P1.5 TOWARD A BETTER UNDERSTANDING OF ELEVATED CONVECTION

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1. INTRODUCTION

The term "elevated convection" has come into general use in the past two decades to denote convective clouds and/or storms that are based above the planetary boundary layer (PBL). More precisely, elevated convection may be defined as convection that occurs above a near-surface stable layer. Deep elevated convection, manifesting itself in the form of thunderstorms, is of considerable interest as such activity can produce hail, damaging surface winds and excessive rainfall in areas well-removed from regions of strong surface-based instability (e.g., Colman 1990; Grant 1995; Branick et al. 1988; Moore at al. 1998; Schmidt and Cotton 1989; Moore at al. 2003; and Horgan et al. 2006). Shallower forms of elevated convection, commonly referred to as *castellanus*, tend to be more benign, being patchy or streaky clouds with comparatively weak updrafts.

It would seem easy enough to determine the layer of origin of a given convective cloud or of an area of convection with the aid of an appropriate proximity sounding. In practice, however, this is not always the case. For example, "boundary layer" cumulus clouds and thunderstorms routinely ingest parcels from above the boundary layer. Similarly, air from stable near-surface layers can be incorporated in the updrafts of developing storms as long as the resulting parcels remain positively buoyant. Allowing that the air entrained within "surface-based" convection is derived *mainly* from the PBL begs the question, "what is mainly?"

It is also often not readily apparent when a given cloud or storm will transition from being surface-based to elevated, and vice-versa. For example, operational experience and visual observations suggest that thunderstorms originating in the deeply mixed environment of the Plateau and High Plains of the United States often become elevated as they move east into the lower plains. Even in the absence of strong convective inhibition, such storms never appear to "tap" the cooler but more moist PBL over the lower terrain. On other occasions, similar storms clearly do become surface-based upon encountering regions of greater boundary layer moisture. At the same time, shallow, initially elevated convection sometimes "builds down" to the surface, often with a corresponding increase in strength. Questions regarding the primary level of inflow of a given convective cloud and its relation to the PBL are not strictly academic as such factors can affect the cloud's subsequent evolution and propensity for severe weather.

This paper will attempt to clarify the subject of elevated convection and encourage additional discussion on the topic. In particular, we hope to raise interest in the genesis and evolution of elevated thunderstorms so that both understanding and forecasts may be improved. The presentation will begin with a brief introduction to castellanus, since to many castellanus is more or less synonymous with elevated convection. We then present several examples of elevated convective clouds as seen from the ground. These are used to illustrate the wide range of forms exhibited by elevated convection, and to show that the division between elevated and surface-based activity is rarely distinct. Subsequent examples demonstrate the significant role that even shallow elevated convective clouds may play in fostering surface-based thunderstorm development. Finally, a brief discussion is included on elevated clouds and storms that transitioned to surface-based forms. Emphasis is placed on the physical processes likely involved with these events, and related forecast implications.

2. CASTELLANUS

Clouds have been classified since the late 19th century using a scheme similar to that introduced by the English pharmacist Luke Howard in 1803. 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* in the early 1900s (World Meteorological Organization 1956). Application of the scheme has facilitated the use of cloud observations in synoptic meteorological analysis, especially before the advent of geostationary satellite imagery.

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The *Atlas* identifies ten basic cloud types or *genera*[1] that are separated into "low," "middle" and "high" categories based on their commonly observed heights above the ground. Specific nomenclature does not exist for elevated convection. The *Atlas* does, however, recommend use of the term "castellanus" to designate patches or layers of cloud at any level that assume turreted or cumuliform parts on their upper surfaces. While the word "elevated" is not contained in the *Atlas'* definition, since castellanus is to be applied to selected cloud types at any level (including cirrus), implied is the notion that at least some castellanus are elevated. A typical mid-level castellanus formation is shown in Figure 1. In places the turrets are very ragged and the cloud bases have dissolved (presumably the result of updraft dilution by entrainment of dry air). The *Atlas* refers to castellanus of this type as *floccus*.

Figure 1. Castellanus and floccus near Valentine, NE, c. 1400 CDT 28 May 1988, looking south.

Turreted clouds can and do, of course, occur at all levels in the troposphere. In practice, nevertheless, largely because of the requirement by official meteorological codes that observed clouds be classified into one of the ten genera, castellanus has come to be viewed almost exclusively as a form of *mid*-level cloud of the genus altocumulus. In the United States, association of castellanus with altocumulus has been furthered by widespread adoption of the aviation acronym "ACCAS" (altocumulus castellanus) in surface airway observations and operational weather discussions.

In contrast to the definition based on appearance given in the *Atlas*, R. S. Scorer (1972) offers a physically-based definition of castellanus. Scorer uses castellanus to refer to any cumuliform cloud that owes its buoyancy to the occurrence of condensation, rather than to the presence of pre-existing thermals based in the PBL. The condensation involved can result from any number of processes, including uplift within orographically-induced waves (most likely responsible for the clouds in Figure 1), ascent of potentially unstable air ahead of mid-tropospheric disturbances, and saturation of humid layers ascending beneath widespread precipitating cloud decks such as those associated with upper lows. The examples provided by Scorer (1972) illustrate that castellanus is actually quite common and can include formations not traditionally considered to be castellanus.

Despite being more physically-relevant than that of the *Atlas*, Scorer's definition of castellanus has not received widespread acceptance. Most still consider castellanus to be strictly a mid-level cloud with turrets, more or less as described in the *Atlas*. This limited view, unfortunately, perpetuates the notion that castellanus is somehow a distinct cloud type of its own, set apart from other forms of moist convection. In contrast, Scorer's broader approach recognizes that castellanus is in fact part of a convective continuum that ranges from PBL-based "fair weather" cumulus and cumulus congestus on the one hand, to various elevated forms such as altocumulus castellanus and tufted cirrus (cirrus uncinus) on the other (see, for example, Heymsfield 1975, Ludlam 1980, Stull 1985, and Atlas 2001).

3. EXAMPLES OF ELEVATED CONVECTION

In this section several examples of elevated convection are presented to illustrate the wide range of forms such clouds can assume. Some of these clouds will be recognizable as "traditional" castellanus, whereas others likely will not. We adopt Scorer's definition of castellanus, since it emphasizes the unique physical processes that distinguish castellanus from other types of convective clouds.

Patches of mid-level castellanus such as that shown in Figure 1 frequently appear in regions of ascent ahead of mid-tropospheric disturbances. They are especially common in elevated mixed layer (EML) plumes extending downstream from high-level heat sources such as the Mexican plateau. As discussed by Carlson and Ludlam (1968), castellanus are a visual manifestation of isentropic ascent of moist layers in the EML. The moist layers typically originate from the evaporation of ordinary PBL cumulus clouds within the heated layer. Castellanus of this type usually first appear in the crests of low amplitude waves set up by the underlying topography. Initially laminar, the wave clouds subsequently break into cumuliform turrets aligned with the mean flow at their level as latent instability is released through condensation. Such clouds in many parts of the world have long been considered to be precursors of thunderstorms.

Castellanus is also commonly observed atop thunderstorm outflow, as seen in Figure 2. Such convection is elevated in the sense that buoyant parcels in the clouds do not originate in the PBL beneath them,

[1] These include cirrus, cirrostratus, cirrocumulus, altostratus, altocumulus, nimbostratus, stratus, stratocumulus, cumulus and cumulonimbus.

but rather arise due to condensation in a layer of mixing-type cloud that forms along the interface between the outflow and undisturbed air. In this case, a storm off the view to the left embedded in weak easterly shear (easterly winds that increased with height) has produced outflow that is moving left to right across the view. The castellanus form as the outflow undercuts the more slowly-moving, undisturbed air. The wavy bases are characteristic of dense areas of elevated convection, and reflect the forced nature of the ascent initially responsible for their development.

Figure 2. Castellanus sprouting from a layer of cloud produced by forced ascent above an expanding thunderstorm outflow. Norman, OK, 2005 CDT 6 August 2006, looking south southwest.

Figure 3. Castellanus band above the gust front of an approaching MCS. Kansas City, MO, 0730 CDT 16 June 1996, wide angle view looking northwest.

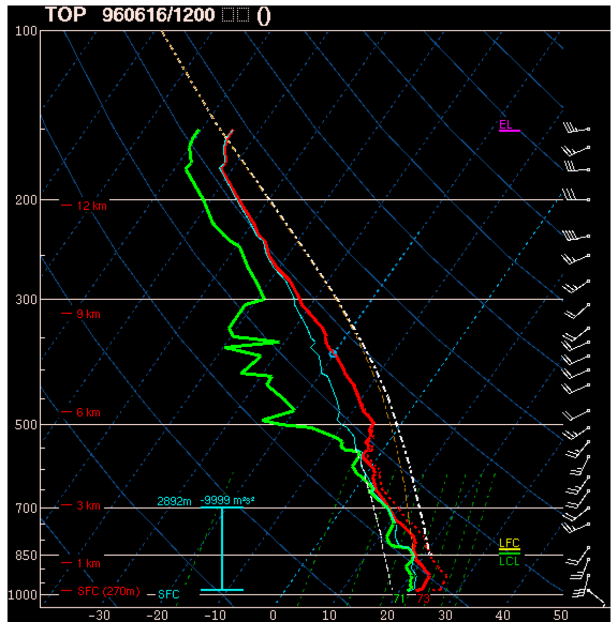

Figure 4. Rawinsonde analysis, 0700 CDT 16 June 1996 at Topeka, KS, made just east of the MCS shown in Figure 3. Wind speeds in knots.

Long-lasting, regenerative bands of castellanus sometimes form on the leading edge of forward-propagating mid-latitude mesoscale convective systems (MCSs). The bands are often best developed when the cold pool has begun to out-run the main convective core late in a system's life cycle. An edge-on view of such a formation is shown in Figure 3. The great horizontal extent of the cloud (it continued in both directions beyond the field of view of Figure 3), its quasi-steady nature, and the absence of convective towers ahead of it all suggest the presence of a broad, slab-like swath of forced ascent, similar to that discussed by Bryan and Fritsch (2001). Bryan and Fritsch (2001) showed that such environments can be associated with moist absolute instability, and, indeed, the proximity sounding in Figure 4 shows the existence of such a layer between 750 and 650 hPa.

Radar observations of MCSs with regenerative elevated convective bands similar to the one in Figure 4 suggest that as the cold pool deepens beneath the clouds, the towers also deepen and subsequently merge with the parent MCS. In this manner the clouds eventually become an integral part of the convective system. Thus, in at least some cases, it appears that MCS propagation is furthered by the development of castellanus, and that such clouds may be visual manifestations of the presence of moist absolute instability.

Elevated convection, with depths that range from that of the shallowest castellanus to more than 10 km in the case of thunderstorms, is commonly present in areas of isentropic ascent along frontal zones. This is especially true of warm and stationary fronts, where a substantial component of relative motion often exists toward the colder air (anabatic flow). As already noted, such activity has been the subject of numerous studies given its potential to produce severe weather even deeply within the cold air (e.g., Grant 1995). Figure 5 shows elevated thunderstorms forming about 150 km north of a slowly moving warm front. The convective towers are sprouting from a laminar cloud layer that is based at the same level as the patchy wave clouds in the foreground. These thunderstorms and others just to the south continued to strengthen after the picture was made. Area wind profiles exhibited strong low- to mid-level veering, with cloud-bearing layer shear magnitude in excess of 25 m s^{-1} (not shown). Supercell storms that evolved from this activity near St. Joseph, MO produced several tornadoes, even though conventional surface data and visual observations continued to suggest that the updrafts remained elevated (not shown).

Figure 5. Elevated thunderstorms forming above a stationary front. Near Omaha, NE, c. 1830 CDT, 25 June 1994, looking south.

The examples of castellanus just presented are more or less traditional in the sense that the updrafts involved were not based in the boundary layer. Implicit in Scorer's definition of castellanus, however, is the notion that such clouds can originate at any level, *including* the PBL. An example of PBL-based castellanus is shown in Figure 6. This form of castellanus is most common over oceanic regions in the low-latitudes, and over other areas where surface-based updrafts tend to be weak. Feeble but sustained boundary layer convergence in such environments can promote formation of shallow convective clouds that later deepen through continued latent heat release. "Cumulus castellanus" like those in Figure 6 are not supported by sustained boundary layer convergence; as a result, the clouds soon entrain dry air and become spindly. The narrow towers of these clouds contrast with the broader outlines of true cumulus congestus, the sustaining parcels of which encompass the depth of the PBL.

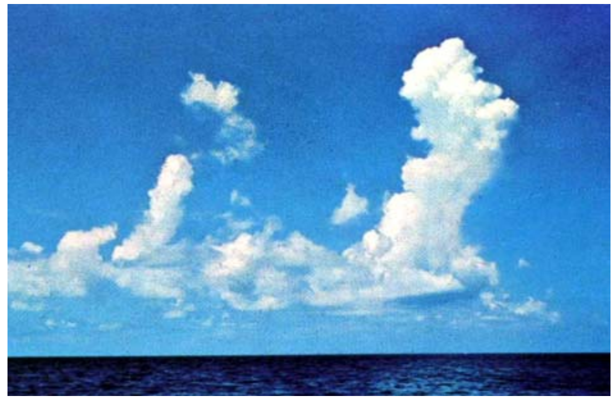

Figure 6. Castellated cumulus developing from a foundation of shallower PBL clouds over the subtropical Atlantic. (From Scorer 1972)

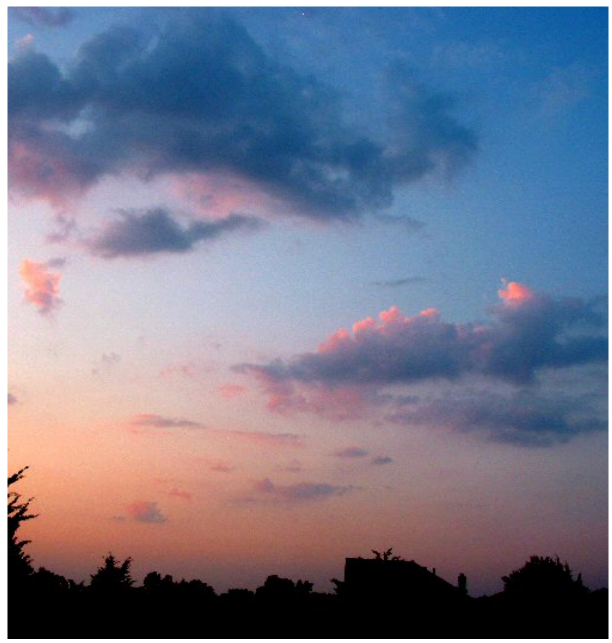

Figure 7. PBL castellanus at sunset, forming in the crests of waves left moistened by ordinary diurnal boundary layer cumuli. Norman, OK, 2044 CDT 1 July 2006, looking north.

Another variety of PBL-based castellanus is shown in Figure 7. These clouds are occasionally observed around sunset following a day of shallow diurnal convection. The turrets form in patches of cloud that develop in the crests of shallow orographic waves left moistened by evaporation of the previous afternoon's cumulus. Such formations are often dismissed as being the dying remnants of ordinary diurnal cumulus. But careful observation reveals that the turreted clouds rise from recently-formed patches of wave clouds, and that the turrets derive their buoyancy from condensation in the waves.

PBL-based castellanus, like most shallow forms of convection, typically are of minimal forecast significance. They serve, however, to illustrate that the partition between purely elevated and purely surface-based convection is far from distinct. Further, these examples, along with the others presented earlier, illustrate that by failing to adopt a more precise classification scheme with respect to elevated convection, we may be ignoring valuable clues that such clouds provide about the state of the atmosphere in their vicinity, and about convective initiation in general.

4. FORECAST IMPLICATIONS OF ELEVATED CONVECTION

While shallow elevated convection often can be ignored from a forecast perspective, there are occasions when such clouds intimately are tied to the development of significant convective weather. The satellite sequence in Figure 8 illustrates a situation in which outflow from an area of mid-level castellanus that formed ahead of a south-moving cold front altered the pattern of low level convergence in the prefrontal warm sector. The presence of castellanus-derived outflow reduced convergence along the front. As a result, the front remained largely storm-free through late in the day. In contrast, surface-based thunderstorms with hail did form at the intersection of two castellanus outflow boundaries in southeast Wisconsin (Figure 8c). In this region, surface heating and enhanced pre-frontal convergence eliminated modest convective inhibition. This case illustrates how the location and evolution of deep surface-based convection can be affected by the presence of castellanus.

Another example of the influence of elevated convection on subsequent convective development is shown in Figure 9. Here, the location and areal extent of diurnal thunderstorms over northern and western Arkansas appears to be related to the shape and motion of a morning castellanus field over Oklahoma (for an animation of this imagery, visit http://www.spc.noaa.gov/publications/corfidi/castellanus/index.html). We speculate that the castellanus was associated with a region of enhanced mid-level moisture that reduced entrainment and thereby fostered deep PBL-based convection as the moisture moved downstream (east northeast) into Arkansas.

Some of the most challenging forecast situations involving elevated convection are those in which the activity deepens and ultimately becomes surface-based. For ease of reference, cases of this type herein are referred to as conversion events. Questions as to if, when and where a conversion event will occur are complicated by the fact that many of the determining factors involved include processes that are themselves difficult to forecast. For example, the strength and areal extent of convective inhibition, the location and depth of outflow boundaries, and spatial and temporal changes in mesoscale forcing for ascent all can affect the likelihood for conversion.

One of the more dramatic conversions in recent years occurred on 17 August 1994, when an area of

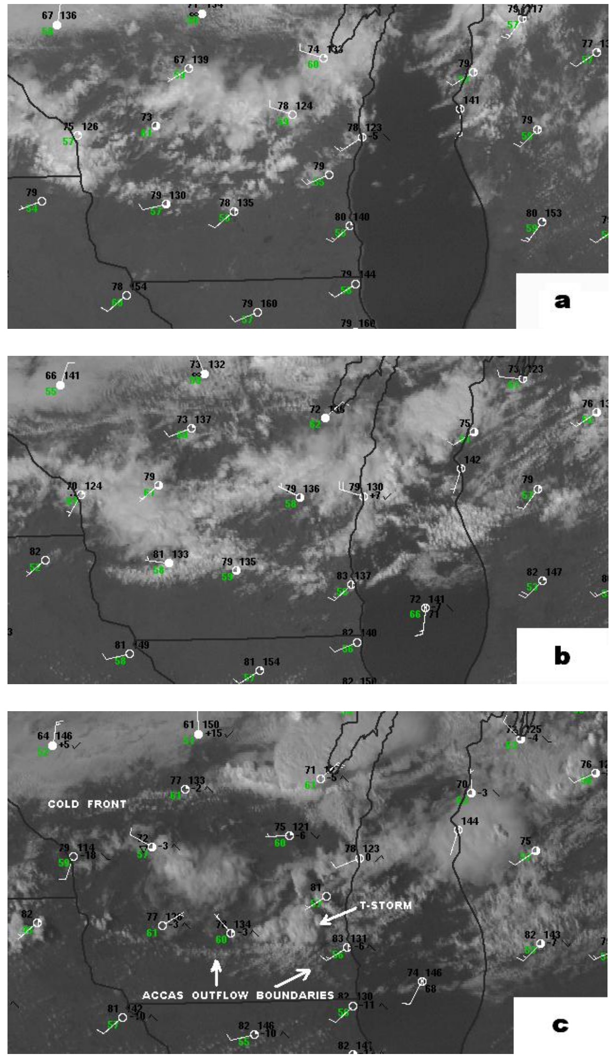

Figure 8. Visible data satellite data and surface observations (English units) over Wisconsin and Lake Michigan at (a) 1215, (b) 1415, and (c) 1615 CDT 8 September 2006. Mottled clouds over central and southern Wisconsin are castellanus based near 700 hPa (per area rawinsonde data). Winds at this level were west northwest at 15 m s^{-1}. Pertinent features mentioned in text shown in (c).

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 the town of Lahoma, Oklahoma (Janish et al. 1996). Another derecho that evolved from convection that appears to have been at least partly elevated was discussed by 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.

Convection with both the Lahoma event and with the system investigated by Rockwood and Maddox (1988)

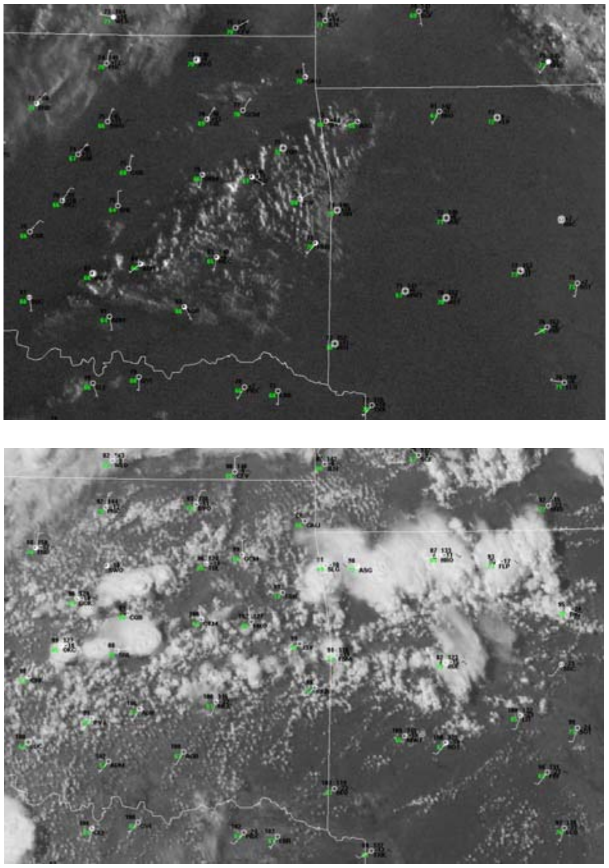

Figure 9. Visible data satellite data and surface observations (English units) over Oklahoma and Arkansas at (a) 0715 and (b) 1515 CDT 14 August 2006. Area soundings suggest that the castellanus in (a) was based near 700 hPa; winds at this level were west southwest at 10 m s^{-1}.

attained maximum intensity shortly after the existing elevated storms moved or developed into a region experiencing strong low-level destabilization (mainly in the form of moisture advection). In contrast, Coniglio and Corfidi (2006) present an example of an elevated severe wind-producing MCS that *weakened* as it moved from the cool to the warm side of an Oklahoma cold front. Although the forward-propagating system encountered enhanced surface-based instability as it crossed the boundary, wind profiles appeared more favorable for deep ascent on the downwind side of the system cold pool on the cool side of the front. In this region, easterly low-level winds were surmounted by west to northwest flow at mid and upper levels. Apparently the instability increase in the warm air was insufficient to offset the more hostile kinematic environment that existed there (reduced cold pool-relative flow).

The system just discussed, while perhaps uncommon, is not unique. Similar events are observed each season that seemingly defy common wisdom regarding expected convective evolution. Cases such as this raise questions as to not only what truly constitutes an elevated storm (sounding and profiler data indicate that the MCS was indeed elevated while north of the front), but also how such convection can, on occasion, produce damaging surface wind.

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