APPROACHES TO COMBINE TECHNOLOGIES FOR WEATHER OBSERVATION, STORAGE AND ANALYSIS

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Cover Photo: Satellite dish, Meteo Rwanda Credit: Asher Siebert

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ACRONYMS AND ABBREVIATIONS

ACLE	African Center for Lightning and Electronics
AGRHYMET	Agriculture, Hydrology and Meteorology Research Center of West Africa (Niamey, Niger)
AWS	Automated Weather Station
CCA	Canonical Correlation Analysis (a statistical forecasting technique)
CCAFS	Climate Change and Food Security (an initiative supported by USAID)
CDT	Climate Data Tools (an R based software for data merging and quality control)
CHIRPS	Climate Hazards group InfraRed Precipitation with Stations
CIRDA	Climate Information for Resilient Development in Africa
CIS	Climate Information Services
CMORPH	Climate Predictability Center Morphing Technique
CPT	Climate Predictability Tool
CRAFT	CCAFS Regional Agricultural Forecasting Toolbox
CSAG	Climate System Analysis Group (based at the University of Cape Town)
ECMWF	European Center for Medium Range Weather Forecasting
ECONET	Lesotho based telecom company
ENACTS	Enhancing National Climate Services
EUMETSAT	European Meteorological Satellite
FEWSNET	Famine Early Warning System Network
GCM	Global Climate Model
GCOSCM	Global Climate Observing System Cooperation
GEOCLIM	Geospatial Climate Analysis Tool
GEOCOF	Geospatial Climate Outlook Forecasting Tool
GEOWRSI	Geospatial Water Requirement Satisfaction Index
GFCS	Global Framework for Climate Services
GIS	Geographic Information System
GLOBE	Global Learning and Observations to Benefit the Environment (international science and education program)
GOS	Global Observing System
GUI	Graphical User Interface
ICPAC	IGAD Climate Prediction and Application Center
IRI	International Research Institute for Climate and Society
IRIDL	IRI Data Library
MLR	Multiple Linear Regression
LSI-LASTEM	Italian manufacturer of high quality meteorological sensors and station components
NMHS	National Meteorological and Hydrological Services
NOAA	National Oceanic and Atmospheric Administration (USA)
PCA	Principal Component Regression
PREPARED	Planning for Resilience in East Africa through Policy, Adaptation, Research and Economic Development (a USAID project)
QGIS	Quantum GIS (freeware open-source version of GIS)

RMA	Rwanda Meteorological Agency
SAS	Statistical Analysis System (a mathematical software)
SASSCAL	Southern Africa Science Service Center for Climate Change and Adaptive Land Management
SPSS	Statistical Package for the Social Sciences, a statistical software
SUMO	Small, Unmanned Meteorological Observer
TAMDAR	Tropospheric Aircraft Meteorological Data Reports
UCAR	University Corporation for Atmospheric Research
UNDP GEF	United Nations Development Programme Global Environmental Facility
USAID	United States Agency for International Development
WHYCOS	World Hydrological Cycle Observing System
WICOS	WMO Integrated Climate Observing System
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

The Global Framework for Climate Services lists meteorological observation as a key pillar in the overall framework, citing observation, data storage and data analysis as integral for serving public needs. In Africa, countries are exposed to a range of significant climate risks, including variability in water resources, environmentally sensitive diseases and dependence on rain-fed agriculture and therefore have a critical need for robust climate monitoring and seasonal and sub-seasonal forecasting to help inform decision-making across multiple sectors.

Over a range of time scales, there is a need to better understand climate variability, from multi-decadal forecasts to near-term impacts of climate change. Reliable evaluations are data intensive and require an appropriate array of meteorological station, atmospheric profiling and satellite observational data. Additionally, long-term planning and effective service provision by the national meteorological and hydrological services and regional climate research centers requires well maintained physical infrastructure, electronic databases, and capacity for sophisticated and appropriately tailored data analyses. Thus, building and maintaining appropriate observational networks for weather and climate observation is of critical importance.

Yet many African countries struggle to meet these needs due to financial constraints, logistical challenges, conflicts, and host of other challenges. This has resulted in decline observation network across Africa. To meet the challenges of a changing climate and growing population highly vulnerable to climate risks, it is imperative that investment in hydrometeorological observations and Climate Information Services (CIS) in Africa. Given the financial constraints, these investments need to reduce costs as much as possible.

This report explores the optimum use of different technologies and associated issues pertaining to meteorological observation, data management, and data analyses for CIS in sub-Saharan Africa. Key types of meteorological observation, including ground weather stations, atmospheric profilers, lightning detectors, weather radar, and satellite observations are reviewed and case studies are presented that showcase initiatives and innovative technologies. Tools and approaches to data management and data analysis are also discussed. Though a detailed analysis of the cost-effectiveness of different technologies is not offered due to insufficient data, the report offers low-cost approaches to address the challenge of sparse station networks and climate data scarcity.

Key recommendations

- When purchasing meteorological instruments, NMHS and donors should consider both the cost of the unit and installation as well as maintenance costs. For instance, the use of automatic weather stations has been rising steadily over many parts of Africa yet the cost of maintenance and spare parts (which have to be imported) have introduced considerable logistical and financial challenges.
- Projects purchasing observing equipment shall seek to ensure that observational data generated by such equipment be made available for international exchange in accordance with applicable WMO Congress Resolutions (Res. 40, 25 and 60) and WMO Regulatory Material, in particular WMO Publication 1160 (Manual on the WMO Integrated Global Observing System). Donors may consider technologies such as 3-D printing of automatic

weather stations and recoverable rawinsonde technologies to expand observational networks at lower costs, however, it is critical that the installation of these systems involve the local NMHS and provide a balanced investment of the real cost of operating and maintaining the system (human resources and capacity).

- Relatively poor status of Climate Data Management Systems (CDMS), particularly in Africa, prevents many NMHSs from efficiently (1) integrating AWS data and rescued data as well as (2) exchanging data, which also heavily impacted by restrictive national data policies. Investing in powerful CDMSs managed by highly-skilled personnel is of utmost importance as it will support efficient weather and climate services delivery. It is recommended that donors fund open source CDMS and ensure continuation of existing functional CDMS and not proposing new systems.
- When evaluating options for filling data gaps or lowering costs, NMHS should consider combining observations from different sources. For instance, optimal combinations of station rainfall measurements with satellite rainfall estimates can reduce the number rain gauges needed. Furthermore, leveraging satellite data may be particularly useful where there are gaps in historical data.
- Governments should consider public-private partnerships and multilateral donor-supported arrangements to enhance and support the capacity and sustainability of individual NMHS.
- NMHS may need to review data sharing policies in the context of a broader discussion on the benefits of climate services for national development. NMHS may contribute more to the national economy if climate data serve the public good rather than seeking to sell basic climate and weather data. Accordingly, governments need to support their NMHS to reduce their dependence on revenue from selling data. Revenue should only be derived from providing specialized data analysis and services.
- As this research shows, there are number of tools and technologies that could be useful to bridge gaps in data collection, analysis's, storage, and dissemination. Emphasis should be placed on vetting these, recommending those that meet to WMO requirements and guidelines. As the next step, the approved tools and methodologies can be brought under a centralized hub, such as WMO Climate Services Toolkit (CST) that facilitates access to guidance, data, software tools, and training. Subsequently, attention will also need to be focused on developing relevant user capacities as procedural and human resources-related gaps on the user end constitute the biggest stumbling block in efficient use of tools and technologies.

1. INTRODUCTION

1.1. Background

The Intergovernmental Panel on Climate Change (IPCC, 2014) has identified Africa as one of the most vulnerable continents to climate change due to its high exposure to climate stress and low adaptive capacity (i.e., poor infrastructure, limited access to markets, high illiteracy and poverty rates). The impacts from a changing climate are projected to be both far-reaching and spatially variable in Sub-Saharan Africa (SSA). During the last half of the 20th century, most of southern Africa has experienced upward trends in annual mean, maximum, and minimum temperature, with the most significant warming occurring during the last two decades (Cervigni et al., 2015). This changing weather patterns pose a particularly critical threat to African populations given that rain-fed agriculture contributes a significant portion of the national GDP of most countries in the region and provides livelihoods for a large percentage of rural populations -- up to 95 percent in some areas of SSA (Alexandratos and Bruinsma, 2012). . Further, rainfed agriculture tends to be especially important to the extreme poor – who are disproportionally women - and for whom even small changes in inter- or intra-annual rainfall distribution can have devastating impacts. Over the coming decades the situation is likely to be further exacerbated by continuing rapid population growth (United Nations, 2017) and climate change, increasing the need for significant investment in CIS data and services. Failure to adequately address the impacts (and causes of) climate change, especially changes in rainfall patterns, could jeopardize decades of development investments and improvements in livelihood conditions. There is a growing interest in using CIS to strengthen the adaptive capacity of rural communities to reduce their vulnerability to climate change and variability.

CIS encapsulates both the provision of climate and weather information and related advisory services at temporal and spatial scales relevant to a range of stakeholders, including decision-makers at a national (even regional) level and down to smallholder farmers. Successful CIS provide accurate, spatially resolved, daily, ten-day, monthly, and seasonal forecasts and advisories in a timely and accessible manner, as well as historical trends and monitoring products. CIS are important because they address the immediate needs of agricultural communities (e.g., what will happen tomorrow and what will this rainy season be like), while also building the foundation of national and regional information systems to support adaptation to longer-term and larger-magnitude climate shifts. CIS is also essential for insurance products tailored to the needs of small farmers which pay based on defined weather events (e.g., lack of rainfall). Insurance can facilitate access to credit allowing farmers to invest in measures that may improve productivity.

The development of effective CIS requires access to reliable climate and weather information, in most cases involving National Meteorological and Hydrological Services (NMHS) as key stakeholders. NMHS commonly serve a national mandate to observe, forecast, and issue warnings for pending weather, climate and water threats. Accurate forecasting depends on a network of global, regional, and national remote and in situ observations of the atmosphere, oceans, and land that are conducted by NMHS with multiple partners. Climate and weather observations are also often made by other agencies (e.g., agriculture, aviation, water, and energy power) and increasingly the private sector, but and these efforts are not often effectively coordinated. In many African countries, this results in an absence of timely and reliable local weather forecasts. Yet there has been limited research evaluating and synthesizing knowledge that can lead to sustainable CIS models and systems.

1.2. Assessing Sustainability and Effectiveness of Climate Information Services in Africa Project

In light of the needs for reliable, timely, and accurate CIS in Africa, the USAID-funded "Assessing Sustainability and Effectiveness of Climate Information Services (CIS) in Africa" (Sustainable CIS project) program has been designed to conduct research to better understand how to design and implement sustainable CIS models within and alongside NMHS. The project is being implemented by a consortium led by Winrock International,with the International Research Institute for Climate and Society (IRI), the Climate System Analysis Group (CSAG), the AGRHYMET Regional Center, and the Global Framework for Climate Services (GFCS)[1] as partners. The project objective is to develop models and options for the sustainable delivery of CIS in SSA, and to consolidate and extend knowledge on existing CIS in SSA. These project outputs are geared toward identifying and improving existing CIS programs provided by the public and private sectors, as well as to design and assess potential new CIS not yet implemented, but are promising options relevant to local contexts.

The project has three work streams:

1.) Sustainability assessment. This includes the development of metrics to assess effectiveness and sustainability of NMHS to deliver CIS, with a baseline assessment of select NMHS, and advice on how to bridge existing gaps.
2.) Identification of options to improve the sustainability of CIS. This includes an assessment of the market for CIS in SSA, private sector models that participate in CIS, and development of sustainable financial models for CIS delivery in SSA.
3.) Partnership building, synthesis, sharing and uptake of knowledge and lessons learned.

This report is part of the second work stream to identify options to improve sustainability of CIS. It includes some global data and examples but focuses primarily on SSA.

1.3. Report objectives and methodology

This report explores different technologies (or combinations of technologies) for weather observation, climate database management, and climate data analyses. The main objective is to identify combinations of technologies and tools that can help reduce costs for NMHS, presenting the strengths and weakness of the different technologies. This report was produced through a desk study of peer reviewed and grey literature, as well as interviews and solicitation of expert opinions from project staff who offer many years of combined experience in these topic areas.

[1] GFCS is a global partnership of the World Meteorological Organization (WMO) with the UN International Strategy for Disaster Reduction, the World Health Organization, the World Food Programme, the Food and Agriculture Organization of the UN, and others.

2. TECHNOLOGIES FOR WEATHER OBSERVATION

2.1. Introduction

Building and maintaining appropriate observational networks for weather and climate observation is of critical importance for seasonal forecasting as well as a host of weather-dependent sectoral applications. Budgetary constraints, logistical challenges and historical and current realities must be carefully considered, and where possible, observational networks should strive to be compliant with the guidelines established by the World Meteorological Organization (WMO Instrument Guide, 2014).

From the perspective of weather observation, the ideal set-up is a network of spatially dense ground-based weather stations equipped with multiple sensors to monitor different meteorological fields, with stations staffed by well-trained technicians capable of regular maintenance and timely repair as needed. Additionally, this system should be complemented by a series of surface-, air-, and spaced-based observation platforms.

Such a system exists at the global level, and is called the "Global Observation System" (GOS), which monitors the state of the Earth's atmosphere from the surface of the earth, upper air, and outer space(Figure 1). It is operated by multiple agencies including national or international satellite agencies across the globe. The GOS focuses on cost-effectiveness, long-term sustainability, and new collaborative arrangements among WMO members. This system, considered to be WMO's most important program for observing, recording and reporting on the weather, climate and the related natural environment, has two main objectives:

1.) To improve and optimize global systems for observing the state of the atmosphere and the ocean surface to meet the requirements, in the most effective and efficient manner, for the preparation of increasingly accurate weather analyses, forecasts and warnings, and for climate and environmental monitoring activities carried out under programs of WMO and other relevant international organizations;
2.) To provide the necessary standardization of observing techniques and practices, including the planning of networks on a regional basis to meet the requirements of the users with respect to quality, spatial and temporal resolution and long-term stability.

Although the space-based component of GOS is run by NMHS and other actors in the developed world, most of the data could be accessed and fused by NMHS in Africa.

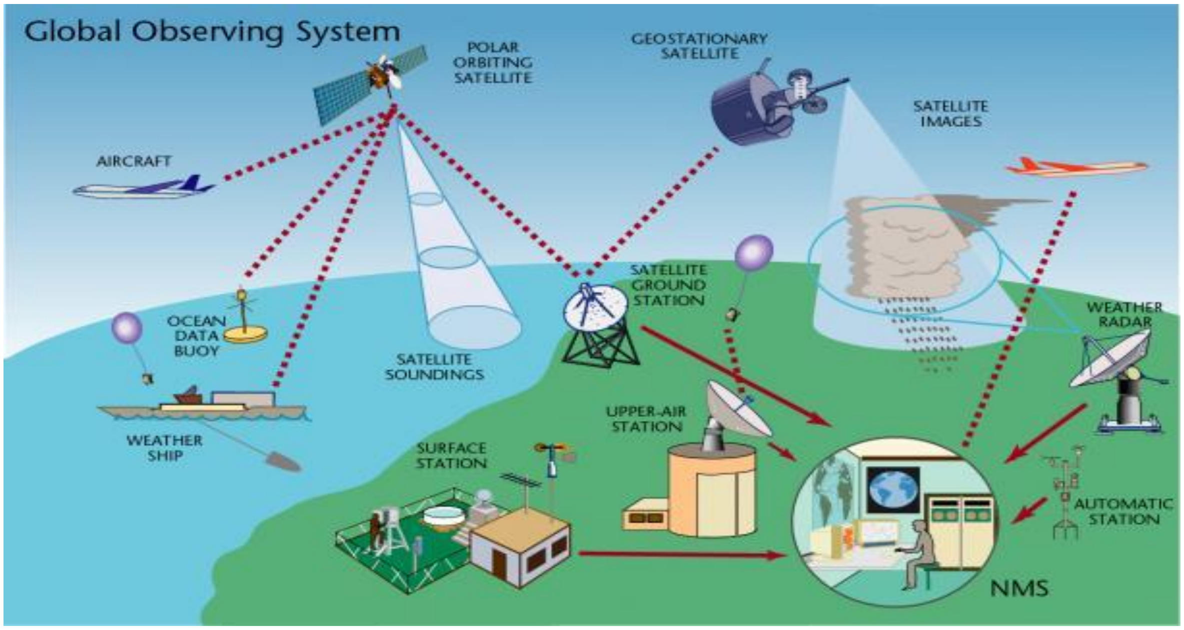

Figure 1: WMO's Global Observing System[2](Global Observing System, 2016)

Different components of the GOS have specific strengths and weakness and serve various purposes. The optimal use of such a system requires complementing the weakness of one component with the strength of the other. For instance, tradeoffs must be made between station density and/or location, sophistication, number of sensors offered by ground instrumentation, and observations from space-based platforms. Factors such as quality, spatial and temporal resolution, as well as accessibility to products from the spaced-based systems all must be weighed. Furthermore, factors such as the cost and frequency of maintenance operation, as well as the spatial coherence of the climate itself, should be part of the decision-making framework to formulate national meteorological and hydrologic services.

To this end, this report will explore various types of station-based, upper air and space-based weather observations and will present important concepts, considerations and tradeoffs to support NMHS in Africa to overcome observation challenges cost-effectively.

2.2. Surface Weather Stations

Measurements collected by weather stations around the world serve as the primary source of climate. The main strength of station observations is that they represent the "true" measurements of the climate variable of interest. However, in many parts of the world data scarcity persists and coverage is thin and/or declining (i.e. oceans, remote regions, and economically poorer regions). In addition, station measurements represent mainly the weather conditions close to the stations (as opposed to a wider area), and because they are often reliant on human observers, are prone to human and other measurement errors.

2.2.1. Conceptual Overview

Broadly speaking, "complete" weather stations that constantly monitor and report a large suite of measurements may be "agricultural" or "synoptic". Agricultural weather stations generally have sensors for wind speed/direction (anemometer), air pressure (barometer), temperature (thermometer), relative humidity (hygrometer and/or psychrometer), precipitation (rain gauge), solar radiation (actinometer), soil moisture (soil moisture sensor), soil temperature, and evaporation (either pan evaporation or by lysimeter).

Synoptic weather stations typically have more sensors, and in addition to most of the sensors included in agricultural stations, they monitor atmospheric visibility and sometimes cloud ceiling (which are critical metrics for aviation applications). Consequently, many airports have synoptic weather stations situated onsite.

Additionally, "climatological stations" may be used to complement stations with a more active recording mandate. Informing a region's climatology may require a smaller suite of observations or a less frequent interval of recording than "operational" meteorological stations. Typically, climatological stations include measurements of temperature, wind, relative humidity, lightning and rainfall. Furthermore, in many contexts in Africa, rainfall is considered the most important climatic variable and there are many rain gauges that are not accompanied by sensors for the other atmospheric variables.

Generally, the higher the spatial density of observation stations and the higher the temporal frequency of observations, the more complete the picture of a nation's or region's climate can be. However, tradeoffs between station density, purchase and installation costs and maintenance, and data processing costs need to be properly managed. Furthermore, in nations with complex topography and different climatological/ecological zones in close spatial proximity, there is greater need for a high density of spatial observation. In regions with less dramatic spatial climatic contrasts, the need for station density may be less.

Further, to enhance cost effectiveness, station density should be focused more on building weather observation capacity and accuracy near population centers and across distinct climate regions more than installing observation stations according to a regular grid. For example, much of Algeria south of the Atlas Mountains is uninhabited desert, so while a few stations in the desert are necessary, building a dense array of ground observations in this part of the country would likely be infeasible, prohibitively expensive, and perhaps unnecessary. By contrast, maintaining a dense array of ground observations in the northern part of the country where the majority of the population lives and there is a sharper gradient of topography and climatic type is of critical importance.

2.2.2. Design challenges

There are several weather station design challenges that are differentiated between tropical developing world contexts and mid-latitude developed world contexts. In tropical humid environments, humidity-induced mold can undermine electronics, while in tropical arid locations dust and sand can cause mechanical corrosion to components. Further, sealed electronics enclosures can reach very high temperatures when faced with intense sunshine of the tropics. In addition, occasionally insects and/or other small animals can gain access to station equipment and compromise function. As such, there is a need for more durable design for AWS in the tropics that require minimal maintenance yet WMO guidelines generally tend to reflect a mid-latitude bias (Snow 2013, Snow et al. 2016).

2.2.3. Overview of Automatic Weather Stations (AWS)

Costs associated with purchase, installation, and maintenance are typically lower for manual instrumentation than Automatic Weather Stations (AWS). As such, manual stations are the most widely used for weather observations over Africa. However, there are additional costs and complications associated with training observing staff and ensuring continuity of observational protocols so many NMHS in Africa are deploying AWS.

Potential vendors who have operated around the world, including in East Africa, include (but are not limited to) Technosky, Vaisala, Lambrecht and Microsure. While personalized multi-sensor weather stations can often sell for under $1,000, most quality, WMO-compliant weather stations for procurement by NMHS can cost in excess of $25,000, but not all need to be as expensive as those listed in the Case Study presented below for Rwanda. Vaisala provides several WMO-compliant automatic weather observing systems and the French company Cimel advertises the durability of their products in harsh weather conditions. Clearly, procurement costs must also be weighed against maintenance and integration costs.

Case study of current practices (Rwanda)

Rwanda is one of the geographically smaller nations on the African continent at 26,000 sq km, and has 36 agricultural stations and 5 synoptic stations (one each at each of the nation's five airports). Additionally, there are many climatological stations and automated rain gauges. The Rwanda Meteorological Agency (RMA) manages Rwanda's stations and the AWS were manufactured by the Italian manufacturing company LSI-LASTEM.

The total purchase cost outlay to RMA for the agricultural and synoptic stations is on the order of $750,000, with costs breaking down to approximately 22,000 Euro ($24,500) for each synoptic station, 15,000 Euro ($16,700) for each agricultural station, 3,750 Euro ($4000) for each climatological station, and $1,800 for each automatic rain gauge. Note that these costs do not include costs associated with installation, maintenance, or staffing (personal discussions with RMA staff member Francois Habineza and LSI representative Jean Francois Gakwaya).

Case study of technological innovation: 3-D printed weather stations

Scientists at University Corporation for Atmospheric Research (UCAR) in the United States have developed an innovative and potentially considerably lower cost approach to ground-based weather observation. Using 3D printing to manufacture automatic weather stations, the estimated cost for the parts and materials for one of these stations can be as low as $300 (for a “complete” multi-sensor AWS). Labor costs associated with manufacture, costs of using the 3D printer, maintenance, and installation are additional to this figure, but it is nevertheless an approach that has the potential to significantly reduce costs in the resource-constrained environment in which many African meteorological services operate (Kucera and Steinson, 2016).

Two initial pilot projects using this approach are now underway in Zambia and Kenya. The project in Kenya has been implemented in collaboration with the GLOBE program and has installed weather stations at various schools throughout the country. After training, partners have built five weather stations using 3D printing, with more expected. In Zambia, there have been challenges associated with resources, such as maintaining air time on SIM cards to enable data transmission. Nevertheless, the two lead scientists for this initiative, Paul Kucera and Martin Steinson, will be launching a broader Southern Africa regional initiative soon (Martin Steinson, personal communication).

While fairly new and perhaps not fully vetted or tested, this cutting-edge technological approach offers the potential to dramatically reduce costs for surface atmospheric observation, which will be a significant benefit to many NMHS in Africa. More complete exploration and vetting of this technology and other available technologies and methods mentioned in this report, such as CHIRPS, ARC, RFE, is encouraged.

Figure 2. Photo of 3D-PAWS location at the Bio-Med College at the Salvation Army Mission, Zambia https://www.iepas.ucar.edu/core-programs/3dpaws/

2.3. Upper Air Observations

A key component of atmospheric observation is the study of variables at different levels of the atmosphere. Thus, upper-air observations are an integral component of the Global Observing System. Historically, this has most often been accomplished by use of sensors mounted in radiosondes or rawinsondes on weather balloons. Radiosonde/rawinsonde observations typically provide measurements of altitude, pressure, temperature, relative humidity, wind speed, and direction during the course of the weather balloon's flight, and may also measure some components of atmospheric chemistry. Currently there are around 1300 radiosonde launch sites globally connected to the World Meteorological Organization's coordinated efforts. The map of the global distribution is shown below (Figure 3). While many African nations have at least one radiosonde launch site, the spatial density of radiosonde launch sites over Africa is very sparse. Further, many of the available sites are not fully operational.

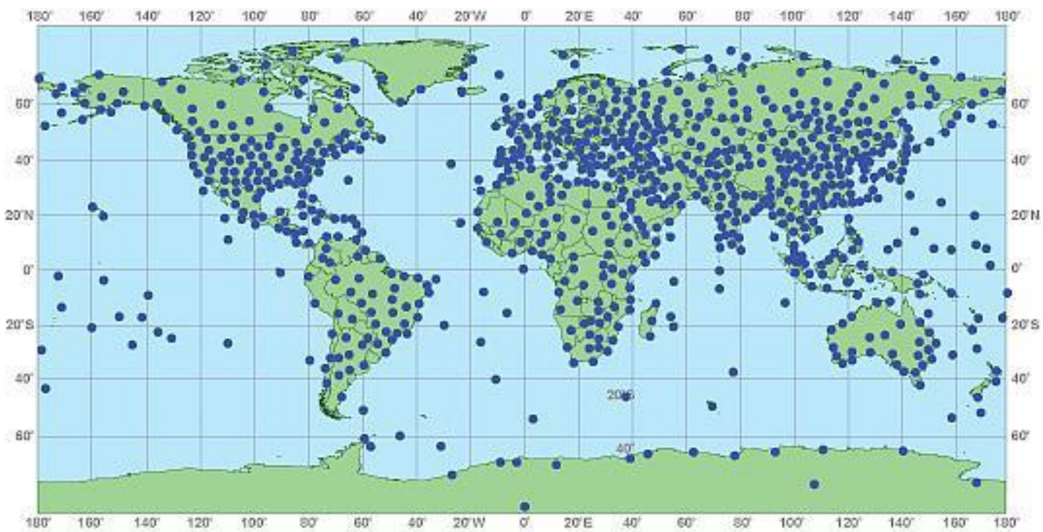

Figure 3. map of the global distribution of radiosonde launch sites ("Radiosondes" National Weather Service, National Oceanic and Atmospheric Administration)

2.4. The Use of Remote Sensing in Observations

2.4.1. Introduction

As described above, conventional surface and upper air stations collect observations of meteorological variables every day at thousands of meteorological stations around the world. However, there are many parts of the world that conventional stations do not cover, such as remote areas like deserts, mountainous regions, and oceans. Further, even areas that are not considered remote have sparse coverage in parts of Africa.

Remote sensing, which is the process of acquiring information about the Earth's surface, subsurface and atmosphere remotely from sensors, has been used to supplement conventions observations. Different sensors, such optical, infrared, radio- and microwave, have revolutionized climate observations by providing better spatial and temporal coverage. Different climate variables such as precipitation; cloud amount; radiation fluxes; radiation budget; sea surface temperature; wind vectors and speed; atmospheric temperature; and humidity and wind profiles can now be measured or estimated using remotely sensing. This has significantly improved access to climate data over areas with limited number of meteorological stations or areas not covered by conventional stations. While remotely sensed weather data are of particular importance to Africa given the sparse conventional station network over the continent, they may fall short of the required accuracy and homogeneity measurements offered by data collected from conventional stations. Thus, remote sensing observations can be used to complement conventional observations, but not as a substitute.

There are three main categories of remote sensing platforms: i. Surface-based platforms such weather radars; ii. Aircraft-based based platforms such as aircrafts with automatic recording systems, and iii. Space-based platforms such satellite sensors. The next section will further discuss these and provide examples.

2.4.2. Surface-based platform

There are different surface-based remote techniques, the most common being weather radar. Others include lightening-detecting networks as well as the use of mobile phone towers. These three different techniques are presented below.

Weather Radars

Weather radar detects precipitation and other atmospheric features (such as clouds) and are typically situated on the ground, though there are also lasso space-based weather radars on satellites. This discussion focuses on ground-based radars. The radar technique works by sending short pulses of high-power microwave energy to a target and then measuring energy scattered back by the target precipitation. The location of the precipitation can be determined from the azimuth and elevation of the antenna and the time between transmitting and receiving the reflected energy. The amount of the received energy provides information about the nature of the precipitation.

There are different types of radars and the primary technical distinction is the wavelength range or specifications of the emitted pulse. In general, longer wavelength radar pulses are better at picking out larger features (hail, large raindrops) and can generally penetrate longer distances. Shorter wavelength radar pulses are more adept at detecting smaller features (the small droplets in fog), but generally experience attenuation and scattering effects at shorter distances, so cannot be used to detect features further away. Common wavelengths in practice are the S band (10cm) and C band (5 cm). X band (3 cm) radars are generally used just for shorter ranges and Ka band (1 cm) radars are generally just used to study small droplet phenomenon like drizzle and fog. Most modern weather radars in practice are Doppler radars, meaning that they operate on the principle of emitting pulses of microwave energy at specific wavelengths at specific time intervals and interpret the amount of energy as well as the shifts in in frequency (Doppler shift). The Doppler shift is a phenomenon by which a frequency (or wavelength) of a reflected wave is modulated by the velocity of the reflecting object with respect to the receiving object. This information is used to estimate speed of the target (e.g., a cloud formation) and its direction of motion.

Weather radar data are used widely for weather monitoring, aviation, research, in television weather forecasts and by national weather services across the world. Radar data can also be incorporated into numerical weather prediction models to improve forecasts.

Strengths

Radars can cover a relatively large area (up to 300km radius) and can provide information every minute. This makes them ideal for monitoring fast moving rainfall system over a wide area. As a result, weather radar technology has been extremely valuable to national and local weather services around the world for critical operational near-term weather forecasting activities. Without reliable networks of weather radar data and imagery, accurately forecasting evolving storms would be exceptionally challenging. In addition to giving indications of the intensity, location, and movement of storms, modern weather radars may also be able to pick out certain dynamic features of the most dangerous types of storms, such as the "hook echo" of tornados where the intensity of microbursts and derechos and the timing of the arrival of rain bands or an eyewall associated with a tropical cyclone. As a result, radars are indispensable for applications such as aviation safety.

Weaknesses

There are different technical challenges with of weather radars. However, the main concerns are their operational weakness, including the following:

- Radars do not measure rainfall. Rather, it is estimated from the measured energy and therefore there may be errors associated with radar data or the estimate derived from it;
- Depending on the size of the country, several radars may be needed to cover the whole country;
- Physical barriers such as mountains can block radars signals, making its use over mountainous regions a challenge;
- In the context of SSA, radars are prohibitively expensive to purchase, install, and maintain (millions of U.S. dollars) and maintenance costs are often overlooked, leading to operational challenges;
- Requires specific expertise to maintain and use, which may not be available in many NMHS in SSA

Summary

Weather radar is a critically important technology for real-time weather monitoring and forecasting. They can provide information over relatively large area at short time intervals. On the other hand, the costs associated with obtaining, running, and maintaining weather radars has to be realistically considered, particularly in the context of SSA.

Lightning Detectors

Lightning sensors scan a range of electromagnetic frequencies to detect electrical discharges inside clouds, between clouds, or between clouds and the ground. There are three basic types of lightning detectors: ground-based systems, mobile systems and space-based systems. Ground-based and mobile systems use radio direction finding techniques to calculate the proximity and severity of lightning activity. Accurate detection of the location of lightning events requires more than one lighting sensor as these ground-based systems use triangulation from multiple sensors to identify the location of a lightning strike. The accuracy and efficiency of a lightning-detector network drops progressively toward its outer boundaries.

Strengths

A network of lightning detectors can be used to obtain data over a large area and it is possible to use data from outside one's country, enabling wider area coverage and accuracy. Data from ground-based lightning detectors and mobile systems can generally be quickly integrated into operational response and forecast operations and are generally cheaper than using radars to cover the same area.

Weaknesses

There are many technical and operational challenges associated with using lightning detectors, including the following:

- Though cheaper than radars, the installation, maintenance and use of lightening sensors can be considerable (the cost one sensor is up to hundreds to thousands of USD);
- Ground-based lightning detectors can only properly locate a lightning event if at least three detectors to triangulate the signals, increasing costs of installation, maintenance and use;
- Lightning sensors detect electrical activity in clouds, which may or may not be related to rainfall amount;
- Lightning detectors only estimate precipitation coming from the kind of clouds that produce lightning (convective clouds) and thus miss rainfall from other cloud types.

Integration with Weather Radar for Aviation applications

To provide the best services, lightning detection systems should be (and often are) integrated with weather radar to offer the most complete picture of evolving intense convective systems. Many modern aircraft use both plane-mounted radar and plane-mounted lightning detection systems to avoid or minimize the risks of flying in strongly convective, lightning prone environments.

Case study (Uganda)

In 2013, a detailed review of Uganda's meteorological services was carried out and recommendations were made by the US Trade and Development Agency. The report found that the Uganda National Meteorological Agency was underfunded, and while staff were generally trained and willing undertake improvements, there were a number of key deficiencies. Recommendations for expanding and improving the coverage of observations were made and acted upon (funded largely by multinational consortia and international financial institutions) in the years following.

Thus far the estimated return on investment is between five and ten-fold (Snow et al., 2016). To address a lack of lightning detection (not just in Uganda, but across much of the continent) a new institution, based in Kampala, Uganda, called the African Centre for Lightning and Electromagnetics (ACLE) was created which established networks of lightning sensors in most of the East African member states. It is difficult to quantify the impacts in terms of lives saved or property damage avoided to date, but this development is clearly a step in the direction of helping to offer protection against severe weather events.

Rainfall Detection from Cellular Communication Networks

Cellular communication-based rainfall monitoring is made possible by the fact that rain droplets absorb and scatter, or attenuate, the signal sent from one telephone tower to another. By measuring the decrease in the signal during rainy weather and knowing the signal level during dry weather, one can estimate the average rainfall intensity between telephone tower antennae. As there are large number of microwave telecommunications links many SSA countries, cellular rainfall monitoring could help supplement ground-based measurements. The data also may be obtained for free, since cell phone companies collect the data to monitor the loss of signal strength between their cell phone towers to assess reliability. Thus, investment in this system is limited to obtaining and analyzing data.

WMO explores development of new standards for estimating rainfall based on cell phone signal attenuation: (i) standard for deriving rainfall estimate from signal attenuation information with WMO Commission on Instruments & Methods of Observations (CIMO) and (ii) standard for exchange of signal attenuation information between cell phone operators and national meteorological services with International Telecommunication Union (ITU). Further steps towards quality assessment and standardization will be presented at the WMO Commission for Instruments and Methods of Observations (CIMO) Technical Conference in October 2018.

Strengths

In regions with sparse rainfall gauge but ample cell phone coverage, this approach offers a cost effective and promising means to fill gaps, so long as the number, density and location of cell phones can be accurately estimated and the attenuating effect of rainfall can be properly estimated and calibrated.

Weaknesses

There are several potential limitations/challenges to this approach:

- Mobile phone usage and coverage varies considerably among countries so the degree of refinement in estimating the rainfall-induced attenuation may vary;
- In regions with weak cell phone signal strength and/or limited cell phone usage, the efficacy of this approach may be limited;
- Rain droplets of different sizes, precipitation types, and levels of intensity may have different attenuation effects which may be difficult to differentiate, so in practice it may be challenging to assess the details of a storm by this type of extrapolation;
- The approach relies on mobile phone companies' cooperation and provision of data.

Summary

The development of the ability to assess extrapolated rainfall location and intensity by the attenuation of cell phone signals is an important advancement and should be explored further in the context of climate information services for Africa. However, there are technical and logistical challenges that should not be overlooked and this technology should be viewed as complementary to the need for expanding and maintaining a reliable network of weather stations.

2.4.3. Aircraft-based platforms

As the name indicates, this approach involves installing sensors onboard aircrafts. One of these types of systems is SUMO (Small, Unmanned Meteorological Observer), where various meteorological sensors are mounted on a lightweight remotely controllable airplane that takes measurements of the atmospheric boundary layer up to an altitude of around 3500m (Reuder et al., 2009). An approach related to SUMO, but with a somewhat improved range, uses "glidersondes" where telemetry sensors and instruments are mounted on a glider that is sent up with a weather balloon. When the balloon pops, the parachute is attached to the glider and when the glider (mounted with sensors) reaches a specified altitude, it is "guided" back to the launch site via GPS navigation (Lafon et al., 2014).

Another approach makes use of commercial airlines. Long-distance aircraft are fitted with automatic recording systems that report temperature and wind, and in some cases humidity along their flight path. The collected data are automatically fed to the aircraft communication system for transmission to the ground, or alternatively, a dedicated processing package can be used on the aircraft to access raw data from the aircraft systems and derive the meteorological variables independently. The TAMDAR (Tropospheric Aircraft Meteorological Data Reports) is one such example. This approach is used in the United States where atmospheric sensors are placed on commercial airplanes and record observations when the flights are below 500 hPa. This helps fill spatial gaps in regions where radiosonde density is low at minimal additional cost and the sensors can be reused if properly designed and maintained (Moninger et al., 2010).

Strengths

Costs associated with traditional weather balloon/radiosonde launches have historically been presented as "non-recoverable", in that new weather balloons with new instrumentation must be constructed for each launch. In a budget-constrained environment, this (often multi-hundred dollars/day) cost clearly represents a significant challenge and drain on resources. Yet many of the aircraft-based sensors have addressed this problem. Further, installation of sensors onboard commercial airlines is an approach to profile the atmosphere at a relatively low cost.

Weaknesses

The main weakness may include the following:

- The use specialized aircrafts would be expensive for most countries in Africa;
- As commercial aircrafts fly mostly at constant altitude, the can only take measurements of the atmosphere along their routes (no vertical profiling);
- There are potentially a large number of error sources contributing to aircraft measurement errors.

2.4.4. Space-based platforms

The most common spaced-based remote sensing is the use of sensors onboard satellites orbiting the Earth. Satellites provide wide geographical coverage, especially over areas with sparse or completely missing ground observations and satellites sensors can be used to estimate climate variables such as rainfall, temperature, wind, cloud type and properties and atmospheric water vapor. Rainfall is the most widely used climate variable derived from satellite measurements.

Rainfall estimates from satellite sensors go back over three decades and there are a large variety of satellite rainfall products freely available from different centers including the Global Precipitation Climatology Project (GPCP, Adler et al., 2003), African Rainfall Climatology version 2 (ARC2, Novella and Thiaw, 2013), and the Tropical Applications of Meteorology using SATellite and ground-based observations (TAMSAT) rainfall estimate (Maidment et al. 2014), the Climate Hazards group InfraRed Precipitation with Stations(CHIRPS, Funk et al. 2015), and Climate Prediction Center Morphing Technique(CMORPH, Joyce et al. 2004). The ARC and TAMSAT products are available only over Africa.

Strengths

The main strengths of satellite estimates include global coverage, improved temporal and spatial resolution, and the fact that many satellite rainfall products are freely available from different centers. As a result, satellite rainfall estimates are used widely by NMHS and other organization in SSA.

Weaknesses

Satellite proxies suffer from several shortcomings including accuracy, short time series, coarse spatial resolutions for some products and variables, temporal heterogeneity, and limited climate variables.

Summary

In addition to ground instrumentation, it is critical for African NMHS to make use of a broad suite of satellite measurements and blended satellite-station products to complement their networks of ground stations and atmospheric profile measurements. However, careful attention should be paid not only to issues of spatial resolution and/or temporal resolution and completeness of data, but also to verification and consistency of the satellite data with ground-based observations.

2.5. Approaches to Reduce Costs

2.5.1. Combining Data from Different Sources

It would be ideal to have a dense rain gauge network for monitoring rainfall over a given country. However, this is very expensive and practically impossible where there are remote and inhabited areas and station security issues. Installing weather radars may help to overcome these challenges, however, radars are prohibitively expensive to install and maintain, particularly for large countries that need many radars to achieve proper coverage. A network of lightning detectors could be used to obtain data over a large area at a relatively cheaper cost compared to weather radars yet they only detect specific cloud types that produce lightning, therefore potentially leaving other types of clouds and associated rainfall undetected. Satellite rainfall estimates can cover most of the globe and are available at no cost to the African NMHS yet suffer from estimation errors.

When balancing technology and cost options, combining data from different sources (station, radar, satellite, etc.) may offer a way for NMHS to fill gaps cost-effectively. For instance, station measurements form a sparse ground network could be combined with estimates from lightning detectors and satellite rainfall estimates. As shown in Figure 4, rainfall estimates from lightning detectors can be used to improve satellite rainfall estimates, because lightning detectors capture convective rain reasonably well. Then, the combined product can be further improved through a correction process using station rainfall measurements. This approach combines the strengths of these different products and technologies and could be cheaper than installing a dense rain gauge station network or using radar. This cost reduction comes mainly from the fact that the satellite rainfall product can be obtained free of charge.

Satellite products may not be as good as station observations yet station measurements have limited coverage. Thus, it would make sense to combine the spatial coverage by satellite estimates with the accuracy of the station measurements. If used wisely, this would reduce the number of rain gauges needed to cover a country and hence reduce costs. This approach has also been used by researchers to overcome data sparsity. For example, Wilby and Yu (2013) combined surface meteorological observations, remotely sensed data, physiographic indices, and regression techniques to produce gridded maps of annual mean precipitation and temperature for Yemen. Most global satellite rainfall estimation methods do blend satellite rainfall data with station measurements yet many global centers have limited access to station data from NMHS in Africa and as a result, the improvements offered by existing blended products are limited.

Combined products may not be as accurate as station measurements but nevertheless offer advantages. In addition to better coverage, they typically better represent rainfall over a large area, as opposed to rain gauges which represent only the area in close vicinity of the station. Yet an important shortcoming is that the combined satellite and ground observation data approach may not be applied to all climate variables. For instance, there are no reliable estimates of temperature from satellite measurements. However, climate model reanalysis model products have been used for temperature (e.g., Dinku et al., 2017)

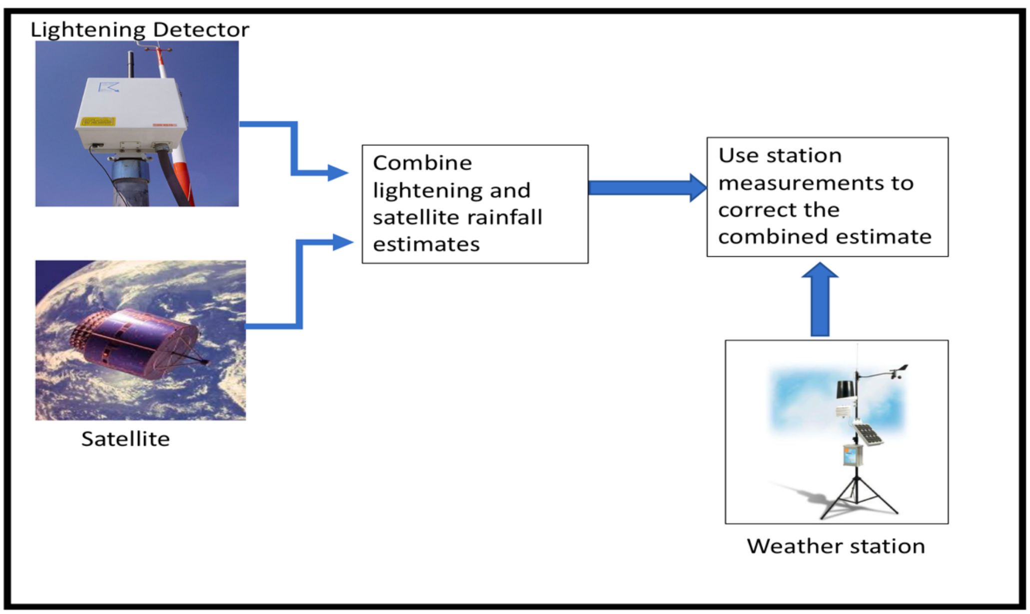

Figure 4: A schematic example of combining rainfall data from different sources.

Most satellite rainfall estimation methods do blend satellite rainfall data with station measurements and these include the Climate Hazards Group Infrared Precipitation with Station (CHIRPS), the African Rainfall Estimate (RFE), the African Rainfall Climatology (ARC), among others. However, many global centers can only access limited number of station data from NMHS in Africa, making these improvements in blended products more limited for the region. CHIRPS could be the exception, in that it was able to access many more stations relative to other similar products, yet the number of stations used in CHIRPS has been declining steadily over many parts of Africa.
The ENACTS (Enhancing National Climate Services) is a unique effort that strives to overcome availability of climate data in Africa (Dinku et al. 2014, 2016, 2017). The main strength of ENACTS

is that it works directly with NMHS to improve the availability of climate data by both organizing and instituting quality-control measures on all available observations from national observation networks and combining this data with data from proxies (i.e., satellite estimates for rainfall, digital elevation models, and reanalysis products for temperature). As a result, ENACTS helps NMHS overcome issues of data scarcity and poor data quality by generating datasets that are spatially and temporally continuous. ENACTS has been implemented in several African countries and has resulted in the production of climatologies at relatively high temporal and spatial resolutions while also improving observed data sets. In addition, new observations are automatically added to the data record. Figure 5 shows an example where data from about 40 stations over Zambia are combined with satellite-only product resulting in a merged product that overcomes the weaknesses of the two inputs, including a sparse station network and underestimated satellite rainfall outputs.

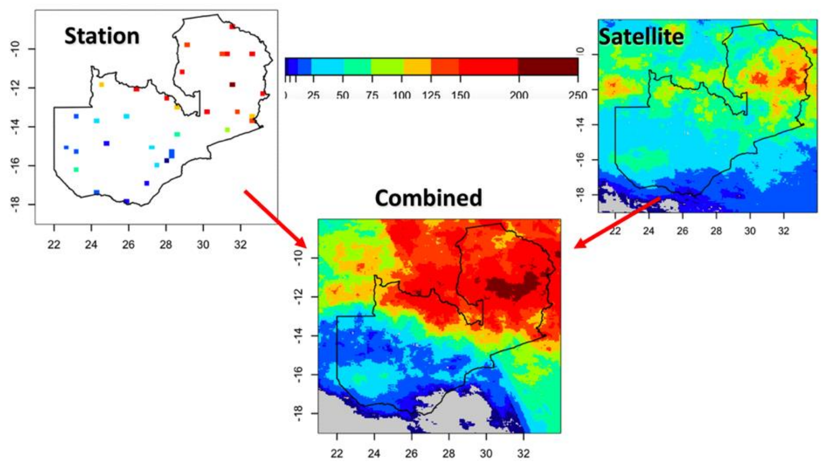

Figure 5. Station observations (top left) from the operational network in Zambia are combined with satellite rainfall estimates (top right) to produce a spatially complete and more accurate product (bottom).

2.5.2. Public-Private Partnerships

Another approach to improve cost-effectiveness is establishing public-private partnerships. Public-private partnerships must be carefully structured to benefit both parties and ensure financial sustainability and avoid stranded assets, but if implemented appropriately, can offer many benefits.

For instance, collaborations between cell phone service providers and NMHS could leverage cell phone networks for mutual benefit. Technical staff of cell phone companies could install weather observing equipment at cell tower sites to improve NMHS observational capacity at a very low cost. There are some challenges to this approach as measurements from a cell towers

Case study (Zimbabwe)

The telecom company ECONET is providing information for multiple sectors in Zimbabwe including agriculture, health, weather, mobile banking, and insurance. There are three tiers of membership: 1.) free whereby very basic information is available; 2.) registered farmers pay a small fee and provide some information to receive more information; and 3.) insured farmers pay an insurance premium and gain access to all the information along with their insurance policy.

ECONET has developed an array of meteorological observations at cell towers and has an information sharing arrangement with the national Meteorological Services (Snow et al. 2016). This approach may be replicable in other contexts.

may not be representative of surrounding regions. One adaptive approach is to use wind sensors on both sides of a cell tower to avoid directional bias. Furthermore, many smart phones can provide additional information on altitude, GPS, temperature, and potentially barometric pressure.

More broadly, there are several arenas in which public-private partnerships may be beneficial and cost-effective. In addition to the advantages of collaborating with mobile phone companies discussed above, interaction with information packaging companies, the airline industry, resource extraction companies, agricultural support companies, banking and insurance companies, the health sector, and the energy and infrastructure sector could all produce cost-effective benefits to both the NMHS and the other respective industries (Snow et al., 2016). For instance, one means of extending the network of upper air observation is to use atmospheric soundings taken from commercial aircraft (Snow 2013). Resource extraction and agricultural support companies have a clear need for high quality weather information and can help provide financial and material support to expand monitoring capacity. Index insurance and development oriented micro-finance can also benefit from timely, well-calibrated station reporting. Further, climate-related diseases pose a serious threat to lives and livelihoods in Africa and accurate monitoring and forecasting of temperature, rainfall, and humidity can help anticipate and adapt to outbreaks and epidemics of diseases such as malaria, meningitis and dengue. Furthermore, energy and infrastructure development decisions should be informed by climatic considerations – especially for very climate-dependent energy resources such as solar and wind energy (Snow et. al., 2016).

In addition to the multiple benefits associated with building and maintaining a dense network of meteorological stations, there is a public need for high quality early warning systems to reduce the impact on livelihoods and loss of life associated with natural disasters. Effective early warning systems improve cost efficacy in managing crises and can reduce dependence on foreign aid (Snow et al., 2016). The dependence these sectors and industries have on accurate climate information can be leveraged by NMHS to solicit financial and operational support in maintaining and/or expanding observational networks.

3. TECHNOLOGIES FOR CLIMATE DATA MANAGEMENT

There are clear advantages to having well-maintained, updated, well-organized electronic databases (with appropriate backup and redundancy provisions) of past instrumental station data, as well as past issued forecasts, pertinent satellite and/or reanalysis products. Thus, NMHS will require technology and infrastructure for data storage and management. This requires both physical hardware (servers, hard drives, etc.) and well-organized databases and protocols for data organization, management, analysis and delivery (Figure 6).

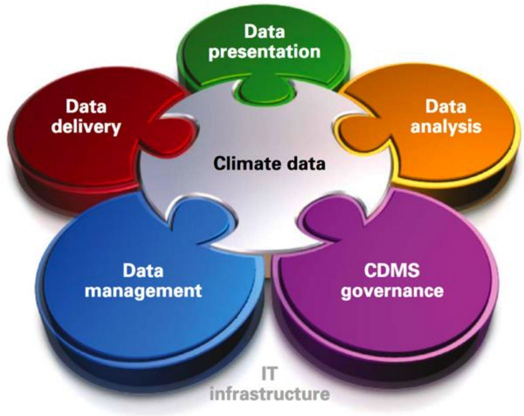

Figure 6. Components of Climate database management system (from WMO, 2014)

Establishing such a system can prove difficult to accomplish in many African NMHS due to financial resource constraints. Another persistent challenge in the African context is inconsistent internet coverage -- often internet coverage is more inconsistent than electrical power coverage and sometimes even the latter is inconsistent. Data storage hardware (servers, processors, hard drive space) and maintenance (sufficiently good power supply and appropriate environmental conditions in server rooms) are also challenges.

While the recent advent of cloud data storage overcomes financial and operational limitations associated with hard drives where space is limited, where internet connectivity is unreliable, cloud storage may have limited utility.

The World Meteorological Organization (WMO) has well-defined specifications and recommendations for climate database systems (WMO, 2014) thus, this section will not explore them in detail. Instead, some of the climate database system stems used by NMHS in Africa will be explored.

African NMHS use different climate data management systems (Figure 7). For example, Ethiopia and West Africa use CLIDATA while most of the southern African NMHS use CLIMSOFT, and there are three NMHS that use CLISYS for climate data management. According to Figure 7, there are also NMHS that have no standard (WMO-recommended) climate data management system.

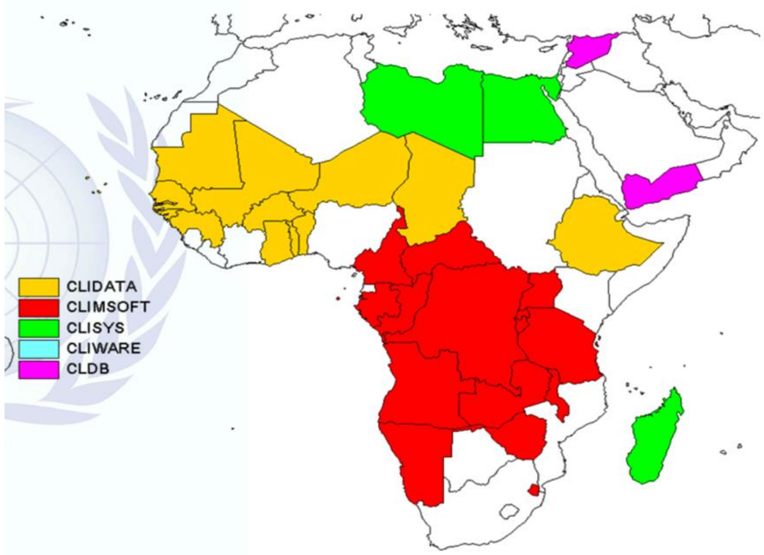

Figure 7. Climate data management systems used by different NMHS in Africa (Kontongomde, 2010)

4. TECHNOLOGIES FOR DATA ANALYSIS

4.1. Introduction

Many software packages and platforms exist for climate data analysis. Many employees of NMHS in Africa also do a great deal of comparatively simple data analysis in Excel, and some cases, use R and other mathematical programming platforms (Matlab, SPSS, SAS) to do more sophisticated forms of analysis. Some measure of statistical analysis in a geographic context is also done with GIS.

In addition to a wide range of mathematical programming languages, there are more specialized software tools for climate data analysis. Among them are CPT (Climate Predictability Tool), CDT (Climate Data Tools), the IRI data library, GeoCLIM, GEOCOF and GEOWRSI. Additionally, for sector specific and/or more specialized applications, there are other programs such as Instat, and CRAFT. This list is by no means exhaustive, but it does provide background on potential tools for use in this context.
CPT is a Windows and Linux-based software used for seasonal climate forecasting based on model output statistics, developed by IRI. It enables the user to do verification of probabilistic forecasts for past seasons, validate GCM projections against observations or to make seasonal forecasts via multiple linear regression, and principle component regression or canonical correlation analysis. More information regarding CPT, including a training manual is accessible here: https://iri.columbia.edu/our-expertise/climate/tools/cpt/.

CDT is a powerful R-based tool with a graphical user interface developed by IRI that enables users to perform quality control of station data, merge station data with satellite and other proxies as well as analyze and visualize station and gridded data.

The IRI data library is a platform wherein users can access several linked climate datasets from around the world and visualize, manipulate, and analyze data. The data library is web-based and has a graphical user interface, but is based on its own computer language called Ingrid developed by IRI. While there are user-friendly, fairly straightforward GUIs and tutorials to enable beginner users to extract and visualize data and do simple operations, there is also an online function index for the Ingrid language for those wishing to do more sophisticated analysis in the expert mode. The IRI data library is accessible here: https://iridl.ldeo.columbia.edu/.

GEOCLIM is a product of the Climate Hazards Group at the University of California Santa Barbara. It is a Windows-based system that enables users to download data, create climatologies, analyze trends, create contour maps and raster files, and visualize data in a spatial data viewer. More information on GEOCLIM, including a user manual is available here: http://chg.geog.ucsb.edu/tools/geoclim/.

The Geospatial Climate Outlook Forecasting Tool (GeoCOF) is a statistical software tool for seasonal forecasting of climatic variables, such as rainfall. It has a graphical user interface and is designed for multiple linear regression and uses GEOCLIM as its data manager. More information on GEOCOF including a manual is available here: http://chg.geog.ucsb.edu/tools/geocof/.

Another tool produced by the same group at the Climate Hazards group at UCSB is the GEOWRSI. This tool uses climate and crop inputs to calculate the water requirement satisfaction index on a gridded basis and is used for food security and famine monitoring applications. It also has a graphical user interface and uses GEOCLIM as a data manager. More information on GEOWRSI, including a manual is available here: http://chg.geog.ucsb.edu/tools/geowrsi/.

Instat is a statistical analysis package developed for scientists by scientists that has both PC and Mac compatible versions, has a GUI and the capacity to do a wide range of statistical analyses. In the climate analysis context, it is often used to study inter-annual and intraseasonal variability and to explore issues such as water balance and crop water satisfaction. More information about Instat, including a guide and targeted question responses is available here: https://www.graphpad.com/scientific-software/instat/.

CRAFT stands for the CCAFS Regional Agricultural Forecasting Toolbox (and CCAFS stands for Climate Change and Food Security). It is a software platform that includes soil characteristics, water balance information, climate forecast information and real-time monitoring to produce and refine intra-seasonal crop yield forecasts. The first applications have been in Asia, but there is interest in expanding the framework to other geographic regions (Shelia et al. 2015). More information about the application of the CRAFT software is available here: https://ccafs.cgiar.org/ccafs-regional-agricultural-forecasting-tool-craft#.WjQWNVQ-eCR.

In addition to the software packages described above, there is a further resource for consideration hosted on the website of the World Meteorological Organization's Climate Services initiative: http://www.wmo.int/cst/software-tools. Some of the software tools listed on this site are region-specific and may not be appropriate for certain applications. Some specific tools or links that may be of interest to NMHS in Africa include CLIMPACT (extremes and sectoral analysis), the KNMI Climate Explorer (various explorations of both observed and projected data), CliWARE, IDARE, ClimatView and MCH (for data storage and management), RegCM4, CORDEX, PRECIS and WRF (for regional projections).

4.2. Strengths and Weaknesses

Each of the tools introduced above has its own set of strengths, weaknesses and target applications. Several mathematical programming platforms that are popular among scientists in North America and Europe have prohibitively expensive licensing costs for many African NMHS (e.g., Matlab, ArcGIS). However, other platforms offer freeware (e.g., CPT, CDT, R, IRIDL, QGIS). With every computer programming language or interface, there is, of course, a learning curve.

For some programs, the operating environment may be a limitation but some of those listed above are very powerful for doing diverse and sophisticated analyses. In addition to being able to do PCR, CCA and MLR as forecasting techniques, along with probabilistic forecast verification and GCM validation, CPT also offers the advantage that analyses in CPT can be run without internet connection. Once an analysis is complete, there are a wide assortment of built in graphics to show the skill of the forecasts, hindcasts, projections for individual grid boxes, mode patterns, and several forecast parameters for each gridbox in the predictand domain.

While the IRI Data Library does require internet access, a wide range of statistical analyses can be performed through this platform, including correlation and regression, PCA, detrending, and any number of averaging and filtering techniques. Among the functions imbedded in the Ingrid language are functions that enable users to extract the number of rainy days or dry spells from a daily rainfall dataset, as well as a function that enables the user to extract a dynamic, user-defined rainy season onset date from a daily rainfall dataset.

CDT has proven to be a powerful, useful tool for helping to create and refine the ENACTS datasets from raw station and satellite data. CDT does quality control, station-satellite merging, spatial interpolation, validation, analysis and display.

4.3. Summary

Climate data analysis is a critical component of the operation of the NMHS. Climate data analysis at the NMHS takes many different forms: climatological statistical analysis; forecasting work; trend detection over longer periods of time; integration/comparison work across regions, etc.. There are a wide array of tools for these analyses with different trade-offs, strengths, and weaknesses. License costs can be an inhibiting factor for certain software packages, but in many cases, freeware exist to serve analogous purposes. Some unique products developed at IRI and UCSB Climate Hazards Group serve specialized functions for climate data analysis: CPT for forecasting, the IRI Data Libray for many types of analysis, CDT for merging, validation and quality control, GEOCLIM for climatological and trend analysis and GEOCOF also for forecasting applications. Other programs, such as CRAFT, merge elements of programming with database information to address climate services issues like yield forecasting.

5. SUMMARY AND RECOMMENDATIONS

Building and maintaining appropriate observational networks for weather and climate observation is of critical importance and investment in hydromet observations and can offer a good return on investment. However, establishing a robust observation network in African countries is not trivial due to financial constraints, logistical challenges, conflicts, and host of other challenges. This has resulted in declining observation network across Africa. Given the financial constraints, these investments need to be cost-effective and combining different observation technologies is a promising means to achieve this.

This report offers an overview of different technologies and tools for observation, data management, and data analysis including ground weather stations, atmospheric profilers, lightning detectors, weather radar and satellite observations. The need for using affordable instruments that are durable enough to withstand the natural stresses of a tropical environment needs to be considered, while following WMO specifications and guidelines.

Key Recommendations

- When purchasing meteorological instruments, NMHS and donors should consider both the cost of the unit and installation as well as maintenance costs. For instance, the use of automatic weather stations has been rising steadily over many parts of Africa yet the cost of maintenance and spare parts (which have to be imported) have introduced considerable logistical and financial challenges.

- Projects purchasing observing equipment shall seek to ensure that observational data generated by such equipment be made available for international exchange in accordance with applicable WMO Congress Resolutions (Res. 40, 25 and 60) and WMO Regulatory Material, in particular WMO Publication 1160 (Manual on the WMO Integrated Global Observing System). Donors may consider technologies such as 3-D printing of automatic weather stations and recoverable rawinsonde technologies to expand observational networks at lower costs, however, it is critical that the installation of these systems involve the local NMHS and provide a balanced investment of the real cost of operating and maintaining the system (human resources and capacity).

- Relatively poor status of Climate Data Management Systems (CDMS), particularly in Africa, prevents many NMHSs from efficiently (1) integrating AWS data and rescued data as well as (2) exchanging data, which also heavily impacted by restrictive national data policies. Investing in powerful CDMSs managed by highly-skilled personnel is of utmost importance as it will support efficient weather and climate services delivery. It is recommended that donors fund open source CDMS and ensure continuation of existing functional CDMS and not proposing new systems.

- When evaluating options for filling data gaps or lowering costs, NMHS should consider combining observations from different sources. For instance, optimal combinations of station rainfall measurements with satellite rainfall estimates can reduce the number rain gauges needed. Furthermore, leveraging satellite data may be particularly useful where there are gaps in historical data.

- Governments should consider public-private partnerships and multilateral donor-supported arrangements to enhance and support the capacity and sustainability of individual NMHS.

- NMHS may need to review data sharing policies in the context of a broader discussion on the benefits of climate services for national development. NMHS may contribute more to the national economy if climate data serve the public good rather than seeking to sell basic climate and weather data. Accordingly, governments need to support their NMHS to reduce their dependence on revenue from selling data. Revenue should only be derived from providing specialized data analysis and services.
- As this research shows, there are number of tools and technologies that could be useful to bridge gaps in data collection, analysis's, storage, and dissemination. Emphasis should be placed on vetting these, recommending those that meet to WMO requirements and guidelines. As the next step, the approved tools and methodologies can be brought under a centralized hub, such as WMO Climate Services Toolkit (CST) that facilitates access to guidance, data, software tools, and training. Subsequently, attention will also need to be focused on developing relevant user capacities as procedural and human resources-related gaps on the user end constitute the biggest stumbling block in efficient use of tools and technologies.

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