2.7 A REVIEW OF ELECTRICAL AND TURBULENCE EFFECTS OF CONVECTIVE STORMS ON THE OVERLYING STRATOSPHERE AND MESOSPHERE

Walter A. Lyons*
FMA Research, Inc., Fort Collins, Colorado

Russell A. Armstrong
Mission Research Corporation, Nashua, New Hampshire

1. INTRODUCTION

According to The National Space Weather Program (NSWP), "space weather" refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-born and ground based technological systems and can endanger human life or health (OFCM, 1997). Well documented have been the impacts of energetic particles and geomagnetic storms on satellite and communication systems, induced currents in the electric power systems due to geomagnetic field fluctuations, and space weather hazards to astronauts. The NSWP Implementation Plan notes that the goals of the National Space Weather Program can be achieved only when the representation of space weather is coupled into a seamless system, starting at the sun and ending at the Earth. One can not dispute this notion, but this paper suggests that a slightly broader perspective might be in order. We note that an indirect solar influence upon the middle atmosphere derived from heating of the surface deserves growing attention. Insolation warms the Earth's surface which in turn generates deep convection, further resulting in significant hydrodynamic and electrodynamic disturbances throughout much of the middle atmosphere. The impacts of tropospheric thunderstorms are now understood to extend through the depth of the stratosphere, mesosphere and even into the lower ionosphere. This region sometimes, only partly in jest, is termed the "ignorosphere," because its presumed quiescence and inaccessibility has lead to a dearth of remote and *in situ* measurements. Satellites and Space Shuttles overfly this region. Sounding rockets can only obtain readings lasting mere seconds. Costs and performance limitations limit aircraft and balloons to brief probes of the very lowest extremity of the region. Yet the thin atmosphere beyond the tropopause is soon to become increasingly populated. Proposed high altitude airships (HAAs), including station-keeping balloons and UAVs, may be deployed for various purposes including research, communications and national security surveillance. Upcoming generations of civil transports and military aircraft will log increasing time in the atmosphere above thunderstorms. The Space Shuttle and its successors must continue to ascend and descend through the region. The speculation (in part fueled by the press) about the possibility that the Shuttle Columbia was felled by interaction with a sprite, and the considerable effort needed to discount this as a plausible cause (NASA JSC 2003), highlighted the limitations in our understanding of the electrodynamics of the region between 20 and 90 km. This paper surveys recent research which suggests that the stratosphere, as well as the overlying mesosphere, are neither electrically nor dynamically "uninteresting." Those planning to operate HAAs within the region should be aware that what has been heretofore presumed about the "weather" of this region may not be necessarily always be true.

2. A CAUTIONARY TALE

During the summer of 1999, the authors were preparing to participate in a major NASA scientific balloon mission to study sprites above High Plains thunderstorms (Bering et al. 2002). Sprites are the most common middle atmospheric transient luminous event (TLEs) induced by intense electrical activity in deep tropospheric convective storms (Fig. 1). Lasting for a few to tens of milliseconds, they illuminate thousands of cubic kilometers of the atmosphere between 30 and 90 km (Lyons et al. 2000), in a fleeting thunderstorm-induced "aurora." It is increasingly agreed that sprites result from conventional electrostatic breakdown at around 70 km, the result of intense electrical fields caused by the removal of large amounts of electrical change from clouds by unusual cloud-to-ground (CG) lightning strokes. Electrical streamers extend both upward and downward, but are generally not thought to contact the underlying cloud tops. During the final planning stages for the 1999 balloon missions, NASA informed the participants that the balloons would not be allowed to directly overfly thunderstorms. This was the result of regulations imposed after a little-known 1989 balloon mishap, which was ranked as the second worst "federal disaster" of that year, behind the crash of an F-15.

On the morning of 6 June 1989, NASA launched a nearly 30 million cubic foot research balloon from its base in Palestine, TX. It carried a two-ton science payload (a laser system for chemical measurements). The balloon, as expected, reached a flight altitude of 120,000 ft (~37 km) and drifted westward. As evening approached it began to overfly a large region of severe thunderstorms in west Texas. The balloon then gradually descended to 110,000 ft (33.5 km) by 0038 UT 7 June 1989, about 55

- *Corresponding Author*: Walter A. Lyons, CCM

FMA Research, Inc., Fort Collins, CO 80524, walyons@frii.com, www.FMA-Research.com

miles (88km) west of Ft. Worth, TX. At that point an uncommanded payload release occurred. The balloon, parachute assembly, and payload descended, landing in three different areas. The 4000 lb science payload, some 6 feet in diameter and 5 feet tall, struck the ground near Graham, TX at an estimated speed of 600 mph, burying itself in a small crater. Fortunately there were no injuries or collateral property damage. Flight 1482P was declared a failure, with a loss of $1 million in equipment and payload.

What caused the uncommanded payload release has been a matter of considerable conjecture and concern ever since. Two PC cards from the flight termination electronics page were retrieved, inspected, and found to have suffered electrical damage and overheating. The command strobing chip was damaged and discolored due to electrical overstress and heating. Several pins were found shorted together with evidence of arc-over.

The investigating committee determined the most likely cause was "low-level high-voltage current induced into the termination electronics package by lightning activity present in the area." However, it seems improbable that activity within the storms below could explain this incident. At the time of the failure, the balloon was approaching thunderstorms with reported radar echo tops to 65,000 ft (19.8 km). Even if directly above the highest part of the storm, the balloon was *fully 14 km distant* from any conventional lightning discharge within the storm.

The event occurred almost exactly a month before the first sprite was imaged by a low level camera above a storm system in Minnesota (Franz et al, 1990), an event which has changed our perception of electrical phenomena in the middle atmosphere above storms. Discoveries since that time may shed new light on the fate of Flight 1482P.

3. A CONNECTION TO THE IONOSPHERE

Since 1989, more than 10,000 low light television (LLTV) images of sprites have been obtained by various research teams (Lyons, 1996; Sentman et al. 1995; Lyons et al., 2000, 2003a). Blue jets (Wescott et al, 1995) and elves (Fukunishi et al. 1995) have also been observed with a variety of sensors. While a sprite is unlikely to have directly interacted with the balloon, the application of theories proposing conventional dielectric breakdown as the initiator of sprites suggests electrical transients on the order of 10^3 to 10^4 V/m may have occurred at flight level (Williams, 2001; Rowland, 1999). Such transients result from rather rare and unusually powerful lightning discharges lowering hundreds of Coulombs of charge to ground, as detailed by Hu et al. (2002), Lyons et al. (2003a) and others. Systems not deigned with the potential for such transients in mind may indeed be expected to encounter failure modes. And in the decade since the discovery of sprites, many other TLEs, many emanating directly from cloud tops, have been discovered. It is certainly not out of the question that the NASA balloon passed far closer than 14 km to an electrical discharge, or possibly was even directly involved in such an event.

Many anecdotal reports in the literature events (Vaughan and Vonnegut, 1989; Lyons and Williams, 1993; Heavner, 2000; Lyons et al. 2003b) described TLEs which can not be categorized as sprites:

"…vertical lightning bolts were extending from the tops of the clouds…to an altitude of approximately 120,000 feet…they were generally straight compared to most lightning bolts…"

"…at least ten bolts of lightning went up a vertical blue shaft of light that would form an instant before the lightning bolt emerged…"

"...a beam, purple in color…then a normal lightning flash extended upwards at this point…after which the discharge assumed a shape similar to roots in a tree in an inverted position…"

"…an ionized glow around an arrow-straight finger core…"

"…an American Airlines captain…near Costa Rica…saw from an anvil of a thunderstorm….several discharges vertically to very high altitudes…the event was white…"

"…the top of the storm was not flat…looked like a dome of a van de Graff generator...clearly saw several bolts of lightning going upwards…dissipating in the clear air above the storm…all in all 5 or 6 occurrences …"

Upward extending white channels topped by blue flame-like features were captured on film near Darwin, Australia (Lyons et al. 2003) and over the Indian Ocean (Wescott et al. 2001). This latter event reached a height of ~35 km. Welsh geographer Tudor Williams, who in 1968 was residing near Mt. Ida, Queensland, Australia, visually observed a series of lightning-like channels rising at least several kilometers above the top of a large nocturnal thunderstorm. He photographed several of the approximately 15 events (using 50 ASA 35 mm transparency film, long exposures) that occurred at fairly regular intervals over a 45 minute period. Figure X shows the bright upward channel along with a hint of a faint blue flame flaring upward and outward from its upper portion reaching a height equal to or greater than the bright channel. Upward-extending electrical discharges from a supercellular thunderstorm over Colorado were observed during the Severe Thunderstorm Electrification and Precipitation Study (STEPS) on 22 July 2000 (Lyons et al., 2003b).

Eyewitness recollections of many lightning-like channels emanating from overshooting convective domes of very active storm cells have a number of common characteristics. They appear bright white to yellow in color, are relatively straight, do not flicker, extend above cloud tops to heights equal to or exceeding the depth of the cloud (10-15 km), are notably long lasting (~1 second) and can be observed during *daylight*. It is difficult to understand how these might represent the faint blue jet phenomenon reported by Wescott et al., (1995).

On 15 September 2001, a team of scientists familiar with sprites and blue jets were investigating the effects of lightning on the ionosphere at the Aricebo Observatory in Puerto Rico (Pasko et al., 2002). At 0325.00.872 UTC, above a relatively small (~2500 km^2) storm cell 200 km northwest of Arecibo, the LLTV video captured an amazing upward discharge, blue in color, one frame of which is shown in Figure 1 (see the full animation at http://pasko.ee.psu.edu/Nature). Clearly seen as brilliant blue to the naked eye, it appeared as a series of upward and outward expanding streamers which rose from the storm top (16 km). The event reached a terminal altitude of 70 km, the estimated lower ledge of the ionosphere. The event lasted almost 800 ms, including several re-brightenings. This case marks the first hard evidence of a direct electrical link between a tropospheric thunderstorm cell and the ionosphere. A series of five similar giant upward jets have since been reported emanating from thunderstorm tops over the Pacific near the Philippines (Su et al. 2003). While sprites are believed to occur with a global frequency of several per minute, the number of upward jets and lightning-like discharges remains unknown. It is becoming clear, however, that they are less rare than once believed.

A wide variety of upward electrical discharge phenomena occur from thunderstorm tops, many penetrating the stratosphere and some extending through the mesosphere. As scientific and defense platforms expand their domain into the stratosphere, it is imperative that the dynamic electrical nature of the region be considered. Sprites, jets and related TLEs are also a potential source "optical clutter" for spaceborne monitoring and missile detection systems. To the extent their optical signatures are not well characterized, the potential remains for natural phenomena to be misidentified.

4. VERTICAL MOTIONS AND TURBULENCE

It has now become recognized that large thunderstorm systems can generate upward propagating gravity waves which often amplify with height, perhaps even breaking in the middle atmosphere (Taylor and Hapgood 1990; Alexander et al. 1995). The large mesoscale convective systems of the High Plains, often prolific sprite producers, have been known to generate gravity wave trains visible from OH airglow emissions at the ~85 km level (Sentman et al. 2002). These waves are often bright enough to be visible with the naked eye.

Yet this energy must first propagate through the stratosphere, a thermally stable layer often characterized as devoid of "weather." The very stability which makes this characterizations true on a global scale also can result in significant turbulence, vertical motions and wind shears on the scale of convective storms. Evidence is accumulating which suggests these storm's impacts may extend for ten km, and maybe much more, above cloud tops. As contemporary aircraft routinely fly around and not over thunderstorms, little operational experience is available documenting conditions above intense convective storms. Occasional ER-2 missions above deep convective storms have tended to concentrate on optical and electrical field measurements. Similarly, high altitude research balloon missions are not instrumented to determine convective scale turbulence, vertical motion and wind shears. Learjet flights investigating tornadic storms by the late Prof. T. T, Fujita nearly three decades ago, used photogrammetric methods to reveal the extreme turbulence and wind shear present at the top and above intense convective storms (Fujita, 1992). Figure 3 shows a montage of phenomena present above thunderstorm tops. The tropopause is not necessarily a boundary for "weather" or even mass flux. We note Wang (2002) has demonstrated that flow around and over deep convection generates intense gravity wave motions which can transport material from the storm into the stratosphere itself. Included in Figure 3 is a scene from a video which reveals a stratospheric cirrus plume several kilometers above the top of a supercell storm observed during the 2000 STEPS program. Animation makes it clear that this plume was formed by intense gravity wave action extending well above the storm top. Such intense motions above storms have also been indicated by high resolution numerical simulations of airflow around and over convective domes penetrating into the stratosphere (Droegemeier et al. 1997). As shown in Figure 4, such motions can reach several meters per sec many kilometers above the visible storm tops. Such "tropospheric style" conditions could well pose control issues for station keeping HAAs or UAVs operating in the lower stratosphere unless accounted for in the design of these platforms.

5. SUMMARY

Research over the past decade has drawn attention to the fact that the middle atmosphere is not devoid of "weather." Intense electric fields and a suite of upward propagating, lightning-like discharges and blue-jet like phenomena are a common, albeit transient, part of the environment. Similarly, the role of thunderstorms in generating hydrodynamical instabilities, shears and significant vertical motions extending many kilometers above visible storm tops is beginning to be appreciated. Those planning to fly a variety of next-generation vehicles in the lower layers of the "ignorosphere" should not assume that this layer is quiescent. While perhaps more properly referred to as "edge of space weather," a better understanding of these phenomena is required for a wide range of disciplines besides aviation operations, including studies of the global electrical circuit (Rycroft et al. 2000), middle atmospheric NOx chemistry, aircraft safety (Uman and Rakov 2003), infrasound research (Bedard and Georges 2000) and RF propagation (Rodger 1999).

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Figure 1. A montage of transient luminous events observed above thunderstorm systems from the ground, aircraft and the Space Shuttle (top). Figure 2. Photograph of an “upward lightning bolt” which penetrated into the stratosphere above an Australian thunderstorm system, while persisting for up to 2 seconds (bottom).

Transient Electrodynamic Events Driven by Thunderstorm-Induced Fields

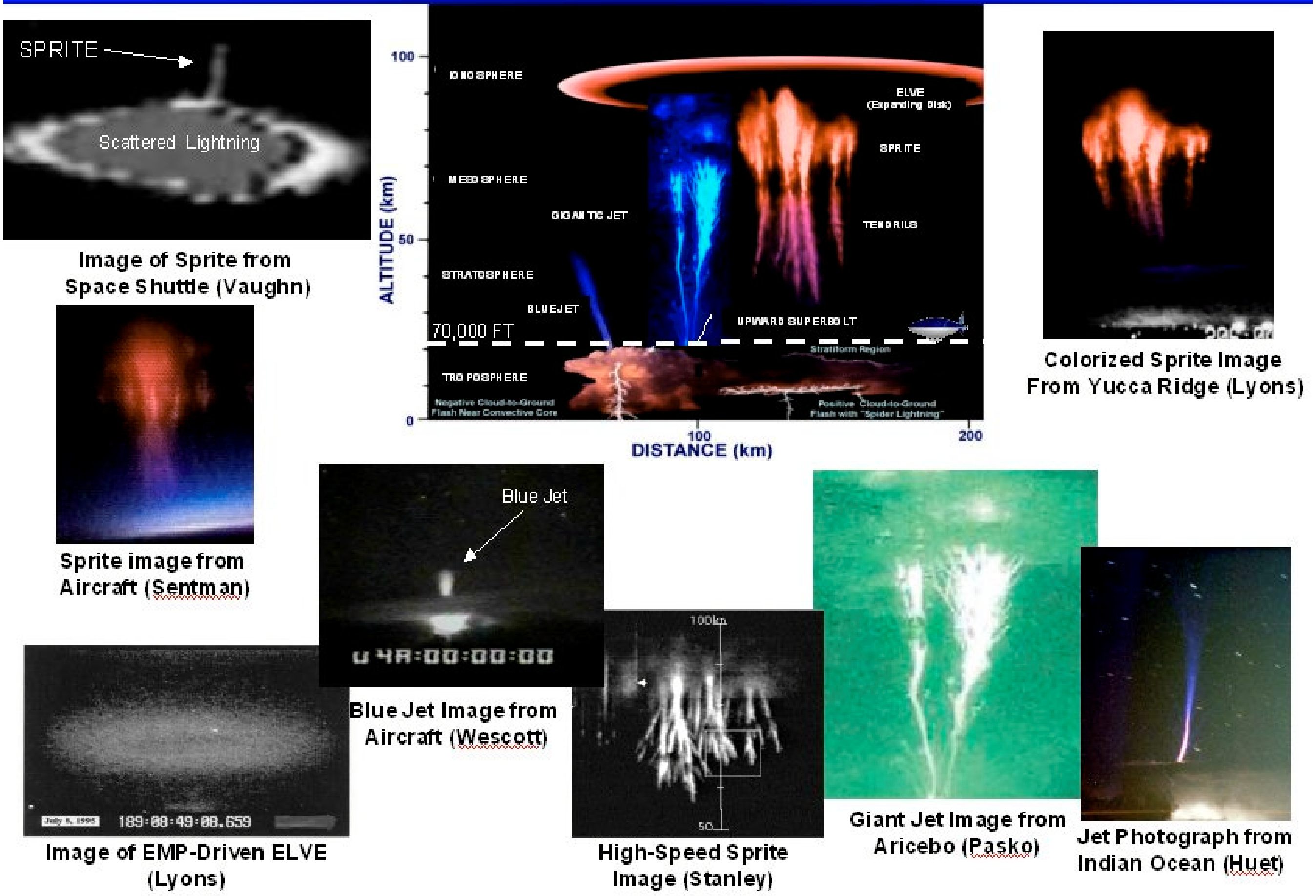


Image of Sprite from Space Shuttle (Vaughn)

Colorized Sprite Image From Yucca Ridge (Lyons)

Sprite image from Aircraft (Sentman)

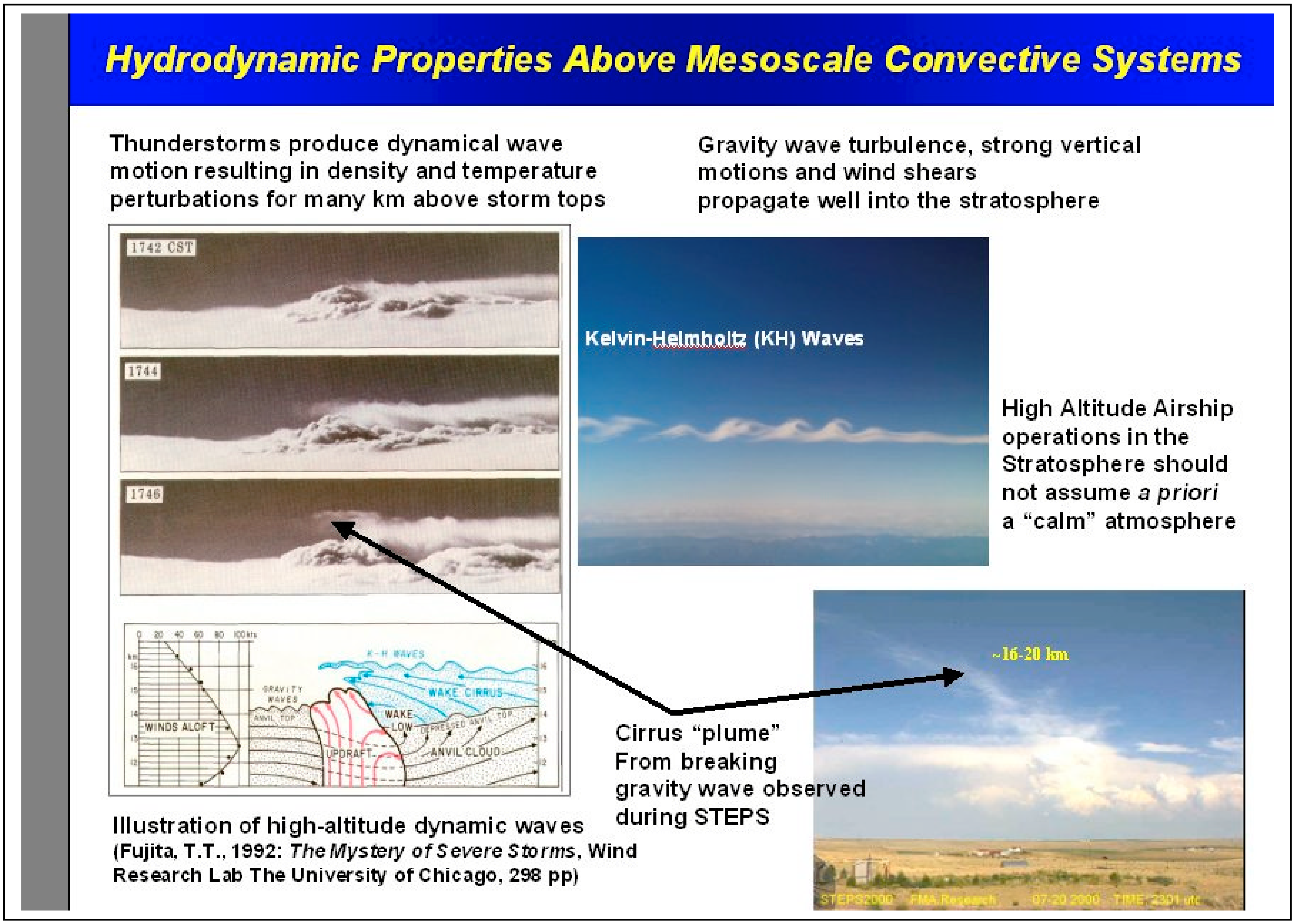
Blue Jet Image from Aircraft (Wescott)

Image of EMP-Driven ELVE (Lyons)

High-Speed Sprite Image (Stanley)

Giant Jet Image from Aricebo (Pasko)

Jet Photograph from Indian Ocean (Huet)



Hydrodynamic Properties Above Mesoscale Convective Systems

Thunderstorms produce dynamical wave motion resulting in density and temperature perturbations for many km above storm tops

Gravity wave turbulence, strong vertical motions and wind shears propagate well into the stratosphere

High Altitude Airship operations in the Stratosphere should not assume *a priori* a "calm" atmosphere

Cirrus "plume"
From breaking
gravity wave observed
during STEPS

Illustration of high-altitude dynamic waves

(Fujita, T.T., 1992: *The Mystery of Severe Storms*, Wind Research Lab The University of Chicago, 298 pp)

Figure 3. Evidence of the turbulent state of the atmosphere in the stratosphere above deep convective storms.

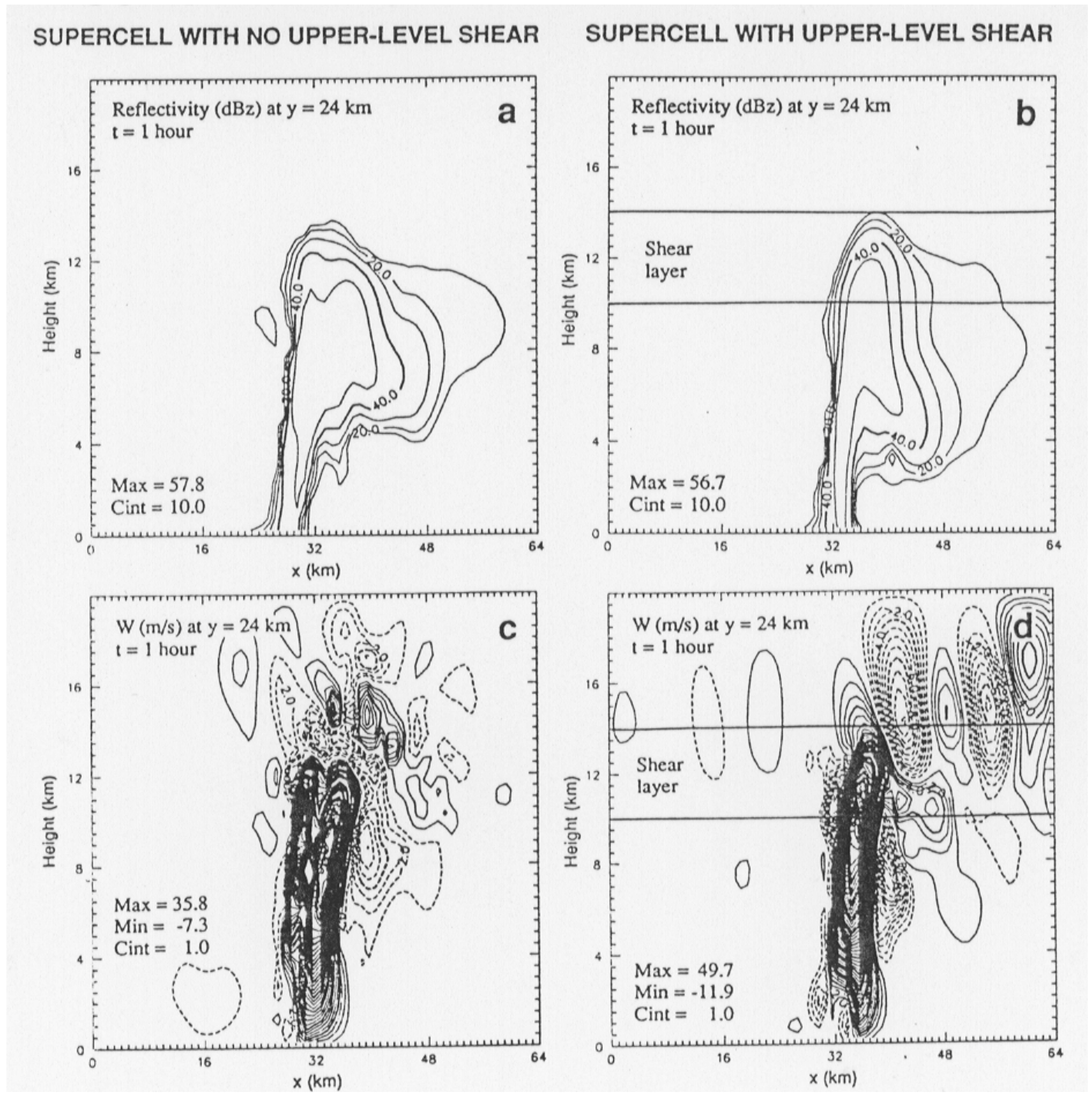


Figure 4. Numerical simulation of the vertical motions (lower panels) induced by an intense thunderstorm in the clear air above storm tops (Droegemeier et al. 1997). Values of several meters per second occur. The top of the modeling domain in this example was set at 20 km. We would expect that if the modeling domain were extended upward to 30 km or higher, the impact of the storm would still be significant at those altitudes.