NOAA Technical Memorandum NWS SR-146

A GUIDE FOR CONDUCTING CONVECTIVE WINDSTORM SURVEYS

William F. Bunting
National Weather Service Forecast Office
Norman, Oklahoma

Brian E. Smith
National Severe Storms Forecast Center
Kansas City, MO

Scientific Services Division
Southern Region
Fort Worth, Texas
February 1993

UNITED STATES
DEPARTMENT OF COMMERCE
Barbara Franklin, Secretary

National Oceanic and Atmospheric Administration
John A. Knauss
Under Secretary and Administrator

National Weather Service
Elbert W. Friday
Assistant Administrator

Preface

This resource guide was written as an introduction to the challenge of conducting damage surveys. The material covers a range of topics including logistics of damage surveys, basic structural engineering principles, and methods of recording and interpreting damage information.

Many people contributed to the development of this resource guide. Valuable reviews and suggestions were provided by Robert Davies-Jones, Charles Doswell, and Harold Brooks of the National Severe Storms Laboratory; Bob Johns and Steve Weiss of the National Severe Storms Forecast Center; David Andra, David Beusterien, Michael Branick, Janice Bunting, and Larry Ruthi of the National Weather Service Forecast Office in Norman, Oklahoma; and Donald Burgess of the WSR-88D Operational Support Facility. Excellent suggestions were also provided by Tim Marshall of Haag Engineering Co.; and Kishor Mehta and James McDonald of the Wind Engineering Research Center at Texas Technical University in Lubbock, Texas.

The authors wish to thank these individuals for their time and expertise in improving the quality of this guide.

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Introduction

Damaging windstorms and tornadoes are a relatively common occurrence across the United States. The impact of such events on people and property is substantial. Since 1940, over 5600 deaths have been attributed to tornadoes alone (U.S. Department of Commerce, October 1990), and wind-induced building damage exceeds three billion dollars each year (J.H. Wiggens Co., 1978). While most damaging wind events (to be referred to hereafter as wind events) occur during the spring and summer, the potential exists year-round. The meteorological scales of these wind events range from a single thunderstorm microburst to widespread convective windstorms which may affect several states at any given time.

It is the mission of the National Weather Service (NWS) to issue timely watches, warnings, and statements before severe weather events. However, the challenges facing the operational meteorologist do not end once the event has occurred. An analysis of the damage must be undertaken in order to determine the type of event (tornado or straight-line wind), event characteristics (path length, width, duration, and intensity), and the effectiveness of the watch and warning system. The performance of the watch and warning system can be divided into two components: 1) Accurate detection of the phenomenon and determination of intensity, and 2) The effectiveness of watches, warnings, and statements in relaying information to users and eliciting the proper response.

There are many uses for the information obtained from damage surveys. The results provide feedback on the effectiveness of the watch and warning system. The information obtained from a survey can be used to verify the accuracy of severe storm warnings and to identify areas for improvement in the watch and warning decision-making process. Survey information can be disseminated to the media, providing a factual basis for reporting the event and placing it in perspective relative to previous severe weather events. Also, damage survey results become official records of the event and serve the legal and insurance communities.

The results of surveys are usually entered into **Storm Data**, which is used extensively by the operational and research meteorology communities for applied research and case studies. The introduction of computer-controlled and algorithm-based radars such as the WSR-88D Doppler radar has necessitated a local severe weather climatology for each area where a radar is to be installed. Jendrowski (1988) found a regional dependence when testing radar-based severe weather detection algorithms in Amarillo, Texas and Oklahoma City, Oklahoma. Regional severe weather databases will be used to further refine algorithm statistical relationships at each location and implicitly will incorporate some unique "regional differences" in storm characteristics. *Storm Data* is used to develop this local severe weather climatology, which can also be used by businesses for decision-making purposes (i.e., where to locate a facility that may be sensitive to large hail, hurricanes, or tornadoes, and how soundly it must be constructed).

It is essential that anyone involved in the process of conducting damage surveys have a thorough knowledge of the meteorological structure and evolution of severe weather events (i.e., the life cycle of a single thunderstorm cell or a bow echo) **and** an understanding of basic wind engineering concepts that relate to the design and construction of a building or other structure (power poles and billboards for example).

The most important factor that determines a structure's response to strong winds is the type of design and construction. Further, it is important to understand that structures (this term will be used to include both buildings and other constructed objects) are affected not only by the strength of the wind, but by its duration, gustiness, and by the direction from which the wind approaches relative to that structure. Airborne missiles (such as wood, concrete, metal, and other objects) also constitute a primary danger to structures in their path. The effect of reduced atmospheric pressure from a tornado passing overhead is generally less of a contributor to observed damage than are effects of wind-induced forces and airborne (or rolling) missiles. Most buildings are not air tight and ventilation systems allow the air pressure inside a building to adjust quickly to outside conditions.

Logistical and scientific issues relating to damage surveys will be discussed. The importance of planning cannot be overstated in any venture, and storm surveys are no exception. The proper equipment, goals, and knowledge are all required to complete a successful survey. While it sometimes will be impossible to state with complete confidence the cause of some particular wind damage, having the proper background information and the ability to piece together clues from different sources certainly will assist the survey process.

PART ONE: LOGISTICAL CONSIDERATIONS

Before beginning a damage survey, some important issues need to be resolved. Foremost among these is a list of the goals of the survey. In an engineering-oriented survey, information is gathered that is of primary interest to the designer or builder of the structure. To the meteorologist, the needed information centers around the type of event that occurred (tornado or straight-line wind), characteristics of the path, and magnitude of the winds. Most surveys conducted by NWS meteorologists usually will be limited in scope, due to time and budget constraints, and the frequent lack of aircraft for aerial surveys.

Some basic goals of a damage survey include:

1. A detailed sketch of the damaged area that shows path length, width, approximate times, and approximate F-scale ratings.
2. Discussions with eyewitnesses, including storm spotters.
3. Attempts to locate photographs or videos of the phenomenon.
4. Documentation of unusual occurrences and airborne missiles.
5. Photographic documentation (including video if possible) of the damaged area.
6. Accounts of the event from those with information could be incorporated in the NWS Preparedness Program.

The survey should begin before leaving the NWS office, and time should be taken to discuss the event with those who were on duty at the time. Information on the radar appearance of the storm, its speed and direction of movement, and changes in intensity along with times of occurrence are particularly valuable clues. If possible, call the local State Civil Emergency Management Agency or law enforcement agency for information and directions to the damaged area. Plot available damage information and storm information obtained from the office on a map before leaving for the field. This will give the survey team an early idea of the scale of the event and areas most affected, and such information will help determine the extent of the damage survey and the number of people involved. Be sure to obtain prior approval before entering a damaged area. Ideally, someone in an official capacity (such as a local police officer or State Civil Emergency Management Agency director) should accompany the survey team. Citizens are much more likely to cooperate with the survey team if they recognize someone as a local authority and friend. However, if time is critical, it is advisable on these occasions to conduct the survey alone or with another NWS employee.

The equipment carried on a survey is something that should be planned in advance. The usual damage survey is arranged hastily and it is easy to forget valuable equipment. The following list of equipment and considerations is suggested:

1. Accurate maps of the area
2. Several sharpened colored pencils
3. Still camera with several rolls of film
4. Compass
5. Hard copies of radar data (WSR-88D, 57, or 74)
6. Video camera with blank cassette
7. Government identification
8. Proper clothing (eg., boots and jacket)
9. First aid kit
10. Tape recorder
11. Note paper and clip board
12. Tape measure (100 ft)
13. Adequate food and water (food may not be available at or near the damage site)

In addition, it is recommended that each office develop a **Field Guide** that consists of a binder notebook with copies of the WSOM chapters pertaining to Disaster Surveys and Storm Data, Storm Data worksheets (See Appendix A), F-scale information, and survey forms and envelopes that can be given to people to complete and return later. A survey form useful for gathering information from eyewitnesses can be found in Appendix B. Such a field guide can be kept in a government vehicle or placed in a box or bag with other equipment that is packed easily before leaving for the survey.

Once the area of interest has been narrowed, a detailed map covering the damage area should be obtained. Generally, United States Geological Survey (USGS) topographical maps are the most accurate to use for damage survey work. These maps are available at libraries, map supply stores, or by mail from the USGS in Denver, Colorado.

The scope of the event will determine the approximate map scale. A localized area of wind damage demands a smaller scale map. Therefore, a 1:72,500 map, sometimes known as a seven-and-a-half minute section map, should be used for this type of survey. Damage that covers a large area such as those produced by an outbreak of tornadoes, a long-track tornado, or a multiple downburst storm dictates a larger scale map. In this case, a 1:250,000 (quarter-million) sectional map would be best. If a USGS type map is unavailable, then an accurate county map or state map with most roads plotted is acceptable.

It is recommended that each office have on hand 1:250,000 scale USGS maps and county maps covering the appropriate WSFO's, WSO'S, or WFO's warning responsibility area. **Hand-drawing your own map is not recommended, because distortions could cause inaccuracies in plotted storm damage.** If the map is going to be re-used, it would be advantageous to photocopy the map. However, photocopying may make it more difficult to locate rivers, lakes, or other usable landmarks.

To plot the direction of wind damage (vectors) on the map, colored pencils are recommended. Pens may be used, but colored pencils can be erased if errors are made. Bring along a variety of colors in case one pencil color blends with the colors on the map. Make sure you have a flat, hard surface to work on (a book or clipboard is recommended).

Photographing the damage is important to confirm the original vector plotting and to evaluate the strength of winds that occurred. Photographs from aerial surveys are especially valuable in evaluating overall damage path length and width, and for locating areas with more extensive damage. If possible, photographs should contain an object or landmark of known size to use as a scale. While aerial surveys are not always available, in some cases local television stations are willing to allow NWS meteorologists to accompany station personnel on aerial surveys. The meteorologist(s) may offer to give the television station an interview about the results of the survey after the survey analysis is complete. Local National Guard, State Police, Civil Air Patrol, or Forest Service offices also may provide aerial survey capability. Ground photos can be used to document damage to specific structures and to record the movement of large objects that may have been rolled or become airborne.

The type of camera to use is at the discretion of the individual(s) conducting the survey. However, a 35mm SLR (Single Lens Reflex) camera with adjustable shutter speeds to at least 1/500 second is probably the most versatile model to use. Such a camera is especially useful during an aerial survey, as the shutter speed can be adjusted fast enough to produce crisp images during aircraft movement.

A zoom lens is the most adaptable type to use for both ground and aerial surveys. For an aerial survey, a 35-105mm or comparable lens is sufficient for producing close-up as well as wide-angle photographs of the damage area. This also prevents the need for numerous changes of altitude for either a close-up or wide-angle view of the damage track. It is a good idea to bracket the exposure (take photographs one f-stop above and below what the camera meter suggests) since reflection of light from the haze layer may give a false light meter reading. A zoom lens is useful for ground survey work when photographing either a large or small object, eliminating time spent moving into position to frame the object.

An ultraviolet filter can be used to protect the lens. Application of black tape around the edge of the filter is recommended to prevent scratching of the survey vehicle's windows (especially when doing an aerial survey). On an aerial survey, the survey team should wear solid dark-colored (navy blue or black) shirts. This prevents reflections from the windows onto the photograph.

Both color print and slide film are useful for surveys. Print film is best for any post-analysis photogrammetric work. Slide film, however, is useful if the damage information is to be shown at a presentation. The ASA type depends on sky conditions (cloudy, sunny, etc.). Again, this is especially critical when performing an aerial survey, because of the need to keep the shutter speed fast. Generally, on sunny days, ASA 100 film is preferred, while on cloudy days ASA 400 is preferred. When unsure of the sky cover, a compromise of ASA 200 is recommended. ASA 100 film or 200 film is less grainy and, therefore, superior for locating small details and for making enlargements. Use a notebook or tape recorder to keep a record of photographs taken and direction the camera is facing.

PART TWO: An Engineering Perspective

The most important variable in the response of a structure to extreme winds is its type of design and construction. Other factors that influence the effect of extreme winds upon a structure include the orientation of that structure with respect to the direction of the winds, the terrain upstream from the structure, the duration and gustiness of the strong winds, and the potential for debris generated upstream to hit the structure. The combination of these factors and the tendency for some wind events to be rather localized explains the often disorganized pattern of structural damage. It follows that a basic understanding of wind-structure interaction is needed in order to conduct a damage survey. In this resource guide, considerable information on engineering concepts is taken from the National Severe Storms Laboratory Technical Memorandum NSSL-82 titled **The Tornado: An Engineering-Oriented Perspective**,by Minor, McDonald, and Mehta (1977). Although this publication is out of print, photostatic copies are available from the National Technical Information Service.

Wind speed estimates are based on the F-scale developed by Fujita (1971). The F-scale chart for various types of structures has been reproduced in Appendix C. Notice the variability in the F-scale for different types of construction. A well-anchored mobile home completely blown off of its foundation is generally caused by an F2 or greater (denoted by the +) wind. However, to blow a concrete building off of its foundation, an F5 or much greater (denoted by the +++) wind is necessary. Therefore, when conducting a damage survey, it is important to consider **both** the quality of the construction of the structure as well as the type of structure. The F-scale was derived to assess the wind speeds associated with tornadoes, hurricanes, and "straight-line" winds based on the observed structural damage. The original intent of the F-scale was to allow for a quick estimation of wind speed. Since the F-scale is a subjective estimate of the wind speed, some accuracy is sacrificed. To obtain a more precise estimation, an engineering survey must be undertaken. However, because of the public's and media's "need-to-know" attitude, the limited amount of time meteorologists have to conduct surveys, and the fact that most meteorologists have no training in structural engineering, the F-scale remains the best way to estimate wind speeds. The F-scale wind speed ranges and representative damage are:

F0	40-72 MPH	Some damage to chimneys and signs, branches break off, shallow-rooted trees pushed over.
F1	73-112 MPH	Surfaces peeled off roofs, mobile homes overturned, automobiles pushed off road.
F2	113-157 MPH	Roofs torn from frame houses, mobile homes demolished, large trees uprooted.
F3	158-206 MPH	Roofs and some walls torn off well-built houses, trains overturned, most trees uprooted, heavy cars lifted off ground and thrown.
F4	207-260 MPH	Well-built houses leveled, structures with weak foundation blown some distance, cars thrown and large missiles generated.
F5	261-318 MPH	Strong frame houses lifted off foundations and disintegrated, and debris carried considerable distances, automobile-sized missiles (debris) fly through air in excess of 300 feet, trees debarked.

The term "failure mode" is used to describe the effects of strong winds on a structure. Often, strong winds result in the destruction (failure) of one component of a structure. The failure of this crucial component then leads to progressive failure of the entire structure. When strong winds approach and surround a building such as that in Figure 1, the flow of air around, through, and over the building combines to produce forces on that building. Figure 1 also illustrates terms used to describe a typical residential structure. In the example illustrated in Figure 2a, as strong winds approach a typical residential structure, the flow of air produces an inward-acting force on the windward wall and outward-directed forces on the roof, the side walls, and the leeward walls. These forces arise, in part, because the approaching flow of air cannot negotiate the sharp corners, eaves, and roof ridges of the structure. As a result, the flow of air "separates" from the surface of the structure at these locations, creating pockets of low pressure downstream from separation points. Figure 2b illustrates that the strongest outward-directed forces exist immediately downstream from corners, eaves, and roof ridges.

In the classic mode of failure of a building, strong inward-directed forces on the windward wall lead to failure of that wall. As the winds rush into the interior of the building, large outward-directed forces are generated. At the same time, outward-directed forces arise from the airflow around and over the building. Outward-directed forces acting vertically on the roof are termed "uplift" forces. The combination of failure of the windward wall and the outward-directed forces may lead to a progressive failure of the entire building. Typically, the windward wall falls inward, while the remaining walls fall outward. In the 1970 Lubbock, Texas, tornado, the damage to many structures could be traced to the failure of a weak link in the building, followed by the progressive failure of the entire structure (Mehta, et al., 1971).

In the 1980 Grand Island, Nebraska, tornadoes, Marshall and McDonald (1982) found that the "weak link" was not just the design and construction of a building, but the orientation of the building to the flow. In their analysis of the damage, 49 percent of observed roof damage could be traced to winds approaching a home on the garage door side, with the resulting failure of the garage door leading to severe uplift forces on the roofing system. In many cases, the stability of the walls was tied to the connection with the roof. As a result, the building sustained substantial damage. The type of roof structure also influences the magnitude of uplift forces by the roof slope and presence of eaves and ridges. Figure 3 illustrates common types of roof structure found on buildings. In general, hip and mansard roofs tend to fare better than gable and flat roofs. This is due in part to the fact that corners on hip and mansard roofs are not as sharp, the slope of the roof is not as steep, and in the case of the hip roof, there are typically no eaves or overhangs present.

The foundation-to-wall connection is another critical link in a building. The type of foundation and the spacing of anchor bolts (if used) affects the resistance to strong winds. Rural structures often are inferior in design and construction compared to those in cities, due to the lack of building code enforcement.

Uncertainties in structural resistance to strong winds is related partially to the strength of the materials used in construction. Furthermore, there is often considerable variability in the strength of similar materials. For example, Marshall et. al (1983) have found that the force required to pull apart two 2 x 4 pieces of wood toe-nailed (nails driven in at an angle) together can differ by 20 percent or more. This variability is due primarily to differences in the strength of wood and the nails used in the connection. The strength of connections, such as the wall-to-roof connection, is affected by the type of materials used. Toe-nailed connections are less effective than those with metal straps or hurricane clips. Also, toe-nailed connections tend to loosen with age, making the structure more susceptible to windstorm damage (Marshall and McDonald, 1982) with time. Glass, concrete, steel, and masonry are also subject to variability in strength. This variability is due partially to quality of materials and differences in manufacturing. Glass windows may differ in strength by 20 percent or more, making assessment of wind speeds needed to result in failure difficult. Appendix D lists typical building materials and factors which affect their strength.

The variability of material strength has important implications in the wind speed assessment process. Instead of defining structural failure in terms of a single wind speed, it becomes appropriate to express a range of wind speeds that may overlap two or more F-scales. The table below illustrates the effect of increasing variability on F-scale rating. The left column lists wind speeds required to produce failure of a hypothetical structure. The following three columns represent wind speed ranges assuming a 10, 20, and 30 percent variability, respectively, in the strength of materials used in that structure. For example, given a structure that would theoretically fail (i.e., be destroyed) at a wind speed of 182 MPH, but which was built with materials that vary in strength by as much as 30 percent, the actual range of wind speeds that could account for that building failure range from 132 MPH (F2) to 232 MPH (F4).

Wind Speed at Building Failure	**Uncertainty in Building Resistance** **10%**	 **20%**	 **30%**
	Range of Windspeeds to Induce Failure (MPH)		
56 MPH (F0)	47-64(F0)	42-69(F0)	38-74(F0-1)
92 MPH (F1)	77-107(F1)	70-114(F0-2)	62-122(F0-2)
135 MPH (F2)	113-157(F2)	103-167(F1-3)	91-179(F1-3)
182 MPH (F3)	152-212(F2-4)	139-225(F2-4)	132-232(F2-4)

Damage to residential structures is, typically, the most frequently encountered type of damage caused by severe windstorms. In order to make accurate assessments of estimated wind speeds, it is necessary to analyze the damage to houses in areas where building codes exist and are enforced. This is most likely in urban areas. A house that appears to be damaged more heavily than nearby houses may have been poorly built, struck by a large piece of debris, or been damaged owing to its orientation to the approaching winds. Also, a structure that was not damaged by strong winds may provide information on the upper bound of wind speeds. Caution must be taken when a multiple vortex tornado has occurred, because homes directly in the path of a suction vortex will suffer significantly greater damage than homes surrounding the path of the suction vortex. In cases where suction vortices have occurred, care in examining the damage area should be taken before rejecting more severely damaged homes.

Grazulis (1991) has developed a list of structures and objects that can be severely damaged or destroyed by winds of F0 or F1 (under 113 MPH). The list, while not exhaustive, is an excellent guide for the meteorologist when attempting to assign an F-scale rating. The list is presented in Appendix E.

PART THREE: Surveying the Damage

An important portion of this guide pertains to the distinction between tornadic and straight-line wind events. In this section, some common fallacies surrounding damage surveys will be addressed and explanations offered for apparent contradictions observed when analyzing damage patterns. Further, there is no rule that requires the origin of wind damage to be **entirely** straight-line or tornadic. It is not uncommon for some thunderstorms to produce tornado damage while, at the same time, straight-line wind damage is occurring in association with the rear-flank downdraft, microbursts, bow-echo induced downbursts, or, occasionally, the low-level mesocyclone inflow. The fact that such complex sources for damaging winds are possible requires the meteorologist to have a thorough understanding of the structure and evolution of various weather phenomena. The introduction of hard copies of WSR-88D radar data (reflectivity and radial velocity) for field use should provide valuable clues to damage survey team members when analyzing damage patterns. It is important for those conducting the storm survey to pay attention to subtle clues in storm damage. There are times when the damage patterns will appear confusing (e.g., tornado and microburst interaction). Therefore, one must be careful not to jump to conclusions in determining what type of storm produced the damage. Only after careful assimilation of all the plotted damage vectors and analysis of radar data should one determine the type of storm that produced the damage.

An accurate determination of the time of the event can be obtained from any of several sources. Eyewitness accounts often provide very good estimates of times. The survey team should look for electric clocks that have stopped when power was lost. It is important to determine if power was lost during the time of damage or if power had failed earlier. Again, eyewitness accounts often will provide this information. Electric power company records can provide very accurate times of power line breaks due to damaging winds. Law enforcement and emergency management communications logs often can provide detailed information on the times of damage in local areas. Radar film, logs, and hardcopies also can provide good estimates of times of severe weather events.

Eyewitness accounts often can provide the survey team with valuable information during a damage survey. The eyewitnesses, however, are often victims of the storm and the survey team MUST be sensitive to the situation and treat those interviewed with concern and respect. Occasionally, even the most well-meaning statement or question can be misinterpreted by those affected by the storm. For example, the statement "We're from the National Weather Service and we are here to determine if this damage was caused by a tornado" may not be received kindly by someone whose home is damaged and who is absolutely certain that a tornado caused the damage. Begin the conversation with concern for the person you are interviewing. Was anyone home during the storm and are they OK? Did anyone see the storm? This is a convenient point to ask more specific questions. If the person does not appear willing to be interviewed, offer to return later, or give the person a copy of a survey form (Appendix B) with a franked and return-addressed envelope to complete and return at a more convenient time. If examples can be found where actions taken before the storm saved lives, document the story with photographs and narrative accounts for inclusion in future preparedness talks. Specific examples of taking proper precautions during severe weather are more effective in encouraging similar behavior in others. Finally, ALWAYS ask permission before entering a damaged building or photographing someone's home or property.

One common fallacy is that "twisted" damage is a sign of rotating winds and, hence, a tornado. A STOP sign that appears to have been twisted is affected by the direction from which the wind approaches relative to the sign at the top of the pole. Strong winds approaching "head on" likely will blow the sign down without twisting the sign pole, while winds approaching at an angle will cause the sign to twist at its base as it falls. Similarly, a tree may be twisted owing to its center of gravity. Debris striking a sign or tree away from its center of gravity also can cause twisting to occur.

The degree of tree damage also is related to the seasons and geographical location. Damage to deciduous trees may not be as extensive or severe during the winter or early spring as in the late spring or summer. The foliage canopy on trees in the late spring and summer changes the center of gravity on a tree. Therefore, in a damaging wind event, this "top-heavy" tree will fall easier than in the winter or early spring when the foliage is not present. Foliage on trees also can create wind resistance, especially in heavily wooded areas. Many times, only the outer edges of the wooded area will contain downed trees, while the inner portions of the wooded area will have little damage, owing to blockage of the wind. Certain geographical areas, such as the southern United States, have trees that are shallow-rooted, allowing them to topple more easily than a deep-rooted tree. The amount of rainfall also can affect the strength of the root system in a tree. Prolonged heavy rainfall can weaken the holding power of a tree's root system, making it easier for the tree to fall.

It often is assumed that tornadoes must produce damage blown in the opposite direction ("uptrack") from the storm's direction of motion. For a typical northeast-moving tornado, some erroneously believe that damage blown to the southwest is required to label the event a tornado. Similarly, it also is assumed that if damage is blown down in one prominent direction, then only straight-line winds or a downburst are responsible. Surveys of several tornadoes by Reynolds (1957) have shown that tornadoes frequently produce damage oriented in one dominant direction (usually in the direction of storm movement). This is particularly true for fast-moving tornadoes (Figure 4). Owing to the fast translational motion of the storm, the wind of in the direction of the storm's movement is enhanced, while the wind blowing in the opposite direction is diminished.

Some straight-line wind events produce damage blown in different directions. This also can be related to the storm motion. Fujita (1985) modeled microburst outflow patterns for various storm motions (Figure 5). Some microbursts, especially associated with a mesocyclones, will twist (Figure 6) and when a tornado is present, will often occur to the right (usually south) of the tornado track. Either microbursts, downbursts, or the rear-flank downdraft can force the tornado track to deviate (Figure 7). Damage blown down in different directions can be explained by terrain effects, nearby buildings or objects that cause the winds to swirl or flow around the obstruction, or by shifts in the direction of the strong winds (Figure 8).

While toppled trees provide one with good vectors, certain types of damaged crops also can be used to identify the direction and strength of winds. Corn is a good example of a crop that produces reliable vectors (Figure 9). Figure 10 illustrates microbursts that produced flattened corn, along with other damage. The direction of the microburst outflow was obtained by plotting vectors where corn stalks fell.

While corn, grain sorghum, and alfalfa are useful crops in determining vectors of storm damage, wheat is not a very useful in determining vectors. The delicate stalks of the wheat plant make it nearly impossible to determine vectors of damage or even the path of the storm. However, when wheat is damaged by strong winds or a tornado, after a few days the damaged wheat will die and discolor, allowing the damage path to reveal itself.

Reports of extremely loud noises or sudden pressure drops often accompany tornadoes, and are sometimes evidence of tornado occurrence. However, strong thunderstorm downbursts and microbursts also are capable of producing very loud roaring sounds and significant pressure changes that may cause one's ears to "pop." Therefore, a loud roaring sound and pressure changes cannot be used reliably to determine if a tornado has occurred.

Many tornadoes have been described as having been funnels at tree-top level and never touching down. In reality, the tornado circulation was probably present at ground level, but friction with the surface and nearby objects reduced wind speeds below damaging thresholds. There also are cases where there is evidence of tornado damage on the ground, but because the condensation funnel did not extend to the ground or no condensation funnel was observed, the event was not designated as a tornado. Tornadoes with little or no condensation funnels are most common in the High Plains of the United States. Thus, when performing a survey in cases where no funnel was observed, one must plot the damage vectors carefully and analyze radar data to indicate evidence of a tornado.

There is a tendency to list some tornado episodes as single, long-track events (see Doswell and Burgess, 1988). While there have been cases of unusually long (i.e., greater than 50 miles) single tornado paths, most cases of apparent long-track tornadoes can be explained more readily using the cyclic model of mesocyclone development. Accordingly, close inspection of damage patterns will usually reveal gaps between successive tornadoes. As discussed by Burgess and Lemon (1990), mesocyclones (the parent circulation of supercell tornadoes) often follow a cyclic pattern of development and decay, with the first mesocyclone cores requiring the longest time to develop. Subsequent mesocyclone cores then form relatively quickly in the vorticity-rich background environment and may lead to additional tornadoes. Figure 11, reprinted from Burgess and Lemon (1990), illustrates the cyclicity of mesocyclone core development. The emphasis here is on the fact that supercell tornadoes are often cyclic in nature, and the survey team must look carefully for gaps in damage that would indicate multiple tornadoes. Often, a tornado will turn to the left (usually north) of its previous direction of motion during the dissipation stage and narrow in width. Each track should be considered as separate tornado events, even though the gap between each track may be small.

An observational study by Johns et. al. (1992) suggests that a majority of mesocyclone-induced tornadoes in the United States are associated with complex storm structures, including line echo wave patterns, spiral bands, and bow echoes. While many strong and violent tornadoes are associated with thunderstorms containing mesocyclones, many tornadoes are not. Several investigators (see, e.g., Wakimoto and Wilson (1989), Brady and Szoke (1989)) have documented the occurrence of damage-producing tornadoes not associated with mesocyclones. The tornado forms in the boundary layer when pre-existing vertical vorticity in the vicinity of a thunderstorm gust front (or intersecting gust fronts) is stretched and intensified underneath a strong updraft. In eastern Colorado, damage up to F3 intensity has been documented in association with this type of tornado (Wakimoto and Wilson, 1989). Radial velocity data from WSR-88D radars may provide useful clues to the type of wind event. The presence of a mesocyclone (Burgess and Lemon, 1990), or strong azimuthal shear (significant velocity differences along adjacent azimuths at the same approximate range) suggests the possibility of a tornado.

Tornadoes also are associated with bow-echo thunderstorms. The locations of tornado development in relation to the bow-echo has been identified by Fujita (1979) and is shown in Figure 12. The tornado in a bow-echo storm either forms at the apex of the bow or in the "cyclonic head" region to the left of the bow. Many times downburst and tornado damage coexist with each other (Figure 13). This can make it difficult for the surveyor to identify or distinguish the type of storm or the storm structure. One clue in recognizing a tornado embedded within a downburst is observing a narrow area of concentrated damage generally stronger than damage surrounding it. The meteorologist must be familiar with environmental conditions under which these non-supercell tornadoes form.

The following guidelines, originally developed by The National Severe Storms Laboratory, are useful for distinguishing between tornadoes and straight-line winds:

Characteristic	**Tornado**	**Downburst**
- Aspect ratio of damage area	long-thin	short-wide
- Gradients of damage	great	lesser
- Trajectories of debris	narrow convergence	broad divergence
- Appearance of damage	chopped up	laid out neatly
- Eyewitness accounts: Visual sighting	funnel/swirl	not seen
- Aerial Survey	vortex mark, suction vortex, herringbone tree damage	no vortex mark divergent damage

In narrow tornadoes, the flow of air near the ground is primarily radial into the vortex. Thus, it is possible to look for evidence of this inflow by observing impact marks of mud on obstacles, and by the collection of leaves, litter, etc., by wire fences (known as captive debris). Also, thin litter lines down the track are sometimes seen where straw and mud is collected. In all tornadoes, the outer low-level flow is convergent into the vortex, and the survey team should look for an inward wind component in the direction trees are felled. The survey team must use caution when drawing conclusions about the location and position of debris before and after the storm, since it may have been moved or disturbed during clean-up operations. This is why it is important for the survey team arrive at the damage site as soon as possible after the event. Eyewitnesses may be helpful in determining if debris has been moved.

A frequent misconception is that a tornado's path width, or a downburst's width, can be measured by the length of downed power transmission lines and trees. Strong winds, particularly winds with considerable gustiness, will exert a force on power lines. As the power lines begin to sway, the force often causes the tower to fail resulting in larger forces and a domino effect. Thus, a one-half mile wide tornado may cause power transmission lines and towers to fail across a wider area. The width of the downed power lines and transmission towers is often more a function of the strength of the towers and weight of the wires than on the width of the meteorological phenomenon causing the damage. Airborne debris and rolled objects also may affect power lines and towers. Caution should be used when interpreting this information.

Many large tornadoes are made up of multiple vortices (Figure 14). This phenomenon was realized by Fujita (1971) when noticing cycloidal damage marks in corn fields during aerial surveys. These marks are not scratches in the ground or exposed soil; rather, they are debris deposits left behind by the suction vortex (Figure 15). Because of the suction vortices' small diameter and spinning motion around the larger circulation, they pick up debris along their path, but not near the center of the larger circulation. Figure 16 shows Fujita's model for a tornado with multiple vortices. A tornado with strong suction vortices can damage homes severely directly along the path of the vortices, while homes located off the direct path of the vortices may have little damage, giving one the illusion that the tornado skipped. The shape of the cycloidal marks left behind by the suction vortices depends on the ratio of the rotational (tangential) velocity and the translational velocity of the tornado (e.g., the velocity ratio). The various suction vortex shapes and their corresponding velocity ratios are shown in Figure 17. No loop will form when the velocity ratio is 1. When the ratio is 1, a "stepping spot" is formed, meaning the suction vortex has stopped temporarily. A photo of a "stepping spot" (or stationary suction vortex) is shown in Figure 18. An aerial photo of suction vortices with a velocity ratio of around 7 is shown in Figure 19. Suction vortices are most visible from the air. However, careful mapping of damage in residential areas from a ground survey may reveal the existence of suction vortices.

Most tornadoes are cyclonic. However, some tornadoes rotate anticyclonically. Again, conducting an aerial survey will distinguish best between anticyclonic versus cyclonic circulations. However, careful plotting of vectors and debris patterns on the ground may help one reveal the rotational nature of a tornado. In west-to-east moving cyclonic tornadoes, the tangential (rotational) velocity of the tornado and the translational velocity of the storm are in the same direction on the south side of tornado. Therefore, a line of debris deposit occurs on this south perimeter. The opposite is true in west-to-east moving anticyclonic tornadoes, via which the debris deposits will occur along the northern perimeter of the tornado (Figure 20).

Plotting of vectors from downed trees or damage debris is very important, in order to identify the type and strength of the storm that occurred. One should drive somewhere in the middle of the storm track where there is known damage. When arriving at the storm damage, one should traverse **all** roads that intersect the damage, plotting all vectors of downed trees, power poles and damage debris (Figure 21). Photos should be taken at confusing or interesting damage areas for further analysis later.

It is imperative that the damage vectors be plotted accurately on a map. Thus, one should pinpoint the location of the damage using accurately the odometer in the vehicle. For example, in a rural area where the damage lies between two east-west/north-south intersections, first write down the odometer reading (to the nearest tenth of a mile if possible) at one of the intersections. Then travel down the road that intersects the damage until you reach the edge of the damage area, and write down that odometer reading. By subtracting the first odometer reading from the second, you obtain an accurate distance to the fringe of the damage area. Double check your results and transfer the location of the damage area to the map. Two examples of vectors plotted and analyzed are shown in Figures 22 and 23.

In cases of a derecho (multiple-downburst storm) (Figure 24) or a downburst covering a large area, it may not be feasible to traverse down every road covering the damage area. In these cases of widespread damage, the surveyor should limit the detail in the survey and travel along various roads, plotting occasional damage vectors and the fringes of the damage area. **A detailed mapping should be done over areas where damage is concentrated and noticeably stronger (indicating possible tornadoes), and over areas that have unusual damage.** If the damage is too extensive to perform an accurate survey, ask law enforcement officials or civil defense personnel that were affected by the storm to produce a mapping in their local area.

When analyzing damage areas, one should also assign an F-scale rating along various portions of the track and label those ratings on the survey map. Remember, a tornado is not a steady-state phenomenon. It changes size and strength along its track. In cases of downbursts or derechos, one also should assign F-scale ratings to damage. Because downbursts cover a large area, isolines of F-scale should be drawn on the map, especially where areas received F2 or greater damage.

If an aircraft or helicopter is available for an aerial survey, then certain rules should be followed as listed below.

1.) Use a single engine high-wing aircraft (such as a Cessna 172 or 182). A low-wing aircraft will obstruct your view and limit your photos.

2.) If you are the navigator on the flight, make sure the pilot understands your intentions and how you plan to fly over the damaged area.

3.) If you determined the damage was due to a tornado, you should instruct the pilot to intersect the damage path. The pilot should fly along the damage path while you plot the track on your map. This should be done at a height where it is easy for you to ascertain the damage path (i.e., narrow tornadoes, fly at a lower level; wide tornadoes, fly at a higher level).

4.) After the track is plotted, instruct the pilot to fly along the track again for you to take high-level oblique-angle photos along the track. These photos will be used as reference photos when re-analyzing the damage. After this is accomplished, fly along the track again and take high-level photos along the track. The width of the tornado track should fit in the frame of the photograph. In order to perform this, the pilot should bank the aircraft at a steep angle directly over the track so that you can obtain nearly vertical photos. Each photo should overlap the previous one, so as to create a complete set of photos along the damage track. Finally, low-level aerial photos should be taken at various points of interest along the tornado track. These photos should be taken as low as possible in order to reveal details in the damage. Low-level photos should include such subjects as suction-vortex marks, structures that are severely damaged, severe tree damage, areas where tornado-downbursts interact, and unusual damage.

5.) For a widespread damage aerial survey (large downburst or derecho), one should fly zig-zag patterns essentially normal to the damage path. Plotting of vectors is important in this type of survey. It is not necessary to shoot photos of the complete path. Photos should be taken over areas of spectacular, or unusually strong damage.

6.) Make sure you number your rolls of film sequentially. This will make it easier for you to identify your locations during post-analysis.

Aerial surveys are not covered in detail in this manual, owing to the infrequency that NWS personnel will be able to conduct such a survey and the complex logistics involved in performing such a survey. Aerial surveys, however, are superior to ground surveys because one can identify storm features and types with greater ease. Aerial surveys will be covered as an addendum to this manual at a later date. For further information on aerial surveys of tornado and downburst damage, many fine references written by the Wind Research Lab (WRL) or Satellite and Mesometeorology Project (SMRP) of the University of Chicago are available. Please contact WRL at the University of Chicago for a listing of available manuscripts involving aerial damage surveys. Also, the Wind Engineering Research Center at the Texas Technical University in Lubbock maintains an extensive library of wind-structure interaction and damage survey information.

Analysis of the photos and mapping may require a considerable amount of time. Sometimes, the complex structure of the storm involved, or interactions between tornadoes and downbursts may make analyzing the event difficult. Remember, careful inspection of all available evidence (radar, eyewitnesses, and damage) is needed to make the best estimate of the cause of a wind event.

PART FOUR: Other Issues

The information presented thus far has focused on surveys from a severe local storm perspective. However, some areas of the country experience hurricanes, downslope winds, or some other severe wind event.

In a landfalling hurricane or tropical storm, the resulting damage depends on three primary factors besides the wind speed. These factors are:

- Damage resulting from storm surge and wave action
- Damage that can result from **prolonged** exposure to strong winds, since a structure may be damaged or destroyed due to fatigue of its parts
- Damage to structures (particularly power lines) sensitive to pronounced **gusts** in wind speeds.

The survey team investigating a landfalling tropical storm or hurricane must separate damage caused by wind from that caused by water. This is most easily accomplished by going inland to a point where the storm surge effects were minimal. However, since the strongest winds often are experienced along the immediate coast, the survey team can look at the higher levels of a high-rise building along the coast for signs of wind-induced damage while recognizing that damage near the ground floors may be due to the influence of surge and wave action.

Hurricanes do spawn tornadoes. Normally these occur in the northeast quadrant of the hurricane's circulation. Many times, hurricane-spawned tornadoes occur away from the center of the storm (being spawned in the outer spiral bands). Because these occur apart from the strongest winds of the hurricane, identification of the tornadoes is not difficult. However, damage due to tornadoes that occur near the eye of the hurricane may be difficult to distinguish from damage due to the hurricane itself. If one finds an a narrow area of concentrated damage embedded within the overall damage, a tornado should be suspected.

Many NWS meteorologists undoubtedly make subjective ratings of tornadoes based on visual appearance, path characteristics, and eyewitness accounts, but a standardized method of accomplishing this has not been developed. Some argue for a pure damage-based definition of the F-scale, while others insist that an accurate tornado climatology should be based on intensity (see Doswell and Burgess, 1988 for a comprehensive discussion of this and related topics). The situation is sufficiently complex that considerable future debate is likely. The survey team can address this issue best by providing as much information as possible in the survey report. Specifically, state what information was used to assess the F-scale rating, describe the nature and extent of damage, the type of structures that were damaged, path dimensions (length, width, and width variations), and times of occurrence. If possible, provide corroborating radar and eyewitness information to support conclusions. This will give other meteorologists and engineers interested in the event the proper background information should the event require further study.

The complex nature of conducting damage surveys requires a broad knowledge of meteorological and engineering principles. Covered in this manual is basic information for NWS meteorologists to use in conducting a ground survey. There are many sources of information that can be used by the survey team to determine the cause of a particular wind event. It is also likely that, at times, a definitive answer is not possible. The situation is not unlike solving a mysterious crime. The quality of the results are directly related to the knowledge and experience of the "investigators" and to the attention to details.

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APPENDIX A

STORM DATA WORKSHEET

____
Intials

Dollar Damages:	Tornado	Wind	Hail	Lightning	Rain
Prop:					
Crop:					

F P P

Remarks __________

____
(Date(s) of Storm)

Other States __________

Place: __________

Day(s) of Month: __________

Time: __________CST

Path Length: __________

Path Width: __________

Killed:

Injured:

Damages (by category)
Property: ______
Crop:

Character of Storm: __________

Textual Description of Storm

NATIONAL WEATHER SERVICE SEVERE STORM SURVEY

Name________________________________ Date of Storm____________________
Mailing Address_________________________ Times (Beginning/End)_____________
____________________________________ Your location during storm_________
Phone # where you can be reached__________ ____________________________
What times may we contact you?____________
*If you live in a rural area, please describe your location from the nearest town
(i.e., 3 miles north and 4 miles west of Smithville)____________________________

Please circle the appropriate answer

1. Did you observe a tornado? YES NO
   If yes, what time did you first observe it?_ It's location from you_
   When were you no longer able to observe it?_ It's location from you_
   Did it dissipate? YES NO
2. Did you observe any damage? YES NO
   If yes, please describe____
   ____
   Please estimate dollar amounts of damage to your property____________
3. Did you hear a roar? YES NO Did you see power transformers flashing? YES NO
4. On the reverse side of this form, please sketch the shape of the tornado.
5. Did you observe strong winds not associated with a tornado? YES NO
   If yes, what were the beginning and ending times?_________________________
6. Please estimate the strongest winds you observed_ _Direction_ _Time_
7. Did you observe any damage? YES NO
   If yes, please describe____
   ____
   Please estimate dollar amounts of damage to your property____________
8. Did it hail? YES NO
   If yes, what size were the largest hailstones? (i.e. dime-size, quarter-size, golfball)
   ________________________ What was the average size?____________________
9. What time did the hail begin?________ End?________
10. Was the ground covered? YES NO
11. Was there any flooding? YES NO How much rain at your area (if measured)
12. Was there any damage from lighting? YES NO
    If yes, please describe____
13. Please describe anything you feel was unusual or significant about this storm.
    ____
    ____
    ____
14. Did you receive warning? YES NO
    If yes, from what source?____

Thank you for taking time to complete this survey. Your answers will assist the National Weather Service in documenting this storm and will provide valuable information for meteorologists to study.

Appendix C

Some typical construction materials and factors affecting variability in strength.

1. Steel

   chemical composition of alloys
   methods of manufacturing and testing
   size and shape

2. Concrete

   - type of cement
   - type of aggregates
   - moisture and air content
   - water to cement ratio
   - quality of workmanship

3. Masonry (i.e., stone, brick, and concrete)

   - bond strength of mortar (depends upon type of mortar)
   - strength properties of masonry
   - quality of workmanship

4. Wood

   - direction of grain
   - position of growth rings (age)
   - moisture content
   - size and distribution of imperfections (i.e., knots)
   - manufacturing (was wood air-dried or kiln-dried?)
   - type of wood (pine, fir, oak, etc)

NOTE: Most wood used for construction purposes consists of two types. Dimension lumber consists of wood cut into specific sizes. The other, known as Glulam lumber, consists of layers of dimension lumber bonded together with adhesive. The grain directions of all layers are essentially parallel, and the strength is greater than that of dimension lumber.

5. Glass

   - type of glass
   - plate geometry (aspect ratio)
   - surface flaws
   - quality of workmanship
   - environment (temperature and humidity changes)
   - type of force affecting glass (small projectile or larger scale force due to wind) and its duration

NOTE: There are two primary types of glass used in building construction. Annealed glass, which is cooled slowly to prevent brittleness, is frequently used in non-engineered structures. Heat-treated glass is frequently used in structures which have been carefully designed and built. Heat-treated glass is annealed glass which has been re-heated to near its softening point and then rapidly cooled. This process strengthens the glass, making it more resistant to strong winds and airborne projectiles.

APPENDIX D

Estimate of F-Scale Wind from Structure Type and Damage Category

By Fujita (1989)

Structure Types	DAMAGE CATEGORIES						
	No Damage	Minor Damage	Roofing Blown Off	Whole Roof Blown Off	Some Walls Standing	Flattened to Ground	Blown Off Foundation
Outbuilding Mobile Home	F0	F0	F0	F1	F1	F1	F2+
Weak Frame House	F0	F0	F1	F1	F2	F2	F3+
Strong Frame House	F0	F0	F1	F2	F3	F4	F5+
Brick Building	F0	F1	F2	F3	F4	F5+	F5++
Concrete Building	F1	F2	F3	F4	F5+	F5++	F5+++

MINIMUM WINDSPEEDS: F0(40 mph) F1(73) F2(113) F3(158) F4(207) F5(261 mph)

Appendix E

A partial list of buildings and other structures which can be severely damaged or destroyed by winds of F0 or F1 (under 113 MPH).

- Athletic field grandstands
- Barns shifted off foundation
- Barns fully collapsed but not blown away
- Barns unroofed
- Boat docks, marinas, and boat storage buildings destroyed
- boats carried into trees
- Brooder houses
- Cars rolled downhill (any distance)
- Chimneys blown down
- Conveyor belts twisted
- Drive-in movie screens destroyed
- Fast Food restaurant unroofed or sign blown down
- Fences blown down
- Haystack blown away
- Homes partially unroofed with no other damage
- House boats overturned
- House destroyed by falling tree
- House rotated on foundation
- Motel partially unroofed
- Open animal sheds and shelters destroyed
- Porches destroyed or removed
- Quonsets destroyed
- Roofs unshingled (frequently called "unroofed")
- School gymnasiums partly unroofed
- Signs destroyed
- Small chicken houses destroyed
- Small airplanes severely damaged or destroyed
- Tourists cabins unroofed
- Tractor of equipment sheds destroyed
- Trailer homes in transit destroyed
- Walls of homes cracked
- Windmills and small oil derricks destroyed

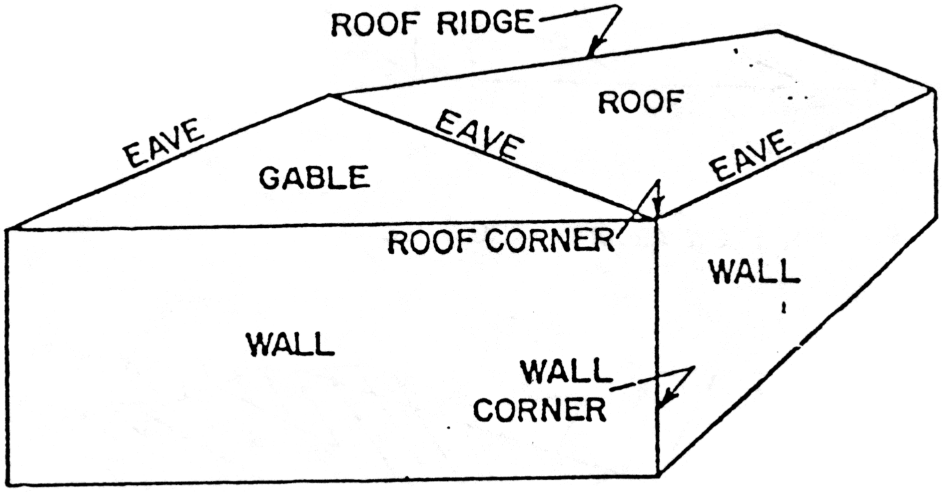
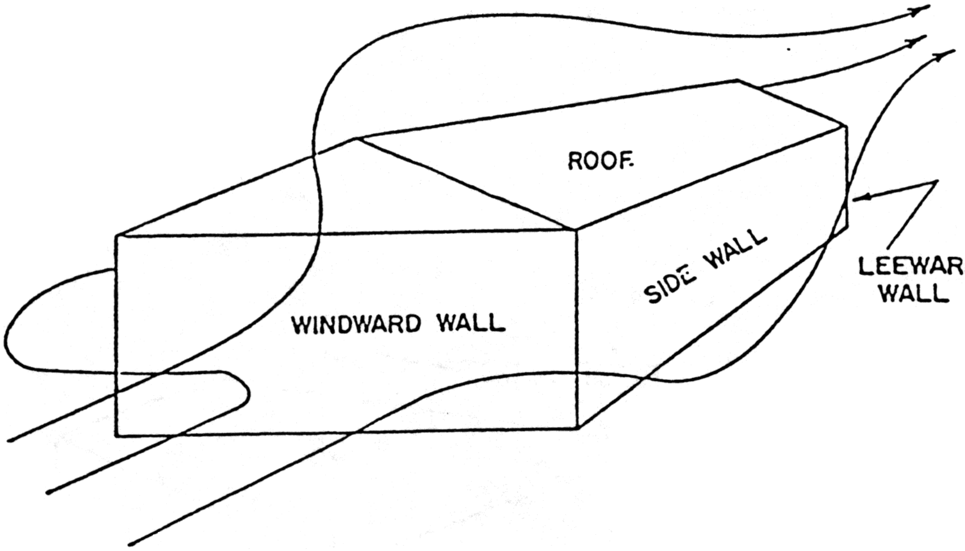


Figure 1. Terminology used in describing a typical residential structure. Building components are termed windward, leeward, or side depending on wind direction (Reprinted from ERL NSSL TM-82).



AIR FLOW AROUND STRUCTURE

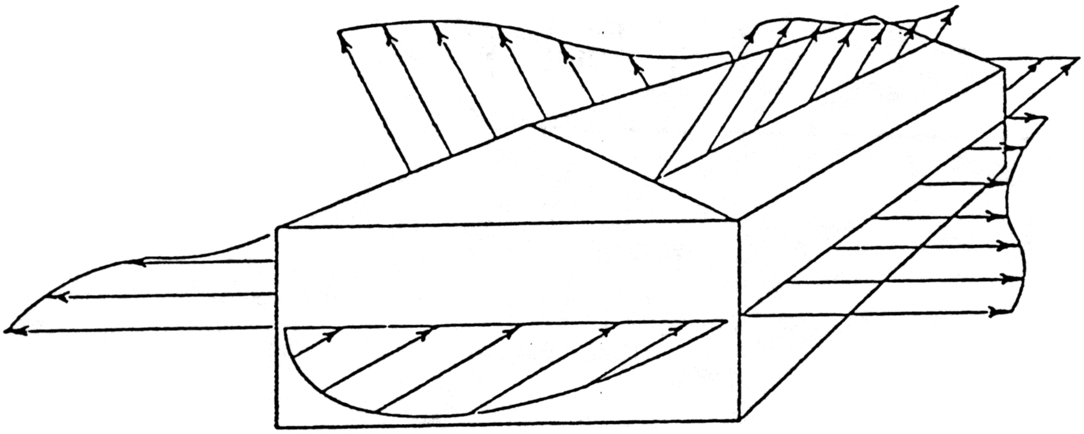


Figure 2. A) Simplified airflow around a structure. B) Overall forces act inward on windward wall and outward on roof, sidewalls and leeward wall (Reprinted from ERL NSSL TM-82).

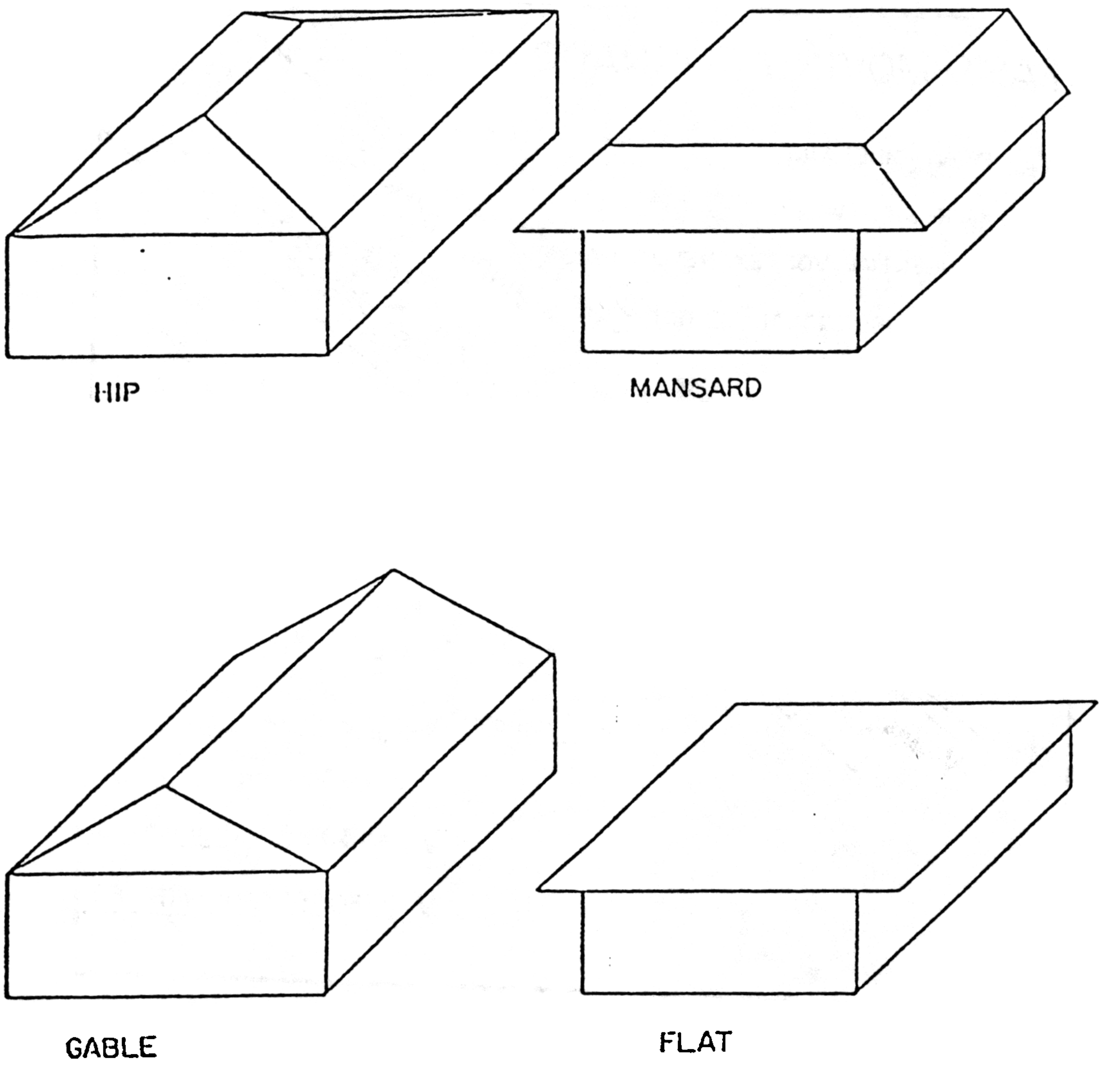


Figure 3. Common types of Roofs (Reprinted from ERL NSSL TM-82).

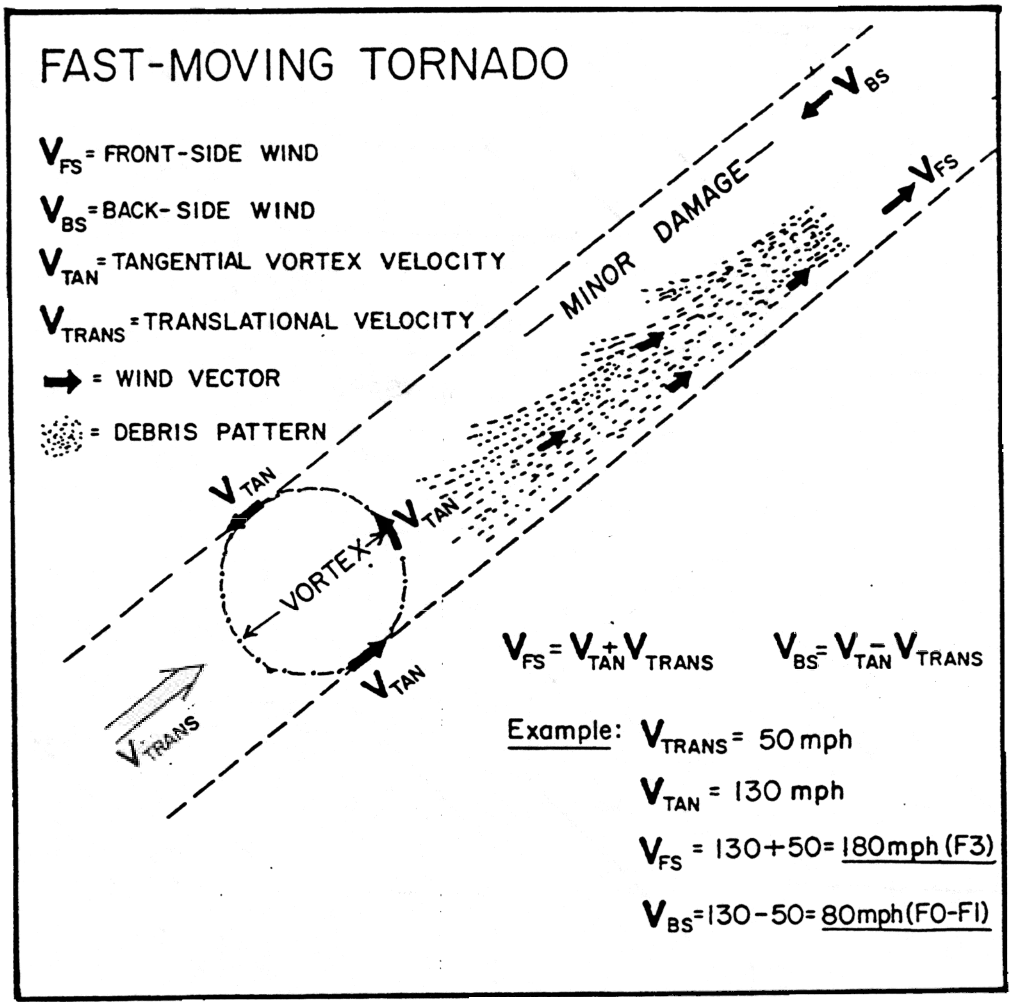


Figure 4. Model of a fast-moving tornado. Debris in a fast-moving tornado is generally blown in the direction of the storm's translational motion. Stronger damage will occur where both the translational motion and the vortex motion are in the same direction.

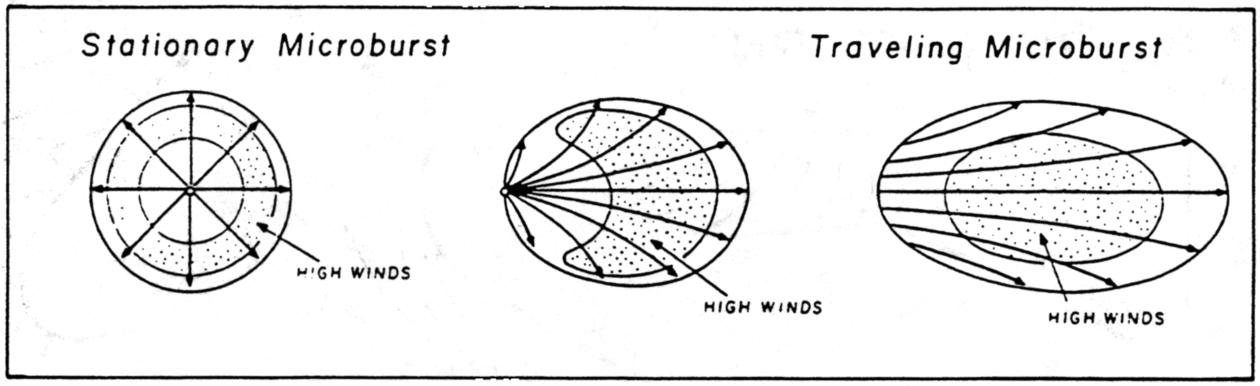


Figure 5. The variation of wind flow inside microbursts with different translational motions. A stationary microburst produces radial (star burst) horizontal wind vectors. With faster translational motions, the wind vectors become closer to straight-line. (From Fujita, 1985)

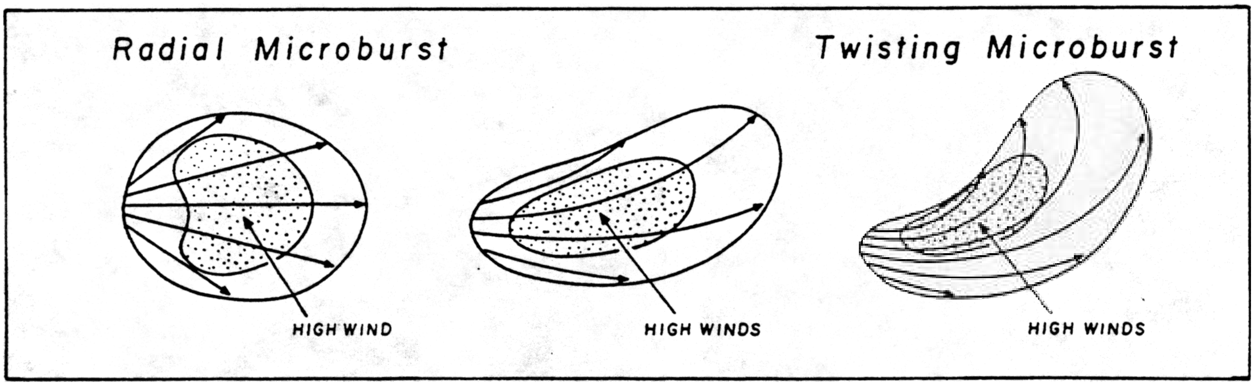


Figure 6. A radial microburst is indicated on the left, where winds radiate from a point in a straight-line fashion. A twisting microburst on the right will have curved wind vectors. Twisting microbursts are most often associated with mesocyslones and generally occur on the right side of a tornado track. (From Fujita, 1985).

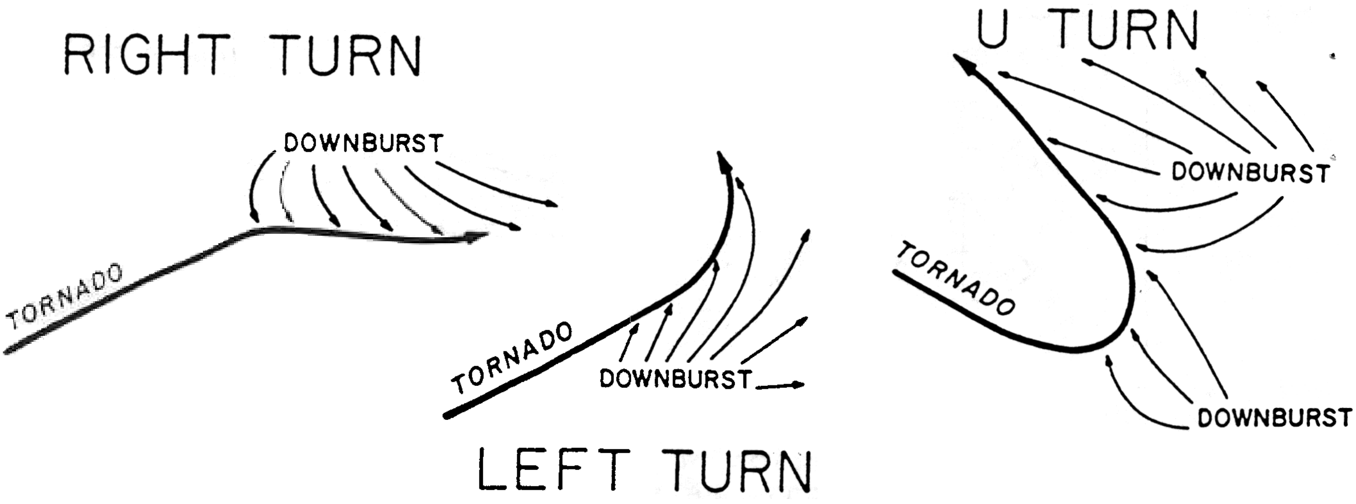


Figure 7. Model of how a downburst or microburst can alter the track of a tornado. (From Fujita, 1978).

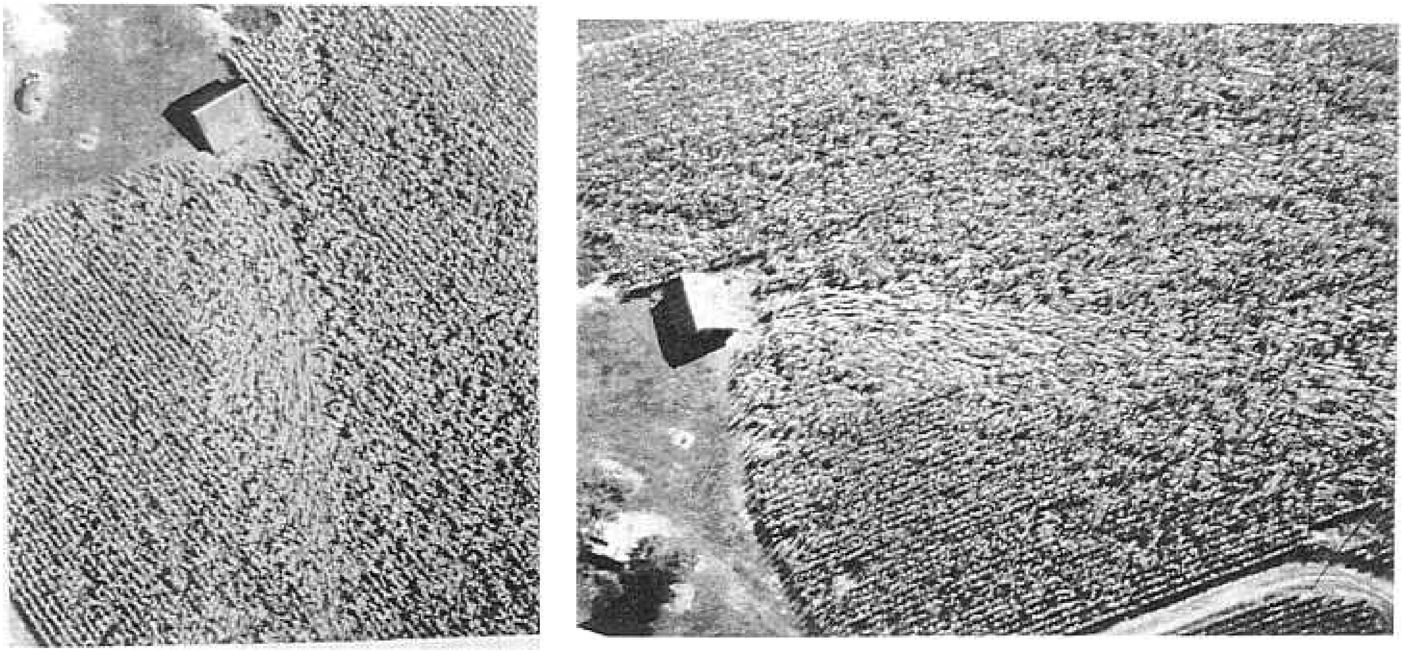


Figure 8. Aerial photos of a slanted roof of a farm that deflected strong horizontal winds into a cornfield. A portion of the tin roof of the farm was peeled back and blown into the corn field. (From Fujita, 1985).

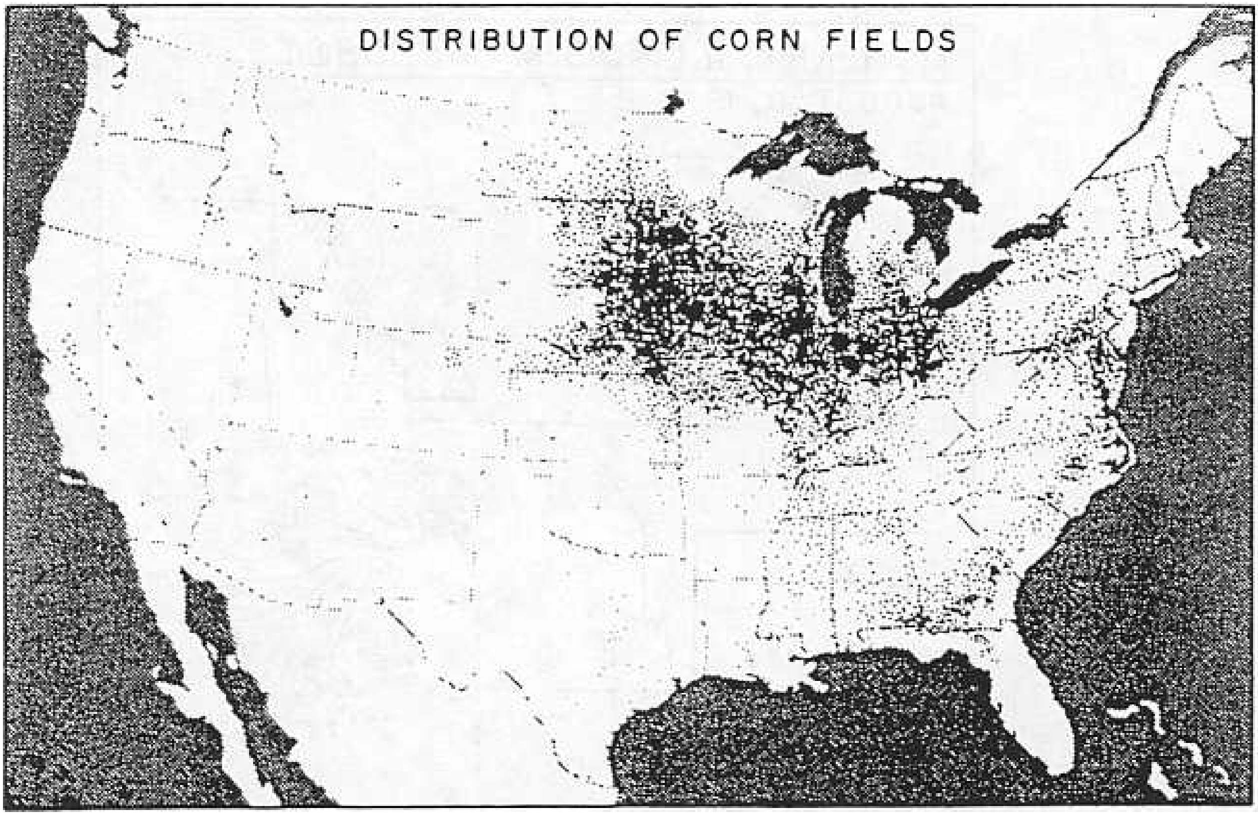


Figure 9. Distribution of corn fields in the U.S. Downed corn stalks are very useful as wind vectors. The high concentration of corn fields from the Northern Great Plains to the Ohio Valley indicates where wind vectors from damaging windstorms in the summertime can be easily obtained. (From Fujita, 1979).

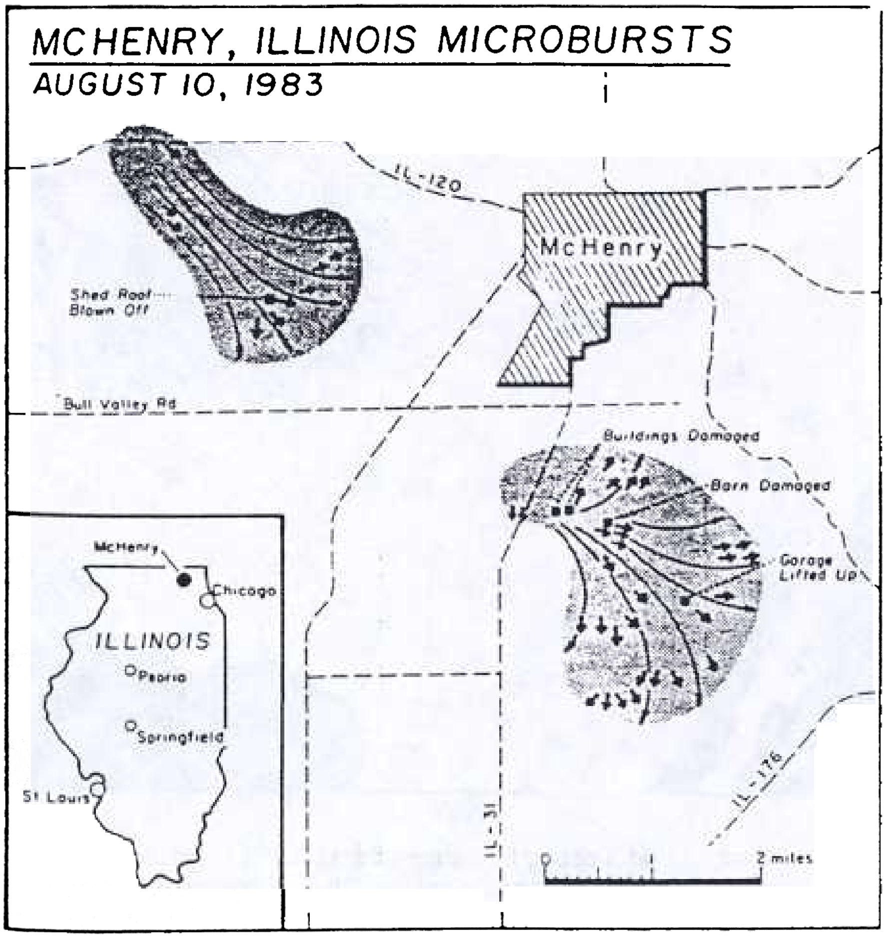


Figure 10. A mapping of the McHenry, Illinois microbursts of August 10, 1983. Much of the wind vectors were obtained by mapping the direction of fallen corn. Smith mapping from Storm Data (1983).

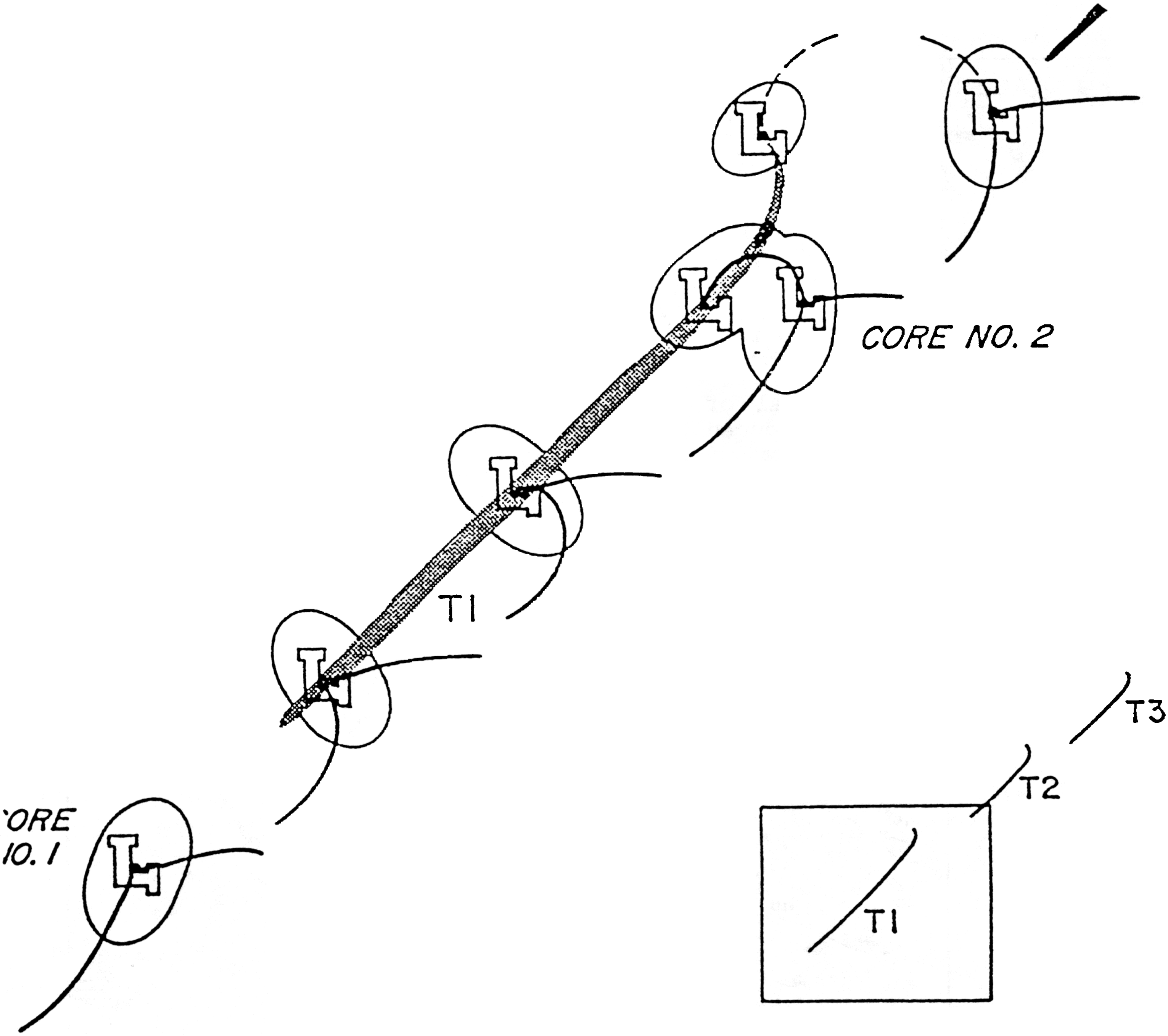


Figure 11. Mesocyclone Core Evolution (Reprinted from Burgess, et.al. 1982).

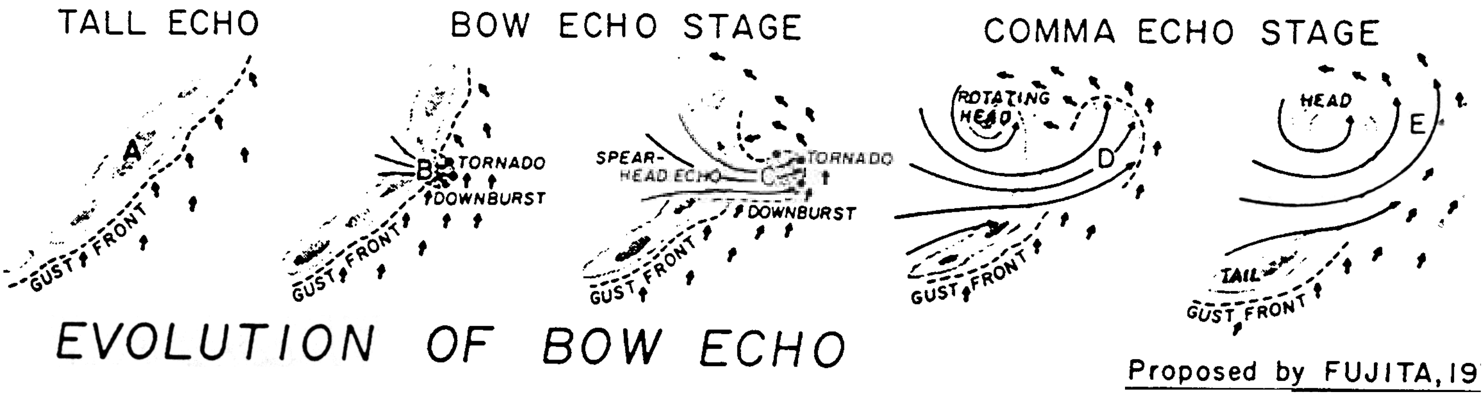


Figure 12. Model of the evolution of a bow-echo by Fujita (1979). Tornadoes are induced by the bow-echo wind flow most commonly at the apex of the bow or in the rotating comma head.

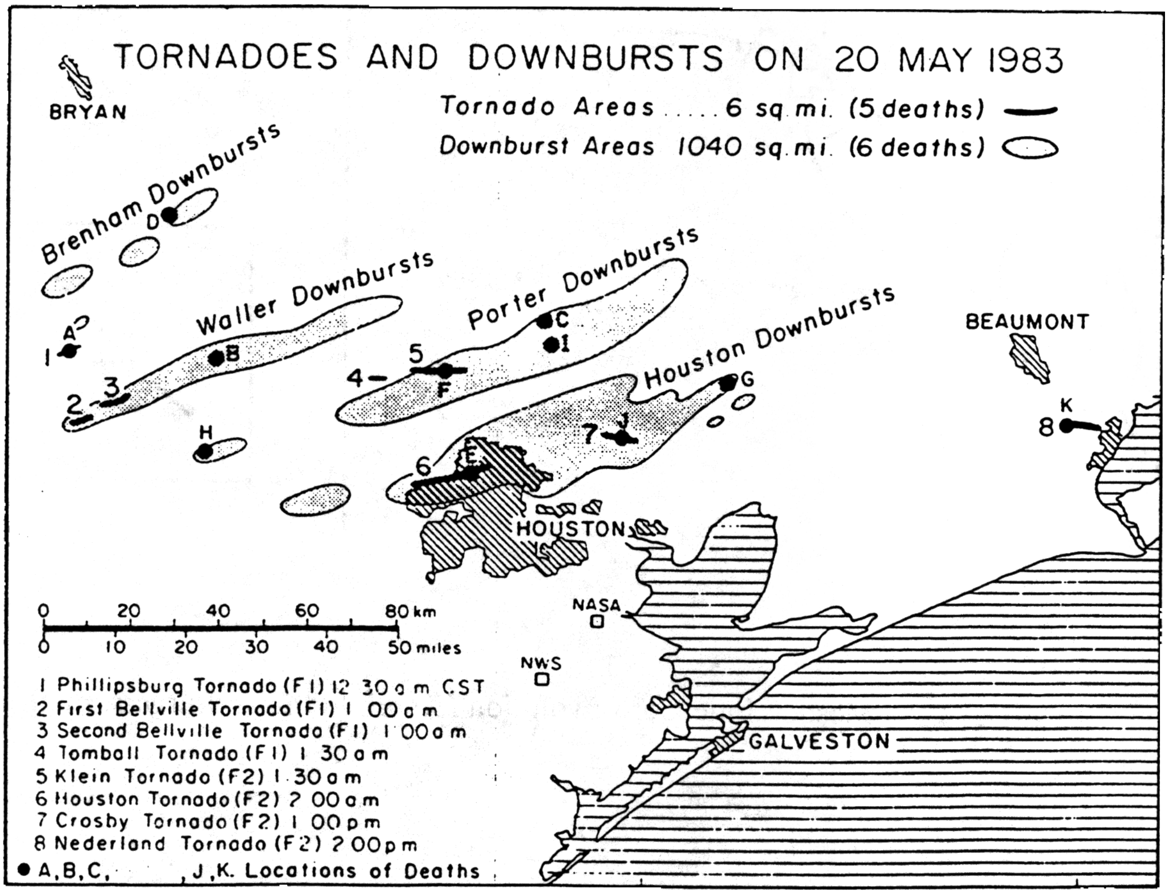


Figure 13. Mapping of tornadoes and downburst of May 20, 1983. Notice that it is not unusual for tornadoes and downbursts to coexist. Fujita mapping from Storm Data (1983).

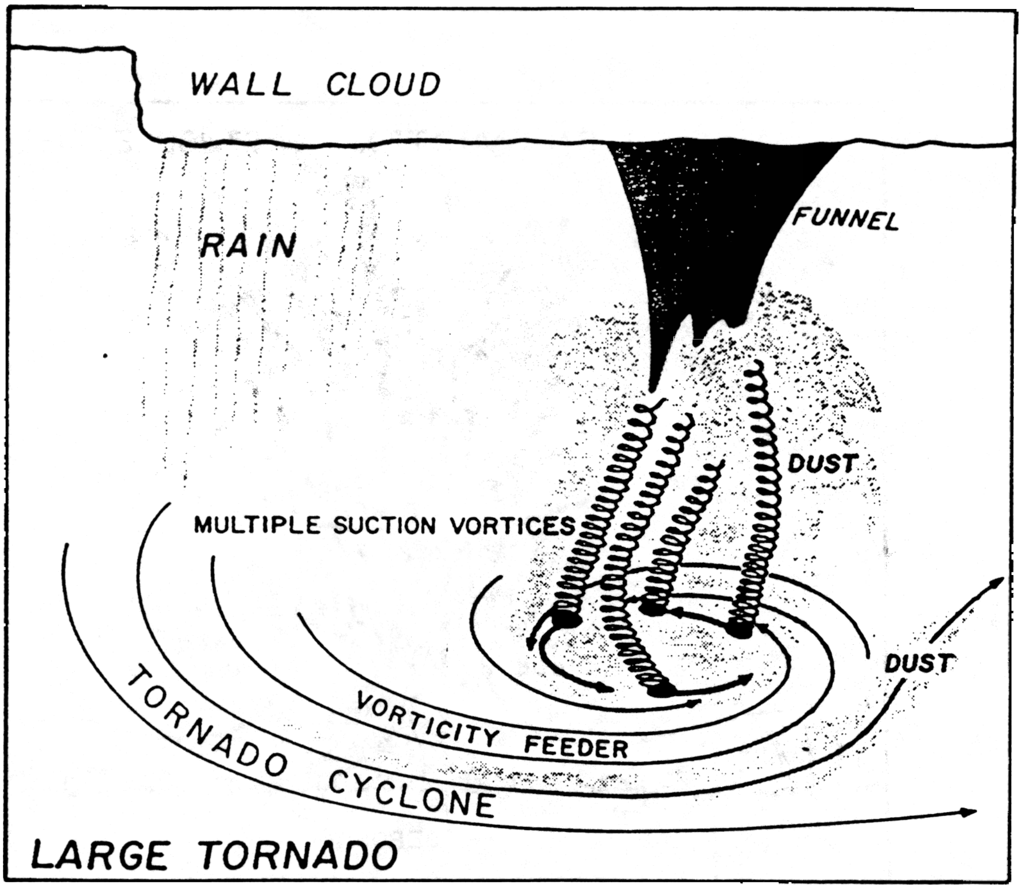


Figure 14. Model of a large tornado by Fujita (1978). Many large tornadoes are comprised of smaller multiple suction vortices.

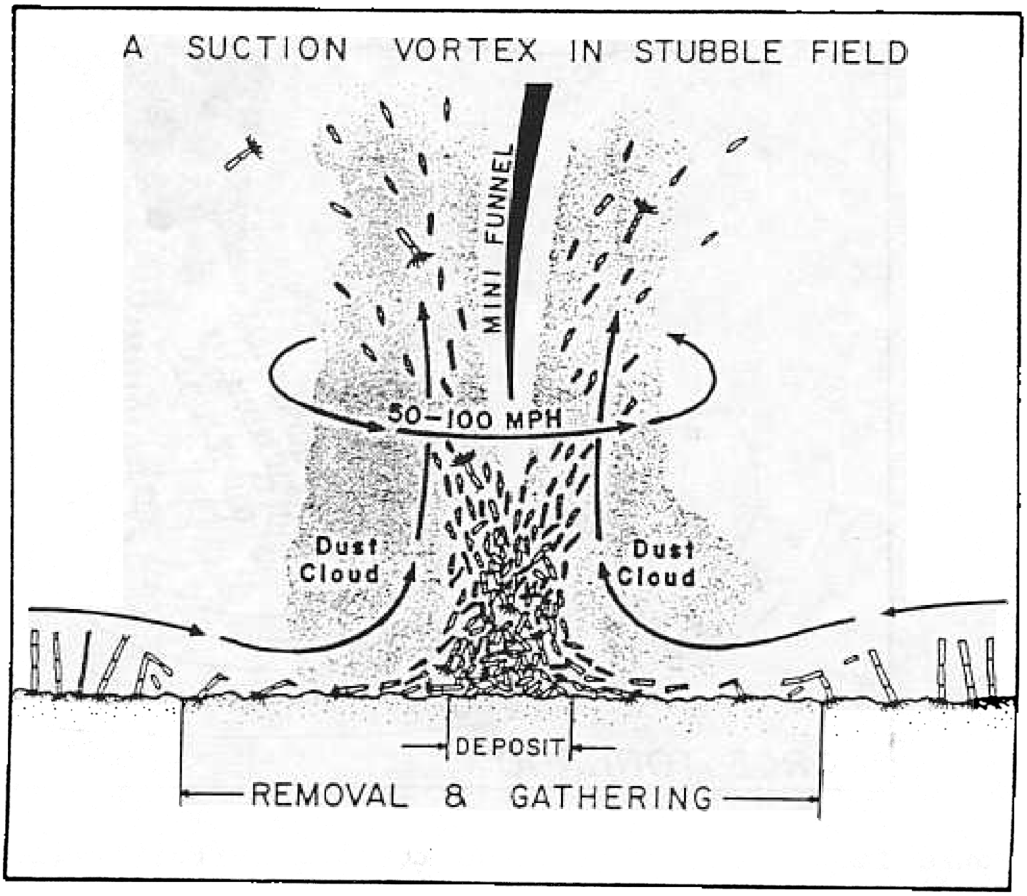


Figure 15. A close-up view of a suction vortex as it moves across a corn stubble field. The suction vortex mark is actually a deposit of corn stubble near the center of the vortex. (From Fujita, 1978).

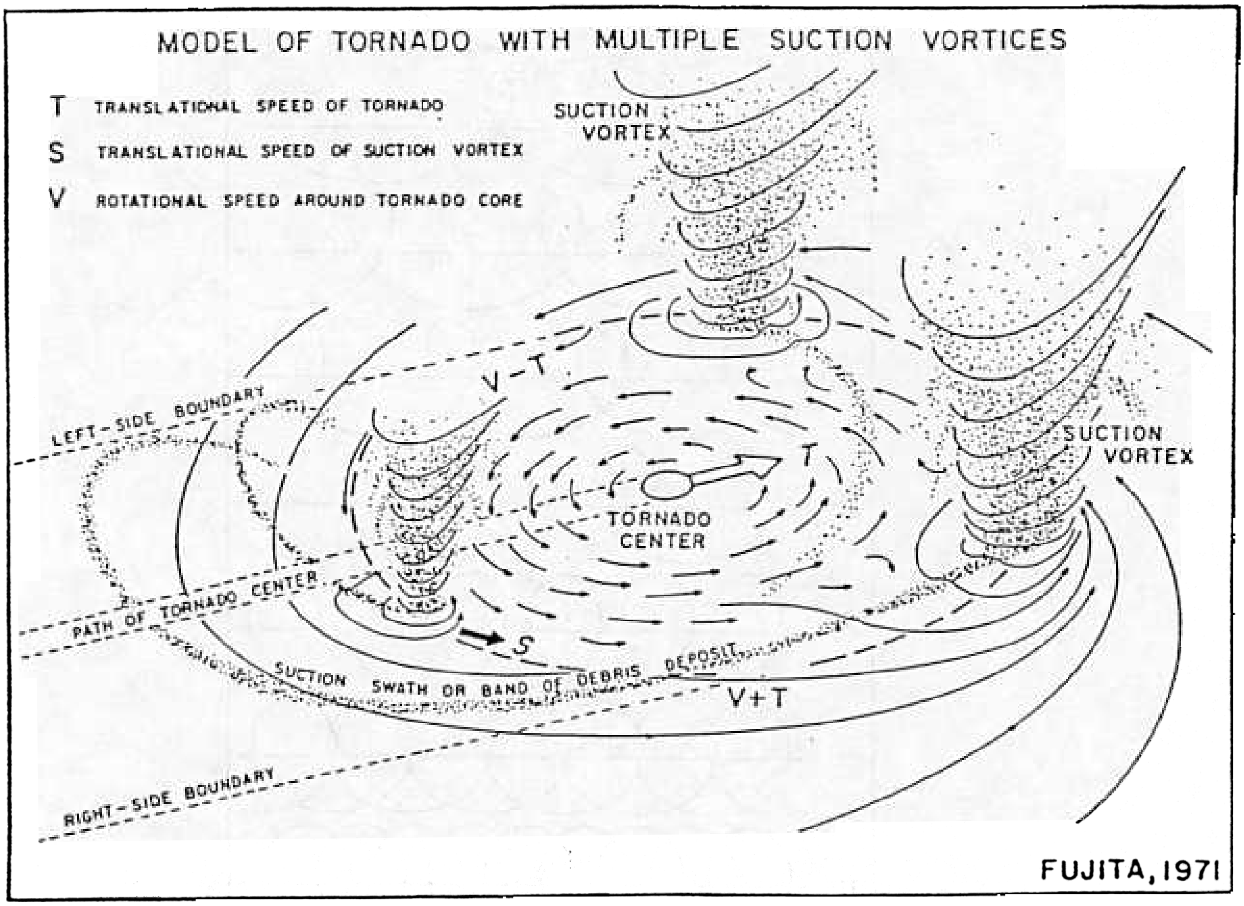


Figure 16. Fujita's 1971 model of a tornado with three suction vortices rotating around the parent tornado. Notice that any structures located directly on the path of a suction vortex may receive considerable damage, while structures offset from the suction vortex may receive minimal damage. To the ground surveyor, a multiple vortex tornado may give one the illusion that the tornado was skipping. From Fujita (1981).

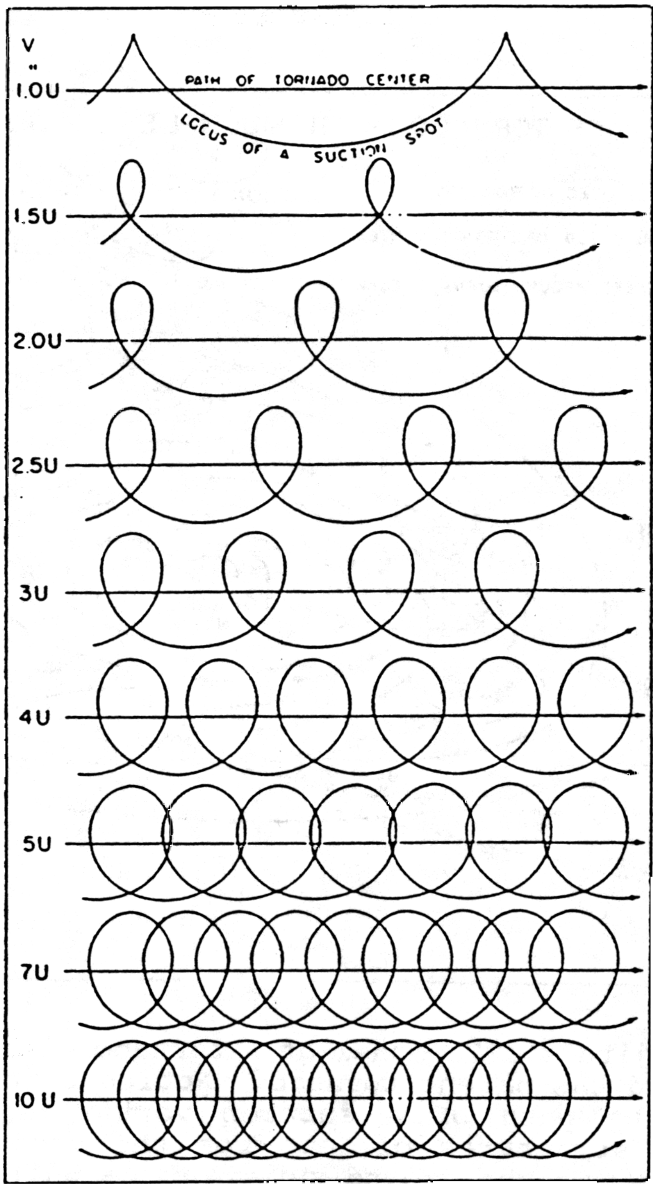


Figure 17. Path of a suction vortex as the velocity ratio is changed from 1 to 10. Notice with velocity ratio of 1, the suction vortex stops momentarily to create a "spin-up mark". Nearly circular suction vortex marks occur when the velocity ratio is 10, indicating the suction vortex rotation was 10 times greater than the translational motion. (From Fujita, et. al 1970).

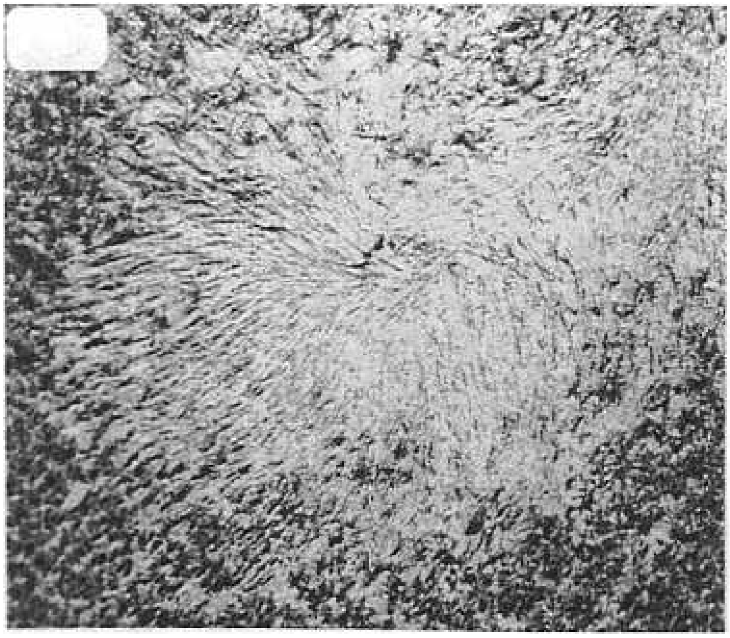


Figure 18. An aerial photo of a "spin-up mark" from a stationary suction vortex from the Mattoon Lake, IL tornado, 21 August 1977. (From Fujita, 1981).

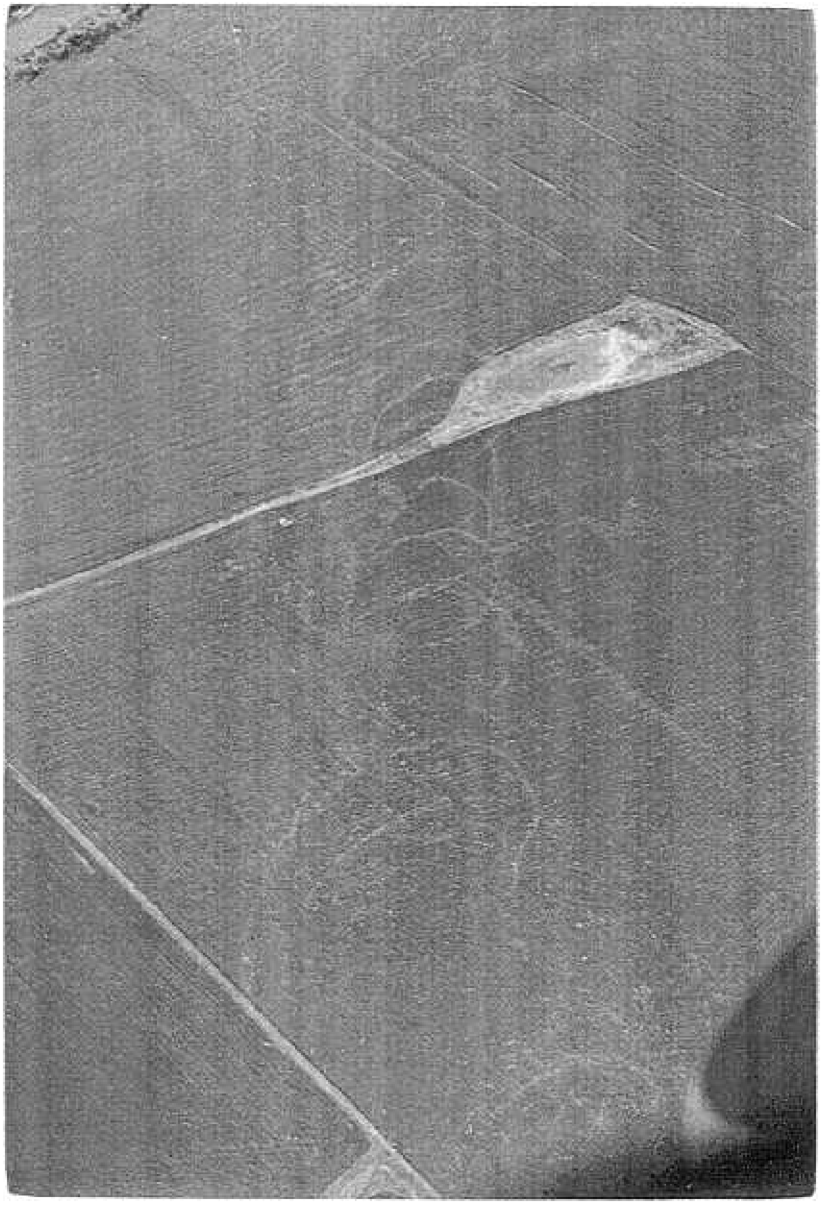


Figure 19. Aerial photo of suction vortices with a velocity ratio of around 7 in the Cowley County, KS tornado of April 26, 1991. (Photo by Brian E. Smith).

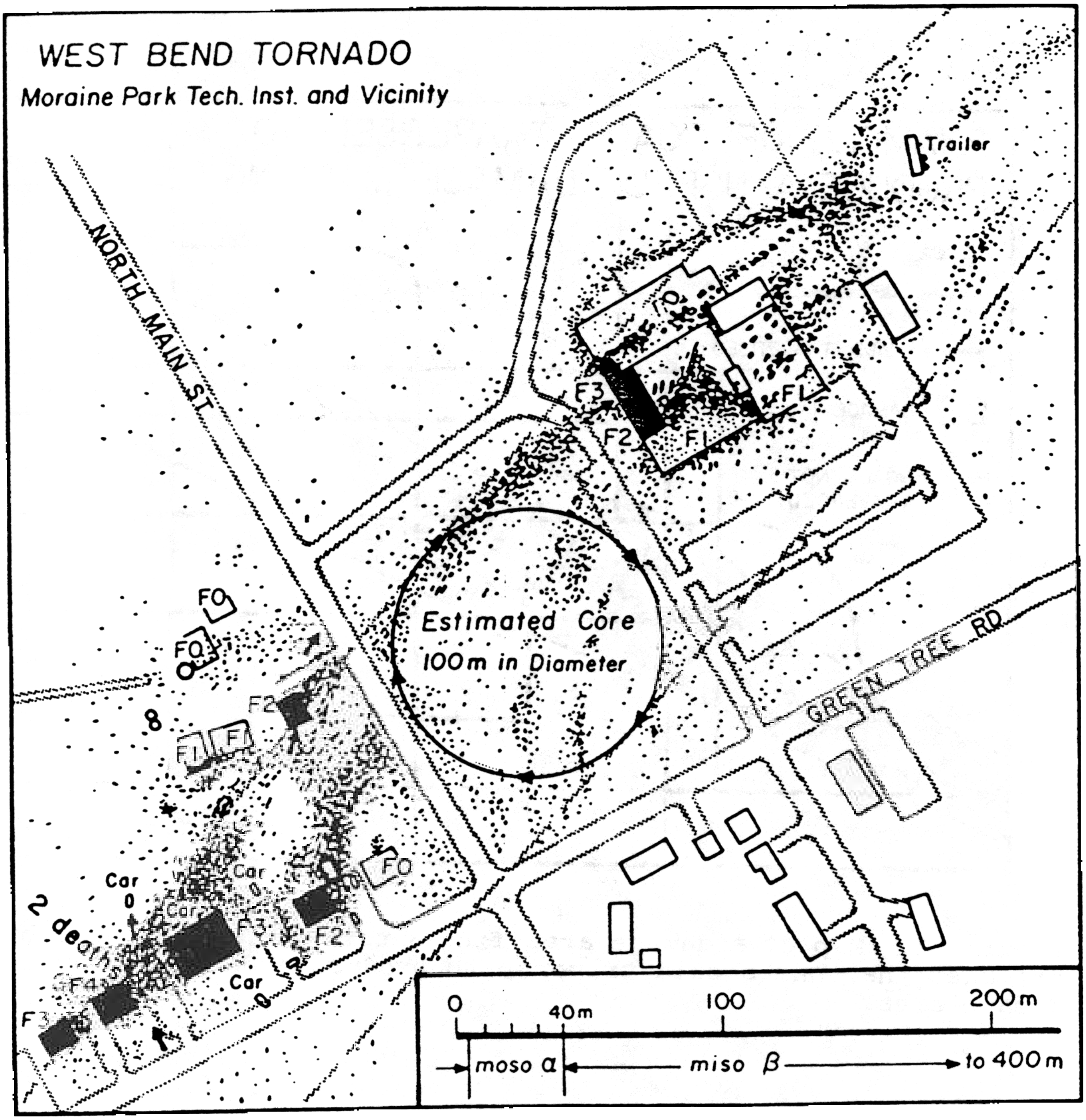


Figure 20. A detailed mapping of the West Bend, WI tornado of April 3, 1981. The tornado was traveling from lower left to upper right in the figure. Notice that the debris deposit occurs on the north side of the damage track, indicating that the tornado was anticyclonic. (From Wakimoto, 1983).

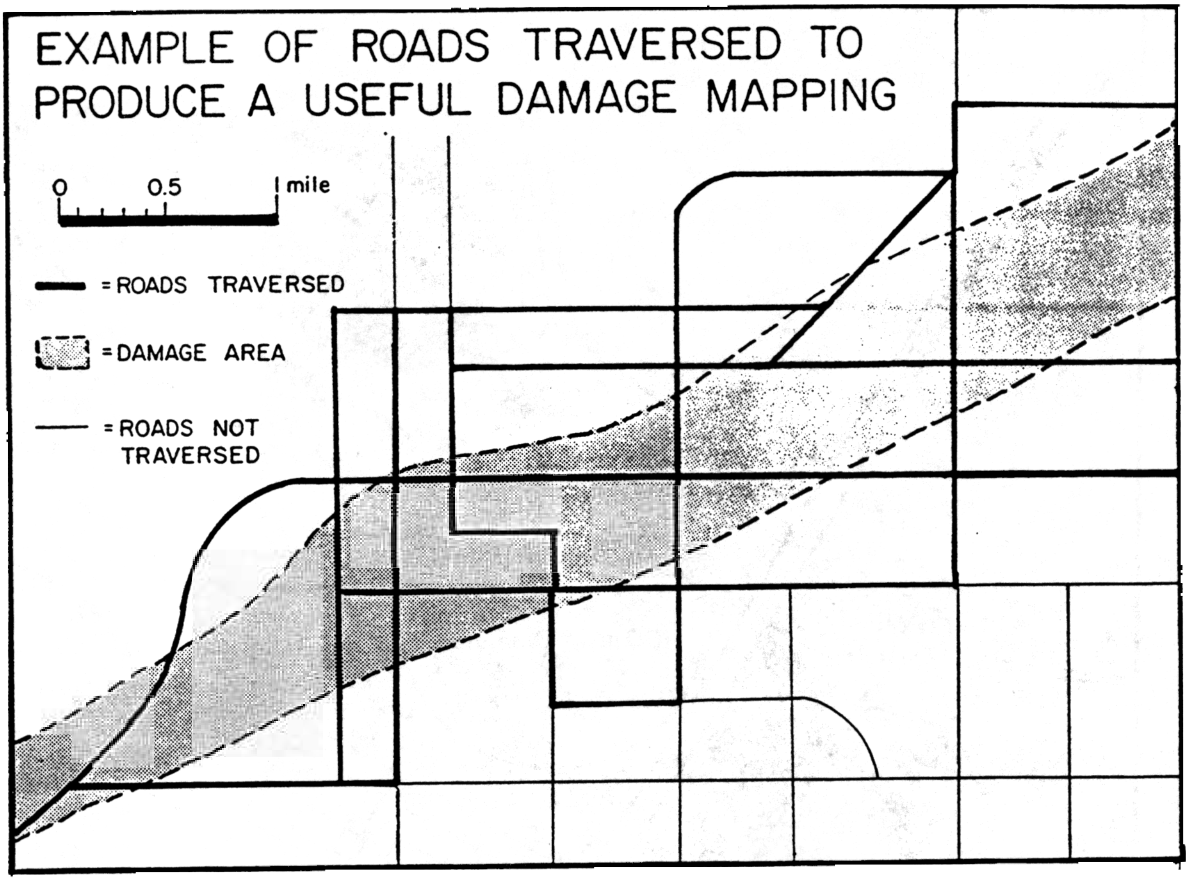
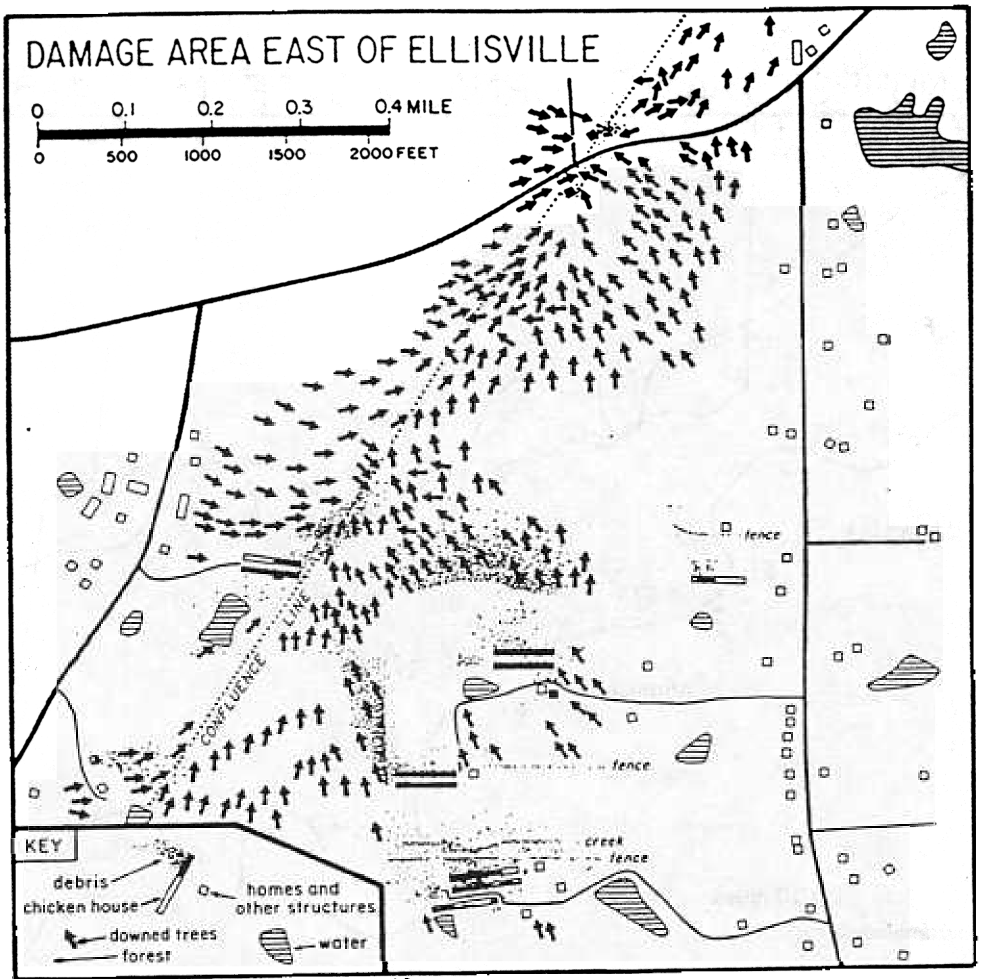


Figure 21. Map of a damage area from a tornado. The highlighted roads are ones that one should traverse to produce a detailed mapping of the damage area.



Survey and mapping by Duane J. Stiegler, University of Chicago

Figure 22. A small section of the F4 Laurel, MS tornado of 28 February 1987 is mapped in this figure from aerial photos taken by Duane Stiegler of the University of Chicago. This mapping indicates how intricate details and vectors can be mapped. Notice the confluence line as indicated by the vectors which identify this storm as a tornado. (From Storm Data, 1987).

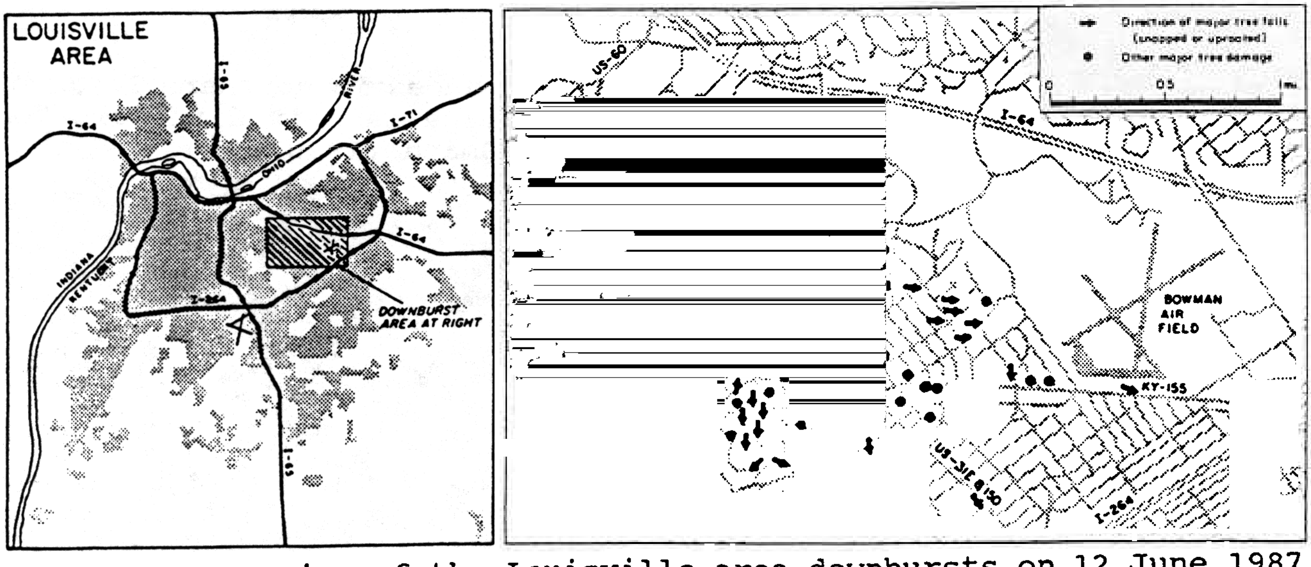


Figure 23. A mapping of the Louisville area downbursts on 12 June 1987 by Ernest H. Goetsch and Joseph D. Ammerman, NWSFO Louisville. This damage map was constructed from a detailed ground survey. The vectors indicate the direction of fallen trees. Notice the diffluent flow pattern of the vectors which identify this storm as a downburst. (From Storm Data, 1987).

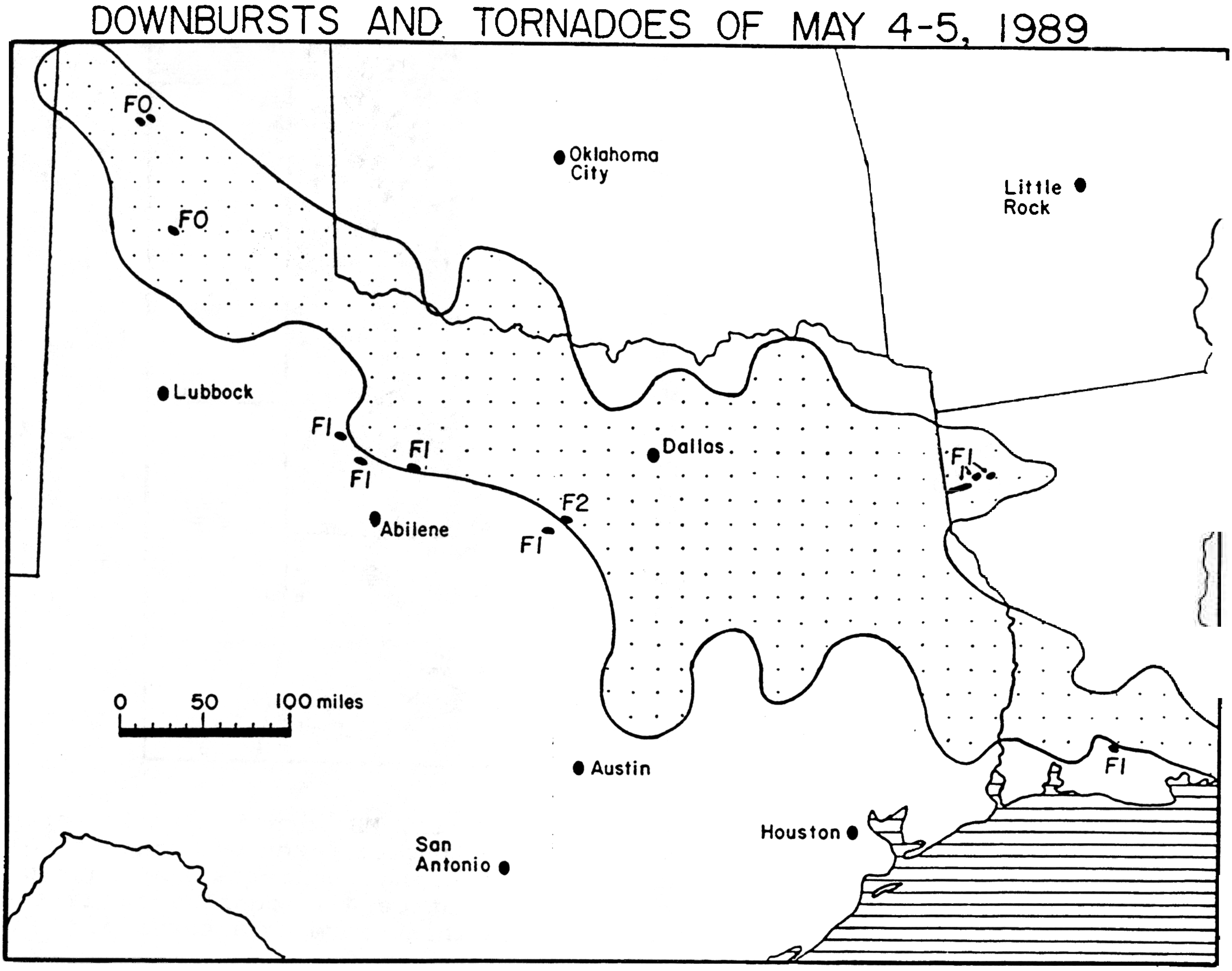


Figure 24. Mapping of downbursts and tornadoes in northern Texas on May 4-5, 1989. Such widespread downburst damage make it difficult for one to conduct a ground damage survey. From Smith (1990).