The African SWIFT project: growing science capability to bring about a revolution in weather prediction.

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ABSTRACT

Africa is poised for a revolution in the quality and relevance of weather predictions, with potential for great benefits in terms of human and economic security. This revolution will be driven by recent international progress in nowcasting, numerical weather prediction, theoretical tropical dynamics and forecast communication, but will depend on suitable scientific investment being made. The commercial sector has recognized this opportunity and new forecast products are being made available to African stakeholders. At this time, it is vital that robust scientific methods are used to develop and evaluate the new generation of forecasts. The GCRF African SWIFT project represents an international effort to advance scientific solutions across the fields of nowcasting, synoptic and short-range severe weather prediction, subseasonal-to-seasonal (S2S) prediction, user engagement and forecast evaluation. This paper describes the opportunities facing African meteorology and the ways in which SWIFT is meeting those opportunities and identifying priority next steps.

Delivery and maintenance of weather forecasting systems exploiting these new solutions requires a trained body of scientists with skills in research and training; modelling and operational prediction; communications and leadership. By supporting partnerships between academia and operational agencies in four African partner countries, the SWIFT project is helping to build capacity and capability in African forecasting science. A highlight of SWIFT is the coordination of three weather-forecasting “Testbeds” – the first of their kind in Africa – which have been used to bring new evaluation tools, research insights, user perspectives and communications pathways into a semi-operational forecasting environment.

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CAPSULE (BAMS ONLY)

Advances in nowcasting and numerical weather prediction are improving African weather forecasts on timescales from minutes to months. The GCRF African SWIFT project is building capability to deliver these solutions.

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1. The urgent opportunity to improve African weather predictions, and the role of SWIFT

Over the past century, accurate and quality-controlled weather forecasting in the temperate regions of the "Global North[1]" has experienced a "quiet revolution" which is one of the most remarkable triumphs of the physical sciences (Bauer *et al.*, 2015). These scientific and operational advances are not yet being enjoyed in economically less developed tropical nations of the "Global South". The populations of the tropics have a greater need for accurate weather predictions, because national economies and personal livelihoods depend heavily on weather-sensitive sectors, including agriculture, water, disaster management, public health and tourism. Africa is particularly 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 (Sanderson and Sharma 2016), but only 44% of Africans have any access to early warnings (Cullmann *et al.*, 2020).

It is often erroneously assumed that the lack of uptake of weather forecasting services in Africa is solely due to problems of forecast communication, and a lack of co-production of services, and these incorrect assumptions are influencing major donors in the international development community (e.g. Bharwani *et al.* 2020). However, a deeper underlying problem is that the quality of global Numerical Weather Prediction (NWP) remains extremely poor for

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[1] https://en.wikipedia.org/wiki/Global_North_and_Global_South

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rainfall over tropical Africa (Vogel *et al.* 2020), implying serious practical and ethical problems for increasing trust in weather forecast services. Improved scientific skill in weather forecasting for Africa, on all timescales, is within our grasp if the right scientific investments are made, in harmony with suitable user engagement.

Improved weather predictions are an essential part of understanding and responding to climate change. Climate change is already bringing more intense storms (Taylor *et al.* 2017), more heat waves (Ceccherini *et al.* 2017), and more persistent dry spells (Panthou et al. 2018) to parts of Africa, and these patterns are projected to get worse (e.g. Kendon *et al.* 2019). A necessary step in understanding and responding to future climate change is to deal with present-day variability.

Recognizing the gap between increasing scientific capability in tropical weather prediction, on timescales from minutes (nowcasting) to months (Subseasonal-to-seasonal, or S2S), and application of this capability in Africa, the GCRF African SWIFT[2] project (2017-2021) has embarked on a program of research and capability-building, aiming to deliver improved forecasts and a stronger research community from which to sustain those improvements. The project was built out of long-standing partnerships between the African and European investigators, and responds to long-term demands from the African meteorological community (e.g. Dike *et al.* 2018). SWIFT is supporting three African

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[2] Global Challenges Research Fund African Science for Weather Information and Forecasting Techniques; https://africanswift.org/

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"weather forecasting testbeds". Testbeds were first conducted in the USA to improve the impact of research on operational forecasting of severe storms: they represent intensive, live, real-time forecasting exercises at which weather forecasters from different institutions come together with researchers to perform operational forecasting. Testbeds are recognized as a key tool to improve weather predictions worldwide (Ralph *et al.* 2013): the SWIFT testbeds are the first such events in Africa.

2. Building scientific capability: addressing the research challenges in African weather forecasting.

a. Exploiting ensemble weather prediction, on subseasonal timescales

Despite the chaotic nature of daily tropical weather, there are sources of predictability on subseasonal timescales (Janicot et al, 2011) including the Madden-Julian Oscillation (MJO); equatorial trapped waves; and long lived soil moisture and vegetation anomalies (e.g. Taylor, 2008). Skillful forecasts on these timescales have the potential to inform decision making and early warning in agriculture and other sectors (e.g. Genesio *et al.*, 2011; Robertson *et al.* 2015; Kilavi *et al.*, 2018). Understanding the regime-dependence of forecast skill allows forecasters and users to make better judgements about their confidence in a shorter-range synoptic forecasts. Our challenge is to advance the theoretical ideas and achieve a useful forecast tool, through understanding statistically and physically how the subseasonal drivers influence the weather over Africa in different locations; evaluating models' ability to forecast those drivers and their influence on the weather; and thereby identifying where, when and why models have skill on subseasonal timescales.

In SWIFT, this challenge is being addressed through study of reanalyses, observations and forecasts and hindcasts from the WMO Subseasonal Prediction Project Database (Vitart *et al.* 2017). For example, de Andrade et al (2020) show that there is skill for weekly rainfall at lead times of up to 3 weeks over parts of Africa in certain seasons, and that the skill can be improved by accounting for knowledge of the statistical response to drivers. Figure 1 shows the correlation between ensemble mean weekly rainfall from the European Centre for Medium-Range Weather Forecasts (ECMWF) hindcasts and Global Precipitation Climatology Project (GPCP) weekly rainfall over East Africa. For week 3 (days 19-25) there are large areas with correlations in excess of 0.3 and some areas in excess of 0.4 (Figure 1a). Removing the response to the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and MJO drivers (Figure 1b) indicates that these drivers are an important source of predictability. A potential operational application of these results (Figure 1c) removes the forecast response to the forecast drivers and adds the observed response to the forecast drivers, leading to a marked increase in skill across East Africa. Correcting with the observed response to the observed drivers (Figure 1d), indicates that the loss of predictive skill in week 3 is broadly attributable to the representation of the local response to the drivers rather than the forecast of the drivers themselves.

To bring the outcomes of such research into sector-facing services, SWIFT is working with forecast users to develop subseasonal forecast products which can inform their decision making on these timescales, through a two-year operational S2S testbed.

b. Synoptic forecasting

In tropical Africa, global NWP precipitation forecasts are currently “hardly better than climatology” (Vogel *et al.* 2020), and we face a major challenge in delivering useful 1-5 day

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rainfall predictions. Haiden *et al.* (2012) noted that day-1 tropical precipitation forecasts had similar skill to day-6 forecasts for the extratropics, and the skill has not improved much since then, to the extent that a simple 1-day statistical forecast outperforms post-processed NWP (Vogel et al. 2021). SWIFT promotes three complementary approaches to improve this situation:

- Advancing the new generation of regional convection-permitting models and ensembles to develop more reliable NWP products for rainfall;
- Using conceptual understanding of the prevailing synoptic circulations to refine predictions based on a hand-analysis of synoptic fields and the forecaster's best judgement; and
- Synthesizing synoptic scale forecasting with nowcasting (as illustrated in Figures 2, 3 and 4), as rainfall will always be chaotic and unpredictable on short time-scales.

We have experienced a revolution in NWP, in being able to simulate convective storms explicitly in "convection-permitting" (CP) computational models on large, limited-area domains, leading to a step-change in model performance for convective rainfall over Africa (e.g. Marsham *et al.* 2013, Maurer *et al.* 2017, Woodhams *et al.* 2018, Stein et al. 2019) and benefits for remote geographic regions including Europe (Pante and Knippertz 2019). In particular, CP models correct some long-standing biases including the diurnal timing of rainfall (Pearson *et al.* 2014), the coupling of rainfall with its underlying moisture availability (Taylor et al. 2013), the temporal statistics of rainfall intensity (Berthou *et al.* 2019), convective organization (Laing *et al.* 2012) and its relationship to synoptic circulations (Vizy and Cook 2018), and the feedbacks between rainfall and the regional water cycle (Birch *et al.* 2014). However, CP models still have limitations: they typically cannot be relied on to improve mean rainfall (Berthou *et al.* 2019), their ensemble distributions are typically underspread, and they typically deliver excessive rainfall maxima (e.g. Berthou *et al.* 2019). It is likely that statistical post-processing will need to be implemented (as demonstrated by Vogel *et al.* (2020) for global NWP), to alleviate these problems. All in all, advances in NWP modelling at CP resolution have been slow to impact on improvement in the *delivery* of weather forecasts in the African tropics. A number of national weather services (including UK Met Office and the South African Weather Service (SAWS)) and private companies (e.g. Ignitia) are now producing CP model forecasts operationally for African regions. The cutting edge of our science is to provide the statistical and physical understanding needed to apply such models to operational weather prediction, and to drive further improvement in the models.

In SWIFT we have performed Africa's first real-time CP ensemble forecast system, showing the potential to yield accurate forecasts of the timing (within around 3 hours), location (within order of 150 km, and within 50 km when combined with manual analysis) and intensity of rainfall in a short-range (24 hour) forecast (Cafaro *et al.* 2021). Significant work is still needed to realize these benefits, and the CP ensemble configuration is under-spread in both rainfall amount and location. While the CP model performs better than global (and some further improvement is found with ensembles), the skill still severely lags that of CP forecasts in the "Global North". A mix of perturbed and time-lagged ensembles is used in the operational Met Office convection-permitting ensemble (Porson *et al.*, 2020), and could be a solution for tropical domains, improving the ensemble spread as well as reducing the operational cost.

An example of NWP forecast evaluation for East Africa is shown in Figure 5. The global configurations do not capture the high likelihood of intense rain over Lake Victoria, nor the rain in the west of the domain. In general, the location of areas with highest forecast probability are similar in the CP deterministic and CP ensemble, but probabilities are too high (the forecast is too certain) in the deterministic compared to the ensemble. In Figure 5f, the Fractions Skill Score (FSS, Roberts and Lean, 2008) shows that the CP configurations outperform the global configurations, and the ensemble configurations outperform their deterministic counterparts. Overall, the improvement in useful scale between global and CP is much greater than between deterministic and ensemble (Cafaro *et al.* 2021).

Synoptic circulations, such as African Easterly Waves (e.g. Figure 4) modulate the daily weather conditions and global NWP models represent these synoptic circulations with some skill (Bain *et al.* 2013), even if their predictive power for rainfall is poor (the poor representation of convective rainfall probably dominates the development of synoptic errors; Elless and Torn 2018, 2019). Therefore, forecasters add value to the rainfall prediction by a hand analysis of the synoptic dynamics. The West African Synthetic Analysis/Forecast (WASA-F) (Fink *et al.* 2011; Lafore *et al.* 2017; Cornforth *et al.* 2019) is an established approach to mapping and communicating the synoptic state (see Figure 4a), but remains underused in forecasting centers because plotting of weather features with the available software is time-consuming. More widely across tropical Africa, there is a lack of consistency in the plotting of synoptic information, which makes forecast communication and evaluation difficult. In support of the WASA-F methodology, in SWIFT we are providing training materials in synoptic plotting, and developing code for automated plotting of synoptic features in Testbed 3 (see prototype in Figure 4b), which will then be available for operational forecasting, and for hands-on training activities.

c. Nowcasting storms and other weather conditions.

The unpredictable nature of deep convection and the lack of consistent skill in global or regional NWP on short timescales, mean that operational nowcasting is vital for short-range

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services. However, outside South Africa, systematic nowcasting is almost non-existent in sub-Saharan Africa[3]. There are enough examples to demonstrate that effective delivery of nowcasting can have major benefits (de Coning *et al.* 2015, Gijben and de Coning 2017)).

At present, nowcasting must make use of satellite products, given the insignificant numbers of weather radars in tropical Africa. The regular occurrence of large, deep and persistent convective systems over Africa (Laing *et al.* 2011; Dezfuli *et al.* 2017) means that satellite-based nowcasting products are valuable. Products developed by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)'s Nowcasting Satellite Applications Facility (NWC SAF[4]) derived from Meteosat data (Roberts *et al.* 2021; Morel and Senesi, 2002), have been available for more than a decade and are being used effectively by SAWS to deliver reliable nowcasts across Southern Africa. However, elsewhere in Africa they have not been used operationally.

Through SWIFT, real-time NWC SAF products are now being generated, with only 30-minute latency, and made available on web pages[5]. In parallel, African SWIFT partners are

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[3] Note that informal nowcasting "by eye" has always been conducted by weather centers for the aviation industry, but this does not follow standard operating procedures or workflows associated with nowcasting, and it is rarely applied to other sectors beyond aviation.

[4] https://www.nwcsaf.org/

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

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installing satellite dishes and computational hardware to produce nowcasting products locally. Examples of the “Rapid Developing Thunderstorm” (RDT) product are shown in Figure 3 and the Convective Rain Rate (CRR) product in Figure 4c-h. Our research has demonstrated that the NWC SAF products have useful skill in representing current rainfall for at least 1.5 hours of forward extrapolation (Hill *et al.* 2020; Figure 4f-h).

Nowcasting also depends on the human application of conceptual and climatological models for weather system behavior, which may be very location-specific (Roberts *et al.* 2017). Integration with synoptic analysis from NWP is essential. SWIFT Testbed 1 has used the NWC SAF tools in a real-time exercise (see Figures 2 and 3) and following the success of these demonstrations, the opportunity now is to co-develop Standard Operating Procedures (SOPs) for the practical implementation of impact-based nowcasting. Looking forward, the increased observational capability of Meteosat Third Generation (MTG) may offer new opportunities for African nowcasting, but significant technical and research effort will need to be made, to ensure that MTG can be exploited.

d. Developing systematic forecast evaluation procedures.

Systematic evaluation of African weather forecasts plays an important role in the effective delivery of forecasts, how they are used and interpreted and long-term improvements in services. In an environment where private sector companies are already competing with the national agencies in African forecast delivery, governments, customers and the public all have a need for guidance on the quality of competing forecast products for their particular needs. For this, we need a seamless evaluation methodology across time scales.

Evaluation of African weather forecasts is limited by lack of observations, and by the sporadic and localized nature of tropical convection. Existing spatial verification metrics for rainfall developed using radar observations or dense gauge networks may not be appropriate for tropical Africa where verification is restricted to the use of satellite products. In many African centers there is a lack of the coding skills required to monitor forecast performance objectively, and there is limited motivation to complete consistent evaluation as there is no framework to feedback forecast errors or biases to global producing operational centers to thereby improve future model performance. An exception is the Severe Weather Forecasting Programme (SWFP[6]), currently active in southern, East, and West Africa, in which severe weather forecasts are frequently evaluated according to standardized forms.

Proper evaluation needs to be conducted against a high quality benchmark forecast, which may be computed statistically from post-processed global NWP forecasts (Vogel et al. 2018, 2020). As lead time increases then the averaging period over which skill is evaluated should also increase (Wheeler et al. (2017), and the spatial scale over which forecasts have skill, at a given lead time, will be variable (Young et al. 2020). SWIFT is critically investigating metrics such as the Fractions Skill Score (which inherently accommodates spatial scale in the evaluation; Roberts and Lean, 2008; Woodhams *et al.* 2018; see Figure 5) and object-based verification for its use with satellite observations across tropical Africa, and sharing the relevant verification practices (including Python scripts) with forecasters. We are evaluating biases in the simulated brightness temperature diagnostic from CP models in preparation for like-with-like verification against satellite observations and to test new forecast products for

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[6] https://community.wmo.int/activity-areas/severe-weather-forecasting-programme-swfp

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convective initiation. For around 30 case studies, we are collaborating on evaluation of CP ensemble simulations to evaluate skill under different synoptic regimes.

3. Implementation and impact of improved forecasting methods.

a. Forecast improvement needs to be developed in an environment of co-production.

Many examples have shown that active engagement and co-production between users and providers is needed for forecasts to meet the needs of users (e.g. Patt *et al.,* 2007; Nkiaka *et al.*, 2019). Insight is urgently needed into how users' interpretation and utilization of forecast information changes across timescales, as identified in a series of SWIFT national and district-level user workshops (Nkiaka *et al.*, 2020). Meeting this challenge, SWIFT is examining user needs from nowcasting to seasonal timescales, addressing questions such as how users understand and respond to the updating of forecasts over time. Findings relate to how the changing nature of uncertainty at different lead times can be more effectively communicated through the use of Impact-Based Forecasting approaches (Nkiaka *et al*., 2020). There is scope for cross-continental learning from successful advances in forecast communications, such as those supported by Climate Change, Agriculture and Food Security (CCAFS) in Senegal targeting both farmers / pastoralists (Diouf *et al*., 2020) and coastal fishing communities (Ouédraogo, 2018) and from various programs across Kenya (Carter *et al*., 2019).

Ongoing studies include an assessment of the end-to-end climate communication chain, government engagement, and assessment of the role/mandate of NGOs and community-based organizations, building on findings from related programs (Carter *et al*., 2019; Cullmann *et al.*, 2020). A key project outcome will be the development and testing of strategies for

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communicating forecasts to users in different sectors informed by the insights from testbed events, resulting in a set of recommendations for good practice in tropical forecast evaluations and communication systems.

It is critical to recognize that given the current poor performance of global NWP and observational systems in Africa, both the co-production process with users and the scientific development are necessary, and neither can be successful in isolation. Therefore, in SWIFT the user-engagement work is being conducted hand in hand with active development of forecast products, particularly in three Testbeds aimed at enhancing capability in the partnering African weather centers, to manipulate and evaluate data locally.

b. Need for integrated forecasting systems and African scientific capability.

Modern weather forecasting demands an integration of information across forecast timescales, with the subseasonal forecast influencing understanding of the synoptic situation, which also influences short-range prediction and nowcasting. This integration of information across timescales is demanded by forecast users, and demands significant human intervention in the forecast production. Three of the six building-blocks of co-production identified by Carter *et al.* (2019) (namely “Co-develop solutions”, “Co-deliver solutions” and “Evaluate”) require that the forecast provider has high scientific skills in order to fulfil their part of the co-production partnership. Overall, this systems-approach to improved forecasting requires high scientific capability in the staff of weather prediction centers.

An example of the scientific capability needed in the production of forecasting services is given by the weekly meningitis bulletin which has demanded the technical integration of different sources of operational data into a quantitative product. The meningitis bulletin has been developed by ACMAD and automated in the SWIFT Testbed 2 co-production

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framework between ACMAD (producer) and the Regional Office for Africa of the World Health Organization (WHO; key user), making use of the research findings of the Meningitis Environmental Risk Information Technologies (MERIT) project (Thompson *et al.* 2013). The product is a vigilance map (Figure 6) of meningitis cases computed using a combination of mean climate metrics (temperature, relative humidity, meridional wind speed) and dust (Martiny and Chiapello 2013, Yaka *et al.*, 2008 and Sultan *et al.*, 2005). Members of the WHO and local medical services are using these maps to support meningitis surveillance and control. Generation of this vigilance product has demanded a process of scientific work to understand climate and meningitis relationships, a process of co-production with the users, and the technical development of the operational product.

In order to put complex forecasting operations into place, the WMO encourages weather services to develop SOPs for particular services, in partnership with the forecast user (Davidson and Gill 2012). SOPs are a way of maintaining quality control over the forecast process, consistency between providers, and tracking of improvements in methodology and service standards.

c. The private sector is playing an increasing role in delivering forecasts in Africa, and will drive improved forecasting and evaluation.

We argue that the advance of the private sector in African weather forecasting challenges public and international agencies, and the development funding bodies, to look hard at their own approaches and question whether the focus on forecast communication has been at the expense of investment in the science of producing forecasts with demonstrable value. Going forward, efforts need to be made to establish protocols for forecast evaluation, so that the claims of commercial forecast providers can be tested objectively. An analogy could be made with the health sector, in which protocols have been defined in order to guarantee consistent quality of services, and consistent skills of practitioners.

The private sector has been able to make profits from forecasting for Africa by focusing on forecast production, delivery and marketing. Commercial companies based outside Africa, such as Ignitia[7], sell forecasts to African farmers on the basis of impressive claims about model forecast skill for extreme rain. Ignitia has been making use of the rapid advance in CP modelling to deliver new products based on cutting edge science, and is arguably leaving the African public-sector agencies behind in this technology. For the private sector, user communication, or co-production, is treated as a commercial rather than an academic activity, and marketing plays a key role in that process. Success is defined by financial revenue from users, or stakeholders with an interest in the users, rather than by objective measures of forecast skill or impact. Customers have very little means to evaluate the quality of forecast information. For example, a one-off independent evaluation of Ignitia's rainfall forecasts for Ghana has been conducted (Goddard *et al.* 2018), but more generally, customers will have no access to such studies to establish the veracity of commercial providers' claims.

Currently, commercial forecast products are almost exclusively delivered from the Global North, and therefore bypass African national agencies and limit the feedback into development of capacity in observations, infrastructure and skills. It is vital that African

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[7] https://www.ignitia.se/

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agencies, and the private sector in Africa, is given the capabilities to match external competition for services.

4. Building capacity for African weather prediction

a. A corpus of people and systems, in Africa and worldwide, to deliver effective forecasts.

We need well trained forecasters who understand the needs of their customers and a body of academics – researchers and teachers – who can support the long-term development of the underpinning science. During the SWIFT testbeds it has become clear that meteorological experts need to have strong basic skills in data handling and presentation to generate new co-produced services in partnership with their stakeholders. As an example of what is needed, the innovation and production of meningitis bulletins illustrated in Figure 6 required high-level scientific skills and coding ability, alongside a process of co-production of the product with its key user. It is conspicuous that the best forecasting centers in Africa have strong partnerships with academia (as exemplified by the SWIFT partner organizations). In-country partnerships combine the strengths of academic and operational perspectives and provide sustainability. Academic institutions hold long-term capacity in terms of academic staff and taught programs that influence generations of students. Through academic partnerships, there are also significant opportunities for cross-fertilization of skills with other fields: for instance, study of artificial intelligence in Africa is being supported by international investment in academic institutions, including the African Institute for Mathematical Sciences (AIMS) and its network of centers right across the continent. Such investment brings opportunities for engaging African applied mathematicians in climate science.

A long-term challenge in raising levels of expertise is to address gender equality. A workshop for Early-Career Researchers (ECRs), run jointly between SWIFT and the Young Earth System Scientists (YESS) Network took place in June 2018 in Nairobi, Kenya, uncovered some of these issues. In Africa, around only 20% of students on meteorology degree courses are female, and those who have the ambition to develop a career in academia often take a long time to progress to PhD studies due to familial responsibilities and cultural expectations. A number of solutions were proposed including short courses that women can take the time away from their families to attend; targeting internships, secondments and fellowships at female scientists, and encouraging women to apply, with flexibility such as the opportunity for sandwich placements; specific funding for women on MSc courses; empowerment of women to take on leadership roles earlier in their careers; female mentors and creating a culture of female empowerment for the better of the collective.

Increasing African capability cannot be in isolation from international capability. For the foreseeable future, tropical African forecasting will be reliant on products delivered from the Global North, such as global NWP and satellite data. Just as James *et al.* (2018) advocated for an “Africa lens” in climate model evaluation, NWP development in the international community needs to maintain quality and relevance for Africa’s users

A number of African centers are now running regional NWP models operationally. Whether local NWP systems provide better quality information than internationally-generated NWP remains a moot point, but modelling systems do provide a hub for scientific expertise. African forecast centers which are generating their own NWP products tend to be those best equipped with the skills to innovate in the communication and co-production of user-focused products from the models. In order to make the most of local expertise in modelling, the capacity in use of such models needs embedding in training at the universities and WMO’s Regional Training Centers (RTCs).

There remain additional, long-standing problems in the meteorological infrastructure in many African countries, including the sparsity of the raingauge, upper-air and other observing networks, which continue to undermine the accuracy of forecast and satellite products. In SWIFT, for example, we make use of research-based raingauge networks for local evaluation of projects, such as the rainfall mesonetwork around Kumasi, Ghana, set up by the Dynamics–Aerosol–Chemistry–Cloud Interactions in West Africa (DACCIWA; Knippertz *et al.* 2015) project. A full discussion of the challenges, and possible solutions to achieving a fit-for-purpose observing network is beyond the scope of this article but we can remark that improving the links between observations, NWP improvement (via data assimilation) and impact-based forecast evaluation is needed in order to connect investment in the observations with the value of improved services to clients. New technology is providing opportunities to tackle such problems afresh, and the Trans-African Hydro-Meteorological Observatory (TAHMO; van de Giesen et al. 2014) is one example of an initiative which seems to be breaking the long-standing deadlock in increasing routine observational coverage.

b. Career-long integration of training.

Training, as a preparation both for research and weather forecasting, requires an integrated program from undergraduate to professional levels. Dike *et al.* (2018) highlighted the career-challenges facing Africa’s young climate scientists, advocating for increased institutional partnerships as well as summer schools and research exchanges. SWIFT is organizing two international Summer Schools in Africa, taking a model of previous events in

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2008/10 (Tompkins et al 2012) and bringing together students from Africa and Europe in a program of lectures, daily forecasting exercises and practical work. SWIFT is also supporting five 2-year early-career African research fellows (two of whom are female), hosted in African institutions and mentored by international and African partners, supporting the development of fellows to become research leaders of the future. To support continuing professional development SWIFT has funded a number of secondments and exchanges while in the management and leadership of SWIFT, a number of ECRs, including a majority of female ECRs, have been given leadership roles, mentored by a more experienced colleague.

c. Maintaining and evaluating standards of training

Training in operational methods is currently coordinated through the RTCs, supported by international workshops organized by the WMO and others. There has been a long-standing lack throughout the tropics of supporting documentation for forecaster training. The “Forecasters’ Handbook” (Parker and Diop-Kane 2017, Parker *et al.* 2018, Cornforth *et al.* 2019) is the first attempt to provide this material comprehensively for one region. SWIFT is working to refine and advance methods described in the Handbook and extend the work to provide a new forecasters’ handbook for East Africa.

Operational forecasters must be trained according to the WMO’s Basic Instruction Package in Meteorology (BIP-M), which corresponds to a university degree level of training and ensures globally consistent standards. The WMO’s Global Campus is a network for the coordination of regional implementation of the BIP-M. Within SWIFT we have extended the vision for evaluation of training to encompass a wider range of career paths (forecaster, researcher, trainer etc), through a skills matrix (Parker 2021) combining academic and practical measures. The SWIFT skills matrix is based on levels of knowledge and

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competence required for the meteorological professions, including research, forecasting, teaching, user-engagement and scientific management skills, and gives a description of the kinds of experience professionals should be able to demonstrate according to 4 levels of expertise, from level 0 (no experience) to level 3 (advanced). By periodically collecting information from project participants on their experiences during the project, we have been able to monitor the general contribution of the project to improving the professional capabilities of its members. This process has a deeper value to individual participants, in helping them to understand the value of different aspects of their work for career development, and to prioritise their professional choices according to skills needed for their careers (Figure 7).

5. Weather forecasting testbeds in Africa

a. SWIFT Testbeds 1 and 3: Synoptic forecasting and Nowcasting.

SWIFT's Testbed 1: Synoptic and Nowcasting[8] was conducted over two periods, 24-29th January 2019 and 23rd April to 6th May 2019, hosted by the Institute for Meteorological Training and Research (IMTR), KMD, Nairobi, Kenya, and attended by 40 researchers, forecasters, and academics, from the UK and 15 African institutions. The forecasting team

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[8] https://africanswift.org/2020/04/16/inaugural-testbed-guides-future-of-nowcasting-in-africa/

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was organized into groups responsible for Evaluation, Synoptic forecasting, and Nowcasting respectively. It was apparent that the strong diurnal cycle of weather conditions in tropical Africa leads to a natural separation of these tasks (Figure 8), which is itself sympathetic to the cascade of spatial scales in the forecasting process. Figures 2 and 3 illustrate products and activities which were synthesized in real time.

Testbed 1 has led to some significant successes in forecasting practice. For many participants this was their first introduction to new data, software and methods, including satellite-based nowcasting, CP NWP products and systematic forecast evaluation. These have continued to be used in the participating forecast centers, and have influenced research being conducted in the universities. Detailed feedback on the performance of the systems has steered ongoing research, and been fed back to the product developers. The program of work for the synoptic, nowcasting and evaluation groups was refined over the course of the testbed, and will be used as the framework for proposed SOPs in Testbed 3.

A final Testbed 3 is planned to for 2021, to include user engagement on the same Nowcasting-Synoptic timescales, and introduce progress in new methods from the SWIFT science program.

b. SWIFT Testbed 2: Subseasonal-to-seasonal (S2S).

SWIFT is running an S2S operational testbed over the two-year period November 2019-October 2021, exploiting real-time access to operational sub-seasonal forecasts through the Real-time Pilot Project of the WMO Sub-seasonal Prediction Project (Vitart *et al.,* 2015). Given the rich opportunity offered by this unprecedented dataset, the goals of the S2S testbed have been focused primarily on the co-production of new services with stakeholders. In particular, Testbed 2’s goals have been to design and evaluate new products in support of decision making; to develop operational best practice in the delivery of sub-seasonal forecasts; and to demonstrate the value of sub-seasonal forecasting.

The testbed methodology is built around the principles of co-production developed as part of the Weather and Climate Information Services for Africa (WISER) and Future Climate for Africa (FCFA) projects (Carter *et al*, 2019). Each Operational Met Service is working with a small number of forecast users and scientists in research organizations to design, produce, evaluate and develop operational forecast products to support decision making in the user's particular application. Across the project we are working with users from the private and public sector (including multi-national institutions); in sectors including Disaster Risk Reduction, Health, Agriculture and Energy. Critically, the access to real-time forecast data allows for the production of products which depend non-linearly on multiple atmospheric fields (and other data), for example as in the meningitis vigilance product described in Figure 6.

6. Conclusions.

There is an opportunity and need for improvements in African weather forecasts from minutes to months. The opportunity is accompanied by the arrival of commercial agencies, and this increases the need for sound scientific methods and evaluation.

We propose four short but challenging steps to achieving high-impact weather forecast services in Africa:

I. Scientific work, particular to each timescale and outlined in this paper, involving international research collaborations and operational delivery, is necessary if forecast

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skill and impact is to improve, because performance of the scientific solutions is currently very low for Africa relative to other parts of the world. We argue that improvement in this skill is achievable, with impacts within months, right across the timescales.

II. Co-production of new services is also necessary, if the benefits of forecasts are to reach a majority of African stakeholders, and the potential of forecast information is to be achieved. Such services need to include sustainable SOPs and clear funding streams.

III. Transparent, systematic and independent evaluation of weather information services is needed in order to improve services, justify investment and allow customers to judge competing products.

IV. Building capability in African skills is necessary, to take ownership of the co-production of services. This requires improvement of skills both in scientific methods and in user-engagement practice. We argue that this will best be achieved by investment in operational-academic cooperation within Africa. Empowering women and prioritizing gender equality will bring more talented scientists to the forefront of this challenge.

This paper makes a bold statement that a transformation of weather services in tropical Africa is within our reach in the coming years, and we propose these four steps as the route to achieve this. History shows that bold ambitions to transform African services can lead to disappointment, and the challenges in taking these four steps should not be underestimated. On the other hand, it is vital that the international community does not give in to pessimism or a *laissez-faire* attitude, and there are numerous examples of success. For instance, the African Monsoon Multidisciplinary Analysis (AMMA; Redelsperger *et al.* 2006) was

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successful in implementing a number of changes across the West African observing networks (Fink *et al.* 2011). More recently the TAHMO network (van de Giesen *et al.* 2014) is making advances in delivering sustainably-funded surface observations and the CCAFS program (Ouédraogo, 2018; Diouf *et al*., 2020) has shown how forecasts can be communicated to millions of vulnerable people.

SWIFT is a 4-year program ending in 2021. By investing in existing partnerships, particularly between universities and operational centers, and through international activities of the WMO, ACMAD, ICPAC and the Met Office, we have attempted to produce outcomes with a significant legacy for years to come. Training materials in the universities and the increasing expertise of researchers, reflected in the skills analysis of Figure 7, will influence generations of future scientists. SWIFT has begun to have an influence on forecasting practice across timescales, in the weather centers and through partnerships with their stakeholders, and we hope that creating working examples of this process is a valuable step towards wider impacts in future. Beyond SWIFT we recommend that testbeds be continued in the region periodically, as they are in the USA for instance. Delivery of solutions on all these timescales will demand international cooperation, scientific research and co-production of services, but all are within our reach today if suitable investment is made.

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DATA AVAILABILITY STATEMENT

Figures 1 and 6 make use of data held on the S2S database hosted at ECMWF as an extension of the TIGGE database (Vitart *et al.,* 2017). Met Office Unified Model data including global and convection-permitting deterministic and ensemble configurations, are available on the Met Office Managed Archive Storage System (MASS) with the following path: moose:/devfc/u-be957: more information on how to get access to these data can be found at https://www.ceda.ac.uk/blog/access-to-the-met-office-mass-archiveon-jasmin-goes-live/. Analysis products used in Figures 2 and 4 were obtained from the National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce (2015). GPM data for this study were obtained from the University of Washington GPM-Ku Data Set located at http://gpm.atmos.washington.edu and supported by the NASA Earth Sciences PMM Program and Huffman *et al.* (2019). Figures 3a-e and 5c-h were produced using software developed by the EUMETSAT Nowcasting Satellite Application Facility (NWC SAF; http://www.nwcsaf.org) and an archive of images is held at https://sci.ncas.ac.uk/swift/. Figure 6 also uses data from the Barcelona Dust Forecast Center (https://dust.aemet.es/). The SWIFT Skills Matrix can be obtained from Parker (2021).

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FIGURES

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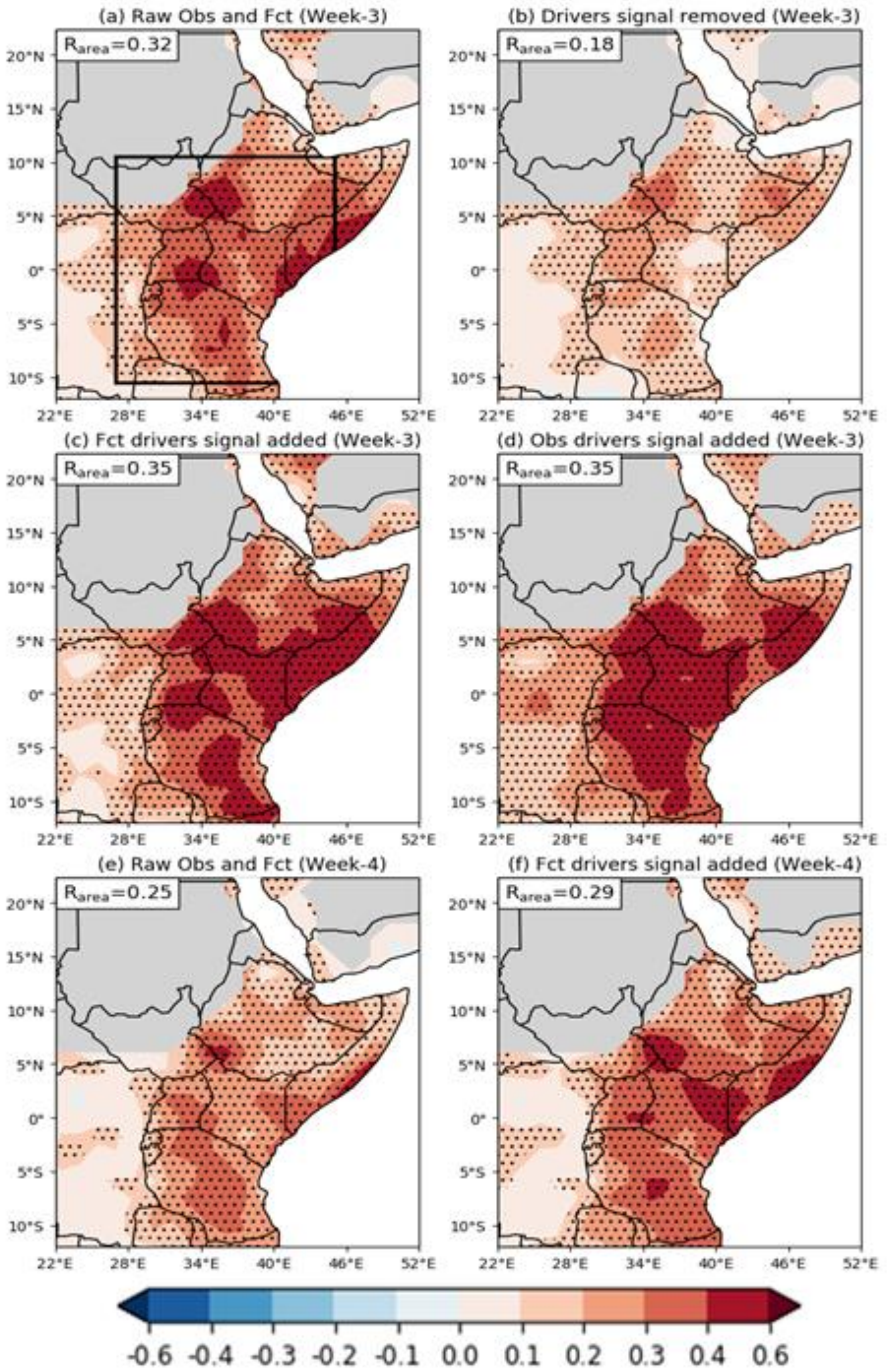

Figure 1: Pearson's correlation coefficients computed between ECMWF hindcast ensemble mean and GPCP accumulated precipitation anomalies for Week-3 (forecast days 19-25) and Week-4 (forecast days 26-32) using initializations within October-November-December from 1997 to 2014. Correlations for Week-3 were obtained with (a) raw observations and hindcasts, (b) drivers' signal removed from hindcasts and observations

using appropriate linear regression patterns, (c) hindcasts adjusted by adding observed linear response to forecast drivers' signal in place of forecast response in hindcasts and (d) hindcasts adjusted by adding observed response to observed drivers in place of forecast response to forecasted drivers, indicating the potential skill with a perfect forecast of both the drivers and the local response. (e) and (f) show the same as (a) and (c) but for Week-4: the skill for week 4 shows a decrease from week 3 (e) but correcting the response to the forecast drivers improves the skill (f). Drivers' activity was represented by the Niño 3.4, DMI, and RMM indices. Square in (a) denotes the region used to calculate the regional average of the correlation shown on the top left of each panel. Stipples indicate correlations statistically significant at the 95% level (two-sided Student's t test). Grey shading denotes a dry mask applied over regions where the observed weekly precipitation climatology is less than 1 mm for more than 50% of initializations within a season. See de Andrade et al (2020) for details.

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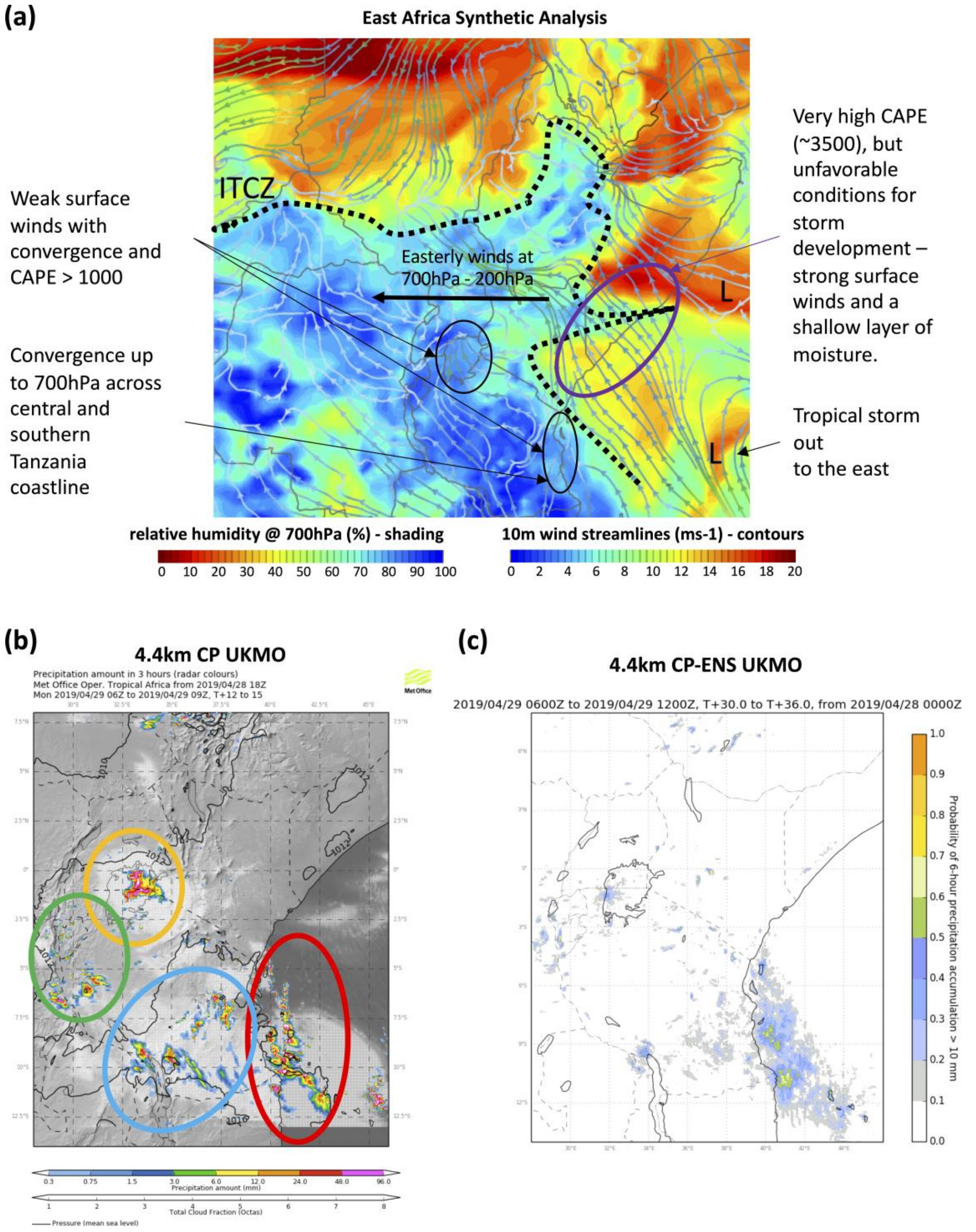

Figure 2: (a) Synthetic analysis for East Africa for April 29 2019 at 0600 UTC, including annotations by testbed participants in the synoptic team to describe the synoptic situation. Shading shows 700 hPa humidity and contours show 10 m wind streamlines from the 1800 UTC GFS run on April 28. Black dashed line shows the position of the ITCZ diagnosed by testbed participants. (b) 3h precipitation accumulation forecast from the April 28 1800 UTC

run of the UK Met Office Tropical Africa convection-permitting (CP) deterministic model (4.4 km horizontal grid-spacing) for 0600-0900 UTC on April 29, used to identify regions of interest for high-impact weather (colored ovals). The timings and locations of such events were entered into a shared spreadsheet by the testbed participants. (c) Probability of 6h precipitation accumulation exceeding 10 mm between 0600-1200 UTC on April 29 from the April 28 0000 UTC run of a CP ensemble configuration of the Met Office Unified Model (also 4.4 km horizontal grid-spacing) which was run especially for the testbed. The CP ensemble was used to add confidence to the forecast from the CP deterministic model.

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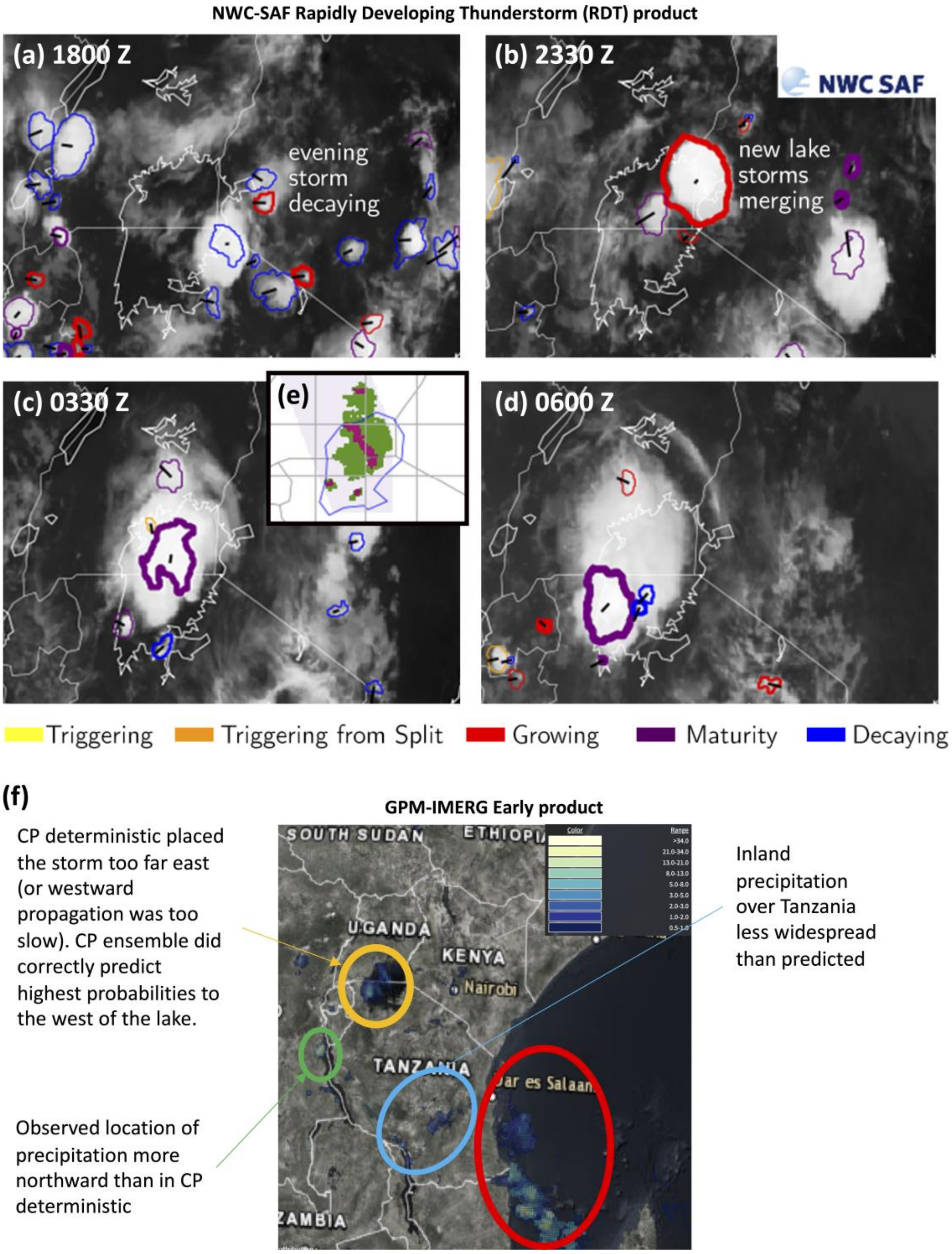

CP deterministic placed the storm too far east (or westward propagation was too slow). CP ensemble did correctly predict highest probabilities to the west of the lake.

Observed location of precipitation more northward than in CP deterministic

Inland precipitation over Tanzania less widespread than predicted

Figure 3 (a-d) Rapidly Developing Thunderstorm (RDT) product from NWC-SAF for various times between 28 April 1800 UTC and 29 April 0600 UTC 2019. This product was used by the nowcasting team to track storms, for example over Lake Victoria as they propagated in from offshore, merged, and strengthened overnight. (e: inset within panel (c)) Analysis using the UWGPM product (Houze et al. 2014) from a GPM overpass around 0345

UTC: pink shading shows regions where the GPM Ku-band radar identified contiguous regions with reflectivity greater than 30 dBZ, with the storm identified in green and Lake Victoria outlined in blue. This product shows good agreement with the RDT product. (f) GPM-IMERG early product for 29 Jan 0600-0630 UTC taken from the NASA GPM NRT viewer (NASA/JAXA, https://storm.pps.eosdis.nasa.gov/storm/cesium/GPMNRTView.html). This product was used by the evaluation team at the testbed for verification of the precipitation forecast from the previous day. The image includes annotations made during the testbed. The observations were compared against the forecasts recorded by the high impact weather team in the shared spreadsheet. Hits, misses, false alarms and correct negatives were recorded in the same spreadsheet.

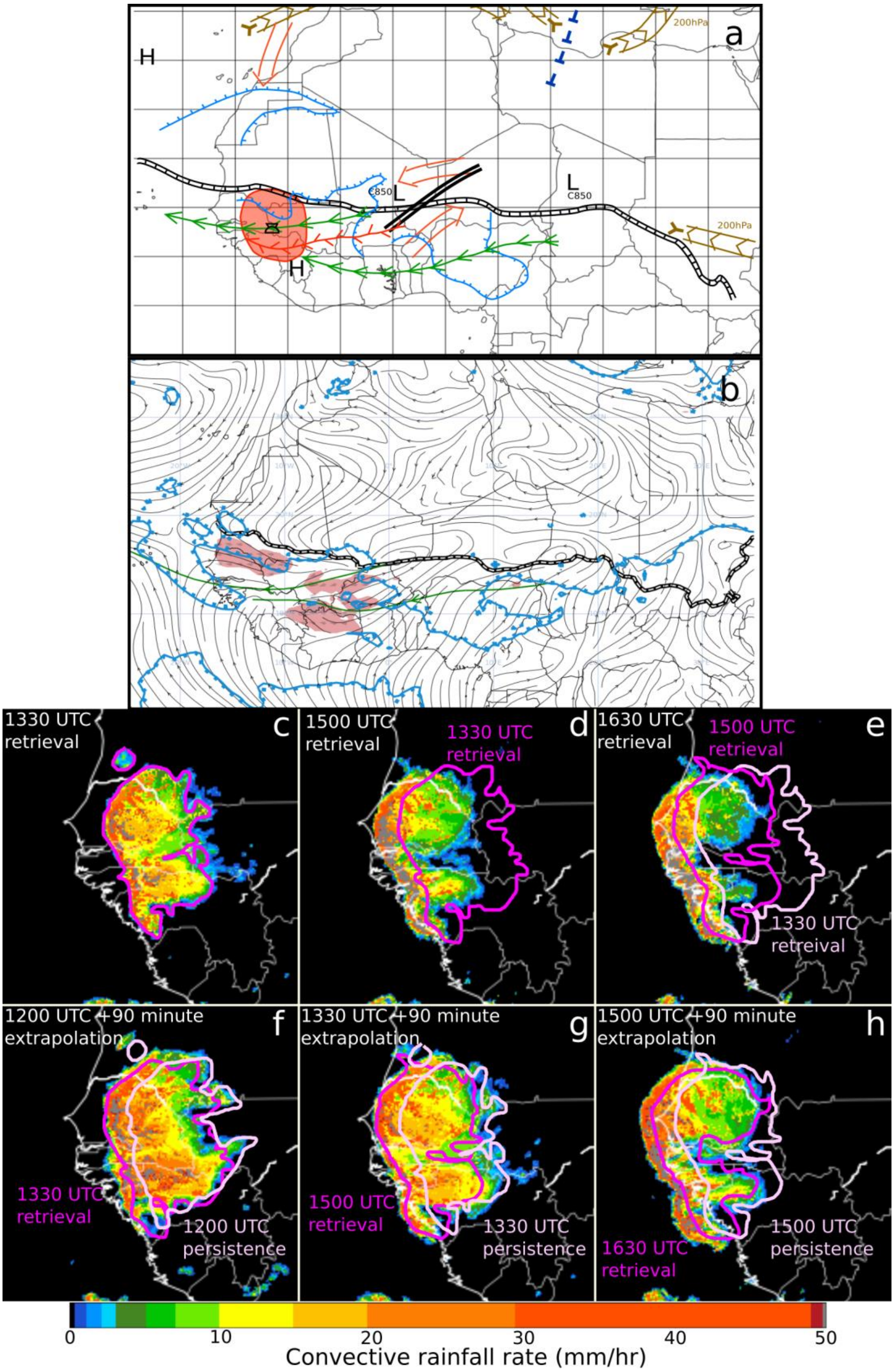

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Figure 4: Example of the synthesis of synoptic analysis and satellite-based nowcasting tools for the Mesoscale Convective System which caused significant hardship in Senegal, 27th June 2018. (a) A hand-drawn synoptic analysis for 1200 UTC (using conventions from the West African Synthetic Analysis, WASA) shows an African Easterly Wave trough at 700 hPa (bold parallel lines), a 200 hPa trough (line of “T”s), African Easterly Jet cores (green curved arrows), upper level jet cores (brown tramlines), the 850 hPa monsoon trough (red curve with feathers), low level advection (open red arrows), midlevel dry intrusion boundary (thick blue line with ticks on the dry side) and the region of active convection (pink shading). In (b), WASA features are computed numerically from the 1200 UTC GFS analysis fields, superposed on the 925 hPa streamlines and 925-650 hPa wind-shear (vector and magnitude, pink shading above 15 ms^{-1}), including the southern boundary of a 700 hPa dry intrusion from the Sahara at 60% relative humidity. Senegal lies on the edge of the dry intrusion boundary, and is characterized by strong easterly wind-shear, dry mid-levels and high CAPE (not shown). This system delivered unseasonally cold temperatures for a few hours at the surface (arriving at Dakar between 1500 and 1600 UTC) which caused widespread death of cattle: strong cold downdraughts were presumably supported by the dry mid-level air.

Panels (c) to (e) show NWCSAF Convective Rainfall Rate (CRR) satellite rainfall retrievals at 90 minute intervals from 1330 to 1630 UTC, with outlines of the previous retrievals added to (d) and (e): the case is a typical example of a storm moving at near-constant speed, meaning that nowcasting can be used to make forward predictions for several hours into the future. Panels (f) to (h) show 90 minute extrapolations of the CRR field with valid times matching panels above. The outlines of the retrievals (from (c) to (e)) are overlain on the extrapolated imagery, along with a “persistence” outline, to illustrate the quality of the extrapolation field relative to persistence, over this 90-minute period.

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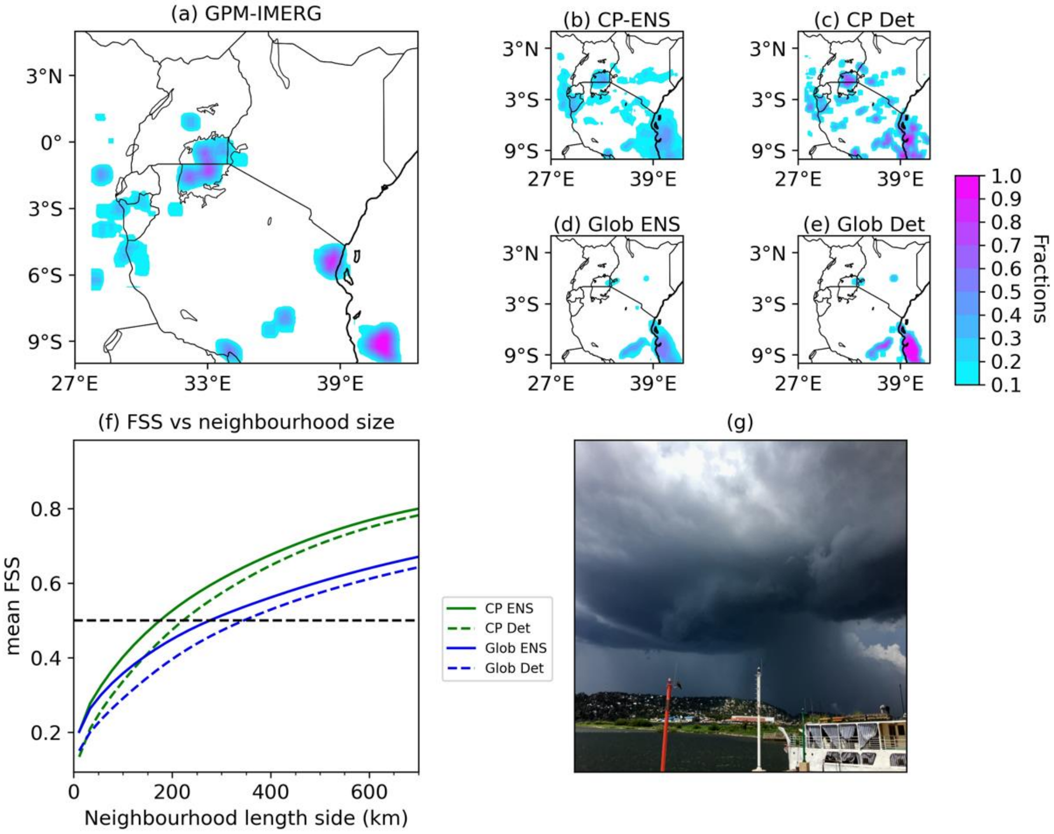

Figure 5: Evaluation of MetUM forecasts. (a-e) show observational or forecast probability of 24h rainfall accumulation exceeding 30mm on 29 April 2019 (during SWIFT Testbed 1, during which the ensemble configurations were run with 18 ensemble members). Forecast data are taken from the 12UTC initialisation on 28 April 2019 (T-12--36) and all forecasts are interpolated to the observations grid (0.1°). Probabilities are from (a) GPM observations, (b) CP ensemble, (c) CP deterministic, (d) global ensemble and (e) global deterministic. The probabilities from the observations and deterministic models are neighbourhood probabilities derived from the fraction of grid points within an n=15 (~165 km) area exceeding the accumulation threshold within the neighbourhood. For the ensemble forecasts, the probabilities are neighbourhood ensemble probabilities which include the fraction across ensemble members, as well as a spatial fraction. (f) Mean Fractions Skill Score, where higher values indicate greater skill and values over 0.5 indicate the scale at which each forecast

becomes ‘useful’, as a function of neighbourhood size for 24h rainfall accumulations above the 97th percentile (top 3% of events) for the T+12-36 and T+36-60 accumulation periods from the 12 UTC model initialisations between 19 April–12 May 2019, for the four models in (b-e). (g) Photograph of a storm over Lake Victoria, taken from Mwanza, Tanzania in December 2016.

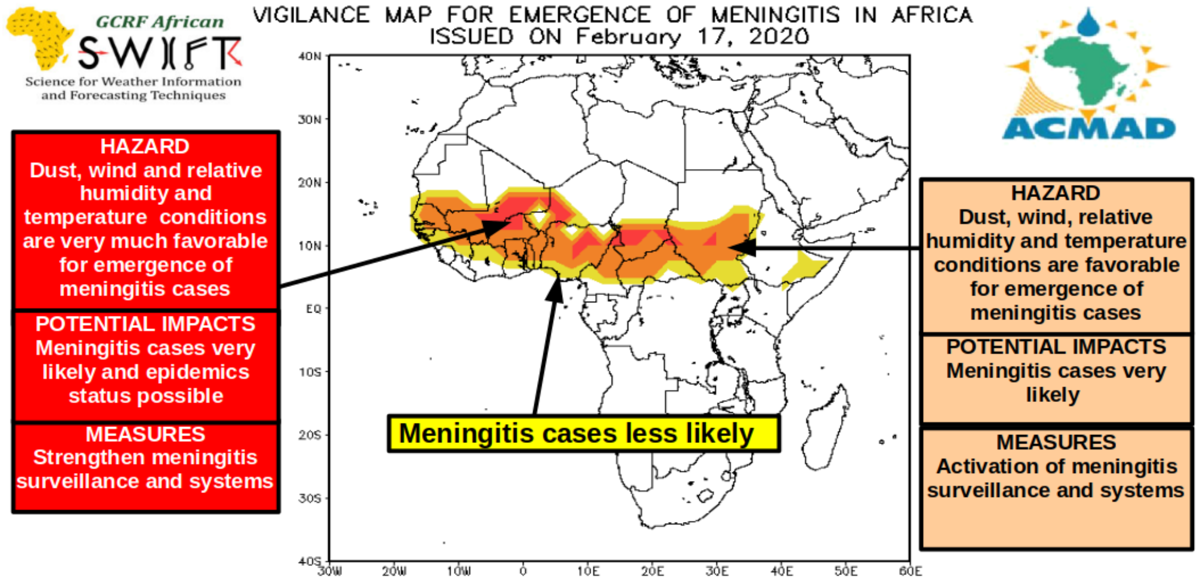

Figure 6: Weekly vigilance map of meningitis cases expected during the week from 17th to 23rd February 2020. Weekly mean surface dust concentrations during the past week (based on an NWP product from the Barcelona Supercomputer Center (BSC)) are combined with 1000 hPa atmospheric fields extracted from the S2S forecast database of ECMWF data (1.5° x 1.5°, weekly mean, bias-corrected using ERA5 reanalysis). For the meridional wind speed, the most important information is to characterize the change between the monsoon (wet) flow and Harmattan (dry). The bulletin is produced from January to June (mostly dry season) and focusses on the African epidemic meningitis belt.

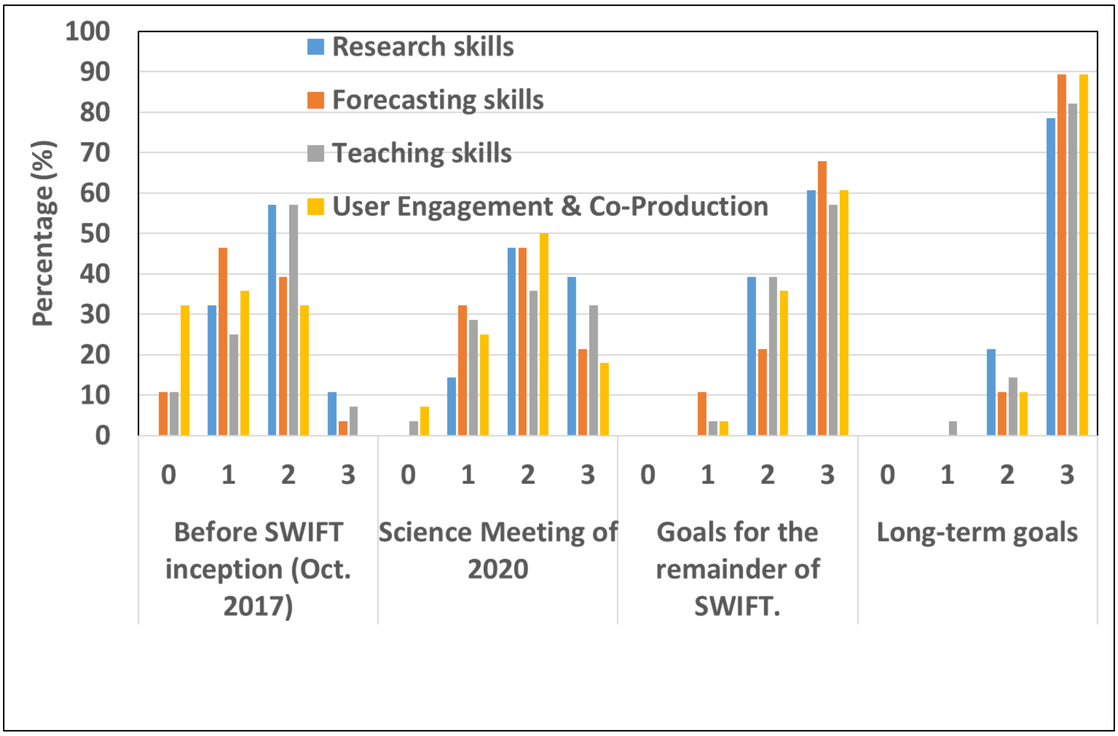

Figure 7: Distribution of skills of SWIFT African members for 4 different time categories (Before SWIFT Inception; at July 2020 Science Meeting; by the end of SWIFT, December 2021; and long-term), as a percentage according to four categories of experience (0 – No Experience; 1 – First Experience; 2 – Experienced; 3 – Advanced). Data are based on 43 respondents.

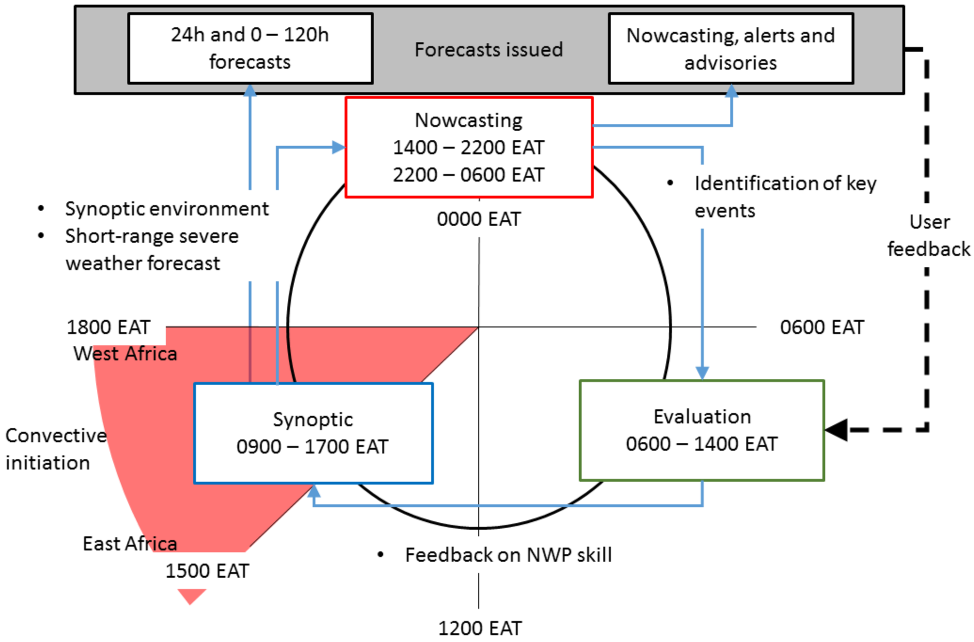

Figure 8: Schematic diagram of the forecasting daily cycle of activity among the teams delivering Testbed 1 (Evaluation, Synoptic and Nowcasting teams). The three groups worked in shifts following the natural cycle of convection, shown here in relation to Eastern Africa Time (EAT). The cycle of activity enables information to be passed from one team to another in order to inform their work: for instance, the Nowcasting team begin their shift making use of the synoptic analysis and forecast prepared by the Synoptic group. A rapid increase in deep convective activity tends to occur around 1500 local time, which corresponds to 1500 – 1800 EAT for activity occurring from East to West Africa.

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