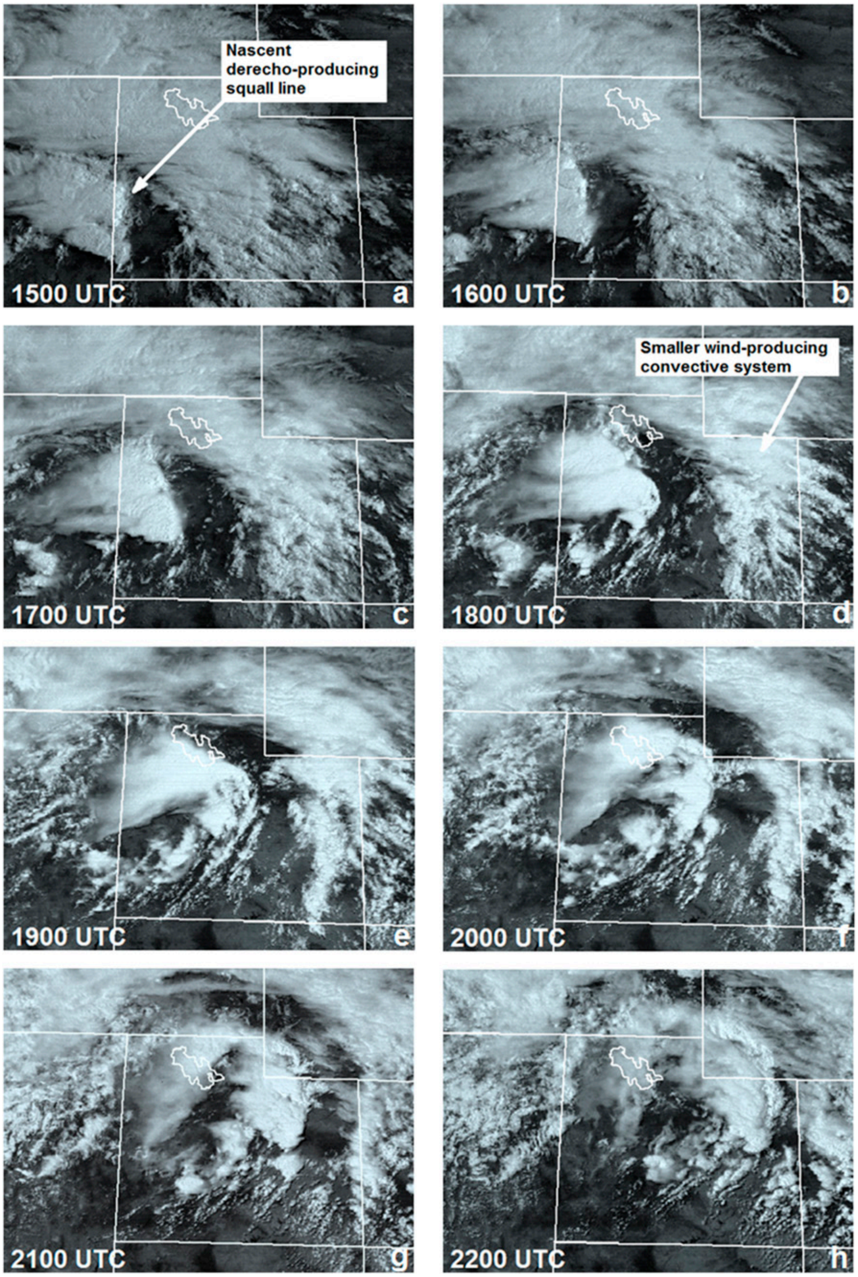

FIG. 3. GOES visible satellite sequence showing hourly development and movement of the 31 May 1994 derecho-producing mesoscale convective system between (a) 1500 and (h) 2200 UTC. (See http://www.spc.noaa.gov/misc/AbtDerechos/images/94may31loopviswidereversemed for an animated view of this imagery using half-hourly data.)

line crossed the several north–south ridges over western Utah at an oblique angle before encountering the broader and more abrupt elevated terrain presented by the Wasatch Mountains and Uinta Mountains of northeast Utah (Fig. 1). Temporal resolution of the available radar and satellite data does not permit a detailed assessment of the influence of terrain on individual storms. Given the pattern of severe wind reports (especially considering the region's low population density), what can be said is that the larger convective system does not appear to have been adversely affected by its encounter with the western Utah ridges. Temporal resolution (approximately 30-min intervals) of the animated satellite imagery is, unfortunately, also not sufficient to determine whether or not discrete, forward propagation was promoted by the terrain in the manner described by Frame and Markowski (2006), nor whether terrain channeling like that described by Wu et al. (2010) may have augmented surface gusts in the Provo area. It does, however, appear that forward propagation continued and perhaps increased as the squall line continued northeast across the elevated plateau of southwest Wyoming beyond the Uintas (Fig. 3).

The satellite sequence also shows a smaller wind-producing convective system that formed around noon local time (1800 UTC) over northeast Utah and subsequently moved northeastward into parts of northwest Colorado and southern Wyoming, several hours before the main derecho-producing complex affected the region. This system arose within a band of weak convection oriented roughly parallel to and approximately 175 km northeast of the derecho-producing squall line (see 1800 UTC image in Fig. 3). The smaller storm complex also produced damaging straight-line winds, with a gust of 38.0 m s^{-1} (74 kt) recorded at Great Divide, Colorado. Additional severe and near-severe wind gusts occurred before this system weakened over south-central Wyoming.

4. Noteworthy upper-level and surface features

At 0000 UTC 31 May 1994, the evening before the event, a well-defined short-wave trough with a significant vorticity maximum was approaching southern California from the eastern Pacific (Fig. 4a). By 1200 UTC 31 May 1994, the trough had moved northeastward into the southwest United States and had assumed a slight negative tilt, with the trough axis extending from just east of Reno, Nevada, to northern portions of the Baja Peninsula (Fig. 4b). Negatively tilted short-wave troughs often are present during severe weather episodes over the interior western United States (Evenson and Johns 1995). During the next 12 h, the trough accelerated northeast across the Great Basin, ahead of a larger-scale trough that was amplifying or ''digging'' southeastward toward the Pacific Northwest (Fig. 4c).

It was during the acceleration phase of the negatively tilted trough that the derecho-producing convective system developed and moved northeastward. The upper-air pattern appears similar to the ''dynamic'' pattern found by Johns (1993) to be associated with squall lines that produce vigorous bow echoes with damaging wind (his Fig. 5b). The pattern also is similar to that of the ''strong forcing'' derechos identified by Evans and Doswell (2001) and Coniglio et al. (2004). The details of the associated upper trough appear to fit the Coniglio et al. (2004) ''cluster 1'' pattern because of the negative tilt. However, the strength of the wind field is weaker than that associated with their cluster 1 pattern and better matches that of their cluster 2 or cluster 3 events.

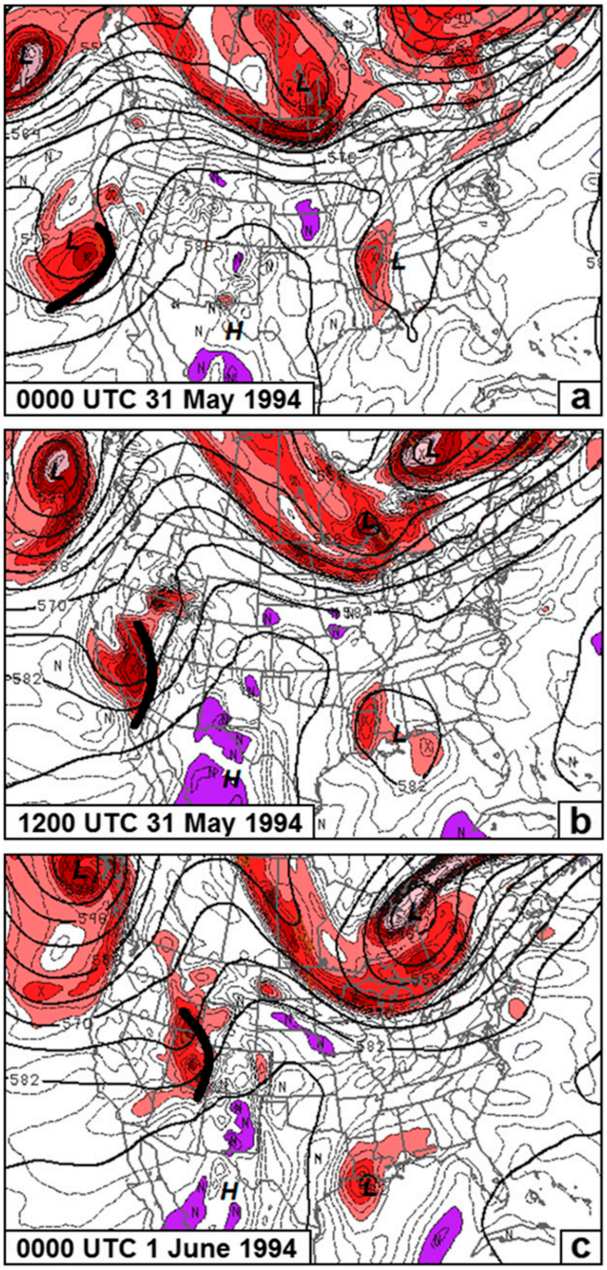

FIG. 4. The 500-mb height and vorticity analyses at (a) 0000 UTC 31 May, (b) 1200 UTC 31 May, and (c) 0000 UTC 1 June 1994. Thick, solid, black arcs depict approximate positions of the short-wave trough mentioned in the text (based on subjective interpretation of differential vorticity advection fields). Areas of comparatively low absolute vorticity are shaded purple; areas of comparatively high relative vorticity are shaded red [NCEP–NCAR reanalysis data (Kalnay et al. 1996; Kistler et al. 2001), modified from display of The Pennsylvania State University's Department of Meteorology].

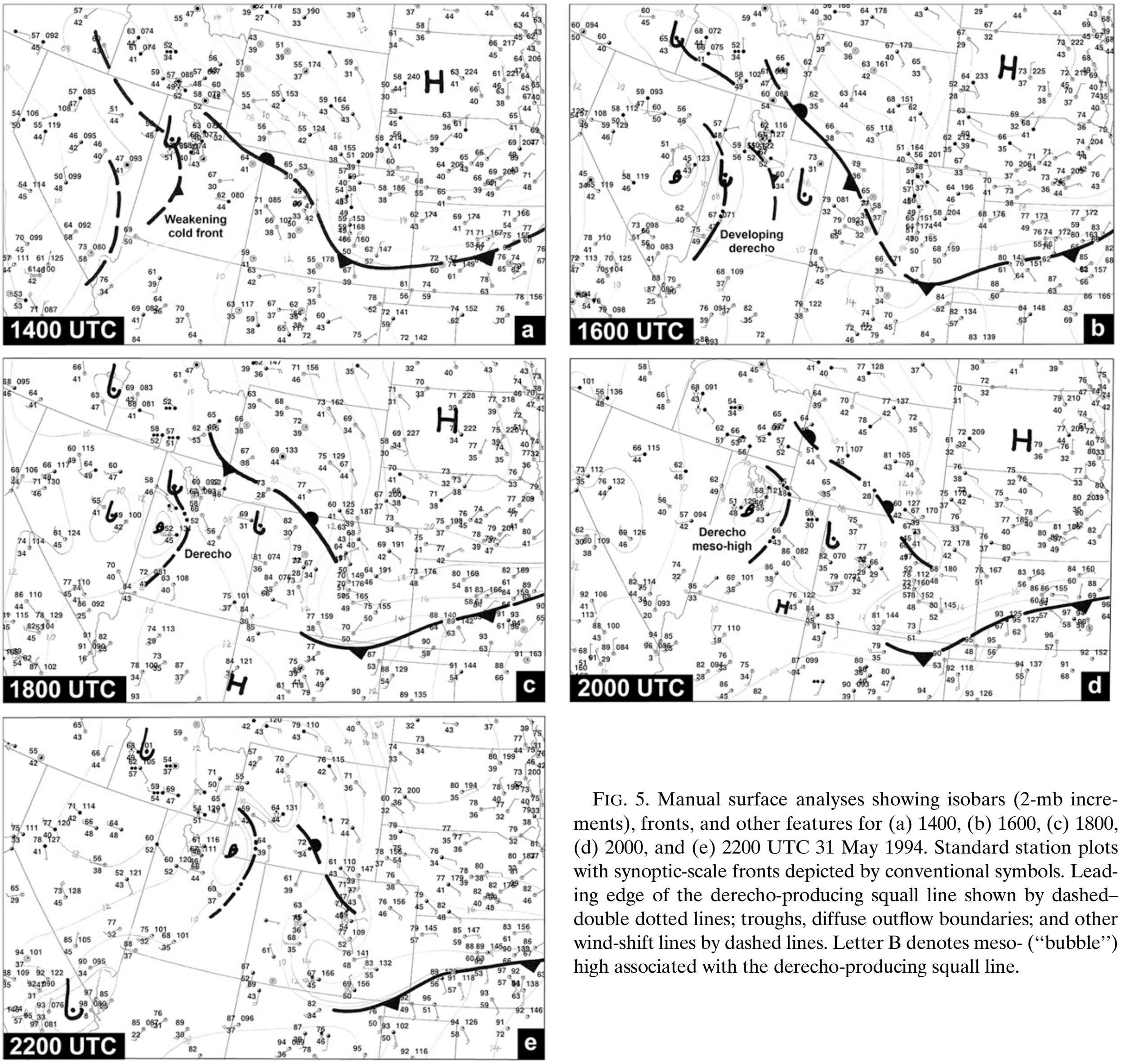

FIG. 5. Manual surface analyses showing isobars (2-mb increments), fronts, and other features for (a) 1400, (b) 1600, (c) 1800, (d) 2000, and (e) 2200 UTC 31 May 1994. Standard station plots with synoptic-scale fronts depicted by conventional symbols. Leading edge of the derecho-producing squall line shown by dashed–double dotted lines; troughs, diffuse outflow boundaries; and other wind-shift lines by dashed lines. Letter B denotes meso- ("bubble") high associated with the derecho-producing squall line.

Corfidi et al. (2006) studied a series of severe wind-producing convective systems in the United States that occurred in environments characterized by limited low-level moisture. They termed these events low-dewpoint derechos, or LDDs. One of their LDD events was the 31 May 1994 derecho. Most of the other LDDs examined in that study occurred east of the Rocky Mountains. The mean mid- and upper-tropospheric height fields identified were similar to those observed with the 31 May 1994 derecho. Corfidi et al. (2006) also noted that as the events evolved, the damaging surface winds typically occurred beneath the exit region of a mid-tropospheric jet streak, close to the wind maximum at this level—as was the case with the 31 May 1994 derecho. However, as will be seen, the low-level environment of the 31 May 1994 storm differed from the mean pattern presented by Corfidi et al. (2006).

The 31 May 1994 derecho occurred over a region of rough, elevated terrain in the western United States, where the identification of surface weather features often is challenging (e.g., Williams 1972). Overall, the general pressure pattern in the region of derecho genesis was not well defined, characterized by minimal near-surface baroclinity. Nevertheless, hourly, hand-drawn surface analyses made for the 12-h period leading up to and including the event, some of which are included in Fig. 5, do reveal several features that maintain hour-to-hour continuity. Observed temperature and moisture

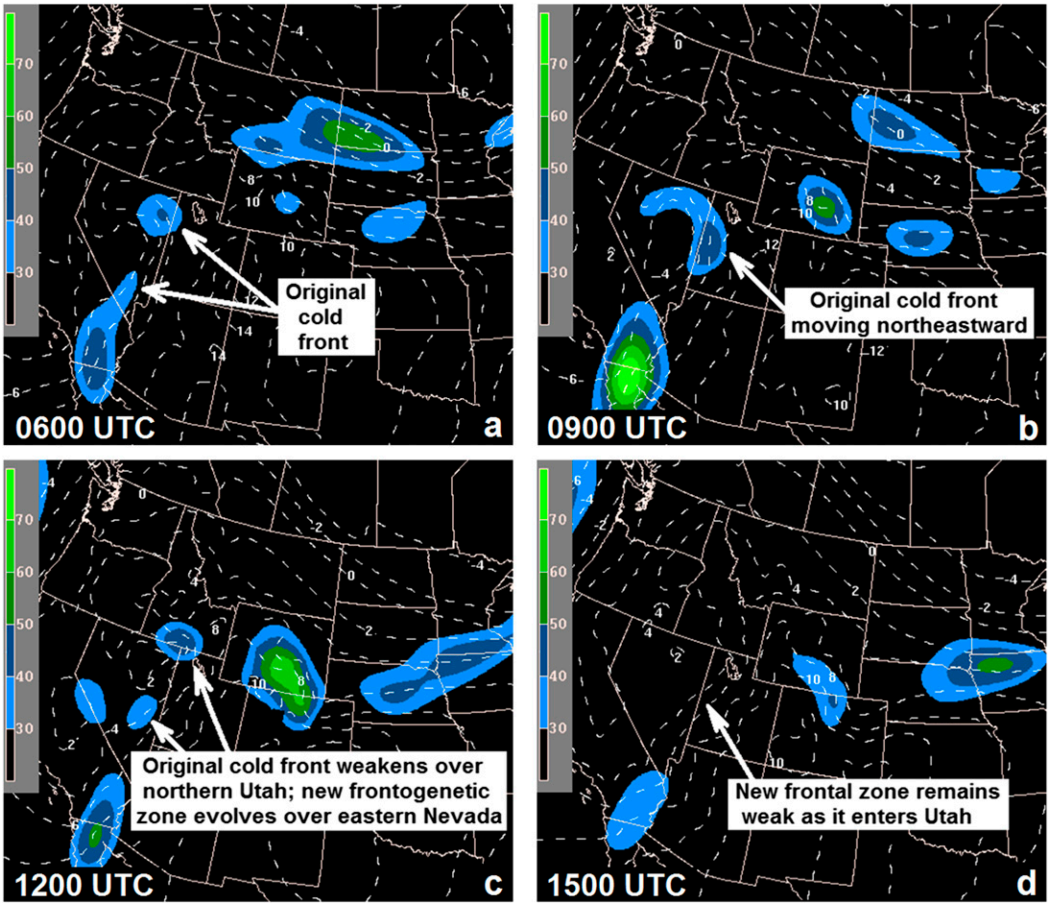

FIG. 6. NCEP–NCAR reanalysis 800–600-mb mean frontogenesis [K (100 km)$^{-1}$ (3 h)$^{-1}$; shaded, scale at left], and temperature (°C, dashed) for (a) 0600, (b) 0900, (c) 1200, and (d) 1500 UTC 31 May 1994.

gradients in the 0000 and 1200 UTC 31 May and 0000 UTC 1 June 850- and 700-mb radiosonde data helped refine the analyses, as suggested by Williams (1972), as did observations from the Remote Automated Weather Station (RAWS) network. Cloud-to-ground lightning data (not shown) further assisted in the placement of the derecho-producing convective system's gust front in more remote areas.

Figures 5a and 5b show the main features of the pre-derecho surface environment. A cold front attendant to the upper-level trough was located over western Utah at 1400 UTC (Fig. 5a). This front had moved rapidly northeast across eastern Nevada during the overnight (i.e., before 1200 UTC) and was accompanied by a band of light showers. The front was weakening at the time of the analysis (depicted by frontolysis symbols in Figs. 5a,b), and became indistinguishable as it continued northeast and encountered a weak stationary front over southwest Wyoming later in the day (Figs. 5b,c). The boundary was accompanied by an arc of weakening 800–600-mb frontogenesis, as shown in the sequence of National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis plots (Kalnay et al. 1996; Kistler et al. 2001) in Fig. 6.

At the same time, the surface and reanalysis data suggest that the convective band present along the Nevada–Utah border at 1500 UTC (Fig. 3a)—the band that ultimately evolved into the derecho-producing squall line—also may have been associated with a secondary axis of frontogenesis attendant to the upper trough (Figs. 6b,c). Although the pressure gradient along the incipient squall line somewhat increased through the day, most of this increase was associated with the development of a convectively induced meso- or "bubble" high (depicted by B in Figs. 5b–e) beneath the convection, rather than with a strengthening, synoptic-scale surface low and cold front. In this manner, the surface pattern differed from the mean pattern for LDDs presented in Corfidi et al. (2006), where most of the convective systems occurred along strong fronts. Additionally, while the composite gust front ultimately

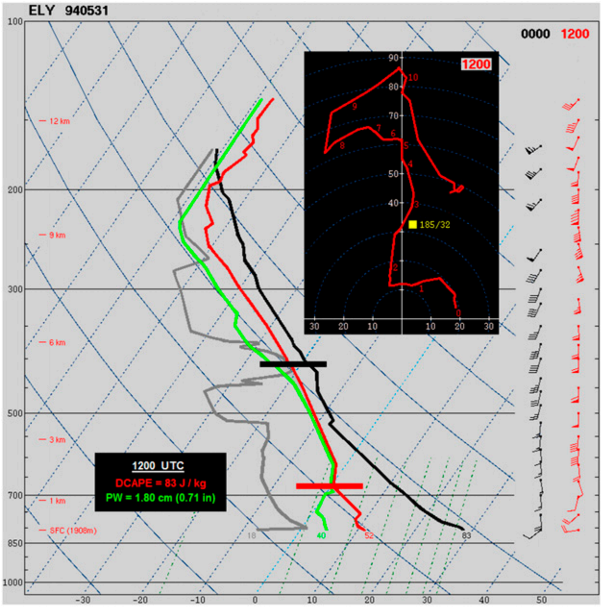

FIG. 7. Overlaid skew *T*–log*p* radiosonde temperature and dewpoint profiles for Ely (ELY) at 0000 UTC (black and gray, respectively) and 1200 UTC (red and green, respectively) 31 May 1994. Wind profiles (kt; 1 kt = 0.51 m s^{-1}) shown in vertical columns at right, using conventional barb format, with surface air and dewpoint temperatures (°F) at bottom. Thick horizontal bars indicate approximate height of lowest cloud bases at 0000 (black) and 1200 (red) UTC. Inset shows hodograph at 1200 UTC, with speed contours (kt) and surface–300-mb mean wind shown by the yellow square. Numbers along hodograph indicate height (km). Downdraft CAPE (DCAPE) and precipitable water (PW) shown for the indicated time.

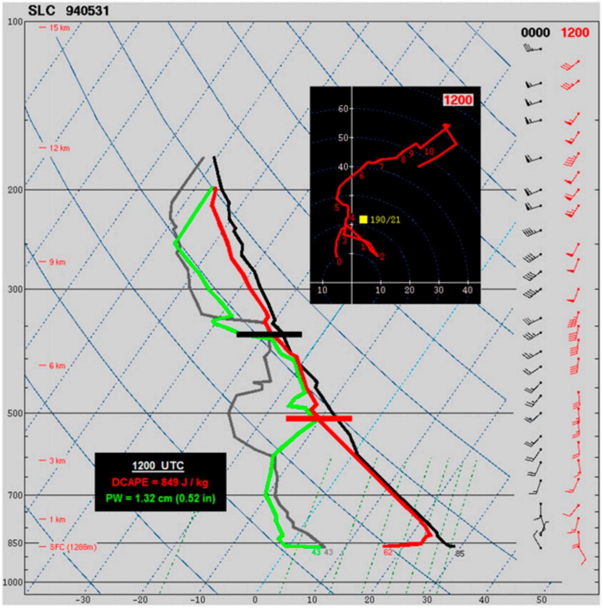

FIG. 8. As in Fig. 7, but for Salt Lake City (SLC).

generated by the derecho-producing squall line might be considered more or less a new synoptic-scale cold front attendant to the upper trough (e.g., cf. surface temperatures and dewpoints over southeast Utah and vicinity with those in northern Utah in Figs. 5d,e), the derecho-producing MCS clearly evolved in the wake of the original cold front, rather than along it. Individual post-cold-frontal thunderstorms occasionally produce cool-season severe convective episodes, particularly in California and other parts of the West (e.g., Hales 1985; Braun and Monteverdi 1991). But severe, postfrontal squall lines are rare in the United States, and in this sense, the 31 May 1994 event also was unique.

5. Thermodynamic environment

Above-normal surface temperatures had prevailed over the Great Basin in the days prior to the derecho, with afternoon maximum temperatures that approached 30°C (86°F). The associated warm air mass was characterized by a deep, surface-based mixed layer (with lapse rates close to dry adiabatic), and limited moisture (total precipitable water 0.75–1.25 cm), especially below 500 mb. Such thermodynamic conditions are common over the Great Basin during the warm season (Krumm 1954), and are similar to the "inverted V" environments associated with the dry microbursts examined by Wakimoto (1985). The 0000 UTC 31 May soundings at Ely and Salt Lake City in Figs. 7 and 8, respectively (see Fig. 1 for locations of Ely and Salt Lake City), show that this type of environment was present over the derecho-affected area on the evening preceding the event.

The thermodynamic profiles over eastern Nevada and Utah changed markedly during the night before the derecho as the upper-level trough approached from the southwest and enhanced large-scale ascent. The 1200 UTC 31 May sounding at Ely, representative of the genesis region of the derecho, featured a deep, saturated layer that extended from 700 mb to above 500 mb (Fig. 7, red and green profiles). This moist layer likely corresponded to the weakening cold front mentioned in section 4, and to the arc of multilayered clouds extending from northeast Nevada into south-central Utah in the 1500 UTC satellite image (Fig. 3a). Although moisture remained sparse by comparison to derecho events over the central and eastern United States, precipitable water at Ely did increase from 0.90 cm at 0000 UTC to around 1.80 cm at 1200 UTC (Fig. 7).

Showers and thunderstorms crossed southern Nevada during the predawn hours of 31 May, along and behind the weakening lead cold front discussed in section 4. The convection moved through the Ely area before 1200 UTC. Surface temperatures decreased and dewpoints rose

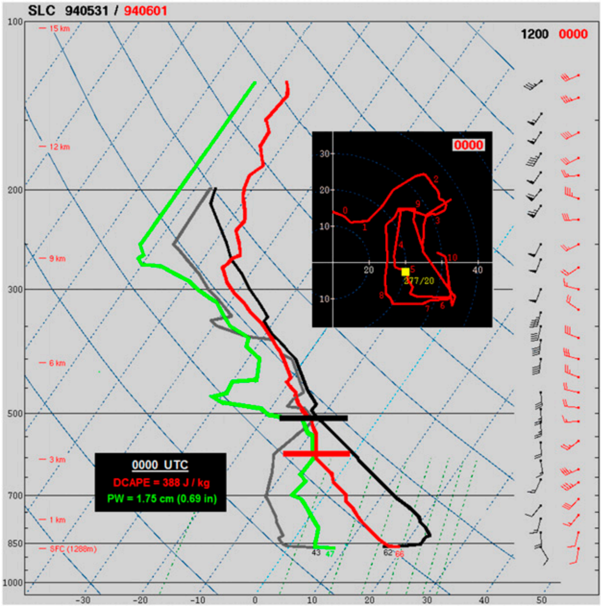

FIG. 9. As in Fig. 7, but for SLC at 1200 UTC 31 May (black and gray profiles) and 0000 1 Jun 1994 (red and green contours). Thick horizontal bars indicate approximate height of lowest cloud bases at 1200 UTC 31 May (black) and at 0000 UTC 1 Jun (red). Hodograph as in Figs. 7 and 8, but for 0000 UTC 1 Jun.

following the onset of the showers, suggesting that some of the boundary layer modification depicted in the 1200 UTC Ely sounding was due to precipitation. Another band of convection moved through Ely around 1430 UTC (dashed line over southeastern Nevada in Fig. 5a). As was seen in section 4, it was this line that ultimately evolved into the derecho-producing squall line over western Utah a bit later in the day. Although thunder occurred as the line passed Ely, strong winds were not reported.

Farther northeast, at Salt Lake City, the prefrontal vertical temperature profile at 1200 UTC 31 May also displayed overnight modification, presumably related to the approaching upper trough (Fig. 8, red and green profiles). The changes were most apparent at midlevels, where saturation occurred, yielding an inverted-V thermodynamic profile. Precipitable water, however, remained unchanged at 1.25 cm. The data suggest that the lowest cloud bases at the time of the sounding were near 4.5 km AGL.

The weakening cold front that moved through Ely around 1200 UTC reached the Salt Lake City area with light rainshowers around 1600 UTC (frontolytic cold front symbols over central and northwest Utah in Fig. 5b). Hourly surface data (not shown) suggest that outflow from the showers and/or airmass change with frontal passage modified the near-surface environment. At Salt Lake City International Airport, the temperature fell from 21°C (70°F) to 16°C (61°F) between 1500 and 1800 UTC, while the dewpoint rose from 5°C (41°F) to 13°C (55°F). These observations suggest that the late morning boundary layer over Salt Lake City likely differed somewhat from that depicted in the 1200 UTC sounding. Surface temperatures nevertheless recovered to around 21°C (70°F), largely in response to surface heating in the wake of the showers (Figs. 3c–e), as the derecho approached from the southwest during

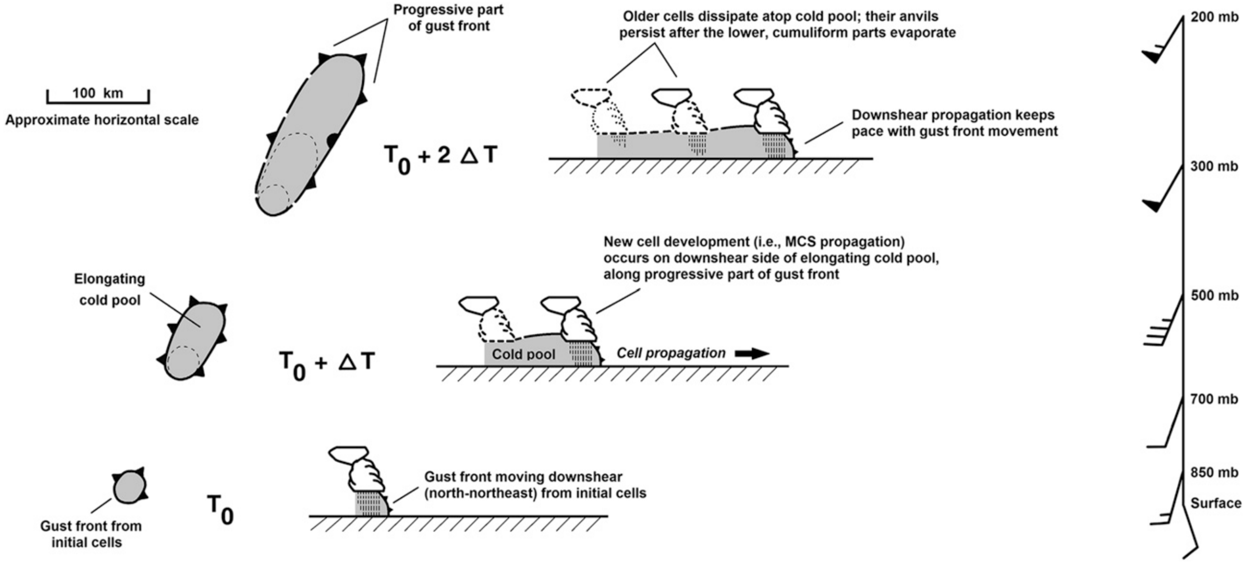

FIG. 10. Temporal schematic of the 31 May 1994 Great Basin derecho, with (left) plan view of elongating cold pool (north at top), and (center) south-southwest to north-northeast cross section of cold pool, showing downshear cell propagation along progressive part of the associated gust front. (right) Estimated wind profile ahead of the derecho-producing MCS is based on 1200 UTC Ely and SLC radiosonde data. Time is indicated by T, with ΔT on the order of 1 h. Vertical scale exaggerated in cross sections.

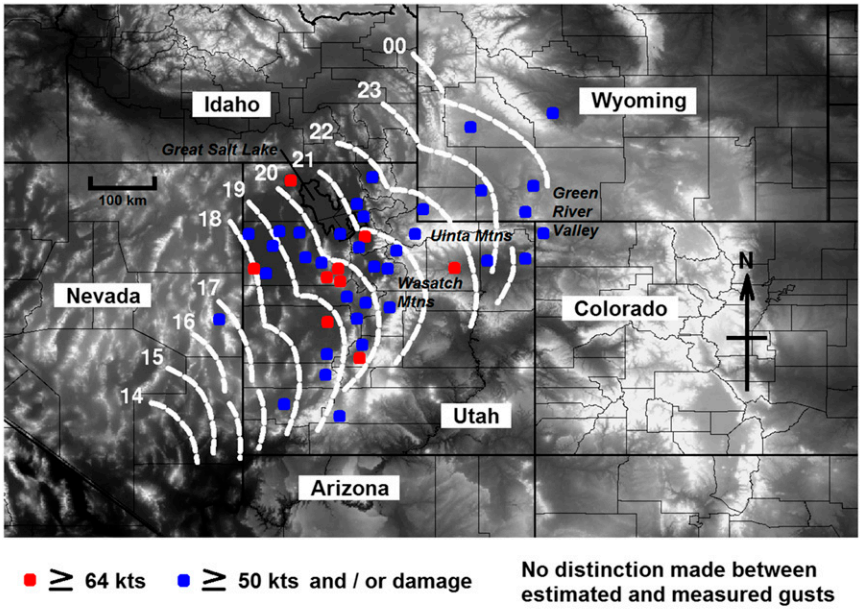

FIG. 11. As in Fig. 1, but for the derecho of 1 Jun 2002. [Note: As supplementary wind data were not obtained for this event (in contrast to the 31 May 1994 derecho), no subsevere wind reports are plotted.]

the early afternoon (1900 UTC). Dewpoints, however, remained around 12°C (54°F).

By 0000 UTC 1 June, several hours after the derecho had passed, the sounding at Salt Lake City still exhibited an inverted-V profile. The boundary layer, however, was not as dry, and the low-level lapse rate was not quite as steep (Fig. 9, red and green profiles). The sounding suggests that the lowest cloud bases at the time were around 3 km AGL, about 1.5 km lower than that suggested by the 1200 UTC 31 May data (Fig. 9, black and gray profiles). Given the surface conditions present at Salt Lake City immediately before the derecho, it would seem that the low- to midtropospheric thermal profile just ahead of the derecho may have more closely resembled that of the evening (0000 UTC 1 June) sounding, rather than that of the morning (1200 UTC 31 May) release, although it is impossible to know for certain.

Although the details of the prederecho thermodynamic environment are open to speculation, what can be said with greater certainty is that while lower-tropospheric lapse rates were sufficiently steep to support deep convection, moisture was comparatively sparse relative to that of derecho events east of the Rockies. As a result, buoyancy and updraft strength likely were limited. The soundings in Figs. 7 and 8 confirm this, with a dearth of convective available potential energy (CAPE) reflecting the absence of appreciable moisture. Even at Desert Rock in south-central Nevada, where thunderstorms were in progress in association with the upper trough, the 1200 UTC sounding (not shown) displayed only weak buoyancy (~500 J kg^{-1} mixed-layer CAPE) and modest precipitable water (2.25 cm); values that, in all likelihood, represented the maxima of those variables in the prederecho environment over Utah later in the day (note that CAPE was zero or negligible at the time of the Salt Lake City soundings depicted in Figs. 8 and 9).

In short, buoyancy in the area affected by the 31 May 1994 derecho was quite low compared to that commonly present with most warm-season derechos over the central and eastern United States. East of the Rockies, derechogenesis areas typically are characterized by warm, moisture-rich boundary layers surmounted by deep elevated mixed layers. Such environments yield very high CAPE (e.g., greater than 4000 J kg^{-1}) that can support intense, sustained convection (e.g., Evans and Doswell 2001; Cohen et al. 2007). If relatively dry layers are present, they most often are found in the midlevels (e.g., Johns et al. 1990). In contrast, the inverted-V thermodynamic profile associated with the 31 May 1994 derecho featured a deep, relatively dry surface-based layer beneath modest midlevel moisture. The thermodynamic setup was, therefore, quite different from that common to most warm-season derechos east of the Rockies.

6. Wind environment

The 1200 UTC wind profile at Salt Lake City was not particularly favorable for sustained, organized convection,

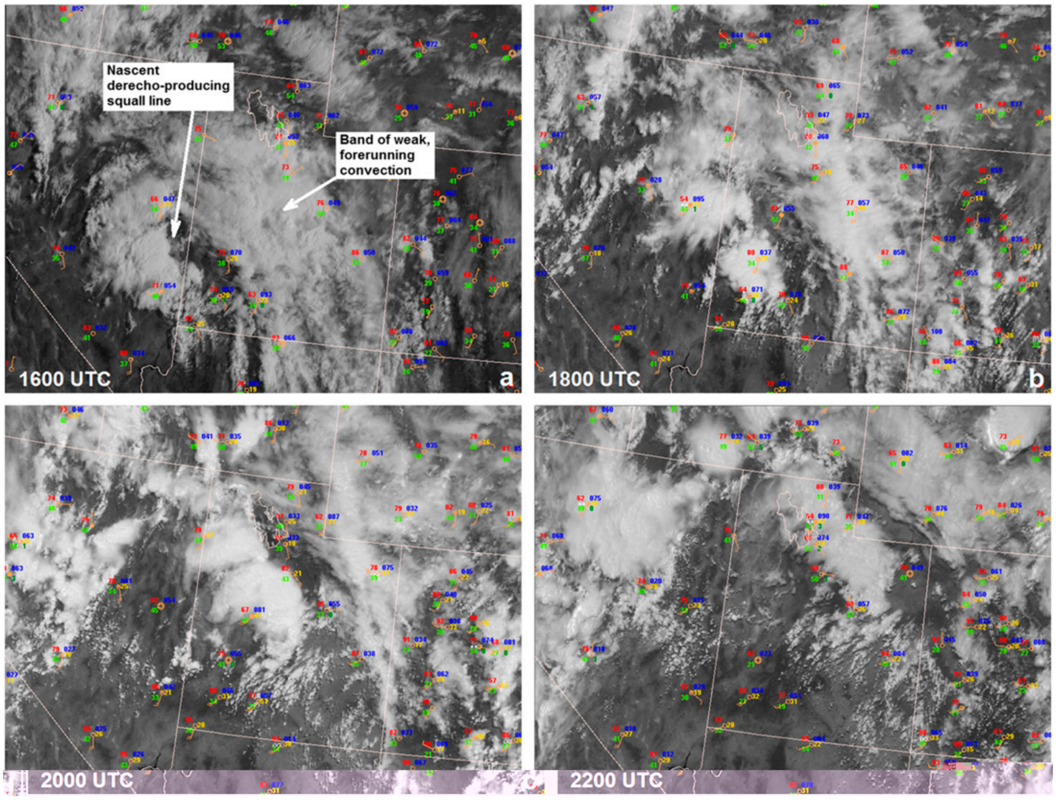

FIG. 12. GOES visible satellite sequence showing 2-hourly development and movement of the 1 Jun 2002 derecho-producing mesoscale convective system between (a) 1600 and (d) 2200 UTC. Surface observations depicted with conventional station plots. (See http://www.spc.noaa.gov/misc/AbtDerechos/images/02jun01loopvis.gif for an animated view of this imagery using hourly data.)

especially at lower levels (Fig. 8). The profile, however, likely became more supportive by midday as the Nevada short-wave trough continued northeastward. For example, the magnitude of 0–6-km shear at Salt Lake City at 1200 UTC was approximately 15.4 $\mathrm{m\,s^{-1}}$ (30 kt), while closer to the trough, southerly 25.7 $\mathrm{m\,s^{-1}}$ (50 kt) 500-mb winds contributed to 32.4 $\mathrm{m\,s^{-1}}$ (63 kt) 0–6-km shear at Ely (see hodographs in Figs. 7 and 8). Presumably, the wind profile at Ely was representative of the environment immediately ahead of the incipient derecho, and this wind field moved northeast toward the Salt Lake City area during the day. Deep southerly flow at both locations yielded decidedly unidirectional, southerly 0–6-km shear. The slightly veered flow above 6 km at Salt Lake City further contributed to largely unidirectional, south-southwesterly 0–12-km and cloud-layer shear.

The shear profiles favored north-northeastward elongation and overall movement of the storm-produced low-level cold pools, as discussed by Corfidi (2003; his Fig. 2). Low-level uplift was focused on the most progressive (i.e., most rapidly moving) north-northeast part of the composite gust front, where south-southwesterly storm outflow winds overtook the lighter, ambient surface flow. New thunderstorms, therefore, preferentially formed along the north-northeast part of the composite gust front. The combination of deep, seasonably strong south-southwesterly flow; linear ascent along the gust front; and an inverted-V thermodynamic environment appears to have been favorable for the sequential production of microbursts. Together, these microbursts produced the swath of strong-to-damaging wind gusts that ultimately constituted the derecho, in a manner analogous to that of a significant arid-region derecho described by Mitsuta et al. (1995) and Takemi (1999).[2]

In the wake of the derecho and with the passage of the upper trough, the midtropospheric flow weakened

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[2] This event, essentially an intense, squall line–induced dust storm, occurred over northwest China in May 1993, in a synoptic regime similar to that of the Great Basin on 31 May 1994. The Chinese storm caused 49 deaths and affected an elevated, arid plateau similar to that of Utah and Wyoming.

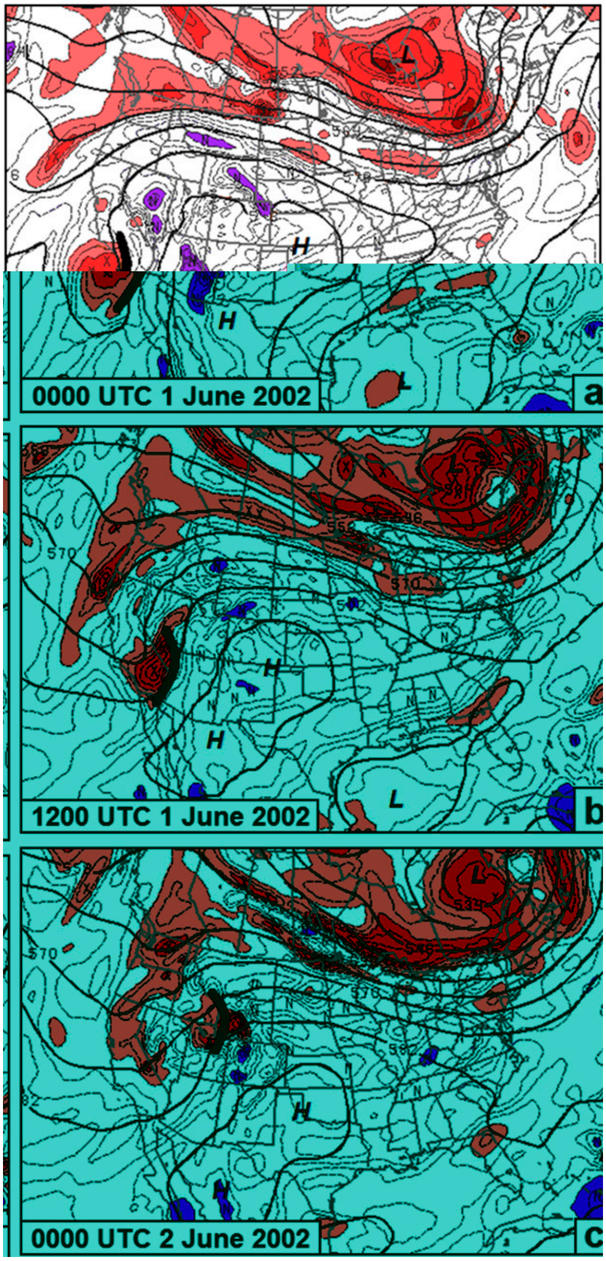

FIG. 13. As in Fig. 4, but for (a) 0000 and (b) 1200 UTC 1 Jun, and (c) 0000 UTC 2 Jun 2002.

and veered to westerly over Utah by 0000 UTC 1 June (Fig. 4c). While light southwesterly winds persisted near the surface, the onset of diurnal cooling, large-scale descent, and weakening shear together prohibited the development of additional sustained storms over central Utah. The derecho-producing squall line, meanwhile, weakened as it continued farther northeast across Wyoming and far eastern Utah, encountering greater static stability [mainly weaker midlevel lapse rates per the 0000 UTC 1 June Riverton, Wyoming, sounding (not shown)].

7. Summary and discussion

By limiting CAPE, sparse low-level moisture over the western United States limits convective updraft strength and longevity, making true derechos rare over and west of the Rocky Mountains. When more localized wind-producing convective systems do arise over the region, they most often are associated with inverted-V thermodynamic profiles, as was the case with the derecho of 31 May 1994. Although the thermodynamic environment of 31 May 1994 did bear some resemblance to the mean profile for low-dewpoint derechos depicted in Corfidi et al. (2006), the steepest lapse rates in this case were in the boundary layer, not aloft. In addition, the convective system formed in the wake of a weakening, early-day cold front, not along or ahead of a strong front, as was true of most of the events in that study. Thus, as a low-dewpoint event, the 31 May 1994 derecho was unique.

The available data indicate that modest low-level moistening occurred over Utah early on the morning of 31 May following the passage of a weakening cold front. The moistening primarily was due to the evaporation of precipitation that accompanied and followed the front (Figs. 8 and 9). Despite limited buoyancy, this moistening likely somewhat reduced convective inhibition by lowering the level of free convection in the wake of the boundary. Coupled with daytime heating, the arrival of midlevel cooling and ascent, and possibly some degree of low-level frontogenesis immediately ahead of a seasonably strong short-wave trough, thunderstorms formed and strengthened over eastern Nevada and western Utah a bit later in the morning. Some degree of boundary layer moistening also may have occurred over far northeast Utah and southern Wyoming during the afternoon, in the wake of the small convective system that formed over that region around midday, as mentioned in section 3.

Steep lower-tropospheric lapse rates and sizable boundary layer temperature–dewpoint spreads associated with the inverted-V thermodynamic environment, in turn, likely fostered the development of strong, evaporatively induced, convective downdrafts. Given the increase in unidirectional south-southwesterly cloud-layer shear that occurred immediately ahead of the trough, the downdrafts quickly merged into a composite cold pool. Wind profiles favored north-northeast elongation of the composite cold pool (i.e., in the direction of the cloud-layer shear) toward the Great Salt Lake and the Uinta Mountains, as diagrammed

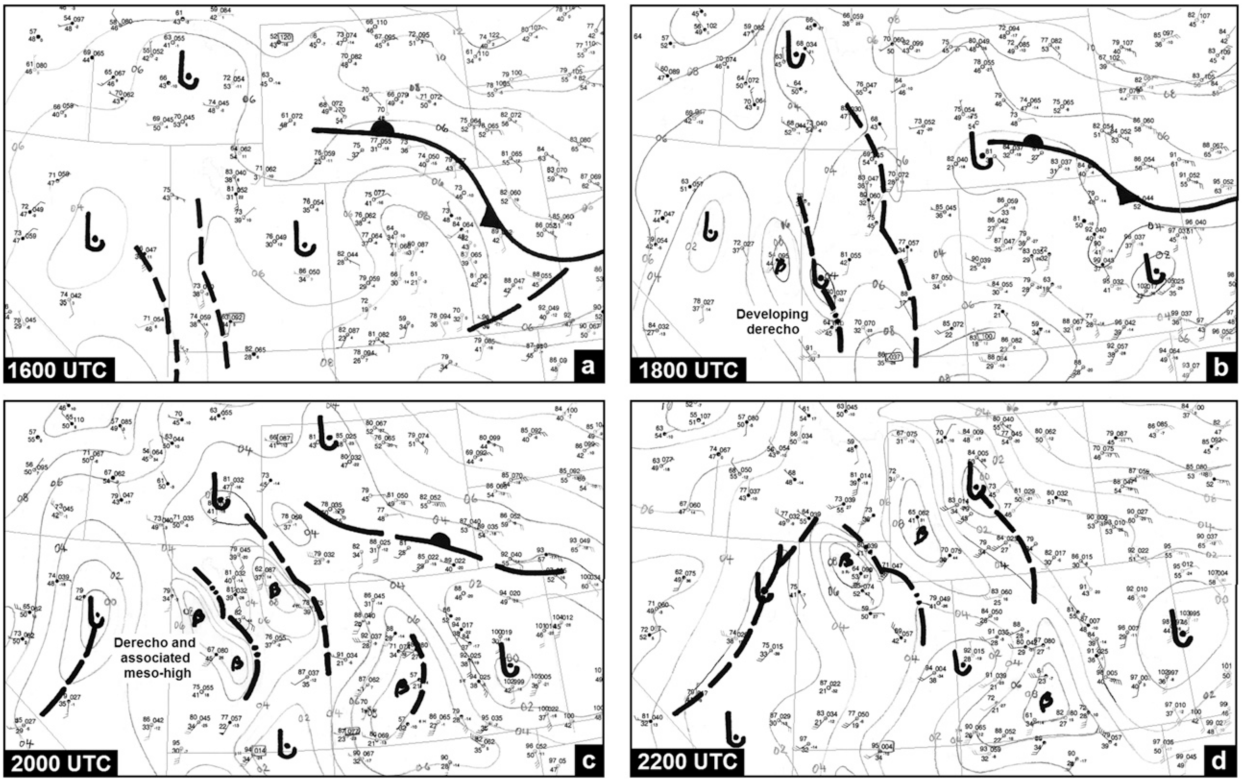

FIG. 14. As in Fig. 5, but for (a) 1600, (b) 1800, (c) 2000, and (d) 2200 UTC 1 Jun 2002, corresponding to the satellite imagery in Fig. 12. Pressure data surrounded by small rectangles are believed to be erroneous.

schematically in Fig. 10. Forced ascent along the progressive part of the cold pool's gust front then lifted boundary layer parcels beyond their level of free convection and gave rise to forward-propagating, bowing line segments—a "progressive"-type derecho (Johns and Hirt 1987)—that produced long-lived swaths of damaging surface wind, despite meager buoyancy.

To place the 31 May 1994 Great Basin derecho in perspective, it is worth considering how many similar events have occurred over that region in more recent years. Negative-tilt or "ejecting" short-wave troughs occur with fair regularity over the western United States each spring and fall, often in the presence of dry low-level (inverted V) thermodynamic environments. Such setups typically are associated with the localized wind-producing convective systems previously mentioned. *Storm Data* suggests that about one of these events might approach or marginally exceed derecho length criteria every other year. The damaging gusts in these situations, however, often appear to be incidental to the thunderstorms, being as much a product of the background pressure gradient as convective outflow. Based on storm reports and radar imagery available since completion of the WSR-88D radar network over the Great Basin in the mid-1990s, progressive derechos—those derechos whose gusts are most directly related to convective downdrafts—appear to be much rarer. As far as the authors are aware, only one event similar to the 31 May 1994 derecho has occurred over Utah and adjacent states since that time, and this storm is introduced briefly below. It appears, therefore, that a unique set of conditions must arise, most likely with particular spatial and temporal organization, to realize progressive-type derecho development in areas of limited moisture. For example, the rate of cell development along the gust front in the 31 May 1994 event was such that the boundary remained in phase with development, rather than outpacing it. The factors and processes responsible for such fortuitous phasing are not immediately evident and are worthy of future research.

A derecho quite similar to the 31 May 1994 storm and which affected much the same area occurred on 1 June 2002 (Fig. 11). This derecho also was largely diurnally driven; it began around 1800 UTC 1 June (1100 LST) and continued beyond 0000 UTC 2 June. More than three dozen instances of damaging wind and/or measured severe gusts occurred along a southwest-to-northeast swath across Utah and adjacent parts of

Nevada, southeast Idaho, and southwest Wyoming. Gusts to 38 m s^{-1} (74 kt) were recorded at Gold Hill and Vernon, Utah. Near Green River, Wyoming, 28 m s^{-1} (54 kt) winds were sustained for 1 h.[3]

As seen by satellite, the convective system associated with the June 2002 derecho bore close resemblance to that of the 1994 event, with the squall line consisting of two broken arcs of storms oriented roughly north-northwest to south-southeast (Fig. 12). As in the earlier event, forward propagation is apparent in the satellite sequence; new convective towers form repeatedly on the sharply defined, downshear (northeast) side of the squall line, leaving diffuse anvil material in their wake. The system's average forward speed was 23.2 m s^{-1} (45 kt), nearly twice the speed of the mean 850–300-mb flow (12.3 m s^{-1} or 24 kt) based on the 1200 UTC Salt Lake City radiosonde data discussed below. The synoptic setup also was quite similar; the derecho occurred immediately downstream from a short-wave trough in moderate, southwesterly midlevel flow (Fig. 13). The trough in this case was, however, somewhat weaker, and the disturbance experienced further deamplification as the convective system developed (cf. Figs. 4 and 13).

As on 31 May 1994, the surface pattern over the Great Basin on 1 June 2002 was fairly nondescript, dominated by weak, largely transitory, thermal or terrain-induced features (Fig. 14). Only the cold pool/mesohigh associated with the wind-producing convective system exhibited much temporal continuity. A modest increase in low-level moisture occurred ahead of the squall line in association with a forerunning band of showers (marked by the cirroform clouds east-northeast of the squall line in Fig. 11, and depicted by dashed lines in Fig. 14). And, as with the 1994 event, the convective band formed along what might be characterized as a weak surface front attendant to the upper impulse (depicted by dashed line along the Nevada–Utah border in Fig. 14a), near the upper feature's enhanced 700–500-mb thermal gradient (not shown, but implied by the vorticity gradient shown in Figs. 13a–c). Frontogenesis in the 800–600-mb layer, based on the NCEP–NCAR reanalysis, was even weaker than that in the earlier event (not shown).

The thermodynamic profile on 1 June 2002 also was similar to that of the 1994 storm, with midlevel (500–600 mb) moisture above a deep, dry, well-mixed boundary layer. As a result, estimated convective cloud bases were quite high (at or above 500 mb; red bar in Fig. 15), and the overall thermodynamic environment was favorable for dry microbursts. The relatively modest lower-tropospheric wind field (Fig. 15; hodograph and right-most wind profile) suggests that downward transfer of gradient flow likely was not the dominant factor in the production of damaging surface gusts. Unlike the 31 May 1994 derecho that occurred prior to completion of the WSR-88D radar network, the June 2002 event was reasonably well sampled by area Doppler radars. Several images of mosaicked base reflectivity are provided in Fig. 16. The most notable aspects of the imagery include the weak nature of the echoes and the absence of sustained bowing structures; individual frames are more reminiscent of those associated with localized dry microburst events than with an organized, traveling convective system.

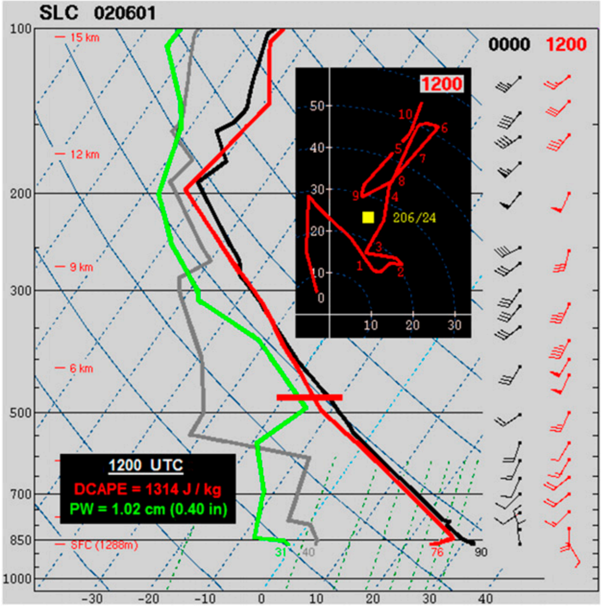

FIG. 15. As in Fig. 7, but for SLC at 0000 and 1200 1 Jun 2002. Thick, horizontal red bar indicates approximate height of lowest cloud base at 1200 UTC 1 Jun. Hodograph is for 1200 UTC.

To our knowledge, derechos occurring in inverted-V thermodynamic environments in the absence of strong, low-level baroclinity thus far have not been documented in the literature, and a convective wind event in the Great Basin so similar to the 31 May 1994 derecho has not occurred since 2002. The unique nature of the 31 May 1994 and 1 June 2002 derechos and their significant human impacts make them worthy of further study. In particular, knowledge of the potential influence of topographical features in channeling low-level flow (e.g., Wu et al. 2010) and in locally influencing the rate and direction of new convective cell development

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[3] Additional strong-to-severe gusts also may have occurred considering that supplemental and subsevere wind data (e.g., such as that provided for the 31 May 1994 derecho in Table 1) were not sought for this case.

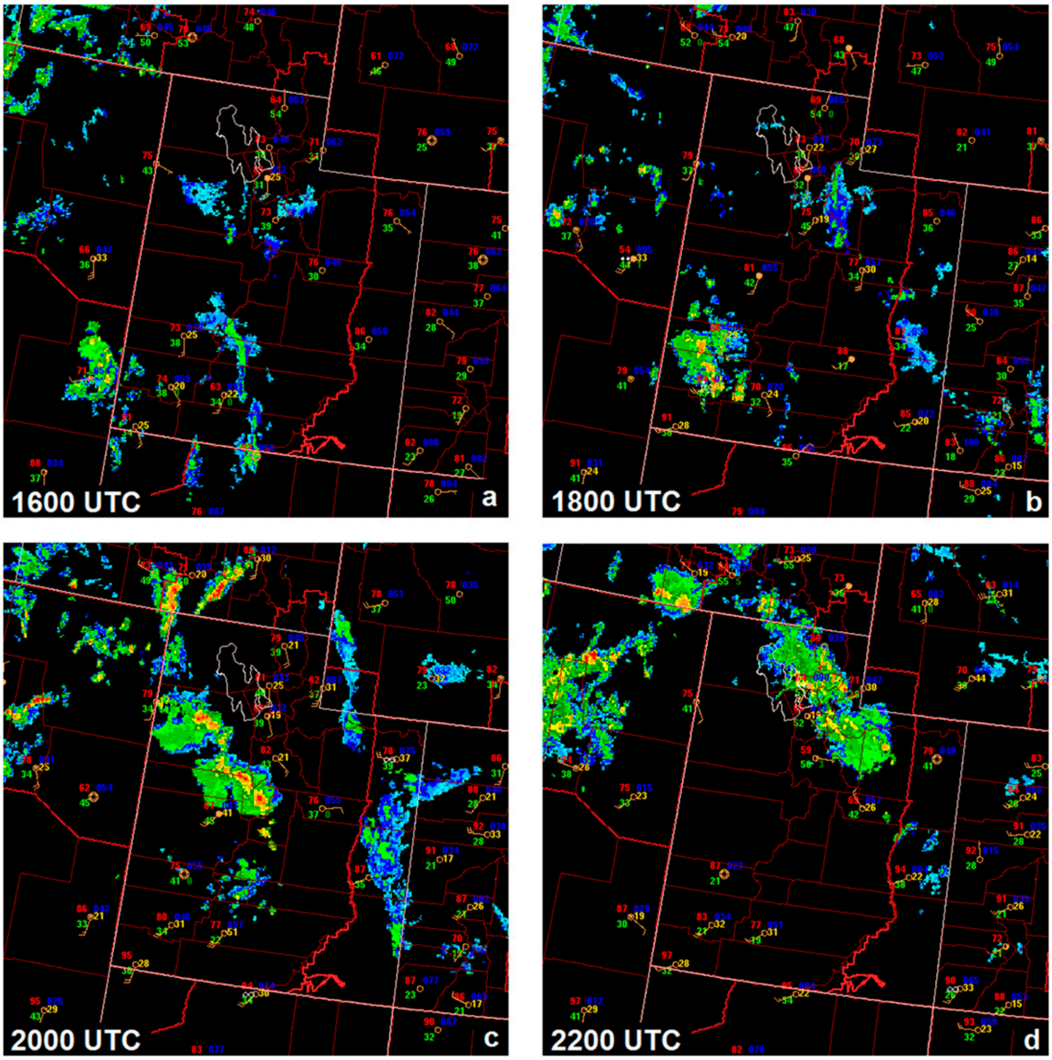

FIG. 16. Mosaicked base reflectivity radar data showing 2-hourly sequence of the development and movement of the 1 Jun 2002 derecho-producing mesoscale convective system between (a) 1600 and (d) 2200 UTC, corresponding to the satellite imagery in Fig. 12. Surface observations are depicted with conventional station plots.

could provide further insight into the behavior of severe convective storms in complex terrain. For example, Letkewicz and Parker (2010), in a study that examined the behavior of convective systems crossing the central and southern Appalachian Mountains, noted that systems that crossed the mountains occurred with weaker shear and lower-tropospheric mean flow than did systems that failed to cross. Cloud-layer shear was weak in both the 1994 and 2002 events relative to typical warm-season derecho environments. It is not clear, however, that weak shear was a contributing factor in the genesis and maintenance of the 1994 and 2002 storms, especially considering that the thermodynamic and moisture fields differed considerably from those associated with Letkewicz and Parker's cases.

Examination of the Utah derechos with convection-allowing numerical models might shed light on those factors responsible for the apparent propitious balance that existed between new storm development and gust front movement (as shown schematically in Fig. 10). Such work ultimately could provide us with a better understanding of the processes that enable individual convective cells to organize into forward-propagating, damaging wind-producing convective systems in more moisture-rich environments.

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