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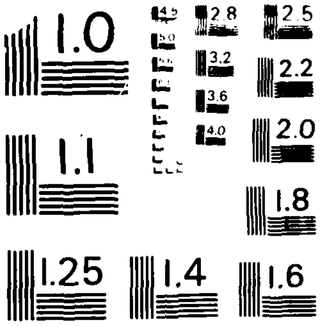

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THUNDERSTORM INFLUENCE ON BOUNDARY LAYER WINDS

A Thesis

by

JILL MARIE SCHMIDT

Submitted to the Graduate College of
Texas A&M University
in partial *fulfillment of the requirements* for the degree of

MASTER OF SCIENCE

December 1986

Major Subject: Meteorology

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THUNDERSTORM INFLUENCE ON BOUNDARY LAYER WINDS

Jill Marie Schmidt, Capt, USAF

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The objective of this ~~research~~ was to develop a conceptual model of selected pre-storm ambient conditions as a function of the strength of a thunderstorm's outflow. The time of maximum rainfall in relation to the time of maximum outflow was a thunderstorm characteristic which helped explain the downdraft mechanism and was included in the model.

The results indicated that two conceptual models were necessary to describe the pre-storm ambient conditions that led to thunderstorm development and outflow. One model contained the weaker outflows and the other described the stronger outflows. Six significant ambient conditions contributed to the thunderstorm building process, i.e., 1) horizontal moisture convergence below cloud base, 2) vertical flux divergence of latent heat energy below cloud base, 3) vertical wind shear in the 850 mb to 500 mb layer, 4) an environmental lapse rate approaching dry adiabatic at least in the lower subcloud layer, 5) potential instability below cloud base and, 6) potential evaporative cooling below cloud base. The model for the weaker outflows had relatively small magnitudes of ambient conditions, while the model for the stronger outflows had relatively large magnitudes of ambient conditions.

The weaker outflows were associated with maximum rainfall that occurred 1 h after maximum outflow. Frictional drag of the falling raindrops was the dominant mechanism over evaporative cooling in maintaining the downdraft. The stronger outflows were associated with maximum rainfall that occurred 1 h prior to or during maximum outflow. Evaporative cooling was the dominant mechanism over frictional drag in maintaining the downdraft.

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THUNDERSTORM INFLUENCE ON BOUNDARY LAYER WINDS

A Thesis

by

JILL MARIE SCHMIDT

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ABSTRACT

Thunderstorm Influence on Boundary Layer Winds (December 1986)
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The objective of this research was to develop a conceptual model of selected pre-storm ambient conditions as a function of the strength of a thunderstorm's outflow. The time of maximum rainfall during the thunderstorm in relation to the time of maximum outflow was a thunderstorm characteristic which helped explain the downdraft mechanism and was included in the model.

The data were taken from the Texas High Plains Experiment, a mesoscale experiment during the summers of 1977 and 1978. Six thunderstorm cases were selected for study from well-defined Code 3 cells (thunderstorms).

The results indicated that two conceptual models were necessary to describe the pre-storm ambient conditions that led to thunderstorm development and outflow. One model contained the weaker outflows and the other described the stronger outflows. Six significant ambient conditions contributed to the thunderstorm building process, i.e., 1) horizontal moisture convergence below cloud base, 2) vertical flux divergence of latent heat energy below cloud base, 3) vertical wind shear in the 850 mb to 300 mb layer, 4) an environmental lapse rate approaching dry adiabatic at least in the lower subcloud layer, 5) potential instability below cloud base and, 6) potential evaporative cooling below cloud base. The model for the weaker outflows had relatively small magnitudes of ambient conditions, while the model for the stronger outflows had relatively large magnitudes of ambient conditions.

The weaker outflows were associated with maximum rainfall that occurred 1 h after maximum outflow. Frictional drag of the falling raindrops was the dominant mechanism over evaporative cooling in maintaining the downdraft. The stronger outflows were associated with maximum rainfall that occurred 1 h prior to or during maximum outflow. Evaporative cooling was the dominant mechanism over frictional drag in maintaining the downdraft.

Average profiles of horizontal moisture convergence and the vertical flux of latent heat energy for both the weaker and stronger outflows showed that the greatest magnitudes of these ambient conditions were in the boundary layer and lesser magnitudes occurred in the upper subcloud layer. This demonstrated the importance of certain conditions in the boundary layer to thunderstorm development.

DEDICATION

This thesis is dedicated to my deceased sister, Tina Gaye Schmidt, whose untimely death in her senior year of college ended not only her life but the fulfillment of her educational and occupational dreams. Even in death, her inspiration and love of learning lives on in the author and hopefully, the attainment of this advanced degree will be as much a credit to her talents and potential, had she been spared, as it is for the author who was given the opportunity.

ACKNOWLEDGEMENTS

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Special acknowledgements go to Dr. Grant L. Darkow and Dr. Wayne L. Decker, Atmospheric Science Department, University of Missouri--Columbia, for their encouragement to the author as an undergraduate and their continued interest in her Air Force career and her pursuit of this Master of Science degree.

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1. INTRODUCTION

All convective clouds contain updrafts and downdrafts. The smaller scale and stronger intensity downbursts and microbursts are particularly hazardous to aviation. Downbursts and microbursts are of such a small horizontal scale and are so short-lived that their occurrences are not readily detected. Little or no real-time warning of these events is possible.

Downbursts typically range in diameter from 4 to 10 km and last 10-60 min, while microbursts are 1 to 4 km in size and last from 2 to 20 min (McCarthy and Wilson, 1982). Downbursts and microbursts are classified as mesoscale and misoscale phenomena, respectively (Fujita, 1985). Therefore, the existing national synoptic-scale observing network is not dense enough nor are observations taken often enough to routinely detect the presence of downbursts and microbursts unless occurrence is in close proximity to an observing site and time. Even downdrafts, with larger dimensions in space and time (10-100 km and 1 to 10 h, respectively) than downbursts and microbursts, are not easily detected since they, too, are mesoscale events (McCarthy and Wilson, 1982; Fujita, 1985).

The best setting for the study of downbursts and microbursts is within a mesoscale or misoscale observing network, available only during specially designed research experiments. Even these networks have difficulty detecting downbursts and microbursts but the odds are increased since the chances of them occurring near an observing site are increased. The detection of the larger and more persistent downdrafts,

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The Journal of the Atmospheric Sciences was used as a model for this thesis.

however, is virtually assured in special networks. Downdrafts, downbursts, and microbursts apparently describe the same type of meteorological event, scale and intensity being the only distinguishing feature. Therefore, it seems reasonable that a thorough study of measured downdraft events could be used to infer concepts about the nearly undetectable downbursts and microbursts, which are more intense forms of downdrafts.

2. LITERATURE REVIEW

Though earlier research and theories about thunderstorm development and life cycle exist, the Thunderstorm Project conducted by Byers and Braham in Florida and Ohio in the summers of 1946 and 1947 probably single-handedly revolutionized the knowledge of the thunderstorm (Byers and Braham, 1949). The observational existence of both updrafts and downdrafts in thunderstorms was well documented and attempts were made to physically explain the mechanisms of each. Byers and Braham observed the instability of the atmosphere prior to thunderstorm development. They also noted that: 1) the processes involved in the formation of the downdraft included the drag on the ascending air by the precipitation which is falling relative to the air itself; 2) at the surface the area of heaviest rain is coincident with the area of maximum divergence in the surface winds; 3) vertical wind shear produces considerable tilt to the updraft of the cell and to the visible cloud itself; and 4) in the presence of a strong wind shear the drag effects of the falling water are not imposed upon the rising currents within the thunderstorm cell which permits the updraft to continue until its source of energy is exhausted.

Byers and Braham considered downdraft formation dependent on the existence of updrafts containing greater-than-saturated adiabatic lapse rates caused by entrainment of environmental air. But observations of cumulus clouds suggest entrainment of mid-level environmental air is only important in clouds with diameters less than 1 km (Warner, 1955; McCarthy, 1974). Similarly, Srivastava (1985), in his numerical simulations of downdrafts, discovered that downdraft radii greater than 1 km, with entrainment, produce practically the same strength downdrafts as does no mixing.

Byers and Braham observed maximum rainfall to be coincident with the maximum strength of the outflow, and were aware of the frictional drag imparted by the raindrops in the downdraft process. However, they did not associate evaporative cooling and the need for a less-than-saturated subcloud layer to maximize the process with the downdraft mechanism. Kamburova and Ludlam (1966) found the most favorable conditions for the production of strong downdrafts to be an environmental lapse rate close to the dry adiabatic from the ground into the middle troposphere, and a great intensity of rainfall. They noted that the weight of the rain and the enhanced cooling by evaporation provided an important downward buoyancy force. The additional negative buoyancy force is created by evaporative cooling. As the moist downdraft descends, initially triggered by the drag force of the raindrops falling out of the updraft, it mixes with the drier subcloud layer and raindrops rapidly evaporate. The latent heat of evaporation cools the mixed air making it colder than its environment and thus, negatively buoyant, enhancing the downward movement of a now drier downdraft.

Hjelmfelt (1984), examining two microburst events near Denver on 22 Jun 82, observed convergence in the area of the downdraft within the dry layer just below cloud base, and subsaturated surface conditions in the microburst outflows which suggested active evaporation processes. He noted that precipitation loading may be an important forcing mechanism. McCarthy and Wilson (1984) corroborated the contributions of evaporative cooling and precipitation frictional drag on the air in their studies. Kamburova and Ludlum (1966) found that an unstable layer allows deeper penetration of the downdraft below cloud base by reducing the rate at which compressional heating causes the virtual temperature of the descending parcel to approach the environmental temperature.

The preceding discussion described how particular ambient conditions affected downdraft production from existing thunderstorms. Following is the discussion of the ambient conditions considered important to thunderstorm development.

Hjelmfelt (1984) saw the need for convergence in the layers below cloud base for cloud development, and Doswell (1982) observed that two of the primary factors in developing severe weather potential are low-level convergence and a supply of moisture; surface moisture convergence precedes the development of convection. He noted that the depth of the moist layer has a large impact on severe weather. If the moist layer is too shallow (less than 50 mb deep) there may be insufficient water vapor to support intense convection. If the moist layer is exceptionally deep (200 mb or more), the likelihood of non-severe heavy rainstorms is greater.

Upward vertical motion in the lower layers is required in conjunction with an adequate moisture supply and low-level convergence to lift the air to saturation and cloud formation. Doswell (1985) noted if the moisture content is sufficient, thermals rising out of the surface layer can result in cloud formation, and the air rising through the cloud converges into the developing cell. Doswell (1982) succinctly stated where there is cloud, there is upward vertical motion.

Klemp and Rotunno (1983) agreed with the requirement for low-level moisture convergence for thunderstorm development but observed, as did Byers and Braham, the need for vertical wind shear for strong thunderstorm development. Thunderstorms evolve in strong environmental wind shear and are sustained by the continuous supply of moisture from low-level inflow on the front side of the storm and by the transport of precipitation out of the updraft and into the downdrafts on the back side.

Lilly (1986) stated that the most intense storms often develop in regions of strong vertical shear, but he further noted that an updraft is initiated by an ellipsoidal parcel of warm air rising through a conditionally unstable environment with westerly shear in the lower troposphere.

3. OBJECTIVE

The objective of this research was to develop a conceptual model of selected pre-storm ambient conditions as a function of the strength of a thunderstorm's outflow. The time of maximum rainfall during the thunderstorm in relation to the time of maximum outflow was a thunderstorm characteristic which was used to help explain the downdraft mechanism and was included in the model.

4. DATA SELECTION

The data were taken from the Texas High Plains Experiment (HIPLEX), a mesoscale experiment during the summers of 1977 and 1978 in the area of Big Spring, Robert Lee, Snyder, and Post. The following data were used: surface observations, upper-air soundings, radar echoes, and rainfall amounts. A network of special surface stations approximately 40 km apart, hourly measured temperature, relative humidity, pressure, and wind direction and speed. Atmospheric soundings were made at four locations at 3-h intervals beginning at 1500 GMT and ending at 0300 GMT. The soundings were recorded at 25-mb intervals from the surface to approximately 100 mb. The National Weather Service radar facility at Midland was used to record the convective echoes. The data were coded using the following system: 1--tops less than 6.1 km; 2--tops between 6.1 and 9.1 km; and 3--tops exceeding 9.1 km. Rainfall was measured in 15-min intervals using recording rain gauges in a network with stations spaced approximately 10 km apart (Scoggins, *et al.*, 1979; Sienkiewicz, *et al.*, 1980).

5. CASE SELECTION

Thunderstorm cases for this study were selected from well-defined Code 3 cells (thunderstorms) in three categories: 1) isolated cells; 2) cells embedded in limited overcast containing some showers; and 3) cells embedded in extensive overcast with numerous showers. All or most of the storm's life cycle had to be observed in the HIPLEX area via radar and be long-lived through several hours so the time of maximum surface wind velocity divergence could be readily identified and analyzed. Six cases met these criteria and were the object of this study.

6. PROCEDURE

The ambient conditions of horizontal moisture convergence, vertical flux divergence of latent heat energy, vertical wind shear, environmental lapse rate, potential instability, and potential evaporative cooling were studied for the period from before storm formation until the storm reached its dissipation stage. This was necessary so that the occurrence of the maximum surface wind velocity divergence could be readily identified. This moment of maximum outflow was the primary period of interest in this study because it indicated the strongest downdraft in the thunderstorm. The values of the ambient conditions which were before the time of maximum surface wind velocity divergence were studied and compared, and were the basis of the conceptual model. Rainfall, a thunderstorm characteristic, was studied for each hour of the life of the storm in which it occurred. The time of maximum rainfall was compared to the time of maximum outflow.

a. Surface wind velocity divergence

Downdrafts from a thunderstorm, upon reaching the surface, spread out horizontally along the surface away from their original point of impact, i.e., a divergent pattern. Therefore, a quantitative measure of the divergence below and away from a storm would be a measure of the intensity of the thunderstorm's downdraft and subsequent outflow. Assuming a stationary storm in a calm environment, the outflow would be circular with $\vec{\nabla} \cdot \vec{v}$ equal to a maximum near the center of the circle, i.e., a maximum directly below the cloud base at or near the area of maximum rainfall rate. Decreasing values of divergence would be found with increasing radius r away from the maximum point until eventually, $\vec{\nabla} \cdot \vec{v}$ equals zero.

However, thunderstorms are not stationary and are embedded in ambient winds so outflow is not perfectly circular but distorted. The ambient winds enhance the size of the outflow area on the downwind side of the storm and lessen it on the upwind side.

Using calculated divergence patterns for each hour, it could be determined when in a thunderstorm's life cycle the strongest divergence is produced, i.e., when the strongest outflow occurs. However, values of the surface wind velocity divergence alone cannot be used for comparison purposes because the area of the divergence pattern must also be considered. Integrating the surface wind velocity divergence over the area of the outflow produces a better indicator of the strength of the divergence/outflow area.

The strength of the outflow from the thunderstorm downdraft was measured by integrating over the area of the patterns formed by the surface wind velocity divergence. Surface wind velocity divergence was calculated using the expression

$$\vec{\nabla}_2 \cdot \vec{v}_2 = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \cong \frac{u_2 - u_1}{\Delta x} + \frac{v_2 - v_1}{\Delta y}$$

where u and v are the components of the wind. The subscripts 1 and 2 are grid point values surrounding the "center point" and in the positive direction, respectively, and $\Delta x = \Delta y = 16$ km (Scoggins, et al., 1979; Sienkiewicz, et al., 1980).

With a grid consisting of 16 km x 16 km squares, the surface wind velocity divergence was integrated over the outflow pattern for each hour of the storm's life using the relationship

$$\int \vec{\nabla} \cdot \vec{v} \; dA \propto \sum_{i=1}^{N} (\vec{\nabla} \cdot \vec{v})_i$$

where N is the number of squares defining the outflow area. Since relative values of the integral were needed, only divergence was summed.

The maximum integral value of the surface wind velocity divergence of each storm was defined to represent the strongest downdraft. These maximum values constituted the basis of comparison with the other thunderstorms. Values are in units of $s^{-1} \times 10^{-6}$.

b. Horizontal moisture convergence

The ambient condition, horizontal moisture convergence, through the vertical, was determined using the vector identity

$$\vec{\nabla}_p \cdot q\vec{v}_2 = \underset{(1)}{\vec{v}_2 \cdot \vec{\nabla}_p q} + \underset{(2)}{q \, \vec{\nabla}_p \cdot \vec{v}_2}$$

where q is specific humidity.

Term 1 was computed by the centered finite difference formula

$$\vec{v}_2 \cdot \vec{\nabla}_p q = u \frac{\partial q}{\partial x} + v \frac{\partial q}{\partial y} \cong \bar{u} \frac{(q_2 - q_1)}{\Delta x} + \bar{v} \frac{(q_2 - q_1)}{\Delta y}$$

where $\bar{u}$ and $\bar{v}$ are the average wind components, and

$$\frac{q_2 - q_1}{\Delta x} \quad \text{and} \quad \frac{q_2 - q_1}{\Delta y}$$

are the horizontal components of the gradient of q in the x and y directions, respectively.

Term ? was calculated by multiplying q (an average for the pressure surface) by the horizontal velocity divergence, i.e.,

$$q\, \vec{\nabla}_p \cdot \vec{V}_2 = \frac{\bar{q}}{\bar{A}} \frac{dA}{dt} \cong \frac{\bar{q}}{\bar{A}} \frac{\Delta A}{\Delta t}$$

where A is the horizontal triangular area determined from the three rawinsonde balloon locations in the HIPLEX area, $\bar{A}$ is the average area of the triangle formed by the balloons at pressure surfaces 50 mb apart, and ΔA is the change of triangular area that occurs as the balloons move through a pressure layer 50 mb thick in time Δt. The velocity divergence represents a 50 mb layer mean value so Term 1 was computed as a mean horizontal advection by averaging data from three 25 mb data levels constituting the 50 mb layer used in the velocity divergence calculation. Vertical profiles of this parameter were computed at 1500, 1800, 2100, 0000, and 0300 GMT (Scoggins, _et al_., 1979; Sienkiewicz, _et al_., 1980).

Horizontal moisture convergence in the subcloud layer is required for release of conditional instability and to provide adequate moisture for continuing convection. Integration of the horizontal moisture convergence was performed from 900 mb to the level of zero divergence, in 50 mb increments, to measure the amount of moisture convergence over the general area where thunderstorms occurred. Using the relationship

$$- \int_{p=900}^{p_o} (\vec{\nabla} \cdot q\vec{V})\, dp \quad \propto \quad - \sum_{i=1}^{N} (\vec{\nabla}_i \cdot q\vec{V})$$

where N is the number of 50 mb pressure levels beginning with the 900 mb level to the level of zero divergence, p_0, the integral of horizontal moisture convergence was determined by summing values as in the case of surface wind velocity divergence. For each profile time before the storm, the horizontal moisture convergence profile was integrated (summed) until the level of zero divergence was reached. The relative integral value before the storm's time of maximum outflow was compared, quantitatively, with the other thunderstorms. Values are in units of $s^{-1} \times 10^{-7}$.

c. The vertical flux divergence of latent heat energy

The integral form of the latent heat energy budget in the x, y, p, t system is given by

$$\frac{1}{g} \int \frac{\partial}{\partial t} (Lq)\, dv + \frac{1}{g} \int \vec{\nabla} \cdot (Lq)\, \vec{v}\, dv + \frac{1}{g} \int \frac{\partial}{\partial p} (Lq_{\omega})\, dv = \int R dv$$

where L is the latent heat of vaporization and q is specific humidity. The last term on the left-hand side of the equation, the vertical flux divergence of latent heat energy, was the only one used in this study.

Vertical motion was computed on constant pressure surfaces using the formula

$$(\omega_p)_k = \omega_s + \sum^{k} (\vec{\nabla}_p \cdot \vec{v}_2)_k\, (\Delta p)$$

where $(\omega_p)_k$ is the vertical velocity on a constant pressure surface k, ω_s is the vertical velocity at the ground (set to zero), $(\vec{\nabla}_p \cdot \vec{V}_2)$ is the 50 mb layer mean divergence below layer k, and p = 50 mb. Vertical integration was performed over 50 mb intervals using the trapezoidal rule (Scoggins, et al., 1979; Sienkiewicz, et al., 1980).

Integration of the vertical flux divergence of latent heat energy was performed from the 900 mb level to the level of zero flux divergence, in 50 mb increments, to measure the integral amount of vertical flux divergence of latent heat energy over the general area where thunderstorms occurred. The last term on the left-hand side of the latent heat energy budget equation may be rewritten as

$$\frac{1}{g}\int \frac{\partial}{\partial p}(Lq\omega)\, dv = \frac{1}{g}\int \frac{\partial}{\partial p}(Lq\omega)\, dxdydz$$

$$\propto \quad -\frac{1}{g}\int \frac{\partial}{\partial p}(Lq\omega)\, dp \quad \propto \quad -\frac{1}{g}\sum_{i=1}^{N}\left[\frac{\partial}{\partial p}(Lq\omega)\right]_i \Delta p$$

where the area, dxdy, and density are assumed constant, and N is the number of 50 mb pressure levels beginning with the 900 mb level to the level of zero vertical flux. The pressure interval, Δp, and gravity, g, were left in this equation to permit easy integration of the profiles given by Scoggins, et al. (1979) and Sienkiewicz, et al. (1980). The vertical flux divergence of latent heat energy for each profile was summed before the storm. The integral value before the time of maximum outflow was compared, quantitatively, with the other thunderstorms. Values are in units of W $m^{-2} \times 10^2$/50 mb.

d. Vertical wind shear

The vertical wind shear determines whether a thunderstorm will tilt with height (much shear) or will be nearly vertical (little or no shear). This is a primary factor in whether a storm will be short- or long-lived. A nearly vertical storm will be short-lived because the downdrafts, influenced by gravity, will blow straight out the bottom of the cloud in the same place where the moisture-laden low-level updrafts are entering the storm. As the storm matures, the downdrafts become stronger than the updrafts and effectively, cut off the low-level moisture supply fueling the storm, initiating rapid decay. Downdrafts don't have time to get very strong because the mature stage is short.

However, in a leaning thunderstorm, the downdrafts blow out of the storm in a different location from where the updrafts come in so the moisture supply is preserved. The building process continues for a longer life cycle and the potential for a strong downdraft increases as the mature stage persists.

The vertical wind shear was determined using the expression

$$[(u_2 - u_1)^2 + (v_2 - v_1)^2]^{1/2} / (z_2 - z_1)$$

where the subscripts 1 and 2 refer to the lower and upper atmospheric levels, respectively, u and v are the components of the winds, and z_1 and z_2 are the heights in the atmosphere where these winds occurred (Duffield and Nastrom, 1983). For this study, 850 mb and 300 mb were chosen for the lower and upper pressure levels, respectively, which were used instead of actual geometric heights. Only the magnitude of the shear was considered.

The u and v wind components, from the sounding data, were used to determine the vertical wind shear. The values from the sounding closest to the storm activity and before the time of maximum surface outflow were calculated and compared, quantitatively, to the other thunderstorms. Values are in units of m s^{-1}/(850 mb - 300 mb) layer.

e. Environmental lapse rate

The steepness of the environmental lapse rate compared to dry adiabatic in the subcloud layer of air is important because the average lowest relative humidity of the subcloud layer occurs when the environmental lapse rate approaches the dry adiabatic lapse rate (assuming a constant average mixing ratio in the subcloud layer throughout the day). As the moist downdraft descends, it mixes with the drier subcloud air and the precipitation it contains begins to evaporate. The latent heat of evaporation cools the subcloud air making it colder than its environment and thus, negatively buoyant, enhancing the downward movement of the downdraft. The closer the environmental lapse rate approaches the dry adiabatic lapse rate, the more the contribution to negative buoyancy.

How conducive the subcloud layer was to evaporation was evaluated from the sounding data by comparing the environmental lapse rate to the dry adiabatic lapse rate. The height, in pressure, of superadiabatic lapse rates, or those approaching dry adiabatic, were compared to the height of the storm's cloud base to determine how much of the subcloud layer approached the dry adiabatic lapse rate. Noted was how many millibars difference there was between the cloud base and the top of the layer that approached dry adiabatic. This information was analyzed from the sounding nearest to the storm activity and before the time of maximum surface outflow and compared, quantitatively, to the other thunderstorms. Values are in units of mb.

f. Potential instability (P.I.)

Potential instability refers to the condition a moist layer of air would be in if the entire layer were lifted adiabatically in the atmosphere. A layer is potentially unstable if the equivalent potential temperature (or wet-bulb potential temperature) decreases with height through the layer. A pronounced stratification of the moisture distribution may cause layers that are initially stable to be potentially unstable when lifted. The environment is usually potentially unstable in the low-levels of strong downdraft-producing thunderstorms (Byers, 1974).

A measure of potential instability during the time of maximum outflow for each storm was determined from the sounding data using the expression

$$\text{P.I.} = (T - T_d)_{\text{c.b.}} - (T - T_d)_{\text{sfc}}$$

where c.b. is the cloud base, sfc is the surface, T is temperature, and T_d is the dewpoint temperature. The less negative results of this operation were indicative of more potentially unstable subcloud layers. The sounding data closest to the storm activity and before the time of the maximum outflow was used to evaluate this ambient condition and was compared, quantitatively, to the other thunderstorms. Values are in units of °C.

g. Potential evaporative cooling (P.E.C.)

The quantity resulting from the expression

$$\text{P.E.C.} = (T_s - T_w)$$

where T_w is the wet-bulb temperature and T_s is the surface environmental temperature, indicates the potential evaporative cooling capacity of the subcloud layer air. This was calculated from the soundings and the value from the sounding nearest the storm and before the time of maximum outflow was compared, quantitatively, to the other thunderstorms. Values are in units of °C.

h. Rainfall

Rainfall from a thunderstorm contributes to two of the major forces driving downdrafts, i.e., (1) the cooling of the air by the evaporation of falling rain, and (2) the frictional drag from falling precipitation. The evaporation of raindrops is the same process as the evaporation of cloud drops discussed under the environmental lapse rate section--evaporative cooling results when precipitation falls into the drier subcloud air. This contributes to the negative buoyancy of the descending air. The frictional drag results from the downward motion of the raindrops. This descending air is also changing temperature as it falls moist adiabatically so that it is more dense than the environment. Therefore, the downdraft continues to descend as a result of both the density difference and the frictional drag. This drag is, most likely, the initial mechanical mechanism for inducing downdrafts.

Studies show that a large fraction of the raindrops in a thunderstorm are used for maintaining the downdrafts through evaporative cooling (Byers and Braham, 1949). However, barring very high-based clouds, the raindrops in most typical thunderstorms are usually not all evaporated away into the environment before reaching the surface. This is the rainfall experienced at the surface. The more raindrops available in the downdraft for evaporation upon descent, the greater the potential for negative buoyancy (if the subcloud layer is nearly dry) and the stronger the downdraft and subsequent outflow. The unevaporated raindrops fall to the surface as rain.

Rainfall amounts were plotted and contoured for each hour of the thunderstorm's life. This was accomplished after each rain gauge's 15-min rainfall amounts were totaled for each hour. Using a grid with 10 km x 10 km squares (the approximate spacing of the rain gauges), the rainfall was integrated over the rainfall area for each hour of rainfall using the relationship

$$\int R \, dA \propto \sum_{i=1}^{N} (R)_i$$

where R is the rainfall and N is the number of squares defining the rainfall area. Since relative values of the integral were needed, only the rainfall was summed.

The occurrence of each thunderstorm's maximum hourly rainfall over the rainfall area was noted in relation to the storm's time of maximum surface wind velocity divergence. Whether the maximum rainfall occurred prior to, during, or after the maximum outflow was determined for all storms.

7. THE CONCEPTUAL MODEL

The hypothesis underlying this research is that the intensity of the outflow is directly related to the strength of the pre-storm ambient conditions and how they interact in developing the thunderstorm. Horizontal moisture convergence and the vertical flux divergence of latent heat energy work together to provide for continuing convection. How conducive the subcloud layer air is to ascent, enhanced by the potential instability, aids these two ambient factors. The potential evaporative cooling of the subcloud layer is a function of how closely the environmental lapse rate approaches the dry adiabatic lapse rate. Assuming an average constant mixing ratio throughout a given day, the average relative humidity is lowest, in the subcloud layer, when the environmental lapse rate approaches the dry adiabatic lapse rate. The subcloud layer, therefore, is most receptive to evaporation during this time. Vertical wind shear acts to lengthen the life of the thunderstorm and thereby gives each of the aforementioned parameters more time to strengthen and contribute to the development of the thunderstorm and the outflow.

The rainfall rate is a function of the strength of the thunderstorm these ambient conditions produced. Small moisture convergence and small vertical flux divergence of latent heat energy would, intuitively, result in a weak thunderstorm, since small quantities of water vapor would be transported upwards and the upward vertical velocity, ω, necessarily would be weak. The weak vertical velocity, in most cases, would be associated with a subcloud layer that was minimally potentially unstable. This small amount of moisture condensed into a cloud would provide a small amount of raindrops available for evaporation upon descent of the downdraft and small excess as precipitation measured at the surface. A small value of potential evaporative cooling would indicate that only small amounts of raindrops could evaporate, therefore, more rain would reach the ground. If only a shallow layer of the subcloud layer's environmental lapse rate approached the dry adiabatic lapse rate, this would limit the potential for evaporation in the subcloud air. With limited capacity for evaporative cooling, the frictional drag from the falling raindrops would be the more dominant factor in the downdraft process. Finally, small vertical wind shear in the general area of potential thunderstorm development would produce thunderstorms with little tilt and subsequently, short-lived storms that would have little time to develop strong outflows.

The above concepts of thunderstorm processes result in the conceptual model that weaker ambient conditions develop weaker thunderstorms which contain smaller amounts of raindrops in the cloud leading to smaller amounts of rainfall measured at the surface. These factors suggest that weaker ambient conditions generate weaker outflows. Similarly, the opposite rationale would be true for strong thunderstorms and strong outflows.

From this discussion, conceivably two conceptual models need to be developed--one to describe the weaker outflows and one to describe the stronger outflows.

a. Model 1 - weaker outflows

The following ambient conditions and their strengths will be associated this this outflow: 1) weak horizontal moisture convergence below cloud base; 2) weak vertical flux divergence of latent heat energy below cloud base; 3) weak vertical wind shear in the 850 mb to 300 mb layer; 4) an environmental lapse rate approaching dry adiabatic that begins at the surface but ends well short of the cloud base; 5) weak potential instability below cloud base; and 6) weak potential evaporative cooling below cloud base. Frictional drag will be dominant over evaporative cooling.

b. Model 2--stronger outflows

The following ambient conditions and their strengths will be associated with this outflow: 1) strong horizontal moisture convergence below cloud base; 2) strong vertical flux divergence of latent heat energy below cloud base; 3) strong vertical wind shear in the 850 mb to 300 mb layer; 4) an environmental lapse rate approaching dry adiabatic that extends from the surface to just short of, or at, cloud base; 5) strong potential instability below cloud base, and; 6) strong potential evaporative cooling below cloud base. Evaporative cooling will be dominant, or of comparable magnitude to, frictional drag.

8. RESULTS

The results of the six cases researched clearly indicated that two distinct conceptual models were necessary to adequately describe the pre-storm ambient conditions that led to thunderstorm development and subsequent outflow. The time of maximum rainfall associated with the thunderstorms also demonstrated two distinct patterns that supported the models.

Model 1 contains two cases and describes the weaker outflows, and Model 2 has three cases and describes the stronger outflows. One case was spurious in virtually all comparisons and could not be considered in either Model 1 or Model 2. Perhaps more cases would have revealed a third model to include this case but the scope of this research did not discover one. Therefore, this case was not considered.

The results of the two models are shown in Table 1, in order of increasing strength of thunderstorm outflow. Presented are the five cases with the maximum integrated surface wind velocity divergence for each storm. The ambient conditions and the time of maximum rainfall, listed in Table 1, are the values corresponding to the time of maximum outflow. The ambient condition values revealed some overlaps for the weaker and stronger outflows, and if examined individually, might bring into question these particular groupings for the two models. However, considering all factors collectively, including the rainfall results, the grouping of cases as presented was the most logical. Included in the table are typical values for the parameters of each model. These formulate the conceptual models and display the obvious differences between the two models.

Table 1. Ambient conditions and the time of maximum rainfall associated with the maximum outflows for the two cases in Model 1 and the three cases in Model 2.

	Outflow	Ambient conditions						Rainfall
Date	A	B	C	D	E	F	G	H
MODEL 1								
23 Jun 77	1806	-10.4	+4.1	17.3	0	-3.5	+4.0	+1
30 Jun 78	2164	-6.5	+9.2	4.3	20	-8.1	+9.2	+1
Typical	2000	-8.0	+6.0	11.0	10	-6.0	+6.0	+1
MODEL 2								
1 Jul 78	2991	-11.7	+10.6	6.0	50	-4.5	+7.8	0
25 Jun 77	3306	-18.0	+9.6	22.1	80	-10.6	+10.1	-1
5 Jun 78	3350	-13.5	+16.3	27.9	80	-8.9	+8.5	-1
Typical	3200	-14.0	+12.0	19.0	70	-8.0	+9.0	-1

A - Maximum surface wind velocity divergence ($s^{-1} \times 10^{-6}$)
B - Integrated horizontal moisture convergence ($s^{-1} \times 10^{-7}$)
C - Integrated vertical flux divergence of latent heat energy ($Wm^{-2} \times 10^{2}$)
D - Vertical wind shear (ms^{-1}/850 mb - 300 mb layer)
E - Difference between the top of the subcloud layer where the environmental lapse rate approaches the dry adiabatic lapse rate and the cloud base (mb)
F - Potential instability (°C)
G - Potential evaporative cooling (°C)
H - Time of maximum rainfall compared to the time of maximum outflow (h) [+1 indicates 1 h after maximum outflow; -1 indicates 1 h before maximum outflow]

Of the six ambient conditions, four displayed significant differences in their typical values, i.e., 1) horizontal moisture convergence, 2) the vertical flux divergence of latent heat energy, 3) vertical wind shear, and 4) environmental lapse rate. These conditions, apparently, are the more important factors of the six in the development of thunderstorms and their outflows. Certainly, the other two factors considered contribute to the development process but based on these results, must play minor roles since little distinction can be made between values for the weaker and stronger outflows.

As predicted in the conceptual models, the weaker outflows of Model 1 tended to have the weaker ambient condition values, and the stronger outflows of Model 2 had the stronger values (Table 1). This confirmed the assumption that the ambient conditions are all interrelated in contributing to the thunderstorm building process and in the ultimate strength of the outflow. Horizontal moisture convergence varied in the same manner as the vertical flux divergence of latent heat energy to provide moisture and latent heat energy necessary to induce saturation and to fuel the storm. Smaller amounts of these quantities, along with smaller values of potential instability (indicating the atmosphere was not overly receptive to upward motion), resulted in weaker storms and also weaker downdrafts and outflows (Table 1).

The average profiles of horizontal moisture convergence for Models 1 and 2 (Fig. 1), and the average profiles of the vertical flux divergence of latent heat energy for Models 1 and 2 (Fig. 2), clearly show how these two ambient conditions were important to the thunderstorm building process and ultimately the strength of the outflow. In both

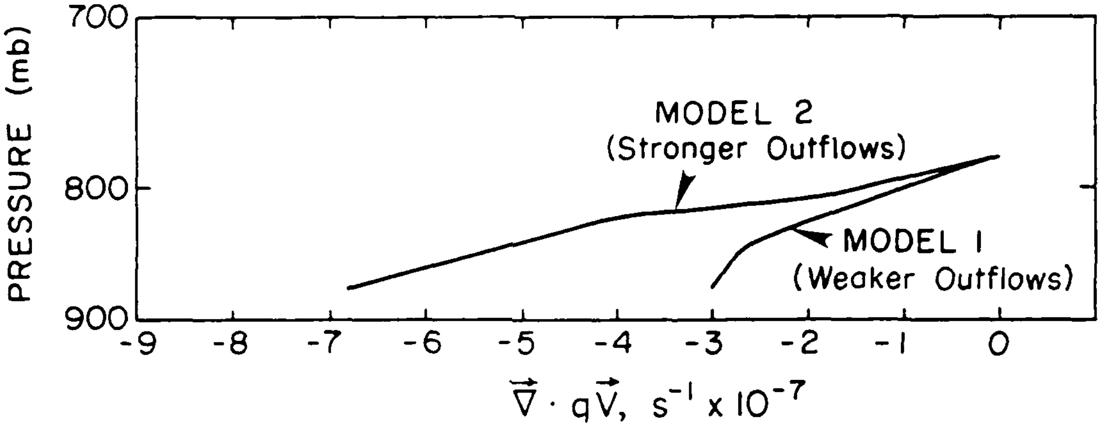

Fig. 1. Average profiles of horizontal moisture convergence for Models 1 and 2.

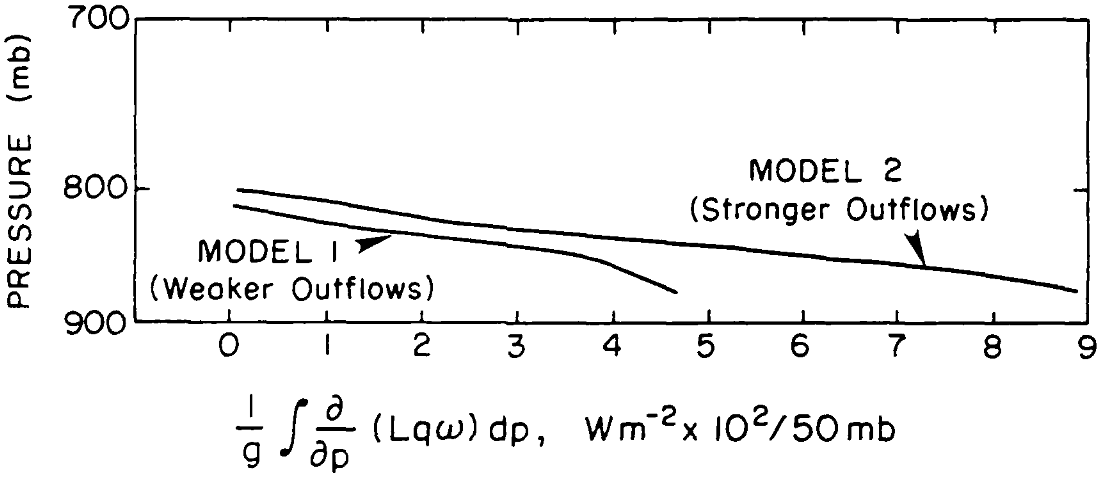

Fig. 2. Average profiles of the vertical flux divergence of latent heat energy for Models 1 and 2.

models greater horizontal moisture convergence and vertical flux divergence of latent heat energy occurred in the lower layers while lesser amounts of these quantities occurred at higher levels in the subcloud layer. This demonstrated the importance of the boundary layer in thunderstorm development and the lesser importance of the contribution from higher levels. The entire subcloud layer was involved but the brunt of these conditions came from the boundary layer. Even though Figs. 1 and 2 display average profiles, they depict the results discussed previously that the weaker outflows had the smaller values of horizontal moisture convergence and the vertical flux divergence of latent heat energy, and the stronger outflows had the larger values of these ambient conditions.

The potential evaporative cooling of each thunderstorm's subcloud layer was related to how closely the environmental lapse rate approached the dry adiabatic lapse rate. Shown in Table 1, the stronger outflows in Model 2 were associated with the subcloud layers where the environmental lapse rate approached and/or exceeded the dry adiabatic lapse rate at the surface and above but ended well short of the thunderstorm's cloud base. However, the weaker outflows of Model 1 were associated with dry, or nearly dry, adiabatic lapse rates throughout all, or nearly all, of the subcloud layer. Correspondingly, the stronger thunderstorms exhibited greater values of potential evaporative cooling indicating the greater likelihood for evaporative cooling to be a dominant factor in the downdraft mechanism. Conversely, the weaker storms, with their smaller potential evaporative cooling, were affected less by evaporative cooling in driving the downdraft (Table 1).

The results conflicted with the conceptual model which assumed that if the subcloud layer approached the dry adiabatic throughout the entire layer, a stronger downdraft and outflow would be produced. These cases showed that the rationale for this ambient condition for the weaker and stronger outflow conceptual models should be reversed. Apparently, the depth of the layer where the environmental lapse rate approached the dry adiabatic lapse rate was not a major determinant of the strong downdraft. The thunderstorms with the subcloud layers that approached the dry adiabatic lapse rate throughout the layer produced the weaker outflows. Those thunderstorms with subcloud layers that approached the dry adiabatic lapse rate only in the lowest layers of the subcloud layer produced the stronger outflows.

The stronger outflow thunderstorms were associated with the stronger vertical wind shears while the weaker outflow storms had the weaker vertical wind shears. The greater vertical leaning of the thunderstorm affected the outflow by allowing the downdraft to exit the cloud base in a location different from the updrafts feeding the storm. This allowed the outflow to impact and diverge at the surface unimpeded by the updraft area.

The rainfall during the storms' lives displayed the interesting pattern that both weaker outflow thunderstorms in Model 1 had the maximum rainfall occur 1 hr after maximum surface wind velocity divergence, and the stronger outflow thunderstorms in Model 2 had the maximum rainfall occurrence either during or 1 hr prior to maximum outflow. The research focused little on the role of the raindrops in the evaporative cooling and frictional drag processes in downdraft maintenance, thus definitive results are not available. However, the following concepts, based on when the maximum rainfall occurred in relation to the time of maximum outflow, are offered as possible explanations.

The stronger thunderstorms of Model 2, with the maximum rainfall 1 hr before maximum outflow (Table 1), displayed the dominance of evaporative cooling in producing stronger outflows. With the reasoning of the conceptual model that stronger thunderstorms have numerous raindrops available, and coupled with a subcloud layer with lower relative humidity in the lower layers, evaporative cooling occurred 1 hr prior to maximum outflow but all the drops were not evaporated. The excess was measured as the maximum rainfall of the storm. Because many of the raindrops were not evaporated, the downdraft did not experience the maximum cooling possible and, therefore, produced a weaker outflow than the following hour. However, during the hour of maximum outflow, more of the downdraft's raindrops were evaporated. This large amount of evaporation cooled the downdraft to near maximum cooling and accelerated the downdraft to its maximum of the storm. Only a small amount of drops remained to reach the surface as rainfall. The case where the maximum rainfall coincided with the maximum outflow similarly was dominated by evaporative cooling. This thunderstorm apparently contained such an abundance of raindrops that enough were evaporated to create the strongest downdraft of the storm and still plenty of drops remained unevaporated to produce the maximum rainfall measured at the surface. The frictional drag of the raindrops also accelerated the downdraft but was overshadowed by the evaporative cooling process.

The weaker thunderstorms, with maximum rainfall occurring 1 hr after the maximum outflow (Table 1, Model 1), had frictional drag as the more important mechanism for downdraft maintenance. The rain descending through the subcloud layer was nearly adequate to create the maximum outflow, even though a lesser number of raindrops (assumed in a weaker thunderstorm) was dragging the air downward. Evaporative cooling also contributed since nearly the entire subcloud layer approached the dry adiabatic lapse rate (Table 1, Model 1, column E) but was not the dominant mechanism in forcing the downdraft. This smaller quantity of raindrops, and small effect from evaporative cooling, resulted in smaller amounts of rainfall measured at the surface during the maximum outflow. The maximum rainfall fell 1 hr later, when more raindrops were available, and again, the downdraft was dominated by frictional drag with small effect from evaporative cooling.

9. CONCLUSIONS AND COMMENTS

a. Conclusions

The objective of this research was to develop a conceptual model of selected pre-storm ambient conditions as a function of the strength of a thunderstorm's outflow. The outflow resulting from the downdraft of the thunderstorm was defined and studied using the surface wind velocity divergence patterns formed by the outflow. Six ambient conditions were identified as being important to the thunderstorm building process and were studied for their contribution to thunderstorm growth, the downdraft, and the outflow. The time of maximum rainfall occurrence in relation to the time of maximum outflow was examined as a thunderstorm characteristic once the storm developed. Five cases of thunderstorm activity were analyzed for these factors and the results were used to formulate the conceptual model. The following conclusions resulted from the research:

1. Six significant ambient conditions contributed to the thunderstorm building process, i.e., i) horizontal moisture convergence below cloud base, ii) the vertical flux divergence of latent heat energy below cloud base, iii) vertical wind shear in the 850 mb to 300 mb layer, iv) an environmental lapse rate approaching dry adiabatic at least in the lower subcloud layer, v) potential instability below cloud base, and vi) potential evaporative cooling below cloud base.

2. Two conceptual models were necessary to adequately describe the ambient conditions and their roles in the thunderstorm building process and the subsequent downdraft and outflow. One model contained the

weaker outflows and the other described the stronger outflows. These models demonstrated that the ambient conditions of horizontal moisture convergence, the vertical flux divergence of latent heat energy, vertical wind shear, and the environmental lapse rate contributed the most to thunderstorm development since the typical values of these ambient conditions for the models were distinctively different. The values for the other two ambient conditions were not so definitive, therefore, played more minor roles in the process.

3. The weaker outflows of the one model tended to have the weaker values of ambient conditions while the stronger outflows of the other model had the stronger values of ambient conditions. The weaker outflows were associated with maximum rainfall that occurred 1 h after maximum outflow but the stronger outflows had the maximum rainfall 1 h prior to or during maximum outflow. The weaker outflows were associated with subcloud layers where the environmental lapse rate approached the dry adiabatic lapse rate through nearly the entire layer. The stronger outflows had subcloud layers where the environmental lapse rate approached the dry adiabatic only in the low layers.

4. The average profiles of horizontal moisture convergence and the vertical flux divergence of latent heat energy for both the weaker and stronger outflows showed that the greatest magnitudes of these ambient conditions occurred in the boundary layer and lesser magnitudes were found in the upper subcloud layer. All levels of the subcloud layer contributed these ambient conditions to the continuing convection but the lower subcloud layer provided the greatest magnitudes.

b. Comments

By inference, the thunderstorms containing the stronger downdrafts and outflows would have a greater likelihood of containing the smaller scale and more intense downbursts and microbursts. An operational forecaster could make use of these conceptual models for use in forecasting these events by examining the ambient conditions of vertical wind shear, environmental lapse rate, potential instability, and potential evaporative cooling from the latest and closest upper-air sounding. Ideally, the strength of these values could help a forecaster determine the possibility of strong downdrafts, which could be used to infer the occurrence of downbursts/microbursts and a precautionary advisory for these events could be issued.

In reality, these models contain several inherent problems that hinder the forecaster, who is making real-time decisions, from using them fully. Foremost is that the data routinely available to the typical forecaster are synoptic-scale data which cannot be used to accurately forecast the mesoscale events of downdrafts/downbursts/microbursts. The resolution of the synoptic-scale data is not small enough to detect crucial atmospheric conditions that trigger these meso- and misoscale events.

Secondly, data available to the forecaster, i.e., the upper-air sounding data, may be several hours old and therefore, would be too untimely to be a viable real-time forecasting tool to be used in forecasting the possible occurrence of these very current and short-lived events. At best, the vertical wind shear and the environmental lapse rate would be the only really valuable pieces of information taken from the sounding for use in distinguishing between weak and strong outflows. The potential instability and the potential evaporative cooling, as evinced in the models, were not good indicators of strong versus weak outflows and would not be very helpful, at least by themselves, in aiding a forecaster's decision to forecast downburst/microburst occurrence.

And thirdly, the important ambient conditions of horizontal moisture convergence and the vertical flux divergence of latent heat energy are data available only from a special mesoscale observing network. These are never available to the forecaster for determining how strong a building thunderstorm will be in order to forecast the strength of the downdraft and outflow.

The conceptual models determined from the research are applicable when used for after-the-fact analysis of recorded thunderstorm activity. However, they are only minimally useful in real-time operational forecasting because 1) routine synoptic-scale observing stations do not observe some of the ambient conditions, and 2) those ambient conditions that are observed are sometimes from data too old to be timely or are not convincing enough in predicting the differences between strong and weak outflows so that a decisive forecast for downbursts/microbursts can be made.

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