Tropical Africa's first testbed for high-impact weather forecasting and nowcasting

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Tropical Africa's First Testbed for High-Impact Weather Forecasting and Nowcasting

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ABSTRACT: Testbeds have become integral to advancing the transfer of knowledge and capabilities from research to operational weather forecasting in many parts of the world. The first high-impact weather testbed in tropical Africa was recently carried out through the African Science for Weather Information and Forecasting Techniques (SWIFT) program, with participation from researchers and forecasters from Senegal, Ghana, Nigeria, Kenya, the United Kingdom, and international and pan-African organizations. The testbed aims were to trial new forecasting and nowcasting products with operational forecasters, to inform future research, and to act as a template for future testbeds in the tropics. The African SWIFT testbed integrated users and researchers throughout the process to facilitate development of impact-based forecasting methods and new research ideas driven both by operations and user input. The new products are primarily satellite-based nowcasting systems and ensemble forecasts at global and regional convection-permitting scales. Neither of these was used operationally in the participating African countries prior to the testbed. The testbed received constructive, positive feedback via intense user interaction including fishery, agriculture, aviation, and electricity sectors. After the testbed, a final set of recommended standard operating procedures for satellite-based nowcasting in tropical Africa have been produced. The testbed brought the attention of funding agencies and organizational directors to the immediate benefit of improved forecasts. Delivering the testbed strengthened the partnership between each country's participating university and weather forecasting agency and internationally, which is key to ensuring the longevity of the testbed outcomes.

KEYWORDS: Africa; Tropics; Forecasting techniques; Nowcasting; Decision making; Emergency response

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Convective storms in tropical Africa cause numerous deaths and significant damage each year as a result of flooding, high winds, lightning strikes, hail, and haboobs. Even when storms are not severe, they can disrupt daily life—for example, a harvest can be ruined if unexpected rain falls on crops left to dry in the sun. Startlingly, for much of tropical Africa, the 1-day rainfall forecast from a state-of-the-art ensemble prediction has less skill than an ensemble climatology (Vogel et al. 2020). Skilled forecasters presumably add significant value to a forecast, and so the baseline quality of forecasts as issued operationally in tropical Africa is likely higher than suggested by Vogel et al. (2020); on the other hand, most tropical African forecasters do not have access to the best available tools for near-term forecasting and nowcasting. As of 2018, there was no evidence that forecasting services provided operational nowcasting in tropical Africa outside of major airports, and even there, retrieval products and automated forward extrapolations were not used (Roberts et al. 2022a). The skill of nowcast products in Africa (Hill et al. 2020) even at lead times of 4 h (Burton et al. 2022) therefore provides a major opportunity, but there is a need to familiarize forecasters with nowcast tools and approaches, and to demonstrate their usefulness to stakeholders.

The African Science for Weather Information and Forecasting Techniques (SWIFT; Parker et al. 2022) program was designed to bring significant improvements in African forecasting capability. African SWIFT is built on collaboration between researchers and operational forecast services in four African countries—Kenya, Nigeria, Ghana, and Senegal—and the United Kingdom, as well as several regional and pan-African weather and climate services. A cornerstone of African SWIFT is the implementation of forecasting testbeds in each of the above African countries. Building on the model of testbeds held in the United States (e.g., Ralph et al. 2013; Jedlovec 2013; Bernardet et al. 2015; Shao et al. 2016), African SWIFT testbeds aim to bridge the gap between research and operations by trialing new forecasting tools and methods in a quasi-operational environment where forecasters and researchers work side-by-side, and where outcomes not only affect operations but also guide future research directions. Crucially, African SWIFT testbeds also include forecast users in not just the testbeds but also in their planning and preparation.

Because SWIFT aims to improve weather forecasts across a range of time scales, it has held two types of testbeds: one aimed at subseasonal-to-seasonal forecasts, held over an 18-month period (Hirons et al. 2021) and two (a pilot testbed and a final testbed) aimed at time scales from hours (nowcasting) to days (synoptic forecasting). This paper focuses on SWIFT's final nowcasting to synoptic forecasting testbed. The planning, implementation, and execution of this testbed was a transformational exercise: it allowed forecasters to discover and evaluate new tools and methods, and it required researchers to think through every step needed to bring their proposed tool or method into operations and to get a taste of the realities of operational forecasting. Furthermore, interaction with users promoted an impact-based approach to the development of products and communications in the testbed. Finally, forecast users gained a new appreciation for the challenges in forecasting and developed stronger working relationships with weather forecasting services in their country.

Testbed operations

The testbed was held in late 2021. Figure 1a shows the locations in Africa that participated and the region over which synoptic forecasting was conducted, and Fig. 1b gives a rough timeline of the preparation and delivery of the testbed; about one year was devoted to testbed preparation, discussed in detail in appendix D. Due to the COVID-19 pandemic it was not possible to travel internationally, and so the testbed was conducted in national hubs that interacted virtually with each other and with international participants in the United Kingdom and in regional and pan-African weather and climate service organizations. The primary testbed locations (Fig. 1a) were Dakar, Senegal; Accra, Ghana; Abuja, Nigeria; and Nairobi, Kenya, with remote support from Niamey, Niger (ACMAD and MetNiger), and various locations in the United Kingdom (see appendix A). The primary locations held their testbed events at different dates for logistical reasons and to align with their rainy seasons (Fig. 1b), with participants from the national operational weather forecasting agency and cooperating university (appendix A). The hybrid nature of the testbed was an unexpected silver lining because it allowed more countries to carry out their own testbed than originally envisioned, and it exposed all participants to a wide range of methods and user perspectives.

A significant innovation of African SWIFT testbed was deep engagement with users, specifically expert technicians in sectors with interest in meteorological hazards and who make decisions or give advice to an entire sector based on the forecast. Users were invited to participate in the testbed based on their prior engagement with forecast agencies in their country and the interest they expressed in receiving weather information at lead times of hours to days. The most common sectors represented by the 34 users who participated in the testbed were agricultural, disaster management, and water resources and transportation (Fig. 2). Prior to the testbed, iterative discussions between testbed planners and users were the primary vehicle for developing the impact-based forecast templates used in the testbed.

Each primary testbed location delivered daily synoptic forecasts out to 3-day lead time, followed by 1-day high-impact weather forecasts issued around midday, and nowcasting in the afternoon and early evening as storms developed. The synoptic forecasting was conducted using bespoke forecast charts and informed the high-impact weather forecasts that used global and regional ensemble prediction systems. These in turn informed the nowcasting that was done using satellite-based nowcasting products. Each day testbed forecasters delivered

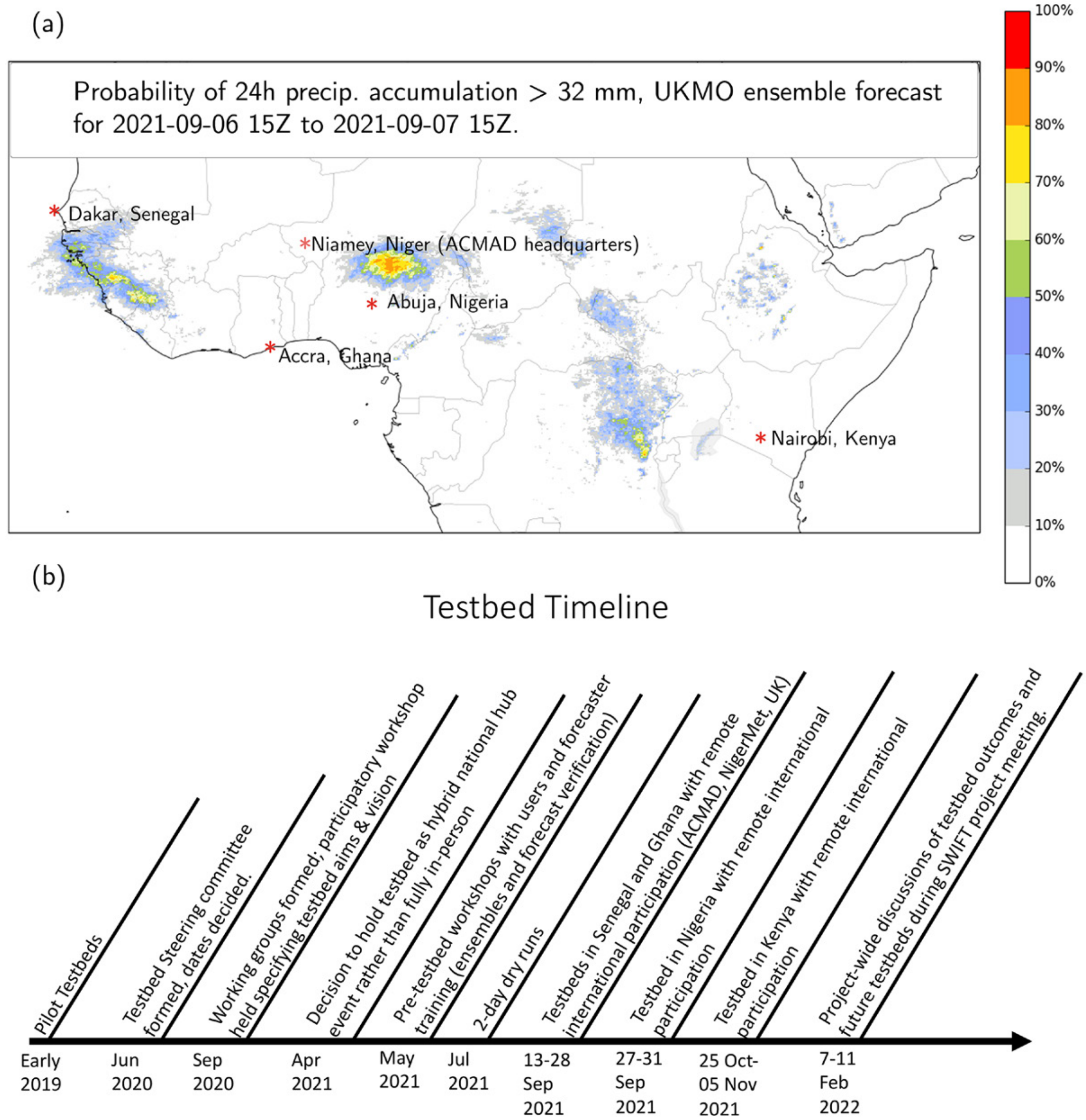

Fig. 1. (a) Example probability of rainfall accumulation map from the Met Office regional convection-permitting ensemble forecast system, with the locations of the African testbed participants indicated by red stars. (b) Timeline of testbed preparation and delivery (see appendix D for details on testbed preparation).

high-impact weather (HIW, here meaning heavy rain, strong winds, dust, and hail for land, marine, and lake environments) forecasts and nowcasts to participating users following a predefined template; they also discussed the forecasts face to face with users throughout the testbed.

Daily operations. Daily operations, summarized in Table 1, varied across location, but the broad focus was synoptic forecasting in the morning, with a synoptic briefing held at about 1400 local time. The synoptic briefing was held for 1 h via videoconference, allowing SWIFT members to get a window into each testbed, and covered the synoptic forecast for the region and the national high-impact weather forecasts. This was followed by evaluations of the previous day's forecasts using station data and IMERG early run rainfall observations (Huffman et al. 2015) and discussions of any technical or logistical problems. After the synoptic briefing, testbed forecasters delivered the aforementioned HIW forecasts to users; they also discussed the forecasts face to face with users throughout the testbed.

Forecasters dedicated to nowcasting began in in the afternoon, with nowcasts issued to users every 2 h. Forecast verification and evaluation occurred in parallel, with scientists carrying our objective verification of the global operational Met Office Unified Model (MetUM) forecast and the convection-permitting deterministic MetUM and other researchers carrying out subjective evaluation of the forecasts with users.

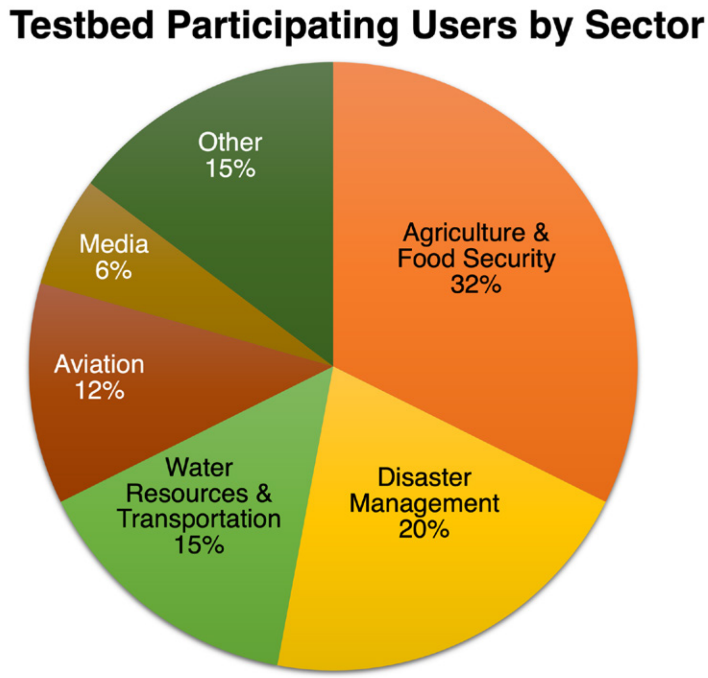

Fig. 2. Breakdown by sector of the 34 participating users across Senegal, Ghana, Nigeria, and Kenya in the testbed. The "Other" category is one of each of the following: insurance, health, community organization, climate NGO, and transport.

For each location the forecasting was done by a mix of on-duty forecasters, forecasters who had had some duties relieved, and scientists employed at the in-country university or operational center, with individuals specializing in synoptic forecasting or nowcasting as much as logistically possible. Because the testbed was held in the home cities of each participating forecasting center, participants still had ordinary work and life obligations, and it was generally not possible for them to work night shifts. The operational centers do have a forecaster working overnight, but this person had too many usual duties to take on testbed duties as well. Therefore, nowcasting typically stopped at 1800 local time, with a few exceptions (when a big storm was expected) where a testbed nowcaster would issue nowcasts from home into the night. This was enabled by, and highlights the benefit of, the products needed for nowcasting being available online.

During the testbed, users, forecasters, and scientists worked together in the same room on most days. Users and scientists attended the daily synoptic briefings. Users gave regular feedback on the forecasts and nowcasts and were given the chance to learn more about both the constraints and possibilities for operational forecasting. The regular interaction fostered stronger relationships between users and forecasters, building trust that is needed for uptake of forecast products. It also gave time for forecasters and scientists to explain technical terms

Table 1. Summary of daily and weekly timetable during the testbed.

Daily events	Daily event details	Weekly events	Weekly event details
Synoptic and HIW forecasting	Morning, in person, 2–5 people per location	Opening ceremony, final training	Day 1, hybrid, 10–50 participants
Synoptic and HIW brief, issuing of HIW forecast to users	Around 1300 local time, virtual, ranged from about 5–30 participants	Midpoint evaluation meeting	Around day 7, hybrid, about 10–50 participants
Nowcasting, with nowcasts issued to users every 2 h	Afternoon and early evening, in person (with virtual delivery of nowcasts to users if needed), 1–5 people per location	Final evaluation meeting	Around day 14, hybrid, 10–50 participants
Evaluation	Concurrent with other activities, in person with support from remote partners, about 1–5 people per location	Closing ceremony	Final day, hybrid, 10–50 participants

to help users better understand forecasts—in Senegal about 30 min day^{-1} were dedicated to this, with much of that time dedicated to discussion of probability and uncertainty in forecasts.

A key role in the testbed was that of the scientific secretary. At each primary testbed location, this person was tasked with uploading all documents used for the weather briefs and all products issued to users to a shared repository. They also filled in a daily sheet, stored in the cloud, naming the forecasters on duty, any significant weather events from the day, and any other details of note.

Synoptic and high-impact forecasting. Testbed forecasters carried out synoptic forecasting and HIW forecasting using bespoke products generated as part of the African SWIFT program, following a standard operating procedure (SOP) developed for the testbed (Clarke and Ansah 2022). They then delivered the synoptic forecasts to other testbed participants primarily through the daily synoptic brief, while for HIW forecasting they followed a predefined template to issue the HIW forecast to users.

Synthetic analysis and forecast charts. Testbed planners wrote new algorithms to automatically generate so-called synthetic charts for West Africa and East Africa using data from the National Centers for Environmental Prediction Global Forecast System. These charts are made through objective identification of key features forecasters use such as the African easterly jet. Synthetic charts enable forecasters to quickly view the relative timing and locations of multiple important features to diagnose the likelihood of convective storms. In Fig. 3, the example synthetic chart shows fairly high convective available potential energy and moderate convective inhibition over eastern Senegal and southern Mauritania and Mali (circled in blue), where the African easterly jet and associated low-level shear are strong and the intertropical discontinuity is just to the north. However, the low monsoon depth and southerly position of the midlevel dry intrusion suggest lack of moisture availability for convection. Experienced forecasters can use these features to make quick judgments about the likelihood of storms more readily than for standard forecast model output.

Standard methods of synthetic analysis and forecasting already existed for West Africa (Lafore et al. 2017). For East Africa, new methods were developed by SWIFT researchers in collaboration with SWIFT forecasters at the Kenya Meteorological Department. The synthetic charts were made by downloading GFS data and plotting the features using pre-agreed diagnostic variables, described in appendix A. This was all automated prior to the testbed, and the resulting plots were automatically made available to participants via the web. All required scripts are on GitHub (https://doi.org/10.5281/zenodo.5575865).

Convection-permitting ensemble forecasts. Along with synthetic charts, testbed forecasters used both global and convection-permitting ensemble simulations to issue their 24-h high-impact weather forecasts. The technical details of the ensembles are described in appendix C. Such convection-permitting simulations have been shown to add skill relative to a parameterized global model, especially in the afternoon at the time when most storms initiate. They therefore provide synergy with nowcasting, which is most useful for existing storms and generally unable to predict initiation, although the ensemble is underspread (Cafaro et al. 2021) like many other convection-permitting ensemble systems (e.g., Schwartz et al. 2014; Loken et al. 2019; Porson et al. 2019).

The scripts used to generate the synthetic charts also automatically produced PowerPoint files, which included the synthetic charts and the most-used fields from the ensembles, namely, postage stamps, probability of threshold exceedance plots, and meteograms of surface variables for a variety of locations requested by forecasters and users. The types of plots,

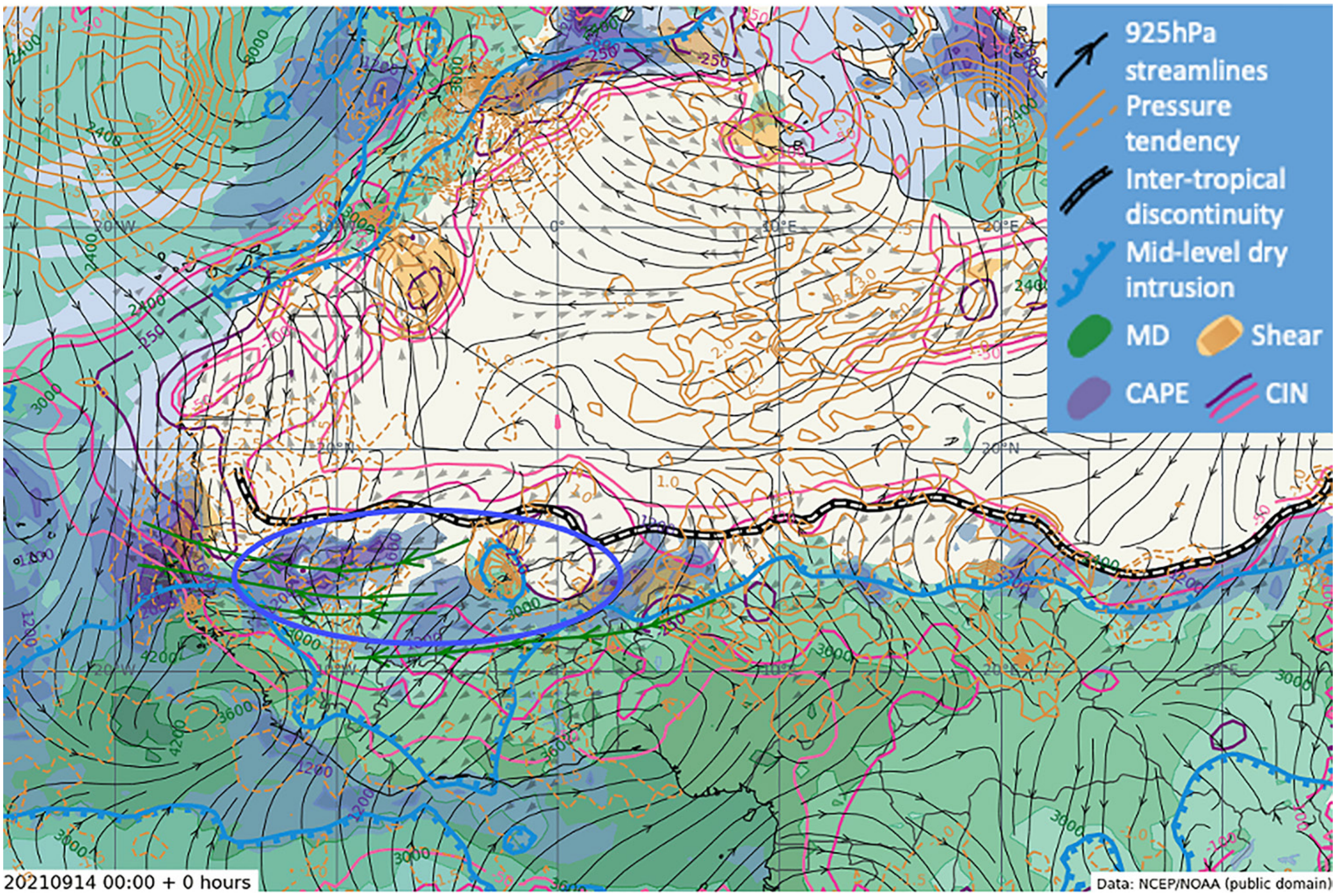

Fig. 3. Sample synthetic chart used by West African forecasters during the testbed. Abbreviations in legend are as follows: MD, monsoon depth; CAPE, convective available potential energy; CIN, convective inhibition. The region discussed in the text is circled in blue.

fields, thresholds, and accumulations were chosen through discussion with forecasters and users during the pre-testbed planning described in appendix D.

An example of the probability of threshold exceedance plots is shown in Fig. 4, where we see the models forecasting 24-h rainfall accumulations exceeding 128 mm in several locations with probability greater than 80%. While such high rainfall accumulations do occur in West Africa, the convection-permitting MetUM has a positive rainfall bias and a too-low ensemble spread (Cafaro et al. 2021), both of which contribute to a positive bias in the threshold exceedance plots. This underscores the need for synergy between operations-aimed research and forecaster training in the implementation of new products: forecasters need to know how to interpret the products given their biases, but some of that knowledge comes from systematically evaluating

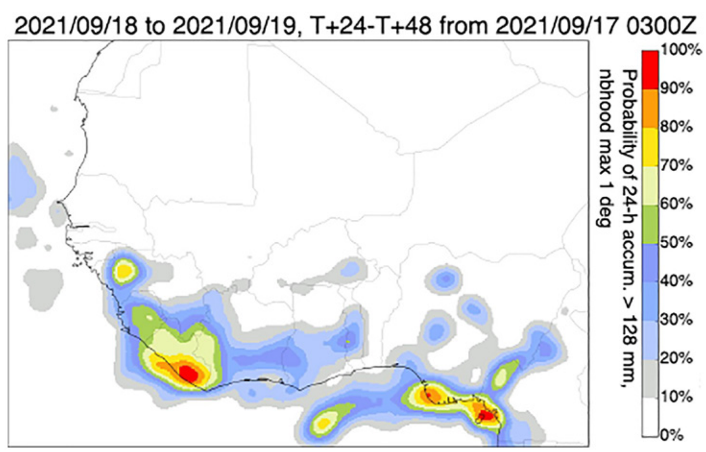

Fig. 4. Example of a convection-permitting ensemble product provided to forecasters during the testbed. The neighborhood method is described in Cafaro et al. (2021) following Roberts and Lean (2008).

the products in an operational environment. This testbed was a start to this procedure for convection-permitting ensembles, but to fully develop operational guidance for use of these products would likely require a testbed dedicated entirely to their evaluation.

The testbed synoptic forecasters used the synthetic charts and ensemble products to issue daily 24-h HIW forecasts to users (Fig. 5). These products indicated the qualitative risks of heavy rain, strong winds, dust, and hail due to meteorological hazards. The risk table used was adapted from similar risk color schemes used in weather and climate services in Africa. The synoptic SOP (Clarke and Ansah 2022) specified the steps taken for all aspects of the synoptic forecast, from assessing the synthetic charts to producing the HIW product.

Nowcasting. The primary satellite-based nowcasting products used in the testbed were the Nowcasting Satellite Application Facility (NWC-SAF, https://www.nwcsaf.org/). NWC-SAF software takes Meteosat and numerical weather prediction (NWP) data to produce a variety of products for nowcasting, including estimates of surface rain rates from convection and forward extrapolations of many products. By default, in NWC-SAF codes such extrapolations are for 30 min, but SWIFT has shown nowcast skill extending to hours (Hill et al. 2020; Burton et al. 2022). The latter paper shows that on average there is skill at a 4-h lead time on 200 km, but skill is higher in evenings and overnight when large mature storms dominate.

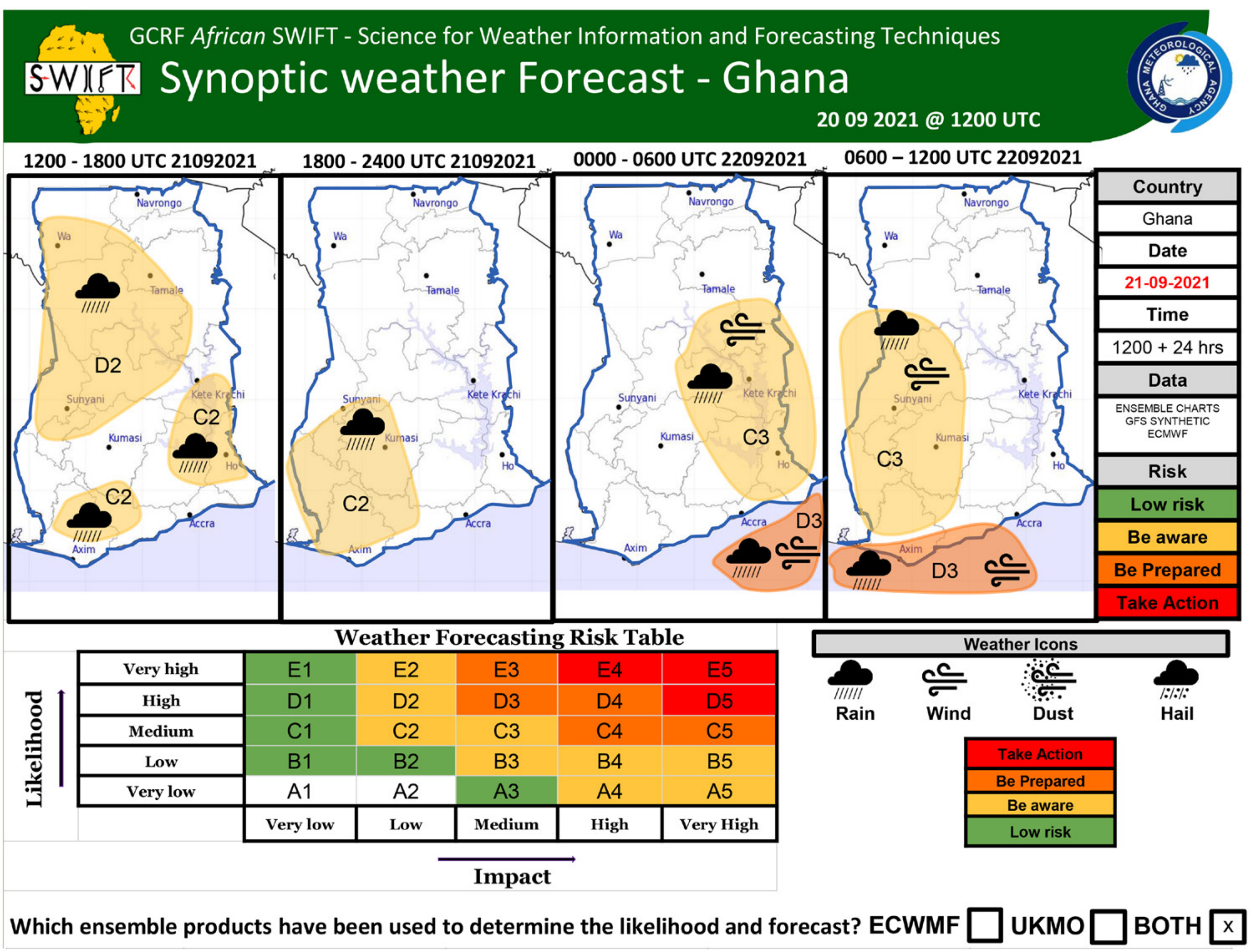

Fig. 5. Example high-impact weather forecast issued to Ghana users during the testbed. These also included regional text forecasts, which have been cropped out for brevity.

Similarly, large mature storms with steady motion are expected to be more predictable than average. The range was therefore extended to 5 h, as long-lead-time products with appropriate uncertainties were perceived as useful.

To facilitate the use of NWC-SAF nowcasting products during the testbed, SWIFT scientists developed an online catalog (https://science.ncas.ac.uk/swift/, Fig. 6). Products from the NWC-SAF software are generally available on the SWIFT catalog with a latency of 30 min. Hosted on the

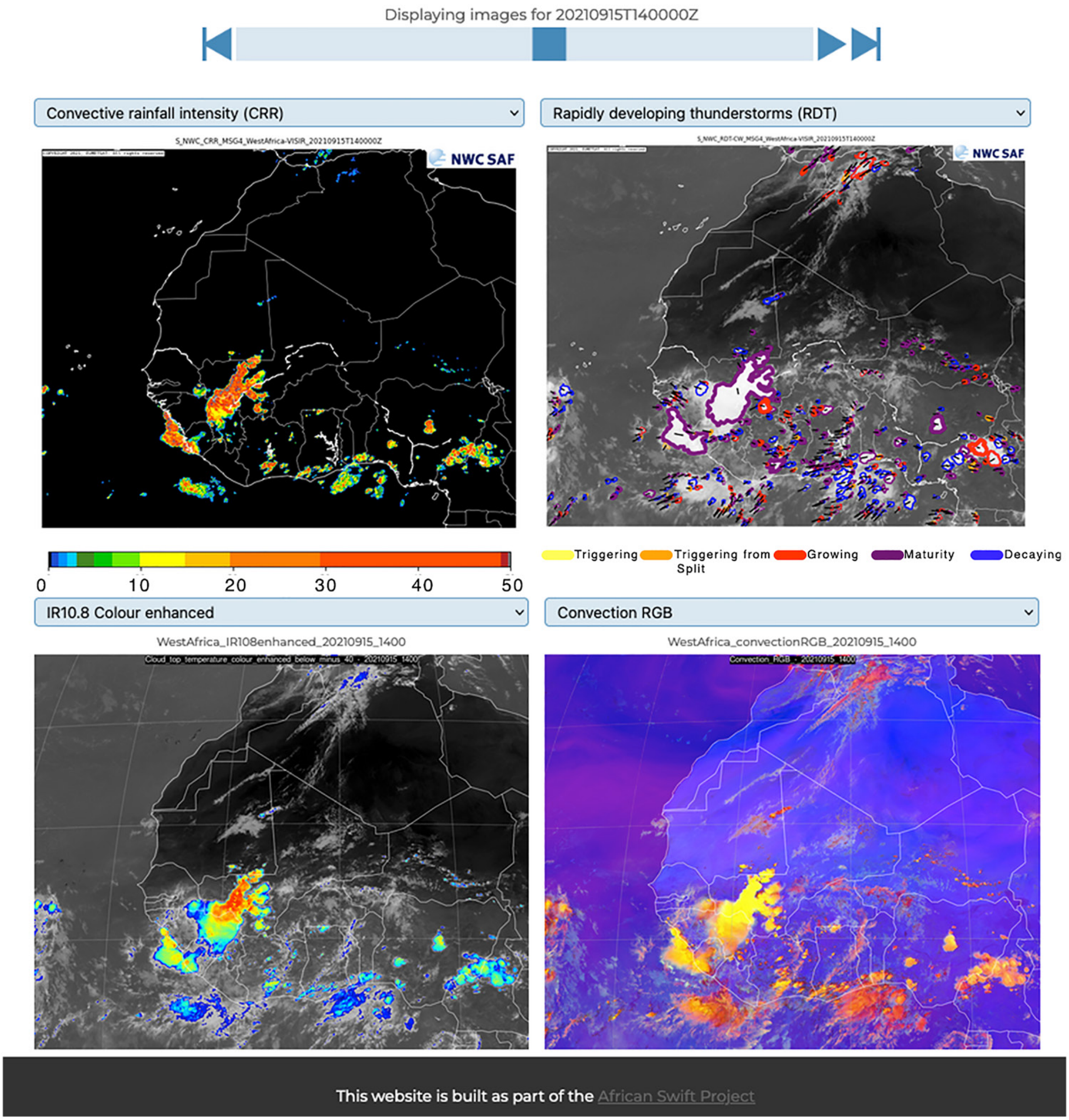

Fig. 6. Screenshot of one possible configuration of the SWIFT nowcasting catalog (drop-down menus offer many possible configurations). (top left) NWC-SAF convective rainfall intensity product (mm h^{-1}), (top right) NWC-SAF Rapidly Developing Thunderstorm product; (bottom right) convection RGB; (bottom left) color-enhanced infrared. All data are from the EUMETSAT SEVIRI instrument. Legends have been annotated for legibility.

catalog alongside NWC-SAF products are a variety of NWP and standard satellite images, allowing forecasters to compare different nowcasting information sources in near–real time. Finally, for the Sahel region, additional nowcast products that relate the likelihood of storm propagation to land surface temperature anomalies (Taylor et al. 2022) were used.

The full nowcasting SOP is described in Roberts et al. (2022b). First, a synoptic overview was provided to nowcasters at the start of their shifts, which were timed to cover the most convectively active parts of the diurnal cycle. From the synoptic conditions and the latest nowcast products, nowcasters generated a 6-h outlook consisting of an outlook risk map and a short text summary. They also produced a 0–2-h risk map with an accompanying text summary. An example of the nowcasting product issued to users is shown in Fig. 7.

The estimates of risk require considerable local knowledge and experience from forecasters to translate the varied meteorological situation into risk estimates aimed at specific users. Nowcasters reported in the daily cross-country chart discussions that they improved their estimates of the risk over the course of the testbed due to feedback from users.

In addition to maps, nowcasters produced timelines of risk over the coming hours for several locations in each country. Some locations important to users were selected to have timelines produced for each nowcast, even if there was no weather event predicted, with additional locations chosen based on need. Nowcasters supplemented NWC-SAF products with model-predicted stability indices to predict the meteorological risk for the next 3 h at 30-min increments for each location, entered into color-coded tables, along with a 6-h outlook.

The three products above were collated into a single document distributed to nowcast users, designed to be understood by nonspecialists with information on qualitative risk rather than quantitative rain rates or wind speeds. Nowcasters issued these documents on a rolling basis, with regular 2-hourly updates during normal operation but more frequent updates during times of extreme weather or rapid divergence from predicted conditions. The details of the presentation of the nowcast were decided with users during the pre-testbed planning.

Evaluation during the testbed

Forecast evaluation. Evaluation activities were carried out in parallel with the daily forecasting activities. Some of this was objective verification, e.g., computation of fractions skill scores (Roberts and Lean 2008) for various configurations of the MetUM over the period leading up to and during the testbed. Mostly, however, the evaluation was subjective or semi-objective involving questionnaires sent to users asking how the forecast affected their decision-making, as well as in-person discussions.

User evaluation. Users who participated responded enthusiastically to the products. Nowcast information had a wide variety of uses beyond predicting severe storms, as demonstrated in Table 2. For example, Senegal nowcasts were issued to a lifeguard agency that provided guidance to beachgoers about the safety of entering the water. The poor rainfall forecast skill in tropical Africa means that these everyday applications of rainfall predictions are rare, but satellite-based nowcasting provided useful, actionable information not normally available to these users. The experience of the testbed strengthened many users' confidence in forecasts received from their national meteorological and hydrological services (NMHSs).

Forecaster and researcher evaluation. At the end of the testbed, participating forecasters and researchers filled in a survey giving feedback on the product templates and on the SOPs. Many forecasters regarded the interactions with users as key to the success of the testbed and argued that such interactions should be brought into regular operations. Participants were asked what practical things would be needed to bring the tools and methods into

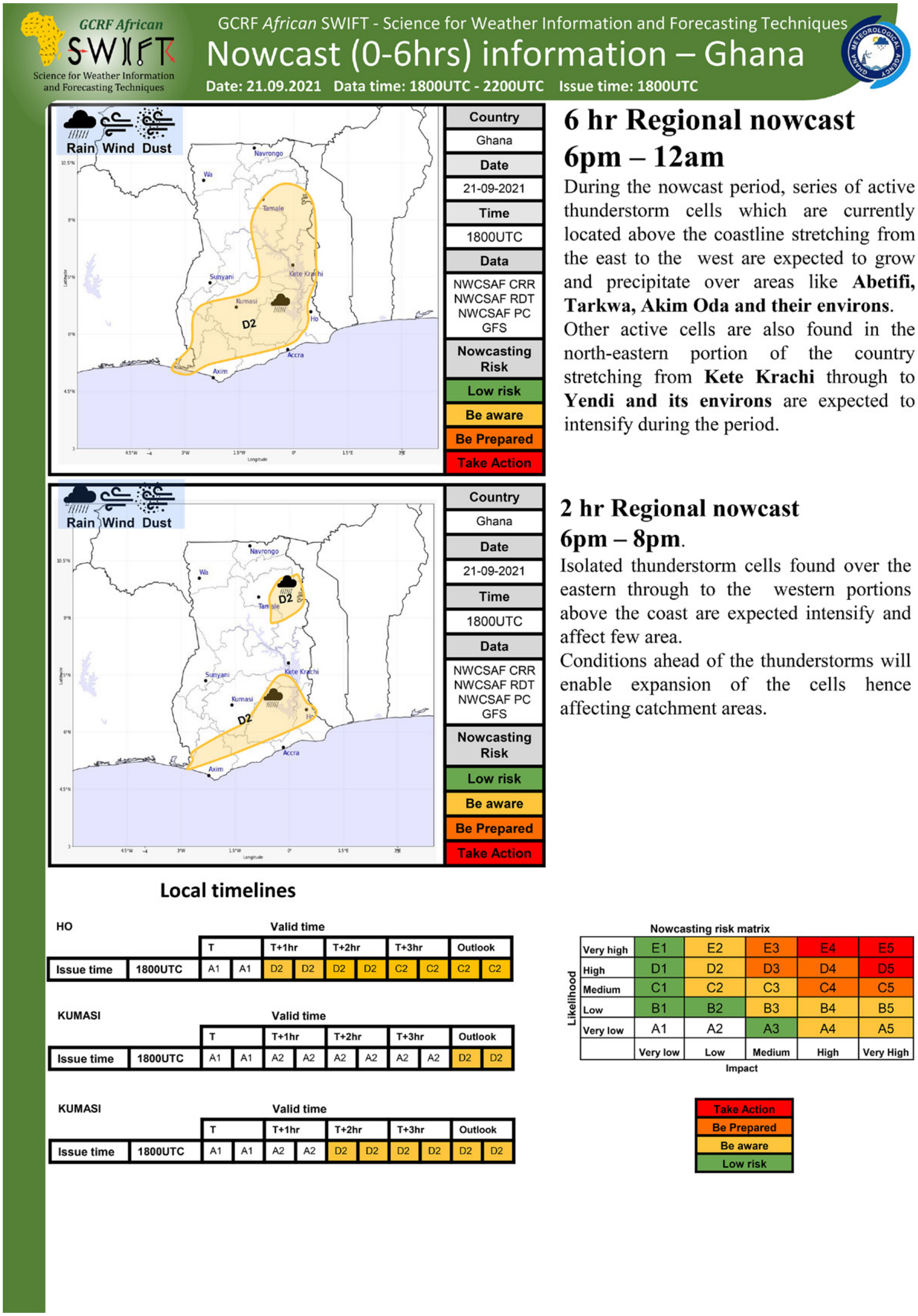

Fig. 7. Example nowcasting product issued to users in Ghana during the testbed.

operational practice. The most named requirements were staff training, more staff time, and reliable data access, with many also mentioning the need for more and improved computing equipment and fast, reliable Internet access.

Some of the most in-depth forecaster feedback was captured in conversation and noted by the scientific secretary or other participants. In conversations several forecasters remarked

Table 2. Some responses from users to an online questionnaire asking "What action did you take based on the nowcast?"

Examples of user actions based on testbed nowcasts
"We had to stop working on a transformer because of the rain [forecast]."
"Asked farmers to stop applying insecticide."
"Dressed with cold protection and didn't bring out my goat to graze."
"I used it to brief some flights I dispatched."
"Stop patrol team from proceeding to sea."
"Informed farmers to continue planting the cocoa seedlings."
"Increased the heat source in my poultry house."
"I informed my people to use sprinklers instead of waiting on rainfall to water their plants."
"Without forecast, I would have panicked expecting heavy rainfall leading to halting/altering planned activities."

that the synthetic charts were easier to interpret than most of their operational products, and that the layering of diagnostics within a single chart was particularly useful. A couple of forecasters remarked that there should have been upper-level fields available, particularly jets, waves, and troughs.

On the ensemble information, forecasters found the information promising but wished for more training on how to interpret it. Forecasters had also found ensemble meteograms difficult to use during pre-testbed exercises, and so they were not used during the testbed. Some forecasters remarked that they found the "poor man's ensemble"—i.e., the use of multiple global model outputs—more useful than an ensemble forecast from a single model, due to the spread being greater.

Forecasters found the satellite-based nowcasting information extremely useful and promising, especially the convective rain rate and rapidly developing thunderstorm product. As discussed below, they requested shorter latency for these products.

Participants supported the benefit of future testbeds in tropical Africa, pointing out how rare it is for forecasters, researchers, and users to work together in the same room. They cited both the learning and training that occurred for all parties involved and the stronger working relationships built between them. One forecaster summarized this as follows: "When testbeds like these are carried out, it brings innovations, development, capacity building, strengthens networks and also it serves as a platform for learning from each other, so it is worth it to carry out such activities."

Impact and legacy of the African SWIFT testbed

The testbed has facilitated tangible developments in technical infrastructure to support satellite nowcasting in Africa. All African NMHSs in SWIFT have all begun setting up the freely available NWC-SAF application locally. Running NWC-SAF locally gives national meteorological services autonomy in choosing domains, developing and changing algorithms, and ensuring the reliability of their system. For example, the Nigerian Meteorological Agency (NiMet) is developing an algorithm to predict the likelihood of microbursts using information from NWC-SAF and NWP. The primary problem with NWC-SAF is the latency of the product—despite best efforts, it is usually not available until 30–45 min after observation time.

Another barrier to satellite nowcasting in tropical Africa is that the primary time for storms is in the evening and night. While operational centers typically have one person working the overnight shift during the rainy season, additional staffing will be required to carry out proper nowcasting when it is most needed. Additionally, producing the nowcast sheets issued to users was time-consuming, and it would be better to have a tool that allows forecasters to indicate areas of risk but that automates some aspects of the process.

The intensive interactions with users provided forecasters and researchers a wealth of information about what information is useful and actionable and prompted a more formalized approach to impact-based forecasting. For example, Agence Nationale de l'Aviation Civile et de la Météorologie (ANACIM) staff worked with users during the testbed to build maps indicating what magnitude of rainfall, wind speed, and temperature are considered extreme for different regions and sectors. From this they will develop guidance for forecasters on the risk that they should estimate for different storms, depending on location, season, and user sector. ANACIM staff aim to produce a first test of the impact-based forecasts using this guidance for selected sectors and regions by the 2022 rainy season.

The new SOPs for high impact weather forecasting (Clarke and Ansah 2022) and nowcasting (Roberts et al. 2022b) are publicly available and can be adapted for specific locations.

African SWIFT's testbeds—the pilot testbed, the testbed described here, and the subseasonal-to-seasonal time-scale testbed described in Hirons et al. (2021)—were the first of their kind in tropical Africa, bringing new NWP and nowcasting tools and leading to significant learning among the team of users, forecasters, and researchers. It was a leap in progress in developing strong links between research and operations, successfully co-producing new products with users, entraining a greater number of forecasters and researchers, and streamlining the operations through new SOPs. Additionally, the SWIFT testbed described here prompted new research questions among participating scientists, highlighting the benefit of testbeds not just for research-to-operations but also for operations-to-research.

To make further advances, we advocate for future testbeds to be held regularly in Africa, led by Africans. We recommend that future African nowcasting testbeds should improve on the SWIFT testbed and prioritize carrying out work at least partially into the night in order to maximize the benefit. Future testbeds could also build on SWIFT by developing structured, consistent methods for evaluating impact-based forecasts and nowcasts, which requires timely, accurate, and comprehensive information about actual impacts. Furthermore, ongoing testbeds should have reliable funding so that they are held not on a project basis but as part of the normal calendar of national, regional, or pan-African activities supporting the development of weather and climate services. These future testbeds will help pave the way for ongoing capability building in tropical African weather prediction.

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Data availability statement. Satellite data presented in figures can be obtained freely from EUMETSAT. The NWC-SAF software can be obtained for free from NWC-SAF and run on real-time or historical EUMETSAT data. Synoptic forecast data was obtained from the National Centers for Environmental Prediction Global Forecast System operational forecast. Met Office convection-permitting ensembles were run only for the testbed and are not publicly available; data enquiries may be made to the Met Office.

Appendix A: Testbed institutions

Table A1 lists participating institutions for each testbed location and for remote participants. The primary locations were where the testbed was held, in person. The remote participants supported testbed activities and led or contributed to testbed planning and evaluation. Remote participants were 1) African Centre of Meteorological Applications for Development (ACMAD, pan-African organization), Niamey, Niger; 2) University of Leeds, Leeds, United Kingdom; 3) Met Office, Exeter, United Kingdom; 4) University of Reading, Reading, United Kingdom; 5) Centre for Ecology and Hydrology, Wallingford, United Kingdom; and 6) Niger Meteorological Agency, Niamey, Niger.

Table A1. Participating organizations in primary testbed locations.

Country	Operational Centre	University
Senegal	Agence Nationale de l'Aviation Civile et de la Météorologie (ANACIM)	Université Cheikh Anta Diop (UCAD)
Ghana	Ghana Meteorological Agency (GMet)	Kwame Nkrumah University of Science and Technology (KNUST)
Nigeria	Nigerian Meteorological Agency (NiMet)	Federal University of Technology Akure (FUTA)
Kenya	Kenya Meteorological Department (KMD)	University of Nairobi (UoN)

Appendix B: List of products used

The synthetic charts all used data from GFS analysis and forecasts. The diagnostics used are listed in Table B1. For a full list of diagnostic definitions, see Clarke and Ansah (2022).

The primary ensemble products used during the testbed are listed in Table B2. These were for forecasts at lead times ranging from t + 24 h to t + 72 h. For a full list of products, contact the corresponding author.

The most used satellite-based nowcasting products are listed in Table B3. Some additional NWC-SAF products were provided but rarely or never used; for a full list, contact the corresponding author.

Table B1. Diagnostics produced for synthetic charts used in synoptic forecasting.

Name and domain	Diagnostics shown
Pan Africa pressure systems; 60°S–60°N, 60°W–90°E	Streamlines and wind speed at 925 hPa; mean sea level pressure, pressure tendency; midtropospheric dry intrusion
West Africa convective; 0°–40°N, 15°W–35°E	Streamlines at 925 hPa; sea level pressure tendency; intertropical discontinuity; midlevel dry intrusion; moisture depth; shear; convective available potential energy; convective inhibition
West Africa low-level; 0°–40°N, 15°W–35°E	Streamlines and wind speed at 925 hPa; mean sea level pressure, pressure tendency; intertropical discontinuity
West Africa jets and waves; 0°–40°N, 15°W–35°E	African easterly jet; African easterly waves; moisture depth; jets at 850 hPa; vorticity at 850 hPa
East Africa convective; 15°S–22°N, 18°–52°E	Streamlines at 700 hPa; sea level pressure tendency; midlevel dry intrusion; moisture depth; convective available potential energy; convective inhibition
West Africa low-level; 15°S–22°N, 18°–52°E	Streamlines at 700 hPa and 10 m; mean sea level pressure, pressure tendency; midlevel dry intrusion; relative humidity at 700 hPa

Table B2. Ensemble diagnostics used in the testbed.

Type of plot	Diagnostics used
Postage stamps	24-h rainfall accumulation; 3-h rainfall accumulation
Probability of threshold exceedance using the neighborhood method (Roberts and Lean 2008)	24-h rainfall accumulation with thresholds of 32, 64, and 128 mm; 3-h rainfall accumulation with a threshold of 16 mm

Table B3. List of nowcasting products used.

Product type	Diagnostics
Standard satellite products	10.8-μm enhanced IR, 0.6-μm visible, convection RGB, dust RGB
NWC-SAF products	Convective rainfall intensity (with forward extrapolation); rapidly developing thunderstorms (with forward extrapolation); chance of precipitation, cloud mask, cloud-top temperature
Land surface temperature products for Sahel (Taylor et al. 2022)	Land surface temperature anomalies; convective cores; land surface modulation factor

Appendix C: Ensemble specifications

The global ensembles were the operational Met Office Global and Regional Ensemble Prediction System (MOGREPS-G) and the publicly available ensemble forecasts from the European Centre for Medium-Range Weather Forecasts.

Convection-permitting ensemble forecasts were produced for the testbed using the MetUM Version 11.7 with the RA2T science configuration (as in Steptoe et al. 2021; Cafaro et al. 2021). The horizontal resolution was about 8.8 km at the equator and the domain was 8°S–28°N, 20°W–54°E. The ensemble model runs were every 12 h, initialized at 0300 and 1500 UTC, and run to a 72-h forecast, with 18 ensemble members.

Appendix D: Planning the testbed

Pilot testbed. African SWIFT held a pilot testbed in two phases in early 2019, hosted by the Kenya Meteorological Department in Nairobi. The purpose of the pilot testbed was for the African SWIFT participants—who had previously never participated in a testbed—to gain some experience in advance of the final testbed, which was the focus of this paper and which was held toward the end of the SWIFT program. The pilot testbed was described in detail in a report by Fletcher et al. (2019). It was agreed among testbed participants that holding a pilot testbed was key to the success of the final testbed for the training and preparation it offered.

Pre-testbed workshops and training. Testbed preparation incorporated several training and other preparation events for participating forecasters (Fig. 1b). SWIFT researchers developed and carried out a 5-day virtual training for forecasters on convection-permitting and ensemble forecasting as well as a week-long training on objective methods of forecast verification. These events not only trained participants on concepts and tools used in the testbed, but also established—or built on existing—working relationships between forecasters and scientists who participated in the testbed.

User engagement and coproduction of products. In the months leading up to the testbed, each African partner country held a workshop with users focusing on key concepts in forecast use, led by SWIFT experts in user engagement with weather and climate information. The most important concepts covered were the use of probabilities in weather forecasting, an introduction to ensemble and nowcasting products, and exercises designed to strengthen confidence in appropriate forecast use within specific decision-making contexts.

At the end of the pre-testbed users' workshop, users answered a list of questions designed to help determine the timing, frequency, and locations they required from products communicating short-term (0–24 h) likelihood of impactful weather (rain, winds, dust, and hail). From the answers given by users, the testbed planners developed templates of products that would be given to users regularly during the testbed. These products included a near-term (24 h) high-impact weather (HIW) forecast as well as regular nowcasts (mainly 0–3 h), both of which were issued for the country as a whole and for specific locations of interest. Testbed planners made a beta version of these template products for a 2-day dry-run in late July 2021, during which users received the forecast products once per day and gave feedback on both the content and presentation of the products, mainly through video-conference discussions and online surveys. From this feedback, testbed planners produced the final versions of the templates.

Training and review days. The first day of the testbed was a training day focused on specific tools unfamiliar to most participating forecasters, particularly the satellite-based nowcasting tools and the ensemble prediction diagnostics. All participants familiarized themselves with the nowcasting and synoptic forecasting SOPs and the details of the methods for producing the forecast products they would be delivering to users.

Cross-country reviews of testbed procedures and products were held halfway through the testbed and again at the end of the testbed. The ongoing discussions between users, researchers, and forecasters that were held locally in each testbed were summarized in the evaluation sessions, as were the outcomes of user questionnaires. Forecasters and researchers also gave feedback on the template products and operating procedures. The midpoint evaluation was an opportunity to refine the SOPs and products sent to users. Given the experimental nature of testbeds, it is expected that some things will go wrong. Allowing time within the testbed to self-correct ensures that lessons can be drawn from problems.

Developing testbed products and methods. Many members of SWIFT contributed to testbed planning, which was overseen by a small steering committee with separate working groups for specific aspects of the testbed: synoptic forecasting, nowcasting, user engagement, and scientific software development. Planning spanned a period of about 12 months, including development of testbed SOPs, user engagement, and the development of needed technical infrastructure. Because the leaders of each working group were experts in their area, the working groups had a high level of autonomy in their planning, with regular meetings to ensure consistency of plans across the working groups and that the objectives were being met. Almost all testbed planning was done online.

As described above, the testbed working groups developed or made accessible a suite of weather forecasting products not previously used operationally in the four participating African countries. They wrote SOPs for synoptic forecasting and nowcasting. Most operational centers involved in the SWIFT testbed do not have formalized SOPs, but those developed for the SWIFT testbed are designed to be taken up operationally, with modifications as needed. The nowcasting SOPs were modeled after those carried out by the South African Weather Service, who use NWC-SAF products to supplement radar-based nowcasting. The synoptic SOP was designed to match as closely as possible with the SOPs currently used operationally by the forecasting centers of ACMAD (pan-Africa), NiMet (Nigeria), KMD (Kenya), GMet (Ghana), and ANACIM (Senegal).

The synoptic forecasting and nowcasting working groups relied on previous experience from the pilot testbed to determine timings for briefings and the amount of time that should be spent on each aspect of the SOP, accounting for the availability of data and other constraints.

References

Bernardet, L., and Coauthors, 2015: Community support and transition of research to operations for the hurricane Weather Research and Forecasting Model. *Bull. Amer. Meteor. Soc.*, **96**, 953–960, https://doi.org/10.1175/BAMS-D-13-00093.1.

Burton, R. R., and Coauthors, 2022: Satellite-based nowcasting of West African mesoscale storms has skill at up to 4-h lead time. *Wea. Forecasting*, **37**, 445–455, https://doi.org/10.1175/WAF-D-21-0051.1.

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.

Clarke, S. J., and S. O. Ansah, 2022: Synoptic forecasting standard operating procedure for African SWIFT Testbed 3. University of Leeds Rep., 7 pp., https://doi.org/10.48785/100/100.

Fletcher, J. K., and Coauthors, 2019: GCRF African SWIFT Testbed 1. University of Leeds Rep., 31 pp., https://doi.org/10.5518/100/73.

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

Hirons, L., and Coauthors, 2021: Using co-production to improve the appropriate use of sub-seasonal forecasts in Africa. *Climate Serv.*, **23**, 100246, https://doi.org/10.1016/j.cliser.2021.100246.

Huffman, G. J., D. T. Bolvin, D. Braithwaite, K. Hsu, R. Joyce, C. Kidd, E. J. Nelkin, and P. Xie, 2015: NASA Global Precipitation Measurement Integrated Multi-satellitE Retrievals for GPM (IMERG). Algorithm Theoretical Basis Doc., version 4.5, 26 pp., http://pmm.nasa.gov/sites/default/files/document_files/IMERG_ATBD_V4.5.pdf.

Jedlovec, G., 2013: Transitioning research satellite data to the operational weather community: The SPoRT Paradigm. *IEEE Geosci. Remote Sens. Mag.*, **1**, 62–66, https://doi.org/10.1109/MGRS.2013.2244704.

Lafore, J. P., and Coauthors, 2017: West African synthetic analysis and forecast: WASA/F. *Meteorology of Tropical West Africa: The Forecasters' Handbook*, John Wiley and Sons, 423–451.

Loken, E. D., A. J. Clark, M. Xue, and F. Kong, 2019: Spread and skill in mixed- and single-physics convection-allowing ensembles. *Wea. Forecasting*, **34**, 305–330, https://doi.org/10.1175/WAF-D-18-0078.1.

Parker, D. J., and Coauthors, 2022: The African SWIFT Project: Growing science capability to bring about a revolution in weather prediction. *Bull. Amer. Meteor. Soc.*, **103**, E349–E369, https://doi.org/10.1175/BAMS-D-20-0047.1.

Porson, A. N., S. Hagelin, D. F. Boyd, N. M. Roberts, R. North, S. Webster, and J. C. Lo, 2019: Extreme rainfall sensitivity in convective-scale ensemble modelling over Singapore. *Quart. J. Roy. Meteor. Soc.*, **145**, 3004–3022, https://doi.org/10.1002/qj.3601.

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.

Roberts, A. J., and Coauthors, 2022a: Nowcasting for Africa: Advances, potential and value. *Weather*, **77**, 250–256, https://doi.org/10.1002/wea.3936.

——, and Coauthors, 2022b: GCRF African SWIFT Nowcasting Standard Operating Procedure (SOP). University of Leeds Rep., 12 pp., https://doi.org/10.48785/100/96.

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.

Schwartz, C. S., G. S. Romine, K. R. Smith, and M. L. Weisman, 2014: Characterizing and optimizing precipitation forecasts from a convection-permitting ensemble initialized by a mesoscale ensemble Kalman filter. *Wea. Forecasting*, **29**, 1295–1318, https://doi.org/10.1175/WAF-D-13-00145.1.

Shao, H., and Coauthors, 2016: Bridging research to operations transitions: Status and plans of community GSI. *Bull. Amer. Meteor. Soc.*, **97**, 1427–1440, https://doi.org/10.1175/BAMS-D-13-00245.1.

Steptoe, H., N. H. Savage, S. Sadri, K. Salmon, Z. Maalick, and S. Webster, 2021: Tropical cyclone simulations over Bangladesh at convection permitting 4.4 km & 1.5 km resolution. *Sci. Data*, **8**, 62, https://doi.org/10.1038/s41597-021-00847-5.

Taylor, C. M., and Coauthors, 2022: Nowcasting tracks of severe convective storms in West Africa from observations of land surface state. *Environ. Res. Lett.*, **17**, 034016, https://doi.org/10.1088/1748-9326/ac536d.

Vogel, P., P. Knippertz, A. H. Fink, A. Schlueter, and T. Gneiting, 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.