FORECASTERS' FORUM

Elevated Convection and Castellanus: Ambiguities, Significance, and Questions

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ABSTRACT

The term *elevated convection* is used to describe convection where the constituent air parcels originate from a layer above the planetary boundary layer. Because elevated convection can produce severe hail, damaging surface wind, and excessive rainfall in places well removed from strong surface-based instability, situations with elevated storms can be challenging for forecasters. Furthermore, determining the source of air parcels in a given convective cloud using a proximity sounding to ascertain whether the cloud is elevated or surface based would appear to be trivial. In practice, however, this is often not the case. Compounding the challenges in understanding elevated convection is that some meteorologists refer to a cloud formation known as *castellanus* synonymously as a form of elevated convection. Two different definitions of castellanus exist in the literature—one is morphologically based (cloud formations that develop turreted or cumuliform shapes on their upper surfaces) and the other is physically based (inferring the turrets result from the release of conditional instability). The terms elevated convection and castellanus are not synonymous, because castellanus can arise from surface-based convection and elevated convection exists that does not feature castellanus cloud formations. Therefore, the purpose of this paper is to clarify the definitions of elevated convection and castellanus, fostering a better understanding of the relevant physical processes. Specifically, the present paper advocates the physically based definition of castellanus and recommends eliminating the synonymity between the terms castellanus and elevated convection.

1. Introduction

The term *elevated convection* denotes convective clouds, storms, or both where the origin of air parcels within the convection lies above the planetary boundary layer (PBL). Specifically, elevated convection occurs above any near-surface stable layer (e.g., nocturnal inversion) or a sloping frontal surface (such as a warm or stationary front) where the instability is above the surface. Although the term elevated convection has been used more widely in recent years, the concept of convection (particularly, deep moist convection) not based in the PBL has been in existence for many decades (e.g., Berry et al. 1945, pp. 714 and 816). Deep elevated convection, generally in the form of thunderstorms, can produce excessive rainfall, hail, and occasionally damaging surface winds and tornadoes in areas

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well removed from strong surface-based instability (e.g., Branick et al. 1988; Schmidt and Cotton 1989; Colman 1990a,b; Neiman et al. 1993; Grant 1995; Bernardet and Cotton 1998; Moore et al. 1998, 2003; Banacos and Schultz 2005; Goss et al. 2006; Colby and Walker 2007; Horgan et al. 2007), as well as lightning-initiated wildfires in the western United States (Tardy 2007).

Determining the source region of buoyant parcels with the aid of an appropriate proximity sounding is not necessarily trivial. Specifically, growing cumulus clouds and thunderstorms based in the boundary layer routinely ingest parcels from above the boundary layer (e.g., Stull 1988, 559–561; Emanuel 1994, 200–204; and references therein). A modeling study by Fovell (2005) suggests that deep convective clouds that form in the vicinity of sea-breeze circulations are composed of air that initially originates above the PBL. On the other hand, air from near-surface stable layers can be incorporated into the updrafts of developing storms as long as the resulting parcels become positively buoyant. In addition, rotating updrafts in supercell storms induce nonhydrostatic vertical pressure gradients that tap non-buoyant boundary layer parcels (e.g., Marwitz 1973; Browning and Foote 1976; Weisman and Rotunno 2000). To define surface-based convection as convection in which the air involved is derived *mainly* from the PBL begs the question, "what is mainly?"

Thompson et al. (2007) provide one approach to answering this question by considering the *effective inflow layer* of a storm. Using proximity soundings to delimit the vertical range of parcels meeting selected convective instability and inhibition criteria, the authors identify the layer that likely serves as the primary source for a storm's updrafts. This layer is then used to compute improved estimates of the magnitude of the environmental shear and storm-relative helicity (Davies-Jones et al. 1990) associated with an elevated storm. Critical discussion of the Thompson et al. technique for identifying effective inflow layers is beyond the scope of this paper. Their scheme is, nevertheless, a first attempt to better quantify the level of potential severity posed by elevated storms. Further, Thompson et al. correctly note (p. 108) that the most buoyant parcel in a storm's inflow layer often exists well above the surface, even with storms whose inflow layers include the surface (e.g., their Fig. 6). Storms of this nature occur frequently in the moist, marginally unstable environments common to severe weather events over the southern and eastern United States. It is not clear if or how storms with elevated, most unstable parcels might differ morphologically and behaviorally from surface-based storms whose most unstable parcel is located at the surface. But the fact that two otherwise identical "surface based" storms might have different levels of most unstable inflow at the very least calls into question the widely accepted notion that a simple dichotomy exists between surface-based and elevated storms.

Efforts to determine storm inflow layers are motivated by the fact that the depth and location of a convective cloud's inflow can affect its subsequent evolution and tendency to produce severe weather. For example, Horgan et al. (2007) showed that elevated convection tends to be associated with a reduced likelihood of producing significant severe winds and tornadoes. Specifically, of all severe-storm reports associated with the 129 elevated severe-storm cases in Horgan et al. (2007), 9% of all hail reports, 3% of all wind reports, and 10% of all tornado reports were significant severe reports, as defined by Hales (1988). These numbers compare to the 9.8% of hail, 15.8% of wind, and 18.3% of tornadoes that are significant reports from all storms during 1970–2004 (G. Carbin 2007, personal communication).

When, or even if, a cloud or storm transitions from being surface based to elevated, or vice versa, is often a difficult forecasting challenge. For example, operational experience and indirect evidence via visual observation suggest that thunderstorms associated with deeply mixed boundary layer environments over the Rocky Mountains and adjacent high plains of the United States frequently become elevated as they move east across the lower plains. Even without strong convective inhibition, the cooler, but more moist, air from the PBL over the lower terrain does not appear to be ingested into such storms, thereby reducing the likelihood for tornadoes (e.g., Horgan et al. 2007). On the other hand, initially elevated storms sometimes clearly do become surface based upon encountering regions with moister boundary layers. Drawing upon this moister air, the circulations of such storms appear to develop downward, often displaying a concomitant increase in strength and severity (e.g., Rockwood and Maddox 1988, 63–65).

Compounding the challenges in understanding elevated convection is that some meteorologists refer to a type of cloud formation known as *castellanus* synonymously as a form of elevated convection. Castellanus (meaning "castle shaped"), in its most common usage, is a patchy or streaky cloud formation with turrets (Fig. 1), although castellanus can also be used to describe the entire cloud containing such turrets or even a whole field of such clouds. These cloud formations typically represent comparatively benign convection with rela-

FIG. 1. Castellanus (arranged in lines arising from a common base, lower left) and floccus (tufted, cumuliform puffs with ragged bases, top center through lower right) near Valentine, NE, about 1400 central daylight time (CDT; CDT = UTC − 5 h) 28 May 1988, looking south.

tively weak updrafts and limited vertical extent. The structure and evolution of castellanus provide insight into the relevant physical processes responsible for such cloud forms, as we discuss later in this paper.

Given the challenges in understanding the origins of air associated with elevated convection, the physical processes involved, and the inconsistent terminology, the present paper addresses elevated convection and castellanus. We hope to not only clarify some aspects that we feel heretofore have been neglected, but also pose questions and encourage additional discussion. In particular, we would like to increase awareness of the genesis and evolution of elevated convection so that both understanding and forecasts may be improved. Section 2 of this article provides a discussion of castellanus and two different definitions of castellanus because castellanus is a familiar, visual vehicle by which many meteorologists are introduced to the concept of elevated convection. Examples of castellanus and elevated convective clouds as seen from the ground are presented in section 3 to illustrate some of the many forms that exist, and to show that the division between elevated and surface-based convection often is indistinct. Why castellanus and elevated convection are important to forecasting is discussed in section 4, including the role that castellanus may play in the development of surface-based convection and the transition from elevated convection to surface-based forms. Finally, section 5 concludes the paper, asking further questions requiring answers from the research and forecasting communities.

2. Castellanus

a. Morphologically based definition

Clouds have been classified since the late nineteenth century using a scheme derived from that introduced by the English pharmacist Luke Howard in 1803 (Hamblyn 2001). This system, based primarily on the shape and appearance of clouds as seen from the ground, was adopted in modified form by the editors of the *International Cloud Atlas* (hereafter the *Atlas*) in the early 1900s (World Meteorological Organization 1956). Application of the scheme facilitated the use of ground-based visual cloud observations in synoptic-scale meteorological analysis, especially before the availability of geostationary satellite data in the 1970s and the implementation of the Automated Surface Observing System (ASOS) network in the 1990s.

The *Atlas* identifies 10 basic cloud types (genera) that are separated into low, middle, and high categories based on their commonly observed heights above the ground (cirrus, cirrostratus, cirrocumulus, altostratus, altocumulus, nimbostratus, stratus, stratocumulus, cumulus, and cumulonimbus). Given the emphasis in the *Atlas* on cloud shapes rather than the physical processes involved in their formation, that specific nomenclature for elevated convection does not exist on the *Atlas* is not surprising. However, the *Atlas* (Vol. 1, p. 12) does recommend the term castellanus to designate patches or layers of cloud at any level that assume turreted or cumuliform parts on their upper surfaces, particularly when the diameter of the towers is small relative to their heights. The turrets are connected by a common base and often are arranged in lines. This morphological definition is consistent with that in the *Glossary of Meteorology* (Glickman 2000, p. 118). A typical midlevel castellanus formation is shown in Fig. 1. In places, the turrets are ragged and the cloud bases have dissolved entirely, presumably the result of updraft dilution by entrainment of dry air. The *Atlas* (p. 12) refers to castellanus of this type as *floccus*. If we allow that the development of turrets on a stratiform cloud reflects, in part, the release of conditional instability (i.e., the turrets result from the presence of condensation) at a level above the surface [e.g., "high-based convective clouds," as described by Houze (1993, 189–191)], then at least some clouds that fit the *Atlas*'s description of castellanus are necessarily elevated—even though the word *elevated* is not part of the *Atlas*'s definition.

Casual observation of the sky reveals that turreted clouds can occur at all levels in the troposphere. In practice, largely because of long-standing requirements by official meteorological codes that observed clouds be classified into 1 of the 10 genera, and because earlier editions of the *Atlas* specifically associated castellanus with the genera altocumulus, castellanus has come to be viewed almost exclusively as a formation typically associated with *midlevel* clouds of the genus altocumulus. In the United States, association of castellanus with altocumulus has been furthered by widespread adoption of the aviation acronym for altocumulus castellanus (ACCAS) in surface airway observations and operational weather discussions.

b. Physically based definition

In contrast to the morphologically based definition in the *Atlas*, Scorer (1972, p. 31) offers a physically based definition of castellanus: any cumuliform cloud formation that owes its buoyancy to the occurrence of condensation, rather than to the presence of thermals reaching the level of free convection (LFC). The condensation can result from any number of processes, including uplift within orographically induced waves, ascent of potentially unstable air ahead of midtropospheric disturbances, and the saturation of layers ascending beneath widespread precipitating cloud decks such as those associated with upper lows. The examples in Scorer (1972, 31–37) illustrate that castellanus can be quite common and can include formations not traditionally considered castellanus.

Despite providing a more physical explanation for castellanus than the *Atlas*, Scorer's definition has not received widespread acceptance. Castellanus is still widely considered to be strictly a midlevel cloud formation with turrets, more or less as described in the *Atlas*. This limited view, unfortunately, perpetuates the notion of castellanus as a small subset of cloud formations set apart from other forms of moist convection. In contrast, Scorer's broader approach recognizes that castellanus is part of a continuum that ranges from the decidedly PBL-based forms of cumulus described by Stull (1985) to various elevated types such as altocumulus castellanus and convective cirrus (cirrus uncinus). Indeed, the *Glossary of Meteorology* (Glickman 2000, p. 119), echoing the *Atlas*, implies such a physically based description of castellanus by stating, "When altocumulus castellanus and stratocumulus castellanus attain a considerable vertical development, they become cumulus congestus and often develop into cumulonimbus." Hereafter in this article, we adopt Scorer's definition of castellanus because it emphasizes the specific physical process that distinguishes castellanus from other forms of convective clouds. Such an approach acknowledges that castellanus is not limited to any particular subset of genera, but rather represents an important *process* that can occur with varying frequency and with minor variation at all levels of the troposphere.

3. Examples of elevated convection and castellanus

In this section, several forms of elevated convection and castellanus are presented. The examples are not meant to be all inclusive; instead, through photographs we emphasize how these formations appear visually, and how they reflect the environmental processes responsible for their development. The presentation begins with two classic forms of castellanus—forms that most likely come to mind when one hears the word castellanus. We start with castellanus because the formation has long been recognized as a distinctive cloud form, whereas elevated convection is a term without clear visual representation.

Figure 1 shows patchy midlevel castellanus of the type that frequently accompanies regions of ascent ahead of midtropospheric disturbances in the westerlies. Such cloud formations are especially common in elevated mixed layers extending downstream from high-level heat sources such as the Mexican plateau and Rocky Mountains. Castellanus is a visual manifestation of the release of conditional instability as a result of large-scale isentropic ascent of shallow moist layers in the elevated mixed layer (e.g., Carlson and Ludlam

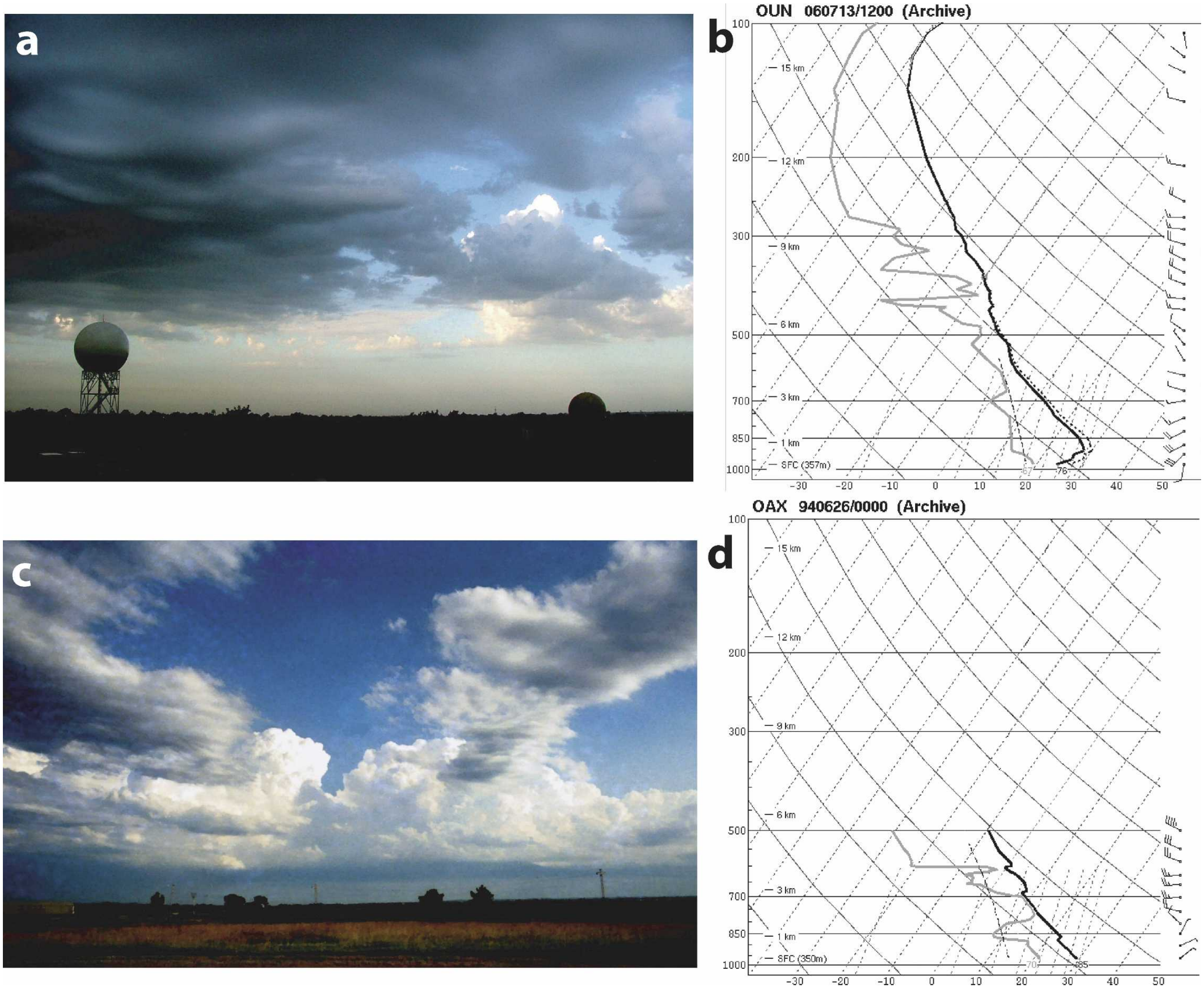

FIG. 2. (a) Western edge of an extensive area of deep castellanus associated with weak 850–700-hPa warm advection on the leading edge of an elevated mixed layer near Norman, OK, 0800 CDT 13 Jul 2006, looking southwest. (b) Rawinsonde observation at 0700 CDT 13 Jul 2006 at Norman, OK. Wind speeds in knots. The sounding suggests that the clouds in Fig. 2a were based around 600 hPa. (c) Elevated thunderstorms forming above a slowly moving warm front near Omaha, NE, at about 1830 CDT 25 Jun 1994, looking south. (d) Rawinsonde observation at 1900 CDT 25 Jun 1994 at Omaha, NE. Wind speeds in knots. The sounding suggests that the storms in Fig. 3a were based around 775 hPa.

1968). The moist layers may be derived from the evaporation of ordinary PBL cumuli within the elevated mixed layers at points upstream from the castellanus or could reflect layers where PBL cumuli spread out (anviled) beneath weak inversions in the elevated mixed layers (Ludlam 1980, p. 246). The castellanus usually first appear in what may be the crests of low-amplitude gravity waves set up by the underlying topography (e.g., Ludlam and Scorer 1957, p. 39; Scorer 1972, p. 22). Initially laminar, the clouds subsequently break into cumuliform turrets aligned with the mean shear at their level as latent instability is released through condensation. In many parts of the world, castellanus formations on clouds have long been considered forerunners of thunderstorms (e.g., Ley 1894; World Meteorological Organization 1956; Ludlam and Scorer 1957, p. 39), and statistical evidence exists to support this (e.g., Brooks 1951).

If the elevated moist layer in a region of isentropic ascent is comparatively deep, castellanus may develop sufficient depth to produce showers. Figure 2a provides an early morning view of the western edge of an extensive area of deep castellanus associated with an area of weak 850–700-hPa warm advection at the leading edge of an elevated mixed layer over the southern plains. A rain shower is present just beyond the left side of the photo. The smooth, laminar cloud bases (Fig. 2a, top left) are especially characteristic of deep and/or widespread areas of castellanus and reflect the isentropic ascent initially responsible for their development. Similar castellanus formations with extensive laminar bases appear frequently above thunderstorm outflow boundaries. The proximity sounding in Fig. 2b suggests that the clouds were based around 600 hPa.

Areas near warm and stationary fronts are frequent sites of deep elevated convection. As previously noted, such convection is of considerable interest given its potential to produce severe weather, even well within the cold air (e.g., Neiman et al. 1993; Grant 1995; Trapp et al. 2001; Horgan et al. 2007). Figure 2c shows elevated thunderstorms forming about 150 km north of a slowly moving warm front. The convection is sprouting from an extensive band of laminar clouds that appear to be based at the same level (around 775 hPa, per radiosonde data in Fig. 2d) as the patchy wave clouds in the foreground. These storms and others farther south (in the direction of this view) continued to strengthen after the photo was taken. Cloud-layer shear was in excess of 25 m s^{-1} (Fig. 2d). Supercell storms that evolved from this convection produced a tornado in northwest Missouri, even though conventional surface data and visual observations of laminar low- to midlevel clouds strongly suggested that the updraft bases were elevated on the cool side of the front.

When the environment is sufficiently cold and ice nuclei are present, convective clouds with limited vertical extent (e.g., altocumulus) can glaciate, producing trails of ice crystals known as fallstreaks (e.g., Scorer 1972; Hobbs and Rangno 1985). Over time, fallstreaks become aligned with the shear at their level, assuming a hooked shape when speed or directional shear is marked (Fig. 3a). Because of the low saturation vapor pressure of ice in their environment, fallstreaks evaporate slowly (compared to liquid or supercooled water droplets) and tend to persist over time. Distorted by the wind, the fallstreaks often assume a fibrous texture when seen from the ground.

Fallstreaks and their parent convective clouds are commonly referred to as cirrus uncinus ("hooked cirrus"), even though such formations often originate from altocumulus and may occur at altitudes lower than those commonly associated with cirrus (at or above 6 km AGL in the midlatitudes according to the *Atlas*). Although cirrus uncinus appear quiescent to casual observation, such clouds actually are in a state of continuous redevelopment. The parent convective elements, known as generating cells (e.g., Heymsfield 1975; Ludlam 1980; Atlas 2001), constantly re-form as latent heat is released via condensation and freezing. Similar generating-cell–fallstreak couplets enhance precipitation in deep nimbostratus cloud systems (e.g., Houze 1993, 205–211), the only real difference being that nimbostratus-generating cells are embedded in widespread light precipitation, whereas cirrus cells are surrounded by clear sky. Cirrus-generating cells appear as small, white puffs above the fallstreaks in the top-left part of Fig. 3a; the clouds were between 375 and 325 hPa according to the sounding in Fig. 3b. If one accepts Scorer's definition of castellanus, the generating cells of cirrus uncinus are, in fact, an aberrant form of castellanus.

Long-lasting, regenerative bands of castellanus sometimes form on the leading edge of forward-propagating midlatitude mesoscale convective systems (MCSs). Such formations are most apparent when the cold pool and gust front have begun to outrun the main convective core late in the MCS's life cycle and the system has developed a significant component of front-to-rear flow (Fig. 3c). Radar observations of MCSs with regenerative elevated convective bands similar to Fig. 3c suggest that, as the cold pool deepens beneath the clouds (in response to the continued advance of the deep convection responsible for the cold pool's development), the towers also deepen and subsequently merge with the parent MCS. In this manner, the castellanus becomes an integral part of the convective system. The cloud formation in Fig. 3c has a great horizontal extent (the band continued in both directions beyond the field of view) and a smooth base typical of elevated convection. The formation changed little over time, and there was an absence of convective towers ahead of it. Together, these observations suggest that the castellanus band reflects the presence of a broad, slablike swath of forced ascent on the leading edge of the MCS, as discussed by Bryan and Fritsch (2001). The distribution, intensity, orientation, and overall character of the radar echoes of the convective system associated with the cloud band shown in Fig. 3c (not shown) bear close resemblance to the example in Bryan and Fritsch (their Fig. 11). As Bryan and Fritsch (2001) noted, such areas of ascent often exhibit moist absolute instability (i.e., persistent saturation in layers with lapse rates greater than moist adiabatic). Indeed, a proximity sounding made just ahead of the convective system shows a moist, absolutely unstable layer between 750 and 650 hPa above a more stable layer at the surface (Fig. 3d). Thus, some castellanus formations may be manifestations of the release of moist absolute instability.[1]

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[1] Because soundings are nominally vertical, yet flow toward and atop the leading edge of an MCS gust front is quasi-horizontal, the true meaning of soundings that contain moist absolutely unstable layers is open to question. Our point here is that castellanus clouds are sometimes present when nearby soundings depict moist absolute instability.

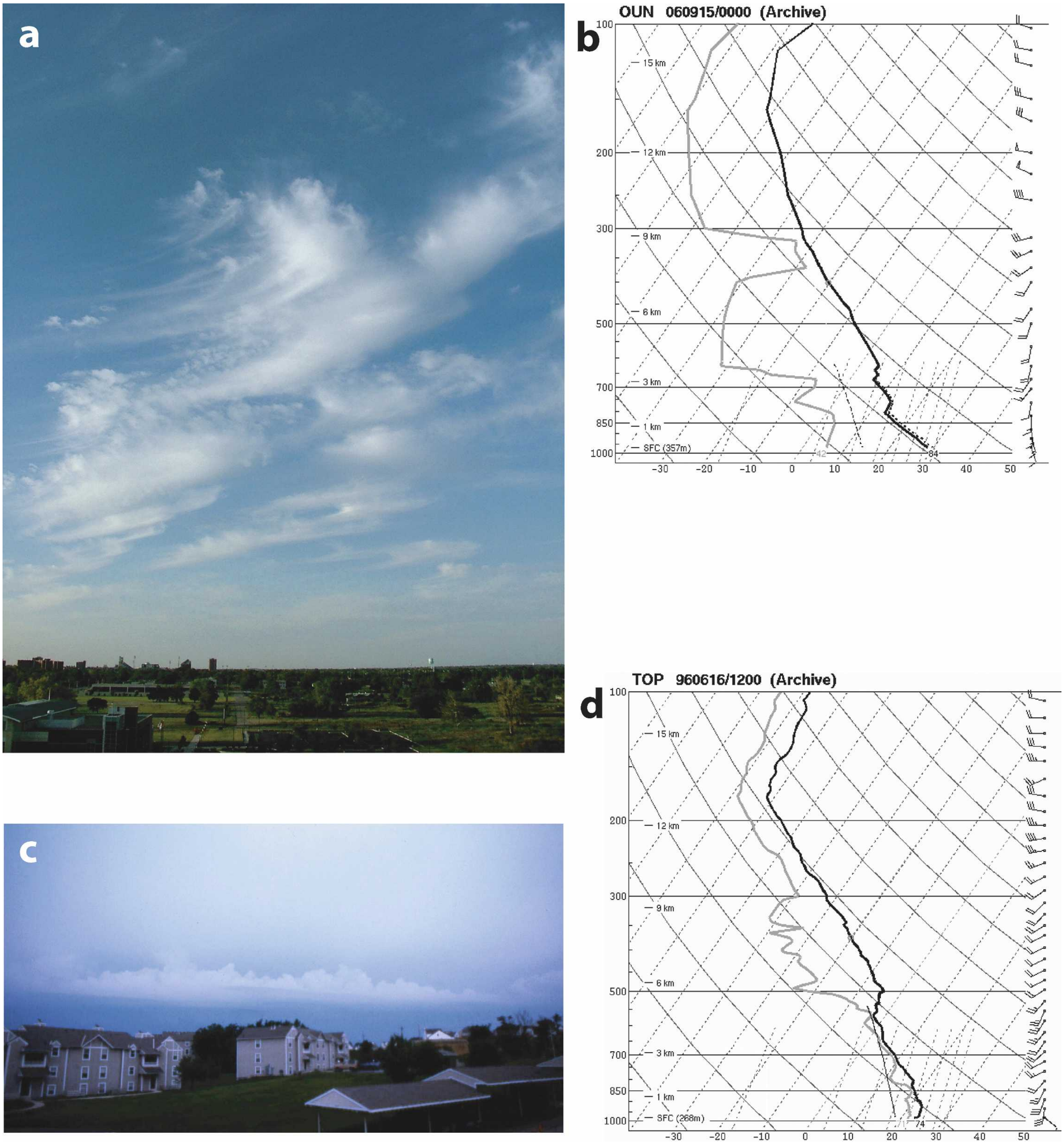

FIG. 3. (a) Hook-shaped fallstreaks trailing from elevated shallow convection over Norman, OK, at 1845 CDT 14 Sep 2006, looking north. (b) Rawinsonde observation at 1900 CDT 14 Sep 2006 at Norman, OK. Wind speeds in knots. The sounding suggests that the clouds in Fig. 3a were between 325 and 375 hPa. (c) Castellanus band above the gust front of an approaching MCS at Kansas City, MO, at 0730 CDT 16 Jun 1996; wide-angle view looking west-northwest. The sky above the castellanus is covered by anvil material spreading toward the observer ahead of the MCS. (d) Rawinsonde observation at 0700 CDT 16 Jun 1996 at Topeka, KS; at the time of the sounding, the observation site was located just east of the MCS shown in Fig. 3c. A moist, absolutely unstable layer is present between 750 and 650 hPa. Wind speeds in knots.

The examples of castellanus and elevated convection presented thus far suggest that the updrafts were not based in the boundary layer. Implicit in Scorer's definition of castellanus, however, is the notion that castellanus can originate at any level, *including* the PBL. Two examples of PBL-based castellanus are shown in Figs. 4a,b. This form of castellanus is most common in areas where surface-based updrafts tend to be weak (e.g.,

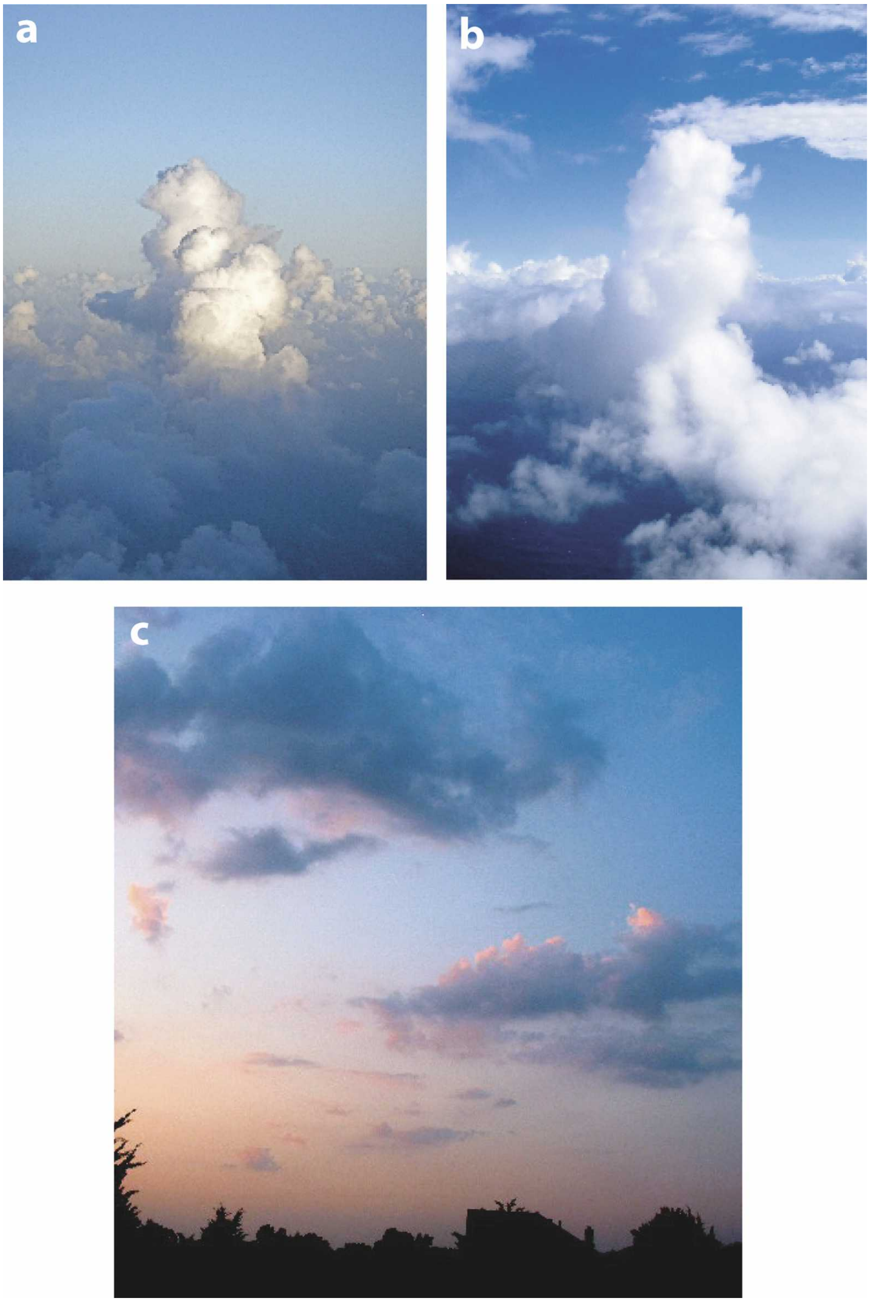

FIG. 4. Two examples of castellanus towers rising from foundations of shallower PBL clouds over the tropical western Atlantic. [Taken near Barbuda on 16 Jan 2005 during the Rain in Cumulus over the Ocean (RICO) field campaign.] (c) PBL castellanus at sunset, forming in the crests of waves left moistened by ordinary diurnal boundary layer cumuli over Norman, OK, at 2044 CDT 1 Jul 2006, looking north. Rawinsonde data suggest that the clouds were based around 700 hPa.

over oceanic regions in low latitudes). Feeble boundary layer convergence in such environments can form convective clouds with limited vertical extent that subsequently deepen through latent heat release. Clouds like those in Figs. 4a,b are not associated with strong low-level convergence; as a result, they are quickly overwhelmed by entrainment of dry air and become spindly. The narrow towers of such clouds contrast with the broader outlines of true cumulus congestus, the sustaining parcels of which involve the depth of the PBL and are supported by more persistent convergence. Somewhat analogously, so-called "turkey-tower" cumulus congestus (e.g., Fig. 1.4 in Doswell 2001), wherein deep, PBL-based convective towers rapidly grow but subsequently quickly dissolve from the base up, might be considered a hybrid form of castellanus by the *Atlas*'s definition, in the sense that the towers are taller than they are wide.

Another variety of PBL-based castellanus is shown in Fig. 4c. Clouds of this type are occasionally observed around sunset following a day of diurnal convection with relatively limited vertical extent. As with other forms of castellanus, the turrets grow from patches of cloud that develop in the crests of shallow orographic lee waves. In this case, however, the waves exist at the top of the PBL, which has been left moistened by the evaporation of the previous afternoon's cumulus (Ludlam and Scorer 1957). Formations like the one in Fig. 4c often are dismissed as being the dying remnants of ordinary diurnal cumulus and, prior to the most recent edition of the complete *Atlas* (1956), were known as *stratocumulus vesperalis* ("evening stratocumulus"). Careful observation, however, reveals that the turrets arise from recently formed patches of wave clouds; the turrets, therefore, likely derive their buoyancy from condensation in the waves. Normally, such clouds are of little significance as they quickly dissipate upon entraining drier air from above the PBL. Operational experience, however, has shown that such clouds, particularly over the central United States, may mark the initial stages of elevated nocturnal thunderstorms, forming on the leading edge of a moisture gradient associated with a strengthening low-level jet stream. Such formations therefore bolster the notion of castellanus as a harbinger of thunderstorms.

PBL-based castellanus illustrate that the partition between purely elevated and purely surface-based forms of convection is far from distinct. Such clouds, as with the other types presented earlier, also remind us that, in failing to adopt a more precise classification scheme for castellanus and elevated convection, we may overlook valuable clues that such clouds provide about the state of the atmosphere in their vicinity, and about convection initiation in general.

4. Some practical aspects of elevated convection and castellanus

Although elevated convective clouds with limited vertical extent often are relatively unimportant for convective storms forecasting, occasions occur when such clouds intimately are tied to the development of significant convective weather. The satellite sequence in Fig. 5 illustrates a situation of this type in which convective outflow produced by an area of midlevel castellanus altered low-level convergence along a cold front. The cold front, oriented west–east and marked by the region of featureless low clouds over northern Wisconsin (Fig. 5a), was preceded by an area of the castellanus over the central part of the state. West-northwesterly midlevel flow mixed to the surface within the castellanus outflow (Figs. 5a and 5b). This weakened convergence along the front as southwesterly surface winds in the undisturbed warm sector became light and variable or west-northwesterly in the wake of the outflow (Figs. 5b,c). The clouds also diminished heating in the prefrontal warm sector. These factors appeared to be at least partially responsible for the absence of deep convection along the front throughout most of the day (Figs. 5a and 5b). In contrast, surface-based thunderstorms with hail formed during the afternoon at the intersection of two castellanus-derived outflow boundaries in southeast Wisconsin (Fig. 5c; an animation of this imagery is available at the Journals Online Web site at http://dx.doi.org/10.1175/2008WAF2222118.s1). In that region, the outflow boundaries encountered unmodified warm, humid southwesterly flow in the prefrontal warm sector, where surface heating and convergence were sufficient to initiate surface-based storms. Cases like this illustrate how the location and evolution of deep *surface*-based convection can be affected by the presence of castellanus clouds.

Another example of how elevated convection may affect subsequent surface-based storm development is shown in Fig. 6. Figure 6a, made shortly after sunrise, shows an elongated field of castellanus with bases near 700 mb (per regional soundings; not shown) over central and eastern Oklahoma. Cloud-layer winds were west-southwesterly at 20 kt (10 m s^{-1}) on the poleward side of a subtropical ridge. The location and spatial extent of diurnal thunderstorms that formed over northern and western Arkansas later in the day (Fig. 6b) bear close resemblance to the extrapolated outlines of the morning castellanus field over Oklahoma (an animation of this imagery is available at the Journals Online Web site at http://dx.doi.org/10.1175/2008WAF2222118.s2). We speculate that the field of castellanus clouds marked a region of enhanced midlevel moisture that reduced entrainment of dry air as it moved downstream across developing PBL-based convection in Arkansas.

Some of the most challenging forecast situations involving elevated convection are those in which the clouds deepen, redevelop nearby, or both, ultimately becoming surface based. Cases of this type herein are referred to as *transition events*. Questions as to if, when, and where a transition event will occur are forecast challenges because the processes responsible for the

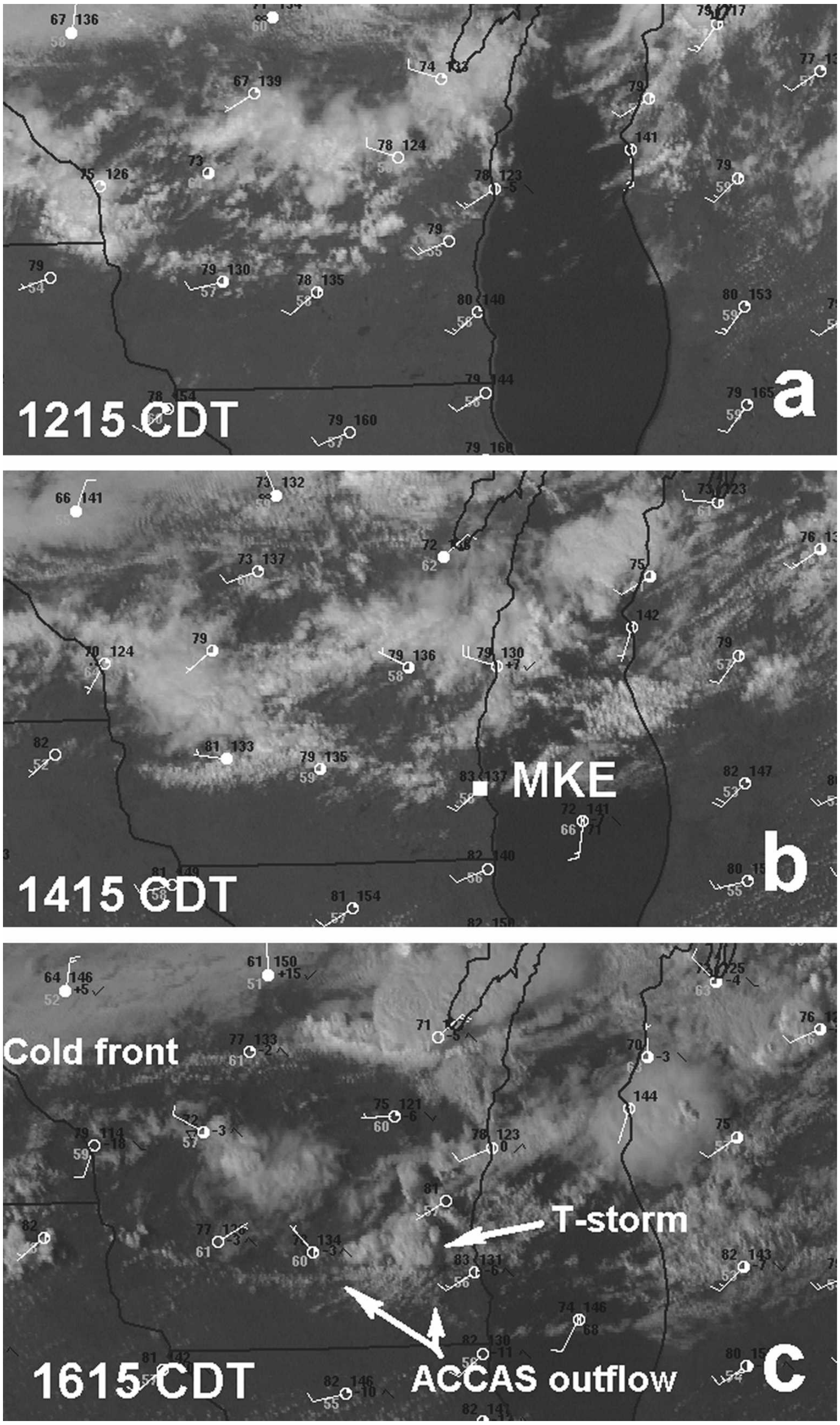

FIG. 5. Visible satellite data and surface observations (English units) over WI and Lake Michigan at (a) 1215, (b) 1415, and (c) 1615 CDT 8 Sep 2006. Mottled clouds over the central parts of WI and Lake Michigan in (a) and (b) are castellanus based near 700 hPa (per area rawinsonde data). Winds at this level were west-northwest at 15 m s^{-1}. "MKE" and white square in (b) denote location of Milwaukee. Pertinent features mentioned in the text are shown in (c), where ACCAS is used to denote altocumulus castellanus. Two castellanus-derived outflow boundaries are visible over southern WI and southern Lake Michigan in (c); they intersect near the developing thunderstorm ("T-storm") west of Milwaukee. The outflow boundaries are identifiable via surface observations in (a) and (b), and become apparent in the satellite imagery in (b) and (c) as they serve as a focus for the development of afternoon boundary layer cumulus clouds.

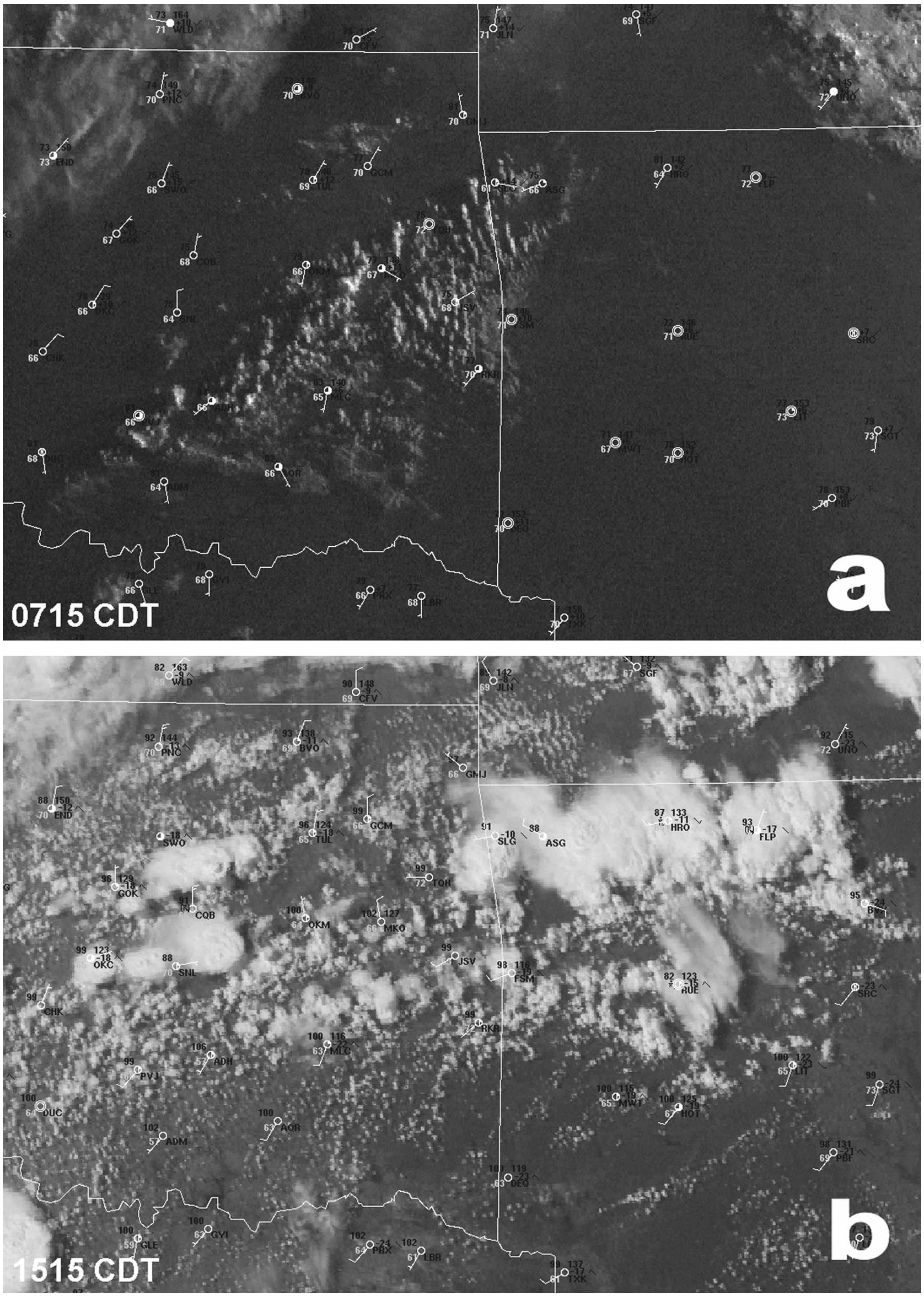

FIG. 6. Visible data satellite data and surface observations (English units) over OK and AR at (a) 0715 and (b) 1515 CDT 14 Aug 2006. Area soundings suggest that the castellanus clouds in (a) were based near 700 hPa; winds at this level were west-southwest at 10 m s^{-1}.

transition are themselves difficult to forecast. For example, the strength and areal extent of convective inhibition (i.e., thermodynamic profiles), the location and depth of outflow boundaries, and spatial and temporal changes in mesoscale forcing for ascent all can affect the likelihood for transition.

In the transition event shown in Fig. 7, elevated thunderstorms developed within bands of morning castellanus over central Nebraska near North Platte (Figs. 7a–c). The castellanus formations were based near 550 hPa (Fig. 7g). The clouds are distinguishable by their frail and tattered appearance in the satellite imagery (Figs.

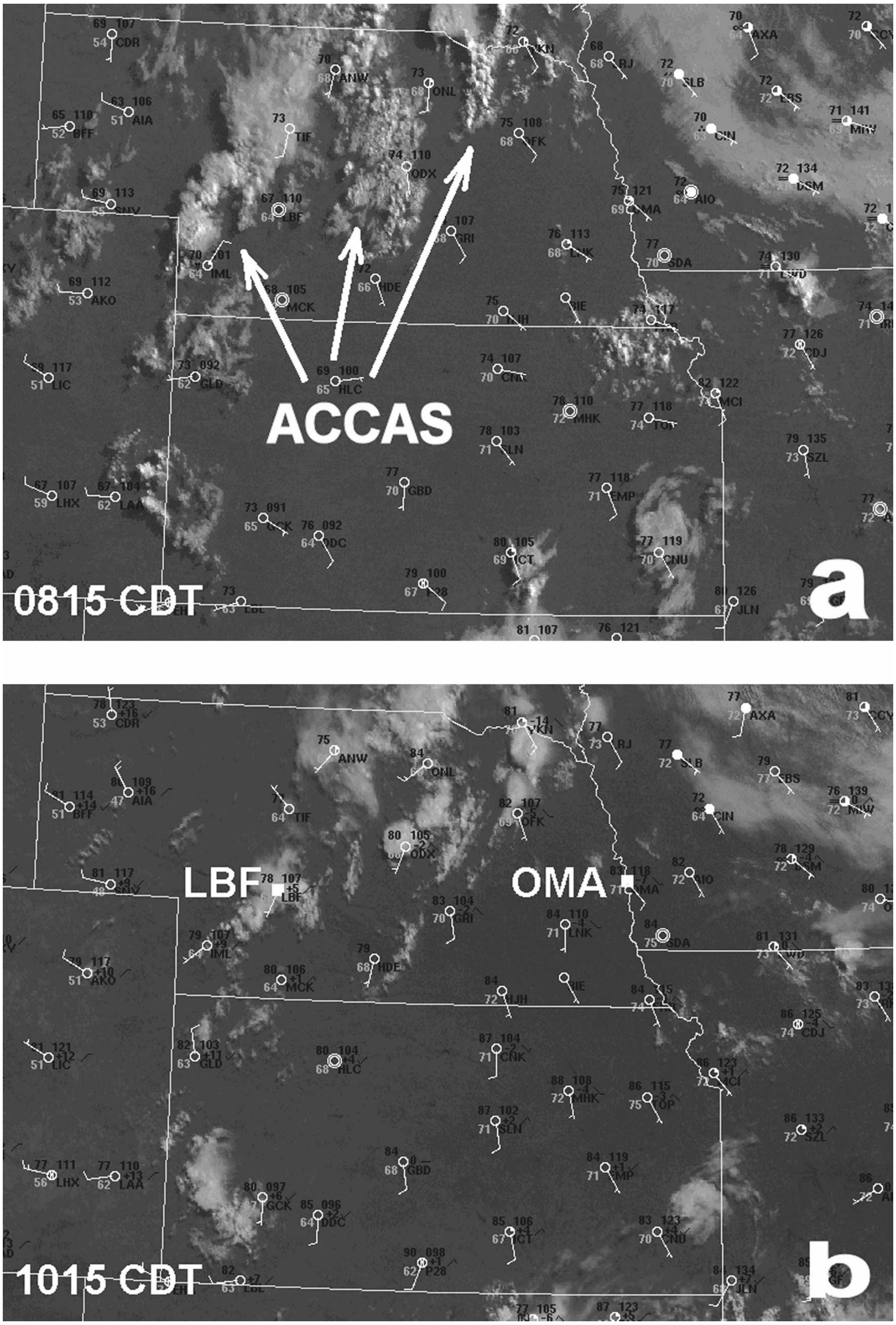

FIG. 7. (a)–(c) Visible data Geostationary Operational Environmental Satellite (GOES) imagery over part of the central United States, and (d)–(f) base reflectivity radar data from Omaha, NE, on 13 Jul 2006, with conventional surface data (English units) overlay and ACCAS used to denote altocumulus castellanus. Times are (a) 0815, (b) 1015, (c) 1215, (d) 1305, (e) 1505, and (f) 1705 CDT. LBF, OMA, and white squares in (b) denote locations of North Platte and Omaha. Rawinsonde observations at 0700 CDT 13 Jul 2006, at (g) North Platte, NE, and (h) Omaha, NE, and at 1300 CDT 13 Jul 2006 at (i) Omaha, NE. Wind speeds in knots. Elevated thunderstorms forming from midlevel convection in (c) became surface based during the early afternoon [shortly after the time of (d)] as surface heating eliminated inhibition present earlier in the day [cf. soundings (h) and (i)]. Surface-based storms forming on outflow boundary in lower-left part of (f) subsequently evolved into a new MCS.

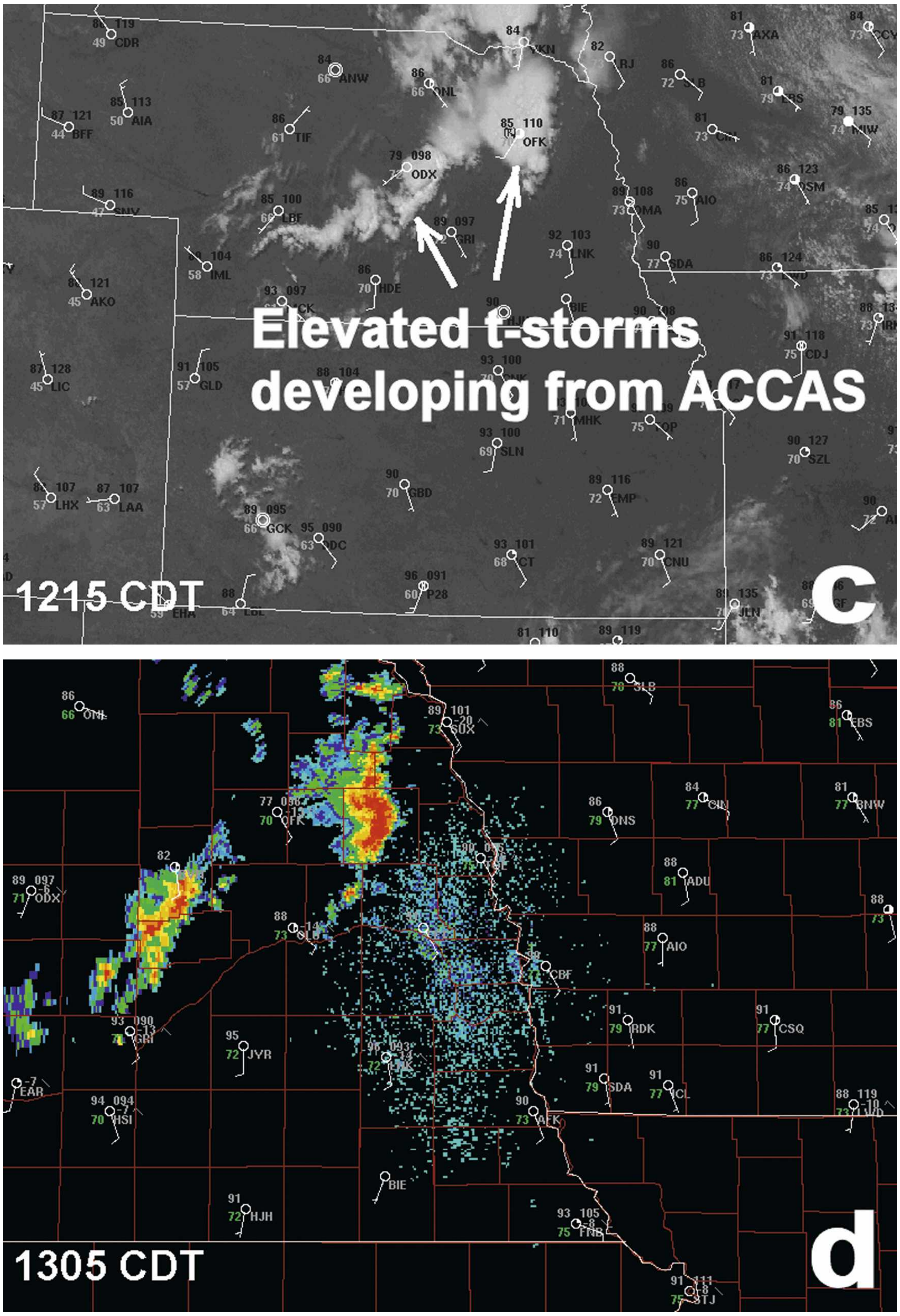

FIG. 7. (*Continued*)

7a–c), and by their comparatively fast motion relative to the surface winds (an animated loop of the imagery in Figs. 7a–c is available at the Journals Online Web site at http://dx.doi.org/10.1175/2008WAF2222118.s3). This convection produced outflow boundaries that later served as a focus for surface-based storm development over southeast Nebraska as the boundaries moved into the region where 1) convective inhibition was weaker (cf. Figs. 7g and 7h) and 2) diurnal heating further lessened inhibition (cf. Figs. 7h and 7i). Rapid increases in radar reflectivity, cross-sectional radar data (not shown), and changes in the speed and direction of storm motion

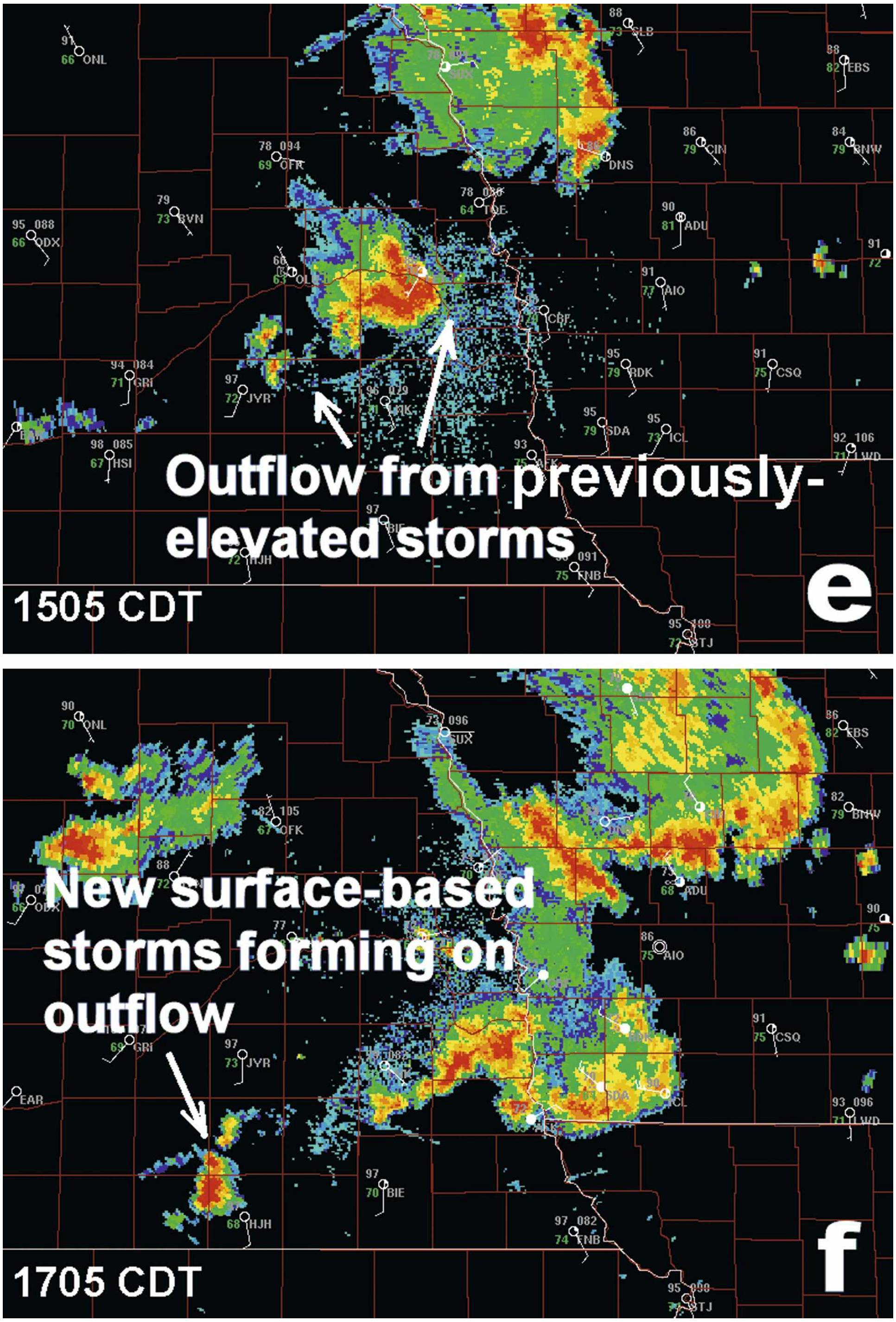

FIG. 7. (*Continued*)

(an animated loop of radar reflectivity over eastern Nebraska is available at the Journals Online Web site at http://dx.doi.org/10.1175/2008WAF2222118.s4) all suggest that some of the elevated storms in Fig. 7c themselves became surface based as they moved into the heated environment near Omaha during the early afternoon (Fig. 7d). Outflow from these more vigorous storms produced strong convective outflows (Fig. 7e) that subsequently fostered the development of additional surace-based storms in southeast Nebraska later

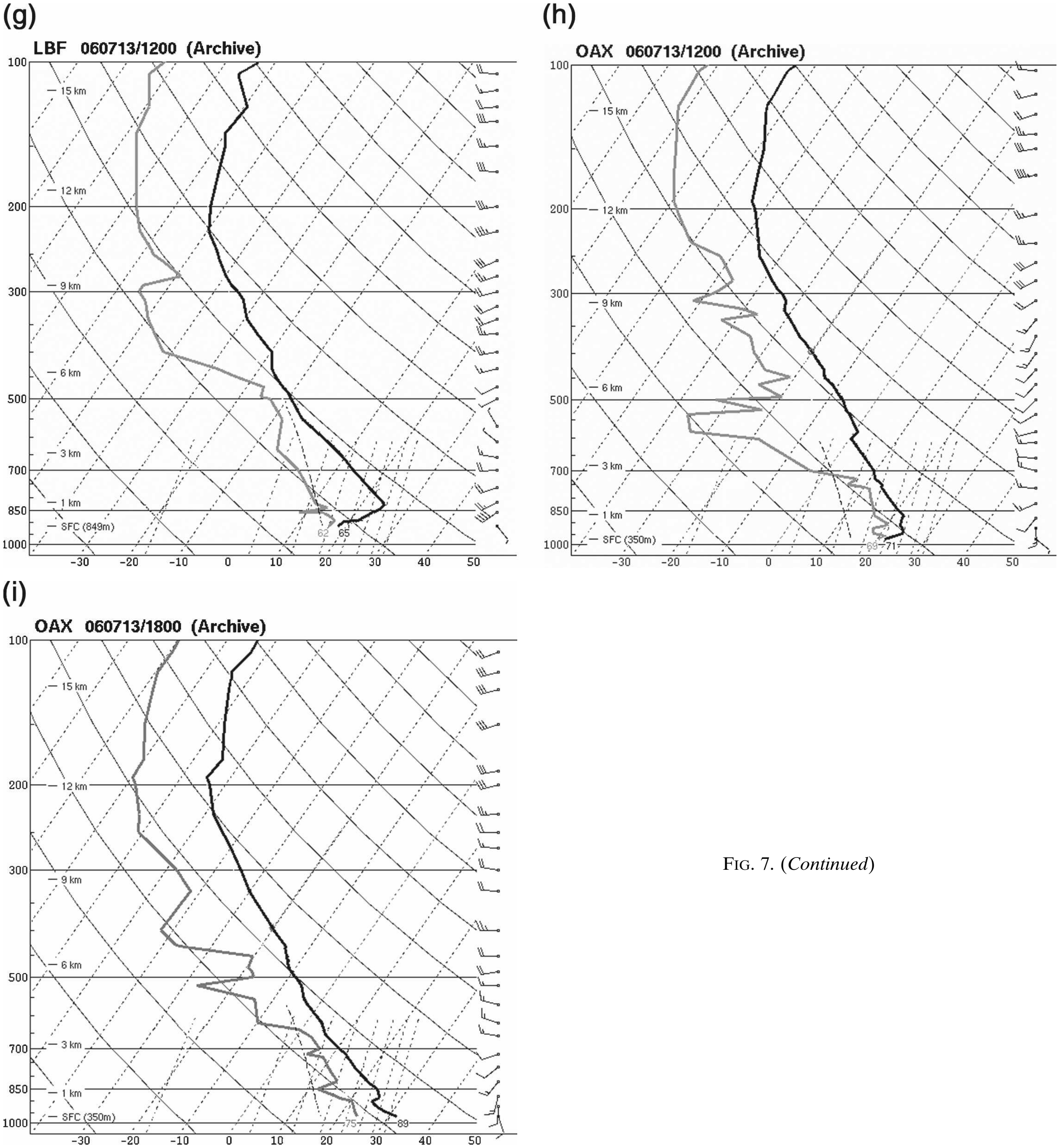

FIG. 7. (*Continued*)

in the day (Fig. 7f). These storms, in turn, merged with other developing surface-based cells to form a larger-scale, forward-propagating MCS that moved south into parts of Missouri and Kansas; the MCS produced damaging wind the following evening.

One of the more dramatic transition events over the United States in recent years occurred on 17 August 1994, when an area of castellanus in southern Kansas evolved into an intense derecho. Supercells in the convective system left a path of destruction that included 50 m s^{-1} wind gusts and grapefruit-sized hail in Lahoma, Oklahoma (Janish et al. 1996). Another derecho that evolved from convection believed to have been at least partly elevated occurred over northern Kansas and Missouri on 2 June 1982 (Rockwood and Maddox 1988). In both of these cases, rapid spatial and temporal changes in boundary layer instability and inhibition were observed in the areas where the convection became surface based.

The Lahoma and Kansas–Missouri events attained maximum intensity shortly after the elevated convection moved or developed into a region experiencing strong low-level destabilization (mainly in the form of moisture advection). In contrast, Coniglio et al. (2007) present an example of an elevated severe-wind-producing MCS that *weakened* as it moved from the cool side toward the warm side of an Oklahoma cold front. Part of the radar evolution of this case is shown in Fig. 8. The front is oriented roughly parallel to the southern edge of the lifted-index maximum that extends from the northern Texas Panhandle into north-central Oklahoma in Figs. 8a–d. The nocturnal convective system evolved from an elevated supercell in southeast Colorado (Figs. 8a and 8b) to a bow echo that produced gusts in excess of 30 m s^{-1} across southwest Kansas and northwest Oklahoma (Figs. 8b–d). The forward-propagating system began to weaken as it encountered higher surface-based instability close to the surface boundary (Figs. 8e and 8f; an animated loop of reflectivity is available at the Journals Online Web site at http://dx.doi.org/10.1175/2008WAF2222118.s5). Based on this, one might conclude that kinematic differences along the MCS's path evidently were responsible for the system's decline. For example, wind profiles were indeed less favorable for renewed cell development on the downwind (southeast) side of the system cold pool on the cool side of the front than they were on the warm side. On the cool side, easterly low-level winds were surmounted by west-to-northwest flow at mid- and upper levels. Such a setup can foster convergence and new cell development on the downwind side of the system cold pool (Corfidi 2003).

Although kinematic factors may have been involved, evidence also suggests that the MCS likely weakened because it moved beyond an axis of maximum *elevated* instability as it neared the surface front. This instability axis was associated, in part, with a plume of steep midlevel lapse rates that extended east-northeast from northern New Mexico (Coniglio et al. 2007, their Figs. 15 and 16). The lifted index data in Figs. 8a–f show that surface-based instability was indeed higher near the front than it was farther north. Evidently, this difference in lifted indices across the front was not sufficient to offset the more hostile midlevel thermodynamic environment and reduced magnitude of cold-pool-relative flow that existed near and south of the front.

The MCS just described involved system propagation (i.e., new cell development) via surface or near-surface convergence at the leading edge of the system cold pool during much of its existence. Yet, surface (Fig. 8), profiler, and sounding data (not shown) indicate that the system clearly was elevated, at least as the system moved into northwest Oklahoma. Cases such as this illustrate that the line between elevated and surface-base convection often is indistinct. Such systems also raise questions as to if, how, and when gradually lowering, elevated convection will produce damaging surface wind.

Although forecasting the behavior of convective systems like the one just described is problematic, storms that remain elevated throughout their lifetimes, yet produce damaging surface winds, are also very challenging. An elevated supercell that produced significant wind damage in northeast Kansas and northwest Missouri on the morning of 12 March 2006 provides an example (Goss et al. 2006). The storm left a swath of surface temperature *rises* in its wake. Proximity soundings suggest that the warming may have resulted from penetration of storm-induced saturated downdrafts through a shallow, but very cool, boundary layer (prestorm surface temperatures were around 8°C). A similar event occurred over southeast Kansas on 8 April 2008, as this paper was in the final stages of preparation. Both cases involved strong low-level warm advection, with a shallow (approximately 0.5 km deep) layer of cold air surmounted by a deep elevated mixed layer that extended from near 850 to 500 hPa (not shown). The storms appeared to be based within 50-hPa-deep saturated layers based near 800 hPa (i.e., within the elevated mixed layers). Events like these are particularly vexing as elevated supercells in similar environments are routinely observed without intense surface gusts.

Elevated thunderstorms that occur in environments of strong warm advection near fronts are sometimes arranged regularly spaced in a line oriented roughly parallel to the isentropic surfaces in their vicinity (Fig. 9a). In other cases storms appear in short bands oriented roughly perpendicular to the isentropes (Fig. 9b). The storms in Fig. 9a, some of which are supercells, are evenly spaced at intervals of approximately 1½ storm diameters. In Fig. 9b, the spacing of the elongated storms varies from about 1 storm width along the Missouri–Illinois border to several storm widths in southeast Illinois. Other degrees of separation also have been observed, and storm spacing sometimes varies over time. The factors governing the regular arrangement of elevated convective cells are not known, and the responsible processes likely are not the same in all cases. Storm spacing does *not* appear to be directly related to the spacing of horizontal roll circulations in the upstream warm sector, nor does it appear to be a function of a readily observable characteristic of the storms themselves. Depending upon the motion of the storms relative to their arrangement, some locations may experience repeat episodes of hail, wind, and rain as individual cells pass by. To our knowledge, documentation of regularly arranged elevated storms has not heretofore appeared in the literature. (Animated loops of radar reflectivity for the cases presented in Fig. 9 are available at the Journals Online Web site at http://dx.doi.org/10.1175/2008WAF2222118.s6 and http://dx.doi.org/10.1175/2008WAF2222118.s7.)

The first case in this section (Fig. 5) illustrated a way in which castellanus can affect surface-based storm development, and we noted in section 3 that the growth and movement of some MCSs involve castellanus formations above the system outflow boundary. In a recent numerical investigation, Fovell et al. (2006) presented evidence that discrete propagation of MCSs sometimes involves the development of castellanus-type formations in areas well removed from the gust front. These clouds form when conditions are favorable for the maintenance of internal gravity waves ahead of the convective system. In their simulation, a shallow low- to midlevel cloud deck is first produced by low-frequency gravity waves excited by the main convective cluster of an MCS. This cloud layer then serves as the seat for new cell formation ahead of that cluster. Formation of the new cells occurs in tandem with passing high-frequency gravity waves associated with individual convective bursts in the storm system. Some of the new cells augment the original MCS by merging with it; other cells, meanwhile, appear to have a detrimental effect on the original storm system. Those cells that have a negative impact ultimately supplant the original updraft cluster, resulting in discrete propagation (i.e., redevelopment) of the convective system in the downwind direction. Details regarding the origin and evolution of updraft development in the shallow cloud layer, and how the convective cells relate to some of the cloud formations discussed in this paper are unclear. However, the new convective towers do not arise from convergence or heating at the surface, and system propagation is not due to uplift along the leading edge of the cold pool. Situations of the type modeled by Fovell et al. (2006) most often occur at night when the lower-tropospheric relative humidity is greatest. These situations also require a forward-tilted anvil to serve as a duct for the high-frequency gravity waves. Coincidentally, these conditions often are satisfied during the later stages of MCSs when, as discussed in section 3, a link may exist between castellanus and the presence of moist absolute instability. Although our intent is not to imply that moist absolute instability is necessarily involved in the form of discrete propagation modeled by Fovell et al., their work does suggest yet another way in which castellanus-type formations might affect the evolution of sensible weather.

5. Concluding remarks

This paper has presented a discussion of elevated convection and castellanus. Our aim has been to encourage more critical thinking about these cloud formations and to demonstrate that our questions are not purely academic—they have real-world forecasting application. This section briefly summarizes what has thus far been presented and provides a few additional thoughts to foster further discussion.

Routinely in the scientific literature and in operational forecast discussions, convection is classified definitively as either surface based or elevated. Given what has been presented in this paper, such statements appear to reflect greater confidence than the current understanding of convective processes supports. Rather than furthering a binary point of view of convective cloud and storm behavior, we argue for a continuum of convection, ranging from purely surface-based types to purely elevated forms. A similar continuum, we suggest, exists between those forms driven predominantly by latent heat release and those associated with thermals rising through the LFC. Between these extremes, an individual convective cloud or storm may exhibit varying "degrees of elevation," "castellanusness," or both. Over time a given cloud or cloud system also may become more or less elevated or more or less castellanus-like in response to changing environmental conditions (as illustrated, e.g., by the case in Fig. 7).

A range of convective clouds sometimes is apparent associated with midlatitude upper-level disturbances. Figure 10, for example, is a visible data satellite image showing part of the cloud system of a weak trough in the westerlies over the south-central United States. The disturbance is typical of those in relatively dry regimes where obscuration by low stratiform clouds is minimal. The axis of the trough, denoted by a dashed white line in Fig. 10, is located just east of the New Mexico–Texas border and is marked by deep surface-based convection (thunderstorms). This convection grades into increasingly elevated forms with eastward extent over Kansas and Oklahoma. The leading edge of the trough-associated cloud system is composed of shallow, highly elevated and glaciated convection; these clouds were seen from the ground in Fig. 3a. Similar gradations in convection are also commonly seen in the cloud systems of stronger midlatitude disturbances. Recognizing the indistinct border that exists between surface-based and elevated forms of convection is key toward achieving a better understanding of convective phenomena in general.

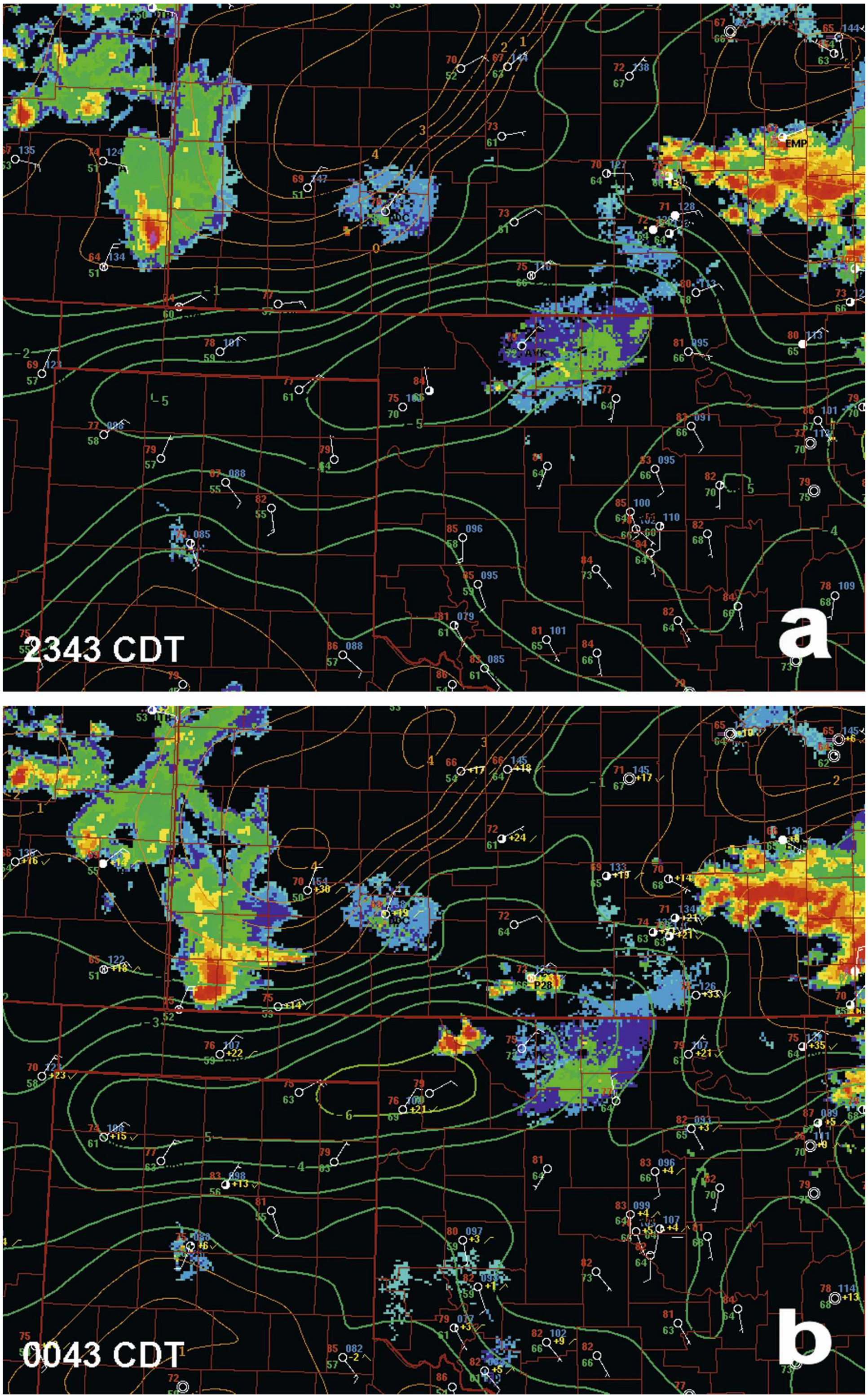

FIG. 8. Composite reflectivity radar sequence over southeast CO, southwest KS, and northwest OK at (a) 2343, (b) 0043, (c) 0143, (d) 0243, (e) 0343, and (f) 0443 CDT 30 Jun–1 Jul 2005, showing an elevated, forward-propagating MCS north of a west-southwest–east-northeast-oriented front. The MCS weakened as it moved into the region of maximum surface-based instability (most negative lifted index values) near the warm side of the front. Conventional surface data overlay (English units) with surface-based lifted index depicted by brown (values greater than and equal to zero) and green (values less than zero) contours (°C).

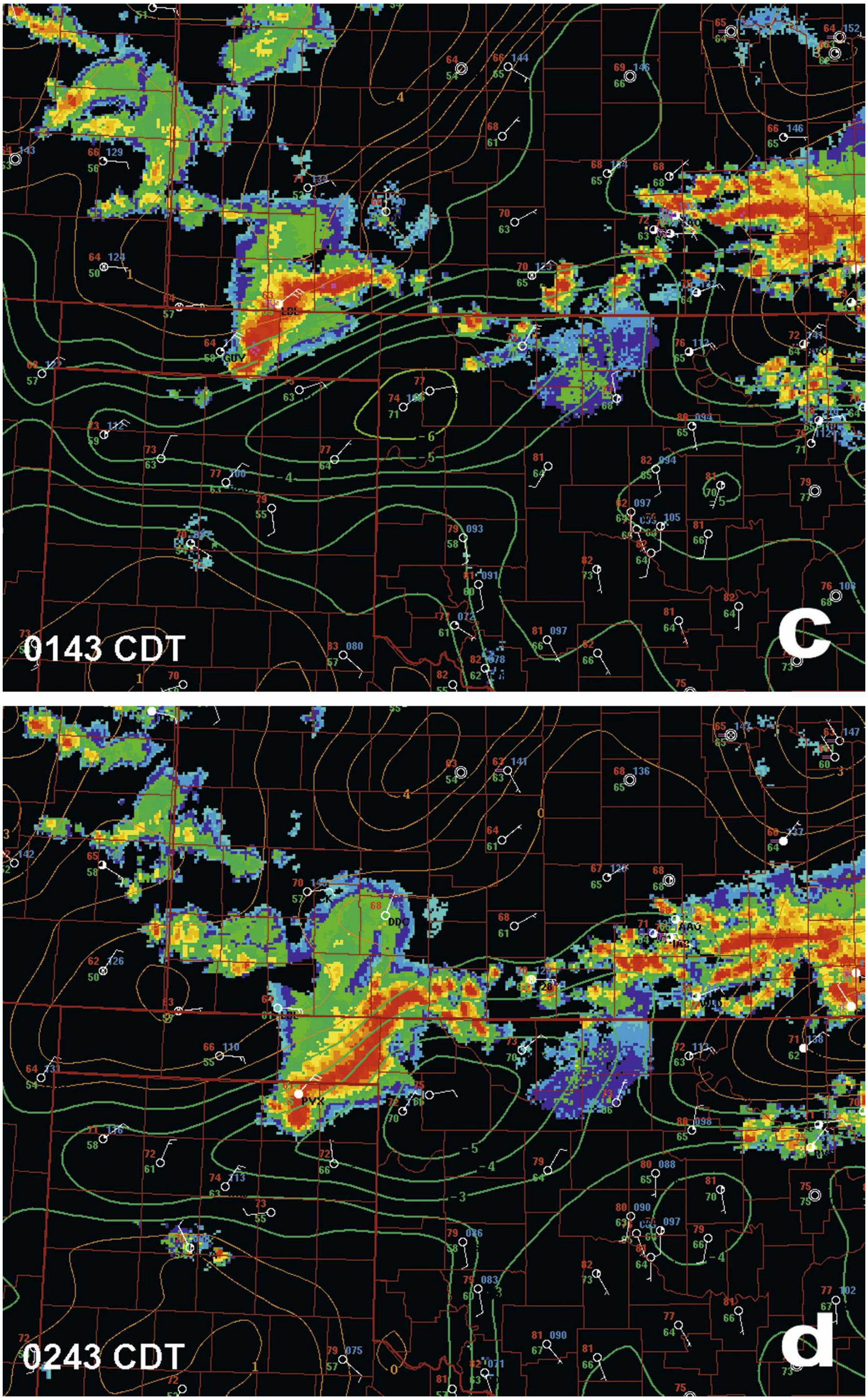

FIG. 8. (*Continued*)

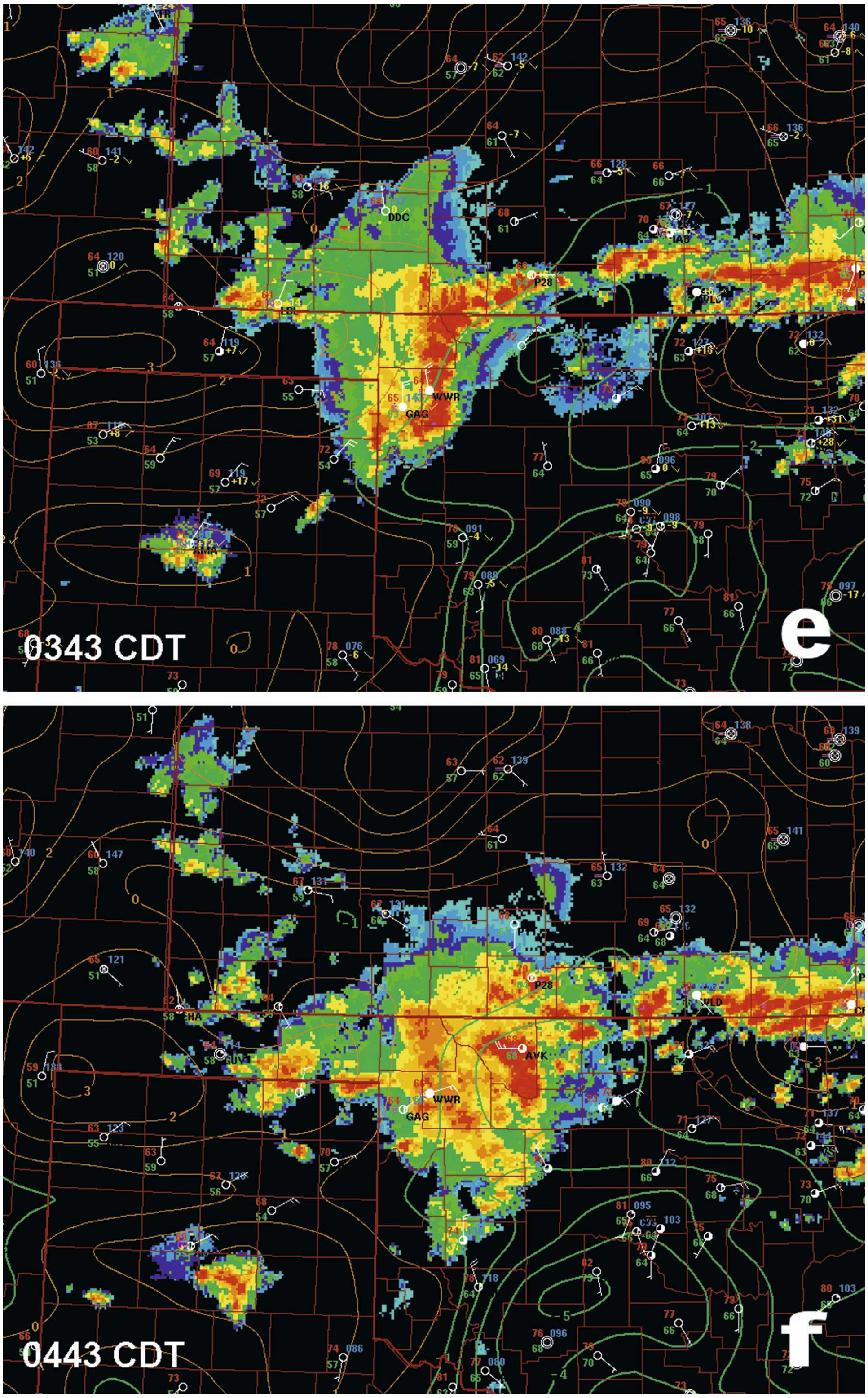

FIG. 8. (*Continued*)

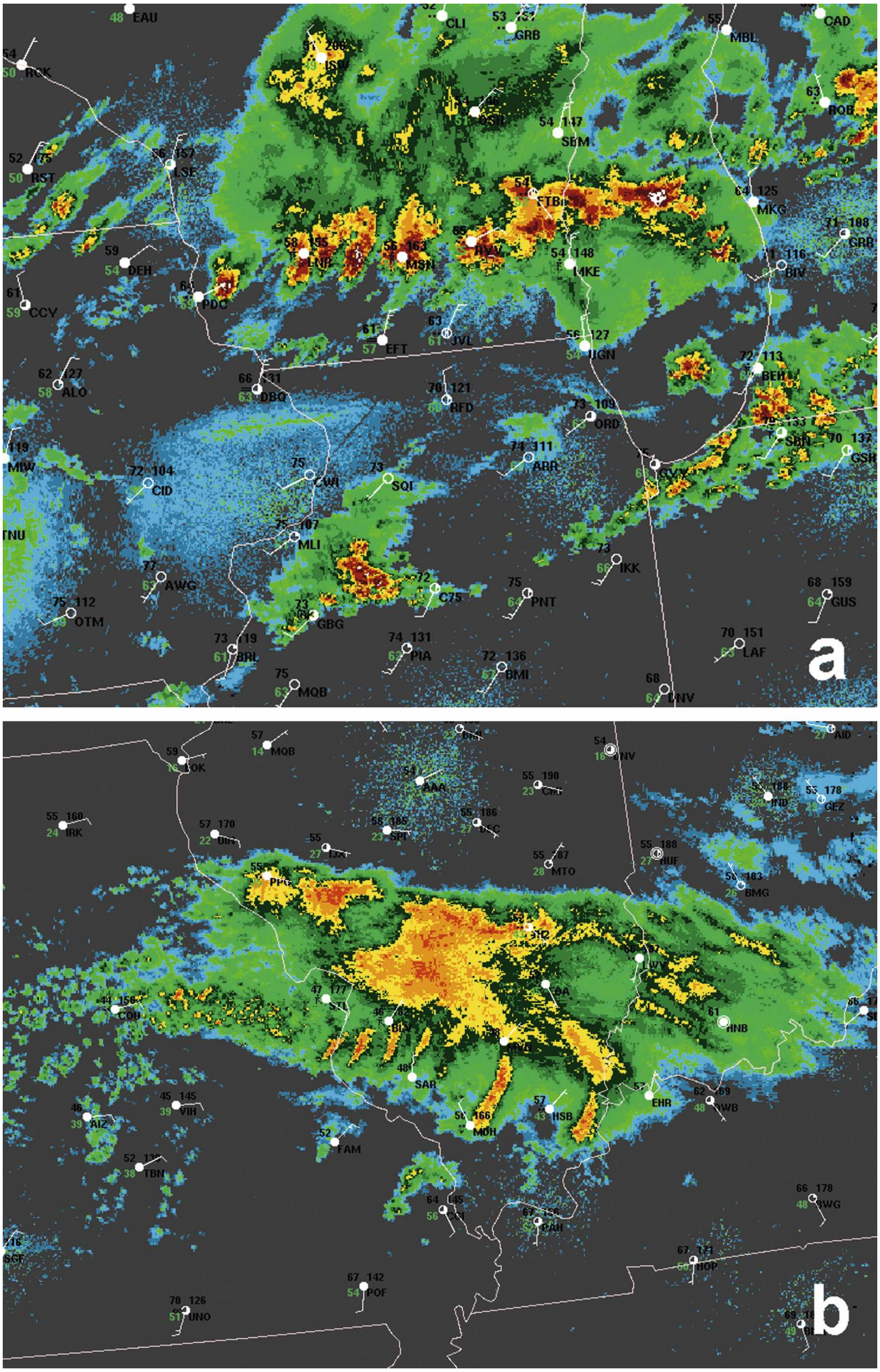

FIG. 9. (a) Composite reflectivity data showing a line of evenly spaced elevated thunderstorms, some supercells, over southern WI at 0600 CDT 4 Oct 2006. Conventional surface data locate west–east-oriented cold front along radar fineline over northern IL. Surface-based warm sector thunderstorms are present over northern IL and northwest IN. (b) Composite reflectivity data showing elevated showers and thunderstorms in short bands over southern IL at 1800 CDT 26 Mar 2008. Conventional surface data show west–east-oriented stationary front extending from southern MO into western KY.

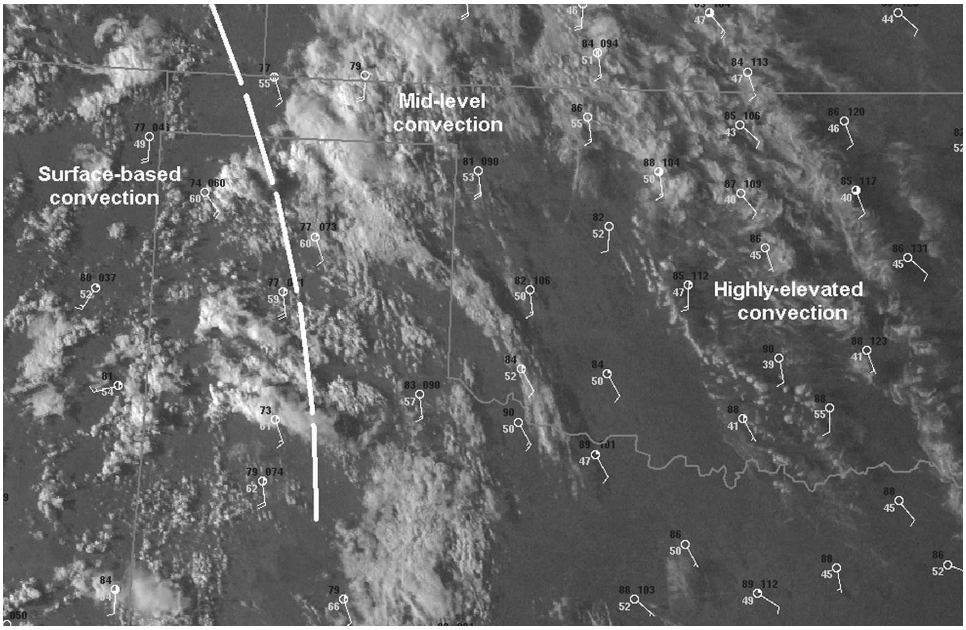

FIG. 10. Visible data satellite image over part of the south-central United States on the occasion shown in Fig. 4 (1801 CDT 14 Sep 2006). Illustration shows the cloud system of a weak upper-level trough in the westerlies, the axis of which (dashed white line) was in west TX at the time of the image. Surface-based convection (including thunderstorms) over eastern NM and western parts of the Texas Panhandle grades into increasingly elevated forms of convection with its eastward extent over the central and eastern parts of OK and KS. Rawinsonde data indicate that the "midlevel" convection was based around 500 hPa, with tops around 300 hPa, while the "highly elevated" convection existed between 350 and 300 hPa.

Ignoring the shades of gray that exist in the natural world is one hallmark of bad science; employing multiple definitions for the same term is another. The existence of more than one definition for castellanus is not in the best interest of science. Restricting castellanus to its traditional morphological definition certainly has appeal based in familiarity. However, cloud definitions based on the primary physical processes involved in their formation and evolution, rather than simply their appearance, seemingly best serve forecasters and researchers alike. Recognizing the improved understanding of the physical processes involved in cloud formation since the last complete *International Cloud Atlas* in 1956, and given that automated observation systems and geostationary satellite data have more or less supplanted human surface cloud observations in the last quarter century, the time has come to move toward a more physically based system of cloud classification, as argued nearly a half century ago by Scorer (1963). Short of advocating a completely new classification scheme based on physical processes, we suggest restricting the use of the term castellanus to turreted cloud forms owing their buoyancy chiefly to the release of latent heat. We argue that castellanus can occur at any level in the troposphere and that not all forms of castellanus are associated with elevated convection. We further argue that different forms of castellanus exist, ranging from traditional displays (e.g., Fig. 1) to those that are more aberrant (e.g., Figs. 2a, 3a, and 4).

The discussion in the preceding paragraphs leads us to propose the following classification scheme for convection in the form of a Venn diagram (Fig. 11). Convection can be either PBL-based or elevated, with gra-

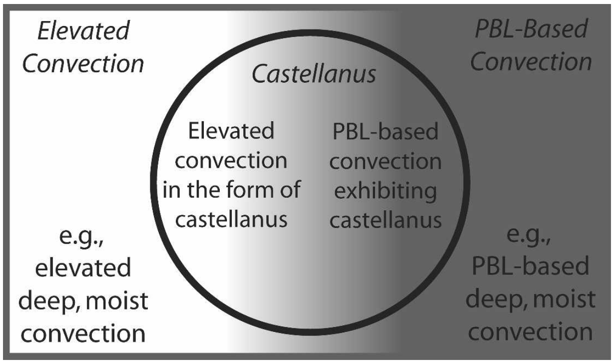

FIG. 11. Venn diagram of the relationship between elevated convection, PBL-based convection, and castellanus. The shading represents a gradation between elevated and PBL-based convection.

dations in between. Within this spectrum lie castellanus cloud formations. Castellanus can be associated with either PBL-based convection (e.g., Fig. 4) or elevated convection (e.g., Figs. 1 and 2a). At the same time, not all elevated convection (e.g., the deep moist convection in Fig. 2c) is associated with castellanus, and not all castellanus (e.g., PBL-based convection featuring castellanus; Fig. 4) is a form of elevated convection.

Section 4 of this paper presented several cases to illustrate the practical significance of castellanus and elevated convection. These cases provide inspiration for many unanswered questions. For example, 1) Why is castellanus frequently banded, what determines the spacing of the bands, and what factors influence the diameter of individual convective towers within them? 2) Why do some elevated thunderstorms produce severe surface winds whereas most do not? 3) What conditions govern the depth, strength, and longevity of elevated convective clouds, and can these variables be observed and forecast? 4) Why do elevated supercells sometimes assume a linear arrangement? 5) Are elevated storms affected by storm outflow and surface cold pools? If so, how? 6) Do elevated storms acquire rotation in the same manner as do surface-based supercells? 7) How can supercells on the cool side of baroclinic zones produce tornadoes? 8) Is there a maximum limit to the depth of the cold air mass for elevated storms to produce tornadoes? 9) How do supercells with most unstable parcels that do not originate at the surface differ from supercells that are more purely surface based or are more purely elevated? These represent some of the unknowns that the events discussed in this paper bring to mind. As some of these questions ultimately are answered, new ones likely will be raised. We anticipate that increased understanding of the physical processes responsible for the observed behavior of elevated convection and castellanus will enhance the quality of both day-to-day forecasts and short-term warnings for hazardous convective weather.

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