Better Local Weather Forecasts

Several years ago, the U.S. National Weather Service (NWS) tried to establish a National Profiler Network to provide humidity, wind and temperature information through the lowest several miles of the atmosphere, providing a critical continuous 3D view of the weather. The NWS planned to use this information to improve local high impact weather forecasting, as recommended by the National Academy of Sciences.

Due to budgetary restraints, NOAA subsequently terminated the contract after delivery of five wind profilers. However, the NWS is now purchasing humidity and temperature information from a commercial data services network[1], through its National Mesonet Program.

National Academy of Sciences

The U.S. National Academy of Sciences recommends more extensive boundary layer humidity, wind and temperature profile measurements to improve local high impact weather forecasting:

"*As a high infrastructure priority, federal agencies and their partners should deploy lidars and radio frequency profilers nationwide at approximately 400 sites to continually monitor lower tropospheric conditions. Humidity, wind, and diurnal boundary layer structure profiles are the highest priority for a network, the sites for which should have a characteristic spacing of ~125 km but could vary between 50 and 200 km based on regional considerations.*" [2]

"Federal agencies and their partners should deploy a national network of profiling devices for mesoscale weather and chemical weather prediction purposes. Such devices should incorporate capabilities that extend from the subsurface to 2–3 km above the surface level. The entire system of observations in support of mesoscale predictions should be coordinated, developed, and evaluated through test-bed mechanisms." [3]

National Mesonet Program

The NOAA National Mesonet Program Alliance (NMPA)[4] leverages existing non-federal environmental observation networks to supply hydrometeorological data to improve the NWS prediction of local weather, including high-impact storms (hurricanes, winter storms, floods, severe thunderstorms, and tornadoes):

"All NMPA mesonets are in geographic areas needed to serve the Weather Ready Nation mission of NOAA for the prediction of high-impact storms. There are surface mesonet observing networks,

[1] Boundary Layer Network operated by Earth Networks and Radiometrics.

[2] Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks, National Research Council, 2008.

[3] When Weather Matters: Science and Service to Meet Critical Societal Needs, National Research Council, 2010.

[4] NMPA includes 32 universities and private weather companies.

which are mostly non-federal automated weather stations that record temperature, wind, moisture, pressure, and precipitation at the surface, as well as observations of soil temperature and soil moisture, solar radiation, and road-surface temperature. Mobile platforms provide additional weather observation coverage along their transit routes between fixed stations. Vertical profilers provide temperature, wind, and/or moisture information at 68 locations."[5]

Microwave Profiling

Penzias and Wilson received a Nobel Prize for their discovery of Cosmic Background Radiation using a Bell Laboratory microwave radiometer. Later, NOAA began developing similar technology for atmospheric remote sensing (Figure 1).

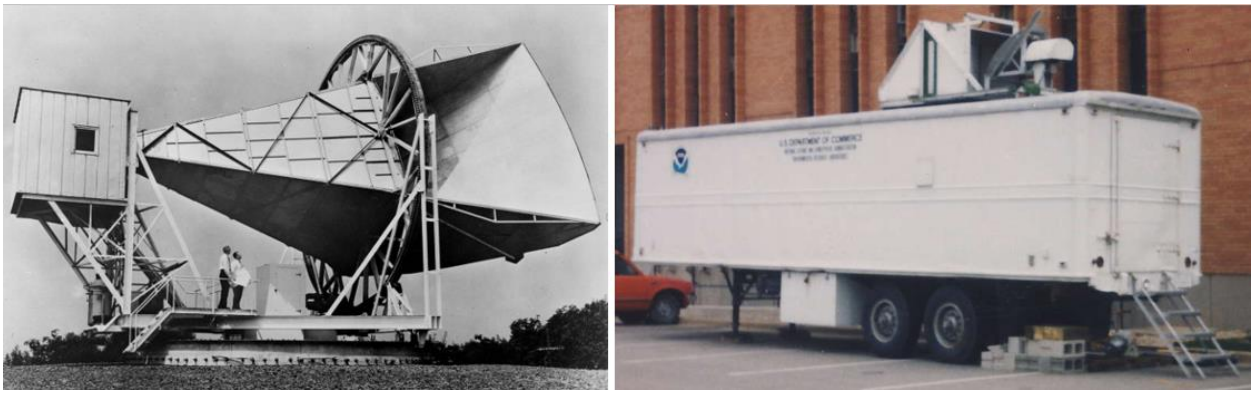

Figure 1. Microwave radiometers operated by Penzias and Wilson at Bell Labs (1968) for cosmology and by NOAA (1978) for atmospheric remote sensing.

NOAA developed temperature, humidity and wind profiler technologies in the 1980's[6]. During the following decade, NOAA supported commercialization of these technologies via Small Business Innovative Research (SBIR) contracts and Cooperative Research and Development Agreements (CRADA).

Radiometrics

A Commerce Department SBIR contract supported NOAA microwave profiler technology commercialization via Radiometrics Corporation thirty years ago. Radiometrics, a Colorado company, is the world leader in the microwave radiometer market with more than 300 units sold worldwide. A Radiometrics microwave profiler is shown in Figure 2.

[5] National Mesonet Program Alliance, 2015.

[6] Automatic Profiler of the Temperature, Wind and Humidity in the Troposphere, Hogg et al, JCAM, 1983.

Economic Impact

The economic impact of local high impact weather for utilities, wind energy, water management, transportation, agriculture, construction and other U.S. industries totals tens of billions of dollars per year -- better forecasts of these events would provide greater productivity and reduced costs[7].

Figure 2. Radiometrics microwave profiler.

Data Requirements for Better U.S. Weather Forecasting

The current NWS radiosonde network cannot cost-effectively support the improvements needed to produce advisories and warnings in a timely manner. The radiosonde network has evolved from technology that is more than 70 years old and for the most part makes observations only twice daily. However, in today's world, there is increased emphasis on continuous up to date measurements. Thus, to meet the growing urgent need for improved high-resolution localized Nowcasts (up to 2 hours) and short-term forecasts (2 to 12 hours), upper air remote sensing technologies are needed that can provide much more frequent automated observations. Crucial atmospheric measurements are required several times an hour at geographical scales more dense than today -- at least twice as dense as a minimum. The benefits of this strategy were shown in the early 1990s when a 33-site national wind profiler network was implemented in the Midwest. These continuous wind observations have provided demonstrable improvements in severe weather forecasting[8], but the network is approaching obsolescence and urgently requires replacement, and enhancement with the latest remote sensing technologies.

Crumbling Barriers to Widespread Deployment

Current commercial microwave profiler pricing is much less than the annual cost for expendables and labor for twice-daily radiosonde launch operations at each of more than one hundred NWS radiosonde launch stations[9]. These instruments require modest maintenance and demonstrate long lifetimes. The first microwave profiler sold by Radiometrics was purchased by the German Weather Service in 1998. It has been in nearly continuous operation since that time; subsequently more than two hundred have been sold and are in service worldwide. Maintenance and repair costs are modest, with procurement and operating costs totaling less than 10% of traditional twice-daily radiosonde costs.

[7] Economic Sensitivity to Weather Variability, Lazo et al, BAMS, 2011.
[8] The Value of Wind Profiling Data in U.S. Weather Forecasting, Benjamin et al, BAMS, 2004.
[9] NOAA Upper Air Observations Program

Public and private microwave profiler networks are emerging in the U.S. (32 BLN[1] and NYSM[10] sites), India (20 sites), Japan (10 sites) and Korea (15 sites). In addition, more than 60 individual Radiometrics MP-3000A profilers are operated in China, with planning underway for a 200-site national network. In Europe, a network of ground-based remote sensing instruments are operating, including 30 microwave profilers (Figure 3).[11]

Figure 3. European ground-based microwave radiometer network. [12]

Microwave profiler cost-benefit is improving via advancement of assimilation methods that optimize data impact in numerical weather modeling[13] and automated calibration methods[14] that minimize maintenance cost.

Case Studies

Microwave profilers detect humidity convergence and atmospheric instability in early stage convection hours before a developing storm is detectable by radar.

Deadly Thunderstorm

A severe thunderstorm produced devastating 100 mph winds in the Washington, D.C. area in June 2012. It resulted in 22 deaths, with widespread damage that left millions without power for up to five days.

Earth Networks operates the Boundary Layer Network (BLN) including a station 15 km north of Washington, D.C., at Germantown, MD. The BLN provides continuous boundary layer

[10] New York State MesoNet
[11] Exploiting existing ground-based remote sensing networks to improve high resolution weather forecasts, Illingworth et al, BAMS, 2015.
[12] MWRnet -- different flag colors represent different radiometer types.
[13] MWR brightness temperature assimilation with 1D-Var, De Angelis et al, COST-TOPROF, 2015.
[14] Joint Microwave Calibration, Pospichal et al, COST-TOPROF, 2015.

temperature and humidity profiles with radiosonde-equivalent accuracy. BLN temperature, humidity and liquid water profiles to 1 km height are shown in Figure 4. More than eight hours before arrival of this destructive storm, BLN-derived forecast indices showed extremely unstable conditions (panel 2 magenta line: CAPE = 5,000 J/kg at 16:00 Z) capable of producing 100 mph winds (panel 3 black line: Windex = 80 knots)[15]. In contrast, forecast indices derived from 12-hr radiosonde soundings (stars, Figure 4) provided less than two hours advance warning.

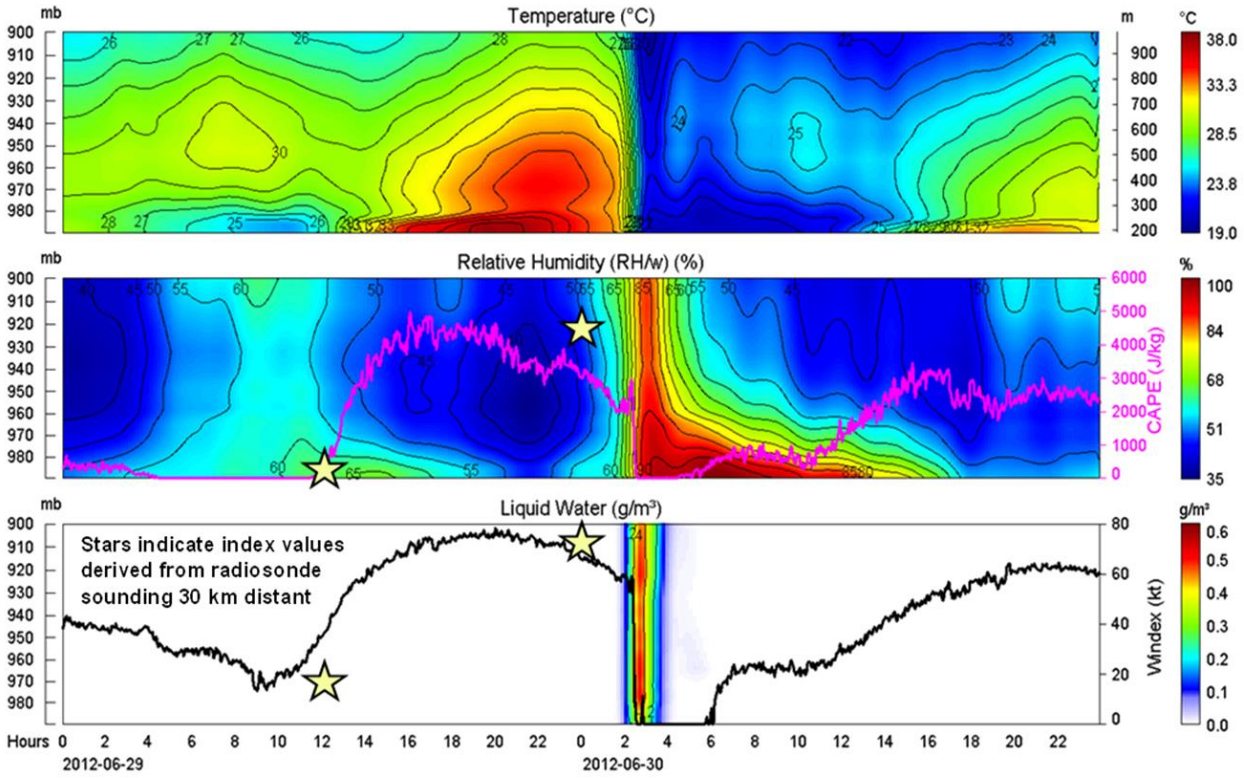

Figure 4. Radiometer and radiosonde (stars) observations preceding a deadly thunderstorm.

This case study illustrates the promise for severe storm forecast improvement based on continuous boundary layer radiometric profiling.

Lightning Advisories >2 hours in Advance

Electric field measurements are widely used at space launch facilities to generate lightning risk alerts. When the electric field gradient exceeds a threshold value (e.g. 1 kV/m) a launch is postponed or cancelled due to high lightning risk. Simultaneous collocated electric field and radiometer observations are shown in Figure 5, on a day that included a local lightning producing thunderstorm. The red arrow in the top panel marks the time (16:20) that the electric field gradient exceeds 1 kV/m, leading to launch cancellation. The red arrow in the bottom panel marks the time (12:00) that the radiometer data would trigger launch cancellation – more than four hours in advance of the traditional electric field method.

[15] Thermodynamic observations of the June 2012 Derecho, Novakovskaia et al, AMS, 2013.

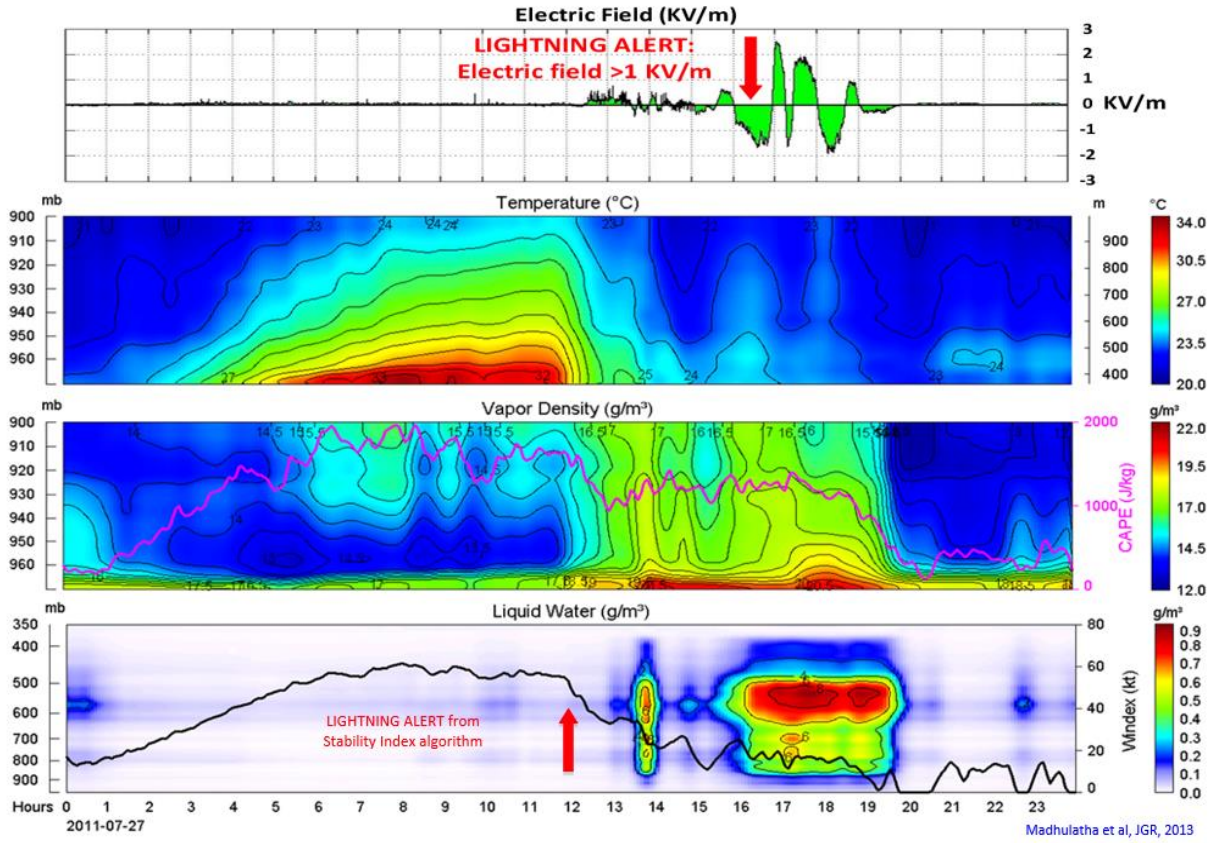

Figure 5. Radiometer-derived lightning advisory more than 2 hours in advance[6].

Comparison of side-by-side radiometer and electric field gradient sensors during more than ten lightning producing thunderstorms led to the conclusion that continuous microwave profile data *"can be used effectively to predict the occurrence of thunderstorms at least 2 hours in advance"*[16] -- before they are visible to the eye or radar. This capability is used by the Indian Space Research Organization at their Sriharikota launch facility.

Green Technology

Microwave radiometry is green. It avoids expendables required by radiosondes (balloons, helium, met sensors and radio transmitters), is used for utility electric load, wind and solar energy forecasting, and is used to augment water supplies and hydropower via weather modification.

Figure 6. Accurate fog forecasts can reduce electricity costs.

[16] Nowcasting severe convective activity over South-east India using ground-based microwave radiometer observations, Madhulatha et al, JGR, 2013.

Electric Load Forecasting

Microwave profiler data are used by California utilities to improve electric load forecasting (Figure 6). The price of electricity in inter-utility trading varies by more than an order of magnitude depending on demand. The marine layer has a strong influence on electricity demand. When the marine layer burns off in densely populated coastal regions, a sharp increase in air conditioning electric demand is common. Radiometer measurements of marine layer liquid can improve burn off time forecasting. A modest 10% forecast improvement corresponds to ~$20M in annual electricity cost savings[17].

Wind and Solar Energy Forecasting

Microwave profiler data are used by utilities to improve wind energy forecasting. Wind energy production is strongly dependent on boundary layer turbulence. Turbulence measurements by radiometers are used operationally to improve wind energy forecasting[18]. In California, a modest 1% improvement in wind energy forecasting would save ~$20M in annual electricity costs[17].

A team including Southern California Edison, the U.S. Dept. of Energy and the University of California are operating microwave profilers for wind energy forecasting at Tehachapi, California (Figure 7). The team is also purchasing microwave profiler data services from a commercial data services network[19].

San Diego Gas and Electric operates two mobile thermodynamic and wind profilers to improve forecasting of Santa Ana winds that caused massive wildfires with multi-billion dollar damages (Figure 8). In the off-season the mobile profilers are moved to urban coastal areas for marine layer fog and solar energy forecasting.[20]

Figure 7. Radiometer data can improve wind energy forecasting.

Figure 8. Mobile profilers used for high wind and solar energy forecasting.

[17] Marine Layer and Wind Energy Data Services, Boundary Layer Network Internal Document, 2012.

[18] Hawaii Electric Company (HECO) uses radiometer data to improve wind energy forecasting at various wind farms in the Hawaiian Islands. Electric utilities, DOE and universities are using microwave profiler data in California and Oregon to improve wind energy forecasting.

[19] EN-RDX Boundary Layer Network

[20] Channel 10 News, SDG&E Unveils High Wind Warning System, 2015.

Weather Modification

Aircraft and ground-based cloud seeding enhances precipitation by distributing microscopic condensation particles into low temperature clouds. Microwave radiometers are used to identify cloud seeding targets for utility and water district weather modification programs in California, Idaho, Texas and Wyoming, and in Asia, Europe and Africa. Aircraft cloud seeding flares and one of four radiometers in use by Idaho Power Company are shown in Figure 9.

Figure 9. Idaho Power Company cloud seeding aircraft and one of its four radiometers used to target seeding opportunities.

Snow water augmentation consistent with winter orographic cloud seeding operations in the southern Sierra Nevada Mountains is shown in Figure 10.[21]

The Colorado Water Conservation Board is using radiometers to optimize ground-based cloud seeding operations[22].

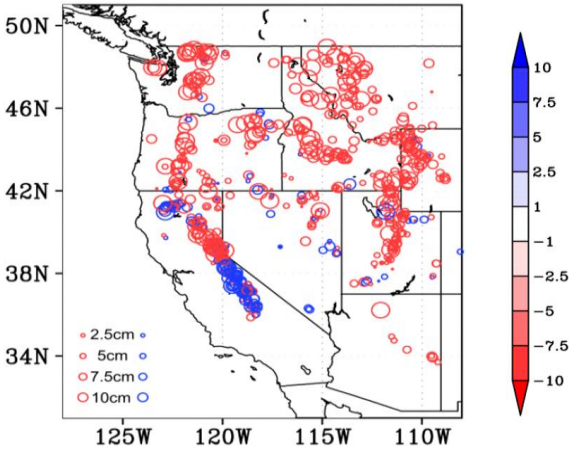

Figure 10. Snow water increases (blue) in cloud seeding areas (Mote et al, 2015).

New York State Mesonet

In January 2014, the Department of Homeland Security established the New York State Early Warning Weather Detection System. The centerpiece of the system is the New York State Mesonet (NYSM)[23], a network of 125 weather stations across the state, with at least one site in every county. Each site will measure temperature, humidity, wind speed and direction, pressure, radiation, and soil information.

[21] Superensemble regional climate modeling for the western US, Mote et al, BAMS, 2015.
[22] Inventory and Assessment of Colorado Weather Modification Programs, Wilson Water Group, 2015.
[23] http://www.nysmesonet.org

A special subset of 17 enhanced stations will provide additional atmospheric data in the vertical (up to 2 miles above ground), flux (the amount of heat and moisture exchange near the ground) and snow depth information. The enhanced stations will be equipped with thermodynamic (radiometer) and wind (Lidar) profilers, providing weather information through the lowest several miles of the atmosphere, providing a critical continuous 3D view of the weather.

The NYSM weather data feeds an advanced warning system with the potential to save billions of dollars by facilitating rapid response to catastrophic weather events.

Renewable Energy. The New York State Mesonet will enable cheaper renewable energy production across the state through improved wind and solar climatologies, more accurate short-term forecasts, and more reliable data for enacting mitigation activities.

Agriculture. Agricultural applications of the Mesonet include improved insect and disease advisories, spraying recommendations, irrigation scheduling, frost protection, planting and harvesting recommendations and prescribed burn advisories.

Weather. The Mesonet will provide continuous, 3D imagery of the weather, allowing more accurate, more reliable forecasts and decision-making.

Emergency Management. Emergency managers will have access to immediate weather information across urban and rural New York, making for safer, more effective disaster preparation and response.

Industries. Data from the Mesonet are expected to save millions of dollars through more efficient, more cost-effective road weather mitigation, aviation services, agricultural practices, and energy production.

Research and Education. As an “end-to-end” system, the New York State Mesonet provides a truly unique learning environment, with research activities ranging from the physical sciences (climate, micrometeorology, instrumentation, numerical weather prediction) to computer science, mathematics, economics, and sociology. These activities are expected to stimulate further advancements in high impact local weather forecasting.

Realization of a National Profiler Network

It is widely acknowledged that a national-scale profiler network providing a continuous 3D view of the weather through the lowest several miles of the atmosphere is needed to provide better weather forecasts. The failed NWS attempt to establish such a network, and its subsequent success in obtaining these crucial data as a commercial data service, provide a promising path (similar to the privatization of satellite digital imaging) toward realization of a national profiler network in a timely and cost-effective manner.