Non-traditional Approaches to Weather Observations in Developing Countries

John T. Snow, PhD, CCM
Principal, Snow & Associates
and
Regents’ Professor of Meteorology
The University of Oklahoma
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Preface

The Group of 20 (G20) nations increasingly recognize the importance of green growth, and many countries are demonstrating strong leadership through effective and progressive policies. However, governments do not act alone—the private sector is an important partner, providing new technologies, business models and investment opportunities across a variety of sectors to help scale up transformation. In 2012 the G20 Development Working Group commissioned the International Finance Corporation, as the largest development finance institution dedicated to private sector development with a strong emphasis on sustainability, to take stock of mechanisms to mobilize private capital, including from institutional investors, for inclusive green growth investments in developing countries. This work is intended to inform the creation of a public-private G20 Dialogue Platform on Inclusive Green Investment.

As part of this effort IFC commissioned a series of supporting documents and materials, including this publication, specifically created as underpinning material to inform the final synthesis report produced by IFC for consideration at the G20 meeting in St. Petersburg in 2013. These publications can all be found at www.ifc.org/Report-MobilizingGreenInvestment.

This paper discusses a selected set of high-end, but relatively low-cost technologies, some well established and some just emerging, that have the potential to overcome many of the traditional barriers to weather observation in developing countries. The new approaches build on the rapidly growing, extensive cellular telephone networks increasingly available even in rural areas as a foundation allowing for a combination of some or all of the following elements:

- The use of cell phone towers as sites for weather observing stations, utilizing telecommunications company staff to install and maintain necessary equipment.
- Deployment of a new generation of low-cost, durable sensing systems appropriate to local conditions that require minimal maintenance and calibration, and can provide automated information via the cellular phone networks.
- Development of innovative public-private partnerships between national weather agencies, national and/or regional telecommunication companies, and international commercial/private sector instrument manufacturers and data services to plan, implement, operate, and maintain an observing network.
- Development of business models based on the value of weather information, which help cover the costs of system operation and maintenance.
Introduction

In many developing countries, given their poor economic circumstances, weather observing networks are usually installed using funds from international development and aid agencies to enhance the capability of local National Hydro-Meteorological Services (NHMS) and to accomplish humanitarian objectives. Such networks can be of great importance because they provide a wide range of data: periodic observations of standard meteorological variables such as temperature, atmospheric moisture, wind, and precipitation; radar reflectivity and Doppler velocity; three-dimensional paths of lightning discharges; and blowing sand and dust. These data are the foundation of meteorological products and services. Such networks almost always consist of stand-alone automatic weather stations operated by personnel of the NHMS. Unfortunately, all too often, these networks have failed to provide the desired data for more than brief periods following installation due to a variety of adverse factors (some of which are discussed below), leading to disappointment on the part of the NHMS, the local government, and international funding agencies.

This paper discusses non-traditional approaches for establishing sustainable weather observing networks in developing countries, beginning with a brief overview of the importance of data from such networks to a NHMS. Some of the challenges inherent in establishing and maintaining weather and climate observing networks in developing countries are described. This is followed by a discussion of how these challenges might be addressed through the development of weather observing networks based on facilities and capabilities of the local cellular telephone network, such as the open lattice tower pictured in the background of the cover photograph.

The paper then reviews and summarizes currently available scientific, technical, and commercial literature regarding use of cell phone towers as observing sites. It provides a few illustrative examples of non-traditional technologies well-suited to making cell-tower-based observations. Other new technologies that could complement or supplement a cell-tower-based network are briefly described. As part of this discussion, a recent largely unsuccessful effort in east Africa—the Weather Information for All (WIFA) initiative—is discussed from a lessons-learned perspective. Finally, some remarks are included regarding the importance of training.

The paper concludes with recommendations concerning how one might work with NHMSs in developing countries to improve the sustainability of their observing networks. These recommendations are focused on partnerships, in the sense of true business relationships, involving the NHMSs with, for example, local telephone companies, other in-country utilities, and commercial/private sector instrument manufacturers and data services.
Continuous collection, analysis, assimilation, and archiving of observations made at fine spatial and temporal scales are necessary to monitor the four-dimensional evolution of a region’s weather. Such data are necessary for a NHMS to provide locally valuable weather and climate services, such as warnings of imminent severe or hazardous weather conditions, or seasonal outlooks for those in agriculture to maximize the nation’s production of food and other natural products. The weather observing networks that collect such data become a critical part of the national infrastructure, providing basic weather and climate information, and daily forecasts and climate outlooks of fundamental importance for farmers, insurers, utilities, aviation, and many other businesses.

*Developed countries* deploy a wide variety of technologies to observe the weather at a range of spatial and temporal scales:

- **From the surface**, numerous technologies probe and observe the atmosphere from the bottom up. These include stand-alone automatic weather observing stations, lidars, acoustic sounders, radiometers, lightning detectors, air quality and chemistry samplers, and vertically profiling and surveillance radars, to name just a few.

- **Within the atmosphere**, observations are made from instrumented tall towers, pilot and other drifting balloons, instrumented tethered balloons (aerostats), rawinsonde systems, and measurements from manned and drone aircraft. The properties and chemistry of the upper atmosphere are probed using sondes (an integrated electronics package of measuring and geolocating devices and radio transmitters) launched with small rockets. The data from the rawinsonde systems are particularly important as they are primary

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1 Each of the four elements—collection, analysis, assimilation, archiving—has its own complexities and challenges. While the last three elements are discussed briefly, here the focus is on “collection of observations,” which is taken to include measurement of atmospheric quantities with appropriate sensing devices, resulting in the production of data; transmission of that data to a central collection point; and quality assurance/control (QA/C) of the values received.

2 A rawinsonde system is a “radio wind sounding system.” Until recently, to obtain wind speed and direction, these systems tracked a radio transmitter borne aloft in a small package suspended beneath an ascending free balloon (a “sounding”). Under good conditions, the balloon can rise to over 35 kilometers, well into the lower stratosphere. Radio tracking, while still done, is being supplanted by precision GPS coordinates reported by the radio transmitter. Instruments in a standard package measure temperature, moisture, and pressure as the balloon ascends, and report the values through time via the same radio transmitter. Per WMO guidance, balloons are launched twice per day, at 00 Z and 12 Z (Z-time is equivalent to Greenwich Mean Time).
inputs to numerical weather prediction\(^3\) (NWP) systems.

- **From low-earth or geo-synchronous orbits**, numerous radiometric, radar, lidar, and visual sensors on satellites probe and observe the atmosphere from the top down. Satellite platforms also carry much of the communications load involved in collecting observations and distributing the resulting weather and climate information.

The data streams obtained from networks of these diverse observing systems are brought to a central point. There they are subjected to rapid QA/C and merged with similar data from surrounding countries, followed by analysis and assimilation.

Analysis and assimilation of the collected observations produce digital fields and graphics describing the region’s current weather. Such descriptions are of value in their own right for many purposes, such as monitoring weather for the onset of hazardous conditions and supporting transportation systems. They also are essential for skillful forecasting of future conditions, particularly in the short range 0- to 12-hour period\(^4\), and are necessary to assess the skill of previous forecasts.

Further, archiving\(^6\) of weather observations produces climatological databases. Subsequent analysis of long duration time series of high-quality weather observations drawn from these databases will reveal and characterize Earth’s climate on local and regional space scales and seasonal and inter-annual time scales.

For deployment of many of these observing systems and for the utilization of the resulting streams of data, the NHMSs of developed countries establish and follow detailed policies and procedures that reflect long local experience and international standards laid out in technical memoranda of the World Meteorological Organization (WMO).\(^7\) These policies and procedures also take into account the requirements of other international agencies that certain types of observations be routinely available, such as the International Civil Aviation Organization (ICAO) for the support of international airport operations.

Given that weather and climate do not recognize geopolitical boundaries and that many nations are relatively small in size compared to the areas influenced by various types of weather systems, the NHMSs of developed nations long ago began routinely sharing weather data of all types. Today a global telecommunications

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3 While simple NWP models can be run on personal or laptop computers, the large global NWP models used to support modern weather forecasting require state-of-the-art supercomputers and extensive supporting staffs. About a dozen nations around the world have made the large (and continuing) investments necessary to develop, run, and maintain NWP models in an operational setting.

4 0- to 1-hour forecasts are often called **nowcasts**. These anticipate what weather will occur at a location over the next few minutes out to one hour. Often the nowcasting goal is to detect and then warn of the imminent onset of severe weather.

5 Skill in weather forecasting is a scaled representation of forecast error that relates the accuracy of a particular forecast to some reference. Common references are climatology and the average or consensus forecast of an ensemble of numerical weather prediction model outputs.

6 Archiving is the systematic accumulation of the collected observations and associated metadata against long-term needs. The result of systematic archiving is climatological databases.

7 The standards, policies, and procedures of the developed nations are taught to weather observers and forecasters worldwide through WMO regional training programs and the in-house schools of the NHMSs in the United Kingdom, France, Finland, and elsewhere. The WMO regional programs are the primary sources of basic training for the staff of NHMSs in developing nations. The in-house schools of the NHMSs in developed nations provide much of the advanced professional development for staff from developing countries.
network managed by the WMO shares observations, output from numerical models, and forecasts around the world. However, while valuable to the NHMSs in developing countries, this global sharing of meteorological information is not a substitute for local weather and climate observation. To have local impact, a NHMS needs a national observing system to monitor local conditions that can evolve rapidly and to produce forecasts that address the small but important details of the national environment.

Finally, NHMSs in developed countries often have experienced administrative, engineering, and technical staff to oversee the acquisition, installation, maintenance, and calibration of their weather observing networks. The operational staff is usually well trained and has opportunities for continuing professional development, which provides the knowledge and skills necessary to apply the data streams to improve weather forecasts and climate outlooks.

Just as in developed countries, developing countries need weather observing networks to accomplish their missions: meeting the local needs for warning of severe weather, promoting
economic growth, and supporting the activities of their nation’s citizenry. However, the NHMSs in most developing countries lack weather observing networks that routinely provide data of the necessary quality, and spatial and temporal density. The hydrometeorological services in most developing countries are able to establish and sustain only the most basic of observing networks.

Some of the NHMSs of developing countries do maintain limited surface observing networks built around airports and/or other national infrastructure, such as dams and hydroelectrical generation facilities. Usually these observations are made with equipment identical to that used by the NHMSs of developed nations. Further, a few NHMSs of developing countries have also been able to sustain the routine launching of rawinsonde systems to make measurements in the upper air, but most have not. In addition to a shortage of trained personnel to make the observations, limited finances often prevent the regular procurement of the expendables required for each launch. In some cases, developed nations have been subsidizing the rawinsonde programs in developing nations. (See Parker et al. 2008 for a discussion of the decline of the rawinsonde network in Africa.)

Since they do not have comprehensive weather observing networks, the NHMSs have to rely on forecast information provided by developed nations via the global telecommunications network. Some NHMSs also make use of imagery and other products received via downlink from satellites launched by the developed countries. In either case, the NHMSs of developing nations have little say with respect to the information they receive in this manner and so must make do the best they can with what is provided. While using such global data allows the NHMSs of developing nations to provide basic general forecasts, they do not provide the local perspective essential for storm warning or fine-scale forecasting.

We explore in the next section in more detail the challenges that NHMSs in developing nations must address when setting up weather observing networks.
Challenges to Establishing and Sustaining Weather Observing Networks in Developing Countries

While each NHMS of a developing country faces challenges unique to its own situation in establishing weather observing networks, there are common factors that impact most such NHMSs. The most frequently cited common challenges are limited (often very limited) budgets, and the lack of technical infrastructure and associated expertise. Successfully establishing and sustaining weather observing networks in developing countries requires that these financial and technical challenges be addressed. (There are also challenges due to political and socio-economic issues, including corruption, civil war, and poverty, but those will not be covered here.)

Let us briefly touch on technical issues. All too frequently, attempts to meet the weather observing needs of developing countries by deploying observing equipment commonly used in developed countries usually result in networks that perform poorly and quickly prove to be unsustainable. This is due in part to the design of the equipment and in part to the lack of supporting infrastructure. Equipment in networks deployed in tropical or arid environments experiences especially harsh environments. Unfortunately, such environments are characteristic of many of the least developed countries, such as those in equatorial and Sub-Saharan Africa.

Designers of meteorological equipment intended for long-term use in tropical or arid regions must consider factors that often are minor considerations in equipment intended for mid-latitude environments. For example, in the warm, moist tropics, moisture and mold can destroy wiring and electrical assemblies. In arid areas, sand and dust will invariably find ways into bearings, switches, and electro-mechanical devices. Blowing sand can strip away protective coatings and accumulate inside many enclosures. Small rodents, snakes, insects, and birds can damage wiring and jam mechanical devices. The intense sunshine in some areas can drive temperatures inside sealed electronics enclosures to very high levels, causing electronic components to fail rapidly. Rain gauges and wind measuring devices are particularly difficult to design for long-term, low-maintenance operation in such environments.

All these design issues have solutions that can significantly increase the operational life of equipment in harsh environments. Unfortunately, those solutions often add significant cost to an instrument.

The situation is further exacerbated by the fact that most of the technologies that comprise the weather observing networks of developed countries are designed with the implicit assumption that there is an extensive supporting infrastructure that provides physical security; high-quality electrical power that is continuous and constant in both voltage and frequency; and secure wide-bandwidth telecommunications. In addition, it is assumed that there is a well-trained technical staff with
the tools and expendable supplies necessary to carry out proper maintenance, calibration, and other logistic support. In tropical and arid regions, the need for maintenance can be especially extensive, entailing more frequent changes of batteries, filters, and special lubricants, and replacement of bearings and wiring. Finally, it is often taken as a given that the NHMS of the wealthier developed nations can easily replace equipment on a routine basis.

All too often, the technical challenges briefly described above are ignored or addressed in only limited fashion in developing countries, resulting in observing networks that perform poorly and quickly prove to be unsustainable.

With respect to the fiscal challenges, because of a limited budget, the NHMS of the typical developing country usually has minimal equipment, expendable supplies, or technical staff. For example, some NHMSs have only one or two staff members dedicated to IT support. These individuals all too often have a limited capability to install and maintain personal-type computers and basic e-mail systems, much less maintain a server farm, work stations, or data ingest/NWP systems.

**FIGURE 2: A Developing Country NHMS Facility**

An example of a present-day computing facility to be found in a NHMS of a developing country. Photo credit: anonymous.
The NHMS of a developing country almost always has to rely on an external agency for the funding required to obtain and install a modern weather observing network. However, even when external support is obtained, the NHMS may lack the administrative and engineering expertise needed to successfully acquire advanced observing technologies and oversee their installation. All too often, the NHMS has to rely heavily on contractor claims regarding system performance, installation, and sustainability. When this situation is coupled with a selection process that emphasizes “lowest bid” in lieu of demonstrated prior performance in the environment of the region, it should be no surprise that newly installed observing equipment fails to operate properly long enough to have the impact anticipated by all concerned.

Additional challenges come following installation of the observing network, when the funding agency and the installing contractor have left the scene and the NHMS becomes responsible for routine operation and maintenance. In many cases, continuing external support is required to sustain the operation of a network (for a specific example, see the caption of the preceding image of a rawinsonde launch in Africa).

The technological infrastructure that is present in the typical developing nation is often concentrated in the larger urban centers and often in a few narrow sectors of the local economy. It is usually well beyond the fiscal means of NHMSs in developing nations to acquire locally or from abroad the services or skills needed to install and maintain advanced observing technologies. This is particularly the case when the equipment is deployed in rural areas, well away from urban centers.

Further, operational staff of NHMSs in developing countries may have limited or no in-house training or professional development opportunities to acquire the new knowledge and skills required for obtaining value from the new data streams. Training provided by contractors deploying the network is valuable, but it generally addresses the fundamentals of operating the system while giving short shrift to operational applications. All too often, a last-minute crash effort is made to train the staff to minimal competency just as the system is accepted from the contractor.

As an additional consequence of these challenges, a NHMS in a developing country often finds itself in a classic chicken-and-egg situation. Because it is unable to sustain weather observing networks, it is unable to provide products and services that contribute significantly to the development of the nation. Thus, the NHMS is often not valued and so receives little consideration for additional government funding.

While warranty services help with initial maintenance, they generally do not prepare NHMS staff to properly maintain a system once the warranty ends. Extended maintenance contracts are often not available or, if available, can be too expensive for the NHMS. The costs of spare parts (which usually have to come from the original manufacturer) and expendables can also become very expensive.
Meeting The Challenges

4.1 Non-traditional but Viable Approaches

Some non-traditional approaches to meeting some of the challenges to establishing and sustaining weather observing networks in developing countries include:

- Leveraging cellular telephone networks as the foundation for a backbone weather observing network (outlined here, discussed in more detail in the following sub-section). Such leveraging offers the NHMS opportunities to address deployment and maintenance issues and can provide long-term sustainability of the observing networks.

- Making cellular telephone network towers (hereafter “cell towers”) the locations of choice for a national network of automatic weather observing stations. Instruments can be either on the tower or in the security area at its base.

- Utilizing the communications network that supports the cellular telephone network as the means to collect observations and to return weather and climate information to users.

- Utilizing the technical staff of the telephone company to install and maintain the observing equipment.

- Developing novel public-private sector partnerships involving the NHMS, other government agencies, telecommunications companies operating in the nation, and commercial weather companies to plan, implement, and operate the cell-tower-based network suggested above.

- For the NHMS to leverage the investments in the cellular telephone network made by the telephone companies, business models are needed that provide a “win” for all parties concerned, including nearby residents who will benefit from enhanced local environmental information. As discussed in more detail in the final section, such business arrangements will need to involve private instrument manufacturing companies, national telecommunications companies, and international aid organizations.

- To ensure “ownership” of the network, it is essential that the NHMS play a co-leadership role and be involved in the establishment of the network from its earliest stages.

- Utilizing sensing systems that:
  - are designed specifically for the environment in which they are to be deployed;
  - can be installed on or co-located with cell towers; and
require only limited maintenance and calibration.
- Employing other complementary or emerging technologies. The following three examples are described in a later section:
  - Obtaining soundings from instrumentation on commercial aircraft.
  - Using smart phones as weather observing systems and for dissemination of weather information.
  - Deploying networks of small X-band radars where active sensing is needed.
- Making training and professional development of operational staff a top priority, while ensuring that such staff members are subsequently retained and properly utilized. When new equipment is involved, ensuring that training is accomplished in parallel with the deployment of the equipment so that those trained can immediately make use of their new knowledge and skills.

## 4.2 The Spread of the Cellular Telephone Network

The key element proposed here—but not offered as a complete solution—is leveraging of local cellular telephone networks to develop a backbone observing network (see discussion of business models that follows). Such an approach is viable in large part due to the rapid rate at which cellular telephone networks are spreading across the globe. In developing nations, the cellular phone has become a “leap frog” technology. Such nations will almost certainly never have a hardwired telephone network. Everywhere there are people, cell towers are becoming ubiquitous.

To meet the growing demand for cellular service, telephone companies are installing new cell towers all across the landscape. Even rural areas are rapidly receiving cellular telephone coverage. Populated areas often have several different telephone service providers. While there will likely remain areas without cellular telephone coverage for some time to come, these are almost certainly remote areas with few inhabitants.

As for-profit ventures, the telephone companies have strong incentives for maintaining the functionality of the equipment supporting the services they provide. They have the cash flow to provide security, reliable electrical service, and wide bandwidth connectivity at each cell tower. The companies also have trained electronics and mechanical staff to properly install and maintain the equipment at each cell tower site.

In addition, some report observing a new phenomenon in Africa—the development of small, local economies around cell towers. This is similar to the appearance of towns around railroad stations during the development of the American West. These emerging communities are ensuring this local asset is secured because access to information via the cell network brings jobs, economic development, and access to communication to all in the village.

## 4.3 Standardization and Representativeness

All technological and business approaches have associated issues and risks. Two such issues that arise with the non-traditional approach discussed here—cell-tower-based observations—concern “standards” for observing equipment and “representativeness” of the observing sites.

As mentioned previously, many of the staff members in the NHMSs of developing countries have been trained in WMO regional training centers and/or the in-house schools of some of the larger NHMSs of developed countries. The instruction emphasizes the WMO guidelines (or developed country NHMS policies and procedures consistent with those guidelines) for
observing networks. Over the years, the WMO guidelines have taken on the characteristics of rigid standards for observing equipment and network sites that must be rigorously followed by all NHMSs in weather observations.

Given that almost all meteorological equipment is designed and manufactured in developed nations in the mid-latitude regions of the world, it should not be surprising that the WMO guidelines have come to reflect the characteristics of that equipment. This situation has had several unintended but negative consequences. One is a strong tendency toward preserving the status quo; development of novel or non-traditional measurement technologies is discouraged due to lack of market. Another is that the NHMSs of developing countries are very reticent to invest in non-traditional observing technologies that may be more appropriate to their situation.

A better approach for the WMO (and by extension, the NHMSs in both developing and
developed countries) would be to focus on the quality of the data produced by observing systems rather than the details of particular instruments. As noted previously, NHMSs in developing countries need local observations to accomplish their missions. As long as a technology provides good quality data and is sustainable, it should be considered for deployment. One could envision that by taking this approach, NHMSs in developing countries could adopt “leap frog” technologies in parallel with what is happening with the cellular telephone networks.

Similarly, picking weather observing sites that are “representative” of the wider area is strongly emphasized in the training programs of developed nation NHMSs, and the WMO. It is largely a holdover from the days when “meteorology” was synonymous with “synoptic meteorology.”

In the approach discussed here, the sites will reflect the telephone company’s need to provide cellular coverage adequate to meet the needs of the company’s customer base. Thus, few cell tower locations likely meet the criteria of traditional “representativeness.” However, one can argue that an observation taken in a place where people live, work, and play is more representative in the modern world than one taken far afield and presumably primarily used to tune some NWP type of process to make general improvements in a regional or global forecast. Local observations, such as those taken at cell towers, can bring weather data directly into the lives of the surrounding community. Few NHMSs in developing countries run their own NWP systems. Their forecasting systems typically are built around using model output statistics (MOS) on NWP products generated elsewhere. A MOS-based near- and medium-range forecast system can be substantially improved if local observations are used in the selection, verification, and fine tuning of the statistics for a community where those observations are taken. It can be strongly argued that an observation at a local cell tower—specifically placed by the mobile telephone companies to serve people where they live, work, and play—is actually better positioned to bring high-quality data to the public when and where

**FIGURE 4: Cell Phone Coverage Across Sub-Saharan Africa**

Note: Table and map illustrating the spread of cell phone coverage across Sub-Saharan Africa during the period 2000 to date, and projected for the next three years. All indications are that this rapid spread will continue for some years to come. Figure from Len Rosen’s blog, 21st Century Tech. entry for 24 December 2012, In Pursuit of a Global Technical Society, to be found at http://www.wfs.org/blogs/len-rosen/pursuit-global-technical-society-21st-century-tech-blogentury-tech-blog.
people need it. It is more “representative” in that sense, than the way meteorologists have been trained for decades.

Given the training the staff members of the NHMS have received in the past, there is likely to be some reluctance by the NHMS to a cell-tower based observing system. This reluctance can be overcome in part by reference to comparison studies that have shown data collected at cell towers to be comparable to those collected at regular observing sites in the vicinity (as discussed in the next section).
Examples of Observing Technologies for A Weather Observing Network Built Around Cell Towers

In this and the following section, we discuss a few innovative technologies for addressing the above issues in ways that may allow developing nations to acquire and sustain networks for gathering much needed meteorological observations.

The technologies discussed here are intended to be examples and are not by any means a complete list of the possibilities. While specific examples of observing equipment are described, their inclusion here is not meant to be an endorsement of that particular product. Indeed, from the author’s perspective, every measuring system being considered for deployment in a tropical or an arid environment should undergo a full year of operation in the actual environment prior to a procurement decision being made. In some cases, systems from different manufacturers can be evaluated simultaneously in the field as part of the procurement process. Sufficient efforts allow procurement decisions to be made on demonstrated performance in the field, not manufacturers’ claims or factory demonstrations.

5.1 Acquisition of Traditional Meteorological Variables, Such as Temperature, Humidity, Wind, Rainfall, and Received Solar Energy, from Weather Instruments Installed on Cell Towers

Measurements of traditional meteorological quantities such as atmospheric pressure, temperature, moisture, wind (speed and direction), and precipitation are essential to the meteorologist for both describing the current state of the atmosphere and forecasting future conditions. Meteorologists and engineers have designed a large number of instruments to measure these quantities.

Today, many of these instruments are combined in “automatic weather stations” that operate more or less autonomously—observations and measurements, now “data,” are transmitted from a remote site and processed with data from other sources; the results are often communicated with minimal or no human intervention. Such equipment can be repackaged—with due concern for the expected operating conditions—to provide observations from wherever cell towers are located. This capability has been demonstrated on several occasions.

However, observations at cell towers have been challenged on the grounds of representativeness; that is, the resulting observations are said to be valid for only a small region around the cell tower. Meteorologists, on the other hand, need measurements that are representative of the atmosphere on the scale being forecast, which for most purposes is the mesoscale. As an example of this common criticism, Bakhtin et al. (2012) commented:

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Mesoscale has a variety of definitions. Here we consider this to be events with space scales of a few kilometers to a few 10s of kilometers and with time scales from 0 to 48 hours, with a strong focus on 0 to about 6 hours.
“... some scientists, and decision makers have expressed a lot of doubt (the discussion was initiated by WMO secretariat on CIMO®-XV meeting in Helsinki at 2010) regarding quality of the data obtained by such “non standard” stations. The terms “non standard” in this case is [sic] not correspond to the sensors—all of them are standard, but it is corresponding to the installation site. The point is that the CIMO guide exactly describes all the requirements to the place, surroundings and the heights of installation of each individual sensor. The cell tower meteorological station is not satisfying any of these requirements.”

To address this criticism, Bakhtin et al. (2012) and others have instrumented cell towers and performed comparison studies of observations from two cell tower stations with those from corresponding “nearby” (7.2 km and 5.4 km) observing sites that meet the requirements of the WMO’s Commission for Instruments and Methods of Observations (CIMO) guide.

Overall, the findings of Bakhtin et al. (2012) are very encouraging. To summarize, they found surprisingly high correlations between observations of temperature, humidity, pressure, and wind speed at a cell tower site and a nearby standard station. Only the wind direction measurements exhibited a loss of correlation when the instrument was in the “wind shadow” of the cell tower. This situation can be determined during the QA/C process since orientation of the wind sensor relative to the cell tower is known from site meta-data. An effective solution is to utilize two wind direction sensors, one on each side of the tower.

Sample results from the Bakhtin et al. (2012) are given in the following figures:

**FIGURE 5: An Open Lattice Cell Tower**

Note: An example of the open lattice cell towers used by Bakhtin et al. (2012). In their case, they used discrete instruments in reasonably close proximity.

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10 CIMO is the WMO’s Commission for Instruments and Methods of Observations. This is the group within the WMO that sets the standards for observations and measurements of the atmosphere.
observations of temperature, humidity, pressure, and wind speed at a cell tower site and a nearby standard station.

Only the wind direction measurements exhibited a loss of correlation when the instrument was in the “wind shadow” of the cell tower. This situation can be determined during the QA/C process since orientation of the wind sensor relative to the cell tower is known from site meta-data. An effective solution is to utilize two wind direction sensors, one on each side of the tower.

Sample results from the Bakhtin et al. (2012) are given in the following figures:

The findings of Bakhtin et al. (2012) indicate that meteorological stations mounted on cell towers are able to provide reliable data for the main meteorological parameters.

**FIGURE 6: Sample Results from Cell Tower Sites**

*Note: Upper plot shows time series of the observed atmospheric temperature at a cell-tower site (blue) and a nearby standard site (red) for a period of 20 days in March 2011. Values are at three-hourly intervals, for eight points per day; lower axis is labeled with the index number of the observation, starting from 1 at the left.*

*Lower plot shows average differences in temperature between the observing sites (with 20 observations at each three-hour observing time) versus observing time: temperature differences never exceeded more than 1.1°C. From Bakhtin et al. (2012).*
Others who have been active in using cell towers for meteorological observations include the company Onsemble, which has been installing wind sensors at several levels on cell towers across the United States. Onsemble is focused on providing the wind energy business sector with precision wind measurements at hub height at high spatial density around where wind farms are located.

FIGURE 7: Wind Direction Analysis from Cell Tower and Observing Site

Note: Two plots showing the results of a correlation analysis of wind direction between cell-tower observations and those at a nearby standard observing site. The data were first sorted by average wind direction. So long as the wind does not blow through the lattice tower before reaching the wind vane, the correlation is quite high, 0.95 (left plot). If the wind blows through the tower before reaching the wind vane, then a significant fraction of the correlation is lost due to local effects, e.g., eddies from the tower structure (right panel). From Bakhtin et al. (2012).

FIGURE 8: A Self-Contained Weather Observing System

Note: Two examples of a small, self-contained weather observing system: the Luft WS401 Weather Station. This multi-sensor device comes in a variety of configurations. Each system shown here measures barometric pressure, temperature, and relative humidity. However, the one on the left also measures rainfalls via a tipping bucket gauge; the one on the right measures solar radiation together with wind speed and direction. The device consumes little power; most configurations have no moving parts. All sensors within the unit are calibrated at the Luft factory. Images from http://www.lufftusa.com/tools/categoryitems.cfm?catid=517.
sector with precision wind measurements at hub height at high spatial density around where wind farms are located.

To simplify the installation and servicing of the measuring system used on cell towers, integrated sensor packages are very attractive. These require only limited servicing in the field. If something goes awry with the package, then it is sent back to the manufacturer for repair.

5.2 Novel Applications of Lightning Data

This section highlights a recently developed technology that shows one does not always need expensive, hard-to-maintain weather surveillance radars to monitor thunderstorms and related phenomena such as squall lines and mesoscale convective clusters.

Thunderstorms (tall, column-like clouds or, in meteorological parlance, “deep convection”) by definition produce lightning, a serious hazard and major cause of death, injury, and fires. In addition to lightning, thunderstorms in their most intense phase can produce intense rain, severe wind gusts, hail, and tornadoes, making them one of the main weather hazards in many regions of the world, particularly in equatorial regions (see following figures).

In locating and then monitoring the intensity of thunderstorms, lightning location data have served for 40 years as a crude but inexpensive proxy for weather surveillance radar data. Recent developments in the passive sensing technology have greatly enhanced the capability to acquire and quickly process signals from a network of detection sensors deployed across a region, resulting in useful data sets of time and location of occurrence, intensity/polarity, and other factors. These networks now also allow the near-real monitoring of the time evolution of the occurrence of lightning.

Note: Thunderstorms begin as small but rapidly growing cumulus clouds (0-minute figure). Lightning (and so thunder) usually begins very shortly after the precipitation core begins to form in the storm (10-minute figure) and continues until the storm rains out (30-minute figure). Under the right conditions of airflow, temperature, and moisture at surface and aloft, storms become locked into the mature phase (20-minute figure) and may persist for hours, traversing the countryside while producing severe weather at the surface. Illustration from http://en.wikipedia.org/wiki/File:Orage_ordinaire.png.

For an example of an early lightning locating and display device, see the Ryan Stormscope, still in use in small aircraft.
in a particular storm, from which much can be inferred regarding the state of the producing thunderstorm.

A number of companies offer lightning detection/locating systems suitable for deployment in such networks\textsuperscript{12}. While intended to provide similar data, the systems offered by different manufacturers differ in several details. Richard Kitel, President of the National Lightning Safety Institute (itself a commercial consulting firm), has provided a brief overview describing characteristics of several of these different systems in a short online article (http://www.lightningsafety.com/nlsi_lhm/detectors.html).

This paper will focus on a relatively new “total lightning” technology\textsuperscript{13}. The term “total lightning” refers to both intracloud (IC) lightning and cloud-to-ground (CG) strikes. Thunderstorms have been found to have high IC flash rates during the storm formation phase. Both Lang et al. (2000) and Lang and Rutledge (2002) have found that a greater volume of strong updrafts in a severe thunderstorm led to greater overall charging, which led to greater numbers of ICs and positive CGs. Williams et al. (1999) observed an abrupt increase in total lightning activity just before severe weather of all kinds, including wind, hail, and tornadoes. The National Weather Service office in Huntsville, Alabama, has used total lightning information...
from the North Alabama Lightning Mapping Array (NALMA) to diagnose convective trends and so to increase warning lead times (Darden et al. 2010). A study based on data from the Lightning Detection Network in Europe (LINET) was even able to track lightning cells using total lightning data (Betz et al. 2008).

Each total lightning sensor system detects the electromagnetic energy that is emitted in all directions when a lightning discharge (IC or CG) occurs. A wideband receiving system (operating 1 Hz and 12 MHz) allows the sensors to detect both strong CG strokes and the weaker IC pulses. Entire waveforms for each flash are recorded and sent in compressed data packets to the central server via the Internet so that the waveform arrival times and signal amplitudes can be used to determine the peak current of the stroke and its location in terms of latitude, longitude, and altitude (Liu and Heckman 2011).
If the flash contains at least one return stroke, it is classified as a CG flash. All other flashes are classified as IC flashes.

Lightning in intense thunderstorms often occurs in “cells,” clusters of flashes within a polygon boundary determined by the flash density value for a given period (Liu and Heckman 2011). The movement of a lightning cell over time can be tracked and trends in lightning flash rate (flashes/minute) within the cell evaluated. Once a lightning cell is located and tracking has begun, the total flash rates are calculated.

While data processing is similar to what has been described, Earth Networks has carried the processing further. Liu et al. (2012) correlated the total lightning flash rates with the corresponding maximum reflectivity values in thunderstorms within the continental United States from May–November 2011. Clear relationships were found between the two factors. Quantitative relationships were derived for different climate zones and seasons to create maps from the total lightning data of simulated radar reflectivity. These pseudo-reflectivity values can be used to enhance thunderstorm prediction and could serve as a cost-effective radar alternative in under-developed regions of the world. By applying formulae similar to those used with Doppler radar, the lightning-based values can be used for precipitation estimates. When accumulated through time, just as is done with radar-based precipitation estimates, one can display accumulated rainfall over periods ranging from one hour to several days, weeks, or months.

By monitoring the changes in these flash rates over time, it is possible to observe a rapid intensification of lightning activity also known as a “lightning jump” (Williams et al. 1999). When a cell is identified and the total lightning flash rate jumps above a given flash rate threshold, an automated weather alert can be issued. Taking into account the motion and size of the cell, a warning area ahead of the cell can be determined.

Liu and Heckman (2011) evaluated the performance of such weather alerts in five different case studies (mostly in the United States where radar data and ground truth reports are readily available) and found they could be issued with lead times of up to 30 minutes before ground-level severe weather developed. Very recent comparative performance of the lightning-base alerts versus United States National Weather Service warnings has been quite good, indicating that it may be possible to bring these types of automated severe weather warnings to developing countries that lack the weather surveillance radars found in the United States and other developed countries.

The lightning detection/locating systems marketed by Earth Networks, the USPLN, and others, and the value-added resellers such as Weather Decision Technologies, Inc., illustrate what can be done with modern detection techniques and advanced signal processing systems.

For current purposes, lightning detection/locating sensors are well suited for installation on cell towers. A network of such detectors is very attractive since the sensors are passive with low power requirements; the telephone network supporting local cell service provides the reliable, wide-bandwidth communications necessary to rapidly move the lightning data back to a central server for processing.

Total lightning and other lightning detection systems have one shortcoming. They require that lightning occur before they can be used to infer the presence of deep convection, precipitation, and other weather elements. With deep convection, this means the initial stages of the formation of a cloud cannot be detected. Further, much rainfall comes from stratiform (layered) clouds that seldom produce lightning. Lightning detection networks need

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14 See Earth Networks, 2013. See also the related discussion at http://www.eenews.net/stories/1059982042).
to be complemented with other observing systems to detect precipitation associated with forming thunderstorms and stratiform clouds.

5.3 Use of “Rain Fade” in Wireless Telephone Signals to Locate and Estimate Intensity of Precipitation

As noted above, a shortcoming of using lightning data as a proxy for radar observations is that lightning is required in order to detect a cloud, and not all clouds produce lightning. Thus the lightning approach to detecting severe weather and/or estimating rainfall works well with mature deep convective clouds but not with early stage convective clouds or with stratiform clouds. Precipitating clouds of this latter type (nimbostratus) are often low-lying, with cloud bases only a few hundred meters above the local surface. Even radars have problems seeing such low-lying cloud decks. Fortunately, there is an emerging complementary technology that may significantly reduce this concern.

The phenomenon of “rain fade,” the attenuation of radio signals passing through rain, has been known and studied extensively since at least the 1940s. In “rain fade,” raindrops absorb part of the transmitted wave and scatter some of the energy out of the beams of radio waves connecting the cell towers and cell phones in the area. This attenuation causes the energy that reaches the receiver to be less than the expected amount. In recent years, with the proliferation of cell phones and other wireless devices, scientific and engineering researchers have come to realize that the rain fade phenomenon can be used to locate and estimate the intensity of rain in the area covered by a cell tower network, at least in populated areas where there are many cell phones and cell towers in use.

It has been known for several decades that microwave attenuation by rainfall is nearly linearly related to the rainfall rate (Wexler and Atlas 1963, Atlas and Ulbrich 1977). More recent studies (e.g., Messer et al. 2006, Berne and Uijlenhoet 2007) have shown that this relationship can be used to estimate path-averaged rainfall rates between radio links in commercial cellular phone networks. The rain attenuation depends on both the size and distribution of the water droplets. The most common approach to relate the attenuation rate \( A \) (in dB/km) with the rain rate \( R \) is through the power law model: \( A = aR^b \), where \( a \) and \( b \) are constants that are functions of frequency and polarization (Messer et al. 2006).

Messer et al. (2006) collected data from digital fixed radio systems in Israel during a January 2005 rain event and found that the cellular rainfall measurements were comparable to both rain gauge amounts and weather radar estimates. Berne and Uijlenhoet (2007) evaluated the influence of both frequency and the lengths of the microwave links on simulated heavy rainfall events in the Mediterranean. They found that the length of the link had no influence on the estimated rainfall, and that for the relationship between rainfall intensity and attenuation to be linear, the frequency needed to be around 30 GHz.

Leijnse et al. (2007) evaluated the performance of cellular rainfall estimates in the Netherlands, a country with a high density of commercial network links. Using data from eight rainfall events over a two-month period in 2003, they calculated rainfall intensities based on attenuation equations taking into account electromagnetic scattering laws and typical parameters of the radio link. They found that the method was effective in estimating rainfall rates with an accuracy that is comparable to that of traditional rain gauges.

Rain fade technology may also help address the issue that the number of rainfall reports from traditional gauging stations has significantly decreased over recent decades. This is due to cost of maintenance and to the changes in societies. See, for example, the comment in http://www.slideshare.net/theradiationdoctor/growing-importance-of-using-cell-towers-to-measure-rainfall.
drop size distributions for the region. When compared to a nearby rain gauge and rainfall estimates from two nearby weather radars, statistical analysis showed that the links compared better to the gauge in uniform rain and better to the radar estimates in variable rain. Other studies in Israel (Rayitsfeld et al. 2012), Luxembourg-City (Fenicia et al. 2012), and the Netherlands (Overeem et al. 2013) also indicate that after proper calibration, these cellular rainfall estimates could be used successfully in operations.

Rainfall estimates from cellular network links are quite useful because they provide information closer to the ground than weather radars (tens of meters above ground compared to hundreds of meters). Further, there is a linear relationship between attenuation and path-average rainfall rate. They could also be incredibly useful in countries where cellular phone networks are in place, but weather observation networks and weather radars are sparse or non-existent. The technology could also be calibrated to detect solid particles such as sleet and hail, and could even be used to measure the refractive index of the atmosphere to determine water vapor levels (Messer et al. 2006). As was stated by Leijnse et al. (2007) and Fenicia et al. (2012), studies will need to be performed to determine representative drop size distributions and other characteristics in the specific region(s) where the cellular network rainfall estimates would be implemented operationally.
Other Complementary Or Emerging Technologies Worth Consideration

6.1 Aircraft Instrumentation for Soundings

Surface observations of temperature, pressure, winds, and humidity are of vital importance to weather forecasters, the general public, and commercial interests. However, surface observations by themselves are not sufficient for skillful forecasting of future conditions. Modern-day weather forecasting relies on obtaining a four-dimensional image of the atmosphere. The traditional method of obtaining data from the surface up through the atmosphere has been to do (at least) twice-daily launches of balloons carrying small instrument packages. Unfortunately, such an approach requires specialized equipment, technicians with some degree of skill, and a regular supply of expendables, such as balloons, instruments (few of which are recovered), and helium. All this is quite costly. As a consequence, many developing countries take few such observations.

One way of addressing this situation is for the NHMS to partner with the airlines operating in the nation to access the meteorological information—usually altitude, temperature, and wind—routinely collected on board many modern commercial aircraft. The issue is one of accessing such data, preferably in real time. The technology to do this has been developed and is readily available.

In the United States, seven commercial airlines with a total of about 1,600 aircraft currently participate in what is termed the Meteorological Data Collection and Reporting System/Aircraft Meteorological Data Relay (MDCRS/AMDAR) system. These aircraft, in the course of their routine operations and with no effort by the aircraft crew, provide the U.S. National Weather Service about 150,000 observations per day, producing 2,500 vertical soundings per day (e.g., during each takeoff and landing) as well as describing en-route conditions. Each sounding includes a sequence of altitude, wind, and temperature measurements, at a minimum. If additional instrumentation is installed, the reports can include measurements of water vapor, turbulence, and icing as well.

FIGURE 13: DATA POINTS FROM COMMERCIAL AIRCRAFT

Note: A plot of the data points related to the U.S. National Weather Service in one day from commercial aircraft using the Meteorological Data Collection and Reporting System/Aircraft Meteorological Data Relay (MDCRS/AMDAR) system. Colors denote the altitude at which the observations are made. The clustering of red colors over airports indicates where vertical soundings can be constructed from the data.
Non-traditional Approaches to Weather Observations in Developing Countries

Newest Android smart phones, as well as some tablets, come equipped with atmospheric pressure sensors to estimate elevation, helping to better determine the geo-location of the phone. Tens of millions of these phones have been sold worldwide (Forbes 2012). Realizing the utility of such a potentially dense network of real-time atmospheric pressure observations for weather forecasting, a Canadian company called Cumulonimbus has implemented a free smart phone app called pressureNET that allows users to track atmospheric pressure at their locations over time using the barometers in their smart phones (pressureNET 2013). More important for weather forecasting, it also allows users to submit the current atmospheric pressure at their exact locations (using GPS and/or cell phone tower triangulation) to a central server for further processing. Cumulonimbus has been working with researchers at the University of Washington to ingest this dense field of pressure data into short-term weather forecast models (University of Washington 2013). The researchers believe that using this dense field of observations could improve short-term weather forecasts (sometimes called “nowcasts”). There is parallel effort by UK-based WeatherSignal (http://weathersignal.com/about/) that includes not only pressure but also observations of present weather.

**FIGURE 14: Supplementary Barometric Readings from Smart Phones**

An example of supplementary barometric readings from smart phones using the pressureNET application to bring out the value of atmospheric pressure sensed by the phones’ integral barometer. In this case, the data are displayed as markers on an embedded Google map provided by the application. From http://www.1mobile.com/pressurenet-347500.html.

**FIGURE 15: Data Visualization Tools in PressureNet App**

Some of the data visualization tools included the pressureNet smart phone application. The panel on the left shows phones reporting pressure values as Hurricane Sandy made landfall just south of New York City. The panel on the right shows the sequence of values submitted by a particular phone as the hurricane made landfall and the eye passed near the phone. From http://www.treehugger.com/clean-technology/app-uses-your-Android-phone-to-give-scientists-weather-data.html.
To access and use these data requires a business arrangement involving the NHMS, the airlines, a company specializing in air-ground communications, and a local or regional telephone company. The data need to be brought into a central point for QA/C and displayed in formats that can be utilized by the forecaster.

6.2 Smart Phones as Weather Observing Systems

The number of surface observing systems that can be deployed and maintained is always less than desired. Fortunately, rapid advances in cell phone technology have produced the “smart phone.” Some smart phones offer interesting possibilities for supplementing the data from a cell-tower-based weather observing network, particularly in areas of significant population. This crowd-sourcing approach to weather observations may be of particular interest in countries with otherwise weak observing infrastructure.

As one possibility, the NHMS, again working with a cellular telephone company, could make use of the atmospheric pressure sensors and geo-locating functions available in many of the ever-growing number of smart phones in use. For example, many of the newest Android smart phones, as well as some tablets, come equipped with atmospheric pressure sensors to estimate elevation, helping to better determine the geo-location of the phone. Tens of millions of these phones have been sold worldwide (Forbes 2012).

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There is parallel effort by UK-based WeatherSignal (http://weathersignal.com/about/) that includes not only pressure but also observations of present weather.

6.3 Deployment of Networks of X-band Radars Where Active Sensing is Needed

In recent years, it has become feasible to deploy networks of X-band weather surveillance radars to monitor weather events over a city or an area within complex terrain, such as a watershed providing water to a hydroelectric plant or an irrigation system.

Compared to the long wavelength S-band and C-band radars, modern Doppler dual-polarization X-band radars are relatively small, lightweight, self-contained units (e.g., no

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16 Most cellular telephones currently in use in developing countries are either “feature” phones or basic “dumb” phones (albeit with SMS capability). As of 2008, it was estimated that in Africa, of the 250 million or so cell phones in use, 7 to 19 percent of the cell phones in use were “smart” (so about 1 in 13 to about 1 in 5). The spread of smart phones is often limited by the availability of electricity to charge batteries. However, it is only a matter of time before the majority of people in these countries upgrade to phones that incorporate “smart” technology.
separate shelter for electronics). They are less expensive in terms of both radar hardware and installation costs. These small radars have a much reduced power requirement, hence less internal heat generation, and can be made very simple to install and maintain, e.g., on top of a 10-meter column such as a light pole. It is very feasible to install such a radar on or in near proximity to a cell tower and use the power and bandwidth available at such locations.

One should not confuse these radars’ relatively small size with simplicity. These are very sophisticated systems incorporating the latest advances in radar hardware and software. The simplest maintenance concept is when a radar goes down, it is replaced with another system. In many situations, this can be done in a matter of a few hours. For repair, the defective radar is then sent back to the manufacturer or serviced at a central maintenance facility, eliminating the need for field repairs.

Since X-band radars are relatively limited in range, they are best deployed as part of a network with a high degree of overlapping coverage between the members of the network. A properly constructed network thus brings a high level of resiliency for the inevitable situations where a radar is down for maintenance or replacement.

The cost for a network of three to seven X-band radars is roughly equivalent to the cost of one S-band radar. Depending on the situation, there may be significant savings in the installation costs of the X-band network, and also a larger return-on-investment due to the greater likelihood that the X-band systems will remain working longer.

Semi-autonomous control systems (now in the advanced prototype stage) operate the network with minimum human input (see Brotzge et al. 2010; Junyent et al. 2010 for details; a few details are given in the example network described below). The control system contains a sophisticated adaptive scanning strategy (i.e., a set of relatively few software commands that specify how the radars in the network should work together), which is worked out in advance. The operation of the radars in the network then adapts as the weather changes in order to optimize observation of the current weather situation, all without human intervention.

Advanced signal processing and synthesis techniques can fuse data from several such radars to reduce attenuation issues in rain and provide gridded fields of reflectivity, microphysics, and Doppler velocity to serve as input to numerical prediction models.

As an example of a modern X-band weather surveillance radar, we consider the Ranger™, a system being offered by the Enterprise Electronics Corporation (EEC). The EEC and the Advanced Radar Research Center (ARRC) at the University of Oklahoma teamed to design and construct high-resolution, compact, lightweight X-band dual-polarization radars designed to be installed in hard-to-reach locations, such as offshore oil platforms, and small airports (EEC 2013). The dual-polarization...
Non-traditional approaches to weather observations in developing countries

An example of a network of four X-band radars operated by a semi-autonomous adaptive scanning control system is provided by the Integrated Project 1 (IP1) of the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) (Brotzge et al. 2010; Junyent et al. 2010). This network was established in southwestern Oklahoma and consisted of four X-band, polarimetric, Doppler radars with overlapping coverage.

CASA aims to develop and demonstrate that networks of short-range X-band, polarimetric, Doppler radars can be a valuable augmentation to the existing national system of 150 S-band radars spread across the United States. Compared to these large, long-range S-band radars, the small, short-range X-band radars can provide more frequent updates and offer a better view of the part of a storm that’s near the ground.

The primary objective for the four-radar network in Oklahoma was to improve observations and forecasting of hazardous Great Plains weather events such as flash floods, tornadoes, high winds, and hail. Such near-surface events are often missed by the S-band radars due to the Earth’s curvature, radar beam refraction, and wide separation between radars.

The four-radar network in Oklahoma proved the worth of this approach on several occasions. This was in large part due to the network being able to better resolve and follow atmospheric phenomena occurring at low levels of the atmosphere. “The CASA radars did a better job than traditional radars because they were able to provide a fresh image of the storm every minute,” said Michael Zink, of the electrical and computer engineering department at the University of...
Massachusetts Amherst. One “... problem is that with the existing system you only get five-minute updates and fast-moving weather events like tornadoes can change,” Zink said. The longer range of the current S-band network comes with the unavoidable problem of the beam becoming further above surface with increasing range due to Earth’s curvature. As a result, “... roughly 75 percent of the atmosphere below one kilometer is not covered by these radars,” Zink said. “And that’s an area where a lot of the weather is happening. The CASA system uses ... many radars so that it wouldn’t have that blind spot. And that could help give people a few extra minutes’ notice that a tornado is coming.” (Michael Zink’s quotes taken from http://www.startribune.com/blogs/124067569.html)
Lessons To Be Learned

7.1 The Weather Information for All Initiative—A Failed Effort

Launched with great fanfare in 2008 by Kofi Annan and the Global Humanitarian Forum (GHF), the Weather Information for All (WIFA) initiative was a public-private partnership formed to increase access to reliable weather and climate information throughout Africa. As announced, the GHF, WMO, Earth Institute at Columbia University, mobile telecommunication companies Ericsson and Zain, and NHMSs and governments of participating countries were to work together to install 5,000 new automatic weather stations at new and existing mobile network sites across the continent by 2013 (GHF 2008).

The project aimed to use the mobile telecommunications network that is spreading rapidly across Africa to improve both the
continent’s weather observing network and the availability of weather information through the dissemination of forecasts and early warnings through mobile short message service (SMS; Ericsson 2013).

This increased access to weather information was intended to help those rural communities most affected by and vulnerable to hazardous weather events and variations in seasonal to inter-annual climate. For example, seasonal outlooks could help farmers decide what and when to plant, likely increasing their crop yields and incomes. Communities, health agencies, and governments could also use early warning of weather patterns to take preventative action to limit the spread of climate-sensitive diseases like cholera and malaria. Early warnings could also be used to alert people on Lake Victoria, where an estimated 5,000 fishermen die each year due to storms and accidents (GHF 2008).

Of the three planned phases of the WIFA initiative, only the first was completed before the GHF ceased all activities in 2010 due to lack of funds (WMO 2013).

In this first phase, 19 automatic weather stations fabricated by Fairmount Weather Systems Ltd. were installed on existing Zain and Ericsson mobile network sites around Lake Victoria, in the nations of Kenya, Tanzania, and Uganda.

Unfortunately, to the best that can be determined, this effort soon failed. Between November 2009 and May 2011, contact was lost with all 19 weather stations17.

7.1.1 Lake Victoria Project(s)

After the initial launch of the WIFA initiative, a sub-project within the initiative was started by the Kofi Annan Foundation. This was intended to improve the weather and climate information received by fishermen and farmers around Lake Victoria (Kofi Annan Foundation 2013). The project was based

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17 See http://betastations.fairmountweather.com/all_locations_page.php for a few details.
in Rarieda Constituency in Saiya County, Kenya, and was supported by the Svenska PostkodStiftelsen, Health and Climate foundation, Aga Khan University and African Centre of Meteorological Applications for Development (ACMAD).

As a first step toward building a lake weather observing network that would meet real needs, surveys were designed and conducted to determine how the communities around Lake Victoria used the weather information they received and to determine what additional services could meet their needs.

Like the WIFA initiative, this sub-project also ended when GHF ceased activities in 2010. It does not appear that any weather observing equipment was deployed.

Less than a year later, management of the WIFA initiative was passed to the ACMAD, where a new project known as Mobile Weather Alert was created to build off of the work previously done under the WIFA initiative (WMO 2013). The objective of this new project was again to use existing mobile phone technology, infrastructure, services, and applications to develop and demonstrate a sustainable warning service in the region around Lake Victoria.

Ericsson, WMO, MTN Uganda, the Uganda Department of Meteorology, the National Lake Rescue Institute, and the Grameen Foundation worked together to test and deliver a range of mobile communication options for pre-disaster weather alerts for fishermen. The pilot study was launched in May 2011 in Uganda at a district along Lake Victoria called Kalangala. A survey of 1,000 fishermen found that they valued the possibility of receiving accurate and specific weather information to their mobile phones in addition to the general weather forecasts on the radio (Ericsson 2012).

No information about the Mobile Weather Alert project can be found after May 2011.

### 7.2 Weaknesses Leading to the Collapse of the WIFA Initiative

It appears that the WIFA initiative provided sufficient motivation, with the potential to assist with hunger/food production/security, health, and poverty issues across a region desperately in need of such assistance. However, it failed within two years of being announced. Further, it appears to have accomplished little beyond having introduced to the region the idea that cell towers might open opportunities not previously considered.

The available reports suggest the following weaknesses in the WIFA initiative led to its premature end:

- **Lack of sufficient capital at start-up and subsequent inability to attract funds for the realization of the announced plan**
- **Simply put, broad ambition was not matched with sufficient capital.** Consequently, the program’s vision had to be continuously scaled back into various “pilot zones,” “concept testing,” and “community based impacts.” It finally reached the point where the broad national and international developmental impact had been designed out of the initiative. In summary, WIFA promised too much for the available resources, and delivered too little to have a real impact.
- **Unable to synchronize funding, an implementing agency, measurement system manufacturing, and deployment cycles, it failed to produce a coherent, sustainable program.** WIFA’s failure became another example of the very different time scales on which the public and private sectors operate.
- **Despite good intent and high-level political support, the organizers did**
not seem to have a business plan focused on funding long-term sustainability; there was no obvious path to data/content commercialization with the insurance industry, the energy industry, the media, and consumers. Lack of such a sustainability plan likely deterred many of the potential investors one would like to attract to such an effort.

- Technology and operations
  - Technology focused on lowest-cost sensors and related field equipment rather than robust, environmentally appropriate, low-maintenance hardware.
  - There was minimal innovation or recognition of opportunities offered by leap-frog technologies.

- Perhaps most importantly, lack of buy-in by the local NHMS’s in the regionThe limited involvement of, and hence limited sense of ownership of the program by the NHMSs in the participating countries (P. Partanen, 2013, personal communication) almost certainly doomed this program from the start. However, it is unclear that the NHMSs, even if they had been involved, had the required expertise or resources to play the roles necessary for the success of the program.

- Siting concerns by the NHMS over representativeness weren’t properly addressed (see remarks above about representativeness issues).

- Public-private partnerships between the NHMS and the providers of the systems weren’t properly addressed (see discussion in the closing section).

- Lack of application development
  - Impactful humanitarian applications of the data were never able to properly get off the ground; data collection was seen as an end in itself.
  - Little attention was given to converting data to actionable information for commercial applications such as energy/utility, insurance, TV, and mobile media. As discussed below, this is the best path to long-term financial stability for such networks.
The success of any effort to install, maintain, and financially sustain a modern weather observing system in developing countries hinges on the buy-in and enthusiastic involvement of the NHMS administrative staff responsible for the project, the operational meteorologists who will be using the data, and the supporting technical staff. To obtain and maintain the desired sense of ownership for the system by these individuals, training and professional development in advance of and/or parallel with the deployment of new technologies are essential. Each group has separate training needs.

Unfortunately, training is often a last thought in the deployment of weather technologies to developing countries. Too often with training, it is a case of “too little, too late” to be effective.

Experience with training NHMSs from developing countries suggests that a major objective for the training should be “confidence building.” The staff members need to feel that they can return to their duties and successfully utilize a high tech piece of equipment or system.

To this end, for the operational meteorologists and the supporting technical staff, the training program should emphasize hands-on activities and practical work with the system being deployed. The administrative staff, in addition to the traditional acquisition and program management skills, needs a range of marketing and new business development skills to aggressively contribute to the sustainment effort (see discussion below).

For the observing technologies discussed here, some form of continuous update training is needed following initial training. All these measurement systems are in continuous development, with new technology and new applications coming out frequently. Much of this can be accomplished online through webinars, mentoring, and sharing among users.

One of the major challenges that some NHMSs face is retention of trained staff. It does little good to expend funds to train a staff member on a piece of technology if, on completion of the training, he or she uses the new knowledge and skills to obtain employment elsewhere. Retention of staff through rewards and incentives such as pay increases and performance bonuses needs to be a priority with the NHMS senior management.
Final Thoughts and Recommendations

This section offers synthesis and reflection on the material presented above. It also provides recommendations based on the above material, discussion with others who have experience with the design and deployment of weather observing networks, and the author’s personal experiences.

9.1 Improving Observing Networks and Enhancing NHMS Capacity

As the preceding paragraphs have laid out, there are both opportunities and challenges to establishing sustainable weather observing networks in developing countries, which usually have very limited supporting infrastructure.

From the author’s personal contacts with individuals who live and/or work in Africa in particular, many staff members in African NHMSs view establishing surface weather observing networks as an important step along the path to becoming independent players in the global meteorological community. Installing, operating, and maintaining a surface observation network is seen as a way to build national capacity, resiliency, and self-reliance. Consequently, there is a high level of frustration among some of the NHMSs that realizing such networks has proved to be especially challenging.

It also seems that simply deploying large numbers of automatic weather stations designed primarily for mid-latitude operation to tropical or Sub-Saharan Africa is not a successful strategy. Rather, the NHMSs in these regions need to be nudged to try a new approach; one that, through partnering with an entity like the local cellular phone company, has a greater probability of success even if the resulting number of observing sites is quite small. Sharing the challenging maintenance requirements with a trusted, technically savvy, local partner would allow a NHMS to focus on using the data to develop and deliver to its nation’s people a wide range of new weather and climate products and services. By using local data to provide even a few basic services to the local insurance industry, utilities, and media, as well as the general public, the NHMS gains credibility and demonstrates it is worthy of additional government support. The experience and confidence gained in operating and utilizing even a modest network will in a few years allow the NHMS to move on to deploying more complex observing systems.

The international development community, characterized by institutions such as U.S. AID, the World Bank, and UNDP, should not fund deployment of equipment by NHMSs unable to utilize or sustain it long-term. Following the maturation principle of “crawl, walk, run,”
fly”, the initial goals should not be to deploy as many technologies as possible but rather to improve the capabilities of NHMSs in small steps, allowing them to become ready for the next level.

9.2 Adopting Appropriate Business Models to Provide Sustainability

The NHMS is the primary caretaker for the “weather asset” in its country. Consequently, any effort to establish a weather observing network, be it in one nation or across a region, must involve the NHMS in all steps, from initial planning through to deployment and operation.

Unfortunately, few if any of the NHMSs in developing countries have staff with the skill sets required (strategic planning; end-to-end systems engineering leading to acquisition and installation of high tech equipment; new business development, marketing, sales; new product development and delivery) to fully play the roles necessary to acquire, install, maintain, and sustain a modern weather observing network. History suggests that neither do most NGOs or government aid agencies. New approaches to deploying sustainable networks are necessary.

One option is carefully crafting public-private partnerships involving private sector entities that have these skills. The international development community should encourage and foster such public-private partnerships by requiring a realistic sustainability plan as a condition for funding. In the absence of a direct budget increase from the national government, an appropriate sustaining arrangement with the private sector is the most viable approach to addressing the current limited capacity of the NHMS for sustaining observing networks. Based on the literature on development in Africa, it appears that Uganda has already adapted national policies in this direction and is enjoying some success.

The private sector entities can be either local, such as the cellular network company, the local electrical utility, or the national airline, or international. Examples of the latter are Earth Networks and Accuweather from the United States and MeteoGroup from the United Kingdom; there are also entities that might be considered “semi-private,” such as MeteoFrance International, which could play useful roles.

This report has emphasized the opportunity presented by the spread of the cellular telephone network for establishing a weather observing network. A simple business arrangement for taking advantage of this opportunity might entail a NHMS partnering with the cellular telephone company and a private sector weather company to establish and sustain a weather observing network. The resulting data are then provided to the NHMS at little or no charge while the private sector weather company and/or the cell company cover their costs and make a profit by marketing the data worldwide. However, such a simplistic arrangement is not likely to be attractive to either the cellular telephone company or the private sector weather company, since it puts all the risk on these two entities.

A solution is for the NHMS, with initial support from a development agency, to take on some of the responsibility and some of the risk for sustainability through commercialization both within the country and in the wider global marketplace. The role of the development agency is to cover the capital costs, as is the case today, while ensuring that the NHMS staff receives the necessary training and professional development required to be a full partner in such a multi-player effort. The NHMS would remain responsible for the accomplishment of humanitarian objectives set by the development agency, and have to learn how to balance that role with the commercialization effort. Success by the NHMS, demonstrated by continuing operation of the observing network
at five years after commissioning, could be re-
warded by further investment by the develop-
ment agency.

As a side note on this, the development agency can play important roles in fostering regional collaboration. This not only increases the size of the potential business opportunity for the private sector companies but also is essential to having an effective early warning network.

### 9.3 Focusing on “Leap Frog” Technologies in Developing Countries

From discussions of the adoption of cell phone technologies and from reviews of related reports in trade magazines, one quickly becomes amazed at how many developing countries are by-passing many of the steps that developed countries took in developing their current technological infrastructure. The most obvious example of these so-called “leap frog” technologies is the cellular telephone. It is reasonable to assume that most developing countries will never be “wired” in a physical sense. Indeed, many developing countries are seeing individuals abandon hard-wired phones as well.

In their strategic planning, perhaps nudged along by international development agencies, NHMSs should consider adopting appropriate leap frog technologies to accomplish their missions. One that seems particular relevant is “cloud computing.” Many NHMSs do not have the proper IT capacity to handle the data processing infrastructure required for doing the analysis, assimilation, product generation, and archiving required to satisfy customers and partners in the previously described sustainability effort. Cloud computing provides a viable and relatively inexpensive alternative to the implementation and maintenance of in-house IT infrastructure at fiscally challenged NHMSs. Going with computing in the cloud, the NHMS and partners can focus on the data collection infrastructure, an appropriate web browser, and an appropriate bandwidth Internet connection.
2. Weather Observing Networks

5. Examples of Observing Technologies for a Weather Observing Network Built Around Cell Towers
5.1 Acquisition of Traditional Meteorological Variables, Such as Temperature, Humidity, Wind, Rainfall, and Received Solar Energy, from Weather Instruments Installed on Cell Phone Towers

5.2 Novel Applications of Lightning Data

5.3 Use of “Rain Fade” in Wireless Telephone Signals to Locate and Estimate Intensity of Precipitation


6. Othercomplementary or Emerging Technologies Worth Consideration

6.2 Smart Phones as Weather Observing Systems

Forbes, cited 29 May 2013: Four Android phones shipped for every iPhone sold, but malware also on the increase. [Available online at http://www.forbes.com/sites/adriankingsleyhughes/2012/08/11/four-android-phones-shipped-for-every-iphone-sold-but-malware-also-on-the-increase/]

pressureNET, cited 29 May 2013: About pressureNET. [Available online at http://pressurenet.cumulonimbus.ca/about/]


6.3 Deployment of Networks of X-band Radars Where Active Sensing is Needed


7. Lessons to be Learned

7.1 The Weather Information for All Initiative—A Failed Effort


Contact Information
Climate Business Department
International Finance Corporation
2121 Pennsylvania Ave., NW
Washington, DC 20433

www.ifc.org/climatebusiness