1.1A THE MST RADAR TECHNIQUE: REQUIREMENTS FOR OPERATIONAL WEATHER FORECASTING

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INTRODUCTION

Recent interest in improving our ability to make mesoscale forecasts has been the result of improving observational technology and theoretical understanding of mesoscale motions. There is a feeling that the accuracy of forecasts for spatial scales of less than 1000 km and time scales of less than 12 hours can be improved significantly if our resources are applied to the problem in an intensive effort over the next decade. Since the most dangerous and damaging types of weather occur at these scales, there are major advantages to be gained if such a program is successful. The interest in improving short-term forecasting is evident in the series of papers resulting from the International IAMAP Symposium on Nowcasting (BROWNING, 1982), the paper on the long-term goals of NOAA as presented by SCHMIDT (1983) at the Fifth Symposium on Meteorological Observations and Instrumentation, and the two handbooks published by the UCAR Committee on the National STORM (Stormscale Operational and Research Meteorology) Program (UCAR, 1982; ANTHES, 1983). The conclusion of all of these publications is that the technology at the present time is sufficiently developed, both in terms of new observing systems and the computing power to handle the observations, to warrant an intensive effort to improve stormscale forecasting.

The National STORM Program handbooks (UCAR, 1982, ANTHES, 1983) are excellent source books on the general problem of short term forecasting. The first handbook summarizes the need for this type of forecasting and the framework for achieving the desired improvements. The second handbook gives a detailed assessment of our capabilities and understanding at the present and the areas of research most in need of attention. Questions that will have to be addressed deal with the type of observing system or systems that will be used to generate data compatible with the scales of motion being discussed and the way the data will be used operationally. HOOKE (1983) summarized the situation as follows:

"Within the next several years, operational meteorology will be facing some crucial decisions regarding measurement systems. The most obvious and important example is the determination of winds. A variety of remote sensing techniques have been used experimentally to measure wind direction and speed in clear air. There is substantial need for an integrated effort to determine which of these techniques is most promising by testing alternative methods in the field. This will be a necessary prelude to the procurement and deployment of a next-generation wind sensing system."

In this review I will attempt to provide an assessment of the extent to which the so-called MST radar technique fulfills the requirements for an operational mesoscale observing network, and I will delineate the extent to which improvements in various types of forecasting could be expected if such a network is put into operation.

CHARACTERISTICS AND CAPABILITIES OF THE RADAR TECHNIQUE

The MST radar measures the vertical profile of horizontal winds based either on the Doppler shift of the signal backscattered from turbulent variations in the refractive index or from the cross correlation between the signals re-

ceived at a set of three spaced antennas. The technique has been described in detail by WOODMAN and GUILLEN (1974), GAGE and BALSLEY (1978), BALSLEY and GAGE (1980), and ROTTGER (1980) among others. Details and advantages of various specific measurement techniques are discussed in much greater detail in other papers in this volume.

I will concentrate on VHF radars that use a fixed dipole array and are capable of measuring the vertical profile of the horizontal winds as a minimum. Some MST radars operating at shorter wavelengths have fully steerable dishes. An example is the 23-cm radar formerly located at Chatanika, Alaska, and now located in Sondre Stromfjord, Greenland. I will not consider such radars here since they are in the same category as the existing weather radar network if upgraded to provide Doppler capability.

The radar's ability to provide wind profiles is something that is duplicated by the standard rawinsonde. However, the radar wind measurements have many advantages, particularly if the mesoscale is of interest. The radar wind profiles can be measured as often as desired down to the imposed equipment limitation of a few minutes. There are no expendables involved except for the power used to run the radar equipment. Also, the radar measures the wind profiled immediately above the radar. During periods of high winds, the rawinsonde can drift as much as 100 km during its ascent. Such an error can be a major one if the scales of motion of interest are of the order of a few hundred kilometers. Finally, a large part of the cost of running a radiosonde station has always been the salaries of the personnel. Since the radar measurements are easily automated, adding VHF Doppler radars to the network would only increase the required extra manpower by a small fraction of the number of personnel needed if an equal number of new radiosonde stations were established. The success of such an approach is already evidenced by the Poker Flat MST Radar which has been operating unattended since 1979.

However, the comparison between the radiosonde and the radar is not really the most appropriate. The possibility of establishing a mesoscale radiosonde observing network has never been considered very seriously since the cost is prohibitive. Most likely the competition will come from satellites or some other ground-based remote sensing system such as sodars or lidars. The primary advantage of the radar over the acoustic sounder is the height range covered and the insensitivity of the former to various forms of noise. A very complete review of the capabilities of the acoustic sounding technique is given by BROWN and HALL (1978). The lidar is competitive with the radar in terms of the height range covered and the time and, certainly, the height resolution, but the lidar is seriously hampered when there is precipitation or fog or simply when it is overcast (STRAUCH and COHEN, 1972). The lidar provides information on atmospheric density and humidity, but the radar provides data on the height of the tropopause and other temperature structure such as inversions and fronts. Further comparison between the advantages of the two techniques is needed, although the main drawback of the lidar for operational applications appears to be the limitations of the technique when used in the presence of clouds.

The satellite has a number of advantages over the radar. Primarily it provides vast areal coverage in relatively short periods of time. Since a very large source of error for large-scale forecasting is due to a lack of data in sparsely populated regions, underdeveloped areas, and the oceans, satellite measurements appear to be the best hope for improving large-scale observations. The radars do not immediately offer any hope for providing data in data-sparse regions. The height and time resolution, and the height range covered by the radar is significantly better than that of the satellite, but the lack of spatial coverage of the radar measurement is still one of the limitations of the technique.

So far, I have compared the advantages and disadvantages of the various techniques. It is clear that the radar by itself cannot replace the other types of measurements, but it can provide a relatively inexpensive solution to the problem of upgrading the observing network to provide mesoscale resolution. Meteorological radars already exist and provide important information for the forecaster. Half-hourly satellite photos are an important input to the forecast process and satellite measurements of temperature and winds are providing data for areas where no information could be obtained otherwise, albeit with less than desirable height resolution. However, the VHF radars can fill the gaps that exist in the present radiosonde network. It has been shown by HOKE and ANTHES (1976), DALEY and PURI (1980), and DALEY (1980) among others that when small scales of motion are of interest, the wind information is more important than pressure and temperature information. Therefore, the fact that the radar only measures the winds, and not also pressure and temperature, should not necessarily be viewed as a compromise of the technique when it is used for meso-scale observations. I will discuss this point in more detail later.

REQUIREMENTS FOR AN OPERATIONAL SYSTEM

Although the topic of the Workshop is the MST (Mesosphere-Stratosphere-Troposphere) radar, the ability to measure winds in the troposphere, stratosphere, and mesosphere is not required of the systems used for mesoscale weather forecasting. A simple "Model T" Radar would be sufficient. With thanks to Henry Ford, such a radar should be simple to mass produce, low cost, and dependable in operation. The reductions in antenna size and transmitter power gained by reducing the design specifications of the system could reduce the cost of the system by as much as a factor of ten when compared to an MST system. That is a crude estimate but probably not unrealistic.

Discussions about the applicability of the radar wind measurements to operational weather forecasting have generally centered on applications to large-scale forecasting with improved spatial resolution so that mesoscale phenomena can be resolved. Of course, it is important that this aspect of the radar technique should be discussed, and that may be how the systems are ultimately applied. However, there are intermediate applications for such systems that would allow the radars to be phased into the large-scale observing network with possible significant forecast improvements at each intermediate step. There are a number of very localized phenomena that lead to severe weather that a small network of VHF radars could be useful in forecasting.

Applications that come to mind include the following. A network of between 3 and 6 radars distributed around the Great Lakes could be used for operational forecasting of lake-effect snows. Typically, the snows are generated by directional changes in the mesoscale flow patterns and eventually mesoscale circulations develop in response to the heating effects of the lakes (ZIPSER, 1983). It should be possible to detect these small-scale circulation changes with a network of radars. More study would be needed to determine the real usefulness of such a system for forecasting this very specific local phenomena.

A second application would involve use of a system of radars as a forecast tool for the severe Colorado wind storms that occur every year in the lee of the Rocky Mountains (LILLY and ZIPSER, 1972; KLEMP and LILLY, 1975). Since a cloudy or precipitating atmosphere is not necessarily associated with this phenomena, a scanning weather radar, even one with Doppler capability, is not particularly useful for forecasting this type of event. Actually, the necessary network may already exist in the form of the PROFS (Prototype Regional Observing and Forecasting System) network of wind profilers operated by the Wave Propagation Laboratory of NOAA (STRAUCH et al., 1982).

Another application of a small-scale system of Model T radars is for stud-
ies of the sea breeze in the Florida peninsula. The sea breeze develops in re-
sponse to the diurnal heating cycle and the temperature differences between land
and sea. The vertical circulation that develops acts as a modulator of the con-
vective activity over the land and over the ocean (LHERMITTE and GILET, 1975;
ATKINSON, 1981). The resulting thunderstorms can be very severe and may involve
large shears, heavy rainfall rates, hail, and turbulence that can be a hazard to
local aviation. A scanning weather radar can be used to detect the developing
cells, but since the lifetime of a single cell is from 30 to 45 minutes, only a
short-term warning can be issued. Clear air wind measurements may be capable of
detecting the buildup of the conditions leading to intense convection.

The possible applications of the radar systems for local forecasting just
named are only a few of the possibilities. The important point is that a small
number of the radar systems can be installed to provide improved forecasting of
specific local phenomena. Confidence in the systems and operational experience
would be gained before making a commitment to use the radars on a network-wide
basis.

Another area in which the radars can be applied for forecasting purposes
relates to pollutant dispersion. Most of the models used to estimate dispersion
of pollutants are based on the Gaussian plume models (HANNA et al., 1982). The
two major input parameters are an atmospheric stability index derived from the
radiosonde temperature profile and the wind at the height of the center of the
plume. A major problem is the significant diurnal variation in the winds that
cannot be resolved by the rawinsonde measurements made once every 12 hours
(DRAXLER, 1983). Only a small system that could measure the winds up to a
height of a few kilometers would be needed to improve the wind information data
base significantly. Other locations that could benefit from such a system would
be airports where the primary hazard is from clear air turbulence and downdrafts
that affect aircraft during takeoff and landings. Again only measurements with-
in the boundary layer or a little higher would be required. There are no doubt
other possibilities.

PREVIOUS WORK

Very little work has been done to date dealing directly with applicability
of the radars to the forecasting problem. BALSLEY and GAGE (1982) have discu-
sed considerations for implementation of an operational radar system including
antenna size needed, most favorable frequency ranges, and the type of power
needed. CARLSON and SUNDARARAMAN (1982) have made a preliminary case showing
that a few percent of the annual fuel consumption of the airlines could be saved
if data from a wind measuring radar network was available for flight planning
purposes. They indicate that a detailed study has to be made to determine if
their rough calculations of potential savings are correct. However, the savings
that they envision would be enough to justify the cost of a radar network within
the first year.

FUKAO et al. (1982) have made a detailed comparison of rawinsonde data from
San Juan, Puerto Rico and wind profiles measured with the Arecibo 430 MHz radar.
Twenty-six separate days from August and September of 1977 were involved in the
study. The comparison indicated a difference of 4.9 m/s in the upper tropo-
sphere and a difference of 3.3 m/s in the lower stratosphere. The difference in
the lower stratosphere could be explained by the experimental error in the raw-
insonde measurement, but the larger difference in the upper troposphere was ap-
parently due to spatial variations over the 80 km distance separating the two
sites.

LARSEN (1983) investigated the effect of high frequency meteorological
noise on the representativeness of the radar wind data. If one is interested in

using the data for input to a numerical model that can resolve synoptic and mesoscale motions down to scales of a few hundred kilometers, any motions with smaller scales are effectively just noise or an error in the measurement. The radar wind measurements from the Poker Flat MST radar were compared to the rawinsonde measurements from Fairbanks, Alaska, and both were compared to the geostrophic wind calculated by applying an objective analysis scheme to the standard radiosonde data from five nearby stations. By averaging the high time resolution radar data over intervals of several hours, the high frequency oscillations could be filtered out. The comparison showed that the radar and rawinsonde data agreed to within 2-3 m/s when the radar data were averaged over 12 hours or more, and that the difference between the radar winds and the geostrophic winds was about the same as the difference between the rawinsonde winds and the geostrophic wind. The two independent wind measurements were most similar, and both differed from the geostrophic wind by 1.5-2.0 m/s more than they differed from each other. The results indicate that it is crucial that the data should be averaged in some way if it is used as input to a numerical model. The errors decrease as the averaging interval is increased. Therefore, the acceptable error for a given model will have to be determined in order to know how to process the radar data.

LARSEN and ROTTGER (1983) have shown that a VHF radar can detect the location of frontal boundary surfaces as enhancements of the radar reflectivity. When coupled to the measurements of the horizontal and vertical wind components, such information would be of value in forecasting the development and position of fronts since such small-scale features are not resolved by the synoptic observing system or in operational numerical forecast models.

GREEN et al. (1978) showed the ability of the radar to detect changes in the jet stream height and intensity in real time, as well as gravity wave activity and vertical velocities associated with the jet stream. Turbulence intensity and location can also be determined along with the rate of turbulent dissipation (GAGE et al., 1978). The results are intriguing, and more work needs to be done in this area. One very interesting aspect of their study is that radar measurements may be used in the future to provide real-time inputs for the parameterization schemes used in numerical models. All processes in a numerical model with spatial scales smaller than the models grid spacing are parameterized. Such things as the vertical fluxes of heat and momentum due to convection and the loss of energy to subgrid scales are included in the parameterizations. The schemes used usually depend in some way on the physical quantities calculated by the model, but the high time resolution measurements of the radar, along with the vertical velocity measurements (e.g., ECKLUND et al., 1982), may provide valuable information on the actual magnitude of these various quantities as a function of time and location.

The most detailed investigation of the applicability of the radar technique to mesoscale forecasting is being undertaken by the Wave Propagation Laboratory of NOAA using their Profiler system (STRAUCH, 1981; STRAUCH et al., 1982). The Profiler uses several microwave radiometers to measure the temperature and humidity profile. A set of three Doppler radars distributed in a triangular network around Boulder, Colorado is used to resolve mesoscale features in the local winds. The system is dedicated to the problem of mesoscale forecasting. Except for results dealing with the measurement capabilities of the system and the corresponding accuracies, few results are available to date. However, the Profiler should provide a good assessment of potential improvements in mesoscale forecasting that can be realized with such a system.

OPTIMAL SPECIFICATION OF INITIAL DATA

Much of the discussion about using the MST systems operationally has focused on the WPL Profiler which uses a clear air radar for wind profiling. How-

ever, the system was designed to test the possibility of replacing the standard National Weather Service radiosonde. To this end, microwave radiometers are used to provide profiles of the temperature and humidity, though to date the achievable height resolution has been less than that of the radiosonde. It remains to be seen whether the difference is significant.

There is little doubt that the thermodynamic and moisture information is valuable, but in this case we should question whether the extra cost would be justified on a network-wide basis. The radiometers are by far the most expensive part of the system. The cost ratio between the Model T radar discussed here and the microwave system may be as great as 1 to 5 for an operational system. The estimated cost of a Profiler system has been given as approximately $500,000 (M. T. Decker, personal communication). CARLSON and SUNDARARAMAN (1982) estimate that a tropospheric wind profiling system, without the radiometers, could be built for 10% of that sum or less.

Will the wind information be useful in and of itself? The answer apparently is yes. Studies by RUTHERFORD and ASSELIN (1972), WILLIAMSON and DICKINSON (1972), HOKE and ANTHES (1976), DALEY and PURI (1980), DALEY (1980), and BUBE and GHIL (1982) indicate that at small scales the wind information is by far the most important. Small scales in this case are defined by a horizontal scale related to the Rossby radius of deformation. The various studies have used either analytic models or numerical models that characterize the dynamics of the atmosphere and considered the problem of how new information is assimilated into the model. The winds and the thermodynamic variables have been given as initial conditions singly and in combination. Updating the calculated fields with the pressure fields would eventually cause an adjustment to the input data, but the adjustment time would be long. However, the wind information is readily absorbed with a minimum of wave noise being generated. The pressure field then adjusts to reflect the changes in the wind field so that a complete set of information relevant to the small-scale motions is obtained even though only the wind fields are used as input. There seems to be agreement that wind information is more important for scales less than 1000-2000 km. At large scales the reverse is true, and the thermodynamic information is more important.

The physical reason for this effect is associated with the process known as geostropic adjustment and first described by ROSSBY (1938). The crucial parameter in the problem is the Rossby radius of deformation given by the ratio of the speed of sound, or the propagation velocity of gravity waves of the appropriate scale, to the Coriolis parameter (BLUMEN, 1972). At scales much larger than the Rossby radius, the wind field will adjust to balance a perturbed pres-u sure field. For scales smaller than the Rossby radius, the pressure field adjusts to balance the wind field. Therefore, the smaller the scale of motion that is of interest, the more useful is the wind information. Since the mesoscale lies in the range of spatial scales where the wind information is most useful, there may be a significant improvement in our ability to forecast for this scale even if only the wind fields are measured. SHAPIRO et al. (1983) also discussed the importance of wind information at small scales, and they indicate that improved spatial resolution may be obtained from the measurements of a single radar if the data are used to extrapolate quantities along air parcel trajectories.

CONCLUSION

This article was meant to suggest a number of possible applications for the MST radar technique in operational weather forecasting. The results to date have shown that there is great promise for the technique as part of the standard observing network once it is resolved to increase the resolution to include mesoscale motions. In reality, very little work has been done to date relating

to the forecast improvements that actually can be achieved with an operational wind profiling system. Forecast improvements due to a network of radars should be investigated both theoretically and experimentally. The possibility of using the radar data to refine some of the parameterization schemes used in forecast modeling should also be investigated. Finally, the applications of the radar systems to forecasting area-specific phenomena should be examined in the near future.

ACKNOWLEDGEMENTS

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