J2.1 THUNDERSTORM NOWCASTING: PAST, PRESENT AND FUTURE

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1. INTRODUCTION

This paper is an abbreviated version of the Remote Sensing Lecture given at the 31st Radar Meteorology Conference. Color figures and animations which were a primary feature of the lecture are not possible here.

The term nowcasting is used to emphasize the very short term nature of the forecast i.e. 0-6 h. In the foreseeable future it is likely that only for this very short time period will it be possible to make forecasts of high impact convective weather events like flooding rains, hail, and damaging winds with sufficient time and space specificity that appropriate actions can be taken to effectively mitigate losses or enhance benefits. Thus the use of the term "nowcasting" to emphasize the specificity and shortness of the forecast.

Historically nowcasting has been almost exclusively based on the extrapolation of radar echoes, satellite imagery of clouds and/or lightning location data. Studies (Browning 1980 and Wilson et al. 1998) have consistently shown that the accuracy of extrapolation nowcasts decreases very rapidly with time, particularly during the first hour. The rate of decline is often closely related to the scale of the precipitating system and forcing mechanism. The rapid decrease in accuracy is more a failure to forecast storm evolution rather than errors in extrapolation position. Nevertheless the use of these data sets to identify and extrapolate hazardous convective weather for periods ~ <30 min has resulted in dramatic improvement in warnings and advisories and resulting savings of life and property (NRC 1995). Fortunately among the more predictable features are well organized squall lines and supercell storms.

Based on this nowcasting success of high impact weather events, on extremely short time scale, there is considerable benefit and pressure from user groups to extend the time period of accurate nowcasts. Among these user groups are: aviation, highway, construction outdoor entertainment, agriculture and public safety.

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Any significant advancement in nowcasting accuracy for longer time periods (>30 min) will require nowcasting storm initiation and evolution. The status of this capability and promising future technologies are discussed in Sections 3 and 4 respectively.

2. PAST

The notion of extrapolating radar echoes to predict thunderstorms is fifty years old (Ligda 1953). The period between 1960 and 1980 was very active in developing and testing extrapolation techniques. Two techniques emerged: the "area tracker" (Kessler 1966) and "cell tracker" (Barkley and Wilk 1970). For the area tracker, the computer was used to cross correlate radar reflectivity images separated in time to find the motion. Originally one vector was determined for extrapolating the entire precipitation field observed by a single radar. Later Rinehardt (1981) obtained differential motions within the echo field. Cell trackers identified individual storms and then obtained the motion of each storm centroid. More recently Dixon and Wiener (1993) developed a robust real-time cell tracker to handle the splitting and merging of storms. Cell trackers have been particularly useful for tracking and warning for individual severe storms.

The first automated operational nowcasting system was implemented in 1976 utilizing the McGill Weather Radar; products were sent to the Atmospheric Environment Service Forecast Centre in Quebec (Bellon and Austin 1978). This system was used to nowcast all precipitation not just thunderstorms. In the early 1980's the U.K. Meteorological Office implemented a precipitation nowcasting system that utilized radar and satellite data as well as forecaster input to edit data and modify nowcasts (Browning and Collier 1982). Subsequently a number of countries have implemented similar operational systems; the U.S. National Weather Service is a notable exception.

As already indicated the accuracy of nowcasts, particularly for convective features, decreases very rapidly with time. Efforts to use trends in echo size and intensity to improve on the nowcasts were largely unsuccessful. As Tsonis and Austin (1981) concluded the physical processes that dictate the change in rainfall patterns with time are not necessarily observable in the past history of a particular precipitation pattern development. In the case of convective storms these physical processes are often events occurring in the boundary layer such as convergence features and stability changes. However, regardless of these scientific findings forecasters frequently use trending when issuing thunderstorm nowcasts.

Insight into boundary layer convergence lines (boundaries) and their effect on storm initiation was pioneered by Purdom (1976) and collaborators. The development of Doppler weather radars and their ability to observe the clear-air boundary layer extended this insight (Wilson and Schreiber 1986). These new observing tools made it clear that thunderstorm initiation was not a random process in an environment ripe for convection rather it was frequently location-specific triggered by boundaries.

During the 1990's forecasters observing boundaries on the WSR-88D or satellite began to make use of this information to anticipate where storms would initiate, particularly when colliding boundaries were anticipated. Also during this time period NCAR developed an automated thunderstorm nowcasting tool, called the Auto-nowcaster (Mueller et al. 2003). The NCAR Auto-nowcaster is a computerized data fusion system that utilizes fuzzy logic to combine forecast parameters derived from the ingest data sets to nowcast storm initiation, growth and dissipation. The fuzzy logic is based on physically-based conceptual models of storm evolution and heuristic[1] nowcasting rules. Data are ingest from radar, satellite, surface stations, numerical models and a 4D variational numerical model that retrieves boundary layer winds from radar and surface stations.

3. PRESENT

In the U.S. the emphasis is on providing the forecaster with tools to identify and track severe weather rather than automated precipitation forecasting tools as is the case in European countries. Two systems that are proving very effective for severe storm warnings within the U.S. National Weather Service are WDSS (Warning Decision Support System (Eilts 1997) and AWIPS (Advanced Weather Interactive Processing System). These systems provide a suite of algorithms for calculating storm tracks, detecting hail, mesocyclones, tornadoes, and damaging winds and interactive display of data and products. Severe storm warnings have shown significant improvements (Polger et al. 1994) largely due to these radar tools and forecaster training.

The international status of nowcasting thunderstorms was demonstrated during a 3 month period in Sydney Australia which included the period of the 2000 Olympic Games. This forecast demonstration was sanctioned by the World Weather Research Program and included nowcasting systems from Australia, Canada, United Kingdom and U.S. In general these systems had limited ability to nowcast storm evolution with echo extrapolation being the primary nowcast tool. The NCAR Auto-nowcaster showed promise in forecasting storm evolution when boundaries were present (Wilson et al. 2003). The UK Meteorological Office demonstrated NIMROD (Golding 1998) a 0-6h nowcasting system that is a blend of radar echo extrapolation and numerical model precipitation nowcasts. For the shorter time periods the primary weight is given to extrapolation of the existing precipitating field which is derived from satellite and radar data. With increasing nowcast time the weight shifts to the numerical model and becomes almost totally dependent on the model for the 6h nowcast. For these later periods the forecasts are no better than the ability of the numerical model which was very low in this case for thunderstorms.

The U. S. Federal Aviation Agency has been particularly active in supporting the development and operational implementation of automated thunderstorm nowcasting systems for the aviation community. There are four airports across the U.S. where MIT-Lincoln Laboratory has installed for operational testing the Integrated Terminal Weather Information System (ITWS; Evans and Ducot 1994). Thunderstorm 0-1h nowcasts are made based on the extrapolation of radar echoes. During the past year Lincoln Laboratory has been conducting a demonstration project where 1 and 2h nowcast products for thunderstorms are issued routinely for the northeast U.S. and available to the aviation community. This product, similar to the ITWS thunderstorm product, is based on the extrapolation of radar echoes after the data have been filtered to remove small scale features. It also incorporates some growth and decay based on echo trending. The Aviation Weather Center provides a 1 and 2h thunderstorm nowcast product for the entire U.S. which was developed by NCAR. This product is based on the extrapolation of radar echoes but allows for growth of thunderstorms based on the presence of a frontal region during the statistically favored afternoon thunderstorm initiation and growth period (Mueller and Megenhardt 2001). Frontal regions are automatically identified from the fuzzy combination of parameters (vorticity, convergence and potential temperature gradients) from the RUC (operational numerical weather prediction model called the Rapid Update Cycle).

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[1] Heuristic is defined here as forecast rules based on experiment, numerical simulations, theory and forecaster rules of thumb.

The only operational statistical method known to this author for nowcasting convective precipitation is that of Kitzmiller (1996) which utilizes radar, satellite, lightning and numerical models.

Presently in the U.S there are several numerical models that make forecasts of convective precipitation for the nowcast period. These include RUC, ARPS, and LAPS/ MM5. These models do ingest some high resolution data like WSR-88D winds and reflectivity and satellite derived winds. It is believed these models tend to have more skill for strongly forced synoptic situations. However, nowcast validation and comparison with extrapolation is incomplete.

Fundamental to improving thunderstorm nowcasting and defining the predictability limits is better understanding of factors that trigger storm initiation and control storm evolution. Improved nowcasting will also require improved measurements and better representation of convection by numerical models. Improvement of these three items (understanding, measurements and models) were goals of the 2002 International H_2O Project (IHOP) and are a principle focus of the U.S. Weather Research Program. These items will be discussed in the next section.

4. FUTURE

Future efforts to improve thunderstorm nowcasting will likely have three primary components: basic research, new observations, and operational test beds; each is discussed below.

4.1 Basic research

There are a number of fundamental scientific issues that need further research. These include: 1) Document the accuracy of present thunderstorm nowcasting techniques (statistical, extrapolation, NWP and fuzzy logic to establish a baseline for monitoring future progress. 2) Determine the predictability of convection for different meteorological scales and situations. 3) Conduct basic research into factors that trigger storm initiation and control storm evolution; this includes both surface based and elevated convection; the distinction indicative of where the roots of the updraft originate. 4) Conduct basic studies into mid and upper level small-scale kinematic and thermodynamic features that impact storm evolution. 5) Improve NWP to better assimilate multi-scale data and to more realistically represent convection, this includes accurately forecasting the occurrence, motion and characteristics of thunderstorm outflows.

a) IHOP

It is expected that results from IHOP will contribute toward progress on the above numbered items. Figure 1 shows the track of one of several aircraft that were collecting data before and during the initiation of a thunderstorm along a boundary. This airplane contained a Doppler radar and a water vapor measuring lidar that continually mapped the 3D water vapor and wind fields with a resolution never before obtained. A number of similar cases were obtained along boundaries that both did and did not initiate storms.

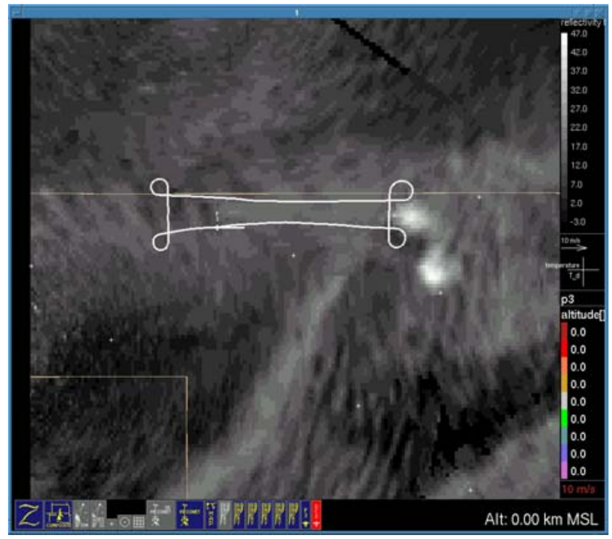

Fig 1. Flight track of research aircraft during IHOP that caught the initiation of a thunderstorm (echo at east end of track). The plane carried a Doppler radar, water vapor lidar and in situ instruments measuring state variables. The deployment of the aircraft was based on radar observations of intersecting convergence lines.

b) Wind retrieval

Sun and Crook (2001) have developed a Variational Doppler Radar Analysis System (VDRAS) that retrieves in real-time high resolution (2 km) wind fields from single Doppler radar data. Fig 2 shows retrieved wind fields from the WSR-88D in Sterling VA as a strong line of thunderstorms develops in the vicinity of Washington D.C.. Wind convergence and vertical velocity derived from these wind fields are being used by the Auto-nowcaster to characterize the potential of boundaries to initiate storms. VDRAS which has a 10 min update rate, is presently implemented on five WSR-88D's in IL, IN, OH and NM. In the future a system like VDRAS could provide a high resolution boundary layer wind analysis on almost a national scale which could then be assimilated into nowcasting techniques.

c) Boundary prediction

Because of the impact of boundaries on the initiation and evolution of thunderstorms it is critical that boundary motion and characteristics are accurately

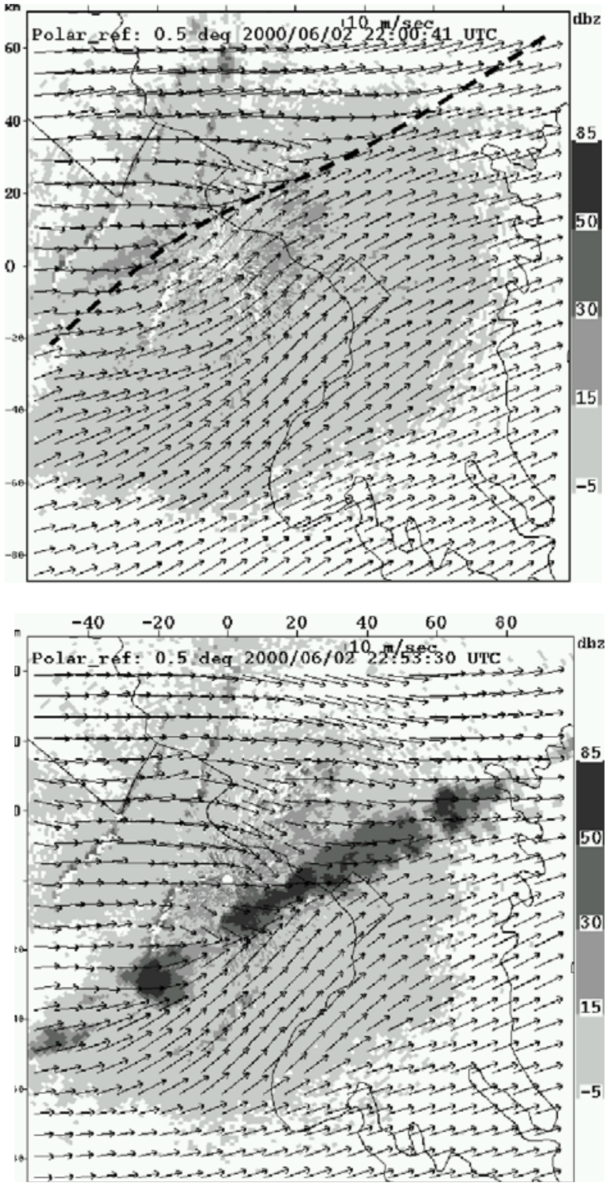

Fig.2 High resolution low-level wind field retrieved from the Sterling VA WSR-88D. a) the dashed line indicates the location of the convergence line that is retrieved by VDRAS from the clear-air return. b) squall line that has developed on the convergence line 60 min latter.

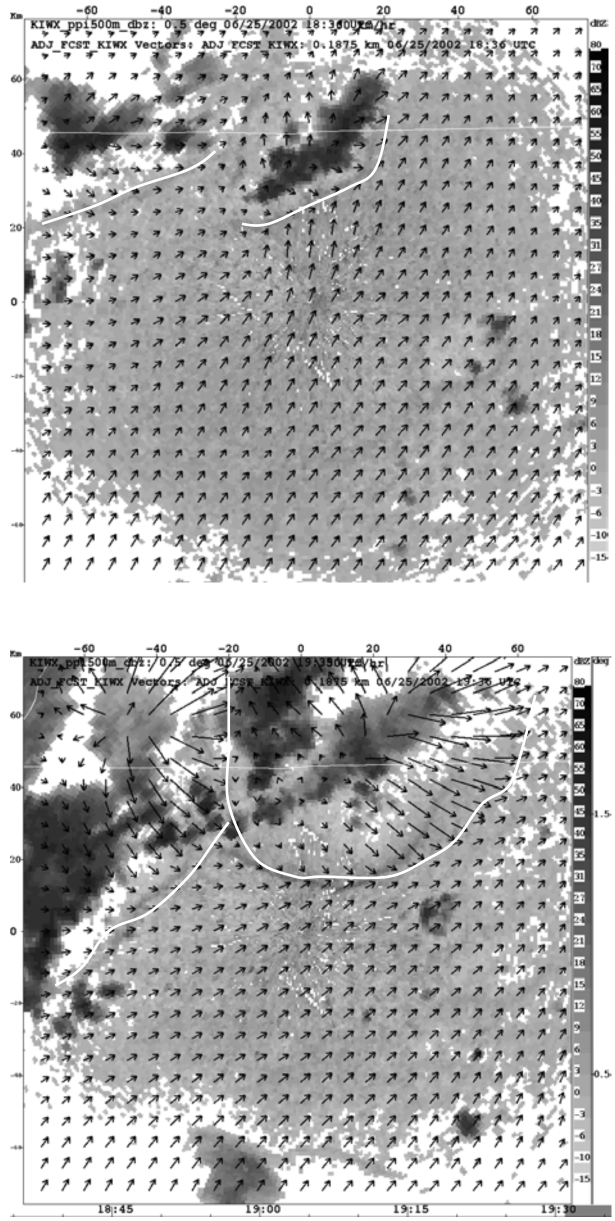

Fig 3. Model 1h forecast of gust front movement and evolution for the case of 25 June 2002 from the KIWX Fort Wayne, IN WSR-88D a) initialization time at 1836 UTC, vectors are retrieved by model and overlaid on reflectivity. b) 1 hr model forecast (wind vectors) overlaid on 1936 reflectivity field. White lines are leading edge of the model forecast gust front. The actual position can be seen as a reflectivity thin line.

nowcast. Present extrapolation techniques fail to account for changes in speed or intensity. Recently Caya et al. (2003 in this preprint) have experimented with four dimensional variational assimilation of WSR-88D data into the boundary layer model of Sun et al. (1991) to forecast the development and movement of gust fronts.

Caya et al. report that the critical factor in obtaining accurate forecasts in this case was applying evaporative cooling during the assimilation process. Figure 3a shows the initialization time (1836 UTC) and Fig 3b shows the 1h forecast of wind vectors overlaid on the radar reflectivity field at 1936 UTC. White lines in b) indicate the forecast position of the leading edge of the gust front. The actual position can be observed as a thin enhanced line of reflectivity. The model has accurately forecast the position of the gust fronts and particularly important has captured the significant increase in convergence since the initialization time.

d) Explicit storm nowcasting by models

Recently some encouraging attempts have been made to predict thunderstorms with cloud scale numerical models initialized with high-resolution Doppler radar data (Montmerle et al. 2001 and Weygadt et al. 2002).

Fig. 4 shows the results of such an experiment conducted by Sun and Miller (2003 this preprint) for a supercell storm near Bird City, KS. The figure shows the 40 dBZ contour and the + indicates the location of maximum reflectivity. The upper panel shows the actual position of the storm over a two hour period and the lower panel shows the corresponding predicted positions. The model shows good agreement with the observations. Significantly it predicted the right turn of the supercell at the correct time.

4.2 New observations

The lack of detailed measurement of water vapor is felt to be a major factor in limiting the forecasting of convective storm precipitation and was a primary motivation for IHOP. A number of new water vapor measurement techniques were tested in IHOP (Weckwerth et al. 2003) that included ground and airborne lidars and satellite instrumentation. One of the most exciting new techniques was the use of radar refractivity measurements to map the near surface distribution of water vapor with a time and space resolution never before realized. The technique developed by Fabry of McGill (Fabry et al 1997) has been installed on two research radars and can relatively easily be installed on the national network of WSR-88D's and TDWR's. Fig 5a shows a sample of the refractivity field obtained from the NCAR S-pol radar during IHOP in the presence of a double structured dry line (from Pettet et al. 2003 this reprint). Fig 5b and c show the extremely high correlation that exists between the radar measured refractivity and that derived from two surface stations. The changes in refractivity are mostly due to changes in water vapor.

4.3 Operational test-beds

In March of 2002 an international team, with expertise in nowcasting thunderstorms, assembled to participate in a USWRP workshop on Warm Season Quantitative Precipitation Forecasting. This team prepared a proposal to outline a future path for developing improved warm season nowcasting techniques. In addition the World Weather Research Program is

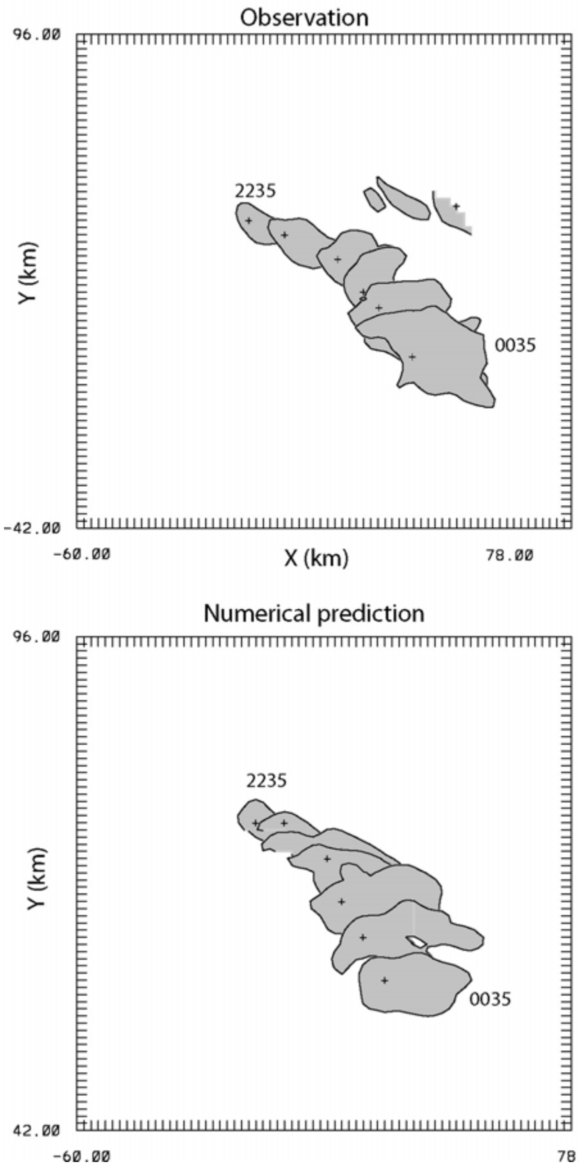

Fig.4. Explicit model forecast of the evolution and movement of a right turning supercell storm. The model was initialized with WSR-88D data from Goodland KS. Storm positions indicated by the 40 dBZ contour lines at 20 min intervals. The + marks the position of maximum reflectivity. The Upper panel shows the observations and lower panel the forecast.

establishing a nowcasting working group for advancing the science and operational use of nowcasting.

Central to this above effort would be regional test beds that had access to both research and operational data sets with users and researchers working as partners. The test-beds would serve as vehicles to develop and evaluate new products in a user environment. Optimum methods would be developed for blending statistical, extrapolation, heuristic and

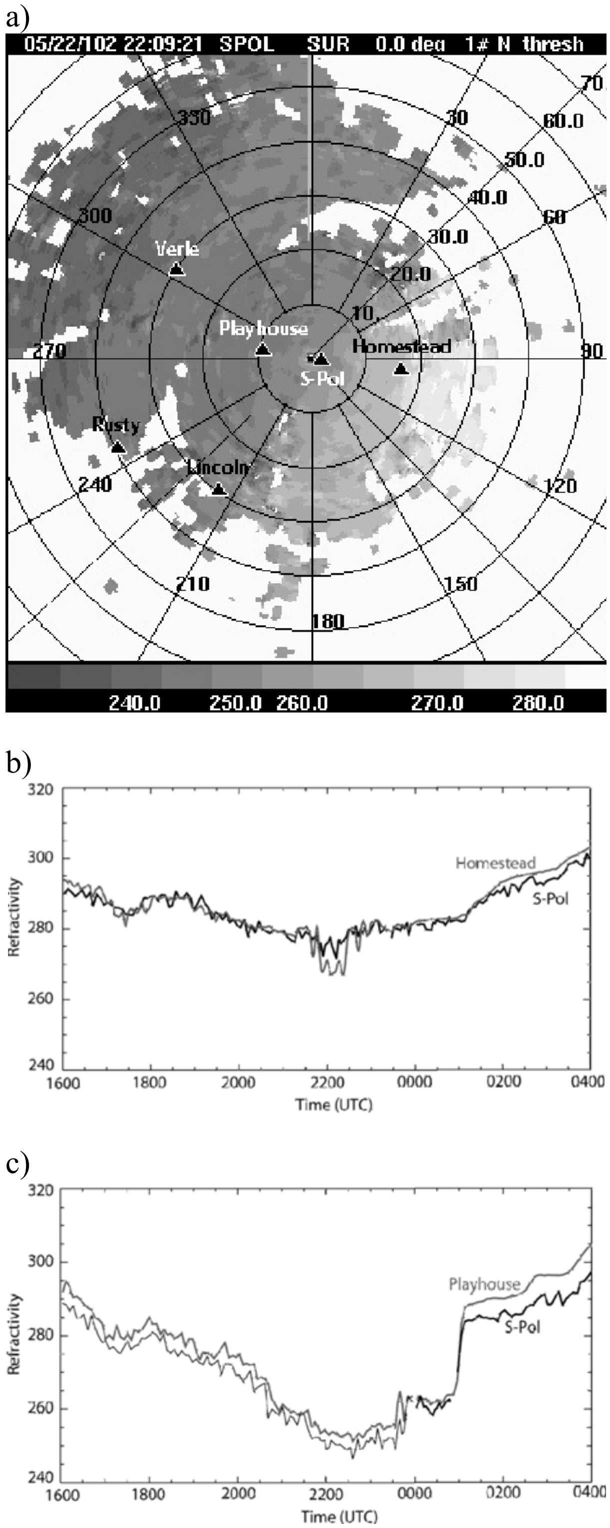

Fig. 5 Radar refractivity retrievals from S-pol radar during IHOP on 22 May 2002. a) map of radar refractivity. The triangles are surface station locations. b) comparison of the radar and surface station refractivity measurements for the Homestead station, c) same as b) except for surface station Playhouse.

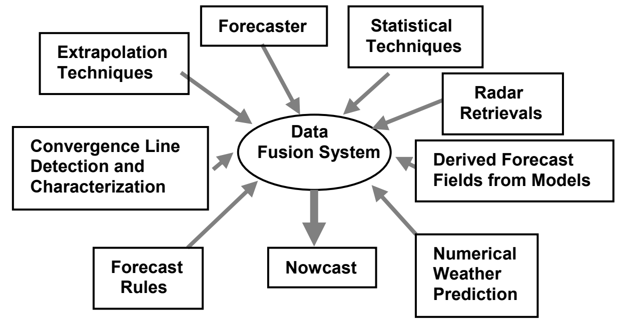

Fig 6. Diagram showing the sources of nowcasting information that flows into a proposed data fusion nowcasting system of the future.

numerical techniques into one nowcasting system utilizing fuzzy logic. This system would be similar in concept to the Auto-nowcaster. Fig 6 is a flow diagram showing the variety of nowcasting techniques and nowcasting information that would be blended together to produce the final product. The specificity of the nowcast would take into consideration the predictability of the meteorological situation. The number of researchers working on the development of nowcast techniques is small; thus the efficient and timely method for achieving success will be for the international community of scientists and engineers interested in nowcasting to work together. This would include collaboration in planning and developing test-beds, conducting research and conducting field experiments.

5. SUMMARY

Nowcasting thunderstorms has been based primarily on the extrapolation of satellite and radar data. Although the accuracy of extrapolating individual convective storms decreases very rapidly within the first hour severe storm warnings based on extrapolation have dramatically improved in the past 10 - 15 years. The lead-time of these warnings is typically < 30 min.

Significant increase in warning lead times beyond 30 min will require major advances in nowcasting storm initiation, growth and dissipation. Critically important will be anticipating mesoscale stability fields, wind fields and in particular convergence lines. Typically it is these features that determine specifics of storm location, intensity and evolution. In the near future numerical techniques most likely will not be able to predict storm outflows and their characteristics with sufficient accuracy to anticipate subsequent storm initiation and evolution. It is felt that the best method for improving thunderstorm nowcasting in the foreseeable future will be by combining extrapolation, statistical, numerical weather prediction and heuristic techniques into one system. This entire procedure can probably best be accelerated by developing regional test-beds where international researchers and users work side-by-side.

The forecaster should play a significant role in the envisioned data fusion nowcasting system. Because of the enormous amount of data on many different scales that must be analyzed and the frequent and rapid update cycle of the nowcasts the system must be highly automated. However, the forecaster needs to play a critical role and that is one of helping to determine the location of boundaries and providing likelihood fields of where thunderstorm initiation, growth and dissipation are expected. During IHOP forecasters at the Severe Storm Prediction Center successfully provided such information to help plan field operations. The automated detection of convergence lines has proved particularly difficult and forecaster input into the procedure is highly desirable. The forecaster could play a central role in preparing a national map of convergence lines that could be eventually utilized by NWP as well as the envisioned data fusion nowcasting system.

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