BAMS Article

The African SWIFT Project

Growing Science Capability to Bring about a Revolution in Weather Prediction

Douglas J. Parker, Alan M. Blyth, Steven J. Woolnough, Andrew J. Dougill, Caroline L. Bain, Estelle de Coning, Mariane Diop-Kane, Andre Kamga Foamouhoue, Benjamin Lamptey, Ousmane Ndiaye, Paolo Ruti, Elijah A. Adefisan, Leonard K. Amekudzi, Philip Antwi-Agyei, Cathryn E. Birch, Carlo Cafaro, Hamish Carr, Benard Chanzu, Samantha J. Clarke, Helen Coskeran, Sylvester K. Danuor, Felipe M. de Andrade, Kone Diakaria, Cheikh Dione, Cheikh Abdoulahat Diop, Jennifer K. Fletcher, Amadou T. Gaye, James L. Groves, Masilin Gudoshava, Andrew J. Hartley, Linda C. Hirons, Ishiyaku Ibrahim, Tamora D. James, Kamoru A. Lawal, John H. Marsham, J. N. Mutemi, Emmanuel Chilekwu Okogbue, Eniola Olaniyan, J. B. Omotosho, Joseph Portuphy, Alexander J. Roberts, Juliane Schwendike, Zewdu T. Segele, Thorwald H. M. Stein, Andrea L. Taylor, Christopher M. Taylor, Tanya A. Warnaars, Stuart Webster, Beth J. Woodhams, and Lorraine Youds

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 Global Challenges Research Fund (GCRF) African Science for Weather Information and Forecasting Techniques (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, modeling and operational prediction, and 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 semioperational forecasting environment.

KEYWORDS: Africa; Forecast verification/skill; Nowcasting; Numerical weather prediction/forecasting; Operational forecasting; Short-range prediction

https://doi.org/10.1175/BAMS-D-20-0047.1
Corresponding author: Douglas J. Parker, d.j.parker@leeds.ac.uk
In final form 20 July 2021

AFFILIATIONS: Parker, Dougill, Birch, Carr, Clarke, Coskeran, James, Marsham, Schwendike, A. L. Taylor, and Woodhams—University of Leeds, Leeds, United Kingdom; **Blyth, Lamptey, Fletcher, Groves, Roberts, and Youds**—National Centre for Atmospheric Science, University of Leeds, Leeds, United Kingdom; **Woolnough and Hirons**—National Centre for Atmospheric Science, Department of Meteorology, University of Reading, Reading, United Kingdom; **Bain, Hartley, and Webster**—Met Office, Exeter, United Kingdom; **de Coning**—WMO, Geneva, Switzerland; **Diop-Kane**—Regional Office for Africa, WMO, Addis Ababa, Ethiopia; **Kamga Foamouhoue and Dione**—African Centre of Meteorological Applications for Development, Niamey, Niger; **Ndiaye and Diop**—ANACIM, Dakar, Senegal; **Ruti**—EUMETSAT, Darmstadt, Germany; **Adefisan**—African Centre of Meteorological Applications for Development, Niamey, Niger, and Federal University of Technology, Akure, Ondo, Nigeria; **Amekudzi, Antwi-Agyei, and Danuor**—Kwame Nkrumah University of Science and Technology, Kumasi, Ghana; **Cafaro, de Andrade, and Stein**—Department of Meteorology, University of Reading, Reading, United Kingdom; **Chanzu**—Kenya Meteorological Department, Nairobi, Kenya; **Diakaria**—ASECNA/EAMAC, Niamey, Niger; **Gaye**—University Cheikh Anta Diop, Ecole Superieure Polytechnique, Dakar, Senegal; **Gudoshava and Segele**—IGAD Climate Prediction and Applications Centre, Nairobi, Kenya; **Ibrahim and Olaniyan**—Weather and Climate Research Center, Nigerian Meteorological Agency, Abuja, Nigeria; **Lawal**—Weather and Climate Research Center, Nigerian Meteorological Agency, Abuja, Nigeria, and African Climate and Development Initiative, University of Cape Town, Cape Town, South Africa; **Mutemi**—University of Nairobi, Nairobi, Kenya; **Okogbue and Omotosho**—Federal University of Technology, Akure, Ondo, Nigeria; **Portuphy**—Ghana Meteorological Agency, Accra, Ghana; **C. M. Taylor**—U.K. Centre for Ecology and Hydrology, and National Centre for Earth Observation, Wallingford, Oxfordshire, United Kingdom; **Warnaars**—U.K. Centre for Ecology and Hydrology, Wallingford, Oxfordshire, United Kingdom

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 2006–15 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).

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

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 coproduction 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 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 time scales, 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 time scales from minutes (nowcasting) to months [subseasonal to seasonal (S2S)], and application of this capability in Africa, the Global Challenges Research Fund (GCRF) African Science for Weather Information and Forecasting Techniques (SWIFT)[2] project (2017–22) 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 "weather forecasting testbeds." Testbeds were first conducted in the United States 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] https://africanswift.org/

Building scientific capability: Addressing the research challenges in African weather forecasting

Exploiting ensemble weather prediction, on subseasonal time scales. Despite the chaotic nature of daily tropical weather, there are sources of predictability on subseasonal time scales (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 time scales 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 judgments about their confidence in 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 time scales.

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. (2021) 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 (Fig. 1a). Removing the response to El Niño–Southern Oscillation (ENSO), Indian Ocean dipole (IOD), and MJO drivers (Fig. 1b) indicates that these drivers are an important source of predictability. A potential operational application of these results (Fig. 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 (Fig. 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.

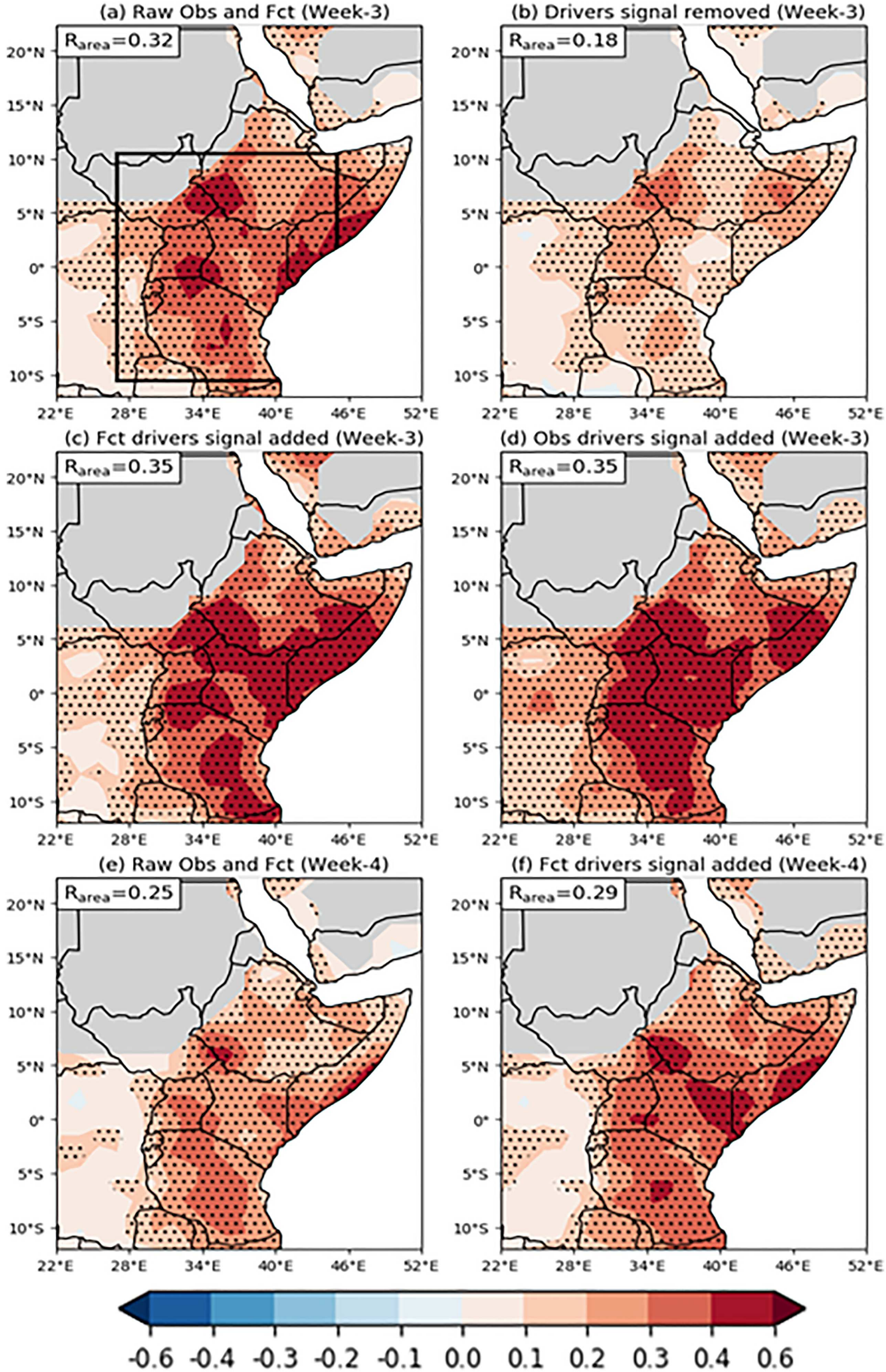

Fig. 1. Pearson's correlation coefficients computed between ECMWF hindcast ensemble mean and GPCP accumulated precipitation anomalies for week 3 (forecast days 19–25) and week 4 (forecast days 26–32) using initializations within October–December from 1997 to 2014. Correlations for week 3 were obtained 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),(f) As in (a) and (c), but for week 4: (e) the skill for week 4 shows a decrease from week 3, but (f)

correcting the response to the forecast drivers improves the skill. 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). Gray 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.

To bring the outcomes of such research into sector-facing services, SWIFT is working with forecast users to develop subseasonal forecast products that can inform their decision-making on these time scales, through a 2-yr operational S2S testbed.

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 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 postprocessed 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 judgment; and
- synthesizing synoptic-scale forecasting with nowcasting (as illustrated in Figs. 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 postprocessing 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 modeling 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 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 h), location (within order of 150 km, and within 50 km when combined with manual analysis), and intensity

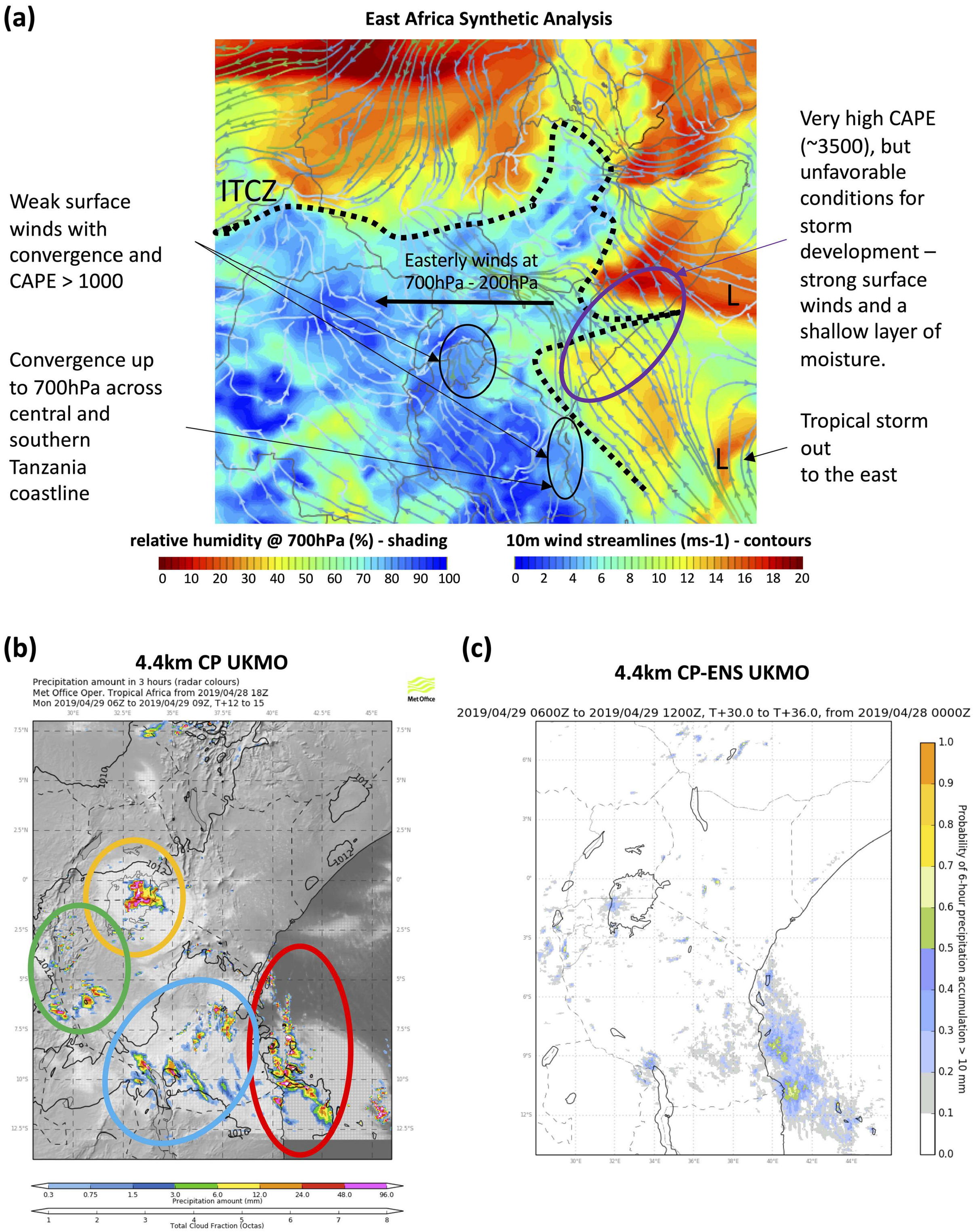

Fig. 2. (a) Synthetic analysis for East Africa at 0600 UTC 29 Apr 2019, including annotations by testbed participants in the synoptic team to describe the synoptic situation. Shading shows 700-hPa humidity and contours show 10-m wind streamlines from the 1800 UTC GFS run on 28 Apr. Black dashed line shows the position of the ITCZ diagnosed by testbed participants. (b) The 3-h precipitation accumulation forecast from the 1800 UTC 28 Apr run of the Met Office tropical Africa convection-permitting (CP) deterministic model (4.4-km horizontal grid spacing) for 0600–0900 UTC 29 Apr, used to identify regions of interest for high-impact weather (colored ovals). The timing and locations of such events were entered into a shared spreadsheet by the testbed participants. (c) Probability of 6-h precipitation accumulation exceeding 10 mm between 0600 and 1200 UTC 29 Apr from the 0000 UTC 28 Apr 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.

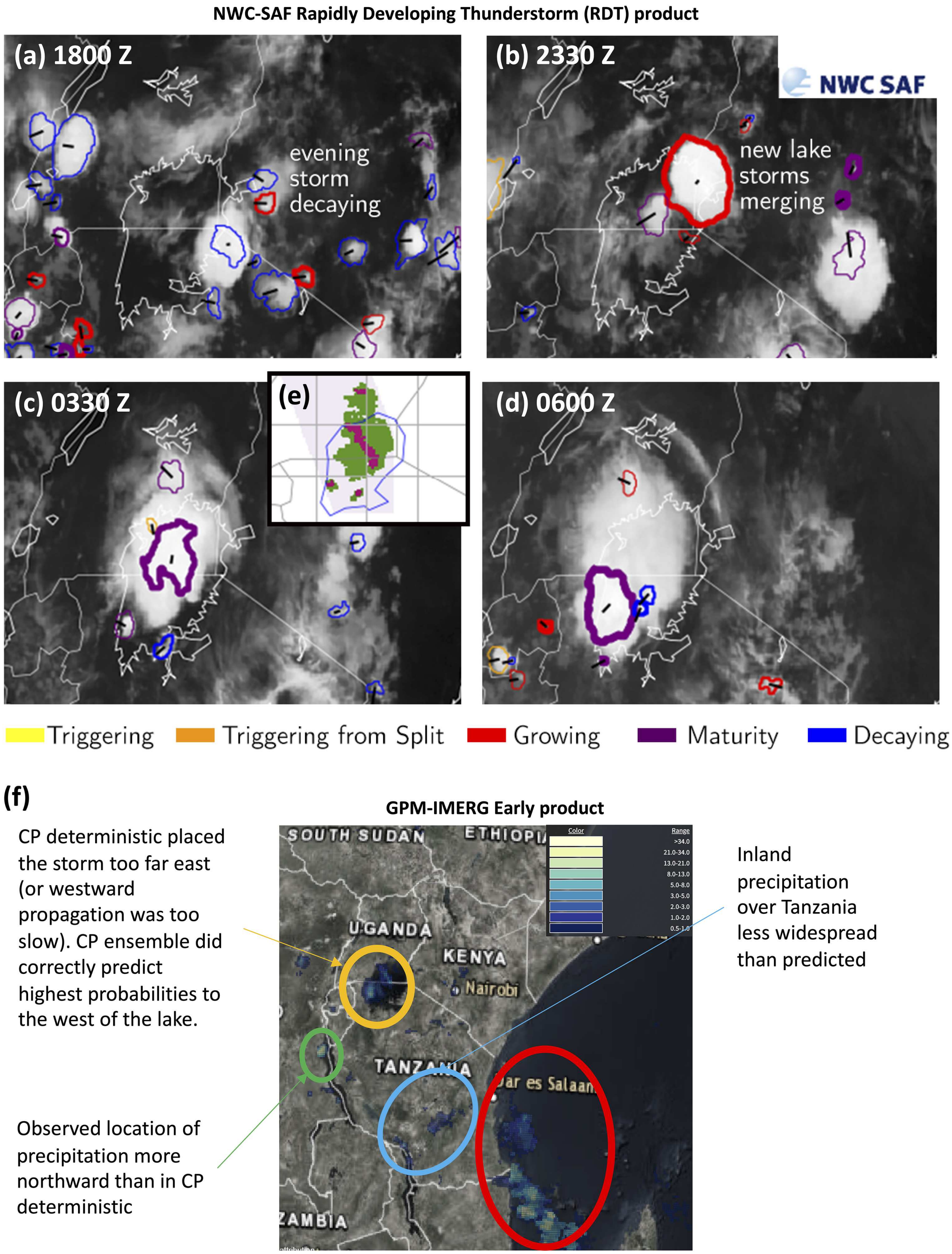

Fig. 3. (a)–(d) Rapidly Developing Thunderstorm (RDT) product from NWC SAF for various times between 1800 UTC 28 Apr and 0600 UTC 29 Apr 2019. This product was used by the nowcasting team to track storms, for example, over Lake Victoria as they propagated in from offshore, merged, and strengthened overnight. [(e) Inset within (c).] Analysis using the UWGPM product (Houze et al. 2015) 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 dB*Z*, 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 0600–0630 UTC 29 Jan 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.

of rainfall in a short-range (24 h) forecast (Cafaro et al. 2021). Significant work is still needed to realize these benefits, and the CP ensemble configuration is underspread 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 Fig. 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 Fig. 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., Fig. 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 Fig. 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 Fig. 4b), which will then be available for operational forecasting, and for hands-on training activities.

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 time scales, mean that operational nowcasting is vital for short-range services. However, outside South Africa, systematic nowcasting is almost nonexistent 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

[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.

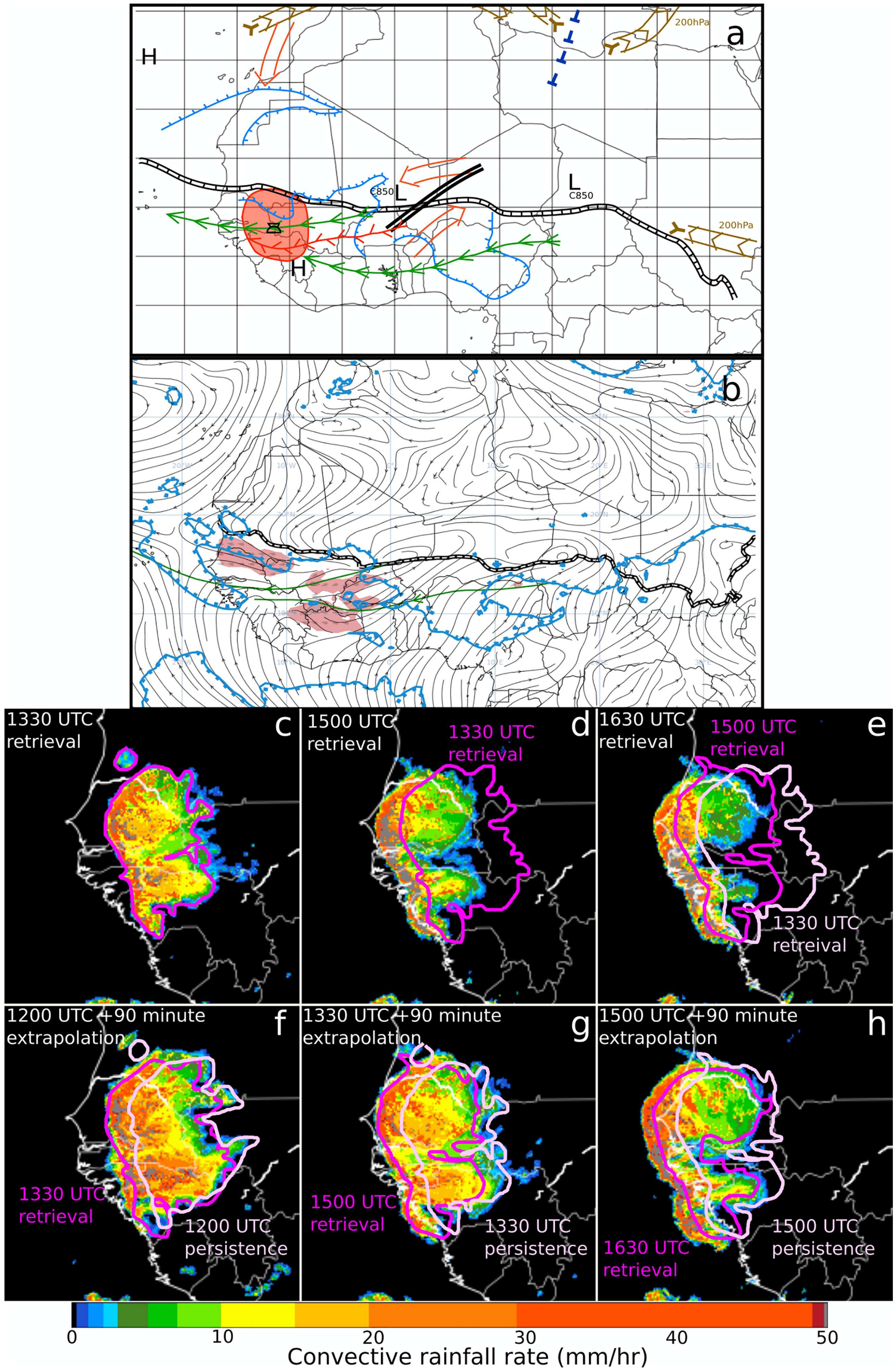

Fig. 4. Example of the synthesis of synoptic analysis and satellite-based nowcasting tools for the mesoscale convective system, which caused significant hardship in Senegal, on 27 Jun 2018. (a) A hand-drawn synoptic analysis for 1200 UTC [using conventions from the West African Synthetic Analysis (WASA)] 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). (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 m s^{-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 midlevels, and high CAPE (not shown). This system delivered unseasonably 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 downdrafts were presumably supported by the dry midlevel air. (c)–(e) NWC SAF convective rainfall rate (CRR) satellite rainfall retrievals at 90-min 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. (f)–(h) The 90-min 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-min period.

of Meteorological Satellites (EUMETSAT)'s Nowcasting Satellite Applications Facility (NWC SAF)[4] derived from Meteosat data (Roberts et al. 2022; 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-min latency, and made available on web pages.[5] In parallel, African SWIFT partners are installing satellite dishes and computational hardware to produce nowcasting products locally. Examples of the Rapid Developing Thunderstorm (RDT) product are shown in Fig. 3 and the Convective Rain Rate (CRR) product in Figs. 4c–h. Our research has demonstrated that the NWC SAF products have useful skill in representing current rainfall for at least 1.5 h of forward extrapolation (Hill et al. 2020; Figs. 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 and Wilson 2017). Integration with synoptic analysis from NWP is essential. SWIFT Testbed 1 has used the NWC SAF tools in a real-time exercise (see Figs. 2 and 3) and following the success of these demonstrations, the opportunity now is to codevelop 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.

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

[4] www.nwcsaf.org/

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

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.

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

Proper evaluation needs to be conducted against a high-quality benchmark forecast, which may be computed statistically from postprocessed 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 Fig. 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 convective initiation. For around 30 case studies, we are collaborating on evaluation of CP ensemble simulations to evaluate skill under different synoptic regimes.

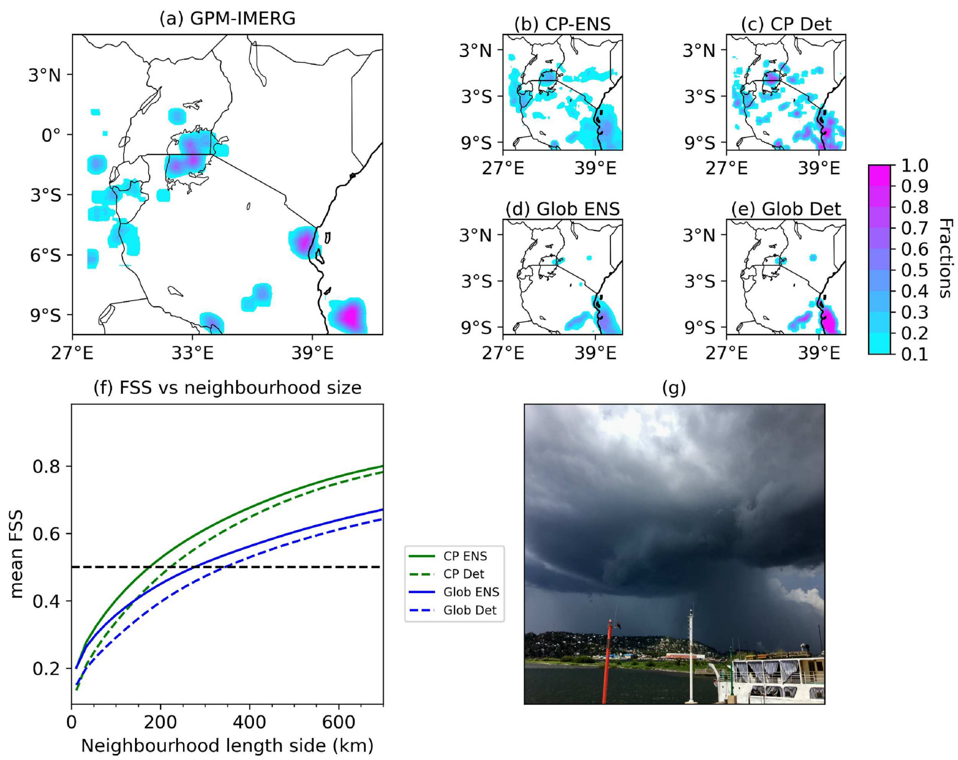

Fig. 5. Evaluation of MetUM forecasts. (a)–(e) Observational or forecast probability of 24-h rainfall accumulation exceeding 30 mm on 29 Apr 2019 (during SWIFT Testbed 1, during which the ensemble configurations were run with 18 ensemble members). Forecast data are taken from the 1200 UTC initialization on 28 Apr 2019 (*T* – 12–36 h) 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 neighborhood probabilities derived from the fraction of grid points within an *n* = 15 (~165 km) area exceeding the accumulation threshold within the neighborhood. For the ensemble forecasts, the probabilities are neighborhood 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 neighborhood size for 24-h rainfall accumulations above the 97th percentile (top 3% of events) for the *T* + 12–36 h and *T* + 36–60 h accumulation periods from the 1200 UTC model initializations between 19 Apr and 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.

Implementation and impact of improved forecasting methods

Forecast improvement needs to be developed in an environment of coproduction. Many examples have shown that active engagement and coproduction 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 time scales, 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 time scales, 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 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 coproduction 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.

Need for integrated forecasting systems and African scientific capability. Modern weather forecasting demands an integration of information across forecast time scales, with the subseasonal forecast influencing understanding of the synoptic situation, which also influences short-range prediction and nowcasting. This integration of information across time scales is demanded by forecast users, and demands significant human intervention in the forecast production. Three of the six building blocks of coproduction identified by Carter et al. (2019) (namely, "codevelop solutions," "codeliver solutions," and "evaluate") require that the forecast provider has high scientific skills in order to fulfill their part of the coproduction 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 the African Centre of Meteorological Applications for Development (ACMAD) and automated in the SWIFT Testbed 2 coproduction 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 (Thomson et al. 2013). The product is a vigilance map (Fig. 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; Sultan et al. 2005). Members of the WHO and local medical services are using these maps to

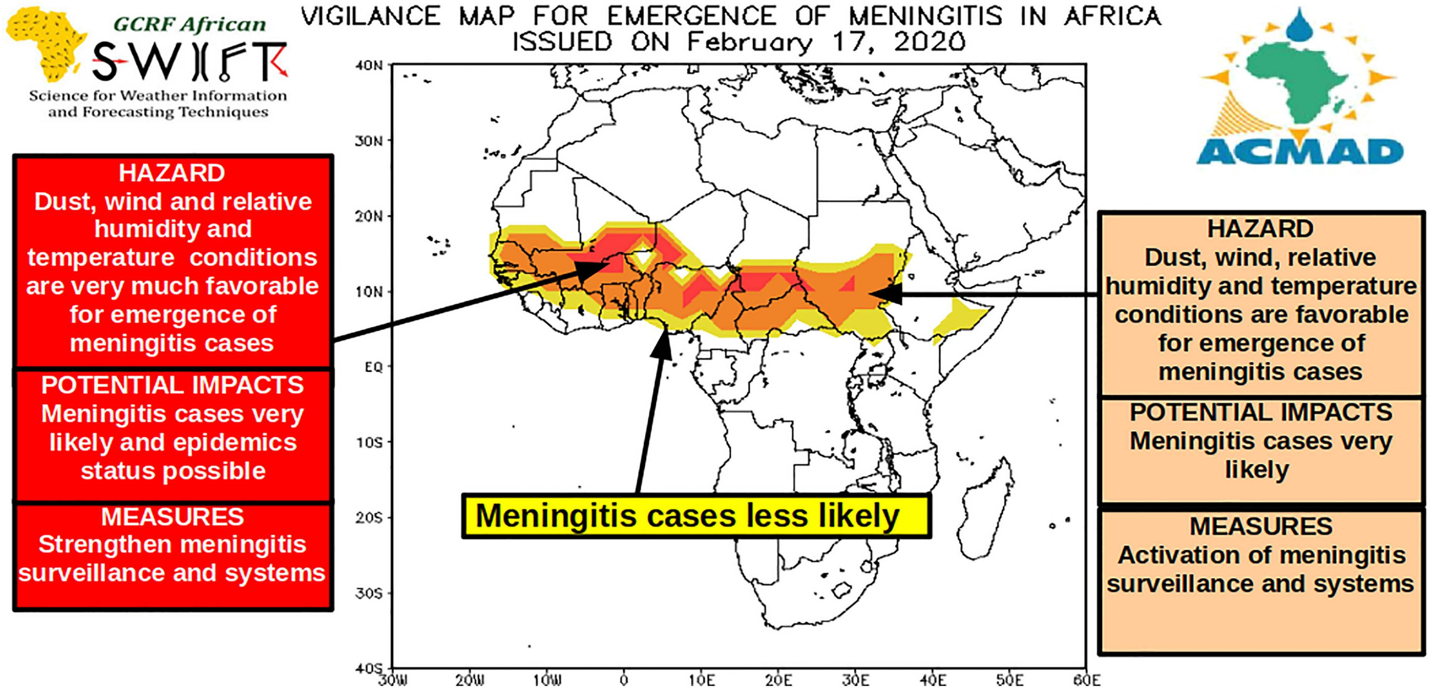

Fig. 6. Weekly vigilance map of meningitis cases expected during the week from 17 to 23 Feb 2020. Weekly mean surface dust concentrations during the past week [based on an NWP product from the Barcelona Supercomputer Center (BSC)] are combined with 1,000-hPa atmospheric fields extracted from the S2S forecast database of ECMWF data (1.5° × 1.5°, weekly mean, bias corrected using ERA5). 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 focuses on the African epidemic meningitis belt.

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 coproduction with the users, and the technical development of the operational product.

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.

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 modeling to deliver new products based on cutting-edge

[7] www.ignitia.se/

science, and is arguably leaving the African public-sector agencies behind in this technology. For the private sector, user communication, or coproduction, 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 agencies, and the private sector in Africa, is given the capabilities to match external competition for services.

Building capacity for African weather prediction

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 coproduced services in partnership with their stakeholders. As an example of what is needed, the innovation and production of meningitis bulletins illustrated in Fig. 6 required high-level scientific skills and coding ability, alongside a process of coproduction 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, and 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 Ph.D. 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 M.S. 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 modeling 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 coproduction of user-focused products from the models. To make the most of local expertise in modeling, 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 rain gauge, 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 rain gauge 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.

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 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-yr 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.

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 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 four 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 prioritize their professional choices according to skills needed for their careers (Fig. 7).

Weather forecasting testbeds in Africa

SWIFT Testbeds 1 and 3: Synoptic forecasting and nowcasting. SWIFT's Testbed 1: Synoptic and Nowcasting[8] was conducted over two periods, 24–29 January and 23 April–6 May 2019, hosted by the Institute for Meteorological Training and Research (IMTR), Kenya Meteorological Department (KMD), Nairobi, Kenya, and attended by 40 researchers, forecasters, and academics from the United Kingdom and 15 African institutions. The forecasting team 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 (Fig. 8), which is itself sympathetic to the cascade of spatial scales in the forecasting process. Figures 2 and 3 illustrate products and activities that were synthesized in real time.

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

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 has since been used as the framework for new SOPs in Testbed 3.

A final Testbed 3 took place in the fall of 2021, including user engagement on the same nowcasting–synoptic time scales, and introducing progress in new methods from the SWIFT science program.

SWIFT Testbed 2: S2S. SWIFT is running an S2S operational testbed over the 2-yr period November 2019–October 2021, exploiting real-time access to operational subseasonal forecasts through the Real-Time Pilot Project of the WMO Subseasonal Prediction Project (Vitart et al. 2015). Given the rich opportunity offered by this unprecedented dataset, the goals of the S2S testbed have been focused

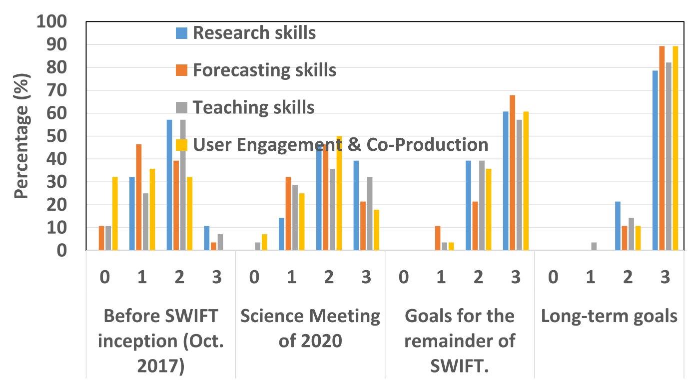

Fig. 7. Distribution of skills of SWIFT African members for four different time categories (Before SWIFT Inception; at July 2020 Science Meeting; by the end of SWIFT, March 2022; and long term), as a percentage according to four categories of experience (0—no experience; 1—first experience; 2—experienced; 3—advanced). Data are based on 43 respondents.

primarily on the coproduction 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 subseasonal forecasts; and to demonstrate the value of subseasonal forecasting.

The testbed methodology is built around the principles of coproduction 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 multinational 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 that depend nonlinearly on multiple atmospheric fields (and other data), for example, as in the meningitis vigilance product described in Fig. 6.

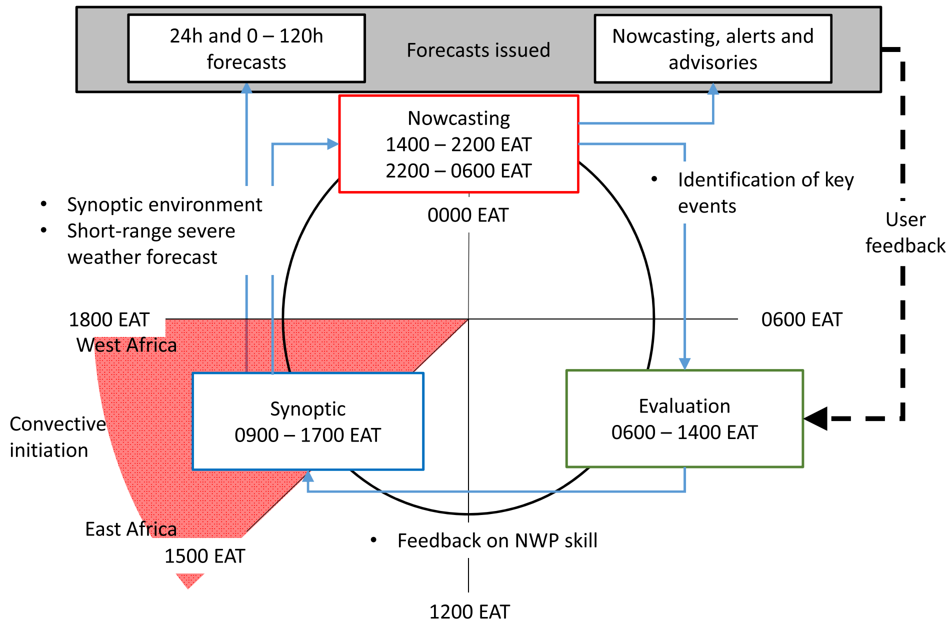

Fig. 8. Schematic diagram of the forecasting daily cycle of activity among the teams delivering Testbed 1 (evaluation, synoptic, and nowcasting teams). The three groups worked in shifts following the natural cycle of convection, shown here in relation to eastern Africa time (EAT). The cycle of activity 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.

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 time scale and outlined in this paper, involving international research collaborations and operational delivery, is necessary if forecast 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 time scales.

(ii) Coproduction 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 coproduction 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 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-yr program ending in 2022. By investing in existing partnerships, particularly between universities and operational centers, and through international activities of the WMO, ACMAD, Intergovernmental Authority on Development (IGAD) Climate Prediction and Applications Centre (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 Fig. 7, will influence generations of future scientists. SWIFT has begun to have an influence on forecasting practice across time scales, in the weather centers and through partnerships with their stakeholders, and we hope that creating working examples of this process is a valuable step toward wider impacts in future. Beyond SWIFT we recommend that testbeds be continued in the region periodically, as they are in the United States, for instance. Delivery of solutions on all these time scales will demand international cooperation, scientific research and coproduction of services, but all are within our reach today if suitable investment is made.

Acknowledgments. This work was supported by U.K. Research and Innovation as part of the Global Challenges Research Fund, African SWIFT programme, Grant NE/P021077/1. We wish to thank Jan Polcher, Barnabas A. Amisigo, Rosalind West, Katherine Marsden, Simon Howe, and Sithembile Ndema Mwamakamba for their advice and guidance as members of the project Advisory Group. Our thanks to Denise Groves for editorial work on the draft. S2S data were kindly provided by the international S2S Project as part of a joint initiative of the World Weather Research Programme (WWRP) and the World Climate Research Programme (WCRP) (Vitart et al. 2017).

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 www.ceda.ac.uk/blog/access-to-the-met-office-mass-archiveon-jasmin-goes-live/. Analysis products used in Figs. 2 and 4 were obtained from the National Centers for Environmental Prediction (2015). GPM data for this study were obtained from the University of Washington GPM-Ku dataset 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; 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).

References

Bain, C. L., K. Williams, S. Milton, and J. Heming, 2013: Objective tracking of African easterly waves in Met Office models. *Quart. J. Roy. Meteor. Soc.*, **140**, 47–57, https://doi.org/10.1002/qj.2110.

Bauer, P., A. Thorpe, and G. Brunet, 2015: The quiet revolution of numerical weather prediction. *Nature*, **525**, 47–55, https://doi.org/10.1038/nature14956.

Berthou, S., D. P. Rowell, E. Kendon, R. A. Stratton, J. Crook, and C. Wilcox, 2019: Improved climatological precipitation characteristics over West Africa at convection-permitting scale. *Climate Dyn.*, **53**, 1991–2011, https://doi.org/10.1007/s00382-019-04759-4.

Bharwani, S., and Coauthors, 2020: Enabling climate science use to better support resilience and adaptation practice: Rapid evidence assessment for the CLARE programme. U.K. FCDO Rep., 79 pp., https://idl-bnc-idrc.dspacedirect.org/handle/10625/58941.

Birch, C. E., D. J. Parker, J. H. Marsham, D. Copsey, and L. Garcia-Carreras, 2014: A seamless assessment of the role of convection in the water cycle of the West African monsoon. *J. Geophys. Res. Atmos.*, **119**, 2890–2912, https://doi.org/10.1002/2013JD020887.

Cafaro, C., and Coauthors, 2021: Do convection-permitting ensembles lead to more skillful short-range probabilistic rainfall forecasts over tropical East Africa? *Wea. Forecasting*, **36**, 697–716, https://doi.org/10.1175/WAF-D-20-0172.1.

Carter, S., A. Steynor, K. Vincent, E. Visman, and K. Waagsaether, 2019: Co-production in African weather and climate services. 2nd ed. Future Climate for Africa and Weather and Climate Information Services for Africa Doc., 156 pp., https://futureclimateafrica.org/coproduction-manual.

Ceccherini, G., S. Russo, I. Ameztoy, A. F. Marchese, and C. Carmona-Moreno, 2017: Heat waves in Africa 1981–2015, observations and reanalysis. *Nat. Hazards Earth Syst. Sci.*, **17**, 115–125, https://doi.org/10.5194/nhess-17-115-2017.

Cornforth, R., and Coauthors, 2019: The first forecasters' handbook for West Africa. *Bull. Amer. Meteor. Soc.*, **100**, 2343–2351, https://doi.org/10.1175/BAMS-D-16-0273.1.

Cullmann, J., and Coauthors, 2020: 2020 state of climate services. WMO Rep. 1252, 25 pp., https://library.wmo.int/index.php?lvl=notice_display&id=21777#.X_SR9zRxfIW.

Davidson, J., and J. Gill, 2012: Guidelines for creating a memorandum of understanding and a standard operating procedure between a national meteorological or hydrometeorological service and a partner agency. WMO Rep. 1099, 34 pp., https://library.wmo.int/index.php?lvl=notice_display&id=14093#.YWcYlxrMKUk.

de Andrade, F. M., M. P. Young, D. MacLeod, L. C. Hirons, S. J. Woolnough, and E. Black, 2021: Subseasonal precipitation prediction for Africa: Forecast evaluation and sources of predictability. *Wea. Forecasting*, **36**, 265–284, https://doi.org/10.1175/WAF-D-20-0054.1.

De Coning, E., M. Gijben, B. Maseko, and L. Van Hemert, 2015: Using satellite data to identify and track intense thunderstorms in south and southern Africa. *S. Afr. J. Sci.*, **111**, https://doi.org/10.17159/sajs.2015/20140402.

Dezfuli, A. K., C. M. Ichoku, K. I. Mohr, and G. J. Huffman, 2017: Precipitation characteristics in West and East Africa from satellite and in situ observations. *J. Hydrometeor.*, **18**, 1799–1805, https://doi.org/10.1175/JHM-D-17-0068.1.

Dike, V. N., and Coauthors, 2018: Obstacles facing Africa's young climate scientists. *Nat. Climate Change*, **8**, 447–449, https://doi.org/10.1038/s41558-018-0178-x.

Diouf, N. S., M. Ouedraogo, I. Ouedraogo, G. Ablouka, and R. Zougmoré, 2020: Using seasonal forecast as an adaptation strategy: Gender differential impact on yield and income in Senegal. *Atmosphere*, **11**, 1127, https://doi.org/10.3390/atmos11101127.

Elless, T. J., and R. D. Torn, 2018: African easterly wave forecast verification and its relation to convective errors within the ECMWF ensemble prediction system. *Wea. Forecasting*, **33**, 461–477, https://doi.org/10.1175/WAF-D-17-0130.1.

——, and ——, 2019: Investigating the factors that contribute to African easterly wave intensity forecast uncertainty in the ECMWF ensemble prediction system. *Mon. Wea. Rev.*, **147**, 1679–1698, https://doi.org/10.1175/MWR-D-18-0071.1.

Fink, A. H., and Coauthors, 2011: Operational meteorology in West Africa: Observational networks, weather analysis and forecasting. *Atmos. Sci. Lett.*, **12**, 135–141, https://doi.org/10.1002/asl.324.

Genesio, L., and Coauthors, 2011: Early warning systems for food security in West Africa: Evolution, achievements and challenges. *Atmos. Sci. Lett.*, **12**, 142–148, https://doi.org/10.1002/asl.332.

Gijben, M., and E. de Coning, 2017: Using satellite and lightning data to track rapidly developing thunderstorms in data sparse regions. *Atmosphere*, **8**, 67, https://doi.org/10.3390/atmos8040067.

Goddard, L., S. Mason, N. Lenssen, T. Dinku, and A. Kruczkiewicz, 2018: Report to Securing Water for Food (SWFF) and USAID on evaluation of Ignitia daily rainfall forecasts for subscribers in West Africa. Securing Water for Food Rep., 32 pp., https://securingwaterforfood.org/wp-content/uploads/2018/06/IRI-validation-study-of-Ignita.pdf.

Haiden, T., M. J. Rodwell, D. S. Richardson, A. Okagaki, T. Robinson, and T. Hewson, 2012: Intercomparison of global model precipitation forecast skill in 2010/11 using the SEEPS score. *Mon. Wea. Rev.*, **140**, 2720–2733, https://doi.org/10.1175/MWR-D-11-00301.1.

Hill, P. G., T. H. M. Stein, A. J. Roberts, J. K. Fletcher, J. H. Marsham, and J. Groves, 2020: How skillful are Nowcasting Satellite Applications Facility products for tropical Africa? *Meteor. Appl.*, **27**, e1966, https://doi.org/10.1002/met.1966.

Houze, R. A., Jr., K. L. Rasmussen, M. D. Zuluaga, and S. R. Brodzik, 2015: The variable nature of convection in the tropics and subtropics: A legacy of 16 years of the Tropical Rainfall Measuring Mission satellite. *Rev. Geophys*., **53**, 994–1021, https://doi.org/10.1002/2015RG000488.

Huffman, G. J., E. F. Stocker, D. T. Bolvin, E. J. Nelkin, and J. Tan, 2019: GPM IMERG final precipitation L3 half hourly 0.1 degree × 0.1 degree V06. GES DISC, accessed 11 June 2021, https://doi.org/10.5067/GPM/IMERG/3B-HH/06.

James, R., and Coauthors, 2018: Evaluating climate models with an African lens. *Bull. Amer. Meteor. Soc.*, **99**, 313–336, https://doi.org/10.1175/BAMS-D-16-0090.1.

Janicot, S., and Coauthors, 2011: Intraseasonal variability of the West African monsoon. *Atmos. Sci. Lett.*, **12**, 58–66, https://doi.org/10.1002/asl.280.

Kendon, E. J., R. A. Stratton, S. Tucker, J. H. Marsham, S. Berthou, D. P. Rowell, and C. A. Senior, 2019: Enhanced future changes in wet and dry extremes over Africa at convection-permitting scale. *Nat. Commun.*, **10**, 1794, https://doi.org/10.1038/s41467-019-09776-9.

Kilavi, M., and Coauthors, 2018: Extreme rainfall and flooding over central Kenya including Nairobi City during the long-rains season 2018: Causes, predictability, and potential for early warning and actions. *Atmosphere*, **9**, 472, https://doi.org/10.3390/atmos9120472.

Knippertz, P., and Coauthors, 2015: The DACCIWA project: Dynamics–Aerosol–Chemistry–Cloud Interactions in West Africa. *Bull. Amer. Meteor. Soc.*, **96**, 1451–1460, https://doi.org/10.1175/BAMS-D-14-00108.1.

Lafore, J. P., and Coauthors, 2017: West African Synthetic Analysis and Forecast: WASA/F. *Meteorology of Tropical West Africa: The Forecasters' Handbook*, D. J. Parker and M. Diop-Kane, Eds., John Wiley and Sons, 423–451.

Laing, A. G., R. E. Carbone, and V. Levizzani, 2011: Cycles and propagation of deep convection over equatorial Africa. *Mon. Wea. Rev.*, **139**, 2832–2853, https://doi.org/10.1175/2011MWR3500.1.

——, S. B. Trier, and C. A. Davis, 2012: Numerical simulation of episodes of organized convection in tropical northern Africa. *Mon. Wea. Rev.*, **140**, 2874–2886, https://doi.org/10.1175/MWR-D-11-00330.1.

Marsham, J. H., N. Dixon, L. Garcia-Carreras, G. M. S. Lister, D. J. Parker, P. Knippertz, and C. E. Birch, 2013: The role of moist convection in the West African monsoon system: Insights from continental-scale convection-permitting simulations. *Geophys. Res. Lett.*, **40**, 1843–1849, https://doi.org/10.1002/grl.50347.

Martiny, N., and I. Chiapello, 2013: Assessments for the impact of mineral dust on the meningitis incidence in West Africa. *Atmos. Environ.*, **70**, 245–253, https://doi.org/10.1016/j.atmosenv.2013.01.016.

Maurer, V., I. Bischoff-Gauß, N. Kalthoff, L. Gantner, R. Roca, and H.-J. Panitz, 2017: Initiation of deep convection in the Sahel in a convection-permitting climate simulation for northern Africa. *Quart. J. Roy. Meteor. Soc.*, **143**, 806–816, https://doi.org/10.1002/qj.2966.

Morel, C., and S. Senesi, 2002: A climatology of mesoscale convective systems over Europe using satellite infrared imagery. I: Methodology. *Quart. J. Roy. Meteor. Soc.*, **128**, 1953–1971, https://doi.org/10.1256/003590002320603485.

National Centers for Environmental Prediction, 2015: NCEP GFS 0.25 degree global forecast grids historical archive. NCAR Research Data Archive, accessed 11 June 2021, https://doi.org/10.5065/D65D8PWK.

Nkiaka, E., and Coauthors, 2019: Identifying user needs for weather and climate services to enhance resilience to climate shocks in sub-Saharan Africa. *Environ. Res. Lett.*, **14**, 123003, https://doi.org/10.1088/1748-9326/ab4dfe.

——, and Coauthors, 2020: Exploring the need for developing impact-based forecasting in West Africa. *Front. Climate*, **2**, 565500, https://doi.org/10.3389/fclim.2020.565500.

Ouédraogo, I., 2018: Forewarned is forearmed: How climate information services are saving the lives and livelihoods of Senegalese fisherfolk. *Int. Symp. on Agricultural Innovation for Family Farmers*, Rome, Italy, Food and Agriculture Organization, 13, https://hdl.handle.net/10568/100125.

Pante, G., and P. Knippertz, 2019: Resolving Sahelian thunderstorms improves mid-latitude weather forecasts. *Nat. Commun.*, **10**, 3487, https://doi.org/10.1038/s41467-019-11081-4.

Panthou, G., and Coauthors, 2018: Rainfall intensification in tropical semi-arid regions: The Sahelian case. *Environ. Res. Lett.*, **13**, 064013, https://doi.org/10.1088/1748-9326/aac334.

Parker, D. J., 2021: GCRF African SWIFT skills matrix for professionals in the field of African meteorology. University of Leeds, accessed 11 June 2021, https://doi.org/10.5518/1003.

——, and M. Diop-Kane, 2017: *Meteorology of Tropical West Africa: The Forecasters' Handbook*. John Wiley and Sons, 496 pp.

——, —— and J. P. Lafore, 2018: Météorologie de l'Afrique de l'ouest tropicale le manuel du previsionniste. EDP Sciences Doc., 756 pp.

Patt, A. G., L. Ogallo, and M. Hellmuth, 2007: Learning from 10 years of climate outlook forums in Africa. *Science*, **318**, 49–50, https://doi.org/10.1126/science.1147909.

Pearson, K. J., G. M. S. Lister, C. E. Birch, R. P. Allan, R. J. Hogan, and S. J. Woolnough, 2014: Modelling the diurnal cycle of tropical convection across the 'grey zone'. *Quart. J. Roy. Meteor. Soc.*, **140**, 491–499, https://doi.org/10.1002/qj.2145.

Porson, A. N., and Coauthors, 2020: Recent upgrades to the Met Office convective-scale ensemble: An hourly time-lagged 5-day ensemble. *Quart. J. Roy. Meteor. Soc.*, **146**, 3245–3265, https://doi.org/10.1002/qj.3844.

Ralph, F. M., and Coauthors, 2013: The emergence of weather-related test beds linking research and forecasting operations. *Bull. Amer. Meteor. Soc.*, **94**, 1187–1211, https://doi.org/10.1175/BAMS-D-12-00080.1.

Redelsperger, J. L., C. D. Thorncroft, A. Diedhiou, T. Lebel, D. J. Parker, and J. Polcher, 2006: African monsoon multidisciplinary analysis: An international research project and field campaign. *Bull. Amer. Meteor. Soc.*, **87**, 1739–1746, https://doi.org/10.1175/BAMS-87-12-1739.

Roberts, A. J., and Coauthors, 2022: Nowcasting for Africa: Advances, potential and value. *Weather*, https://doi.org/10.1002/wea.3936, in press.

Roberts, N. M., and H. W. Lean, 2008: Scale-selective verification of rainfall accumulations from high-resolution forecasts of convective events. *Mon. Wea. Rev.*, **136**, 78–97, https://doi.org/10.1175/2007MWR2123.1.

Roberts, R. D., and J. W. Wilson, 2017: Nowcasting. *Meteorology of Tropical West Africa: The Forecasters' Handbook*, D. J. Parker and M. Diop-Kane, Eds., John Wiley and Sons, 204–254.

Robertson, A. W., A. Kumar, M. Peña, and F. Vitart, 2015: Improving and promoting subseasonal to seasonal prediction. *Bull. Amer. Meteor. Soc.*, **96**, ES49–ES53, https://doi.org/10.1175/BAMS-D-14-00139.1.

Sanderson, D., and A. Sharma., Eds., 2016: World disasters report 2016. International Federation of Red Cross and Red Crescent Societies Rep., 282 pp., https://reliefweb.int/report/world/world-disasters-report-2016-resilience-saving-lives-today-investing-tomorrow-enar.

Stein, T. H. M., and Coauthors, 2019: An evaluation of clouds and precipitation in convection-permitting forecasts for South Africa. *Wea. Forecasting*, **34**, 233–254, https://doi.org/10.1175/WAF-D-18-0080.1.

Sultan, B., K. Labadi, J.-F. Guégan, and S. Janicot, 2005: Climate drives the meningitis epidemics onset in West Africa. *PLOS Med.*, **2**, e6, https://doi.org/10.1371/journal.pmed.0020006.

Taylor, C. M., 2008: Intraseasonal land–atmosphere coupling in the West African monsoon. *J. Climate*, **21**, 6636–6648, https://doi.org/10.1175/2008JCLI2475.1.

——, C. E. Birch, D. J. Parker, N. Dixon, F. Guichard, G. Nikulin, and G. M. S. Lister, 2013: Modeling soil moisture-precipitation feedback in the Sahel: Importance of spatial scale versus convective parameterization. *Geophys. Res. Lett.*, **40**, 2013GL058511, https://doi.org/10.1002/2013GL058511.

——, and Coauthors, 2017: Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. *Nature*, **544**, 475–478, https://doi.org/10.1038/nature22069.

Thomson, M. C., and Coauthors, 2013: A climate and health partnership to inform the prevention and control of meningoccocal meningitis in sub-Saharan Africa: The MERIT initiative. *Climate Science for Serving Society*, G. Asrar and J. Hurrell, Eds., Springer, 459–484, https://doi.org/10.1007/978-94-007-6692-1_17.

Tompkins, A. M., and Coauthors, 2012: The Ewiem Nimdie summer school series in Ghana: Capacity building in meteorological education and research—Lessons learned and future prospects. *Bull. Amer. Meteor. Soc.*, **93**, 595–601, https://doi.org/10.1175/BAMS-D-11-00098.1.

van de Giesen, N., R. Hut, and J. Selker, 2014: The Trans-African Hydro-Meteorological Observatory (TAHMO). *WIREs Water*, **1**, 341–348, https://doi.org/10.1002/wat2.1034.

Vitart, F., and Coauthors, 2015: Sub-seasonal to seasonal prediction: Linking weather and climate. Seamless prediction of the Earth system: From minutes to months, WMO Rep. 1156, 385–405, https://library.wmo.int/index.php?lvl=notice_display&id=17276#.YWciTxrMKUk.

——, and Coauthors, 2017: The Subseasonal to Seasonal (S2S) Prediction project database. *Bull. Amer. Meteor. Soc.*, **98**, 163–173, https://doi.org/10.1175/BAMS-D-16-0017.1.

Vizy, E. K., and K. H. Cook, 2018: Mesoscale convective systems and nocturnal rainfall over the West African Sahel: Role of the inter-tropical front. *Climate Dyn.*, **50**, 587–614, https://doi.org/10.1007/s00382-017-3628-7.

Vogel, P., P. Knippertz, A. H. Fink, A. Schlueter, and T. Gneiting, 2018: Skill of global raw and postprocessed ensemble predictions of rainfall over northern tropical Africa. *Wea. Forecasting*, **33**, 369–388, https://doi.org/10.1175/WAF-D-17-0127.1.

——, ——, ——, ——, and ——, 2020: Skill of global raw and postprocessed ensemble predictions of rainfall in the tropics. *Wea. Forecasting*, **35**, 2367–2385, https://doi.org/10.1175/WAF-D-20-0082.1.

——, ——, T. Gneiting, A. H. Fink, M. Klar, and A. Schlueter, 2021: Statistical forecasts for the occurrence of precipitation outperform global models over northern tropical Africa. *Geophys. Res. Lett.*, **48**, e2020GL091022, https://doi.org/10.1029/2020GL091022.

Wheeler, M. C., H. Zhu, A. H. Sobel, D. Hudson, and F. Vitart, 2017: Seamless precipitation prediction skill comparison between two global models. *Quart. J. Roy. Meteor. Soc.*, **143**, 374–383, https://doi.org/10.1002/qj.2928.

Woodhams, B. J., C. E. Birch, J. H. Marsham, C. L. Bain, N. M. Roberts, and D. F. A. Boyd, 2018: What is the added-value of a convection-permitting model for forecasting extreme rainfall over tropical East Africa? *Mon. Wea. Rev.*, **146**, 2757–2780, https://doi.org/10.1175/MWR-D-17-0396.1.

Yaka, P., B. Sultan, H. Broutin, S. Janicot, S. Philippon, and N. Fourquet, 2008: Relationships between climate and year-to-year variability in meningitis outbreaks: A case study in Burkina Faso and Niger. *Int. J. Health Geogr.*, **7**, 34, https://doi.org/10.1186/1476-072X-7-34.

Young, M., V. Heinrich, E. Black, and D. T. Asfaw, 2020: Optimal spatial scales for seasonal forecasts over Africa. *Environ. Res. Lett.*, **15**, 094023, https://doi.org/10.1088/1748-9326/ab94e9.