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WORKSHOP ON REMOTE SENSING TECHNIQUES WITH APPLICATIONS TO AGRICULTURE, WATER AND WEATHER RESOURCES

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ANALYSIS AND INTERPRETATION OF THUNDERSTORM IMAGES

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I. ANALYSIS AND INTERPRETATION OF THUNDERSTORM IMAGES

I.1 INTRODUCTION

The methods developed to interpret and use satellite data differ considerably from those used for more conventional types of meteorological observations. Satellite observations can provide meteorological information that bridges a continuum of scales ranging from hemispheric wave patterns to individual cumulus clouds. These data are remotely sensed from a space platform and differ in kind and especially in quantity from conventional in situ data. Therefore, we must continue to learn how to use satellite data and how to incorporate them into existing data systems.

Early research at the University of Wisconsin (VonderHaar, 1969; Sidkar et al., 1970) demonstrated the potential value of satellite data for detection and monitoring of intense convective storms and for applied and theoretical thunderstorm research.

The GOES data are routinely available at 30-min intervals; occasionally, however, more frequent collections support field projects or special research efforts. Krietzberg (1977) described the special satellite data taken during 1977 Research Rapid Scan Days to provide special severe-storm and mesoscale numerical-modeling data, and Reynolds and Matthews (1976) reported on the use of satellite imagery by forecasters involved in the Bureau of Reclamation's High Plains Experiment, HIPLEX. HIPLEX involved a study of the feasibility of enhancing convective precipitation over the High Plains.

Multiple-channel radiometric measurements may be used to remotely sound atmospheric profiles of temperature and water vapor (McMillin et al., 1973; Weinreb and Crosby, 1973). Such soundings will play an increasingly important role for forecasting thunderstorm potential and intensity, for studying pre-storm and near-storm environment, and for initialization of regional, or mesoscale, numerical models. The role of satellite observations in numerical modeling has been reviewed by Krietzberg (1976). Remotely sensed atmospheric profiles may be important for future field programs designed to study thunderstorm environments and interactions (Zipser, 1984).

Many interesting cases have been documented that are illustrative of possible relationships between thunderstorms and their mesoscale environment. Examples include a tendency for afternoon storms to form in regions clear during the morning, or to form around the fringes of regions cloudy or foggy during the morning, and a tendency for intense storms to occur where and when cloud lines intersect (Purdom, 1976; Anderson et al., 1974; Scofield and Weiss, 1976). Specific cases demonstrating the use of satellite imagery in thunderstorm detection, monitoring, and forecasting are presented in the following sections.

I.2 MONITORING MOVEMENT AND INTENSITY OF THUNDERSTORM GUST FRONTS

The importance of gust fronts as a hazard to aviation has been emphasized by recent crashes that apparently resulted when aircraft penetrated gust fronts shortly before touchdown or after liftoff. Fujita (1978) believes that the shape of individual storms, as monitored in satellite and radar data, may indicate that strong outflows are present. Gurka (1976) has correlated satellite-observed characteristics of thunderstorm cloud arcs with concurrent surface wind observations. Figures 1a and 1b show the southward progression of a cloud arc across the Baltimore/Washington, D.C., area from 2100 to 2200 GMT on 3 July 1975. Selected surface wind observations have been superposed on the images.

Gurka lists the following characteristics of thunderstorm gust fronts that can be identified using satellite imagery:

(1) Wind gusts and wind shear occur very near to or at the leading edge of the cloud arc.

(2) Strongest winds occur beneath the portion of the arc nearest to the most vigorous convection.

(3) The regions of vigorous convection are pinpointed by the cloud edge brightness gradients on enhanced IR imagery.

(4) Cloud arcs bounding mesohighs associated with a cloudy area and active convection are characterized by stronger gusts than are narrow cloud arcs that are trailed by clear skies.

(5) Rapidly moving cloud arcs are generally associated with strong low-level winds.

I.3 DIFFERENTIAL HEATING

An interesting observation concerning local trigger mechanisms for convective development is the strong influence exerted by differential heating. The land-sea breeze is a well-understood differential heating phenomenon whose effects are routinely observed in satellite imagery. Another is the inhibiting effect that early morning cloud cover has on afternoon thunderstorm development.

It is important to realize that these phenomena are mechanisms which establish local convergence zones that are the result of differential heating. Other properties of the atmosphere help determine the effectiveness of those local mechanisms in their ability to generate new deep convection. They include instability, large-scale dynamics, and the trajectory of the low-level air with respect to the convergence zone (amount of time an air parcel will experience vertical motion in the local forcing region).

I.3.1 Sea, Lake, and River Breezes

Although convective cloud development due to terrain influences may often be very complicated when viewed with high-resolution GOES VIS imagery, many of the cloud patterns are easier to understand. This is because the 1 km resolution of the imagery is close to the cumulus cloud scale, and the frequent interval between pictures allows convective development to be observed from its earliest stages through maturity.

The land-sea breeze, a consequence of differential heating between land and adjacent water, has been one of the most widely studied terrain phenomena (Haurwitz, 1947; Estoque, 1962; Pielke,1973,1974) various factors influence the development of the land-sea-breeze. Among them are (1) the shape of the coast line, (2) the direction and strength of the gradient winds, (3) friction, (4) the Coriolis effect, (5) the stability of the air mass, and (6) the land and water temperature difference. Items 4-6 are not discussed here although infrared data are applicable to item 6 and VAS sounding data have a potential relative to item 5.

Different curvatures in a coast line cause areas of convergence or divergence along the land-sea breeze front, thus leading to a local strengthening or weakening of cumulus activity along that front. As pointed out by Pielke (1974), "Local maxima in vertical motion form in regions where the curvature of the coast line accentuates the horizontal convergence created by the differential heating between land a water". Additionally, a small peninsula is generally an area of earlier strong convective development along the land-sea breeze front because the breezes formed along opposing shores merge near the peninsula's center.

Convective development due to land and water interfaces also occurs regularly around lakes . The factors influencing convective development are the same as those for the land-sea breeze. However, the low-level wind field becomes increasingly important, the smaller the lake involved. Figure 2 shows the convective regime around the Great Lakes under a condition of north by northwesterly flow. Notice the lake breeze convection is close to the shore lines on the windward sides of the lakes and has a further inland penetration to their lee. One might envision frictional influences helping the inland penetration of the lake breeze convection along the easthern shore of Lake Michigan as well as the positioning of the convective line along the easthern shore of the Bruce peninsula which separates Lake Huron from Georgian Bay in southern Ontario.

Although the effects of oceans, lakes, and even cities (Changnon,1976) on convective development have received considerable attention, relatively little work has been done concerning the effects of rivers and adjacent moist or swampy areas on convective development. GOES iamgery has shown that rivers and their adjacent areas at certain times exert a considerable influence on convective development. The influence has been most noticeable when the low-level winds are either nearly calm (generally less than 5 m s^{-1}) or blowing parallel to the river.

I.3.2 Early Morning Cloud Cover

Weak Synoptic Forcing

Purdom and Gurka (1974) discussed the effects of early morning cloud cover on afternoon thunderstorm development under conditions of weak synoptic-scale forcing; the situation is similar to that of the land-sea breeze, with the first shower clouds forming in the clear region near the boundary of the early morning cloud cover -a sort of cloud-breeze front. Additionally, they found that the slower heating rate in the early cloudy areas helped keep those regions free from convection for most of the day. Figure 3 is a good example of this phenomenon.

Although the effect of early cloud cover may most easily be thought of as a simple differential heating mechanism, for mesoscale applications our reasoning must extend beyond that point. Unlike the land-sea breeze regime, the cloud field is constantly changing in character: this can affect the development of instability since varying amounts of insolation will lead to differences in heating and mixing over the land area.

Strong Synoptic Forcing

Early morning cloud cover can also have an important role in helping the stage for intense convection under conditions of strong synoptic-scale forcing. Purdom and Weaver (1982) showed the importance of mesoscale boundary interactions in focusing tornado activity in the Red River Valley area on 10 April 1979. Figure 4a and 4b shows the location of one of the mesoscale frontal boundaries that helped focus that activity. The most probable cause of that meso-front was a differential heating due to the cloudy (stratus) region to the east versus the clear area to the west. The mechanism that led to the development of the meso-front, and subsequent focusing of tornadic activity, also played an important role in the development of instability in the warm sector. As the mesoscale frontal boundary moved eastward, mostly clear skies developed in the warm sector between the boundary and the stratiform overcast to the east. During that period Abilene (ABI) became clear while Stephenville (SEP) maintained its cloud cover. An analysis of surface static energy (Darkow, 1968) pointed to strong potential instability at both ABI and SEP (Purdom and Weaver, 1982). However, time series of horizontal cross sections from mesoscale rawinsonde data showed a marked decrease in the amount of negative buoyant energy at ABI and only a slight decrease at SEP; these changes [are related to changes] in cloud cover. Low-level air, similar in character to that near ABI, fed the tornadic storm system and thus allowed intense thunderstorms to develop.

I.4 SEVERE-THUNDERSTORM/JETSTREAM RELATIONSHIP

Many researchers have presented both observational and theoretical studies that relate positions of jetstreams, or bands of maximum windspeeds, with the development, location, and orientation of severe thunderstorms. Whitney (1977), studying severe-storm occurrences on 16 active days, found that severe activity rarely developed south of the subtropical jetstream. The positions of jetstream features were determined using both satellite photographs and conventional upper-air sounding data.

Figure 5 shows Whitney's analysis of the 30 April 1975 severe-thunder-storm situation. The subtropical jetstream sharply delineates the southern boundary of the large area of severe-storm occurrences. He found that severe thunderstorms usually develop first along the surface front very near to the polar jetstream (note that a double polar jet structure was analyzed in Fig. 5). Activity then moves eastward ahead of the surface front while developing southward across the zone between the diverging jetstreams. Miller and McGinley (1978) have recently developed a technique for forecasting severe thunderstorms that integrates conventional upper-air data, surface analyses, and satellite imagery to identify zones or areas having storm potential. The detection and tracking of various jetstreams and jetstream branches (using both satellite imagery and upper-air reports) play a crucial role in this innovative forecast scheme, and the interested reader should refer to their extensive report for specifics.

I.5 THUNDERSTORM BOUNDARIES AND INTERSECTIONS

Making use of satellite imagery, Purdom (1976) shows that the leading boundary of a thunderstorm-associated mesohigh often appears as an arc-shaped line of convective clouds. He also shows (Purdom, 1973; 1974) that the intersection of such an arc cloud with another boundary marks a local region with a high potential for intense convective development and severe-storm occurrence. These findings provide "photographic" verification of well-known severe-storm characteristics presented earlier by Magor (1959) and Miller (1972).

Such a convective development is presented in Figs. 6a, 6b, and 6c, which show the 2100 GMT GOES-1 photograph on 26 May 1975, a corresponding mesoscale surface analysis, and a subsequent photograph for 2230 GMT. The impressive convective development in south central Oklahoma occurred in the favored arc line/boundary intersection zone at point A.

The ability to locate such boundaries precisely in GOES imagery and to observe their interaction with other boundaries provides the forecaster information that can be use in the short-range prediction of intense convective development. Such data are also valuable for studies of the climatology of such boundary effects and the dynamical reasons for their occurrences.

I.6 CLOUDTOP TORNADIC SIGNATURES

Fujita and his colleagues have tried to relate cloudtop features to severe-weather occurrences at the surface (Fujita 1973; Shenk, 1974). Fujita has proposed that the decay of overshooting cloudtops may be related to tornado development. Figure 7 presents a correlation of overshooting cloudtops with the occurrence of several intense tornadoes in Illinois and Indiana on the afternoon of 20 March 1976. The storm was characterized by overshooting tops prior to and after the tornadoes. Figure 8 shows concurrent radarscope and satellite photographs at the time when the large Sadorus tornado waas known to be on the ground at point A, where the satellite photograph shows a swirl in the relatively flat anvil top. Temporal and spatial satellite data of very high resolution are required if such features are to be closely monitored, and many more case studies are needed before reliable forecast techniques can be developed.

I.7 MESOSCALE CONVECTIVE WEATHER SYSTEMS

The identification of large, long-lived convective weather systems (called Mesoscale Convective Complexes [MCCs] by Maddox [1980]) was made possible by the operational availability of enhanced IR satellite images (see Figs. 9 and 10) at half-hourly intervals. The life cycle of a typical MCC is illustrated in Fig. 11 over US and in Fig. 12 over SAmerica (Velasco and Fritsch, 1987). These systems produce a wide variety of significant convective weather phenomena including tornadoes, hail, wind, flash floods, and intense electrical storms, in addition to widespread beneficial rains. Substantial research efforts are required before we will understand the physical mechanisms that produce MCCs; however, satellite imagery has already proved useful in helping forecasters recognize and track MCCs and thereby improve local weather forecasts.

I.8 THUNDERSTORM RESEARCH TECHNIQUES

The recent development of interactive man/machine computer systems specifically designed for processing and analyzing satellite data has encouraged the undertaking of more quantitative thunderstorm research. Use of digital data transmitted from the satellite and stored on magnetic tape is possible in these systems. Different applications, ranging from sequential looping and cloud tracking to produce a wind field, to color enhancements of specific features, to superposed displays of differing data types, are available. Navigation (earth coordinate location of features) accuracy to within a single data element (pixel) is possible on these systems. Interactive satellite data-processing systems have been developed by Goddard Space Flight Center (NASA), the University of Wisconsin, and Colorado State University. (See, for example, Billingsley's [1976] description of the NASA/AOIPS [Atmospheric and Oceanic Information Processing System], ~~and~~ Anthony and Bristor's [1978] article on interactive systems, and storm prediction)(1)) Specifications and details of the different systems vary, but they allow the reseacher to get at the data in varying ways and process them accurately, pixel by pixel if required.

I.8.1 Cloudtop temperature fields

Sidkar et al. (1970) showed that convective mass fluxes could be estimated using satellite data. Adler and Fenn (1977) used infrared data as a function of time for many cloud systems that included several significant severe thunderstorms. They also used the rate of increase of cloudtop area to estimate anvil divergence. Figure 13 shows a plot of cold cloudtop area with time for a tornadic cloud system over South Dakota on 6 May 1975.

Adler and Fenn found that the first report of tornadic activity took place during, or just after, the rapid expansion of cold cloud area, indicating rapid ascent and growth of thunderstorm tops on the scale observed by the satellite. These findings are different from the results presented in Fig. 7. This discrepancy may be due to the difference in resolution of the IR and visible sensors (overshooting tops must be quite large to be detected in the IR), and the need for further studies of cloudtop activity as a signature of storm severity is apparent. It is possible that such studies may lead not only to improved detection and warning of tornadic storms, but also to better understanding of the dynamics and thermodynamics of tornado development.

Reynolds (1979) studied the IR cloudtop temperature fields associated with a number of damaging hailstorms. In all but one case, he found that the coldest temperatures were located near the hailfall. The cloudtop temperatures were also noted to be 1° to 8° C colder than the environmental tropopause temperature. He thus identified a potential technique for identifying damaging hailstorms through enhancement of digital GOES infrared imagery. However, since all of his cases occurred over the High Plains, further study is required to determine if this technique is applicable to storms over other regions.

(1) Mac Donald, (1987) for PROFS in the US and Undin (198) for PROMIS in Swedish.

CHAPTER I.

REFERENCES AND SUPPLEMENTARY READING

Adler, R.F., and D.D. Fenn, 1977. Satellite-based thunderstorm intensity parameters. Preprints, Tenth Conference on Severe Local Storms, 18-21 October, Omaha, Nebraska. American Meteorological Society, Boston, Mass., 8-15.

Anderson, R.K., et al., 1974. Application of meteorological satellite data in analysis and forecasting. ESSA Tech. Rep. NESC 51, 250 pp.

Anthony, R.W., and C. L. Bristor, 1978. Interactive system requirements for the realtime demonstration of mesoscale weather detection and prediction. Preprints, Conference on Weather Forecasting and Analysis and Aviation Meteorology, Silver Springs, Maryland. American Meteorological Society, Boston, Mass., 219-227.

Bartels, D.L., J.M. Skradski and R.D. Menard, 1984. Mesoscale convective systems: A satellite-data-based climatology. Environmental Sciences Group. NOAA Tech. Memo. ERL ESG-8. Boulder, Colorado. 58 pp.

Billingsley, J.B., 1976, Interactive image processing for meteorological applications at NASA/Goddard Space Flight Center. Preprints, Seventh Conference on Aerospace and Aeronautical Meteorology and Symposium on Remote Sensing from Satellites, Melbourne, Florida. American Meteorological Society, Boston, Mass., 268-275.

Clark, J. Dane, June 1983, The GOES User's Guide. Office of Satellite Data Processing and Distribution.

Changnon, S.A., 1976: Effects of urban areas and echo merging on radar echo behavior. J.Appl.Meteor., 15, 561-570.

Darkow, G.L., 1969: The total energy environment of severe storms. J.Appl.Meteor., 7, 199-205.

Estoque, M.A., 1962: The sea breeze as a function of the prevailing synoptic situation. J.Atmos. Sci., 19,244-250.

Fujita, T.T., 1973. Tornado occurrences related to overshooting cloudtop heights as determined from ATS pictures. SMRP Paper No. 97, University of Chicago, Chicago, Ill., 32 pp.

Fujita, T.T., 1978. Manual of downburst identification for Project NIMROD. SMRP Paper No. 156, University of Chicago, Chicago, Ill., 104 pp.

Gurka, J.J., 1976. Satellite and surface observations of strong wind zones accompaying thunderstorms. Mon. Weather Rev. 104:1484-1493.

Haurwitz, B., 1947: Comments on the sea breeze circulation. J.Meteor., 4, 1-8.

Krietzberg, C.W., 1976. Interactive applications of satellite observations and mesoscale numerical models. Bull. Am. Meteorol. Soc. 57:679-685.

Krietzberg, C.W., 1977. SESAME '77 experiments and data availability. Bull. Am. Meteorol. Soc. 58:1299-1301.

MacDonald, A.E., 1987. Profs.: Status and Plans. Postprints 2nd. Interamerican Meteorological Congress,Bs As, Argentine; CAM., Cap 5.

Maddox, R.A., 1980. Mesoscale convective complexes. Bull. Am. Meteorol. Soc. 61:1374-1387.

Magor, B.W., 1969. Mesoanalysis: some operational analysis techniques utilized in tornado forecasting. Bull. Am. Meteorol. Soc. 40:499-511.

McMillin, L.M., et al., 1973. Satellite infrared soundings from NOAA spacecraft. NOAA Tech. Rep. NESS 65, National Environmental Satellite Service, Washington, D.C., 121 pp.

Miller, R.C., 1972. Notes on analysis and severe storm forecasting procedures of the Air Force Global Weather Central. Air Weather Service TR 200 (Rev.), 102 pp.

Miller, R.C. and J.A. McGinley, 1978. Using satellite imagery to detect and track comma clouds and the application of the zone technique in forecasting severe storms. Project Report, GE/Management and Technical Services Company, Beltsville, Md., 100 pp.

Pielke, R., 1973: A three-dimensional numerical model of the sea breezes over south Florida. NOAA Tech. Memo. ERL WMPO-2, Environmental Research Laboratories, Boulder, Colo. (NTIS#COCM-73-11307/8), 136 pp.

Pielke, R., 1974: A three-dimensional numerical model of the sea breezes over South Florida. Mon. Wea. Rev., 102, 115-139.

Purdom, J.F.W., 1973. Meso-highs and satellite imagery. Mon. Weather Rev. 101:180-181.

Purdom, J.F.W., 1974. Satellite imagery applied to the mesoscale surface analysis and forecast. Preprints, Fifth Conference on Weather Forecasting and Analysis, St. Louis, Missouri. American Meteorological Society, Boston, Mass., 63-68.

Purdom, J.F.W. and J.G.Gurka, 1974: The effect of early morning cloud cover on afternoon thunderstorm development. Preprints, 5th Conference on Weather Forecasting and Analysis, St. Louis, American Meteorological Society, Boston, 58-60.

Purdom, J.F.W., 1976. Some uses of high-resolution GOES imagery in the mesoscale forecasting of convection and its behavior. Mon. Weather Rev. 104:1474-1483.

Purdom, J.F.W., and J.F. Weaver, 1982: Nowcasting during the 10 April 1979 tornado outbreak: A satellite perspective. Preprints, 12th. Conference on Severe Local Storms, San Antonio, American Meteorological Society, Boston, 467-470.

Reynolds, D.W., 1979. Observations of damaging hailstorms from geosynchronous digital satellite data. Mon. Weather Rev. 108:337-348.

Reynolds, D.W., and D.A. Matthews, 1979. Real-time satellite support for the high plains cooperative experiment. Preprints, Second WMO Scientific Conference on Weather Modification, Boulder, Colorado. WMO No. 43, 497-502.

Reynolds, D., 1979: Observations and detection of damaging hailstorms from geosynchronous satellite digital data. Preprints, 11th Conference on Severe Local Storms, Kansas City, American Meteorological Society, Boston, 181-188.

Rodgers, E., and H. Siddalingaiah, 1983: The utilization of Nimbus-7 SMMR measurements over land. J.Clim. Appl. Meteor., 22, 1753-1763.

Scofield, R.A., and C.E. Weiss,1976. Application of synchronous meteorological satellite products and other data for short range forecasting in the Chesapeake Bay region. Preprints, Sixth Conference on Weather Forecasting and Analysis, Albany, New York. American Meteorological Society, Boston, Mass., 67-73.

Scofield, R.A., and V.J. Oliver,1977; A scheme for estimating convective rainfall from satellite imagery. NOAA Tech. Memo. NESS-86, National Earth Satellite Service, Washington, D.C. (NTIS-#PB-270762/8G1), 47 pp.

Scofield, R.A., 1984; The NESDIS operational convective precipitation estimation technique. Preprints, 10th Conference on Weather Forecasting and Analysis, Clearwater Beach, American Meteorological Society, Boston, 171-180.

Scofield, R.A. and L.E. Spayd, Jr., 1984; A technique that uses satellite, radar and conventional data for analyzing and short-range forecasting of precipitation from extratropical cyclones, NOAA Tech. Memo. NESDIS-8, National Environmental Satellite, Data and Information Service, Washington, D.C. (NTIS#PB85-164994), 51 pp.

Shenk, W.E., 1974. Cloud top height variability of strong convective cells. J. Appl. Meteorol. 13:917-922.

Sikdar, D,N., V.E. Suomi, and C.E. Anderson, 1970. Convective transports of mass and energy in severe storms over the United States. An estimate from a geostationary altitude. Tellus 22:521-532.

Spayd, L.E., Jr., and R.A. Scofield , 1984a: An experimental satellite-derived heavy convective rainfall short range forecasting technique. Preprints, 10th. Conference on Weather Forecasting abd Analysis, Clearwater Beach, American Meteorological Society, Boston, 400-408.

Spayd, L.E., Jr., and R.S. Scofield, 1984b: A tropical cyclone precipitation estimation technique using geostationary satellite data. NOAA Tech. Memo. NESDIS-5, National Environmental Satellite, Data an Information Service, Washington, D.C. (NTIS-#PB84-226703), 36 pp.

Spencer, R.W., W.S. Olson, Wu Rongshang, D. Martin, J.A. Weinman, and D.A. Santek, 1983; Heavy thunderstorms observed over land by the Nimbus-7 scanning multichannel microwave radiometer. J. Clim. Appl. Meteor., 22, 1041-1046.

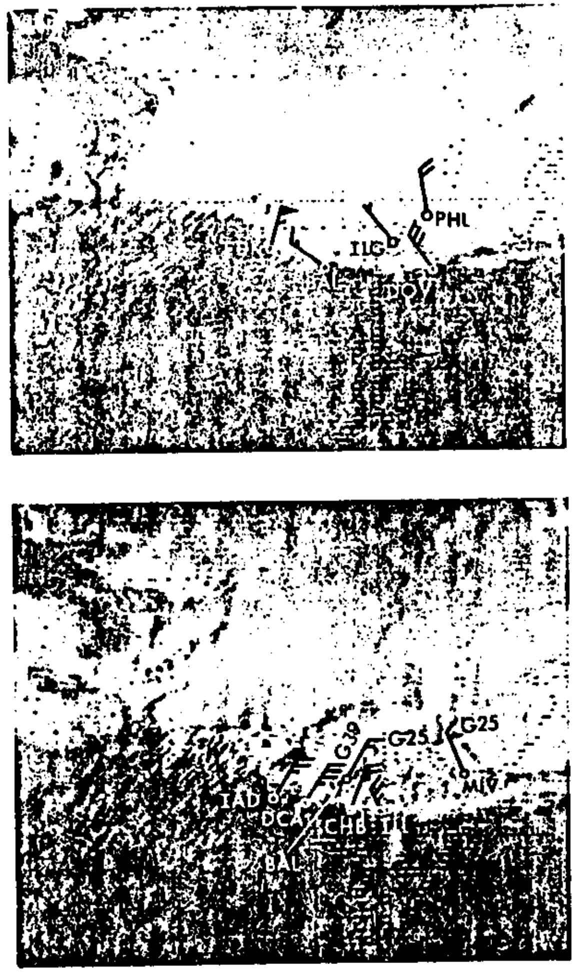
Udin, Ingemar; 1986. The PROMIS project. SMHI Promis-Rapporter, Nr 3, 31 pp.

Velasco, I. and J.M. Fritsch, 1987. Mesoscale Convective Complexes in the Americas. J.Geophys. Res. 92; D8, 9591-9613.

VonderHaar, T.H., 1969. Meteorological applications of reflected radiance measurements from ATS 1 and ATS 3. J. Geophys. Res. 74:5404-5412.

Whitney, L.F., 1977. Relationship of the sub-tropical jet stream to severe local storms. Mon. Weather Rev. 105:398-412.

Zipser, E.J., 1984. The National STORM Program. STORM-CENTRAL PHASE. NCAR. 147 pp.



1a
1b

Figure 1 .--SMS-1 visible 1-km data showing surface wind observations for 2100 GMT, 3 July 1975 (above); 2200 GMT, 3 July 1975 (below) (Gurka, 1976).

Figure 2 Summertime DMSP photograph of convection around the Great Lake.

(From Purdom, 1986)

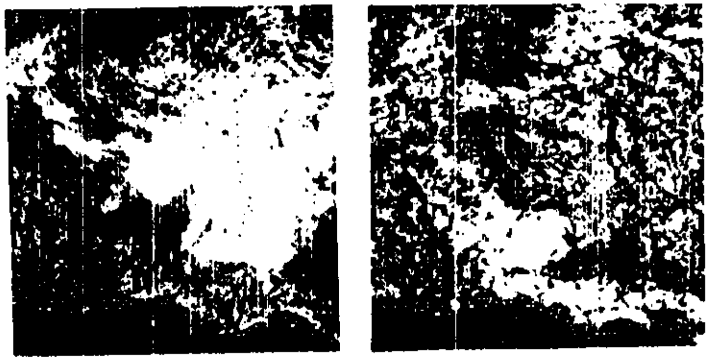


Figure 3 GOES-East 1 km VIS images, 27 May 1977 at 1530 and 1930 GMT. Convective development over Alabama is due to early cloud cover. These images show the effect early cloud cover can have on afternoon thunderstorm development. Note that the early clear region over southwest Alabama becomes filled with strong convection during the day, whereas the early cloud region over the remainder of the state evolves into mostly clear skies. The strongest activity later in the day develops in the "notch" of the clear region in south-central Alabama, as one might expect from merging cloud breeze fronts.

(From Scofield and Purdom, 1986)

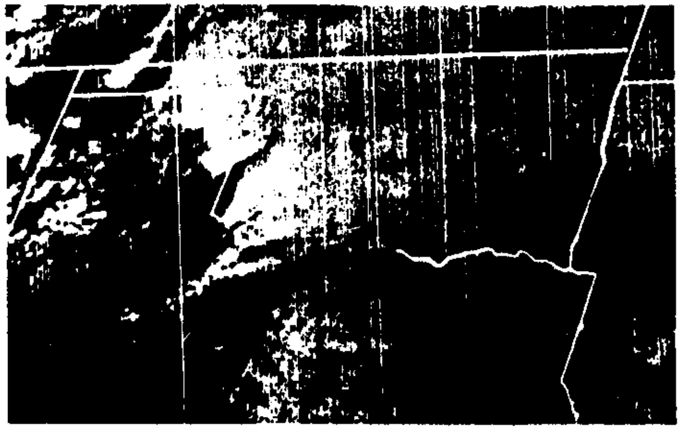
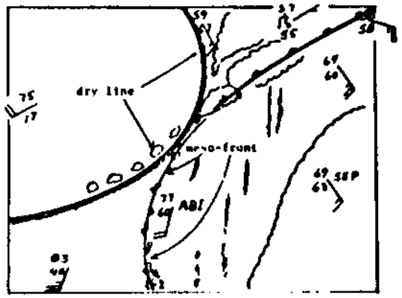


Figure 4a . GOES-East 1 km VIS image, 10 April 1979 at 2126 GMT.



(From Scofield and Purdom, 1986)

Figure 4b Analysis of significant features and cloud patterns in Fig. 7.2a.

Figure 5 .--SMS infrared picture at 0000 CST, 30 April 1975 showing concurrent severe storms and the synoptic features of jetstreams and surface fronts. Bold dashed lines are the axes of the jetstreams. Heavy ×'s are positions of wind maxima. Subtropical windspeed maximum is >100 knots. Thin, candy-striped lines are surface fronts. Dotted lines are geographical and political grid overlay (Whitney, 1977).

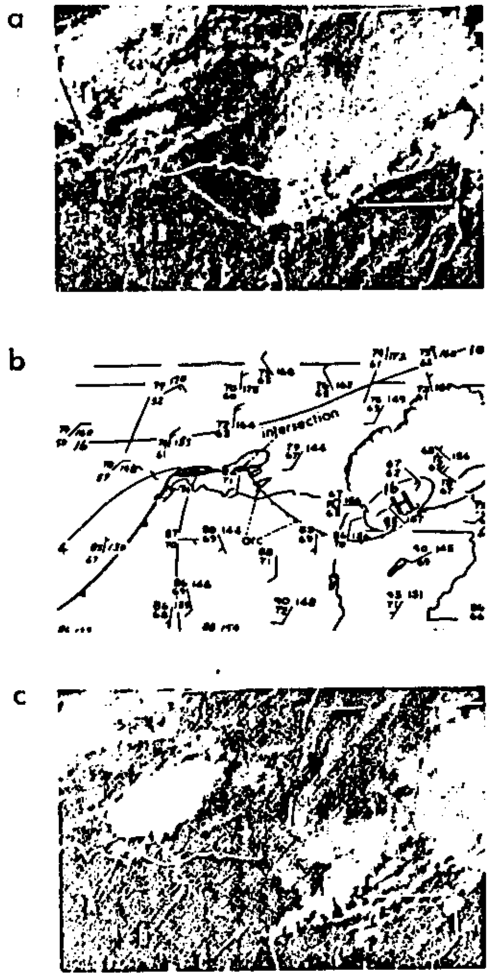


Figure 6 .--(a) GOES-1 1-km visible imagery for 2100 GMT, 26 May 1975. A cloud arc, produced by the storms over Arkansas, stretches from A to B to C. A second arc line is indicated at F. (b) Surface analysis for 2100 GMT, 26 May 1975, showing selected clouds and cloud boundaries. (c) GOES-1 1-km visible imagery for 2230 GMT, 26 May 1975 (Purdom, 1976).

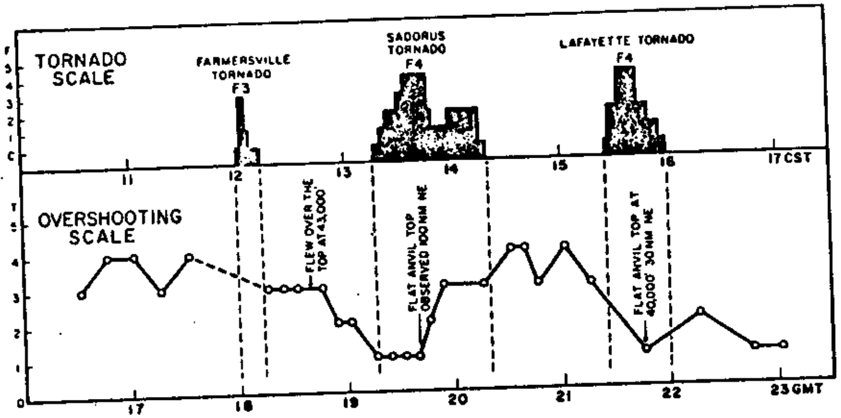


Figure 7 --Change in overshooting scale (5 indicates intense overshooting top activity; 1 indicates very flat anvils) in relation to the intensity of tornadoes spawned by a supercell thunderstorm (Fujita et al., 1976).

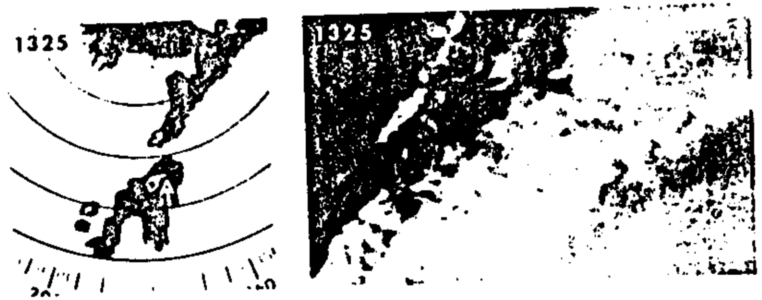


Figure 8 .--Concurrent radar PPI scope and satellite photographs of the tornadic thunderstorm (Fujita et al., 1976).

"For Fig. 9 and 10 see Fig. II.2 and II.3 in Chapter II"

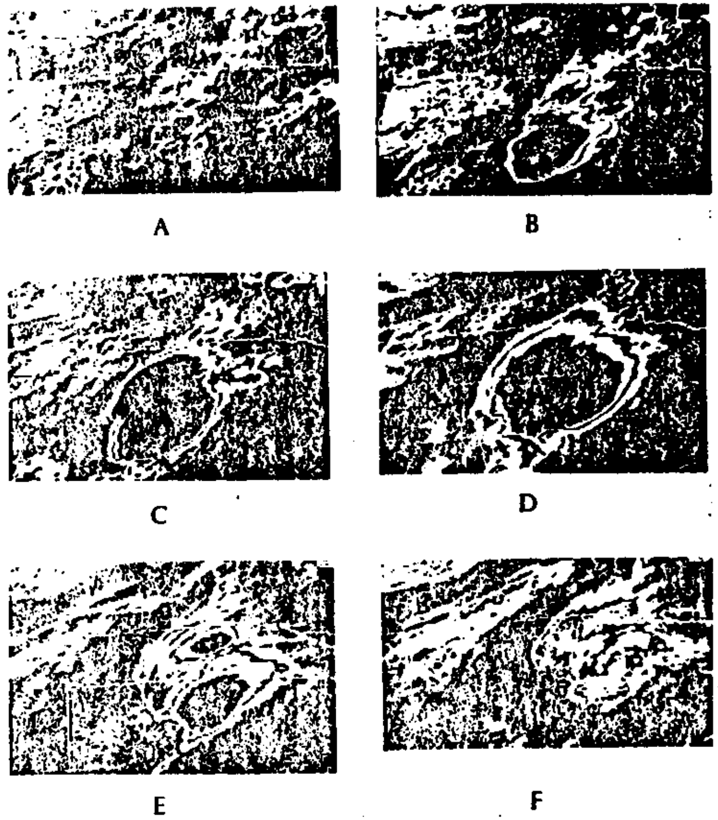


Figure 11 --Series of enhanced infrared satellite images for A) 0030 GMT, B) 0300 GMT, C) 0600 GMT, D) 0900 GMT, E) 1430 GMT, and F) 1630 GMT on 12 July 1979 showing the life cycle of a Mesoscale Convective Complex (Maddox, 1980).

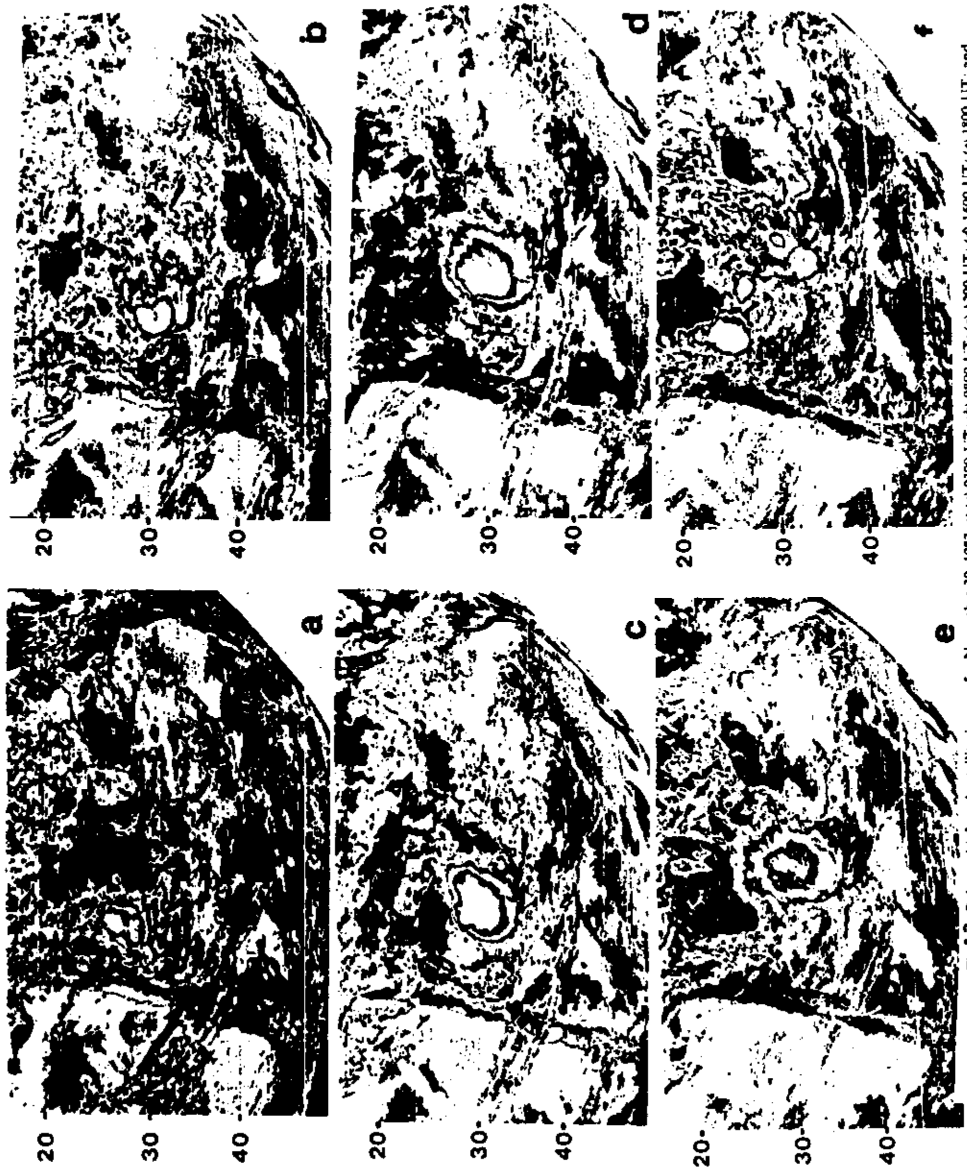


Fig 12 Enhanced infrared satellite images for November 30, 1982, at (a) 0300 UT; (b) 0800 UT; (c) 1200 UT; (d) 1500 UT; (e) 1800 UT; and (f) 2100 UT

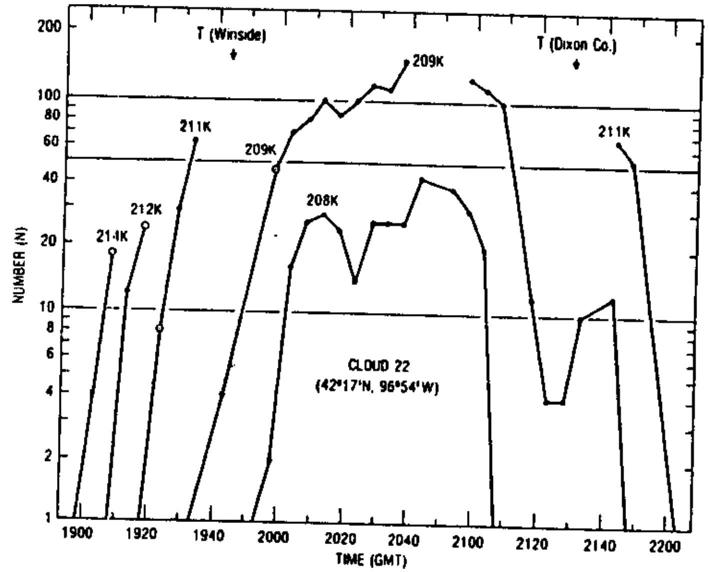


Figure 13.--Thunderstorm growth rate diagram for a tornado over South Dakota on 6 May 1975. The number of pixels (i.e., area) having specific cold radiative temperatures is shown as a function of time. T's indicate time of tornadoes (Adler and Fenn, 1977).

TABLE 2. Classification of meso-α scale, convectively driven weather systems according to physical characteristics, organization, and location.