The Trans-African Hydro-Meteorological Observatory (TAHMO)

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In this opinion article, we present the Trans-African Hydro-Meteorological Observatory (TAHMO). The goal of TAHMO is to develop a dense network of hydro-meteorological measurement stations throughout sub-Saharan Africa. On average, there will be one station per 1000 km². The stations will be cost-effective through the use of new sensor and communication technologies. The station design is robust and aims at minimizing maintenance. Special attention will be paid to data quality assessment and control. Through public–private partnerships, the system will be made financially self-sustaining. Education will play an important role as many stations will be placed at schools, where they will play a role in the curriculum. © 2014 Wiley Periodicals, Inc.

INTRODUCTION

The decreasing number of hydrological and meteorological stations in the world is a major concern for science and society. Figure 1 shows that reporting weather stations are especially sparse in Africa and Latin America. This affects the quality of weather predictions, climate change assessments, and development and management of natural resources. As a result, the knowledge of the global hydrological cycle is rather limited. For example, it was shown1 that the water balance for South America could not be reconciled between different reanalysis and observational products, with differences of up to 50%. The decline from 4267 to 390 stations over the period of analysis was seen as the main reason behind these discrepancies.

In near real-time, the number of reporting stations in sub-Saharan Africa is, with the exception of airports and South Africa, very small. Upgrading existing stations would be costly and would depend on the availability of resources within all different national meteorological services. The small number of stations reporting in near real-time implies that in weather predictions, local ground-based observations are not taken into account. The value of better weather predictions is hard to estimate but it is worth mentioning that the value of weather predictions in the United States is estimated at $30 billion/year. Even a fraction of such an amount would cover more than the costs of building and running the weather and water observation network that TAHMO hopes to be in the near future.

TAHMO seeks to leverage recent advances in sensor and communication technologies to install and operate 20,000 hydro-meteorological stations in sub-Saharan Africa. This would allow Africa to leapfrog to having the densest observation system of any continent. To financially sustain TAHMO, public–private partnerships will be built using new business models. Education will play an important role as most of the stations will be placed near schools, where they will be integrated in the curriculum.

TECHNOLOGY

Design Criteria

TAHMO has the objective of operating approximately one station per 1000 km², which provides
30 km station spacing or a total of about 20,000 stations in sub-Saharan Africa. This will revolutionize the collection of weather and water data in Africa, and moreover, will be the largest (by way of scale and number) network of common sensor systems in the world. This will open the possibility of unprecedented scientific exploration of spatial characteristics of climate at the continental scale. The exact number and placement of stations will be a function of availability of funds, market opportunities, legal barriers, and communication coverage (GSM or better). For certain regions, for instance where crop insurance is prominent, the density may be higher, whereas density in remote locations, say the Ituri forest, may by lack of infrastructure be much less.

The variables to be measured include all standard meteorological variables (air temperature, relative humidity, barometric pressure, wind speed and direction, and rainfall). Technology choices made with respect to these standard parameters will be selected among those accepted within the meteorological community to provide directly comparable values to existing time series arising from standard devices. In addition, TAHMO will add measurements beyond the standard suite of parameters as long as they are of special value and do not hamper the reliability of operation. One may think of photosynthetically active radiation, groundwater level/temperature/salinity, lightning, GPS time and location, precision acceleration, and leaf wetness. Many of these will provide enhanced value for hydrogeologists, crop insurance, and in the development of public service severe weather warnings.

The feasibility of this project hinges on the installation and operation of a uniquely extensive and dense network of weather stations. Although the first generation of stations cost on the order of US$1500, by acquiring large numbers we see opportunity to improve the price/quality relationship continuously. Even more important than capital costs will be the maintenance costs. Technicians who can maintain traditional professional weather stations are typically absent in rural Africa. The stations design limits maintenance to guarding against vandalism and simple exterior cleaning.

To minimize maintenance and maximize reliability, the perfect TAHMO weather station would fulfill the following design criteria:

- Robust (no calibration required for at least 2 years)
FIGURE 2 | Arthropod infestation of meteorological instrumentation in Navrongo, Ghana, February 2014. (a) Left temperature and relative humidity sensor and (b) right tipping bucket within rain gauge.

- No moving parts (these attract attention and are subject to failure)
- No open cavities (to minimize animals taking refuge in the stations)
- Low power (should require no connection to external power or battery replacement)
- Low cost
- Low upkeep
- Near real-time internet connectivity

The first generation stations are Decagon Micro-Environment Monitor stations. The station has no moving parts but some cavities that may be subject to arthropod colonization. Rainfall is measured with a funnel (10 cm diameter) and an optical drip counter. This method has been tested extensively but the exact accuracy has not yet been established. Temperature and relative humidity are measured with a standard sensor with 0.5°C and 2% accuracy, respectively. An Apogee radiation sensor measures incoming solar radiation with an accuracy of 7% over a range of 0–1500 W/m². Wind speed and direction are measured ultrasonically with an accuracy of 0.30 m/s over a range of 0–10 m/s and of 3% for wind speeds greater than 10 m/s. Wind direction accuracy is 3 degrees. Barometric pressure is measured with 1 kPa accuracy. Six AA batteries power the station and are fed by a small (3 × 7 cm²) solar panel. In this configuration, the GSM modem is capable of uploading data to the internet for up to six times per day. Level, compass, and GPS sensors complement this package and provide information on the quality of the installation and exact location.

The logistical advantages of robust, low maintenance stations are fundamental to this project, as station failure and visitation are costly both financially and in terms of quality of the product. To achieve this goal, moving parts are in general to be avoided, but beyond mechanical considerations, the less attention the station draws to itself, the fewer issues are expected with vandalism. Figure 2(b) shows a tipping bucket inside a rain gauge as found in the dry season in Ghana. In addition to the dust accumulation in the buckets and on the axle (which compromises the calibration of depth per tip), there are arthropod webs that hinder movement and proper functioning of the device. That open cavities are not helpful either is also shown in Figure 2(a). In more moderate climates, spiders and insects tend to be less of a problem than in Africa, where termites, ants, wasps, and bees compete with spiders, butterflies, and moths for shaded, well-ventilated, and dry spaces. A Stevenson screen is the perfect home for many small creatures. The most extreme case in our own experience was a tree frog that made its way up the pole of a rain gauge and settled itself inside the cup of a tipping bucket, causing periodic events that were reported by the station as rain in the middle of the dry season.

Air temperature measurements are especially challenging in accommodating this criterion, as thermometers should not be exposed to sunshine. There are, however, workarounds such as using very small white thermometers or using cylindrical or spherical thermometers of different diameter and extrapolating to a zero diameter (this solution was first proposed by Dr. Gaylon Campbell). In addition, ultrasonic devices may be used to determine air temperature, as well as wind speed and direction. Optical instruments would
need special protection and designs to mitigate impact of dust and dirt.

The low power requirement is needed to avoid the use of large solar panels, which tend to be desirable objects for general use around the house, especially in rural Africa where the electrical grid is often absent and/or unreliable. The solar panel must not be viewed as an item of value, being the most common reason for theft. In the current design the solar panel is under $3 \times 7 \text{cm}^2$ in size, and positioned above the data logging system at 2 m height, so cannot be seen by passersby. This provides an example of the synergistic benefits of reducing energy demand: smaller solar panels are not only less likely to be stolen, but also reduce station cost and allow full integration of the solar panel in the mechanical package of the station.

In addition to the more or less standard observations, we hope to have a number of less traditional sensors, such as leaf wetness, soil moisture, groundwater level (where possible), lightning, and atmospheric transparency. In selecting sensors to be included, it is important to give highest priority to those that provide data that are representative of the largest possible area around the point measurement. We call this ‘footprint of observation’, which can be considered as the area that the measurement might be taken to represent. For example, a local soil moisture sample measured with, say, a Time Domain Reflectometry (TDR) sensor with a sampling volume of a few hundred cubic centimeters is useful as extra information about the cumulative water balance but would have little value in absolute terms for validation of large-scale satellite data. Possible instruments with larger footprints are air temperature and humidity, which for a station mounted at 2 m would typically be thought to represent on the order of $100 \times 100 \text{m}^2$. We hope it will be possible to include more advanced sensors at a subset of, say, 5% of the stations to advance quick deployment of promising sensors at a continental scale. One could think of cheap scintillators to measure fast neutrons as indicator of large-scale soil moisture, analysis of GPS signals to determine the atmospheric moisture column or soil moisture. To add measurements that add value to satellite data, one may add measurements of atmospheric transparency at specific radio frequencies to improve the accuracy of radar products such as interferometric surface deformation and altimetry of inland water bodies. These additional measurements are not yet set but would be subject to further discussion within the scientific community.

**Quality Control**

In addition to individual robust sensors, we strive to gain additional operational robustness through cross-calibration between sensors, comparisons between nearby stations, with known values, and through integration of satellite observations. Examples of such opportunities include verification of 100% relative humidity during rainfall, verification of theoretical midday solar radiation based on elevation and latitude, and verification of wind-speed sensor responsiveness based on comparison with station vibration as observed by the on-board accelerometer.

Some of the cross-calibration is likely to come from less traditional methods. CPU temperatures are normally available but cannot be used directly for air temperature or radiation measurements. It will, however, not be too difficult to have an internal temperature model that takes radiation and air temperature as input, thereby providing an additional check on the functioning of the external sensors. During a sensor design competition that we ran for (mainly) African universities in 2013, one entry proposed to weigh the silica absorbent inside the measurement device to have a slow check on relative humidity (and a quick one on leakage!).

Cross-calibration within the network of stations is an important quality control step that is especially powerful given the stations are both closely spaced, and employing identical sensors. Clearly, the longer the time series produced by a (sub)network, the more one can say about outliers. In undertaking this approach, it is essential to develop the best estimates of any actual geographically based discrepancies in measurements taken at neighboring stations (e.g., based on elevation, aspect, and slope). We work together with the Oregon State University PRISM team, who has developed advanced data interpolation and quality assessment procedures. This strategy provides more discriminating power in identification of poorly functioning devices, but also provides the data needed to create optimal interpolated maps of measured parameters, which is of great value.

Satellite data will remain an important source of information for meteorological and hydrological modeling and predictions. Also for quality assessment and quality control, satellite images will play an important role, as well as for interpolation between stations. Radiation sensors can almost directly be compared with satellite observations. Other variables, such as rainfall and temperature can classically only be checked at a level of general consistency. By including both radiation and ‘classic’ sensors, TAHMO ground observations can serve to improve the accuracy of satellite-derived information. Sometimes improved ground observations and satellite-based information systems are seen as independent or even opposing pathways. A structural combination of both
through advanced modeling is, in our view, the way forward.

OPERATION

Education

As part of our operational model, we foresee a school-to-school program in which relatively rich schools will subscribe to a ‘buy one, pay two’ initiative, with one station being installed at a relatively poor rural African school. The two schools would then engage in a sister school arrangement and exchange information initiated with discussion of weather and climate, and the importance of both in their respective societies. By investing in schools, we expect that the stations will receive protection. The added advantage of the installation at schools is that it will be possible to enrich the curriculum with lessons about environmental observations, water, climate, and also electronics and computer science.

Such a model requires development of lecture and communication packages. There are, of course, diverse sociocultural settings in which this program will operate. We acknowledge that the design concept of no moving parts and being as inconspicuous as possible does take away from some of the opportunities for direct student engagement, which represents a significant compromise between system feasibility and the educational mission of TAHMO. One understands immediately how a wind vane makes invisible wind tangible, but its moving parts are subject to many modes of failure and thus is far from robust. The ultrasonic sensor currently being deployed is far more reliable, but essentially opaque to students, and requires special and rather advanced explanations to be understood. This is in part to be attended to by having students make their own devices to measure the wind that they can compare with the TAHMO data, but fundamentally reflects a compromise that illustrates the primacy of robustness in obtaining excellent data over other objectives.

The first modest school-to-school experiments will start this year (2014) by coupling schools in Idaho, USA, with schools in Kenya and schools around Rotterdam and Delft, Netherlands, with schools in Ghana. A sequential selection process was employed to find schools that had the greatest possibility of success. The level of enthusiasm for participation was striking, with African schools being willing to provide exceptional site support (e.g., willingness to cut down trees that contravene station fetch requirements), and happily providing their share of the cost of the stations.

Business Model

The TAHMO initiative addresses factors far beyond technical innovation. As pointed out earlier, these extend to novel strategies for data quality control and cross-cultural educational programs. However, the sustainability of TAHMO rests more on the business model than its scientific and educational value. This model has both economic and social components that address the issues encountered when installing devices across a continent. To motivate, finance, and support the installation and upkeep of the network, new business models had to be envisioned. TAHMO needs to cultivate an environment of supportive governments and a network of educators, scientists, engineers, and entrepreneurs who will employ the TAHMO data sets in building understanding and commercially significant products. The basic operating principle with respect to obtaining operating costs is that the use of TAHMO data for commercial products will only be allowed under contractual control specifying payment to TAHMO for that use. Data for scientific usage will be free of charge. We realize that the arrangements to support such a dual access system may be difficult but they are not unique and can be found, for example, for access to Twitter data and Google Earth Engine.

TAHMO cannot operate outside the public sector. Most countries have strict regulations about the gathering and dissemination of weather data and reserve the right to specific agencies such as meteorological and/or hydrological departments. Historically, monitoring of environmental variables has been tied to issues of state security by way of food security, and road/landscape conditions for potential armed invasions. While yet being relevant, the global availability of satellite estimates of rainfall is sufficient to address these security issues. Thus, ground-based stations no longer present any additional threat to sovereignty. Still, because of this historical consideration, legal arrangements allowing placement of stations are needed on a country-by-country basis. While the negotiation of these memoranda of understanding may appear onerous, in fact it brings buy-in to the program and sets the stage for governments to make use of the data that TAHMO will provide, and to provide TAHMO with historical data records that greatly increase the value of the newly collected data.

Most people find it natural that monitoring water resources, weather patterns, and climate change is important. It is further understood that governments or, perhaps, the United Nations, would be natural agents of such activities. However, since the mid-1980s, governments have sought to reduce spending on environmental monitoring, leaving these tasks to the domain of private initiatives. This can be seen
in the global decline in the number of public-sector observations of the hydrological cycle and associated climate phenomena. Therefore, if we want to fulfill the ambition of the TAHMO initiative, we will have to look for new business or governmental models involving partnerships between the public and private sectors and requires the directing of some of the monetary value of the network to individuals and businesses into its expansion and upkeep.

Most economic value produced by such data would typically materialize in a diffuse manner throughout society. Still, there are many ways in which private partners would profit from the data produced by TAHMO as is evidenced by the burgeoning installation of weather stations for single-uses, such as farm, airport, transit, and energy-sector applications. These single-use stations require the same initial and ongoing investment as do stations satisfying multiple tasks, thus illustrate the pent-up demand and resources available for such systems. As stated earlier, the economic impact of weather data in the United States is over US$30 billion/year, whereas the cost of the system is less than 1% of this figure. This points out the fundamental soundness of the investment in collection of weather data, wherein the returns on the investment far exceed the cost of obtaining these data, and this is all the more true for the TAHMO network that takes advantage of major decreases in sensor and cellular communication costs. We estimate that running one station will cost between $200 and $500/year, about 10% of the cost experienced by government-operated stations in the United States. Despite the relatively lower cost, this may yet sound like much in the context of rural Africa where farmers may earn less than a few hundred dollars per year. It is useful to consider the costs on an area basis: this is less than US$0.005/ha/year. These same weather data will typically allow insurance of crops with value generally exceeding US$1000/ha/year, or 200,000 times the cost of the station. Keeping in mind the agricultural context which represents but one of many applications, the overarching economic rationale for weather data is clear. The question remains how to have a tiny fraction of this value returned to maintain the station network. This is a difficult question to answer, and even more so when governments and scientists are given free access to the data, as is the TAHMO plan.

The fact that harvesting the weather data value is not straightforward explains the apparent dearth of commercial station networks. First, we point out that this perception is actually far from accurate. Although not widely known, there are highly successful continental-scale privately operated systems. A prominent example is that of Earth Networks, which currently operates over 8000 scientific-grade stations across the United States. Earth Networks followed a path akin to that of TAHMO, first gaining investment in stations through the educational value, wherein schools paid the cost of installation, for which they received a station and a highly developed science curriculum based on the station observations. Earth Networks then went on to market these data sets to a broad suite of industrial, agricultural, and governmental customers, with a globally expanding sensing network now including detection of greenhouse gases, lightning, and integrated by using high-performance computational models. Thus, the feasibility of such a network has been demonstrated.

Within the African context, one might first be drawn to direct sale of weather information to farmers. However, farmers typically know if there has been rain or not, so simple observations are far less valuable to them than are predictions. Instead, we observe great potential in value-added services to farmers that are based on weather data. An obvious example is crop insurance, which we discuss in some detail below. However, this is but one of many weather-based products on the market. For example, one of our commercial partners is FarmerLine, a start-up company in Ghana that sells information to farmers through text and spoken messages about market prices. They observe potential in obtaining and selling more content related to weather. This could be information about the onset of the rainy season, risks for certain plant pests and diseases, the location of good pasture sites for cattle owners, and so forth. In each case, the data collected by the weather stations need to be processed to produce information that is of specific use to certain categories of farmers. This opens the possibility that one does not have to charge farmers. Instead, one may sell the information to data enhancing companies such as FarmerLine who will add value to the information by processing it, enriching it with other sources of data or specific topical knowledge and sell their final data products to specific markets. Thus, while we expect it to remain a difficult proposition to sell information to individual farmers, integrators, such as FarmerLine, can realize significant value by developing products that reach populations of farmers.

A very promising broad-based user in the agricultural sector is insurance companies that sell crop microinsurance. Such insurance is considered to address the critical limitation of African agricultural productivity: protection of farmers against loss from investment in seeds and inputs due to unpredictable weather. A remarkable example of this opportunity
is provided by the Kilimo Salama program in Kenya. Kilimo Salama is a company that started out as a non-profit sponsored by the Syngenta Foundation. They have now become financially independent, insuring more than 100,000 farmers, based in large part on their own extensive network of cell phone-based weather stations. Payment to insured farmers depends on weather measurements within 25 km of the insured farm. Although the weather stations represent less than 1% of Kilimo Salama’s operating budget, lack of weather data is a primary constraint on geographic growth. TAHMO will be able to support such insurance schemes across the continent. Because historical data are so important to the development of risk estimates, getting stations running on the ground as soon as possible is essential to the prompt delivery of such valuable services in Africa.

Other services that could add value based on the data measured by the TAHMO stations include: informing commodity traders about harvests; warning air traffic with respect to severe thunderstorms; prediction of road conditions for emergency and commercial transit; protection of children at schools and populations in general from dangerous weather conditions; identification of high-value land due to microclimatic characteristics. Key to all these business models is that TAHMO data are combined with additional knowledge and models to cater to a specific niche. It is unlikely that all these businesses would be developed within TAHMO. Instead, we expect an ecosystem of commercial products to grow across the continent.

CONCLUSION

During the past 2 years, the TAHMO community has grown rapidly. The enthusiasm and energy that the TAHMO initiative generates is truly amazing and very encouraging for us as initiators. The community is very diverse, and we communicate through our website, LinkedIn, Facebook, and a recently started quarterly newsletter.

Equally important as the technological innovations are the business innovations that are needed. Everybody understands the need to measure better the water and weather to make optimal use of the natural resources. However, the time that governments take more tasks upon them is over and we have to look for new commercial partnerships to make this all happen. There are many business opportunities, from the expansion of weather-based micro-crop insurance (e.g., Kilimo Salama in East Africa), to information for farmers (FarmerLine in Ghana), and extreme weather warnings for air traffic (Earth Networks in Guinea). A single application will not be able to support the complete network, so we will have to find smart combinations and work in strategic partnerships for both technological and business development. Figure 3 gives a schematic overview of the different components of the TAHMO.

Owing to the strong support we have received over the past 2-year, we are confident that TAHMO will be a game-changing initiative. We invite all readers to be part of this development and share experiences and thoughts through tahmo.org.

REFERENCES

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