
Monograph:
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GCRF African SWIFT and ForPAc SHEAR White Paper on the Potential of Operational Weather Prediction to Save Lives and Improve Livelihoods and Economies in Sub-Saharan Africa

Lead Authors: Lorraine H Youds, Douglas J Parker

Co-authors: Elijah A Adefisan, Philip Antwi-Agyei, Caroline L Bain, Emily C L Black, Alan M Blyth, Andrew J Dougill, Linda C Hirons, Victor S Indasi, Benjamin L Lamptey, Fionne Marshall, John H Marsham, Thorwald H M Stein, Christopher M Taylor, Martin C Todd, Emma L Visman, Steven J Woolnough

For More Information

GCRF African SWIFT Website: africanswift.org Twitter: [@african_swift](https://twitter.com/african_swift) Email: NCASSwift@leeds.ac.uk
ForPAc SHEAR Website: forpac.org Twitter: [@ForPAc_SHEAR](https://twitter.com/ForPAc_SHEAR)

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Foreword

The ‘silent revolution’ of numerical weather prediction, which has brought tremendous benefits to the mid-latitudes, protecting and improving lives, livelihoods and national economies, has not brought the same benefits to sub-Saharan Africa. Nevertheless, the demand for accurate, timely and well-communicated forecasts is higher in Africa, where lives and livelihoods are much more closely linked to and dependent on weather-sensitive factors. The need for improved forecasts is ever more urgent under the effects of climate change, which are already being felt at huge cost to African peoples and economies.

The GCRF (Global Challenges Research Fund) African SWIFT (Science for Weather Information and Forecasting Techniques) and SHEAR (Science for Humanitarian Emergencies and Resilience) ForPAc (Towards Forecast-based Preparedness Action) programmes have been working with National Meteorological and Hydrological Services (NMHSs), Regional Climate Centres (RCCs) and additional forecast users (including decision-makers and the disaster risk sector) to improve forecasts so that their use can be better applied for early warning action.

In the summer of 2020, the *White Paper on the Potential of Operational Weather Prediction to Save Lives and Improve Livelihoods and Economies in Sub-Saharan Africa* began its journey and development as the GCRF African SWIFT and SHEAR ForPAc manifesto for the future of weather forecasting across sub-Saharan Africa. Both consortia include leading experts from the African and UK weather forecasting communities working collaboratively on these programmes. The paper is based on the collective knowledge of both programmes evaluating the opportunities and challenges for weather forecasting across the continent, and how to maximise forecast use and potential for disaster risk reduction through preparedness action across seamless weather timescales.

When reading and using this document, it should be noted that the prose is presented in sections which are intended to be somewhat stand-alone, therefore there is some repetition between sections, to ensure that they are self-contained and can be used independently of the full paper.

Several documents have already been published based on the ideas generated within this White Paper, including three policy briefs on the Future of African Nowcasting (Youds *et al.*, 2021a); the Future of African Weather Forecasting (Youds *et al.*, 2021b); and Exploiting Sub-seasonal Forecast Predictability in Africa: a key to sustainable development (Hirons *et al.*, 2021b); and a BAMS journal paper on *The African SWIFT project: growing science capability to bring about a revolution in weather prediction* (Parker *et al.,* 2021). This White Paper represents a repository of our ideas, with more detail and citations than is possible in shorter briefs and journal papers.

As a community, we are pleased to present this White Paper on the *Potential of Operational Weather Prediction to Save Lives and Improve Livelihoods and Economies in Sub-Saharan Africa* to all parties who can take forward this manifesto to progress African weather forecasting in the short- to medium-term. Here, we make the case for this huge opportunity for great humanitarian and climate resilience impact on the 5–10-year timescale. We would like to appreciate and offer our thanks to all the co-authors who dedicated their time and expertise to the development of this paper.

Vision

The ‘silent revolution’ of numerical weather prediction (NWP) has led to significant social benefits and billions of dollars in economic benefits to mid-latitude countries (Bauer *et al.,* 2015), however the level of benefit in sub-Saharan Africa has been very limited, despite the potential to save lives, improve livelihoods, protect property and infrastructure and boost economies. Ongoing climate change in Africa, and the associated projected intensification of weather impacts in coming decades, makes the realisation of effective and more reliable weather forecasts and climate services even more urgent. It is widely recognised that to achieve this potential, investment is required in strengthening decision makers’ understanding of weather predictions and confidence in interpreting and appropriately applying forecasts, alongside transparent communication of the levels of skill and probability or certainty in forecast products (WMO, 2021a). However, on all time scales of prediction, it is generally unrecognised that many forecasts that produce user-relevant metrics have such low skill that they are only marginally valuable to stakeholders (for example, Vogel *et al.,* 2020), creating significant practical and ethical barriers to increasing uptake and generating benefits. Here, we present substantial evidence that even a modest investment in science for weather information and forecast techniques, to provide new technology and tools for Africa, can significantly increase the skill of user-relevant forecast products on all time scales. This will be a necessary enabler for building trust in and uptake of decision-relevant forecasts with the potential to deliver significant social and economic benefits. We present here an argument that incremental improvements in the skill of weather forecasting across all timescales in the African tropics, alongside strengthening communication and understanding of these forecasts, is fundamental to saving lives and enhancing livelihoods. Investing in the capacity and capability of National Meteorological Services and research institutions is essential to ensure lifesaving and life-enhancing services continue to be developed with and designed to serve the populations of sub-Saharan countries.

Key messages:

- In Africa, lives, livelihoods, property, and infrastructure are directly and significantly impacted by weather-related events.
- Strengthening national and international meteorological and climate science capacity has the potential for transformational change across the African continent.
- In contrast to mid-latitudes, many tropical forecasts of user-relevant quantities have very low skill, making them of marginal use to stakeholders.
- Research remains to be done, to deliver adequate performance of forecasting systems, but significant improvements in accuracy and relevance are within our reach.
- Co-production (the bringing together of the producers of weather and climate information with those who use the information to make decisions) of weather and climate services is needed, which depends on meteorological agencies having the tools and know-how to meet decision-makers’ needs.
- Systematic and impact-based forecast evaluation, engaging feedback from directly affected populations and decision-makers, is critical to forecast improvement, to economic sustainability of services, and for effective forecast use.
- Partnership between meteorological and climate research-related sectors is needed to sustain scientific and operational improvements.

- Weather forecasting services should be economically self-sufficient, but this is not simple as there is a need to expand capacities, building on current national meteorological services capabilities.
- We outline a roadmap for what can be achieved on a 5-10-year timeframe, signposting the key steps needed to realise the socio-economic benefits of improved weather forecasting across Africa.

Executive Summary

There is a great opportunity for the African continent to benefit from the 'silent revolution' in weather forecasting that has been realised in the mid-latitudes throughout the twentieth century. While there are tremendous societal and economic benefits from advancing the science behind weather forecasting in sub-Saharan Africa, there are also significant barriers to realising advances. This White Paper examines the value of investment in African weather forecasting science, and the technical and communication challenges that wider implementation of climate services across the continent can bring. These advancements are based on the 'environment of progress' that the GCRF (Global Challenges Research Fund) African SWIFT (Science for Weather Information and Forecasting Techniques) and SHEAR (Science for Humanitarian Emergencies and Resilience) ForPAc (Towards Forecast-based Preparedness Action) programmes have created over the past four years.

Over the past century, accurate and quality-controlled weather forecasting in the economically developed countries of the Global North has experienced a 'quiet revolution', considered one of the most remarkable triumphs of the physical sciences. We know that the value, or economic benefit, of these forecasts is great. The UK Met Office valued forecasting in the UK 2015 Public Weather Service Value for Money Review as close to £1.5 billion per annum. However, scientific and operational advances are not being realised in economically less developed countries, including nations within the African tropics. African populations have an even greater need for accurate weather predictions, with lives, livelihoods, and national economies heavily dependent on weather-sensitive environments and sectors, including agriculture and livestock, energy, water resources and fisheries, together with rapidly increasing exposure to pluvial, fluvial and coastal flood risk as populations rise and urbanisation intensifies. Hundreds of millions of people in Africa are vulnerable to weather events, yet the uptake of weather information and services remains low across many parts of the continent.

We present here that substantial improvements in the skill of weather forecasting across all timescales in the African tropics is now within our reach on a 5-10-year timescale. Improvements in forecast products (including the models that drive them, their interpretation and application by trained forecasters and the co-production of products tailored to meet specific decision-making needs) along with better communication and understanding of these forecasts and ensuring the resources to enable forecast-based action, are fundamental to the protection of lives and livelihoods across Africa.

There are significant opportunities for forecast improvement and strengthening uptake across different timescales:

Subseasonal to seasonal (2-4 week) forecasting

- This is an intensely researched area in which forecast skill is improving rapidly. Forecast products on the subseasonal (two to four week) timescales have only very recently become available and the potential for exploiting this skill for improved early warning systems is very high.

- Availability of subseasonal forecast data in Africa is a fundamental issue that needs to be overcome in order for this exploitation to take place.
- Understanding what drives predictability on subseasonal to seasonal (S2S) timescales and being able to accurately model its impact on local weather over Africa is a necessary process, but not sufficient to produce useful and actionable information for users. There remains a further important gap in knowledge: how to improve the appropriate use of operational S2S forecasting products for actionable decision-making.
- It is important to recognise that effective co-production between meteorological services and decision-makers is resource intensive and has typically been applied in project-initiated services, which have devoted significant time and resources to the development and ongoing evaluation of the products. To increase the range of users and decisions being supported by S2S forecasts will require some streamlining of the co-production process, with increased ownership of the process in African centres.
- It is becoming increasingly clear that evaluation of the skill of S2S forecasts is not only a question of meteorological verification, but a comprehensive evaluation process which should combine meteorological skill with evaluation from decision-makers.

Synoptic (1-5 day) forecasting

- The skill of global NWP forecasts for rainfall on these timescales is very low for Africa. The new generation of convection-permitting models offers the opportunity to break the deadlock in rainfall forecasting, but work needs to be done to establish the use of these new and costly models throughout Africa.
- Given the poor skill of NWP rainfall forecasts, global modelling centres need to engage with and support verification and evaluation activities that take place at the African national weather services. This should provide a route to global model improvement and development through which vulnerable users may obtain more reliable information.
- The staff of African national weather services, and their supporting partners need better skills in core data manipulation and management, so that the African centres are able to manipulate data locally and generate their own products. Without these skills, the African centres will continue to be reliant on international assistance.
- More observations (or more reliable functioning of the existing network) are needed to initialise and evaluate models, including observations made away from population centres.
- Across Africa, there is a danger of forecasters not using conceptual models consistently, nor blending NWP products with their conceptual understanding. Plotting of the synoptic situation is generally not being done automatically from NWP. Without this conceptual understanding, forecasters may be using low-quality forecast products uncritically.
- Operational training in the use of NWP, including CP models and ensembles, needs to be linked to training in the conceptual understanding of weather systems.

Nowcasting (0-6-hour warnings and alerts)

- Prior to SWIFT and HIGHWAY (High Impact Weather Lake System project; WMO, 2021b; Roberts *et al.* 2021b), nowcasting has been almost non-existent in tropical Africa, but nowcasting offers the potential to provide critical alerts to vulnerable communities, saving many lives (Watkiss, *et al.*, 2020).

- For nowcasting in Africa, there is a gap in awareness of forecasters of the opportunity and potential for using the products already available. The concept and practice of nowcasting is widely misunderstood.
- Rainfall radars offer the best nowcasting information, and an increase in the number of operational radars in Africa would have major economic and humanitarian benefit. However, installation and maintenance of weather radars requires sound financial and organisational commitments from government and operators: only where these commitments are robust, as has been achieved in South Africa and more recently in Tanzania associated with the Highway project (Roberts *et al.* 2021b), do we see radars working effectively.
- Satellite data provide alternative nowcasting products, at lower accuracy and immediacy than radar data, but with demonstrable value to send alerts of high-impact storms (Hill *et al.* 2020). Due to the current paucity of radar across the continent, an immediate opportunity for rapid progress lies in improvement of the performance and exploitation of satellite-based products.
- Forecasters need adequate training in use of nowcasting products, and the opportunity to develop links with users to generate a market for these new products, as well as sufficient government funding for staff time to generate and issue public warnings based on a nowcast process. The financial model to support nowcasting by weather services is therefore key, both for public warnings, and bespoke forecasts for specific users.
- Nowcasts used in Africa will require significant evaluation on both the skill of the forecasts and their use, especially in view of the Meteosat Third Generation of satellites that will be launched in 2023/24, and the introduction of new imagers, including lightning data.
- It is desirable for forecasters to receive and generate products locally, a task SWIFT has started in four African nations.

1. The Case for Improved Weather Forecasting Capability in Africa

Summary

- Africa has not been party to the benefits of the improvements in weather forecasting seen in more economically developed parts of the world.
- There is enormous potential for weather prediction to give benefits across the African continent.
- Improvements in weather forecasting, and the directed delivery and successful uptake of these improved forecasts, can be achieved quickly and with relatively modest resources.
- Weather prediction is a distinct operational practice, independent of climate science, but supporting the response to climate change. The effects of climate change are being felt now – improvements in weather forecasting (across all timescales) – will contribute to climate resilience.
- There are opportunities to improve capability across all forecast timescales from zero hours to a year.
- Incremental improvements in forecasting, together with co-production of tailored products and strengthened communications, offers the potential for important, life-changing impacts.
- International agreements including the Sustainable Development Goals (SDGs), the Sendai Framework, the UN Framework Convention on Climate Change (UNFCCC), the World Humanitarian Summit (WHS) Agenda for Humanity, regional (African Union Frameworks) and national commitments (National Adaptation Plans, National Frameworks for Climate Services and Nationally Determined Contributions), as well as WMO Global Framework for Climate Services, all demand strengthening of capacities to address weather-related risks and impacts.

a. Africa has not benefitted from the ‘quiet revolution’ of global weather forecasting

Over the past century, accurate and quality-controlled weather forecasting in the economically developed countries of the Global North has experienced a ‘quiet revolution’, considered one of the most remarkable triumphs of the physical sciences, though without the degree of recognition of other physical science breakthroughs (Bauer *et al.,* 2015). In economically developed countries with significant forecasting infrastructure and expertise, we know that the value or economic benefit of these forecasts is great. For example, the UK Met Office valued forecasting in the UK in the 2015 Public Weather Service Value for Money Review to likely be close to £1.5 billion *per annum* (UK Met Office, 2015). However, these scientific and operational advances are not being realised in some economically less developed countries, including nations within the African tropics. The populations of the Global South have an even greater need for accurate weather predictions, with lives, livelihoods, and national economies heavily dependent on weather-sensitive environments and sectors, including agriculture and livestock, energy, water resources and fisheries, together with rapidly increasing urbanisation and informal settlements in often flood-risk zones. Africa, especially in the tropical regions, is vulnerable to weather events: in the period 2006-2015 African floods, heat waves, droughts and storms affected hundreds of millions of people, leading to economic impacts amounting to billions of dollars (International Federation, 2016). Africa is vulnerable to tropical cyclones, both their direct impacts (for example, Cyclone Idai, which affected Mozambique, Zimbabwe, and Malawi in March 2019) and their indirect impacts, such as the influence on the East African rainfall onset and (Finney *et al.*, 2020) and locust swarms. Some nations in sub-Saharan Africa are affected rarely, such as Tanzania (Msemo *et al.*, 2021). In other areas of SSA, such as the North Indian Ocean and specifically, Somalia, tropical cyclones appear to have increased, which has led to locust swarms in the East African region. Cyclone predictability in terms of track can be forecast relatively well, though it is the intensity and changes displayed in cyclones which are harder to predict.

The scoping study of the Weather and Climate Services for Africa (WISER) programme (UK Met Office, 2016) noted that the availability and uptake of weather information and services is still low in Africa, representing a threat to social and economic development (also see Nkiaka *et al.*, 2019). Recognising the lack of large-scale Africa-focused initiatives to comprehensively address these problems, the former UK's former Department of International Development (DFID) (now the Foreign and Commonwealth Development Office (FCDO)) invested in a series of programmes aiming to strengthen resilience to high impact weather events, but significant needs remain.

The impact of severe weather across the continent is manifold. Africa has the highest rate of drowning deaths in the world (WHO, 2014), with a significant number of these due to poor weather. In late 2019, East Africa experienced severe rainfall-related disasters, including flash floods and landslides, which led to more than 280 people losing their lives, and 2.8 million affected through damage to crops, homes, businesses, and infrastructure. The disaster has persisted through into 2020 (FloodList, 2020). Similarly, flooding had affected 1.7 million people within 13 countries across West and Central Africa between 1st and 25th September 2020 (UNOCHA, 2020). It is widely accepted that such extreme events will become more frequent and more intense with climate change (IPCC, 2012; Hoegh-Guldberg *et al.*, 2018). While the wide-ranging socio-economic consequences of high impact weather should be taken into account, unfortunately, reliable data on vulnerability and exposure remain extremely limited. Forecasting in the tropics is a significant research challenge on all timescales of prediction, but equally, recent technological and scientific advancements mean that there is also now opportunity for rapid progress on all of these (seamless) timescales. Forecast reliability is dependant partially on what timescale is being forecast, i.e. how far into the future it is looking, but is also dependent on the methods by which each timescale is forecast, as there are different drivers of weather for different timescales and inherent complexities of modelling each of these systems.

Tropical weather is dominated by highly chaotic convective storms: these systems are also the key events bringing high-impact rainfall, hail, lightning, and strong winds. We are now, for the first time, able to simulate such storms explicitly in large-domain computational models, and the cutting edge of our science is to provide the statistical and physical understanding needed to apply such models to operational weather prediction. While in regions such as the USA, 'nowcasting' methods are used routinely to save lives by predicting violent convective weather, such methods need to be implemented in Africa, where they are yet under-exploited (Roberts *et al.*, 2021a). Africa suffers from a lack of ground-based measurements, especially weather radars, meaning a reliance on satellite observations, which remain under-utilised and explored (de Coning *et al.*, 2015). For instance, the Nowcasting Satellite Applications Facility (NWC-SAF) algorithms have begun to be tested and used in tropical Africa only recently, as a result of the GCRF African SWIFT project, despite the fact that they have been available since around 2006 (Roberts et al. 2021a). Seasonal forecasting allows users to plan for climate-related impacts, such as drought, and flooding, where the impact is due to the accumulation of sustained rainfall throughout the season, or intense rainfall events associated with a wetter than average season. Although tropical climate is highly chaotic, its slower variability on subseasonal-to-seasonal timescales (S2S) may be much more predictable than elsewhere, because of the influence of the more gently varying ocean system and large-scale atmospheric wave-modes (Judt, 2020). There is enormous potential (yet unrealised), for S2S forecasts to provide useful projections for 5-60-day planning in Africa (Robertson *et al.,* 2015). Although the gap between weather and human livelihoods is very narrow in Africa, where many people both depend on the rains, and need warnings for storms for their survival, links between the provision of forecasts and their use remain under-developed.

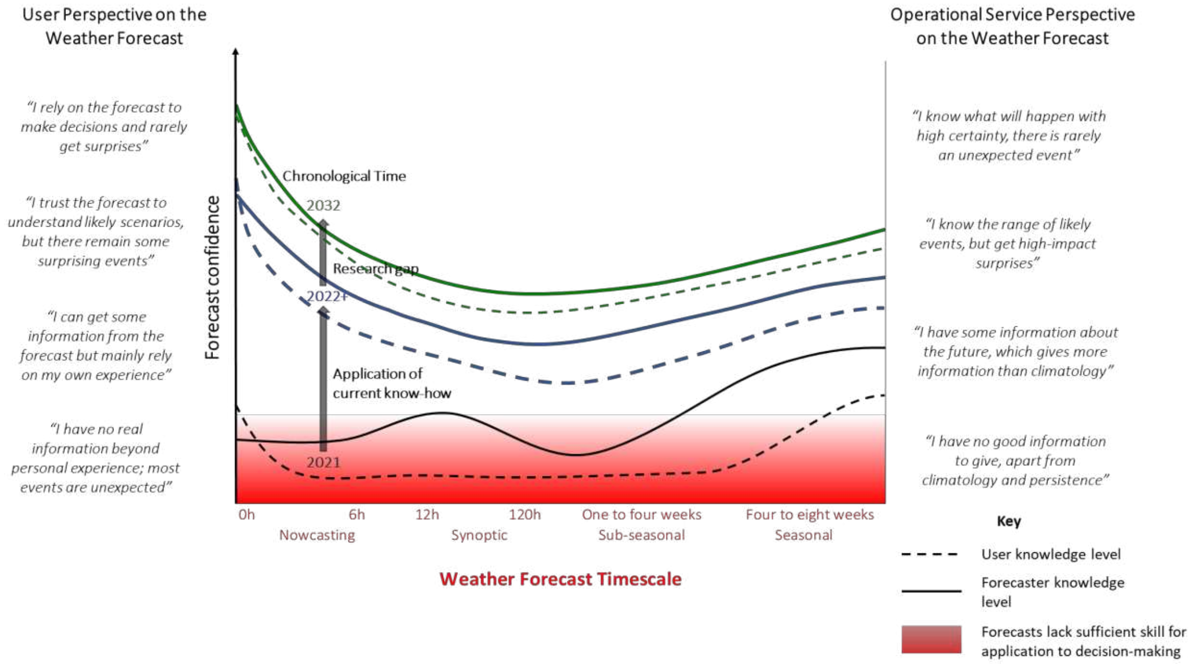

Figure 1. Schematic diagram of current and possible future ability of users to anticipate and operational services to provide early warning for meteorological hazards across timescales from hours (nowcasts) to months (seasonal forecasts), based on the judgement of the authors of this document. The schematic describes the situation for tropical African rainfall, and the statements on each axis describing the confidence in the forecast and its value are implicitly probabilistic. In regard to these statements, it is assumed that the forecasters and users are well informed about the actual value of the information they are creating or using, respectively. Note that actual or scientifically evaluated skill depends on spatial scale, intensity, season, and geographic location, while users' perception of forecast skill depends on a wide range of factors, including their understanding of key climate concepts, the accuracy and transparency and reach of forecast communication, and their personal and professional experience in using forecasts to support for specific decision-making processes. The black lines represent the current status (2021) of confidence in forecasts; the blue lines represent 'realisable' confidence from 2022, or when current know how is applied; and the green lines represent possible confidence levels from around 2032, once the research gap is closed.

The schematic, in Figure 1, above, provides an expert judgement (based on the views of the authors of this paper) of the current (2021, and implicitly prior to the SWIFT and ForPAc programmes), 'realisable' (associated with the immediate development and application of current knowledge, to operational practice), and future ('2032', implying a research gap which may be closed in a few years through advancement and understanding of NWP skill for Africa and through improved methods for exploitation of observations and model products). Our vision for the work needed to close these gaps is presented in this document. It should be noted that commonly, service advances in forecasting tend to lag behind the research and science advances for many years, especially in low- and middle-income countries (LMICs) and the prediction provided in Figure 1 is not that these services will definitively be running within the next few years, but that with the right economic and resource investment, these services could be realisable within the timeframes proposed. We note that the user experience cannot be better than the operational perspective, except where users receive better information from another source. The exception is at zero hours, when the user currently (2021) almost always knows more than the forecaster about prevailing hazards, due to the forecaster having access to imperfect observations: with improved nowcasting tools, it should be possible for the forecaster in future to provide the user with information which they cannot gain from their immediate surroundings, in particular the presence of hazards in close proximity. The gap between the forecaster perspective and the user perspective represents a challenge for risk communication and cany be addressed by improved co-production of services and communications.

'Realisable solutions': What is needed to apply existing know-how?

Application of existing know-how to produce 'realisable' solutions will involve applied research, e.g. the development of climatologies or calibration of algorithms or sensors, which are things we know can be achieved, but are technically challenging:

- Operationalisation of nowcasting in all African countries;
- Evaluation of nowcasting and NWP skill according to location, and development of statistical measures;
- Integration of surface observations and NWP information into nowcasting methods;
- Operational ensembles of convection-permitting models and improvement of products and diagnostics from such models;
- Application of existing statistical methods for exploitation of NWP and S2S ensemble predictions;
- African ownership and generation of diagnostics from observations and models;
- Training in interpretation of dynamics and synthetic models;
- Strengthening existing and co-developing new forecasting services with a number of sectors, where a comparable, existing service already exists elsewhere;
- Co-developing and trialling systems enabling participatory forecast evaluation and monitoring of forecast use and benefits.

'2032': What research is needed over the 5-10-year timescale to improve forecast skill?

These are areas where we can confidently expect progress, but the path and exact outcomes are less certain:

- Improved algorithms, using statistics machine learning, for nowcasting;
- Improved NWP & S2S ensemble simulations, achieved via improved initialisation and improved model physics;
- Improved statistical methods for the exploitation of NWP data, including convection-permitting models and S2S ensemble forecasts;
- Installation and maintenance of radars and forecaster training in using radar data;
- Integration of new data, including crowd-sourced data, rain-rates from mobile phone signals etc., into nowcasting and model evaluation;

- Improvement in channels for systematic engagement with and feedback from users, enabling participatory forecast evaluation and continuous monitoring of forecast use and benefits.

b. The value and impact of African weather forecasting

i. The international development context

African populations and economies are highly sensitive to weather dynamics, so improving the quality and relevance of weather forecasts for Africa is a necessary element in achieving many of the United Nations (UN) Sustainable Development Goals (SDGs) and their targets. Most particularly, accurate weather information is needed to help “make cities and human settlements inclusive, safe, resilient and sustainable” and “significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses…caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations” (Goal 11); and “improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning” (Goal 13).

In regard to the livelihoods of farmers, weather forecasts can help “build the resilience of the poor…and reduce their exposure and vulnerability to climate-related extreme events (SDG Target 1.5); “improve food security” (Goal 2) and contribute to “sustainable food production systems”, “strengthen resilience and adaptive capacity to climate-related hazards” and “raise capacity for effective climate change-related planning and management in least developed countries” (Goal 13). Building resilience across sectors in relation to extreme events is possible through impact-based weather forecasting and enabling preparedness action through the provision of user focused and timely warnings. The focus on both climate and weather-related risks in the UN SDGs strengthens the motivation to mitigate these impacts “for the enhancement of peace, prosperity, eradication of poverty and protection of the planet”. Forecast-based early action to strengthen preparedness, mitigation and prevention of economic loss and humanitarian impact has huge social and economic value across Africa.

The UN’s Sendai Framework for Disaster Risk Reduction (UNDRR) aims to protect development gains from disaster impacts and strengthen national and regional research capacities to support preparedness, disaster risk reduction and sustainable development. This framework works together with both the Paris Accords and the SDGs. The SDG goals mentioned above, 11 and 13, directly cross-reference with the Sendai Framework indicators, exemplifying the need to end poverty, ensure that settlements are resilient and reduce the impact of climate change. Moreover, the UN’s Agenda for Humanity, a five-point plan, which “outlines the changes that are needed to alleviate suffering, reduce risk and lessen vulnerability on a global scale” has the climate crisis at the heart of this agenda, with anticipating crises a key part of the Work Differently to End Need strategic transformation. Beyond the timeline for the UN SDGs, the African Union’s Agenda 2063: The Africa We Want, puts into context the UN’s SDGs for the African people. This strategic framework for sustainable development across the continent explicitly links with SDG 11 through the goal of “Environmentally sustainable and climate resilient economies and communities'' and unequivocally states the pan-African drive for progress through commitment to tackling the climate crisis.

ii. Benefit to the African peoples

There is a clear need in many African countries for significant and urgent steps towards providing better weather and climate forecasts on all timescales, from seasonal, to hourly. For example, in Nigeria, over 70% of the population is engaged in agriculture that is predominantly rain-fed. A reduction in crop yields has already had adverse impacts on the gross domestic product (GDP) of

Nigeria (Ogbuabor and Egwuchukwu, 2017) and in addition, 2020’s heavy rains have significantly affected the country’s flood-prone northern regions, with lives lost and infrastructure damaged. In Senegal, the warming of the Sahel is causing increases in high impact weather events with more intense rainfall and dry spells, as evidenced in 2020’s September flooding, alongside land degradation and drought, reducing water supply for rain-fed cattle there. In Kenya, increased flood events, which, in the past were associated with extreme climate have become much more frequent (Wainwright *et al.*, 2021), destroying national infrastructure and leading to a loss in lives and livelihoods. Therefore, being able to better predict these extreme events hours, weeks, and months before they occur is key in providing economic, societal and environmental security to the regions that most need it. Advances in the physical science of weather forecasting, alongside producing impact-based forecasts tailored for specific sectors, communicated through accessible channels, and ensuring access to the resources and capacities required to make appropriate use of forecasts, offers huge potential gains across the whole continent. There is a clear need for joined-up thinking and action at all levels – local to global – to consider climate-related risks across sectors, timeframes, and decision-making levels.

Consequently, there have been significant investments in initiatives to strengthen resilience to climate-related risks in Africa across timeframes, sectors and regions. UK-funded initiatives have included the Weather and Climate Services for Africa (WISER), Future Climate for Africa (FCFA), Building Resilience and Adaptation to Climate Extremes and Disasters (BRACED), Science for Humanitarian Emergencies and Resilience (SHEAR), Global Challenge Research Fund (GCRF) African SWIFT programmes and initiatives within the Global Framework for Climate Services. The WISER and FCFA programmes included a co-production imperative to support the co-development with user groups of services that can better support specific African sectoral decision-making processes. Recognition of the potential for forecasts to strengthen preparedness for and prevention of severe impacts across Africa for the benefit of its peoples has significantly increased. In addition, the Forecast-based Financing (FbF) efforts and initiation of national Early Action Protocols, spearheaded by the International Federation of Red Cross and Red Crescent Societies (IFRC) and its national societies in conjunction with a wide range of agencies and supported through the Risk-informed Early Action Partnership (REAP) partnership[1], provides a methodology for systematising consistent forecast-based action based on agreed forecast triggers. However, FbF remains dependent on the consistent provision and transparent communication of forecasts with the skill required to justify investment in forecast-based preparedness.

iii. Estimating the value and impact of African weather forecasting

Currently, data on vulnerability and exposure to high impact weather and climate-related risks across the African continent are extremely limited, largely due to insufficient resources for systematic data collection and analysis. Demonstrating the socio-economic value of forecasting provision across timescales is similarly difficult due to incomplete data on incidence of events and their impacts on affected populations and sectors. Where there is monitoring of the impacts of forecast provision, this is often undertaken on a project-specific basis with government agencies lacking the systems and resources to enable regular monitoring.

Without being able to demonstrate the benefits, it is hard to make the case for sustained and extended investment in meteorological services. There is nevertheless widespread recognition that the avoidable losses and potential benefits possible with increasing the capability of weather forecasting across timescales in the African tropics are enormous (Pearce and Lumbroso, 2019). The

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[1] https://www.early-action-reap.org/

Centre for Research on the Epidemiology of Disasters in Brussels reported that 195% more Africans were affected by extreme climate and weather events in 2019 across the continent in comparison with 2018 (CRED, 2019 and 2020). Around 16.6 million people were affected by natural disasters in 29 African countries, in comparison to 5.6 million people in 2018. Although this limited dataset across two years does not necessarily indicate a sustained trend, it demonstrates the large number of people already exposed to high impact weather over time, a trend only set to increase under climate change (IPCC, 2021). Disasters included drought, wildfires, floods, landslides, extreme temperature, fog, and storms – all of which can be predicted, with varying capability and skill – by weather forecasting techniques (Pandey, 2019). There are significant success stories in providing more targeted and accurate weather forecasts in tropical Africa (see Watkiss *et al.*, 2020; WMO, 2021b).

There remain constraints in accurately assessing the socio-economic benefits of improved forecasts despite significant efforts in seeking to develop frameworks for assessing their potential for enhancing resilience. There is a need for low-cost, rigorous cost-benefit analysis (CBA) that can be integrated within institutional monitoring rather than requiring contracting to external evaluation experts. Current CBA methodologies are resource-intensive, constraining national and/or regional assessments of the benefit of public weather forecasting services in African countries across sectors, akin to the UK Met Office's Public Weather Service Value for Money Review. Moreover, assessing the impact of efforts to strengthen resilience to climate-related risks requires consideration of the steps in the process of developing and enabling appropriate use of decision-relevant climate information (Watkiss *et al.*, 2020). Increasing the skill of weather forecasting methods requires a seamless evaluation methodology across time scales, establishing best practice and enabling local capability in Africa. Increasing the skill of forecast will strengthen confidence in them, in turn supporting uptake of forecasts for planning, decision-making and disaster mitigation.

Although detailed information and quantitative data on the socio-economic value of weather forecasting methods are not aggregated fully by nation or by sector in Africa, we here suggest the significant potential value of incremental improvements of weather forecasting across various timescales to positively impact preparedness for weather and climate related risks.

iv. The value of forecasting over timescales

Seasonal forecasting (over two months)

Seasonal forecasting in the African tropics is largely overseen by Regional Climate Outlook Fora (RCOFs), such as PRESAO (West African Climate Outlook Forum) and the Greater Horn of Africa Outlook Forum (GHACOF). The purpose of these groups is largely to foresee early climatic anomalies in forthcoming seasons, over 60 days in advance, and to discuss and co-produce mitigation measures for any potentially impactful and anomalous weather. Those benefiting from seasonal forecasts include stakeholders from sectors who need to plan resource use and management in advance, such as farmers, water resource managers, the energy sector and disaster risk management.

There is a strong need for predictions of the onset of the rainy season on all timescales, including seasonal and subseasonal forecasts. For example, more than 65% of the West African workforce is employed in the agricultural sector providing about 32% of gross domestic product (Fitzpatrick, *et al.*, 2016). The majority of farmland in West Africa is not irrigated, meaning that the success of a harvest is strongly dependent on continuous and sufficient rainfall suitable for crop growing, and the onset of the West African monsoon (WAM) (Ingram *et al.*, 2002; Ewansiha and Singh, 2006), and the timing many actions in agriculture are dependent on the timing of the onset. Fitzpatrick *et al.*, 2016, states that "Of particular interest to local stakeholders is the timing of the WAM onset (Ingram *et al.*, 2002; Sultan *et al.*, 2005a)". Due to this demand, the RCOFs issue forecasts of onset, however skill for onset is regionally and seasonally variable. Some models are showing moderate skill for the regional onset of the West African monsoon (Vellinga *et al.*, 2013), but skill for seasonal prediction of the long rains in East Africa (March to May), is extremely low compared with that of the short rains (October to December) (Walker et al., 2019; Macleod, 2019).

Subseasonal forecasting (two weeks to two months)

Subseasonal to seasonal forecasting can provide information to government ministries and extension services, farmers, individuals and businesses on the timescale of two weeks to two months but is currently not routinely provided operationally over much of Africa. Most leading global forecasting centres run an operational subseasonal forecasting system, but the availability and uptake of these forecasts over Africa is limited. The SWIFT S2S testbed (Hirons *et al*., 2021a) has provided an operational pilot project for subseasonal forecasting within its partner countries and is demonstrating both the demand for forecast information on these timescales and their potential to inform decision making (Lawal *et al.*, 2021). Potential applications include: prediction of the timing of monsoon onset and cessation to inform ground preparation, planting and harvesting; early warning of both prolonged dry spells or excessive rainfall to inform decision making in agriculture or hydropower management; prediction of heatwaves and conditions which susceptible to disease outbreaks (e.g. malaria and meningitis). De Andrade *et al.* (2021) showed that the skill of leading operational systems Is both seasonally and regionally dependent with the highest skill for rainfall occurring during regionally dependent rainy seasons, and skill over East Africa being the highest generally. While the skill of the NWP models for synoptic rainfall remains poor, on subseasonal timescales the predictability comes from both the seasonal drivers such as El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) (Macleod *et al.,* 2021b), and from the predictability of subseasonal atmospheric modes such as the Madden-Julian Oscillation. Information on these timescales, provided it is reliable and actionable, could revolutionise preparedness action and pro-active disaster mitigation over the continent.

Synoptic forecasting (1-5 days)

Synoptic forecasting methods are used to create medium-term, 1–5-day forecasts and are commonly determined through use of NWP products, observational and charting methods over 'synoptic-scale' regions (typically 500 – 5,000 kilometres). While these methods have been the bedrock of weather forecasting in the Global North for decades, with economic value of many billions per annum (Bauer *et al.*, 2015), their use in Africa remains problematic because of the poor observing network and the poor performance of NWP over the continent (Vogel *et al.,* 2020).

The potential value of accurate synoptic forecasts is demonstrated by the Swedish company Ignitia whose forecasts of rainfall are sustained by income from farmers in Ghana. The farmers clearly value the forecasts enough to pay for them, and while the quality of the rainfall predictions seems no better than that of other forecast producers (Goddard et al. 2018; Claremar*,* 2018), Ignitia do seem to have good success at forecasting the heaviest rainfall.

Other sectors with a history of paying for forecasts include global and marine industries, and many other sectors in the Global North are paying for bespoke forecasts routinely (e.g., for power generation, transportation, and supply industries).

Nowcasting (0-6 hours)

Nowcasting describes the 'current' state of the weather, as well as forward-projection of this information on a timescale up to 6 hours in the future (Browning, 1982; Wilson *et al.*, 2010). Nowcasting methods are generally applied to weather systems that occur on the mesoscale and local scales over these short periods of time. In this case, it is often rapidly changing weather systems that are particularly important to be nowcast, including weather phenomena in Africa such as thunderstorms, which can produce lightning, tornadoes, heavy precipitation, hail and high winds.

Nowcasting is particularly important for convective storms, whose synoptic NWP forecasts over 24 hours or more are inherently uncertain, particularly in Africa. When the forecasts of storms are highly uncertain, there is value in knowing and being able to respond to storms, which are observed to be happening now. Despite the critical importance of nowcasting, it has been almost non-existent in tropical Africa, prior to the GCRF Africa SWIFT project (Roberts *et al.*, 2021a, Parker *et al.*, 2021).

The purpose of providing a detailed, reliable and localised nowcast is primarily to save lives and livelihoods within localised regions. For example, increased and intense precipitation at the end of the rainy season in Senegal in September 2020 led to localised and severe flooding in Dakar and placed the entire country in a state of emergency. At the time of the floods, it was almost impossible for the weather service to provide warnings to the stakeholders, decision-makers and public because of the lack of knowledge about the trajectory of the storm system. Nowcasting will provide this. Reliable, localised and impact-based weather information in real time allows disaster risk managers to determine where to strategically focus efforts to save lives and critical national infrastructure, and prepare for a response.

Summary

Improving weather forecasts, on all timescales, have significant potential to strengthen resilience amongst people whose lives and livelihoods are directly affected by weather and climate related risks on the African continent, especially within the tropical region. Communication of these forecasts in understandable language and formats, including decision relevant metrics and accompanying advisories, provided through accessible and trusted channels, can significantly strengthen specific decision-making. Although weather forecasting in the tropics is not currently fully understood in economic terms across the continent and sectors, it is clear that forecasting across timescales from hours to seasons has enormous potential to benefit lives, livelihoods and national economies of tropical African countries.

c. Co-benefit of African weather forecasting to the UK

The primary benefit of this research is for the investment into sustainable capacities within African countries, specifically in the tropical regions. However, there are also important co-benefits for UK research and operational forecasting agencies with regard to the improvement of global models, and more broadly, enabling learning from efforts to support increased uptake of weather and climate information in other countries to inform efforts to strengthen counterpart climate resilience measures in the United Kingdom (for example, in learning how best to build engagement of at-risk populations and supporting agencies within the co-development of forecasts and systems that enable preparedness and prevention actions). Moreover, most of the scientific principles outlined in this White Paper apply globally and can be translated to other continents.

Scientific and technical co-benefits to the UK include, but are not limited to:

- Building capability among UK researchers and operational forecasters to improve, maintain and evaluate operational tropical forecasts.
- Building the capability in innovative use of satellite data for tropical prediction and research, currently under-exploited in the UK atmospheric science community, which can contribute to early-warning systems as well as preparedness and response in Africa and other parts of the developing world.

- Improving UK capability in advanced satellite remote sensing of tropical clouds, especially deep convection.
- Building research capability in the UK to inform the development of operational forecast products on the subseasonal timescale for decision making across a range of sectors.
- Building UK capability in developing and using regional tropical convection-permitting ensembles, which will feed through to future such ensembles at global scale used to drive UK weather prediction.
- Extending understanding of inclusive and sustainable approaches to strengthening resilience to weather-related risks, methods for measuring socio-economic benefits and so justifying increased investment in UK forecasting capacities for the UK and global populations.
- Improved UK forecasts due to improved modelling in the tropics (Pante and Knippertz, 2019).
- Contributing to efforts to reduce national, regional, and international tensions, displacement and migration, and protecting the UK's international interests in areas exposed to weather and climate-related risks (Cabinet Office, 2021).

d. Forecasting across seamless timescales

Weather forecasting is an initial value problem where we use a combination of the current state of the atmosphere-ocean-land system and a 'model' of how the system evolves to predict what the state of the system will be at some future time (note the contrast to climate prediction which, at least traditionally, has ignored the current state of the atmosphere-ocean-land system). The skill of our weather forecasts depends on the quality of our observations of the initial state of the system; our ability to combine those observations (with their errors) to provide a dynamically consistent initial state of the system (the data assimilation problem); the quality of the models we use to predict the evolution of the system; and the inherent predictability of the system.

In the very early days of weather forecasting statistical or conceptual models were used to predict the evolution of the system, but we now use advanced numerical models to integrate forward in time the mathematical (or physical) equations which describe the evolution of the system (it should be noted here that the use of NWP in Africa has been initiated relatively recently in comparison to the Global North, and the skill of global NWP is still relatively low for Africa). However, these conceptual models remain an important tool in the forecaster's arsenal as they enable them to understand the level and sources of predictability at a given time, identify systematic errors in forecast system, and create forecast narratives for users.

Historically, forecasting has been broken down into different timescales, largely based on the tools used to make the forecasts and how often the forecasts were updated, and partly because there was a clear separation between the timescales being considered. 'Weather forecasting' referred to predictions out to a few days with forecasts of the weather at the resolution of a few hours, updated every day (or more frequently), and using a model of the atmosphere-land system to make the predictions. 'Seasonal forecasting' referred to predictions of average conditions for a particular season (3-month period) updated monthly and relied largely on the initial state of the ocean/land/cryosphere for the predictive skill. Until the last decade of the 20th century this forecast would have largely been based on statistical models and, although we now use numerical models of the atmosphere-ocean-land system, at much lower resolution than the models used for 'weather forecasting'.

Over the last decade or two, the distinction between these timescales has become blurred. Improvements in the availability of satellite observations and advances in data assimilation have improved our estimates of the initial conditions, and combined with advances in our numerical models, have enabled us to make useful predictions at the high temporal resolution of 'weather forecasts' (hours/days) further into future (what has come to be known as the 'quiet revolution' in weather forecasting). Meanwhile, advances in our understanding of the climate system, and the availability of computational resource to run multiple weather forecasts (ensembles) out to lead times of the order of a month, has allowed us to bridge the gap between the weather and seasonal timescales. The forecasts in this gap are often referred to as 'subseasonal' (or 'subseasonal to seasonal' (S2S) forecasts) and are typically updated once or twice a week and provide information on a temporal resolution of the order of a week, describing the average conditions or probabilities of particular events.

The erosion of the gap in the timescales means that the boundaries between these types of forecasts have become blurred. This is both an opportunity and a challenge for weather forecasting. There is a need to develop tools, which allow a seamless approach to forecasting so that there are not the large jumps in forecast as you move from one forecasting system to another, and there is a need to think carefully about the period over which we 'average' the forecast at a given lead time and the frequency with which we update them. Both decisions will depend on the region for which forecasts are being developed. In regions dominated by convective systems such as tropical Africa our ability to predict details of the weather 5 days in advance is much reduced compared to, for example, the UK where there are strong synoptic scale weather systems, which are predictable on these timescales. Furthermore, the appropriate 'temporal resolution' of the forecast information and the frequency on which it is updated will be strongly dependent on the forecast user and the timescales for their decision-making processes and forecast-based actions.

Noting that the definitions of boundaries between these forecasts are fuzzy for tropical Africa, it is reasonable to think of the traditional 'weather forecasting' approaches for days 1-5; subseasonal forecasting approaches for 5-30 days; and seasonal approaches beyond these timescales. However, there is scope to improve the way in which we provide forecast information across all of these timescales, and in particular around the boundaries of these traditional distinctions.

e. Weather prediction is a distinct operational practice, independent of, but fundamental to a response to climate change

Weather prediction is an operational activity, which provides information to different users on a day-to-day basis. Even without the presence of global climate change, there are humanitarian, economic and development reasons why we need to invest in improving the science and practice of weather predictions in Africa (see sections above). The existence of climate change, and the vulnerability of Africa to changes in future extreme weather, increases the urgency to improve provision of weather predictions for the continent. Building capacity and capability to produce and effectively use weather forecasts is likely to build the capacity to produce, understand and use longer term climate projections

Climate change is being felt in Africa now. Parts of the continent are already experiencing the detrimental effects of climate change in the form of an intensified water cycle, with longer dry-spells and more intense storms. For instance, over the past 30 years in the Sahel there have been measurable changes in extreme storms (Taylor *et al.*, 2017). It is no longer a theoretical question about how we will respond in the future: we need to improve our responses now. In responding to climate change we need to do more than develop policy for Africa; we need to act in improving our ability to respond to weather events, on an hour-to-hour and day-to-day basis, with immediate effect. People need to respond to events outside the envelope of their experience.

Operational delivery of weather forecasts is different to the delivery of climate change projections. Primarily, weather predictions provide information specific to certain future times, and for relatively short times, while climate projections give statistical information concerning longer time-periods, in future years. That is, weather predictions are relevant for tactical decisions while climate change projections are for more strategic decisions.

Effective weather predictions are always based on a close link with the user or customer (such as the aviation industry). The link is supported by long-term evaluation of the performance of the system, through experience of past forecasts. Our state of knowledge of the information contained in a weather forecast is high, both for a provider (forecaster) and a user, because we have been able to evaluate the system over time. Even if information is uncertain, we have measures of that uncertainty. The value of the information is time-limited and ensuring development and delivery of this is operationally challenging requiring robust and reliable data handling and communication systems. The delivery of information also needs to be maintained regularly and reliably, with some users needing information on an hourly basis (i.e. at high frequency). These various requirements represent high scientific, engineering and organisational management demands. Meeting these engenders a strong culture of trust and understanding between provider and client.

Delivery of climate change information has quite different challenges. Climate change projections require a different level of trust of users in the scientific methods and outputs. Our knowledge about the future is based on our degree of confidence in a range of scientific methods (observations, theory, models; see Pacchetti *et al.,* 2020), but also highly dependent on wide range dimensions beyond scientific capacities (uncertainties include, for instance, uncertainty in the physics of the models, versus natural variability in the climate system and uncertainty in future greenhouse gas emissions leading to potentially different climate futures). Delivery of the information involves interpretation and communication of the results of climate models run internationally, by third-party scientists, and sharing of this information with non-specialists. Delivery of the information is typically not time-limited, but involves considerable learning, which is hampered by the distance (in time and space) between practitioners, researchers and users of climate projections.

Weather predictions are sometimes considered to be a form of climate service because they provide users with information about aspects of the climate system. However, this usage is very misleading: climate information refers to the statistics of a system without reference to specific times; in complete contrast, weather forecasts relate to specific times, and the more specific a weather forecast can be, the more useful it is likely to be. The phrase ‘Weather and Climate Services’, a term which is relatively more common in the development sector than the research sector, encapsulates services from both weather and climate time scales (WMO, 2021a).

Although there is considerable overlap, improvement of weather forecasts and improvements in projections of future climate have different scientific and research demands. Weather prediction, as an inherently ‘initial-value’ problem requires significant effort in observational analysis; data assimilation; initial-conditions (and potentially physics) ensemble prediction; explicit simulation of weather systems (as opposed to statistics of these); and the highest-resolution limited-area modelling systems. These areas of progress are a lower priority in climate change science.

Although weather prediction and climate prediction are operationally different functions, and have some different scientific demands, there is also considerable synergy in the science. The physics of clouds, land-atmosphere exchange and tropical circulation are equally important on the 1-hour timescale as the 100-year timescale, and we need to represent this physics accurately in weather and climate models alike. The Met Office has a Unified Model for weather and climate prediction for this reason: the same unified computer code, solving the same equations, is used as the basis for both weather and climate prediction purposes, and improvements in the weather model lead to improvements in the climate version of the same model, and *vice versa.* Numerical weather prediction (NWP) and seasonal model biases resemble climate model biases and by understanding and improving the physical processes in NWP models (which are easier to evaluate against observations), we can improve climate models (Palmer, 2020). Furthermore, we need to understand the behaviour of high-impact weather in the present day, and how the physical processes used to predict high-impact weather are represented in our models, to know how it will change with climate change (Taylor *et al.*, 2017, Fitzpatrick *et al.*, 2020) and to understand current inter-annual variability to fully comprehend how this will change.

In summary, weather prediction is operationally distinct from climate projection, and has some different scientific demands and priorities. However, there are considerable and critically important synergies. Improved weather prediction is vitally needed right now in Africa, as part of the response to the climate, which has already changed, and which is projected to become more severe in the coming decades.

2. Capacity of African Operational Centres and the Requirements for Improved Seamless Weather Forecasting

a. Institutional capacity

Delivery of weather forecasts is a complex scientific and operational challenge. While every country has a national weather service, there is considerable variation in the capability and capacity of each. African weather services typically identify the challenges of lack of funding for infrastructure and equipment for observations, and lack of access to staff training and continuing professional development (CPD) opportunities, both for technical skills (such as Python programming) and non-technical (management, strategic working, forecast communication and presentation) skills. While scientific progress is needed, to accelerate the improvement of African forecasts, this needs to be balanced with institutional support to the services delivering the forecasts.

The WMO makes policies and recommendations (see for example, WMO 2021a; WMO Education and Training Programme[2]), and coordinates support to the national services, but is mainly reliant on funding from third-party organisations and programmes to support development work and cannot directly implement its practices in countries. In order to make progress, it is necessary to make changes within centres, such as national meteorological services and research centres that can support NMHSs in the development of training programmes. Training and building a critical mass of expertise is needed in most African centres (WMO, 2015). Training provision needs to recognise the need for translating individual skills into institutional capability. Ensuring forecast usage is also dependent on the risk communication and decision maker engagement capacities of meteorologists and climate researchers, together with resources to support ongoing dialogue between forecasters and users. While not yet recognised as core elements of meteorological training, African SWIFT

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[2] Course: Conference on Leadership and Management of NMHSs in Africa (RA-I) (wmo.int)

partners have supported the development and piloting of Learning to Co-produce[3], a 10-module training designed to strengthen meteorologists' engagement with decision-makers.

b. Human resources and critical mass in skills acquisition

Modern weather forecasting relies on modern computational and communications systems, with which to: acquire, exchange, process, visualise and archive data; run models and generate locally relevant diagnostics; and translate the numerical data into visualisations and messages, which can be understood by forecasters and forecast users.

i. Priorities for training in African weather services

African weather services are aware that they mostly lack the state-of-the-art facilities for these functions, and lack the human capacity and in some cases, capability, to update and maintain their systems (WMO, 2015). Basic expertise in computational methods and data handling is a key area in which capacity needs to be built. The current position is that most African centres are reliant on assistance from the Global North, to maintain these technical functions. For example, the Synergie system which is supplied to most centres, to visualise real-time NWP and observational data on the forecast bench, can be a powerful tool for synthesis of model and observational data, but is also a 'black box' from the perspective of most weather centres. Data which are not readily displayed on Synergie are never seen by forecasters (for instance many fields and levels from model data are unavailable), and weather centres have no capability to modify the Synergie functions and tailor solutions to their own needs. Because Synergie is not available outside the weather centres (e.g. in universities) there is no prospect of building a critical mass of people able to develop new diagnostics or functions.

Another immediate priority for the advancement of African forecasting services is to build local capacity to undertake co-production of new services with users. Genuine co-production is unlikely to be successful if local weather services cannot modify products in response to the needs of their customers, and the Synergie system is arguably an obstacle to this process. This capability implies the ability to manipulate NWP and satellite data, demanding core technical skills in programming, data handling, and computational systems. Local critical mass in these computational skills is a necessary condition, to successful forecast services. As a precursor to data manipulation, it is also imperative that NMHSs have access to the raw data required in order to manipulate these data specific to user requirements.

We recommend that the building of a critical mass of scientists with computational and technical skills needed to maintain weather forecasting systems is essential for improvement of forecasting quality in Africa. The GCRF African SWIFT programme has made headway into building the capacity of both forecasters and research scientist in its partner countries (Senegal, Ghana, Nigeria and Kenya) through the provision of computational methods, synoptic meteorology and user co-production training activities (Parker *et al.*, 2021). This critical mass may already be held in some large centres such as the South African Weather Service (SAWS) and the Agency for Air Navigation Safety in Africa and Madagascar (ASECNA), but more widely, we recommend that investing in operational-academic partnerships with universities is a good long-term solution.

ii. Training for seamless forecasting timescales

Modern weather forecasting also demands integration of systems dealing with different forecast timescales (UCAR, 2019). The S2S analysis and forecast provides a framework for synoptic forecasts, which in turn provides the environmental perspective needed for successful nowcasting. Near real-

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[3] http://www.walker.ac.uk/academy/learning-to-co-produce/

time observations are required for forecast evaluation, and this needs to be part of a routine cycle with the forecasting process. Each of these timescales and processes makes use of different model products, different visualisation platforms and different forecaster knowledge and expertise. This integration of timescales and their methods is necessary in order to handle the high uncertainties in existing forecast systems: for instance, the S2S analysis of prevailing tropical conditions is helpful in gauging confidence in synoptic forecasts over a couple of days. These organisationally complex aspects of forecasting across timescales remain a challenge within the Global North.

The consequence of this need to integrate systems and timescales is that forecast offices need strong capacity and skills in a range of knowledge and techniques. It is not enough to specialise in nowcasting, without strong synoptic and S2S expertise in which to embed this. Training of staff is vital, and maintenance of a range of computational systems.

While the forecast office needs to combine these functions in order to generate high quality forecasts, users should not see the joins. For example, a forecast office may see likelihood of a rainy period in the S2S forecast and communicate this to users. As the event approaches, the forecast office will be making synoptic forecasts of rain events, and eventually will be issuing nowcasting alerts and warnings of storms. Communication of these should be organised around the user needs, and not around the tools used in the forecast generation.

iii. Training in African weather services: One size does not fit all

It is likely that not all weather services need to have equal capacity within Africa, and the role of regional centres is likely to become increasingly important. For example, the Nigerian weather service (NiMet) currently provide weather forecasts to neighbouring countries (Liberia, Sierra Leone) under a special arrangement brokered by the WMO, and SAWS (a Regional Specialized Meteorological Centre) has a responsibility to support southern African nations in the provision of nowcasting (Youds *et al.*, 2021). Therefore, it is sensible for the NMHSs with international remit (as guided and overseen by the WMO) to develop the strongest capacity for seamless forecasting, at least in the short-term.

Through the experience of GCRF African SWIFT and work that the project has done to understand the training needs of its partner staff across both weather service and academic institutions, it can be argued that a weakness of current international efforts in training is that events are piecemeal, and lack coordination or collective evaluation, for instance against skills frameworks.

Training needs to be commensurate with the overall aims in terms of improving quality, applicability, and use of forecasts by decision-makers. The linking of training programmes directly to the development of standard operating procedures (SOPs) for forecasting would ensure that training is directed towards improving forecast provision in a standardised framework. In addition, a quality standard and evaluation of participants' achievement would allow for quality control of training activities and the skills attainment of students. For instance, training associated with the WMO's Basic Instruction Package in Meteorology (BIP-M) includes key areas of knowledge and competence which are needed by professional forecasters to deliver forecasts: achievement of these standards should be a benchmark for training activities, and students should be assessed according to these standards, to demonstrate professional capability. A syllabus for training (giving regional focus to the BIP-M and WMO Global Campus) needs to be developed, with a clearly defined set of skills and competencies and training modules linked to learning outcomes for students, and which are inclusive of risk communication and stakeholder engagement.

c. Robust funding for activities

i. Funding for the provision of seamless forecasts across sectors

Weather forecast services have a large potential economic benefit in Africa. However, most national weather services suffer from lack of funds, when the provision of their services ought to be economically effective and lucrative to government, business, and individual livelihoods.

A range of funding routes for long-term support of weather forecasting services exists now (government/public weather service, aviation, commercial). There is evidence from the success of some private-sector enterprises in Africa, such as the European commercial company Ignitia, which markets localised forecasts to farmers in Ghana (Goddard *et al.* 2018), that commercial funding is viable. Ideally, the funding of weather forecast services should be linked directly to the users or sectors it supports (such as aviation, public weather service including TV, radio and other media, or commercial customers). This direct link between forecast provider and forecast user maintains a sustainable stream of funding for the public weather service. Evaluation of forecast skill should be used to inform funding, in order that resource is directed to both expanding skilful forecasts (spatially and across sectors) and developing the science behind those with less skill. An example where this link between funding and services works effectively is ASECNA (the international aviation-security agency covering most of francophone Africa): in the ASECNA countries, taxes from commercial flights are channelled directly into the services supporting aviation, rather than being amalgamated by government. Under these circumstances of transparent funding from the customer, aviation provides reliable income related to service delivery, and as a result, ASECNA is able to outperform most equivalent African national weather services in terms of expertise, technology and reliability of meteorological services, despite one or two ASECNA countries being amongst the globally most deprived economically. This effective and transparent deployment of finance is essentially the reason why Niger, an ASECNA country, has a far better record of radiosonde measurements than Nigeria, despite the substantially higher GDP of the latter.

ii. Core funding

While funding may be linked to explicit services, core funding is also needed to maintain infrastructure, in particular those functions where the benefit of an activity is indirectly connected to the quality of the resulting forecast. The observational networks are needed vitally for data assimilation and evaluation of NWP models, but this requirement is not well understood by customers of forecasts. If a nation fails to make its upper-air balloon soundings (radiosoundings) then NWP forecasts will continue to be delivered by the international centres, but their quality, over a wide area, will be degraded. This loss of quality will not be easily apparent to customers, or even to forecasters, in the current environment where forecast evaluation is very limited. The upper-air network operated by ASECNA outperforms most national weather services, likely because of ASECNA's successful connection of funding to its operational duties.

Development of weather forecasting services in Africa based on the provision of overseas aid funding has suffered for many years from the provision of capital funding without longer-term operational funding to support services. A clear example of this pattern is the number of weather radars which have been provided by donors from development funds, but which have never provided useful services, because there has not been associated funding both to form an organisation of skilled engineers and for the maintenance contracts required to keep the radars operational. Only when there is sound financial and organisational support for radars, including long-term investment in a critical mass of technical skills to maintain a radar and exploit its data, are radars successful. A network of radars has been operating in South Africa for a few years, and recent advances associated with the Highway project have been made in Tanzania and neighbouring countries (Roberts *et al.* 2021b), where several radars are currently operational, and it is to be hoped that by learning from these successes, more radars can be operated successfully across Africa.

d. Observational data

i. Background to African weather observations

A reliable network of *in situ* observations is vital to weather prediction and nowcasting services. These data are required for a number of purposes:

- Local 'synoptic' observations are needed for nowcasting and for synoptic analysis. These data are vital for many applications e.g., for rainfall and thermodynamic parameters needed for planning and decisions on agricultural activity. They are assimilated into NWP models and provide vital ground-truth data to correct the models' representations of pressure, thermodynamics and soil moisture
- Upper-air data, provided by radiosondes, is a vital ingredient for data assimilation into NWP models; these data are also required to give stability measures for the forecasting of deep convection, and to advise on levels of windshear, for the convection forecast and for aviation forecasting.
- Any calibrated observations can serve as a source of evaluation data for NWP products, without which the NWP quality is compromised.
- *In situ* data are required for calibration of satellite data products and for the generation of merged products with the satellite data.

For longer-term, S2S prediction, most of the constraints are similar to operational NWP. Atmospheric initialisation still matters, soil moisture is an obvious additional need on subseasonal timescales, but it might be just as (or more) important on NWP timescales.

The decline of the African observing networks over recent decades is well documented (Fink *et al.*, 2011) and the current data coverage is inadequate for the provision of high-quality services. It is easy to be pessimistic regarding this situation and imagine that in the face of long-term decline no improvement is possible. However, there is evidence from the AMMA programme (Parker *et al.* 2008, Fink *et al.*, 2011) that it is possible to overcome many of the assumed barriers to progress, and initiatives such as TAHMO[4] are showing how new approaches to instrument deployment and data transfer can overcome long-standing problems.

The question of African meteorological observations is multifaceted and complex. There is unlikely to be any single solution which will, in isolation, solve the widespread problems, and a multiplicity of solutions is probably going to be most effective. There is not space here to document all the issues and potential solutions. We confine ourselves to a few general remarks: many of these remarks are based on the experiences of the African Monsoon Multidisciplinary Analysis (AMMA) project, some of which are documented by Parker *et al.* (2008) and Fink *et al.* (2011). The key conclusion from the AMMA work is that the most important factors in improving data collection across Africa will be communication of data in real time to the Global Telecommunication System (GTS) and effective international management of the networks.

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[4] https://tahmo.org/

ii. Known challenges and possible solutions for African weather observing networks

The lack of observational data (i.e., the density of the network relative to other continents) limits the provision of weather prediction services on the range of timescales discussed in this paper. At many stations, the equipment is in a low state of repair. Anemometers may be worn out and fail to record low wind-speeds (for example). Refurbishment of existing stations will improve the accuracy of those measurements. Challenges include the following:

- Communications and sharing of data

Many stations are invisible to the outside world because they are not communicating data outside their national services (Parker *et al.*, 2008). A large amount of data is lost this way, all the time. Improvement in communication of existing measurements to the Global Telecommunication System (GTS) is probably the most effective way to increase data coverage across Africa. However, solving the communication problems are not trivial and are likely to involve multiple solutions in parallel (Parker *et al.*, 2008).

More generally, there is a problem across Africa of a failure to share data freely; rainfall data in particular. This problem is long-standing and widespread. The RAINWATCH programme has had some success in overcoming the problem by generating real-time products from the data (Boyd *et al.*, 2013) but access to detailed rain gauge data across the continent remains very difficult.

- Exploitation of existing data

Records may still be hand-recorded and fail to be archived on international databases. Archiving of data is problematic. There are many hand-records of data going back over decades, in storerooms in the weather services. A number of projects over the years have made progress in the rescue of this historical data. While this issue does not impact daily weather prediction directly, the archived data is a source of evaluation material for NWP models which is not being exploited.

- Data for Nowcasting

Nowcasting has been held back for several decades by the lack of radars. Weather radars are certainly the most valuable tool for nowcasting of precipitation. The South African Weather Service (SAWS) operates a radar network and recently Tanzania has also made progress in installing and operating several radars. The Highway project used data from these radars to implement nowcasting services across the Lake Victoria Basin (Waniha *et al.*, 2019; Roberts *et al.* 2021b). Unfortunately, other programmes to install weather radars in Africa have had very limited success despite several decades of effort, due to a failure to invest in a critical mass of skills to maintain a radar and exploit its data, and a failure to maintain secure long-term funding for operation and maintenance.

Despite the lack of radars across the continent, satellite nowcasting solutions demonstrate useful skill (Hill *et al.,* 2020) and there is an opportunity to deliver operational satellite-based nowcasting in Africa without delay. Real-time surface observations are also vital: there remains no substitute for the surface networks, to evaluate Nowcasting.

- Training and capacity building

It is vitally important that African organisations have the know-how to operate and service observational instrumentation, and the lack of training is often cited as a limitation to the performance of the observing networks. On the other hand, high-level observational capacity and capability do exist in Africa, and were the basis for the success of the AMMA Upper Air network, almost entirely operated by the African services (Parker *et al.,* 2008).

For high-tech instrumentation like weather radars, the lack of local engineering and data handling expertise in Africa is probably the key reason for the failure of many initiatives to install radars. Donors have tended to provide significant capital funding to install a radar without consideration of the operational funding required to maintain it, and in particular the need for the local operators to be trained to high levels of expertise in engineering and data handling.

iii. Wider solutions to the challenges facing the African observing networks

International strategy and, critically, international tools for implementation of strategy, seem to be vital to the African observing network. For example, the ASECNA network across much of francophone Africa has a more effective observing network than many of its neighbours, despite some ASECNA countries being among the poorest in the world. ASECNA's success is in part due to its critical mass enabling it to maintain good training, engineering know-how, technical problem-solving and so on.

In documenting the success of the AMMA upper air programme, Parker *et al.* (2008) recommended that the international community should fund a modest coordination office to monitor performance of the African networks and hold a modest budget to implement solutions when problems arise. This approach has since been working effectively in Europe in the form of the WMO's Integrated Global Observing System (WIGOS) Office. It is to be hoped that WIGOS regional centres in Africa are able to become effective in driving solutions to real-time problems in the networks.

The priority of observations for data assimilation for NWP is not often raised highly enough with African centres as a motivation to meet their observational responsibilities. For instance, the value of a local upper air (radiosonde) sounding in improving the NWP extends over a very wide region (van der Linden *et al.*, 2020), but this value and impact of the data is generally not perceived. The connection between data collection and its value to local forecasters and clients is one potential driver of improvements in observations, which is not being fully realised. Modern weather forecasting is more reliant on NWP products which rely on observations for their data assimilation but will still be generated without those data. There is a disconnect between the observations, their communication, assimilation into models, and use of those models by the local forecaster, which distracts from the vital importance of the data to the outcome. A much stronger emphasis on NWP evaluation by local agencies may therefore be one driver to improve the quality of the data serving the NWP models.

Prioritisation of observations is also related to the budgets available to the weather agencies. While aid money is often used to direct capital funding at the refurbishment of observing systems, securing operational funding for the observing systems is typically much more difficult for operational agencies. Financing of observations remains challenging, and it seems natural that a closer connection between an observation and the revenue associated with that observation should strengthen the drivers to maintain the networks. A new initiative to address the challenge of sustainable funding for observations is being driven by the WMO's Systematic Observations Financing Facility[5]. The private sector may have an unappreciated role to play in observations too. Following the AMMA campaigns, a private company operated by African experts has delivered observations to international field experiments in Africa including Fennec and DACCIWA on a commercial basis, delivering data to a standard that no non-African operators would be likely to achieve in those circumstances.

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[5] https://library.wmo.int/index.php?lvl=notice_display&id=21769#.YN83TuhKg2x

Exploitation of satellite remote sensing is an area of massive potential to improve monitoring over Africa. Many solutions are already available, but there is massive potential to increase the value and impact of satellite products. The new products provided by Meteosat Third Generation (MTG), such as lightning observations, are a key opportunity to anticipate, and the development of machine-learning methods are a new opportunity to innovate new products.

Improvement of satellite data products and co-production of services around these products will require research, innovation and development. There is a need for African ownership of the science, in order that African agencies can actively develop co-produced services for their clients. This in turn demands core skills among the African community in data handling and scientific understanding. New data science areas such as machine-learning may be fruitful avenues for African researchers to innovate new satellite data products.

It should be noted that satellite data have tremendous value for data assimilation into NWP models, and as such have transformed the skill of global NWP, but satellite data are not sufficient for data assimilation. In particular, satellite data still struggle to provide adequate low-level thermodynamic information required for the convective tropical environments, so that the *in situ* measurements remain vital.

Looking to the future there are many possible innovations offered by the rapid developments in technology and communications in recent years. The TAHMO network has demonstrated how relatively cheap sensors and communications systems can deliver remarkable data coverage. Other initiatives are exploring the use of mobile phone signal attenuation to compute rainfall intensity[6]. With increasing mobile phone network access, especially in densely populated regions, the possibilities of accessing more crowd-sourced data in future are very interesting.

Final remarks: It is easy to be pessimistic about the state of the observing networks in Africa, noting decades of decline, and the lack of success of a number of efforts to reverse that. Many efforts to install weather radars have met with failure. Rainfall data continue to be hoarded by national agencies, and not shared internationally. On the other hand, the experience of the AMMA programme, centred on 2005-2007 field observations, has been that obstacles can be overcome, and that a number of the widely quoted problems are not so hard to deal with. AMMA found that the capacity and skill of African groups should not be underestimated, and that there are significant budgets available in Africa for observations, if these budgets are suitably directed. More recent initiatives such as TAHMO and Highway (with the associated successful installation and use of radars in Tanzania) are also giving cause for optimism.

e. Models and infrastructure

African agencies need ownership of the forecasting products, if they are to engage in effective co-production of services with their user communities. This ‘ownership’ implies the ability to design and tailor forecasting products to suit the needs of each client, and it demands suitable levels of meteorological and computational skill. Computational skill is needed in handling observations and model data; generating new diagnostics; generating new visualisation; and archiving and communicating data and its products. There are clear examples from GCRF African SWIFT in Nigeria (GCRF African SWIFT 2021a), Kenya (GCRF African SWIFT 2021b) and Niger (Parker *et al.*, 2021) of groups being able to innovate new products to the benefit of their communities, given access to the appropriate data. Underpinning this ownership of the data is the need for suitable infrastructure in

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[6] E.g., https://www.knmi.nl/research/observations-data-technology/projects/rainfall-estimation-using-commercial-cellular-communication-link-networks

terms of hardware and communications systems to handle data, and African expertise in their maintenance.

Many African centres are now running their own local NWP models on regional domains. There remains an international debate as to whether African-run NWP is valuable, or whether African centres should rely on NWP data generated in the Global North. It is argued that the lack of supercomputing in Africa, and the lack of a critical mass of experts to run models, means that attempting to deliver effective NWP within Africa is a waste of limited resources in terms of staff time and hardware.

We argue here that locally generated NWP in some African centres should be regarded as a necessary step to building the critical mass of expertise in those centres to take ownership of the whole forecasting process. There is a need for African NMHSs to undertake comprehensive verification of their NWP products, but we have to recognise that this takes substantial human and computational resource. While the performance of an African regional NWP model may not be superior to a model run from centres with much more computing power, outside Africa, there are several benefits of Africa-run NWP:

- Ownership of the data production will lead to ownership of the data products, encouraging bespoke products to be created for local needs; and it is vitally important that the African centres have access to data rather than just plots from these centres, and develop the skills to produce diagnostics from those data.
- An NWP activity in-country contributes to a growing body of experts, a critical mass, with scientific capability to use forecast data – whether the data are generated locally or imported from the Global North.
- In-country NWP will stimulate collaborations with universities and other centres in the country or region (as has been seen in Senegal in the SWIFT project where a university scientist seconded on a SWIFT fellowship to the weather service, ANACIM, has made major contributions to the ANACIM NWP capability). Ideally, where a university and operational partner are using the same model, there are many opportunities for mutual support, with the university partner transferring skills to a significant number of students.

Although we argue here that local generation of NWP is an important development step for a number of the top African centres, it must also be recognised that modern weather prediction is highly international, and African centres will always need to access products generated from the big producing centres of the Global North, regardless of any local NWP production (the same is true of all nations worldwide). For this reason, it is vitally important that the African centres have access to data rather than just plots from these centres and develop the skills to produce diagnostics from those data.

f. Operational centre opportunities and gaps according to forecast timescale

i. Subseasonal to seasonal timescales

From an operational perspective, understanding what drives predictability on S2S timescales and being able to accurately model its impact on local weather over Africa is necessary, but not sufficient to produce useful and actionable information for forecast users. There remains a further important gap in knowledge: how to improve the appropriate use of operational S2S forecasting products for actionable decision-making.

Outputs from state-of-the art forecast models underpins the provision of forecasts to users in support of their decision making, but the development of forecast products requires an ongoing collaboration between the forecaster provider and forecast user, this is the process of co-development or co-production (Visman *et al.*, 2019). This iterative process requires:

- a common understanding of the users' decisions and the role that weather information can play in informing that decision.
- developing reliable and timely forecast products that can inform that decision.
- evaluating these products, from a meteorological perspective, in the context of the decisions that they are informing, and their communication.
- further development, based on ongoing evaluation, or the availability of new research.
- In particular, it has typically been applied in project-initiated services, but to increase the range of users and decisions being supported by S2S forecasts will require some streamlining of the co-production process, and the best way to achieve this requires exploration and a dedicated resource as, if done effectively, the process is resource-intensive.

It is important to recognise that effective co-production is resource intensive. Therefore, in order to sustain project-initiated services the knowledge-exchanges between individuals in the coproduction process need to be documented and institutionalised. Specifically, this may require identifying particular parts of the coproduction process as priority for investment of resource (e.g. initial co-exploration of needs and co-evaluation).

Such an approach is being explored within the S2S operational testbed of the GCRF African-SWIFT project (Hirons *et al.*, 2021a, Parker *et al.*, 2021), a Real-Time Pilot Initiative of the WMO S2S Project (Vitart *et al.*, 2018).

It is becoming increasingly clear that evaluation of the skill of S2S forecasts is not only a question of meteorological verification, but rather a comprehensive evaluation process which should combine meteorological skill with evaluation from decision-makers who are actually using the forecast products in their sectors. It could be argued, for example, that a forecast on these timescales is only 'skilful' if it has helped inform a particular decision. Therefore, it is key that a combined evaluation system can be developed incorporating, through co-production, different knowledge sources and practices from all groups to develop shared understanding and jointly agree metrics or indicators of 'success' that can be adequately tracked (Carter *et al.*, 2018).

ii. Synoptic timescales

On the synoptic timescale, the opportunity is to exploit the new generation of convection-permitting models which transform the representation of African rainfall systems. Such models are running operationally for tropical Africa and southern Africa and have been demonstrated to make many improvements to rainfall in the models (Marsham *et al.,* 2013, Maurer *et al.,* 2017, Woodhams *et al.,* 2018, Stein *et al.*, 2019, Cafaro *et al.,* 2021). However, the models create new challenges in handling of data and uncertainties, and high forecaster skill is needed for their use.

An equally important opportunity is to bring new understanding of African weather systems from successful international research programmes into operational forecasting practice. Since the AMMA project (Redelsperger *et al.,* 2006, Lafore *et al.*, 2017), efforts have been made to standardise the analysis of weather patterns in NWP data. This work is having an impact on training and skills in the region but needs to be rolled out more quickly, extended to other parts of Africa, used in co-production of services with clients, and integrated into the forecasting SOPs for the continent.

A number of areas of development are needed in order for the weather centres to deliver more effective synoptic forecasts, as follows.

- The staff of African national weather services, and their supporting partners (in particular, universities) need better skills in core data manipulation and management, so that the African centres are able to manipulate data locally and generate their own products. Without these skills, the African centres will always be reliant on international assistance, and progress will be slow.
- More observations (or more reliable functioning of the defined network) are needed, especially radiosondes, to initialise models, including observations made away from population centres.
- Across Africa, forecasters are not using conceptual models consistently, and are not blending NWP products with their conceptual understanding. The Forecasters' handbook for West Africa, and the planned volume for East Africa, are making progress in this area, but need to be linked with structured training programmes.
- Plotting of the synoptic situation is not being done automatically from NWP. This means that forecasters are always in danger of using the NWP products uncritically: in the case of rainfall, we know that NWP is unreliable. The Synergie software used in many forecasting centres is holding us back in this regard: Synergie does not allow forecasts much freedom to plot conceptual features such as fronts, troughs, and convergence lines. More meaningful synoptic maps need to be generated automatically for Africa, containing these features plotted computationally, as they are for the 'Northern' weather services.
- Operational training in the use of NWP, including CP models and ensembles, needs to be linked to training in the conceptual understanding of weather systems.

iii. Nowcasting timescales

As mentioned above, nowcasting holds massive potential in Africa, where storms are severe, rapidly changing, and poorly forecast by NWP. However, before the GCRF African SWIFT project, nowcasting had been almost non-existent in tropical Africa (Roberts *et al.*, 2021a). The Highway project (WMO, 2021b; Roberts *et al.* 2021b) has demonstrated the potential value of African nowcasting, in saving lives on Lake Victoria. There is a tremendous opportunity now to establish nowcasting services in every country on the continent.

For nowcasting in Africa, there is a gap in awareness of forecasters of the opportunity and the potential of using the products already available (even though those products could be greatly improved with even moderate research investment). GCRF African SWIFT has made products available online through the GCRF African SWIFT Nowcasting Catalogue[7], it is desirable for forecasters to receive and generate products locally, a task SWIFT has started in four African nations.

Forecasters then need adequate training in use of nowcasting products, and the opportunity to develop links with users to generate a market for nowcast products: there is still widespread misunderstanding of what nowcasting really is. Sufficient funding is needed for staff time to generate and issue public warnings based on a nowcast process, which requires forecaster attention 24 hours per day. The financial model to support nowcasting by weather services is therefore key, both for public warnings, and bespoke forecasts for particular users such as aviation, shipping,

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[7] https://sci.ncas.ac.uk/swift/

transport etc. All of these functions need to be associated with a suitable Standard Operating Procedure for nowcasting to support a given client – to the best of our knowledge such SOPs do not exist for (tropical) African nowcasting.

In conclusion, nowcasting offers an opportunity, almost immediately, to provide African people with real-time alerts of severe weather in their vicinity, with which to take short-term action saving lives and property. The immediate gap lies in implementation of the solutions within the African agencies, and in co-production of nowcasting services with their clients. Satellite-based nowcasting products exist now and have been tested and made available by SWIFT: future improvement in the quality of these products should be a focus on ongoing research and offers great potential. Well-managed programmes may also be successful in installing rainfall radars more widely, as has been successful in Tanzania (Roberts *et al.* 2021b). A hybrid nowcasting system making use both of satellite and radar data is very effective in South Africa, and similar solutions need to be implemented across the continent.

3. Maintaining, Improving and Communicating Forecast Quality through Evaluation

Weather forecasting information is vital to the lives and livelihoods of vulnerable people in Africa, and therefore the evaluation of that information has critical significance, commensurate with the opportunity to save lives and the implications of people basing their actions on poor information. Similar to concerns regarding maladaptation, failure to provide comprehensive evaluation of weather prediction products is to offer life-critical information whose value we do not know, and which could potentially be harmful.

The status quo for tropical Africa is that very little forecast verification and evaluation is being done outside the WMO's Severe Weather Forecasting Programme[8]. One important distinction needs to be made between the verification of the forecasting system and the evaluation of individual forecasts. The former requires a longer time frame to build up the relevant statistics. Both the forecasting system and observing system need to be reliable and consistent over the course of that time frame, so that verification can become a routine procedure to monitor performance. Over the period of a month or a season, verification can highlight biases or other erroneous behaviours that can be fed back to the developers of the forecast product. By carrying out verification over longer periods of time, sufficient statistics can be gathered to learn how forecast skill varies with particular synoptic regimes. The forecast verification outcomes allow the forecaster to better interpret the forecast products, for instance through bias correction, and, ideally, to generate more skilful and useful forecast products. A meaningful operational verification practice requires investment in appropriate long-term archiving and documentation of forecast products and observations. However, access to such archives will provide new training opportunities for forecasters in handling these data and trying out various verification techniques, ultimately developing in-house operational verification practices.

The next step is evaluation, which is to understand why these biases or other erroneous behaviours appear. This can be done by identifying individual cases in which the forecast showcased such biases and studying these forecasts and the observations in more detail, for example, with additional satellite observations, NWP models or reanalysis data. To support case study identification, it is recommended that forecasters make regular (e.g. weekly) note of the quality of the forecast

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[8] Severe Weather Forecasting programme (SWFP) | World Meteorological Organization (wmo.int)

product, for instance using a questionnaire or form as used in the GCRF African SWIFT Testbeds (GCRF African SWIFT 2021 c, d, e; Parker *et al.,* 2021); a Testbed environment such as the SWFP is another route to identify case studies. Evaluation is most useful if the outcomes can be fed back to improve the forecast product. If the forecaster can influence the forecast product design – for instance, if the product is derived from an in-house NWP model – sensitivity analysis can be carried out to test if a different product design would have produced a better forecast. Successful evaluation practices require good knowledge of the forecast product, observational data, and of the meteorology of the case of interest. Consequently, evaluation is often best done in collaboration, not just across different teams at NHMSs, but also involving national academic (university) and research institutions. In addition to the long-term archive required for verification, data sharing agreements and knowledge exchange between national institutions will improve the capacity to evaluate and improve forecast products. Rainfall data continue to be protected by national agencies, and not shared internationally, while there is ongoing frustration about the use of African data by projects in the Global North and agencies without much benefit returning to Africa.

The focus of verification and evaluation for tropical Africa has historically been on deep convection, not just because of the local impacts, but also because of the accessibility and reliability of satellite-based observations. While satellite products have proven useful for verification, more meaningful evaluation requires additional key meteorological variables, including surface temperatures and winds. Improved access to and availability of surface-based observations will not only allow more informed analysis of surface impacts from deep convective storms, but also a shift of focus in verification and evaluation practice to other weather hazards including heat waves and fog.

Certain aspects in evaluation and verification require international and global collaboration. Global forecast products from Global Operational Forecasting Centres form an integral part of the forecasting chain for NMHS across tropical Africa. These international centres currently lack feedback on model performance from NMHS (and don't have much resource to evaluate this themselves). However, in order for NMHSs to provide this feedback – i.e., meaningful verification and evaluation – a process must be in place to act on the feedback and improve the global forecast products. The previous examples of routine and descriptive feedback via questionnaires could be followed, perhaps with a 'digest' version on a monthly basis highlighting persistent biases or failures of a particular model. Analogous to internal procedures, a ticketing system could also be considered. However, a more involved approach could be considered: the SWIFT Verification Workshop brought forecasters and researchers together for a 2-week period to verify Met Office rainfall and temperature forecasts from 2019-2020. The event benefited forecasters in acquiring skills required for verification (handling large data sets, scripting in Python, statistics of verification) and it benefited the international centre in receiving detailed feedback on otherwise poorly studied regions. Repeating such a workshop or similar exercise annually would allow us to close the feedback loop, to encourage the international centre to act on the feedback and to find out if the forecast has improved accordingly. Regardless of the approach taken, given the importance of global forecast products in the forecasting chain for tropical Africa, international centres should develop a framework for feedback from NMHSs, establishing the quality of feedback required, and a procedure to act on this feedback.

In an increasingly competitive commercial market for weather prediction products, communicating forecast performance is essential to build trust and customer confidence, as well as vital to FbF. To build trust and confidence for local forecasts, a NMHS can share its performance with customers, as done for instance by the Met Office[9]. An increasingly effective approach is to bring users into all aspects of the forecast product design, including verification and evaluation. In such an approach, users and forecasters will jointly set performance targets – which should be relevant to the user – and jointly consider the best practice for verification and evaluation. For forecast products that have a broader customer base, such as severe weather alerts or the national forecast, user consultation should occur frequently to foster user engagement and trust, considering quantitative (e.g. value-based) and qualitative (e.g. verbal comments) evidence. It should be noted that participatory evaluation is novel for weather forecasting in general, not just for tropical Africa. Impact-based forecasts, specifically, require a participatory approach to verification and evaluation to build trust and confidence in both forecasters and forecasters. The Met Office, for instance, apply a qualitative and user-focussed approach[10]. Impact-based forecasts are designed to provoke action, so their value must be verified based on user feedback. Inaction can have various causes, including the timeliness and specificity of the forecast, the lack of trust in the forecast product or NMHSs, or perceived irrelevance to the user. Evaluation thus requires a multidisciplinary approach, incorporating behaviour science, science communication, forecasting, and other disciplines. Further collaboration between NHMSs, universities and other national organisations is recommended to develop these multidisciplinary approaches.

4. Specific Challenges of Forecasting across Seamless Timescales, and Expected Solutions

a. Seasonal and subseasonal prediction: challenges and solutions

i. Definition and potential

Beyond the limits of traditional weather forecasting timescales (~5 days) there remains the opportunity to exploit the predictability of the climate system to provide useful forecasts on timescales from a few weeks up to a few months. These forecasts include established 'seasonal forecasts' - predictions of the mean conditions for a season about a month in advance (e.g. predictions of the Oct-Dec East African Short rains in late August /early September), and the newly developing subseasonal (to seasonal; S2S) forecasts which typically focus on predictions for 2-4 weeks ahead (Vitart *et al.*, 2012; Robertson *et al.*, 2014), between synoptic and seasonal timescales.

Given the uncertainty in convective rainfall even over 24 hours, the methodology for forecasting for a few days and beyond, in the 5-14 day 'gap' between synoptic and S2S forecasting, corresponds much more closely with the methodology for subseasonal forecasting than that of synoptic forecasting; dominated by a consideration of the state of large-scale drivers (tropical and extratropical waves, SST etc.) and dependent on statistical or probabilistic analysis.

Predictability on seasonal timescales depends largely on slowly evolving variability of the surface boundary conditions, particularly sea-surface temperature (Kolstad *et al.,* 2021) but also soil moisture, snow cover or sea-ice. This slow variability often arises from coupled modes of variability in the climate system, e.g., El Niño, is predictable on timescales of a few months, depends strongly on the initial state of these surface conditions and is largely independent of atmospheric initial conditions. This variability in the surface can lead to predictable changes in the large-scale atmospheric circulation which, whilst not leading to predictability of day-to-day variations in

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[9] Comparing forecast accuracy - Met Office

[10] https://www.metoffice.gov.uk/about-us/what/accuracy-and-trust/your-say

weather can lead to predictability for appropriately time- aggregated quantities like seasonal mean rainfall, or seasonal number of tropical cyclones.

Producing reliable forecasts on subseasonal timescales (2-4 weeks ahead) that are useful for decision-making is an extremely complex interdisciplinary challenge. From a meteorological perspective forecasting such timescales is challenging because it is sufficiently long that there remains only limited predictability from the initial atmospheric conditions; but the forecast period (e.g., weekly or decadal mean quantities) is sufficiently short that short time-scale variability of the atmosphere can dominate over the influence of the seasonal and longer modes of variability (Vitart *et al.*, 2012) on which seasonal forecasting depends. Subseasonal prediction therefore depends on being able to exploit both the remaining predictability from the atmospheric initial conditions and the slowly varying boundary conditions. As with seasonal prediction, this means moving away from predicting individual days, but predicting appropriate time-aggregated quantities based on the predictability in the large-scale environmental conditions which produce the local weather of interest (Koster *et al.,* 2011; Vitart *et al.,* 2015; Sossa *et al.,* 2017; Vigaud and Giannini, 2019; Moron and Robertson, 2020, Macleod *et al.*, 2021b). Therefore, rather than being able to predict, for example, a rainfall extreme on a particular day, a subseasonal forecast would be able to inform you of the likelihood of heavy rainfall or drought averaged over a given period. The nuanced differences between such information, the confidence of which is often also regime-dependent, presents the other side to this complex challenge; namely how you communicate such forecast information appropriately and effectively to decision-makers (Cash *et al.,* 2003; Vaughan and Dessai, 2014; Bremer and Meisch, 2017; White *et al.,* 2017; Vincent *et al.,* 2018; Carter *et al.,* 2019).

Despite these challenges the provision of reliable and actionable forecast information on subseasonal timescales has huge potential to support better planning and early warning which would contribute to increasing people's resilience to weather-related extremes (Jones *et al.,* 2015; Williams *et al.,* 2015; Coughlan de Perez *et al.,* 2016; White *et al.,* 2017; Nkiaka *et al.,* 2019). However, despite their huge potential, advances in subseasonal forecasting are not being translated into effective operational forecast products (Dilling and Lemos, 2011), particularly across the African continent (White *et al.,* 2017). Advances in subseasonal prediction also offer opportunities to transform the practice of seasonal forecasting, by developing products which predict more than just mean conditions, and through advances in our understanding of large-scale controls on synoptic variability, develop predictions of the likelihood of particular types of high impact weather within the season, e.g., extended dry spells.

In this section we will focus on developments and opportunities in subseasonal prediction, noting where appropriate the contrasts and similarities to seasonal prediction, and common opportunities.

ii. Current status

The last four decades have seen an increase in the provision of seasonal forecast information in Africa. Initially, seasonal forecasts would have been largely based on statistical models, but over recent decades there has been a transition to the use of dynamical models for seasonal forecasting (see ICPAC, 2019). These models are run in major weather prediction centres in the Global North and a limited number of products are distributed via the WMO. Regional Climate Outlook Fora play a major role in interpreting these forecasts and combining them (including with information from statistical models) to provide a consensus forecast often in the form of probabilities of below normal, normal and above normal categories, although normally only once before the onset of a rainy season. Regional Climate Centres (such as ICPAC) have been increasingly providing updated forecasts on a monthly basis and making use of publicly available forecast data to provide additional products, including dynamical downscaling.

While producing accurate forecasts on subseasonal timescales remains challenging, significant progress has been made over recent decades, notably in the skill of forecasts of the Madden-Julian Oscillation (MJO), the major mode of tropical intraseasonal variability (Woolnough, 2019; Vitart, 2014). However, accurate forecasts don't depend just on the predictability of the large-scale drivers of variability, but also their influence on the local weather patterns (e.g., modulation of precipitation by the MJO; Berhane and Zaitchik, 2014, Sossa *et al.,* 2017) and the representation of these impacts in models (Vitart, 2017). There has been less emphasis on this in the evaluation of forecast models. Furthermore, whilst the MJO (the major mode of tropical variability on subseasonal timescales, with a global influence) has received much attention, other important drivers of variability have received less attention.

Despite this progress over the last decade or more, the current use of forecasts on subseasonal timescales across Africa is extremely limited (White *et al.*, 2017), largely due, but not limited, to challenges of access and usability (Dinku *et al.*, 2018, Nkiaka *et al.*, 2019), but also because of gaps in knowledge on the sources of predictability. Increasing the use of subseasonal forecasts in Africa depends on improving our understanding of the sources of predictability for Africa on these timescales; an evaluation of forecast models' ability to represent these sources of predictability and its skill; and increasing the availability of forecast data.

Regarding access, there are a small number of global forecast models capable of producing skilful forecasts on subseasonal timescales, and access to such data for operational forecasting in Africa is extremely limited. The potential benefits of increased access to appropriate forecast products on subseasonal timescales is currently being piloted as part of the African SWIFT project in collaboration with the WMO S2S project Real Time Pilot Initiative (Hirons *et al.*, 2021a, Parker *et al.*, 2021). Whilst the WMO is currently in the process of establishing a lead centre for subseasonal forecasting to distribute basic subseasonal forecast products in a similar manner to its processes for seasonal forecast products, these products are likely to be extremely generic and limited and not easily tailored to support decision making for specific users or applications.

The issue of usability of subseasonal forecasting is two-fold. Firstly, many existing subseasonal forecast products are not currently designed with decision-makers in mind (Lemos *et al.,* 2012), so can be extremely generic, often containing non-actionable information (Dilling and Lemos, 2011). Secondly, for forecasts to be used appropriately in decision-making they need to include transparent information on the spatial and temporal forecast skill. Such information is often either lacking, unclear or insufficient.

iii. Research gap

There remain considerable gaps in knowledge which can be broadly broken down into three categories: i) improving our understanding of the drivers of S2S variability and their local weather response; and ii) evaluating the ability of models to accurately represent those drivers and their local weather response; iii) forecast calibration to account for mean biases in the forecasts or errors in the simulation of the drivers or their local impact.

Drivers of S2S variability

There is still a lot to be learned about the predictability of S2S drivers relevant for Africa. New research is continuously emerging linking large-scale modes of variability, like the MJO, with the modulation of local African weather, such as the diurnal cycle of rainfall over East Africa (Camberlin *et al.*, 2019), or the level of African Easterly Wave activity (Ventrice *et al.*, 2011). However, there remain significant gaps in our understanding of the local response to known large-scale regimes or drivers in observations (e.g., Gulf of Guinea and Indian Ocean sea surface temperature, Tropical Easterly Jet), and in model response. In addition, there may be other unknown, or at least under documented, large-scale drivers affecting weather systems across the African continent.

There is also an important question around what drives variability in (e.g., rainy seasons) in the absence of large-scale drivers. This is particularly clear, for example, with the stark contrast between the main rainy seasons in East Africa. The influence of large-scale seasonal drivers (IOD/ENSO) on the short rains (from Oct-Dec; OND) is well known and documented, whereas our understanding of what controls interannual variability in the long rains (from Mar-May; MAM) is far weaker. Recent studies have emerged presenting evidence of a potential MJO influence (Vellinga *et al.*, 2018) during MAM. However, in this case, and others, the dynamical mechanism behind the statistical relationship found requires further research.

Evaluating S2S simulations

The evaluation of the forecasting systems can be further broken down into two activities. Firstly, we need to know whether models are able to simulate the large-scale drivers *and* their impact on the local weather. This kind of evaluation depends on the detailed understanding of the drivers and the mechanisms through which they impact the local weather and is key to understanding the skill of the forecast systems. The second kind of evaluation is the formal evaluation of the skill of the system (de Andrade *et al.*, 2020), but in addition to a general meteorological focussed assessment of the skill, there is a need for developing more user focussed assessments of skill (see 'What is needed to make this solution a reality?' below). The process-based evaluation and the skill assessment can be further linked to improvements in our understanding of the regime-dependent skill of S2S models. That is, do we understand what large-scale conditions result in higher forecast skill (where and when), or potentially useful skill at longer lead times? A corollary question to this, is do we also understand why there isn't skill at certain times? This is a complex question because a lack of skill could be for a variety of reasons. For example, it may be that the model has a limit in the prediction of the large-scale driver, or that the mode is unable to capture its local response.

Forecast calibration

Subseasonal to seasonal forecast models develop biases (e.g., errors in the forecast mean, or the variance), particularly at longer lead times, which can make translating forecasts into useful products to support decision making challenging, particularly for example if the meteorological forecasts are used as an input to a downstream impact model (e.g., flood, crop). Statistical post-processing or forecast calibration (Siegert and Stephenson, 2018) can be used to account for these biases. There are a number of approaches for forecast calibration, the choice of which will depend on the nature of the bias (such as error in the mean, or error in the variance); and the variable of choice (Hagedorn *et al.*, 2008; Hamill *et al.*, 2008); and which address errors locally (Model Output Statistics; Glahn *et al.*, 2009) or considering the spatial correlation of the modes of variability and the model errors (e.g. empirical orthogonal function-based methods, Feudale and Tompkins, 2011). Understanding the source of these biases and their impact on the forecast skill and characteristics are important steps in selecting or developing appropriate calibration methods, but a further important consideration will be the intended use of the recalibrated forecast (see below).

iv. What is needed to make this solution reality?

There are a number of barriers to advancing operational subseasonal to seasonal prediction in Africa:

- Access to data - The process of co-production inherently requires that forecast providers have ongoing access to raw forecast data in order to develop tailored products for forecast users. Whilst the planned provision of forecast products should enable some operational S2S forecasting development in Africa, it is unlikely to match the potential benefit that tailored co-produced forecasts can achieve to support decision-making.
- Co-producing bespoke forecast products is resource intensive. Therefore, for the potential to be realised and sustained, sufficient resource must be invested in the coproduction *process* (which is often hard to quantify).
- Improvements in understanding, evaluation and calibration of forecasts will inform, and can be informed, through the process of co-production. There is a need for sustained collaborations amongst researchers, forecast producers, forecast communicators, and forecast users to co-produce new forecast products and tools which are tailored towards particular decision-making needs, and to maintain the improvements in systems over time.
- The experience of project led initiatives has shown the enormous potential of S2S forecasting developed through the process of co-production, but these projects often develop *individual capability*, but that capability is lost as the individuals involved move on or projects end. There is a clear need to build *institutional* capacity not just *individual* capability. The development of standard operating procedures (SOPs) can aid this.
- Capacity building of all groups involved in the co-production process is needed. This includes better understanding of the co-production process itself, the context of decision-makers, the ability to communicate complicated forecast concepts clearly and regime-dependent skill, in addition to computer training for improved data manipulation.

The challenges above point towards the value of some key partnerships:

- The combined challenge of the underpinning research to improve our understanding of the predictability on subseasonal timescales and the capability of the forecasting systems would benefit from strong sustainable partnerships, combining the expertise and resource within NMHSs and local and international research institutions to motivate and jointly deliver the underpinning research, and develop individual skills and appropriate training programmes.
- To deliver the sustainable resource to make products operational, develop new ones and support the on-going co-production will require exploring potential partnerships with e.g., private-public partnerships/business models.

b. Synoptic/short range (12 to 120h): challenges and solutions

i. Definition and potential

Predictions on the synoptic timescales of 1-5 days have traditionally been the bedrock of weather prediction and are useful to humanity in very many contexts. Synoptic forecasting for the tropics is currently much less accurate than for the mid-latitudes, especially for rainfall. Successful synoptic forecasting in the mid-latitudes relies on Numerical Weather Prediction (NWP) systems. In general, these systems are currently performing very poorly in the tropics, with significant biases for rainfall and circulation, even at short lead times of 24 hours or so (Woodhams *et al.,* 2020; Vogel *et al.,* 2020).

Given the uncertainty in convective rainfall even over 24h, the methodology for forecasting for a few days and beyond, in the 5-14 day ‘gap’ between synoptic and S2S forecasting corresponds much more closely with the methodology for subseasonal forecasting than that of synoptic forecasting; dominated by a consideration of the state of large-scale drivers (tropical and extratropical waves, seas surface temperatures, etc.) and dependent on statistical or probabilistic analysis.

It is even likely that this approach of using ‘S2S-like’ methods can be applied to even shorter timescales, even a 24-hour forecast. Vogel *et al.* (2021) have shown how a simple statistical model can outperform 1-day NWP forecasts for Africa.

In the mid-latitudes, forecasts on the synoptic timescales have been a triumph of modern science (Bauer and Thorpe, 2015) and forecasts of circulation (pressure systems, fronts and winds), are extremely accurate. Scientifically, the reason for the skill of synoptic forecasting in the mid-latitudes is the role of planetary rotation, which means that the relatively slow geostrophic dynamics dominate atmospheric circulation, with faster processes like convective storms and surface processes being, by and large, slaved to those rotational flows. In the tropics, this geostrophic balance is too weak to control the circulation, convection and surface processes dominate the weather, and the weather is much more unpredictable. The coupling of convective and surface processes with atmospheric circulation in the tropics remains a poorly understood and poorly predicted process. The convective dynamics controlling tropical weather occurs on timescales of hours, and therefore ‘chaos’ develops very rapidly in predictions of the tropical weather.

It is common for practitioners with experience outside Africa to make an erroneous assumption that for Africa the weather forecasts are just as accurate as they are in the Global North, and therefore that the challenge in this area is implementation of forecasting services - in fact much of this implementation will be premature until scientific improvements in the information are made.

Faced with very poor NWP performance, tropical synoptic forecasting currently demands much more human (forecaster) intervention in the forecasting process than is employed in mid-latitudes. Forecasters need to recognise weather situations in which the NWP solution may be expected to be more or less reliable. An important specific example is the control of tropical weather by mid-latitude systems: the high predictability in the mid-latitudes on 1–5-day timescales means that in cases where a mid-latitude event (e.g., an upper-level trough) influences Africa, the African predictability will be much higher (Davis *et al.,* 2013).

The operational forecaster, faced with high uncertainty over future conditions, also needs to take ‘situational awareness’ from the synoptic situations. Situational awareness is the overall understanding of the weather situation which a forecaster needs, in order to respond actively to the changing weather conditions: for example, forecasters will know that certain large-scale patterns of high- and low-pressure systems are likely to increase the likelihood of certain high-impact weather. Although the forecast is highly uncertain, the forecaster is alerted to the chance of certain events being possible. In this way, the NWP model is not being used to predict the weather, but to describe the large-scale circulation conditions in which the weather may occur. This situational awareness also builds on understanding of the prevailing S2S conditions (e.g., the prevailing global sea surface temperatures, large scale modes such as the Indian Ocean Dipole, and subseasonal tropical waves) and is therefore part of a ‘seamless’ approach to weather prediction.

The human input into synoptic forecasting relies on good conceptual models of weather systems. For the mid-latitudes, this includes the classical models of cyclones and fronts. In the tropics, the conceptual models are much less well developed, and in some parts of Africa, they are really lacking. As a generalisation, conceptual models for West Africa and Southern Africa are better advanced, with structures such as African Easterly Waves and Tropical-Temperate-Troughs having been described for several decades, while the conceptual models for East and Central Africa are more limited. Without good conceptual models, forecasters are blindly using NWP products which we know to have low levels of accuracy.

Faced with this weak performance of synoptic forecasts currently, there is significant potential to improve forecast quality on the basis of existing know-how. In particular, based on existing and expected science and technology, generally held in the Global North, it should be possible within a 5-year timeframe to achieve the following:

- Delivery of 24–48-hour forecasts of high-impact weather (HIW), with statistical information and degrees of confidence based on good evaluation, tailored to customer needs.
- 5-day outlooks based on known sources of predictability where it exists (mid-latitude influence, tropical wave modes, S2S view).
- A range of visualisation and communication products for forecasters and users, with local agencies getting ownership of the generation of new products.
- Good communication of forecast situation based on communication of the underlying synoptic controls: "We have high confidence in tomorrow's forecast because we are being influenced by a certain large-scale weather pattern".
- Forecasters with the deep understanding of weather systems and NWP which is needed if they are to work with users and co-develop forecast products.

This situation may include:

- African centres (i) running NWP locally (e.g., on reliable shared HPC); and (ii) generating products locally (from their own or from internationally provided data).
- Commercial interests paying for forecasts.

ii. Current status

African weather services have challenges in delivering accurate weather forecasts for high-impact conditions, notably rainfall, on synoptic timescales. NWP models have poor skill, especially for rainfall, and the overall performance of NWP models is not generally well characterised or understood.

While the skill of NWP is particularly poor for rainfall, the model representation of large-scale circulations is more reliable. Forecasters need to interpret the prevailing situation through their own experience and knowledge of the behaviour of weather systems and use this to infer the expected weather conditions (rain, winds, etc.). This knowledge is fragmented, incomplete, and not systematically documented. The Forecasters' Handbook for West Africa (Parker and Diop-Kane, 2017) has been the first attempt to collect meteorological methods in a single place and is now starting to be used by weather services and training centres, to encourage a systematic scientific approach to the interpretation of African weather patterns. Preparation of the Forecasters' Handbook also acted to identify and stimulate research priorities for African weather forecasting and has been the basis for the structure of the GCRF African SWIFT research programme. This approach, of collecting existing knowledge in and about Africa, and using it to stimulate research priorities, should be reinforced, and extended elsewhere in the continent: within SWIFT, an East African handbook is now also in preparation.

The WMO Severe Weather Forecast Project (SWFP) programme, initiated in Southern Africa, then East Africa, and now with examples mimicking this around the world, has led the way in advancing the operational use of current knowledge regarding short-range weather forecasts in the developing world. SWFP has been very influential in promoting high quality scientific methods, including:

- Consistent use of information from NWP models.
- Consistent use of observations.
- Focus on high-impact weather with clear, methodical structure to the output information.
- Systematic evaluation of forecasts.
- Training and knowledge-sharing among participants.

While SWFP has made great steps forward in Africa, its implementation remains limited to a set of centres and users, and it has only limited resources to advance its methodology.

Evaluation of synoptic forecasts is currently very limited (see Section 3). This is probably in part because the high uncertainty of the predictions on these timescales means that messages, with a high degree of human input, are often lacking in quantitative detail. At the same time, good evaluation is vital, to establish whether there is significant, useful skill in the forecasts at these timescales at all.

Prior to provision of NWP, African forecasters plotted synoptic charts by hand, from observations. They had poor predictive skill for T+24h, but high situational awareness. Now, with NWP products available, they no longer plot charts by hand - but the NWP products are not well configured to display the coherent structures present in the weather situation. It could be said that the forecasters are worse off - the NWP rainfall products are very often no more reliable than a persistence forecast or climatology, but forecasters no longer have the conceptual picture and situational awareness they gained from hand-analysis of charts.

There is significant potential to increase the commercial use of forecasts on the synoptic timescales. Private firms are offering increasing numbers of products from NWP and making profits from this provision. The success of private enterprises demonstrates the potential value of forecasts to customers, but does not demonstrate that the forecasts are of value (since the customers may be mistaken in the value they perceive they are paying for). In this environment, good evaluation is vital.

iii. Research gap: Use of CP models and ensembles; conceptual models

While tropical forecasts remain highly uncertain due to the inherently chaotic nature of deep convection, there are practical solutions which are expected to improve the quality of information in the coming years. Research in these areas is likely to much improve the information available for forecasters to interpret and deliver useful forecasts.

- **Identification of sources of predictability.** While storms remain chaotic and unpredictable, there are circumstances in which we may have confidence in the forecasts. For example, storms may be preferentially generated over mountains or coastlines, and an improved NWP model may start to capture this predictability (in comparison with flat regions of West Africa where they remain unpredictable). Certain large-scale situations, perhaps dominated by a mid-latitude weather event, might confer greater predictability. Can we use our understanding of these processes to deliver better rainfall predictions in some circumstances? This question remains open.

- **Global model improvements.** For example, the ParaCon programme[11] (NERC-Met Office £10 million) is currently improving the convection scheme in the Met Office Unified Model and is likely to improve the model performance for rainfall over Africa.

- **The new generation of CP models** capture the larger African storms explicitly and have been shown to capture the relationship of those storms with their drivers (e.g., large-scale flow) better. The CP models capture the general behaviour (diurnal cycle, speed, land-surface coupling etc) of large organised convective systems, and the geographical distributions, but still struggle to maintain these systems overnight (Woodhams *et al.*, 2018, Crook *et al.*, 2019, Taylor *et al.*, 2013). Ongoing research is investigating how to further improve the performance and application of these new models.

- **Ensemble prediction:** global model ensembles probably do not help to achieve better rainfall prediction (Vogel *et al.*, 2020), particularly because of major systematic errors such as the diurnal cycle of rainfall. CP ensemble simulations have been successful at improving prediction of intense rain in the UK, but there are many different issues in Africa. It is not clear how to set up CP ensembles optimally, for instance in relation to ensemble perturbations in circulation, relative to 'physics' such as soil moisture uncertainty.

- **Data Assimilation for tropical CP models** is an area of active research right now, and the best approach is yet to be identified. This is a particular challenge for Africa where the *in-situ* data may be sparse, or at least of very variable density and quality.

- **Embracing statistical forecasts for 1-day timescales and integrating with NWP model solutions** is likely to be fruitful (Vogel *et al.*, 2021). While statistical forecasting for the mid-latitudes has been quite unfashionable in recent years due to the very high skill of NWP models, the inherent uncertainty of convective systems over 24-hour timescales seem to indicate that we need to do much more with statistical tools. Machine-learning may be a major opportunity to integrate the existing skill within NWP (particularly large-scale circulation) with information offered statistically from observations and climatology.

- **Better conceptual models** are needed, to inform the quality control of NWP and the situational awareness that feeds into user alerts and eventually, nowcasting. Without this, forecasters are blindly using NWP products which we know to have high levels of inaccuracy.

- **More systematic evaluation of models** is vitally needed to underpin all of the above improvements. Without evidence of the efficacy of these changes, it is impossible to make progress.

iv. What is needed to make this solution a reality?

Exploitation of the new generation of NWP ensembles and CP models

The UK Met Office, SAWS, Meteo-France and others are offering CP models which are very much under-exploited. These centres want the models to be used and want feedback to improve their models. There are tremendous current opportunities to exploit these resources within Africa, in order to generate better forecasts and better services for users. SWFP has already created a critical mass of forecasters with the skills to deliver high-impact alerts using state of the art NWP products, and to evaluate these forecasts. This programme should be advanced, to keep up with the

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[11] ParaCon - Representation of convection in models - Met Office

improvements in NWP, and extended to other centres and regions. There is very great potential to advance the progress of SWFP, in:

- using new scientific tools to increase the quality of the forecasts delivered, for instance in temporal and spatial refinement, making use of CP models and global ensembles.
- expanding the user focus of the forecast outputs to a wider range of stakeholders. In particular, while NWP rainfall predictions are currently poor, the predictions of circulation are likely to be much better, and for some users there are likely to be more reliable products already available (e.g., winds at sea).
- advancing forecast evaluation, for instance in collecting more details of forecasts made, including the information obtained and acted-on by users, and conducting research into the value of the information.

Better scientific understanding of synoptic dynamics, coherent structures and local controls on African weather

The AMMA programme has advanced and documented West African synoptic dynamical understanding, captured in the 'Forecasters' Handbook' (Parker and Diop-Kane, 2017). Similar efforts are underway for East Africa. This synoptic understanding is needed by forecasters to interpret NWP products, because of the inherent uncertainty of convective rainfall on the 24-hour timescale, and the poor quality of NWP rainfall currently.

- Integration of this understanding and associated methods into training supported by documentation and case-studies is a real opportunity now. In GCRF African SWIFT, new practical training materials have been developed and are being used regularly now in 2 West African centres (KNUST, Kumasi, Ghana, around 120 students per year: and Oshodi WMO Regional Training Centre (RTC), around 40 forecaster trainees per year). There is an opportunity to expand this training, to develop more materials and to advance the methods and training for East Africa and other parts of the continent.
- This conceptual understanding should also be linked to visualisation and generation of products from NWP data. Work on this, from AMMA (Lafore *et al.*, 2017) and continuing in SWIFT, is enabling us to make standard synoptic charts available on the web, but these solutions should be expanded, and it is vital that the African centres have the know-how and data access to generate bespoke products locally.

Advance of NWP for Africa (and the tropics more widely) and its use

Delivering useful forecast information for African rainfall from NWP systems is a major research challenge, significant scientific research is needed to realise this potential and without it, co-production enterprises are significantly compromised on these synoptic timescales. In particular, research is needed in the following areas:

- Understanding of predictability under different weather patterns and regimes. Better ensemble NWP, better understanding of where NWP is reliable, and improved statistical post-processing of ensembles.
- Global model improvement (for instance through improved parametrisations, offered by the ongoing NERC-Met Office ParaCon project, and through Africa-focussed model evaluation).
- Convection-permitting (CP) models, CP ensembles, and learning to best use them.

- Understanding, observations and operational modelling of feedbacks to improve models and conceptual models (for instance, land surface feedbacks with the atmosphere).
- Increased use of statistical forecast models, integrating NWP and observations, and likely using machine-learning tools, to optimise the prediction of rainfall.
- Link from conceptual understanding to the generation of Africa-focussed diagnostics from NWP, and visualisation of NWP products.
- Expertise in Africa to make meaningful contributions in all of these areas.

Increased local capability in data handling, notably critical mass in core computational and technical skills

Increased local capability in data handling, and critical mass in core computational and technical skills, is needed to coproduce services suited to the African community needs. We argue that this will require investment in cooperative activity between the operational and academic sectors in Africa.

c. Nowcasting: challenges and solutions

- African nowcasting is very limited at present; it could be extensive and very high impact, on mobile phones and as the basis for alerts to commercial agencies. This would transform high impact weather prediction in Africa. Nowcasts could be distributed on mobile phones and used as the basis for alerts to commercial agencies.
- Satellite nowcasting products have been available, but not used, for 15 years. We urgently need to invest in the delivery of satellite-based nowcasting, which both has proven value and can be improved.
- Radars are the best observational system for nowcasting, especially for small and rapidly developing weather systems. While many initiatives to install radars over the past 4 decades have failed due to inadequate long-term commitments in technical training and maintenance, radars are now operating successfully in South Africa and Tanzania. We need to learn from the implementation of these successes and translate them to more countries.
- Any individual radar has limited spatial coverage and the long-term solution for delivery of African nowcasting is likely to include a hybrid of radar and satellite information, as is currently used in South Africa.
- Effective implementation of nowcasting, including co-production of services with users in Africa, cannot be done without long-term training in use of the products in Africa, and in the technical acquisition and processing of data.
- Research, e.g., in machine-learning methods, additional channels of data, or land-atmosphere feedbacks, will increase the quality of the products for users over time.

i. Definition, potential and current status

We consider that research, operational implementation and co-production of services in the nowcasting area has very high potential for high-impact benefits in Africa. These benefits can start to be achieved very quickly, within weeks and months, if sufficient resources are deployed. GCRF African SWIFT has a programme in this area which aims to deliver operational services to users within the lifetime of the project (by end March 2022) (Parker *et al.*, 2021), but the work can be accelerated and expanded.

As discussed in Roberts *et al.* (2021a), strict definitions of nowcasting are hard to find, but in the context of Africa we use a broad definition that defines nowcasting as:

(i) having at its basis the analysis of near-real-time observations to define the current weather conditions;

(ii) including forward projection of the weather features (either by extrapolation of observed weather features, or by making use of wind profiles and data from model analysis and short-range NWP forecasts); and

(iii) requiring continued monitoring of current atmospheric conditions and regular, rapid issuing of observations, predictions and warnings (and sometimes withdrawal of warnings).

A survey by SWIFT found minimal evidence of nowcasting being delivered in sub-Saharan Africa outside of South Africa. Met Services regularly use satellite imagery to monitor weather, especially for aviation, but perform no automated forward projection of observations, nor services beyond standard messages to aviation. Generally, the term 'nowcasting' was found to be poorly understood, being confused with short-range NWP.

In Africa, both the inherent challenge of predictions of deep convection by NWP systems and current poor skill of NWP generally means there is a great need for predictions made via nowcasting. In an environment where the 24-hour forecast of rainfall is unreliable, and even a perfect NWP system would likely give 24-hour rainfall forecasts with wide ranges of probabilities, forecasters and users need to monitor real-time conditions as they evolve.

The organised long-lived nature of some convective storms in Africa, especially the storms that provide much high-impact weather that can span 100s of km and last more than 24 hours, means there is huge potential for prediction of storms by forward extrapolation of observed systems. Although there are very few active meteorological radars outside of South Africa and the countries north of the Sahara, geostationary satellites such as Meteosat give high spatial and temporal resolution data (about 4 km and 15 min), providing an alternative data source for convection, and an opportunity for nowcasting these long-lived storms. Other causes of HIW include dust storms and fog, which are also both generally detectable from space and challenging for NWP, also lend themselves to nowcasting.

There is a wide range of sectors that would benefit from routine nowcasting of relevant weather and associated hazards. Historically aviation has been a major user, and this includes not only major international airports, which do already make use of expert assessments of imagery and models to inform decisions, but the numerous smaller airports which provide vital lifelines for many remote locations. Deep convective storms, and the associated strong winds, rapid changes in winds, waves and intense precipitation provide a hazard to coastal and inland shipping and fishermen. Land transportation is frequently delayed by flooding, or washed-out roads, and vehicles currently will often set-off on a route that is already being affected by severe weather. Many agricultural decision-making contexts, such as harvesting and drying of crops, management of herd animals, as well as transport to market, benefit from weather information on timescales of hours, and this is true both for large commercial activities and small holders. For flooding and landslides, warnings on nowcast timescales can allow actions that limit damage, such as evacuation of people and property. Other sectors which nowcasting would clearly benefit include construction, gas/oil extraction and solar/wind energy generation. In addition, disaster response benefits from up-to-date information both on the recent past weather to identify where help is needed, and on the evolving hazard to plan the response. Finally, the evidence is that by making information and warnings public, information benefits a very wide range of activities, many of which may not be anticipated by the nowcast provider.

ii. Research gap: refinement of satellite tools; exploration of user benefits and communication pathways; co-production of services

The USA and Europe have invested significantly in radar-based nowcasting, supported by dense networks of surface observations as well as NWP and satellites. Radars provide the optimal measurements for nowcasting of severe storms, especially smaller and rapidly developing systems, but there remains minimal radar coverage in Africa outside of South Africa or the countries north of the Sahara, and a very limited network of surface observations. Building on successes in radar operation in South Africa and more recently, Tanzania (Roberts *et al.* 2021b), it is to be hoped that radar coverage in Africa will increase over the coming decade, if supported by robust management, finances, and training. In the meantime, satellite nowcasting solutions are available to be implemented now, offer significant potential for further improvement and in many regions are very likely needed long-term due to the cost and limited coverage of radars.

In contrast to radar, satellite observing systems are already in place, with reliable datasets having been provided for several decades. There has not been anything like comparable investment in satellite-based nowcasting for the tropics, as there has for radar-based systems in the mid-latitudes. SWIFT's baseline survey revealed that in African SWIFT nations, and to our best knowledge in sub-Saharan Africa outside of South Africa, the NWCSAF satellite-nowcast products generated by EUMETSAT were being transmitted, but not visualised or used. These products, that include retrievals of rain rate, and thunderstorm growth, have not been setup, or tuned, for the tropics. SWIFT research has shown that although the rain-rate products have skill (Hill *et al.,* 2020) other products such as those for initiation of new storms are essentially useless without research to configure them for the tropics/Africa. Forward extrapolation is only 30 mins in default NWCSAF settings, but SWIFT research has shown the same algorithms have skill to more than 1.5 hours (Hill *et al.* 2020). Ongoing NFLICS and SWIFT research is both showing skill to 4 hours or more and that use of satellite-based land surface information can improve predictions (Klein & Taylor, 2020; Burton *et al.,* 2021). Other ongoing research has shown the potential to improve forward extrapolation techniques, both with and without machine-learning (Hickey, 2020), and research is needed to blend such extrapolated observations with NWP products effectively in a tropical environment with low NWP Skill. Dedicated research is also needed to make the best possible inferences about hazardous weather on the ground (or in the air) from the satellite observations of the clouds.

Although a nowcast system based purely on visible and infrared satellite imagery is demonstrably useful, it is clear that this would be greatly improved by ingestion of near-real-time lightning data, due to the close correspondence between lighting and severe weather. Such data from ground-based systems is currently prohibitively expensive, but the launch of a satellite-based sensor in geostationary orbit in 2023 onwards will improve this situation. Ultimately ground-based lightning sensors will also be beneficial, as they give a different sensitivity to cloud-ground lighting versus cloud-cloud lightning when compared with satellite-based observations. Near-real-time high-frequency surface observations of temperature, winds, pressure, visibility and precipitation, as well as, ideally, profilers, not only monitor HIW as it reaches stations, but provide information on boundary-layer evolution in the pre-storm environment to inform nowcasts of initiation of new storms and growth of existing ones. Mobile phone networks mean that high-frequency data should now be cheap, but the reality is that few data are available in near-real time, even to operational forecasters.

iii. What is needed to make this solution a reality?

What then is needed to transform nowcasting in Africa over the next years? It is clear that investment in research on satellite-based systems will generate products with skill far greater than those we have now, that are useful for decision-making across sectors, with co-production allowing products designed for specific sectors and decisions. Scientific and user-centric evaluation are essential to support their use. Demonstrably useful products will greatly aid user-engagement in their further design and use and will allow investment in nowcasting operations by both governments and the private sector, due to the demonstrable value to each. This will support both fully automated products made available at scale with no or minimal cost per user, alongside bespoke systems with forecaster input, as needed for specific applications, and where the investment will generate valuable returns.

Alongside investment in satellite-based nowcasting, any development of high-frequency near-real-time surface observing networks will support nowcast quality.

Setting up radars to cover Africa's major population centres is costly but not prohibitively so, and various radars have been set up in the past, particularly when supporting aviation (e.g. Dakar, Accra, ASECNA). However, radar systems require both expensive staff time, components and expertise to maintain them, long-term service contracts, as well as training of forecasters. A number of these past initiatives have thus been short-lived after inevitable hardware failures as the initial capital expenditure has not been matched by long-term commitment of operational expenditure. For example, a few years ago, West Africa had an impressive network of radars (Lamptey et al., 2009); very few data were archived from these systems, and currently this network is non-existent. Well-managed investment in radars in locations of particular need, critically with long-term investment in the expert staff to run them, with money for maintenance costs, would support nowcasting in those specific locations. The recent successful setup of Mwanza Tanzania radar (Waniha *et al.*, 2019; Roberts *et al.* 2021b) and long-term investment in India (Bhowmik *et al.*, 2011; Roy *et al.*, 2019) offer considerable reason for optimism that a much-increased radar network could be operational across Africa within a few years, provided sound long-term financial and operational management is secured. Furthermore, this would, through research on storm properties and behaviour, support satellite-based nowcasting over the remaining much wider region as is delivered in Southern Africa by SAWS.

Given the poor quality of current NWP rainfall, improved NWP is not an immediate way to improve nowcasting, but NWP fields such as winds already contribute to the algorithms giving forward projection of storms. Future systems would support both use of NWP information in nowcast systems to extrapolate observed weather and blending of observation-based nowcasts with NWP on longer lead times.

Investment in co-production, research and technology must run in parallel with awareness raising and training in use of nowcasting, to create funding streams to support its widespread deployment. One benefit of nowcasting is that with users using products so regularly and being able to regularly feed-back on them to producers, it creates dialogue, building trust and supporting use of predictions on longer timescales. Without investment in improved and well evaluated satellite-based nowcast systems, it is clear that we will not be exploiting the observations that we essentially already have to provide the non-stop stream of real-world information that is needed to support decision-making and save lives and livelihoods.

Implementation of high-quality user-focussed weather predictions needs to address the question of sustainable funding for infrastructure, production, communication and user-based evaluation and feedback.

5. Communication and Delivery of Weather Forecasts

In sub-Saharan Africa, the majority of the people are vulnerable to high impact weather due to the magnitude of impacts and the lack of capacity to respond to the threats posed by climate change (Masih *et al.*, 2014, Quenum *et al.*, 2019; Hallegatte *et al.*, 2016; Handmer *et al.*, 2012; Tschakert *et al.*, 2010). Timely access to useful and accurate weather forecast information can help individuals and communities to address the threats of climate change (Antwi-Agyei *et al.*, 2021a; Singh *et al.*, 2018; Jones *et al.*, 2015). Evaluating the quality and use of climate information and effectively integrating this information into decision-making processes within key sectors can build climate resilience, but only if steps are taken to make sure the communicated information is useful, useable and used (Vincent *et al.*, 2018). It is recognised that there are several constraints to the optimal use of these products in Africa. Alongside limitations on resources available to act on forecasts, communication challenges impede easy access to relevant forecast information and its translation to direct action-based advisories that are so badly needed by users across the continent (Antwi-Agyei et al., 2021b; Vincent et al., 2018).

Improved weather forecasting information on a range of timescales and their improved evaluation must be accompanied by factual and timely communication of forecast information. Where possible, such information should be integrated with local indigenous knowledge and directly linked to agronomic advice, in the case of agriculture. In addition, multiple user groups across different sectors should be engaged in new and innovative ways that are accessible, understandable and provide a useful input into decision-making processes of these user groups (Taylor *et al.*, 2018). A clear set of communications protocols and resources is essential for ensuring coherence and consistency in communicating weather and climate forecasts. While these may vary from country to country, and within sectors, common crosscutting themes have been suggested by Taylor *et al.*, (2018) to include:

1. The move towards providing impact-based weather warnings to better support decision-making processes.
2. Trust and its relationship with forecast uncertainty.
3. Tailoring forecasts and warnings to meet the decision needs of different user groups.
4. The emerging role of social media in the dissemination and verification of weather warnings.
5. The wider behavioural, social, cultural, and political context in which weather warnings and forecast information used in decision-making.

Investing resource to aid decision makers' understanding of and confidence in using forecasts to support decision-making is vital. Co-identifying thresholds of forecast skill and probability, together with the development in understanding of exposure and vulnerability amongst at-risk groups (for development of standard operating procedures and to enable finance-based preparedness action) furthers stakeholder confidence in forecast use, where and when benefits to forecast application are understood (Mwangi and Visman, 2020).

It is also important that communication of weather and climate information addresses the lack of trust, by users, in information generated by NMHSs. We stress that with greater collaboration between different stakeholders then it is possible to realise positive changes that enable people to make weather and climate sensitive decisions fully informed by the best available knowledge. Active user engagement and empowerment in forecast testbed events offers an innovative way to build deeper shared understanding of both forecast skill and communication pathways and it is vital that recent lessons are shared widely to this end. Such interactive two-way discussions will enable the communication of weather and climate information in the form of useful agro-meteorological advice or practical application of such information for various decision-making sectors and stakeholders at different scales across every African country. Over the years, local households and communities have relied on their indigenous knowledge to address the threats of extreme weather (Mafongoya and Ajayi, 2017; Codjoe *et al.*, 2014). It is therefore critical that decision makers find improved ways of integrating local indigenous knowledge with the physical scientific information to improve the local relevance of communications on weather patterns, impact-based forecasts and the practical advisory messages shared widely to smallholder farmers, fishermen and urban residents (Kniveton *et al.*, 2014). For instance, smallholder farmers in northern Ghana have often employed traditional agro-ecological knowledge including the flowering of certain plants, movement of certain birds, etc. to predict impeding rains or dry spell (Nyantakyi-Frimpong, 2013). Such local traditional knowledge systems are often linked to changes within the agro-ecosystems.

In Kenya within the disaster preparedness and risk management, it has been identified that lack of time synchronicity between communicated forecasts and disaster preparedness and management planning processes is one of the reasons for low uptake of these forecasts (Mwangi and Visman, 2020; MacLeod *et al.*, 2021a). Every year, in Kenya, the National Drought Management Authority (NDMA) conducts a Short Rains Assessment (SRA) and Long Rains Assessment (LRA) to analyse and determine the impact of the Long (March-May) and Short (October-December) rain seasons, as well as the food security prognosis for the next six months. Climate forecasts could inform the food prognosis; however, the forecasts are not available at the time when assessments are conducted. The Kenya Meteorological Department issues the long rains forecast towards Mid-February while the short rains forecast is issued in September, which are times when the SRA and LRA have been concluded (Audia *et al.*, 2021; Mwangi *et al.*, 2021).

The rate of spread of digital technologies, especially the mobile phone, across Africa offers an unprecedented opportunity for a marked step-change in the scope and scale of communications on weather services information over the coming decade. Information that has been held in Met Services globally can now be shared almost instantly and transferred to early warning systems capable of reaching hundreds of millions across the continent. This has started in the form of SMS messages, voice messages but with the increasing spread of smart phones the opportunities will spread rapidly beyond the private sector companies already utilising this information successfully. It is the meeting of the scientific advances in forecast accuracy together with the harnessing of the digital communications revolution that the real benefits to livelihoods and community well-being will be realised. The interactive dialogues, including the GCRF African SWIFT testbeds (Parker *et al.*, 2021), alongside a wide range of approaches developed through the various climate and weather service programmes outlined in this paper offer a clear starting point for planning the critical next steps in this journey to the free flow of weather service information across all parts of the African continent to complement and inform the daily conversations on changing weather patterns across the African tropics.

6. Concluding Remarks and Policy Recommendations

There is a huge opportunity for the African continent to benefit from the ‘silent revolution’ in weather forecasting that has been realised in the mid-latitudes throughout the twentieth century. While there are tremendous societal and economic benefits from advancing the science behind weather forecasting in sub-Saharan Africa, there are also significant barriers to realising advances. This policy brief examines the value of investment in African weather forecasting science and the technical & communication challenges that this will bring with wider implementation.

Throughout Africa, lives and livelihoods are directly impacted by weather- and climate-related risks. Strengthening national meteorological capacities holds transformational potential for strengthening the continent’s resilience to weather- and climate-related risks in the coming decade.

The translation of best practice, research and methods across the continent will maximise the ability of the meteorological services and science community to better protect lives and livelihoods throughout Africa. Weather forecasting research and development (throughout the full chain from model development to user communication and feedback) should be a key aim of climate preparedness for the future, strengthening the United National Framework Convention on Climate Change (UNFCCC) and the Paris Agreement for all African nations, as well as supporting fulfilment of national commitments to support the Sendai Framework and the Sustainable Development Goals.

Co-production of a range of services is needed, but this depends on African meteorological agencies having the technical tools and know-how to adequately meet decision-makers’ information requirements.

Investment should be made into transdisciplinary weather and climate research projects to ensure comprehensive forecast development, encompassing delivery and inclusive evaluation. WMO can promote this approach and fill gaps in specific needs-based research gaps, so that investment can readily produce tangible results.

There is significant progress to be made based on scientific development and exploitation of existing, and next-generation know-how, e.g., satellite nowcasting, convection-permitting NWP ensembles, and S2S databases.

It should be recognised that some existing forecast products, which work effectively in the mid-latitudes, are inadequate for Africa at present, particularly for prediction of rainfall on daily timescales. Skill in the management and manipulation of data; use and application of forecast models and products; and fundamental research to improve prediction skill across all timescales should be key areas for future programmes. Generation of useful products will facilitate user uptake. Directed research projects that can fill this fundamental research gap should be supported and implemented by WMO. Training programmes, focused on capacity building in the use and manipulation of data, and the application of forecast products, should be a key priority for international agencies such as WMO and EUMETSAT.

Systematic and impact-based forecast evaluation is critical to forecast improvement, to economic sustainability of services, and to effective forecast use.

Directed efforts into evaluation and socio-economic assessment of the benefits of weather forecasting will strengthen the investments from both private and public funders to NMHSs. National Frameworks for Climate Services in Africa should share learning to support the development of a transferable, cost-effective evaluation methodology, together with capacity

building through directed training programmes. This will allow nations to keep their frameworks flexible, applying evaluations to sectors and users of highest priority in each country.

Cooperation between the academic and operational sectors within Africa is a tremendous opportunity for increasing the long-term sustainability of solutions developed within projects and programmes. Partnership with the private sector offers an opportunity for more sustainable resources to support forecast services financially.

In improving African weather forecasting services, the role of international partnerships cannot be neglected. Major elements of the forecasting delivery process, including models, observing systems and know-how, are held in international centres outside Africa. The improvement in such systems cannot be achieved without effecting change within international as well as African partners.

Core funding, led by international agencies, should be directed to the long-term investment in and maintenance of observational networks.

The above recommendations outline the key steps needed to realise the socio-economic and environmental benefits of improved weather forecasting across the African continent.

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