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Improved sub-seasonal forecasts to support preparedness action for meningitis outbreak in Africa

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ABSTRACT

West African countries are hit annually by meningitis outbreaks which occur during the dry season and are linked to atmospheric variability. This paper describes an innovative co-production process between the African Centre of Meteorological Applications for Development (ACMAD; forecast producer) and the World Health Organisation Regional Office for Africa (WHO AFRO; forecast user) to support awareness, preparedness and response actions for meningitis outbreaks. Using sub-seasonal to seasonal (S2S) forecasts, this co-production enables ACMAD and WHO AFRO to build initiative that increases the production of useful climate services in the health sector. Temperature and relative humidity forecasts are combined with dust forecasts to operationalize a meningitis early warning system (MEWS) across the African meningitis belt with a two-week lead time. To prevent and control meningitis, the MEWS is produced from week 1 to 26 of the year. This study demonstrates that S2S forecasts have good skill at predicting dry and warm atmospheric conditions precede meningitis outbreaks. Vigilance levels objectively defined within the MEWS are consistent with reported cases of meningitis. Alongside developing a MEWS, the co-production process provided a framework for analysis of climate and environmental risks based on reanalysis data, meningitis burden, and health service assessment, to support the development of a qualitative roadmap of country prioritization for defeating meningitis by 2030 across the WHO African region. The roadmap has enabled the identification of countries most vulnerable to meningitis epidemics, and in the context of climate change, supports plans for preventing, preparing, and responding to meningitis outbreaks.

Practical implications

During the last two decades, the influence of climate and its variability on certain diseases has been well documented. Many studies have shown a clear link between the occurrence of meningitis epidemics and the intra-seasonal variability of climate and environmental conditions in Sub-Saharan Africa. It is now urgent to operationalize this scientific understanding by producing useful climate information services to support early warning and preparedness in the fight against meningitis outbreaks. Therefore, this timely paper describes the first example of an operational weather-meningitis forecast over Africa. These new meningitis vigilance maps have been co-produced by a pan-African climate centre (ACMAD; African Centre of Meteorological Applications for Development) with the African branch of the World Health Organisation (WHO AFRO) to support the response to meningitis outbreaks across Africa.

By combining longer-term weather forecasts with existing meningitis vigilance, this study has extended the warning of likely meningitis outbreaks across Africa by two weeks. Crucially this

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gives time to take life-saving preparedness action in regions predicting epidemics. Given the known links between meningitis outbreaks and temperature, humidity and surface dust concentrations, this study combines forecasts of these environmental variables to generate an epidemic risk map across the African meningitis belt. Epidemic risk maps for one and two weeks ahead are generated from defined and tested thresholds on climatic and environmental variables.

The evaluation of these new epidemic risk map forecasts shows them to be reliable and actionable. Firstly, sub-seasonal forecasts have high skill to predict atmospheric conditions associated with the epidemics in the African meningitis belt. Secondly, warning levels based on forecasted atmospheric conditions agree with observed meningitis cases across the region. These results show that the thresholds used on environmental variables are well suited for predicting the risk of meningitis across Africa.

This co-production has strengthened the collaboration between the two institutions on the integration of environmental and climate risks into the new WHO AFRO's agenda on its strategy to defeat meningitis by 2030. Based on this study, a road map which prioritizes countries that should receive more support to eradicate meningitis has been established. This collaboration will be reinforced by the development of new weather and climate services for other climate sensitive diseases (Malaria, Cholera, Rift Valley Fever) across Africa.

Data availability

The data that has been used is confidential.

Introduction

Meningitis is a deadly and debilitating disease that hits several countries in Africa every year. It remains a major public health concern in Sub-Saharan Africa, especially in the twenty-six countries of the African Meningitis Belt (AMB), which extends from Senegal to Ethiopia (Greenwood, 1999) (Fig. 1). Zhao et al., 2018 found that the meningitis outbreaks in the belt spread from west to east during the period from 2006 to 2016. Meyer and Novak (2017) and Trotter et al., 2017 showed that the introduction of meningitis A conjugate vaccine (MenAfriVac) in the AMB starting from 2010 has led to a significant decrease in the incidence of meningococcal meningitis cases, consequently a reduction in the number of meningitis epidemics, and a change in the bacterial profile of meningitis, with a predominance of meningococcal meningitis C (Sidikou et al., 2016). However, thousands of people, particularly children under five years of age, are still affected by this disease every year in Africa. Major sporadic epidemics continue to be recorded in several countries in the central and eastern parts of the AMB.

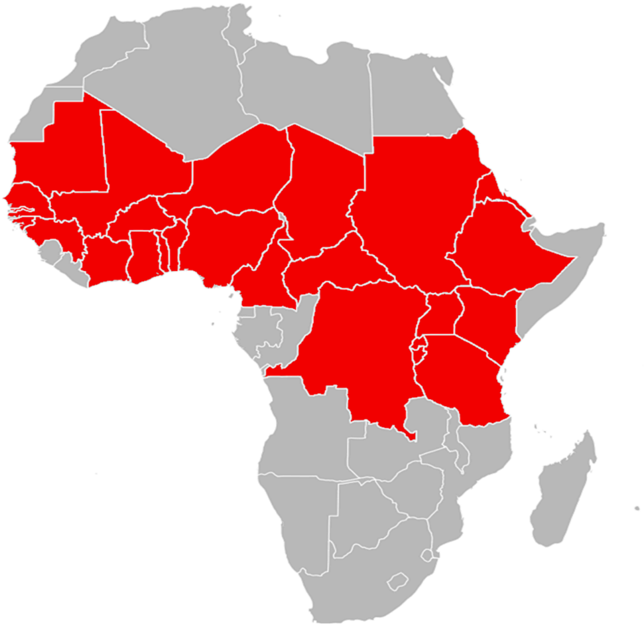

Fig. 1. Map of Africa illustrating country borders. Countries in the African meningitis belt are coloured in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Climate variability and change influences the seasonality of several bacterial and virological diseases across the world. These impacts are expected to be stronger across the Sahel, a vast semi-arid region of Africa separating the Sahara to the north and tropical savannas to the south. The Sahel is characterized by two dry and wet seasons. During the dry season, meningitis epidemics are mostly observed over parts of the continent close to the sources of desert dust inside the dust belt (De Longueville et al., 2013, Dominguez-Rodriguez et al., 2020). Previous studies have established links between climate variability and the occurrence of meningitis in the AMB (Lapeyssonnie, 1963, Yaka et al., 2008, Palmgren, 2009, Roberts, 2010, Dukić et al., 2012, Agier et al., 2013). Molesworth et al., 2003 quantified the evidence of the relationship between environmental variables (absolute humidity, dust and rainfall profiles, land-cover type, and population densities) and the location of meningitis outbreaks. They proposed a model based on environmental variables to identify regions at risk of meningitis epidemics. Sultan et al., 2005, Yaka et al., 2008, and Hayden et al., 2013 showed that meningitis epidemics develop during the dry season (January to June) under Harmattan flow (northerly wind, very dry and warm air) and dusty atmospheric conditions. Nakazawa and Matsueda (2017) used a differential equation for meningitis incidence applied to multivariate log-linear regression analysis to estimate the individual contribution of wind speed, temperature at 2 m, rain and dust to meningitis incidence in Burkina Faso during the 2006–2014 period. They found that the more meteorological variables correlated, the higher the correlation coefficients between the estimated and observed tendency of meningitis incidence. Using univariate and stepwise multi-variate linear regression, Thomson et al., 2006 developed a model to predict the incidence of meningitis based on dust, rainfall, Normalized Difference Vegetation Index (NDVI) and cold cloud duration. Meningitis epidemics are known to be driven by climate metrics and environmental conditions, therefore forecasting the intra-seasonal variability of these atmospheric conditions is key to prevent epidemics in the AMB.

Base on the seasonality of meningitis occurrence, the first tools used to predict meningitis outbreaks were based on statistical models using reported meningitis cases as an input variable (Moore 1992). During the last few decades, particularly during the Meningitis Environmental Risk Information Technologies (MERIT) project funded by the World Health Organisation (WHO), innovative research has been carried out on the link between meningitis epidemics and climate conditions (Thomson et al. 2013). Through MERIT project, it has been demonstrated that the main climate metrics required to develop an early warning system for the meningococcal meningitis outbreaks are near-surface temperature, humidity and dust. These results led to the development of a meningitis warning system by the African Centre of Meteorological Applications for Development (ACMAD). This warning system was based on expert assessment of reanalysis atmospheric conditions from the National Center for Environmental Prediction (NCEP) (Saha et al., 2010) of the previous seven days and dust forecasts from the Barcelona Supercomputer Center (BSC). ACMAD's bulletin identified locations where weather conditions have been favourable for meningitis cases and outbreaks. However, one of the key challenges presented by this bulletin was the one week forecast lead-time. Thereby, there is a need of useful climate services using forecast data to further prevent and manage epidemics related to the meningitis over Africa. This requires a co-production approach to support the development of a useful meningitis early warning system (MEWS). Co-production is a procedural theory used to better understand the way that scientific knowledge is interpreted and exchanged in different sectors for decision-making (Bremer and Meisch, 2017, Vincent et al., 2018, Visman et al., 2018, and Bremer et al., 2019). In the context of climate services, co-production can be defined as the deliberate, collaborative product-development work between climate scientists, or producers of climate data, and practitioners, or weather/climate forecast users, including potential or even 'imagined users' (Porter and Dessai, 2017). Co-production is recognized in climate service policy and has being incorporated into the Global Framework for Climate Services (GFCS) (Hewitt et al., 2012). Using a co-production approach is allowing climate experts to develop useful weather and climate services (Carter et al., 2019). Therefore, climate and health experts need to bring together knowledge, experiences and working practices, to jointly develop a new warning system which aids the management of meningitis outbreaks across Africa. Sub-seasonal forecast data are needed to support the development of this new early warning system.

This study aims to make the most of newly-available real-time forecasts on sub-seasonal timescales to extend the existing early warning system for meningitis outbreaks in the AMB. Trough a co-production approach, this study brings together health-sector forecast users, forecast producers, and scientific researchers, to jointly develop new bespoke forecast tools to extend the lead-time of MEWS by two weeks. Having knowledge of forecasted meningitis occurrence by an extra two weeks has huge potential to improve the forecast-based actions required to be better prepared for outbreaks.

Section 2 describes the data and co-production approach used in this study. Section 3 gives the results of this co-production process including the co-developed solutions for developing the MEWS, the roadmap to defeat meningitis by 2030 in the WHO African region, and forecast verification. Section 4 discusses the lessons learnt from this co-production process.

Data and methodology

Sub-seasonal forecast and reanalysis data

To produce extended early warnings of meningitis outbreaks, we use sub-seasonal forecast data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and 72-hour dust forecasts. Meningitis vigilance maps are generated by combining near-surface temperature, relative humidity, and surface dust concentration forecasts.

S2S forecasts from ECMWF (1.5° x 1.5° horizontal resolution) at 1000 hPa are used to predict the atmospheric conditions which will prevail during the next two weeks. The climate metrics used in this early warning system are weekly mean relative humidity and temperature forecasts. The weekly mean of each variable is computed using the daily mean of the 51 ensemble members. The S2S forecasts are issued every Monday, and are available the following day, and are used for the following week's early warning. Thus, there is a latency of one week between the issued forecast date and the date that they are used. Before using forecasted weekly-mean temperature and specific humidity (used to compute relative humidity), we apply a bias correction to calibrate the forecast data. A linear scaling methodology assuming that the cause of the biases does not change in the future (Guillod et al., (2018), Lafon et al., (2013), Watanabe et al., (2012)), is used in this study. The bias correction in each case is based on the difference in climatology between the previous 20 years of ECMWF reanalysis v5 (ERA5; Hersbach et al., 2020) data which an horizontal resolution of 0.25° X 0.25°, and reforecast data (hindcasts). To increase the number of reforecast ensemble members used, we also use reforecasts that are initialised on the previous and following Thursday from the forecast date. Temperature bias is computed by subtracting the mean difference between reforecasts and ERA5 from the forecasts. Whilst for the specific humidity, the bias is defined as the product of the ensemble-mean forecasts and the fraction between mean ERA5 and reforecasts. Through applying this bias correction, we remove any biases that regularly occur or develop throughout the forecasts. Once bias correcting specific humidity forecasts, we computed relative humidity using the Tetens's formula (Bolton, 1980). Note that when using reforecasts to evaluate forecasts, we apply the same bias correction to all years of reforecasts.

ERA5 hourly temperature and relative humidity at 1000 hPa from 2017 to 2019 period were also used as climatic risk factors to predict occurrence of meningitis to support country prioritisation for the implementation of the framework to defeat meningitis by 2030 in the WHO Africa region. This dataset is also used to evaluate S2S forecasts.

Dust forecasts

On a daily basis, the Barcelona Supercomputer Center produces short-range (3 days) dust forecasts (temporal resolution of 3 h) using several dust models on global and regional domains to support different communities as air quality management, private and public stakeholders providing services, meteorological and regional climate centers in Northern Africa and the Middle East. These data are available on the center's website (https://sds-was.aemet.es/forecast-products/dust-forecasts). Scientists at ACMAD have access to the forecasts and are using the surface dust concentration forecasts from the Copernicus Atmosphere Monitoring Service (CAMS)-ECMWF model (0.4° x 0.4° horizontal resolution) to provide additional climate information for the surveillance of the meningitis outbreaks. CAMS aerosol forecasts are run using as input aerosol analysis from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua and Terra satellites estimated aerosol optical depth (AOD) at 550 nm (Morcrette et al. 2009, Benedetti et al. 2009). The real-time verification of dust forecasts is based on AErosol RObotic NETwork (AERONET) data and available on the BSC website. Surface dust forecasts are interpolated to the horizontal resolution of the forecasted meteorological variables (section 2.1). The weekly mean forecast of surface dust concentrations during the past week is analysed with forecasted climate metrics to generate the vigilance map. This approach is based on Martiny and Chiapello, (2013), who highlighted a latency of one to two weeks between dust events and meningitis outbreaks. The forecasted mean climate during the first week is combined with dust forecasts from the previous week to generate the MEWS for week one. For week two, the forecasted mean climate for that week is combined with the dust forecast at a 3-day lead-time to issue the MEWS.

Co-production approach

The Science for Weather Information and Forecasting Techniques (SWIFT) project aimed to promote sustainable science and capacity building across Africa (Parker et al., 2021). Within the project there was a two-year S2S forecasting testbed (Hirons et al., 2021) which aims to co-produce real-time S2S forecast products to support decision making processes in sectors such as agriculture, energy, health, and disaster risk reduction. The S2S forecasting testbed was a forum where prototype forecast products were co-produced and operationally trialled in real-time. The SWIFT S2S forecasting testbed took advantage of the S2S Real-time Pilot Project (Vitart and Robertson (2018) and developed a co-production process to deliver useful, actionable weather and climate information services to key users. The co-production framework allowed country and regional level discussions between forecaster producers, scientists, and forecast users on co-exploring needs, co-developing solutions, co-delivering solutions and forecast evaluation (Carter et al., 2019, Hirons et al., 2021). In this context, ACMAD, a pan-African institution and partner of the SWIFT project promotes the use of these data to deliver real-time climate information to key users. Therefore, ACMAD's weekly meningitis bulletin is developed for the first time using S2S forecasts in the co-production process framework with the WHO regional office for Africa (WHO AFRO) Intercountry Support Team West

Africa (IST WA) based in Ouagadougou, Burkina Faso which supports countries in the AMB with their fight against meningitis. ACMAD's experts generated the MEWS using S2S forecast data whilst WHO AFRO provided feedback on the assessment of meningitis climate risk factors, and coordinated meningitis prevention, preparedness and response in countries of the AMB. As part of the evaluation and feedback process, a quarterly questionnaire was completed by the WHO AFRO. This questionnaire explored the effectiveness of the co-production approach and enabled user-guided iterations to be incorporated into future forecast development. The evaluation of the forecast products was developed using weekly reported meningitis cases from WHO AFRO. The meningitis cases are reported by country health services. They are the amount of expected and confirmed by laboratory meningitis cases during the whole week. The meningitis cases are collected at district level and sent to the national management office of meningitis disease. The meningitis weekly bulletin can be downloaded in this link: https://www.who.int/csr/disease/meningococcal/epidemiological/en/.

Results

Co-developed solution on meningitis prevention

The development of weather and climate information services for health sector is not as obvious as one thinks because the indices or variables used to define an outbreak in each area are different. The WHO defined two thresholds to monitor the occurrence of meningitis outbreaks (WHO, 2015). An alert threshold is given when three suspected meningitis cases are reported in a week for every 100,000 inhabitants in a given area. Whereas, an epidemic threshold is reached when ten suspected cases of meningitis are reported in a week for 100,000 inhabitants in a given area. Part of the collaboration in this study was to co-produce, with the WHO AFRO and national health services, a useful extended MEWS based on S2S forecast data. Therefore, the results of the Meningitis Environmental Risk Information Technologies (MERIT) project, to call for defining the alert levels corresponding to those of the WHO by choosing to add an orange intermediate threshold corresponding to the yellow alert for the WHO. In this co-production process, we are using temperature, relative humidity and surface dust concentrations forecast data to automate the production of the meningitis early warning systems. The MEWSs are mapped using four vigilance levels (red, orange, yellow and white). Table 1 indicates the criteria used to define each vigilance level. Each criterion is objectively based on temperature, relative humidity and surface dust concentrations, with a qualitative description of each warning level provided below:

- Red vigilance level means that forecasted atmospheric conditions predicted during the week are very favourable for meningitis outbreaks. This warning level recommends that health services strengthen meningitis surveillance and preparedness to respond to outbreaks as appropriate. The red vigilance level is defined when the weekly mean relative humidity is 20% or lower, surface dust concentration is greater or equal to 400 μg m-3, weekly mean temperature greater or equal to 30 °C. These atmospheric conditions are associated with northerly winds.
- Orange vigilance level means that forecasted atmospheric conditions predicted during the week will be favourable for the occurrence of meningitis cases. This vigilance level recommends health services to activate the meningitis surveillance and systems. This alert is given when one of the following criteria in Table 1 is met based on predictions.
- Yellow vigilance level means that forecasted atmospheric conditions predicted are not favourable for the occurrence of meningitis cases. This vigilance is defined when one of the criteria in Table 1 is satisfied. Yellow vigilance indicates that meningitis cases are less likely.
- White vigilance level is defined when the forecasted relative humidity is above 60% whatever the temperature and surface dust concentrations. It means that meningitis cases are not expected.

Table 1

Criteria use to define four levels of vigilance of expected meningitis cases over the African meningitis belt. Red vigilance means that meningitis outbreaks are expected. Orange vigilance indicates that the meningitis cases are very likely. Yellow vigilance indicates that the meningitis cases are less likely. White vigilance indicates that meningitis cases are not expected. These criteria are defined using relative humidity (RH), air temperature (T), and surface dust concentrations (sdc) forecasts from ECMWF. Temperature and relative humidity are extracted at 1000 hPa.

Vigilance levels	Criteria	Air temperature (°C)	Relative humidity (%)	Surface dust concentration (μg/m^{-3})
Red	1	$T \geq 30$	$RH \leq 20$	$sdc \geq 400$
Orange	1	$27 < T < 30$	$RH \leq 20$	$sdc \geq 400$
	2	$T \geq 30$	$RH \leq 20$	$150 < sdc < 400$
	3	$T \geq 30$	$40 < RH \leq 60$	$sdc \geq 400$
	4	$27 < T < 30$	$20 < RH \leq 40$	$150 < sdc < 400$
Yellow	1	$T > 27$	$RH \leq 60$	$sdc \leq 150$
	2	$T > 27$	$40 < RH \leq 60$	$150 < sdc < 400$
White	1	$\forall T$	$RH > 60$	$\forall sdc$
	2	$T < 27$	$\forall RH$	$\forall sdc$

Fig. 2 shows examples of meningitis early warning vigilance maps generated on 15th March 2021 for the following two weeks using S2S forecasts issued on 8th March 2021. Fig. 2a) indicates the warning for the first week of the forecast (15-21st March 2021) and shows that meningitis outbreaks are likely over northeastern Mali, and central Chad. Meningitis cases are very likely to occur in central and northern Chad, central Sudan, southern Algeria, many parts of Mali, northern Nigeria, extreme northeastern Central African Republic (CAR), several parts of Niger, southern and northern Mauritania, northern Burkina Faso, eastern Gambia, and much of Senegal. Over the rest of the meningitis belt, meningitis cases are less likely. Fig. 2b) shows that during the second forecasted week (22-29th March 2021), meningitis outbreaks are likely in central Chad, northeastern Mali, southern Algeria, northern Niger, and northwestern Chad. Meningitis cases are highly likely to arise in large parts of Chad, northern Nigeria, central Sudan, Niger, southern Algeria, extreme northeastern CAR, several parts of Mali, extreme southern and eastern Mauritania, many parts of Senegal, and northern and eastern Burkina Faso. In the rest of the belt, meningitis cases are less likely to occur. In southern Gulf of Guinea countries, and central, eastern, and southern Africa, meningitis cases are not expected.

Co-delivered solution for meningitis preparedness action

The MEWS is produced every Monday during the epidemic season which usually lasts from January to June each year, when the atmospheric conditions are conducive for the occurrence of meningitis outbreak. The MEWS is shared by email with staff from WHO AFRO, who also send the bulletin to their technical partners and national health services involved in the surveillance and prevention of the meningitis epidemics.

During the epidemic season, the WHO AFRO organises fortnightly coordination meetings to follow up on the meningitis epidemiological situation in countries that experience epidemics and those that are at risk. These meetings are attended by affected and at-risk countries as well as partners including ACMAD, Centers for Disease Control and Prevention (CDC) and Médecin Sans Frontières (MSF). The meetings provide a platform to discuss actions implemented by countries to respond to meningitis outbreaks, and to identify appropriate gaps and corrective measures. The regular update on climate and environmental

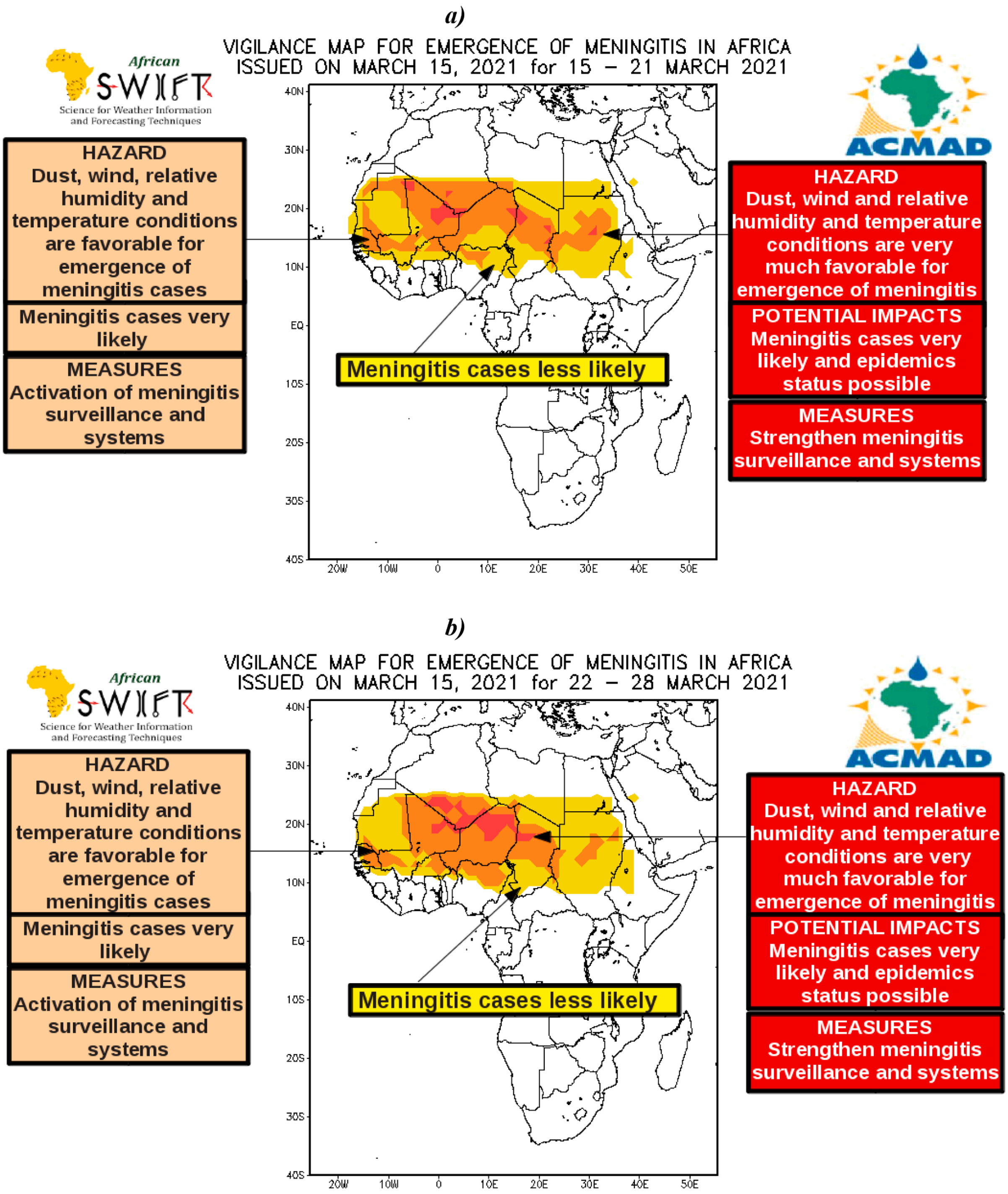

Fig. 2. Vigilance map of meningitis cases over Africa produced on 15 March 2021 and valid for (a) week from 15th to 21st March 2021 and (b) week from 22nd to 28th March 2021. The vigilance map is computed based on temperature, relative humidity and surface dust concentrations forecast from ECMWF model. Climate variables are from the S2S database and surface dust concentration from the Barecelona Supercomputer Center (BSC).

conditions during these meetings provided a more comprehensive risk analysis and subsequently pave the way for an informed decision-making on surveillance, preparedness, and response to meningitis outbreaks. The extended MEWS is presented and adds two weeks lead time to guide the recommendations and decision making by health services and increase awareness and prevention of an outbreak. Based on both climate information services and reported meningitis cases, the WHO AFRO is being able to strengthen meningitis outbreak preventing measures over the entire AMB. For example, when a red vigilance level is associated with reported meningitis cases, local health services are recommended to submit a request to MenAfriNet. MenAfriNet is an international consortium of partners working to establish a regional surveillance network to collect and analyse high quality case-based meningitis surveillance data from representative sites across the AMB. Local health services are encouraged to collect funds to support sample transportation of vaccine doses; manage available supports to improve performance; continue to improve meningitis surveillance, and reinforce surveillance system for the upcoming few weeks; and countries under epidemic to introduce a request for vaccine doses to the international coordinating group on vaccine provision (ICG). For example, in 2021, the growth of epidemics in western Niger and northern Ghana were rapidly stopped by mass vaccination.

Framework for implementation of the roadmap to defeat meningitis by 2030 in the WHO African region

In an effort to strengthen the fight against meningitis, the WHO and its partners developed a Global Roadmap to Defeat Meningitis by 2030. The roadmap is fully aligned with the WHO's 13th General Program of Work (GPW13) 2019–2023 and summarizes the essence of the WHO's threefold mission: promote health, ensure world security, and serve the vulnerable. The Global Roadmap to Defeat Meningitis by 2030 was endorsed by Member States at the 73rd World Health Assembly that was held in November 2020. Subsequently, the Framework to defeat meningitis by 2030 in the WHO African region was endorsed by Member States at the 71st Regional Committee in August 2021. The co-production approach implemented by ACMAD through the GCRF African SWIFT project, aims to contribute in defeating meningitis by 2030 in the WHO African region. As well as developing a sub-seasonal forecasting warning system of meningitis, WHO AFRO and ACMAD have developed a method for prioritizing the African countries which require increased vaccinations most imminently. Thus, the co-production group worked to develop a tool to prioritize countries for the implementation of the Regional Framework. The country prioritization tool was applied to all 47 member states of the WHO African region using landscape analysis and climate and environmental risks during 2017–2019 period to estimate the score of each country. Landscapes analysis included meningitis burden and country health services assessment. Meningitis burden is scored 50%, country health services assessment for 40%, and climate and environmental risks for 10%. Meningitis burden is evaluated using the total meningitis cases, deaths, attack rates, total Disability Adjusted Life Years (DALYs), and the number of districts in epidemic. For each country, the health system capacity to detect, confirm and treat meningitis was assessed using the case fatality rate (CFR), vaccination status, capability of laboratory to identify meningitis cases and surveillance system, the universal health coverage index (UHC index), and the pneumococcal conjugate vaccine (PCV) status. The associated climate risks were analysed using seasonal-means (January-March, April-June, July-September, and October-December) of temperature and relative humidity both at 1000 hPa from the ERA5. Temperature and relative humidity are combined using the criteria described in section 2.3 to generate risk maps of a meningitis outbreak each season. The environmental risks are associated with seasonal climate variability in each part of Africa. In this study, these risks are quantified using the wind trajectories, the relative distance from dust sources over Africa, and air pollution (figure not shown). The analysis of the categorization of the countries reveals that on the basis of the highest scores, they can be subdivided into three categories: countries in the AMB, those bordering the belt, and those outside the belt. The countries with the highest scores in the belt are Nigeria, Chad, Niger, South Sudan, and Mali. All of them experienced meningitis outbreaks every year. The category of countries bordering the belt include Cameroon, Democratic Republic of Congo, Central African Republic, Guinea and Uganda. These country experienced episodic epidemics. Countries outside the meningitis belt with high scores include Angola, South Africa, Sierra Leone, Zambia and Malawi.

Forecast evaluations

Evaluating sub-seasonal forecast data

To evaluate whether it is appropriate to use sub-seasonal forecasts of temperature and relative humidity to produce early warnings of meningitis outbreaks, we evaluate 20 years of reforecasts. For every Monday from January to June 2020, we evaluate whether the ensemble-mean of reforecasts correctly predict red vigilance (Table 1), characterized by air temperature above 30 °C and relative humidity below 20%, or conditions typical of orange and yellow vigilances (Table 1), with air temperature above 27 °C and relative humidity below 40% but excluding regions with red conditions. Given that each set of reforecasts has 20 years of data, and there are 26 Mondays in January to June 2020, we have assessed 520 weekly-mean predictions in temperature and relative humidity.

Fig. 3 shows the probability of detection, false alarm rate, and equitable threat score for red and orange/yellow conditions at a one (7 to 14 days) and two week (14 to 21 days) lead-time. The probability of detection illustrates the number of events correctly forecasted, and is defined by the number of correct forecasts divided by the sum of correct and missed forecasts (Fig. 3a,d,g,j). Across the Sahara, Sahel, and Sudanian savannah, the probability of detecting atmospheric conditions typical of a red warning is >0.7, for both a one and two week lead-time, giving confidence that sub-seasonal forecasts can predict extreme warm and dry conditions. The false alarm rate (Fig. 3b,e,h,k), which illustrates the fraction of predicted events that did not occur, shows that sub-seasonal forecasts rarely falsely predict extreme warm and dry conditions. Climatologically, dry, warm conditions are typical across West Africa. Therefore it may be the case that the skill already inferred from the probability of detection and false alarm rate, is due to high occurrence of red conditions in climatology. To analyse the forecast skill with respect to climatology, we computed the equitable threat score, which indicates the fraction of events correctly predicted relative to events that could occur due to random chance (Fig. 3c, f, i, l). An equitable threat score of one and zero indicates perfect and no skill respectively. The equitable threat score for red conditions illustrates a high skill at predicting extreme dry and warm conditions even when taking into considering the climatology. There is less predictive skill for atmospheric conditions typical of orange/yellow warnings, however the equitable threat score illustrates that sub-seasonal forecasts provide more information than the climatology alone.

There are significant atmospheric changes during the North African dry season, including the pre-onset of the West African monsoon and the intensification of the Saharan heat low, which may influence the predictive skill of dry and warm conditions. To investigate the influence of these atmospheric changes on predictive skill, we have taken a zonal-average of the probability of detection and the climatology between −10.5 to 30.0°E longitude (zonal-region illustrated in Fig. 3). Fig. 4 shows the zonal-mean probability of detection, false alarm rate, and equitable threat score for red and orange/yellow atmospheric conditions. Focussing on the probability of detection and false alarm rate for red conditions during week 1 (Fig. 4a, b), sub-seasonal forecasts correctly predict dry and warm conditions associated with the Saharan heat low. Whilst forecast skill reduces to the north and south of the Saharan heat low and still relatively high for the two-week forecasts (Fig. 4c, f). Orange/yellow atmospheric conditions are more likely to be observed at the beginning of the calendar year, or to the north and south of the Saharan heat low (Fig. 4g, j). Whilst the number of events is much smaller than red conditions (not shown), the equitable threat score shows that sub-seasonal forecasts better detect the occurrence of orange/yellow events than using information from climatology alone (Fig. 4i, l). Fig. 4 also emphasises the improved detection of red and orange/yellow conditions at a one week lead-time compared to a two week lead-time. Our assessment illustrates that for the majority of the time, sub-seasonal forecasts correctly predict warm and dry conditions. Sub-seasonal forecasts have greater skill at predicting warm, dry conditions compared to using climatology alone. This is particularly true before the Saharan heat low is fully developed, or in regions surrounding the Saharan heat low. In summary, these results indicate the high accuracy level in the S2S forecast data which demonstrated their usefulness in generating climate information services particularly for the health sector.

Evaluating the meningitis early warning system

As well as assessing the ability of ECMWF sub-seasonal forecasts to

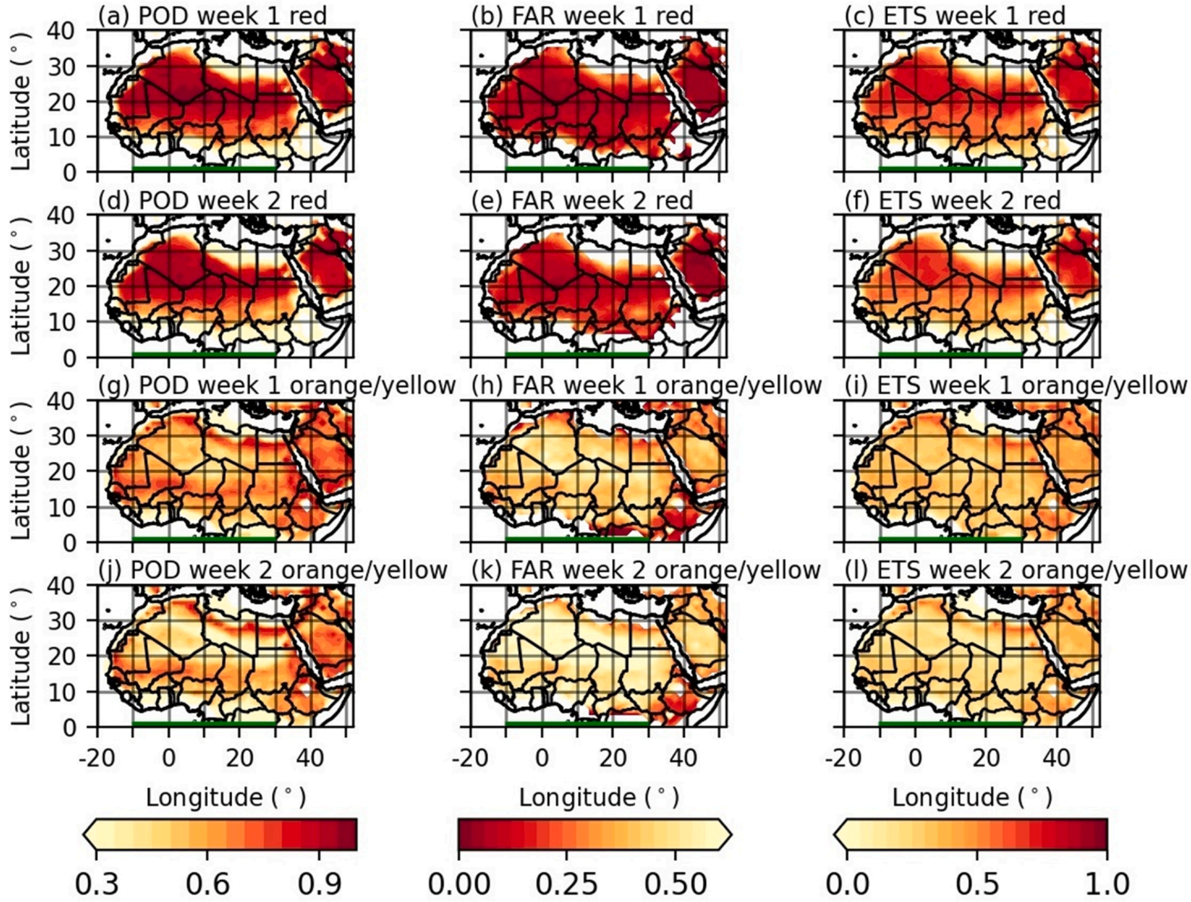

Fig. 3. Probability of detection (left), climatological occurrence (middle), and difference between probability of detection and climatological occurrence (right) for reforecasts initialised between January to June 2020. First and second rows (a-f) show values for red conditions (T ≥ 30 °C, RH ≤ 20%) with first row (a-c) showing forecast values for days 0 to 7 and second row (d-f) showing forecast values for days 7 to 14. (g-l) is a repeat of (a-f) however, these maps show predictive capability for typical orange/yellow conditions (T ≥ 27 °C, RH ≤ 40% but not including red regions). The green line on each x-axis highlights the longitudinal region used when calculating zonal-means shown in Fig. 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

predict atmospheric conditions which favour meningitis outbreaks, we have also evaluated each meningitis vigilance map issued throughout 2021. The weekly meningitis vigilance maps are evaluated using the weekly country-level reported meningitis cases by the WHO AFRO. Reported weekly meningitis cases are compared to the vigilance level covering the largest area in each country. Fig. 5 shows the number of weekly reported meningitis cases compared to vigilance levels from January to June 2021. During this season meningitis epidemics occurred in Niger (2 districts), Ghana (1 district) and Benin (1 district) (figure not shown). The magnitudes of these epidemics were <120 cases per week per country. The meningitis epidemics in Benin and Niger were controlled following reactive mass vaccination campaigns using vaccines provided by the International Coordination Group on vaccine provision (ICG). Fig. 5a shows that the vigilance levels of the first week forecasts are consistent with the reported meningitis cases at country level. The forecasts for week 2 also captured the magnitude of weekly meningitis cases (Fig. 5b). Fig. 5 also illustrates that the number of meningitis cases decreases from red to white vigilance levels. A high number of meningitis cases are observed in countries given an orange vigilance level or red warning. The results are consistent with the model developed by Pandya et al., 2015, who showed that relative humidity is highly correlated with the number of meningitis cases. The fact that this direct comparison with recorded meningitis cases shows that the vigilance maps are able to successfully capture the outbreaks and highlights that there is indeed useful information from the S2S forecasts. However, accurately capturing the red vigilance areas remains a challenge. Often red vigilance warnings are issued in uninhabited areas or regions which are hard-to-reach by health services. As well as, the failure of communities to report suspected meningitis cases to national health services and the decreased number of reported meningitis cases due to the COVID-19 pandemic are other challenges that impede the smooth implementation of this co-production framework.

Discussions and lessons learnt

Having direct access to S2S forecast data, rather than receiving off-the-shelf forecast product outputs, has been transformational for ACMAD as it has allowed bespoke user-focussed products to be designed. It has also supported the development of useful climate services in Africa. Access to S2S forecast data in real-time has allowed ACMAD to co-design products for specific decision-making which has made it more actionable and useful. In this study, reliable sub-seasonal forecasts are combined to produce a single vigilance map which illustrates forecasted meningitis outbreaks at a two-week lead-time, A product which was previously based on expert assessment of current atmospheric conditions and was therefore capable at predicting meningitis cases for the following week.

The use of the sub-seasonal forecast data to produce a MEWS demonstrates the potential for real-time climate information to guide decision making on preparedness. During the first year of co-production, new vigilance forecasts were provided and the results highlighted a decrease in meningitis outbreaks in 2021 across the AMB. This situation

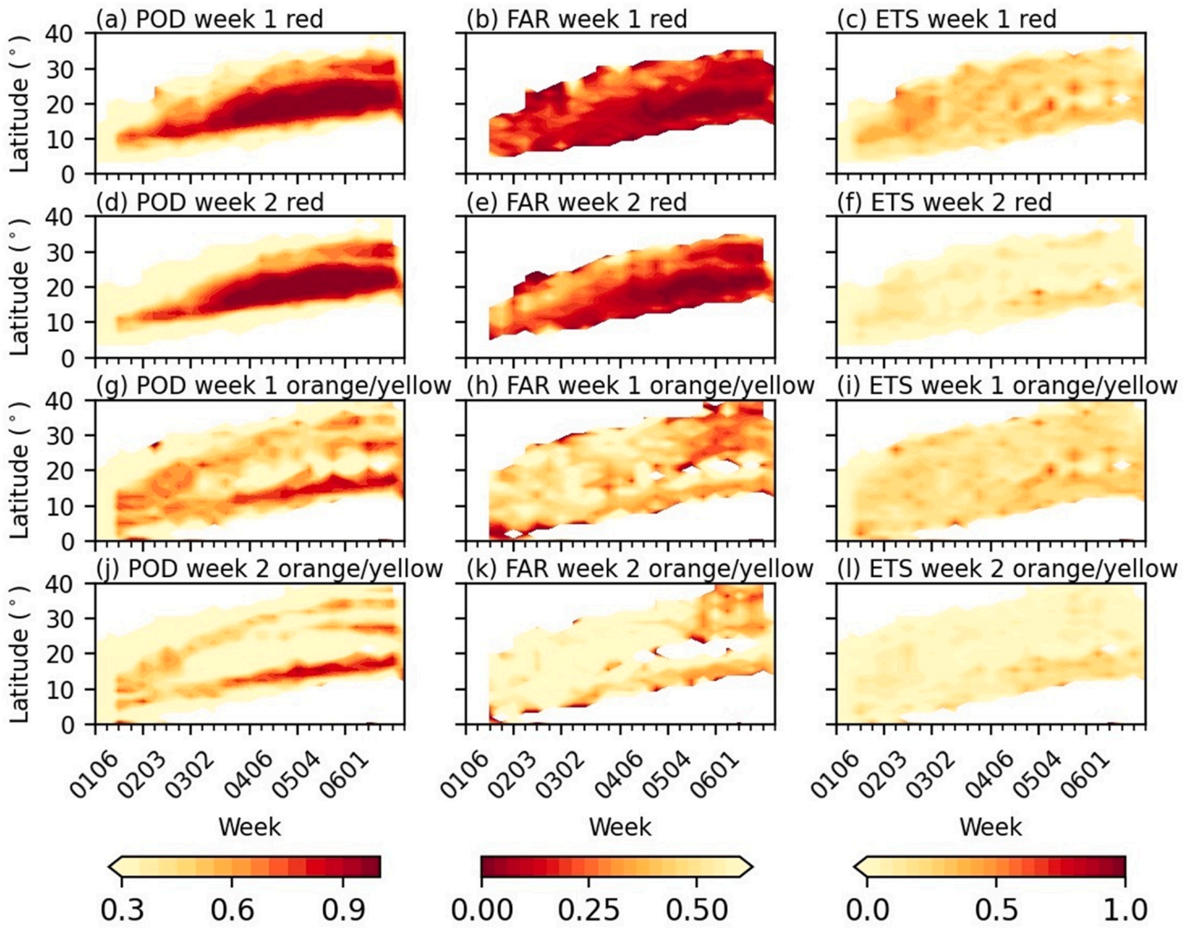

Fig. 4. Zonal-mean (-10.5 to 30.0°E longitude) average of probability of detection (left), climatological occurrence (middle), and difference between probability of detection and climatological occurrence (right) for reforecasts initialised between January to June 2020. First and second rows (a-f) show values for red conditions ($T \geq 30$ °C, $RH \leq 20\%$) with first row (a-c) showing forecast values for days 0 to 7 and second row (d-f) showing forecast values for days 7 to 14. (g-l) is a repeat of (a-f) however; these show predictive capability for typical orange/yellow conditions ($T \geq 27$ °C, $RH \leq 40\%$ but not including red regions). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

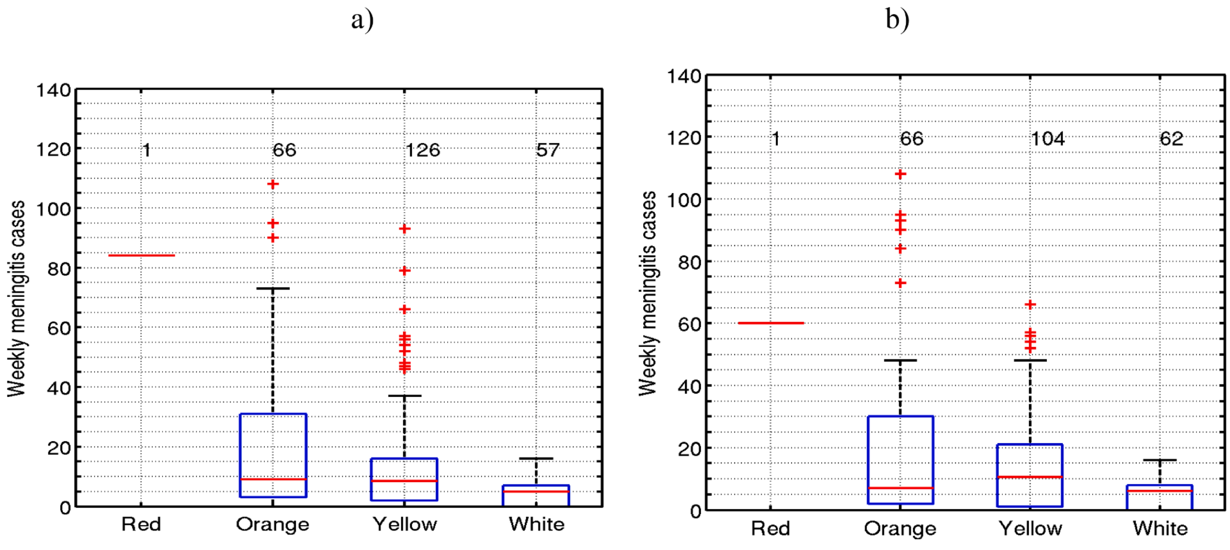

Fig. 5. Weekly reported meningitis cases from WHO AFRO compare to vigilance levels of the meningitis early warning system for week 1 (a) and 2 (b). Here, from week 1 to 26 in 2021, the dominant vigilance level over each country is used to evaluate the forecasts. The number of observed weekly meningitis cases is indicated by the number above boxplots. Red crosses indicate outliners in the number of meningitis cases for each vigilance level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was facilitated by fortnightly coordination meetings between the WHO AFRO, ACMAD, and local health services. The presentation of meningitis forecasts encouraged the WHO AFRO to recommend to countries in alert or epidemic to strengthen their systems over the next two to three weeks and request vaccine doses to ICG. In 2021, few rare epidemics observed in Niger, Ghana and Benin were contained by a rapid response from the WHO and local health services to conduct a mass vaccination in the affected districts in Benin and Niger. The co-production framework highlighted in this study enables climate and health experts to better share their knowledge on meningitis. It supports capacity-building for both climate and health experts with the mission to eradicate meningitis across Africa. Climate scientists have played a key role in guiding the support provided to countries by WHO AFRO and other partners for effective preparedness and adequate response to meningitis outbreaks.

The co-production process gave opportunities to forecasters to develop and validate bespoke climates services designed for a specific key user. For this piece of work, we also developed a useful documented standard operational procedure (SOP) as a legacy for the weather and climate services over the African meningitis belt. Developing a meningitis early warning's SOP means that project-initiated services are sustained and knowledge gained through co-production is institutionalised rather than remaining with single individual involved in the project. The SOP contains all procedures required to generate the products needed for this MEWS.

The evaluation of the vigilance map of the meningitis highlights encouraging results on the predictability of meningitis prevalence using climate forecasts. However, the limited temporal and spatial resolution of dust forecasts does not allow the MEWS to be extended over Central Africa where meningitis cases are also observed. For example, the northern part of the Democratic Republic of Congo reported suspected meningitis cases every year. To further develop the MEWS, the domain for the dust prediction model should be extended to cover the Congo Basin and the Namibian dessert, where cases of meningitis are regularly reported. Beside technical issues of the production of climate information, there is a need to train local medical staff to enable them to better understand climate information services.

Using a co-production approach, which incorporates the knowledge of the user into the forecast development process, is contributing to the implementation of the WHO project to defeat meningitis in Africa by 2030. Specifically, it has providing quantitative and qualitative analysis of the climate and environmental risks of meningitis outbreaks for the prioritization of countries that will receive greater attention for the roll out of WHO strategy.

In the context of the Global Framework for Climate Services, ACMAD has had the opportunity to strengthen its partnership with the WHO AFRO, local health services, and other technical partners in the health sector by providing key weather and climate information services for public health decision making. This co-production approach initiated by African SWIFT will continue to be supported by ACMAD over the upcoming decade. The collaboration between health services and climate scientists should be strengthened when developing new useful products tailored for other vector-borne diseases (Malaria, dengue, Rift valley fever etc.), heat wave impacts, and respiratory infections, water-borne diseases (Cholera, typhoid fever, hepatitis A and B, etc.) to help medical services over Africa to reduce their impacts.

CRediT authorship contribution statement

Cheikh Dione: Conceptualization, Methodology, Investigation, Validation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Joshua Talib:** Conceptualization, Formal analysis, Resources, Writing – original draft, Writing – review & editing, Visualization, Validation. **Ado A. Bwaka:** Conceptualization, Investigation, Methodology, Resources. **André F. Kamga:** Conceptualization, Investigation, Resources, Funding acquisition, Writing – review & editing. **André A. Bita Fouda:** Resources, Investigation, Writing – review & editing. **Linda Hirons:** Resources, Investigation, Writing – review & editing. **Anderson Latt:** Investigation, Resources, Writing – review & editing. **Elisabeth Thompson:** Investigation, Resources, Data curation. **Clement Lingani:** Resources, Data curation. **Victor Savatia Indasi:** Investigation, Writing – review & editing. **Elijah A. Adefisan:** Investigation, Funding acquisition. **Steve J. Woolnough:** Conceptualization, Formal analysis, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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