Recommendations to improve the interpretation of global flood forecasts to support international humanitarian operations for tropical cyclones

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Recommendations to improve the interpretation of global flood forecasts to support international humanitarian operations for tropical cyclones

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Abstract

International humanitarian organisations increasingly turn to forecast teams to support the coordination of efforts to respond to disasters caused by hazards such as tropical cyclones and large-scale fluvial floods. Such disasters often occur where there is limited local capacity or information available to support decision making and so global forecasting capacity is utilised to provide impact-based flood forecast bulletins. A multidisciplinary team joined together to provide forecast bulletins and expertise for such events through the UK

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Foreign and Commonwealth Development Office (FCDO). This paper captures the successes and challenges from two cyclones: Hurricane Iota in Central America (November 2020) and Cyclone Eloise in Mozambique (January 2021). Recommendations to improve global forecasting systems are made which will benefit the international community of researchers and practitioners involved in disaster prediction, anticipatory action and response. These include the need for additional data and expertise to support the interpretation of global models, clear documentation to support decision makers faced with multiple sources of information, and the development of user relevant metrics to assess the skill of global models. We discuss the value of effective partnerships and improving synergies between global models and local contexts, highlighting how global forecasting can help build local forecasting capability.

KEYWORDS

anticipatory action, Eloise, global flood models, impact-based forecasts, Iota, tropical cyclones

1 | INTRODUCTION

An appeal for international humanitarian assistance is made by the government of the disaster-affected country when the magnitude and/or duration of an emergency is beyond their response capacity (UN General Assembly, 46th Session, December 1991). In these situations, international humanitarian organisations require impact-based forecasts and assessments to support coordination, logistics and decision-making (Nauman et al., 2021).

Tropical cyclones (also known regionally as hurricanes or typhoons) are associated with strong winds, heavy rainfall and in some cases storm surges. There are also often impacts from fluvial flooding which can extend far from the landfall location and last long after the initial landfall (Titley et al., 2021). When responding to such disasters humanitarian organisations may have access to a variety of products and services such as local maps, data feeds and translators. The availability and quality of this information varies by location. Global-scale flood forecast models, though often at a course resolution, can provide a consistent and timely source of information when forecasts from national mandated authorities are not easily accessible, where transboundary impacts are possible or where longer lead times or probabilistic forecasts are required (Emerton et al., 2016; Hirpa, Pappenberger, et al., 2018; Lavers et al., 2019; Ward et al., 2015). This approach was first piloted to produce impact-based flood forecast bulletins to support humanitarian operations for the devastating floods in Mozambique caused by Cyclones Idai and Kenneth in 2019 (Emerton et al., 2020). Through co-ordination and interaction between forecast producers, translators, intermediaries and users (see Table 1) the approach has been improved and systematised.

This paper aims to share our experiences of using global flood models to support humanitarian decision making in Central America and Mozambique through a Flood Early Warning Pilot funded by the UK Foreign and Commonwealth Development Office (FCDO). Specific examples from case studies of Hurricane Iota (November 2020) and Cyclone Eloise (January 2021) are drawn on to identify recommendations to provide more robust and actionable impact-based flood forecasts from global models. The users in these examples were largely humanitarian organisations however the discussion and recommendations presented in this paper are also valid for other local, national and international emergency management organisations who use global models to inform their decision making. It should be noted that although we used the terminology "Flood Early Warning Pilot", users held the responsibility for communicating any resulting flood warnings and taking action.

1.1 | Humanitarian anticipatory action

The impact-based flood forecast bulletins have been developed alongside a growing use of forecasts by humanitarians to support anticipatory action. Acting in advance of disasters is a cost-effective way to reduce the impacts of major weather and climate driven events by increasing the resilience of local communities and targeting humanitarian response to the areas most in need (Coughlan de Perez et al., 2015; Gros et al., 2019, 2022). The success of this approach is contingent upon the

TABLE 1 Organisational roles in the provision of flood bulletins during the Flood Early Warning Pilot.

Organisational role	Definition	Organisations involved
Forecast producers	"Those who produce weather and climate data and information" and who are responsible for long term improvements to the forecast through scientific and technological development	Joint Research Centre (JRC), European Centre for Medium Range Forecasting (ECMWF), HR Wallingford, FATHOM, national hydro-met agencies, Joint Typhoon Warning Centre (JTWC), Regional Specialised Meteorological Centres (RSMC)
Forecast translators	"Those who have the responsibility for converting this data into a form that is appropriate for the user" by translating the complex forecasts into key decision relevant messages and informative graphics	University of Reading (UoR), University of Bristol (UoB), HR Wallingford, ECMWF, FATHOM
Intermediaries	"Those who support engagement between producers and users… Intermediaries have content knowledge and play the role of a knowledge broker, or connector, in co-production"	UK Foreign, Commonwealth & Development Office (FCDO), Red Cross Red Crescent Climate Centre, Start Network
Users	"Those who will take action based on the weather and climate information"	FCDO, United nations Office for Coordination of Humanitarian Affairs (UN OCHA), National Red Cross / Red Crescent Societies, World Food Programme (WFP), Start Network Members

Note: Definitions in quotation marks are as described by Carter et al. (2019).

increasing sophistication of impact-based flood forecasts and warnings (Merz et al., 2020), driven by technological advances in data availability (Nauman et al., 2021), continued development of hydro-meteorological models (Emerton et al., 2016; Wu et al., 2020) and a growing commitment to collaborative and multi-disciplinary ways of working (Golding, 2022).

Warning systems are only effective if appropriate action is taken on the basis of the warning. In the humanitarian anticipatory action framework, Early Action Protocols (EAPs) are formal plans produced by Red Cross National Societies (other humanitarian organisations have also developed similar procedures) which outline the early actions to be taken, and the organisations responsible for them, when a specific hazard is forecasted to impact communities. When the forecast reaches a pre-defined trigger, funding for these forecast based actions is released from the International Federation of Red Cross and Red Crescent Societies (IFRC) Disaster Response Emergency Fund (DREF) (IFRC, 2022).

The provision of impact-based flood forecast bulletins supports humanitarian anticipatory action by providing early notification of the potential activation of EAPs, real-time information to support decision making before and during major events, and helps builds familiarisation with forecasts. Evaluating the utility of global forecasts in real-time for specific events (as opposed to skill evaluation using reforecast datasets) provides an alternative way of highlighting where further research or investment is needed to improve their usability.

2 | APPROACH TO PRODUCING AND EVALUATING THE IMPACT-BASED FLOOD FORECAST BULLETINS

2.1 | Organisational roles

There are multiple roles involved in the provision of these impact-based flood forecast bulletins (hereafter referred to as flood bulletins). These are detailed in Table 1 using the definitions developed in the Weather and Climate Information Services for Africa (WISER) co-production manual (Carter et al., 2019), but with the important role of forecast interpretation explicitly acknowledged with the addition of a forth category for 'forecast translator'.

2.2 | Operating procedure

The trigger to produce the bulletins is a collaborative decision based on a preliminary assessment of likely impact as well as the likely information needs of the humanitarian community, and the feasibility of using the available forecasting tools given the hydrometeorological situation for the event (Figure 1). Following the trigger, a preagreed operating procedure is followed which addresses the flow of data and information, timing of calls and production of the bulletin (Figure 1). Examples of the bulletin content and presentation, and a

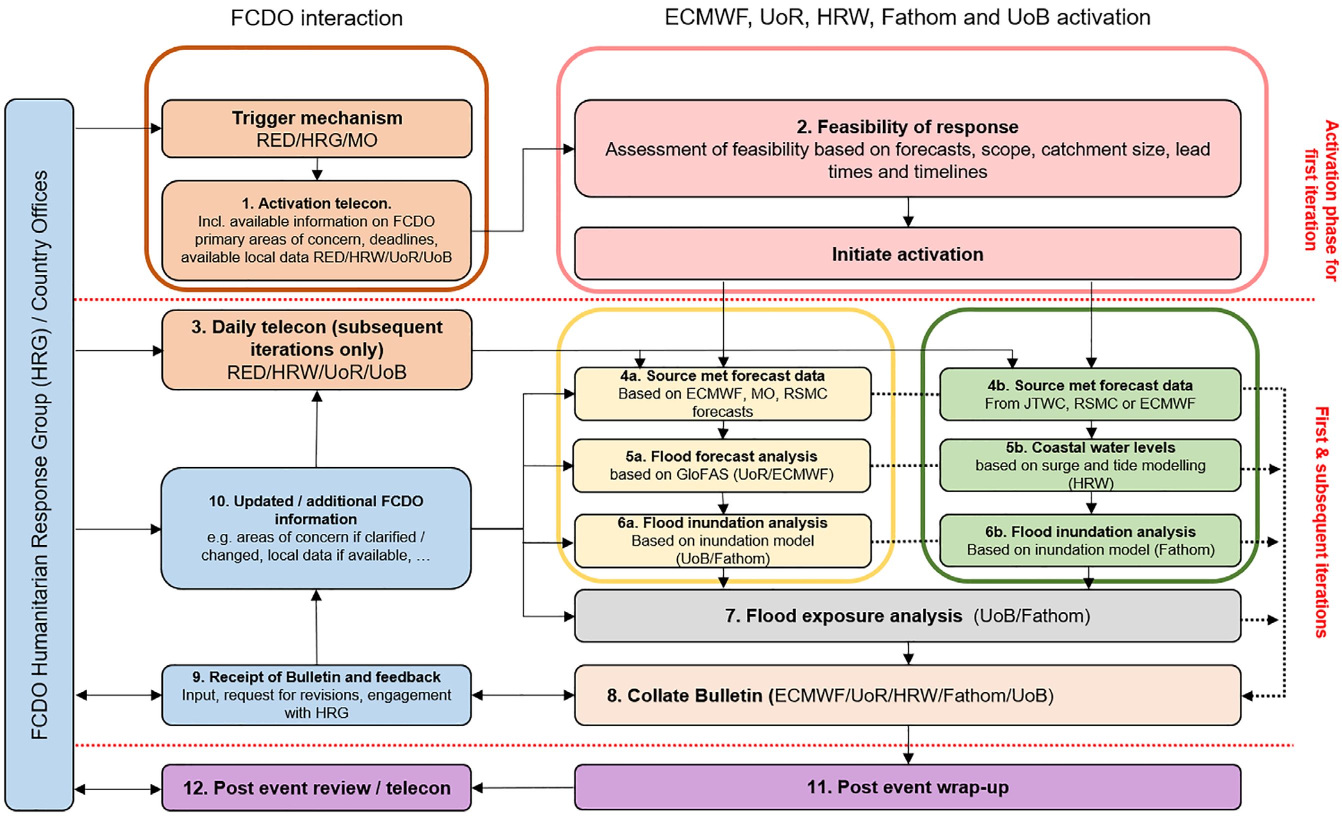

FIGURE 1 Flood early warning pilot operating procedure. Foreign, Commonwealth & Development Office (FCDO) Humanitarian Response Group (HRG), FCDO Research and Evidence Directorate (RED), Met Office (MO), University of Reading (UoR), University of Bristol (UoB), HR Wallingford (HRW), European Centre for Medium Range Forecasts (ECMWF), Joint Typhoon Warning Centre (JTWC), Regional Specialised Meteorological Centres (RSMC). Colours: Orange—trigger process, pink—feasibility assessment, yellow—fluvial analysis, green—coastal analysis, grey—exposure analysis, cream—reporting, feedback and incorporation of additional information, blue—FCDO input to bulletin focus and content, purple—post event evaluation.

discussion of its evolution, are provided in Emerton et al. (2020) and Budimir et al. (2022). After the event a post event wrap-up provides a process for documenting learning and deciding on any ways forward. As the organisations involved in producing the bulletins included research organisations who do not have a 24/7 operational remit (see Emerton et al., 2020), bulletins during this pilot project are not produced on weekends or public holidays.

2.3 | Forecast methods

Impact-based forecasts should provide details of the timing, location and severity of potential impacts to inform appropriate action (Harrowsmith et al., 2020; Robbins et al., 2022; WMO, 2015; WMO, 2021a).

The impact-based forecasts bring together global scale methods for flood forecasting, hazard mapping and exposure analysis. Meteorological forecasts of precipitation, wind speed and tropical cyclone track locations are sourced from the Regional Specialised Meteorological Centres (RSMC), the Severe Weather Impact Assessment report produced by the UK Met Office, and ECMWF data.

The fluvial flood forecast uses the Global Flood Awareness System (GloFAS; www.globalfloods.eu), an early warning component of the European Commission Copernicus Emergency Management Service (emergency.copernicus.eu). Fluvial flooding is estimated by combining GloFAS forecast probabilities of exceeding the flood alert thresholds, with pre-computed 3 arc second (~90 m) flood hazard maps from Fathom (Sampson et al., 2015). These flood inundation maps are produced by a hydrodynamic model based on the numerical scheme of LISFLOOD-FP (Neal et al., 2012) and a global flood inundation model framework (Sampson et al., 2015). Population exposure is estimated by intersecting flood inundation extents with population counts constrained to buildings from WorldPop (Bondarenko et al., 2020; Bondarenko, Kerr, Sorichetta, & Tatem, 2020; Lloyd et al., 2017).

Cyclone track forecasts from the appropriate operational Tropical Cyclone (TC) forecasting centre are interpreted to create time-varying wind and pressure fields which are applied to a regional or global TELEMAC-2D model (Hervouet, 2007, www.opentelemac.org) to predict storm surge. To estimate storm-surge flooding, water levels along the affected coast are extracted from TELEMAC2D model and then applied to the boundary of the LISFLOOD-FP inundation model run in near real time.

The methodology is described in detail by Emerton et al. (2020) and summarised in Appendix A.

2.4 | Post event review

Post event review is an integral component of the Flood Early Warning pilot (Figure 1). There are two stages to the process, an immediate post event wrap-up to collate initial thoughts and feedback, followed by the production of a post event review report and review meeting. Input is sought from all organisations identified in Table 1.

The post event review combines an assessment of the forecast evolution alongside available observations and impact data, and feedback on the use and usefulness of the bulletins (Table 2). The aim is to document the strengths and limitations of each activation and identify recommendations for both operational and scientific improvements. The approach taken for the post event reviews has been largely qualitative. This reflects both the limited observations available (especially immediately) to support the review, and, most importantly, that while post event reviews can be a useful learning process, analysis of any one individual event provides limited information about the skill of a model in forecasting other events (either in the same region or elsewhere). For these reasons a more quantitative approach to the post event reviews is not considered appropriate. The content of this paper is based on the post event reviews completed following Cyclones Iota and Eloise.

TABLE 2 Post event review topics and example questions.

Areas covered	Example questions
Approach	• Were there any difficulties encountered with the modelling approach? • Were there any difficulties encountered with the bulletin production?
Dissemination	• Did the bulletins reach the right people? • Was any additional information shared that could be incorporated into the methodology?
Forecasts	• How far in advance was the event forecasted? • Could the trigger process have been initiated earlier? • Were the areas most impacted correctly highlighted? • Was the event more or less extreme than anticipated in the bulletin?
Further activities	• Is this work leading to any subsequent activities? (e.g. has data been found that will be incorporated elsewhere, what collaborations have developed?).

3 | SUMMARY OF CASE STUDY EVENTS

3.1 | Tropical cyclone Iota

The 2020 Atlantic Hurricane season (June–November) was the most active Atlantic hurricane season on record with 30 named storms and 7 major hurricanes (NOAA, 2021). The last of these, Hurricane Iota, affected Nicaragua, Honduras, Guatemala, and parts of other bordering countries. The category five hurricane made landfall on 17 November 2020 03:40 UTC (16 November, 10:40 EST local time), south of Puerto Cabezas in northeast Nicaragua. River levels in the region were already high and the humanitarian community was already in response mode following Eta, a category 4 hurricane which had made landfall just 24 km north of Iota's landfall location 2 weeks earlier. The reported maximum event rainfall from Iota was 510 mm in Guatamala—including 94 mm falling in a 6 h period on 18th November (Stewart, 2021) and the resulting storm surge was reported to be up to 8 m around the village of

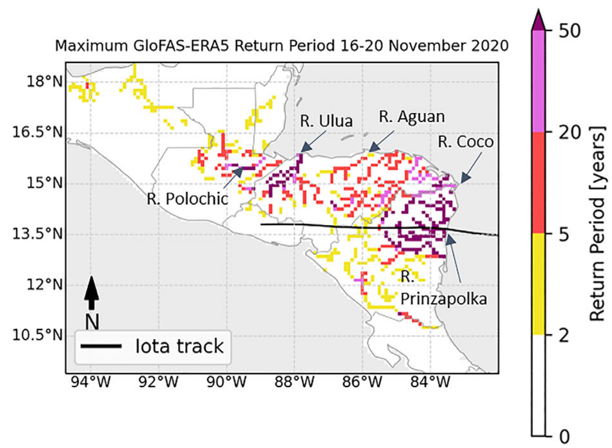

FIGURE 2 Iota maximum GloFAS-ERA5 return period 16th–20th November 2020. The purple colours indicate the expected locations of the most severe inland flooding. Labels identify major river of interest.

Haulover, Nicaragua (Stewart, 2021). Figure 2 shows the maximum flood return period exceeded in the GloFAS-ERA5 reanalysis.

The humanitarian response to Eta and Iota was combined into a single operation and it is difficult to differentiate the compound impacts of the two events separately (UN OCHA, 2020a). In total 5.2 million people were affected across nine Latin America and Caribbean countries (UN OCHA, 2020a). Widespread mud and rockslides and flooding of up to 2 m was reported across central America causing loss of life and damage to property, roads and infrastructure (IFRC, 2020a; UN OCHA, 2020a, 2020b). A storm surge caused coastal flooding to air and sea ports across the region hampering response efforts (Shultz et al., 2021; Stewart, 2021). The immediate response from the Red Cross included activating emergency response centres, supporting evacuation and rescue missions, distributing humanitarian aid included food packages and hygiene kits, and damage assessment (IFRC, 2020a). Longer term humanitarian response is ongoing and expected to last for many years to come (UN OCHA, 2020b).

3.2 | Iota forecast bulletins

The evolution of the cyclone forecast for Iota and resulting rainfall is shown in Figure 5. A consistent signal for severe flooding in GloFAS (coinciding with the increase in confidence in the TC position and rainfall

TABLE 3 Timeline of Tropical Cyclone Iota evolution and bulletin activity 12th–19th November 2020.

Date	Hydro-meteorological situation	Bulletin activity
12th November	• Broad low-pressure system develops over Caribbean Sea • Signal for severe flooding first seen in GloFAS	Internal discussion on potential need for bulletins started
13th/14th November	• Tropical storm develops • Hurricane forecast advisory issued by the National Hurricane Centre • River catchments already very wet following Eta	Continued monitoring of forecasts
15th November	• Hurricane Iota passes over islands of Providencia and Santa Catalina • Notable increase in GloFAS forecast probability of severe flooding and reduced spatial variability in cyclone track forecast (Figure 5)	
16th November	• End of period of rapid intensification • Iota upgraded to category 5 hurricane	First flood bulletin issued. Key messages: • Severe flooding likely across northern Honduras and eastern Guatemala (Figure 4) • Coastal surge expected around landfall • Flash floods and landslides in areas of heavy rainfall
17th November	• Iota makes landfall then weakens as it passed over mountainous terrain in Northern Nicaragua • Storm surge of up to 8 m in parts of Nicaragua • Heavy rainfall, landslides and flooding reported across central America	Flood bulletin issued with no major change from previous bulletin
18th November	• On-going inland flooding	Flood bulletin issued. Key messages: • Widespread flooding similar to Eta occurring across the region • Levels currently above government thresholds and continuing to rise in Guatemala and Nicaragua
19th November	• On-going inland flooding	Last flood bulletin. Key messages: • Further rainfall expected in Guatemala • Flooding ongoing

accumulations) was identified on 12th November, 5 days before landfall. At this point an initial discussion started around the possible need to provide briefings (Table 3). This extended lead time allowed forecast translators time to collate useful data sets and other resources before the official activation. The first flood bulletin was produced the day before landfall (16 November) highlighting the exposure in Honduras, Guatemala and Nicaragua (Figure 4 and Table 3).

The surge forecast was based on the NHC forecast released at 0900 16/11/2020 UTC and predicted a maximum surge of up to 6 m north of Puerto Cabezas (Figure 3). The coastal model bathymetry was based on General Bathymetric Chart of the Oceans data (GEBCO Compilation Group, 2020) which is often poor in coastal areas away from main navigation routes where there is unlikely to have been a dedicated survey. For the stretch of coast on which Hurricane Iota made landfall near Puerto Cabezas the combination of coarse regular grid (node spacing of approximately 16 km) and likely sparse source bathymetry data produced a poor representation of the coastline (Figure 3). The small islands northeast of Puerto Cabezas are represented in the TELEMAC-2D model as connected to the mainland forming a peninsular. The coarse regular mesh creates triangular elements along the coast which lead to localised enhancement of surge at the apex of the triangles. In addition, the global model does not predict tide well, although in this case, the local tide has a small range and is relatively unimportant.

The hurricane made landfall further south than forecast. The predicted peak surge of 6 m was less than the reports of 8 m at Haulover and Wawa Bar (Stewart, 2021). It is not known how the surge quoted in Stewart (2021) was estimated or whether it is relative to the astronomical tide or a fixed vertical datum. Both Haulover and Wawa Bar are located near river mouths and it is possible that the surge combined with river flooding to produce a very high compound flood level. The global coastal global model was useful in identifying the overall area of coastline at risk and the approximate time of landfall but only a qualitative indication of the magnitude of the surge.

The bulletins were successfully used by humanitarians to inform actions on the ground prior to the floods occurring:

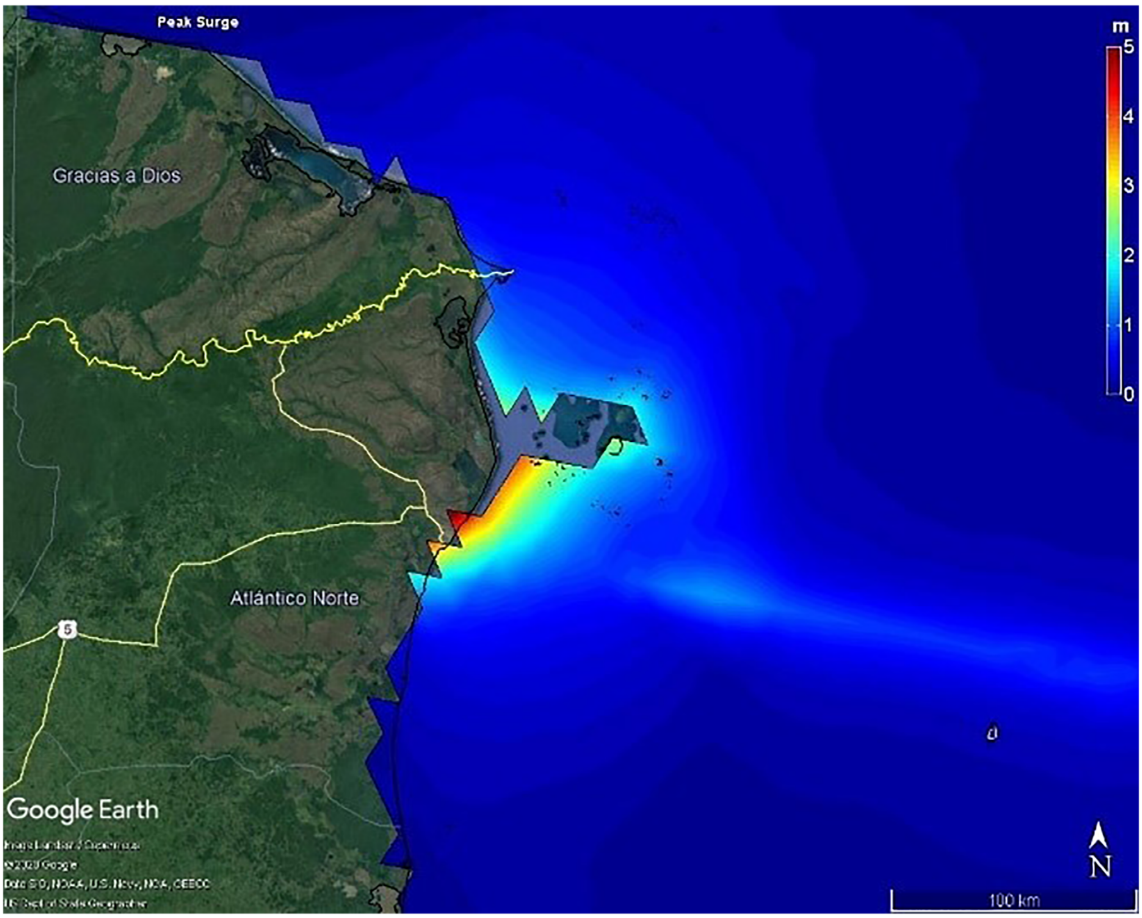

FIGURE 3 Peak surge from Hurricane Iota predicted by the TELEMAC-2D global model.

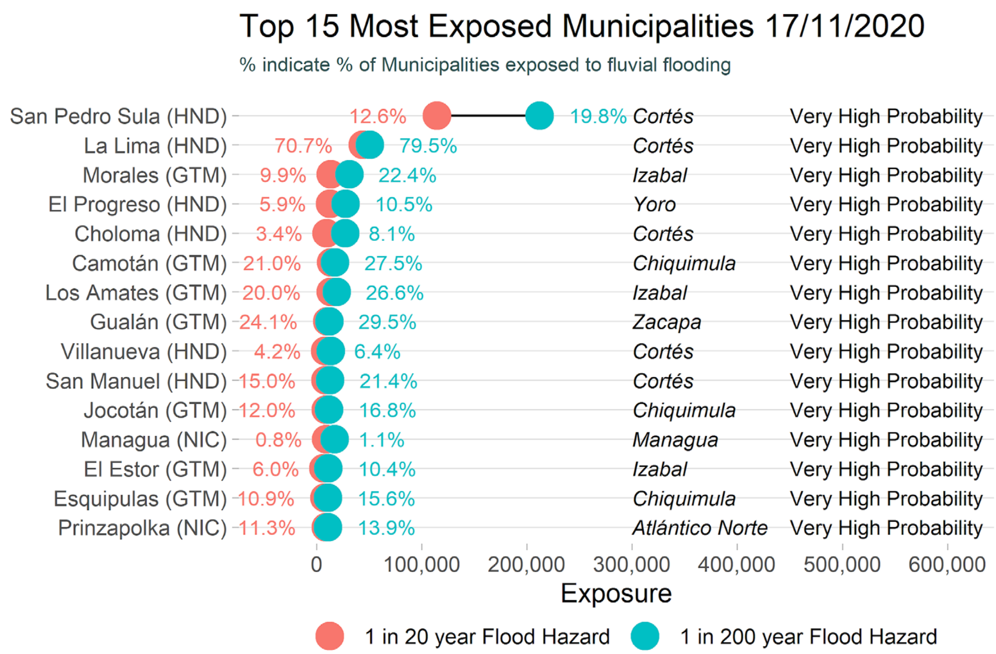

FIGURE 4 Forecast exposure of population by municipality from Iota. Estimated exposure per municipality for a less extreme 20-year return period (red dot) to the more extreme 200-year return period (blue dot). The percentages indicate the proportion of the municipality population that could be exposed. The probabilities refer to the probability of exceeding the GloFAS severe alert threshold (20-year return period with the following probability thresholds: Very-High (Expected) > 70%; High (Probable) 50%–70%; Moderate (Possible) 25%–50%; Low (Unlikely) < 25%.

> The bulletin was very helpful in communicating to IFRC colleagues and National Societies who were deployed on the ground conducting humanitarian operations, the potential impact that Hurricane Iota could bring to communities that had already been struck by Eta. With this information we were able to give early warning so that Start Network volunteers and staff as well as IFRC could be prepared in areas such as San Pedro de Sula in Honduras where Eta had already caused extensive damage and losses and where forecasts were once again predicting severe impacts.
>
> Juan Bazo, Red Cross Red Crescent Climate Centre

3.3 | Key reflections from the Iota post event review

3.3.1 | Balancing skill at longer lead time with operational decision making and response capacity

Figure 5 shows that the risk of heavy precipitation along the north coast of Honduras was predicted four to 6 days before landfall, indicating that if flood bulletins had been produced at longer lead times they would have identified a similar severity of flood impacts for this area. For areas close to the landfall location (the east coast of Nicaragua), the rainfall forecasts were more sensitive to correctly forecasting the landfall location, and so the lead times at which forecasts signalled the heavy rain was lower (1–3 days). For the Río Grande de Matagalpa in Central Nicaragua, the GloFAS signal only stabilised once the rain has fallen. There was a notable increase in the probability of exceeding the 20-year return period in the correct locations from the 15 November run onwards. From this point the main rivers expected to experience severe flooding (>20-year return period) remained consistent in GloFAS over time indicating good forecast confidence (Figures 2 and 5).

One of the advantages of global probabilistic models is providing information at longer lead times compared to local forecast models (Lavers et al., 2019). However there is always an inherent trade-off for humanitarians between the benefit of acting early and the potential of acting in vain or in the wrong location (Bischiniotis et al., 2019). Post event discussion with users indicated that despite the potential to identify areas of high risk four to 6 days before landfall, it was unlikely producing earlier bulletins would have changed the timing of actions taken by humanitarians. For Eloise an interim

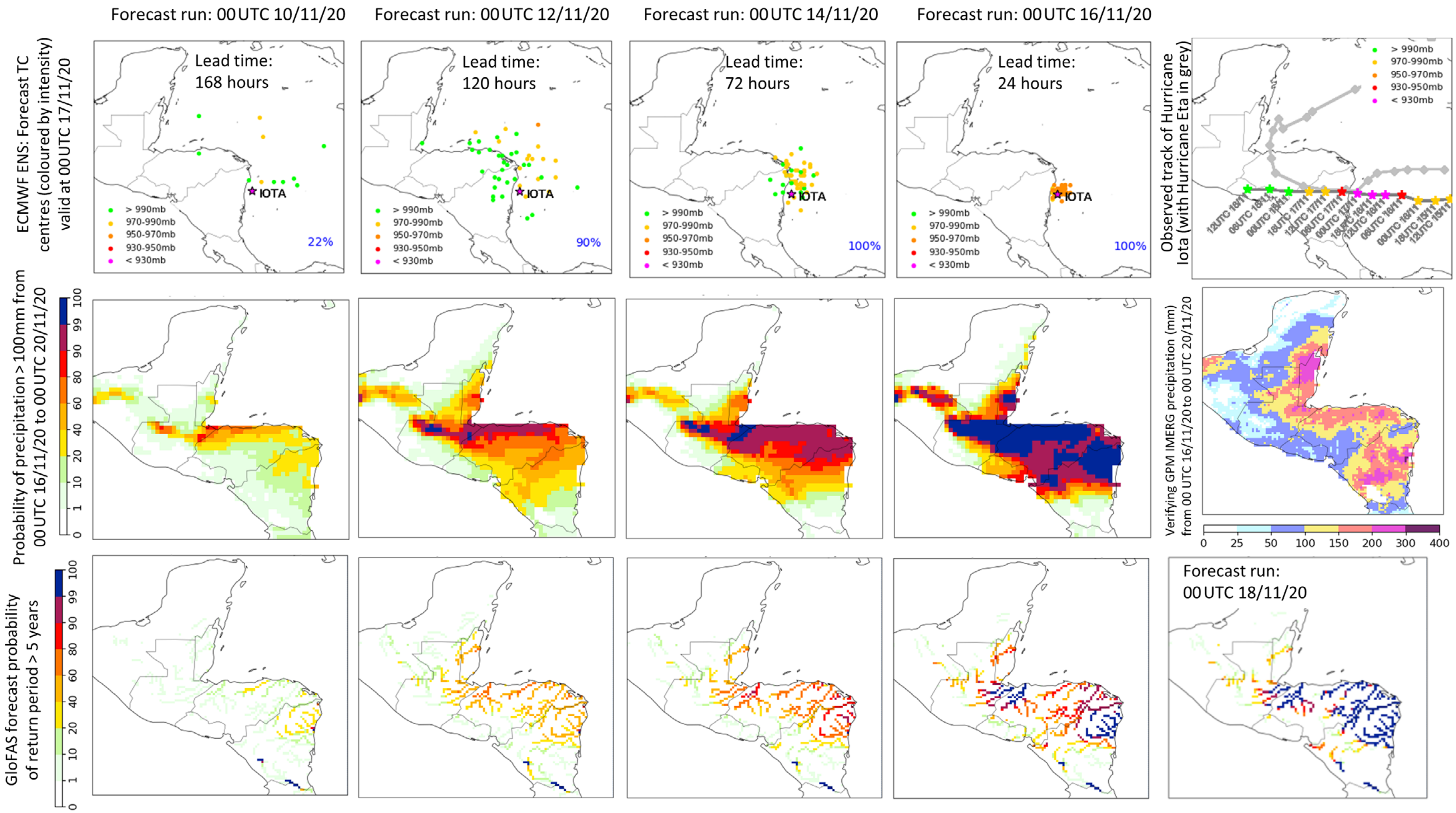

FIGURE 5 Iota cyclone, rainfall and flood forecast evolution—In the top row the star shows the observed centre position of TC Iota at 00:00UTC on 17th January (just before landfall), the coloured dots show the forecast positions valid at this time from each EC ENS member. The percentages indicate the percentage of members that had a cyclone centre forecast within the frame. The far-right image shows the observed cyclone tracks of Iota and Eta. The second row shows the precipitation probability forecasts from EC ENS for 4-day event precipitation totals >100 mm, with the verifying GPM data for the same period in the far-right column. The bottom row shows the forecast GloFAS return period of exceeding the 5-year flood threshold, with an additional forecast from a post-landfall GloFAS run on the right.

step of providing short written forecast briefing paragraphs to FCDO in the lead up to the event was added to the operating procedures, enabling humanitarian to benefit from early indication of potential impacts whilst balancing the resource commitment of producing a full bulletin against the potential actions.

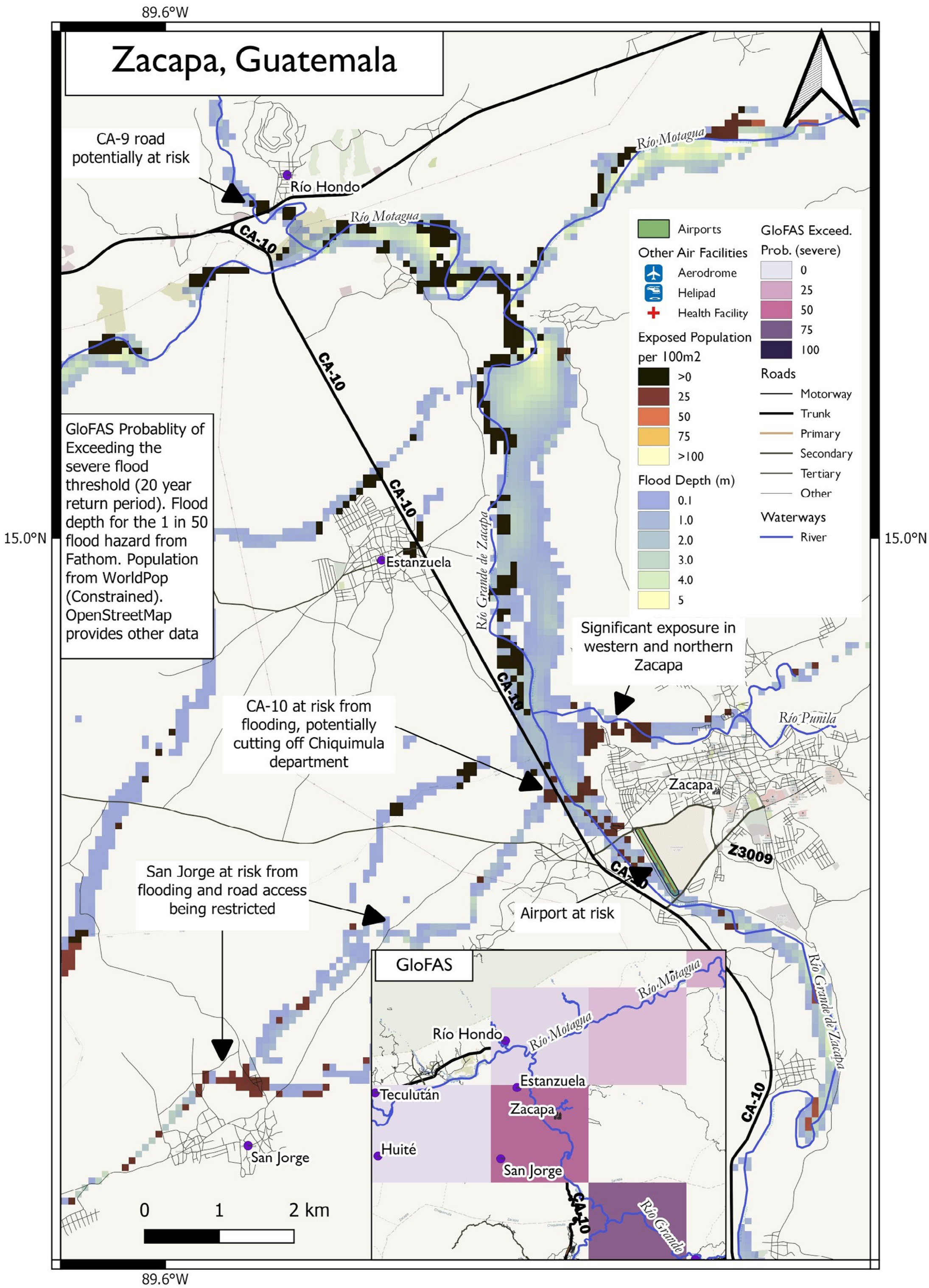

FIGURE 6 Example flood hazard map for Zacapa, Guatemala on the confluence of the Grande de Zacapa and Motagua rivers from 18 November illustrating identification of flooding to access roads. The map shows the 1 in 50 year flood hazard depth (blue to yellow) and the probability of exceeding the severe flood level (purples), which is high in this region (∼50%). Exposed population is shown (black to yellow), as well as roads and airports.

3.3.2 | Providing information at decision relevant scales in mountainous catchments

Multiple landslides, surface water flooding and flooding on smaller mountainous rivers occurred during Iota (Amnesty International, 2020; FloodList, 2020). This was of concern to humanitarian responders but these processes are not well represented in GloFAS which is only recommended for use in catchments greater than 1000 km^2 (Hirpa, Salamon, et al., 2018). By using knowledge of the large-scale situation from GloFAS and local gauged data (where available) some information could be provided on flood exposure for these regions by interpolating between known points. Information was also provided on flooding on access roads further down the river that could isolate mountainous communities (Figure 6). The focus on access roads was a pragmatic solution as many of the reported impacts of Eta and Iota involved road damage and closure which affects the ability to access and support affected communities (IFRC, 2021c).

3.3.3 | Use of real time observations to support interpretation of forecasts in Central America

The operational skill of GloFAS in Central America was largely untested before Iota. The interpretation of GloFAS forecasts was therefore based on model producers' knowledge of model performance in other catchments with similar hydro-meteorological drivers. An immediate "sense check" of the forecasts was conducted using publicly available rain gauge and hydrometric data from national agencies which was used to compare the observed flood situation with previous forecasts. Inundation and exposure estimates were compared to satellite imagery and available data (news reports, photos and videos) of impacts. Access to this information enabled forecasted producer to include an assessment of forecast confidence in the bulletins. The flood levels forecasted by GloFAS (event return periods) and flood exposures closely matched available observations in large river basins such as Ulua and Motagua. In addition, the available satellite data showed good agreement with the modelled flood inundation. One of the key risk areas highlighted in the bulletin was the River Chamelecón where floods of up to 2 m were reported which totally destroyed many properties along the river (IFRC, 2021c).

3.4 | Tropical Cyclone Eloise

Tropical Cyclone Eloise made landfall in central Mozambique, near Beira, on 23 January 2021 around 2 am local time (00:00UTC). The Sofala Province (of which Beira is the provincial capital) was still recovering from tropical cyclone Idai which had made landfall in the same region in 2019. In addition, many people were already displaced across the region following the impact of Tropical Storm Chalane 3 weeks earlier on 30th December 2020. Due to this, there was already an active humanitarian presence in the area. The World Meteorological Organisations (WMO) Regional Specialised Meteorological Centre La Réunion and the Mozambique National Institute of Meteorology (INAM) issued warnings of high winds, heavy rainfall and coastal flooding before Eloise made landfall (WMO, 2021b). Windspeeds of 140 km/h with gusts up to 160 km/h were reported by INAM along with 250 mm of rainfall in 24 h in Beira which resulted in flooding in the Buzi catchment and surrounding areas. Eloise continued to track southwest across Mozambique and into South Africa and Botswana over the following days (Reliefweb, 2021).

Figure 7 shows the maximum flood return period exceeded in the GloFAS-ERA5 reanalysis for Eloise and Figure 8 shows the forecast peak surge.

Eloise did not meet the trigger specified in the Mozambique Early Action Protocol on Cyclones (IFRC, 2019) at the pre-defined decision-time 3 days before landfall, however based on the information from national authorities and international forecast models (including the forecast bulletins reported here), the Mozambique Red Cross (CVM) decided to deploy a readiness team to Beira and to the bordering Province of Ihambane (IFRC, 2021a). Flooding affected large parts of the city of Beira and surrounding agricultural regions

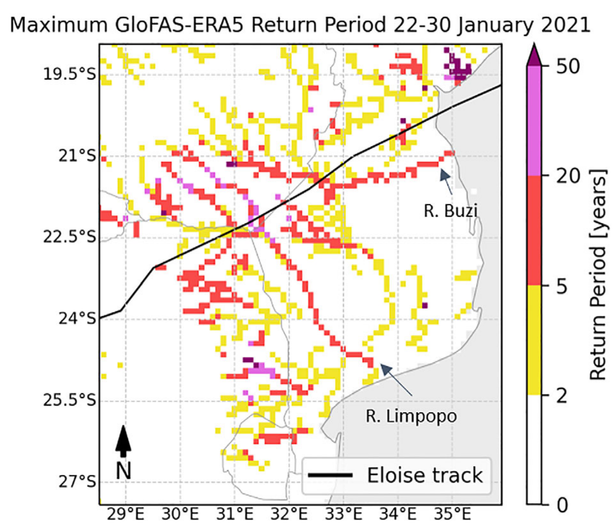

FIGURE 7 Maximum GloFAS-ERA5 return period 22nd January—30th January 2021. The purple colours indicate the expected locations of the most severe inland flooding. Labels identify major river of interest.

(Frey, 2021). Although widespread, it was not as severe as the flooding from Cyclone Idai in 2019 (Figure 11).

Following the flooding in Sofala province, there was a second phase of impacts in Southern Mozambique centred on the Gaza province. The heavy rainfall following Cyclone Eloise, combined with existing high water levels and full upstream dams meant that on 1st February the observed water level on the Limpopo reached the trigger of the Limpopo Flood Early Action Protocol (IFRC, 2020b), the flood peak was expected to reach the district of Chokwé on February 4th (IFRC, 2021b). The Mozambique Red Cross (CVW) responded by distributing early warning messages, assisting in the evacuation of vulnerable communities, reinforcing housing structures and distributing jerry cans and WASH and COVID-19 hygiene kits.

OCHA reports there were 12 deaths from Eloise (one in Madagascar and 11 in Mozambique) with more than 467,000 people affected (UN OCHA, 2021) and 56,000 houses severely damaged or destroyed (International Organisation for Migration, 2021) across Madagascar, Mozambique, South Africa and Zimbabwe. Mozambique's central provinces, which were still recovering from the devastation wrought by Cyclone Idai in 2019, were hardest-hit (UN OCHA, 2021).

3.5 | Eloise forecast bulletins

GloFAS identified the potential of impactful flooding as early as 14th January (9 days before landfall, Figure 10) and internal discussions with FCDO started at this point. The first full bulletin was produced on 22nd January, the day before landfall (Table 4).

For the forecast of cyclone surge, a regional TELEMAC-2D model was available covering the full east coast of Mozambique and the Mozambique Channel. The cyclone surge forecast was up to 2 m in the vicinity of Beira but coincided with neap tide so that the forecast peak water level remained less than the highest astronomical tide (Figure 8). Therefore, widespread coastal flooding was not expected, and, from anecdotal reports, this appears to have been the outcome. No quantitative reports of peak sea levels were available to validate the forecast. In contrast to Central America, the TELEMAC-2D model resolution was 1 km along the Mozambique coast, made use of good quality digitised nautical chart data and was validated in its representation of the tide. This allows greater confidence in the surge forecast for Eloise compared to Iota.

Humanitarian partners on the ground, such as the Red Cross Movement, received the bulletins and were able to utilise them for the purpose of early, informed decision-making alongside other international and national forecasting products. Of particular benefit was the identification of two distinct phases of impacts and the flood extent maps:

> The bulletins put the FbF [Forecast based Financing] mechanism in Mozambique on alert, signalling early on with significant lead time that precipitation related to TC Eloise would lead to flooding in the Limpopo river basin, long before national hydrological forecasts reflected this. The information allowed the Mozambique Red Cross and Governmental partners to focus multi-hazard anticipatory actions two-fold: On Cyclone impact close to Beira, as well as associated flooding in southern Mozambique. The bulletin's flood extent maps, indicating critical infrastructure forecasted to be impacted by the flooding, were used in overlay with Mozambique Red Cross's composite vulnerability index to identify the districts for anticipatory action interventions.
>
> Anna Lena Huhn, German Red Cross

3.6 | Key reflections from the Eloise post event review

3.6.1 | Building networks benefits local and global partners

Following the experience of producing flood bulletins for previous cyclones Idai and Kenneth in Mozambique (see Emerton et al., 2020), the bulletins benefitted from the existing relationships with national hydrometeorological organisations and humanitarian teams on the ground;

> We were in direct contact with the scientific team behind the bulletins and were able to be informed by them, as well as feedback information on national-level hydrological forecasts we received from our focal point at the national hydrological services DNGRH[1] from our end. It was good to see how the bulletins were evolving and started to reflect additional information coming from the team in the field.
>
> Jânio Dambo, Mozambique Red Cross

Eloise was the fourth major cyclone to make landfall in Mozambique in less than 3 years. It was evident that humanitarians had an existing awareness of the type of issues they would face and the important questions to ask

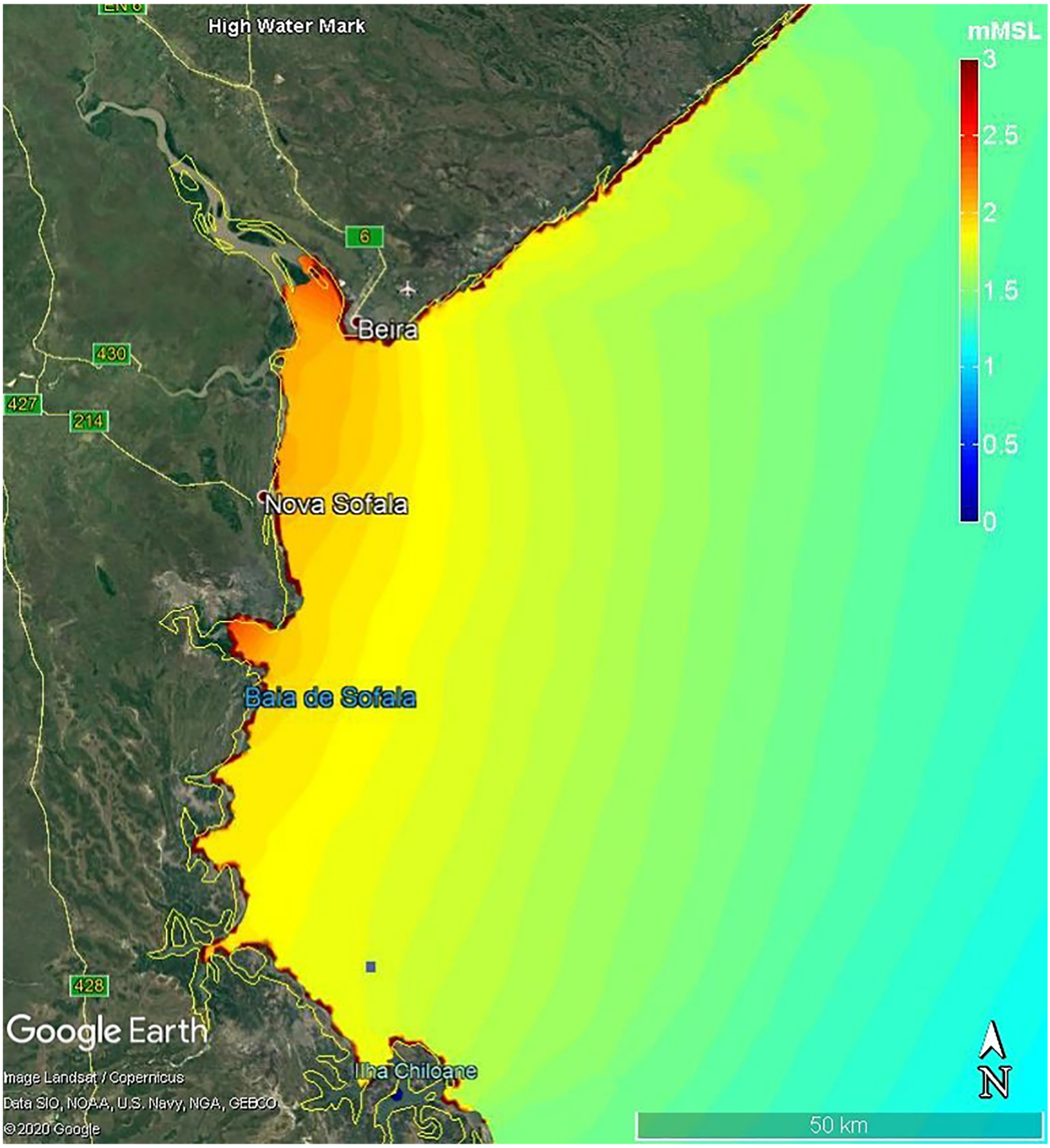

FIGURE 8 The maximum water level during Cyclone Eloise predicted by the Mozambique Channel TELEMAC-2D model.

the forecast translators. Demonstrating a growth in capacity since 2019 when a post event review of Idai reported that warnings were not taken sufficiently serious as individuals and organisations failed to appreciate the magnitude of the upcoming event (Norton et al., 2020).

3.6.2 | Flexibility helps to respond to user requests for contextual information

A key question from humanitarians during Eloise was how bad would the flooding be compared to Idai. The GloFAS forecasts (Figure 9) and exposure analysis (Figure 11) showed that Eloise was a much smaller event than Idai and this was communicated in the first and subsequent flood bulletins. The International Disaster Charter was activated to acquire satellite imagery for the Beira region by FCDO. Once these images were available, this distinction could be clearly communicated by overlaying the satellite observations of inundated area with population and Open Street map data for both events (Figure 10). Feedback from FCDO indicated this comparison was very useful as it made it clear that the response to Eloise was something that could be managed within the existing routine humanitarian response framework.

Meeting the immediate request for event comparison required flexibility from the bulletin producers, additional data processing and the availability of

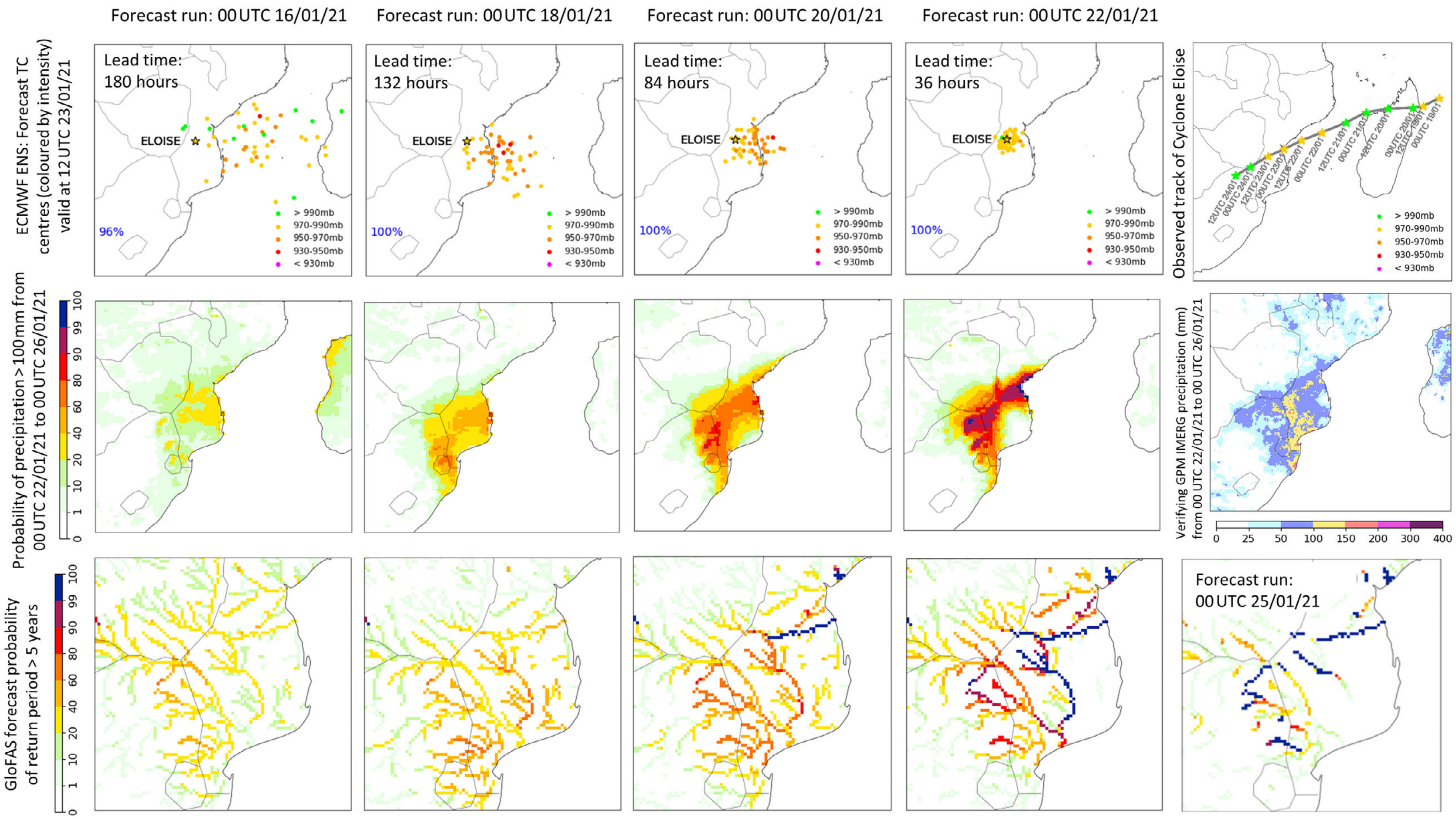

FIGURE 9 Eloise cyclone, rainfall and flood forecast evolution—in the top row the star shows the observed centre position of TC Eloise at 12:00UTC on 23rd January (12 h after landfall), the coloured dots show the forecast positions valid at this time from each EC ENS member. The percentages indicate the percentage of members that had a cyclone centre forecast within the frame. The far-right image shows the observed cyclone track. The second row shows the precipitation probability forecasts from EC ENS for 4-day event precipitation totals >100 mm, with the verifying GPM data for the same period in the far-right column. The bottom row shows the forecast GloFAS return period of exceeding the 5-year flood threshold, with an additional forecast from a post-landfall GloFAS run on the right.

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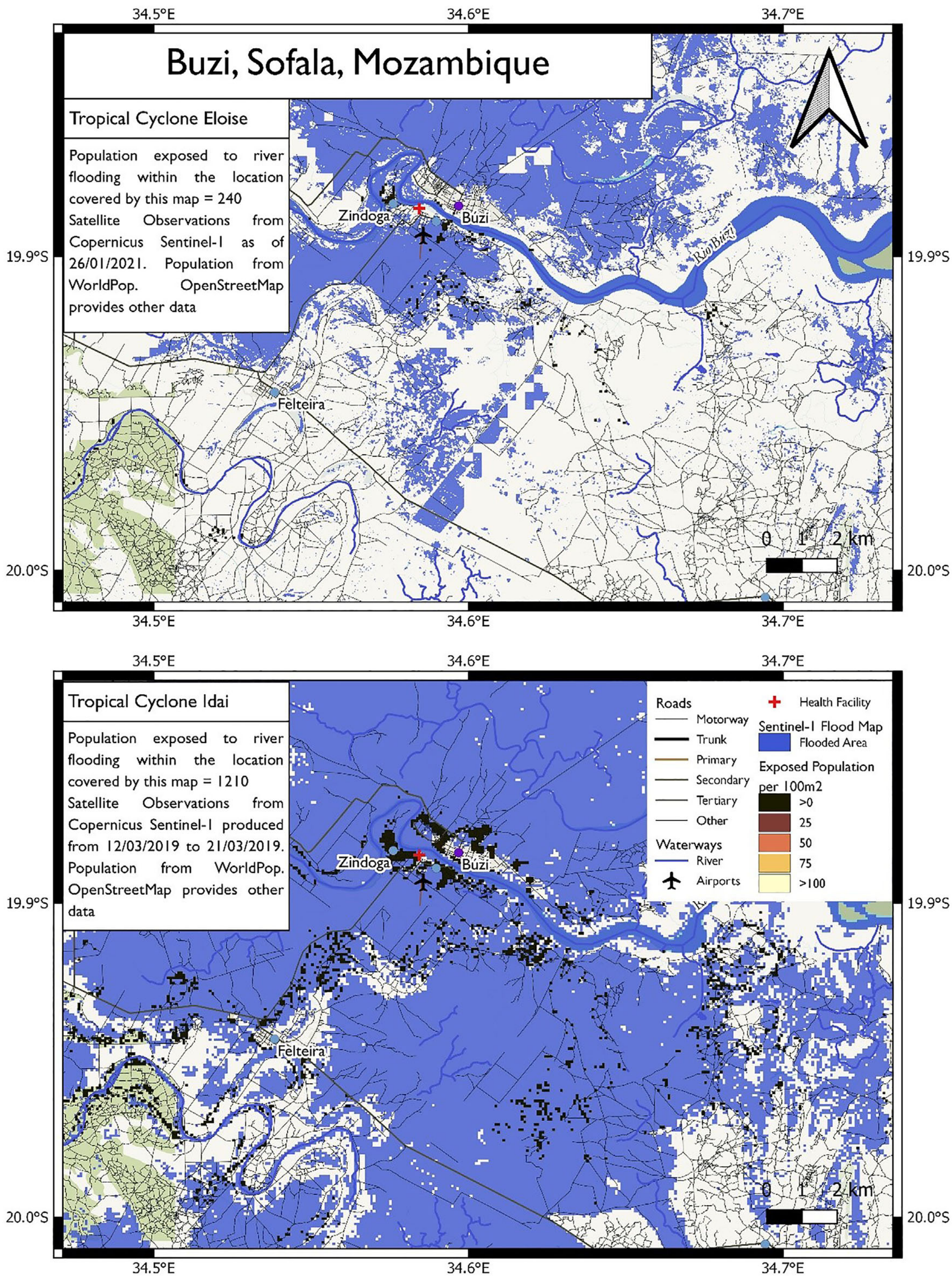

FIGURE 10 Flood inundation maps from Sentinel-1 for cyclones Eloise (top) and Idai (bottom) for the area in and around Buzi. Estimates of exposed population from the Fathom global flood model and WorldPop are overlaid on the Sentinel-1 imagery.

relevant datasets. Scientifically the comparison between Idai and Eloise was complicated, feedback from FCDO suggests this complexity was not fully appreciated by bulletin users. Eloise was a much smaller event than Idai, therefore there was more uncertainty in the inundation and exposure analysis as small differences in the topography or location of buildings and population would lead to large difference in the forecast exposure (Hawker et al., 2020; Smith et al., 2019). Furthermore, a substantial area of flooding related to seasonally flooded wetlands that are not considered by the global flood model,

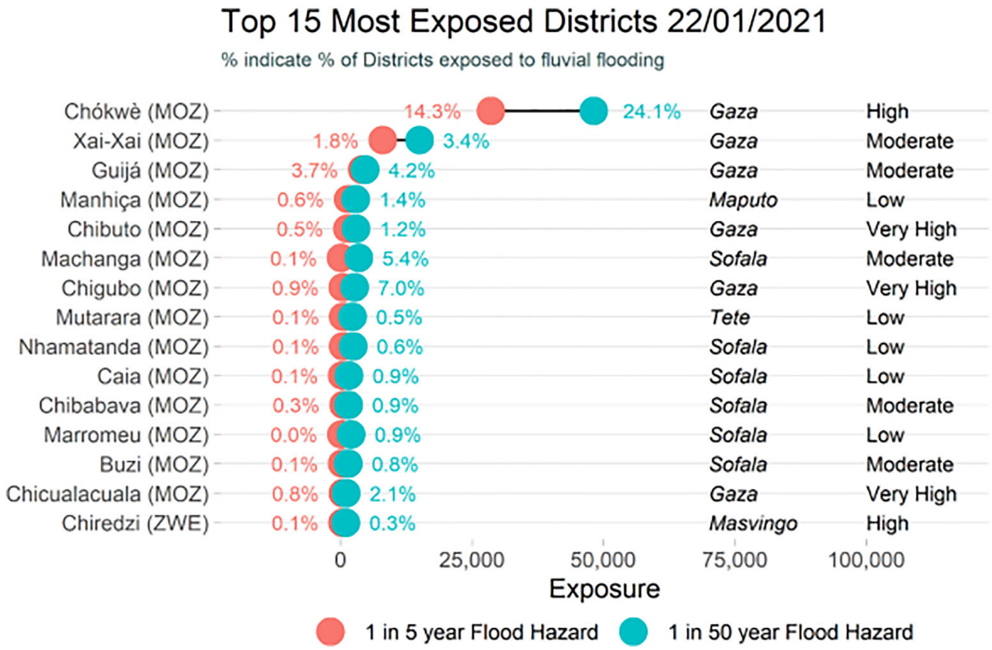

FIGURE 11 Forecast exposure of population by district from Eloise. Estimated exposure per municipality for a less extreme 5-year return period (red dot) to the more extreme 50-year return period (blue dot). The percentages indicate the proportion of the district population that could be exposed. The probabilities refer to the probability of exceeding the GloFAS severe alert threshold (20-year return period) and should be interpreted as: Very-high (expected) > 80%; high (probable) 50%–80%; moderate (possible) 25%–50%; low (unlikely) < 25%.

requiring auxiliary remote sensing data to characterise the floodplain pre-event.

3.6.3 | The value of combining global and local forecasts for the River Limpopo

GloFAS forecast the timing and magnitude of the flood peaks on the Buzi river well however in the Limpopo catchment the forecast was more challenging. First, the lead time of flooding on the Limpopo was much longer than on the Buzi. Recent research has shown that there is a lead time effect on flood thresholds in GloFAS (Zsoter et al., 2020) meaning events with a longer lead time can initially appear less or more extreme in some locations, and the bulletin producers manually incorporated this emerging research into their assessments. Second, a shift in the forecast on 24th January saw the severity of expected flooding on the Limpopo reduce. Third, and most significantly, GloFAS only has a rudimentary representation of dam management (ECMWF, 2022). The river Limpopo has multiple large dams upstream in South Africa and Zimbabwe which, if not at capacity, act to slow the timing of the flood peak and reduce the magnitude (Alfieri et al., 2013). Whilst the bulletin producers had access to some publicly available information on dam levels, there are national hydrological forecasts models available for the Limpopo which include real time observations of water level and therefore provide more reliable forecasts at short leadtimes. The bulletins clearly signposted readers to this stating 'Please refer to DNGRH for the most accurate forecast information for flood magnitude and timing along the Limpopo River, as this incorporates observations of upstream river levels'. Although GloFAS gave an early indication of the potential need to trigger the Limpopo EAP, local models were more reliable for predicting the timing and magnitude of flood peaks.

4 | DISCUSSION AND RECOMMENDATIONS TO IMPROVE THE USE OF GLOBAL FLOOD MODELS

The collaborative post event review process (Figure 1) highlighted areas where further research or investment is needed to make better use of global flood models to support humanitarian decision making. The recommendations in this section were included in a Learning and Recommendations report for FCDO in 2021 (Speight et al., 2021) and seek to identify specific actions and research requirements related to the use of global models. Recommendations for improving other aspects of forecast bulletin design, production and dissemination are discussed in Emerton et al. (2020) and Budimir et al. (2022).

4.1 | Work in partnership

Building effective flood forecasting systems requires working together, understanding user needs, being transparent about scientific limitations and developing strategies to effectively communicate risk (Harrowsmith et al., 2020; Hirons et al., 2021; Robbins et al., 2022; WMO, 2021a).

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TABLE 4 Timeline of Tropical Cyclone Eloise evolution and bulletin activity 12 January–1 February 2021.

Date	Hydro-meteorological situation	Bulletin activity
12th January	• Low-pressure weather system forms in south-west India	Internal discussion on potential need for bulletins started
19th January	• Eloise intensifies into severe storm • Makes landfall in Madagascar • Glofas identifies potential for high-impact flooding (Figure 10)	First briefing paragraph issued
21st January		Briefing paragraph issued
22nd January	• Eloise intensifies into a Tropical Cyclone • River levels already high due to wet start to rainy season • Mozambique Red Cross (CWM) send preparedness teams to Beira and Inhambane, and start to warn and support communities along the River Limpopo	First flood bulletin issued. Key messages: • flooding not expected to be as severe as Idai • Two stages of impacts expected, 23-26th in Sofala province, 25th onwards from the River Limpopo with the highest exposure in Gaza province (Figure 11)
23rd January	• Tropical Cyclone Eloise makes landfall near Beira • 24 hours rainfall 250 mm • Wind speeds of 140 km/h (gusts 160 km/h)	Briefing paragraph issued
24th January	• Tropical Storm Eloise reaches South Africa	Briefing paragraph issued. key message: • GloFAS forecasting a decrease in severity of flooding for the River Limpopo. For example the forecast percentage of population exposed in Chokwe district fell from a range of 14.3–24.1% (Figure 11) to 7.9–11.3%
25th January	• Tropical Storm Eloise reaches Botswana where it weakens	Flood bulletin. Key message: • Flooding on the Limpopo not expected to be as severe as 2013 floods
27th January		Last flood bulletin issues. Key massages: • River levels in Sofala province starting to fall. • Flooding on Limpopo expected in coming days • Upstream dams at capacity
1st February	• Limpopo Early Action protocol trigged from local model	

To provide useful information, forecast translators need to understand how forecasts are used in practice. For example, what are the key challenges for decision makers (Section 3.6.2), what lead time is needed to take anticipatory action (Section 3.3.1), what spatial scale do humanitarians need forecast information at and where are the main areas of concern (Section 3.3.2)? As advocated by (Emerton et al., 2020), maintaining some flexibility in being able to respond to specific questions is valuable, however it is more efficient to identify these questions in advance to enable collation of the required data sets and necessary processing time and skills (Section 3.6.2).

For many users it is difficult to articulate what forecast information is needed without understanding what can be provided given the logistical, scientific and technical constraints (Section 3.6.1). Similarly, for effective post event review, producers need to be clear about what type of feedback is needed and how it will be used. Methods of co-production (see Hirons et al., 2021), such as joint workshops outside of busy operational periods, are key to developing pragmatic solutions that can support decision making within the scientific constraints of global models (WMO, 2021a). For some regions, these topics are already being discussed through the joint development of Early Action protocols and globally partnerships are developing through platforms such as the Anticipation Hub (https://www.anticipation-hub.org/) and research programmes such as SHEAR (http://shear.org.uk/). This network building activity is critical to support the increased effective use of humanitarian forecast based decision making.

4.2 | Provide accessible documentation to support interpretation of bulletins

During major events humanitarians are faced with multiple sources of information. Decisions were not made based on the flood bulletins in isolation. Training and supporting documentations around the strengths and limitations of the global models used and the supporting data sets is required (Alfieri et al., 2018; Ward et al., 2015). The strengths and limitations of any model or data set will not be the same for every event or for all regions of the world. Where local forecast models, which are calibrated based on observations, are available they will usually perform better than global models and this should be clearly signposted to users (Section 3.6.3). The daily discussions with FCDO were invaluable to communicate this local and event specific context.

There were multiple users of the flood bulletins with varying skills in forecast-based decision making. For both Eloise and Iota strategic decision makers used the summary information on the front page whilst the data specialists were interested in the technical figures and asked questions about model uncertainty and comparisons between different population data sets. Technical guidance documents were produced containing information about the methodology, model skill and underlying datasets to share with bulletin users interested in this additional level of detail. To support informed decision making and help increase capacity for interpreting global forecasts this information should be easily accessible alongside the flood bulletins.

4.3 | Improve synergies between global models and local contexts

Information which could support the development and interpretation of impact-based forecasts is from disparate sources, often not easily accessible, and information holders are not necessarily aware of its value to others. Improved global data sharing is essential for the continued improvement of global flood models (Lavers et al., 2019, 2020). During bulletin production access to available in-country data provided valuable information to inform interpretation of the global model forecasts, for example data on vulnerable populations, local knowledge of catchment characteristics, the current operational status of dams and reservoirs and observed river levels before and during the event (Sections 3.3.3, 3.6.1 and 3.6.3). The availability of real time observations of river levels and reported impacts offered a pragmatic approach to incorporate an immediate sensibility check of the model forecasts and helped support post event review. The time forecast translators spent collating such information during events was considerable. In Mozambique the process benefitted from existing established links with the German Red Cross who were receiving information from DNGRH (Section 3.6.1). The dissemination of the flood bulletins also played a valuable role in communicating in country information that was not freely or readily available to all decision makers (Section 3.6.3).

For global forecasting groups building relationships with organisations who may hold this information will help increases access to data. All parties would benefit from building and maintaining a meta-database of links to in country data and integrating this into existing global platforms for data sharing.

4.4 | Improve application of existing and emerging research and knowledge

A strength of the bulletins is their ability to flexibly incorporate emerging developments into global forecast systems, for example TC Eloise demonstrated the advantage of using fine resolution, validated regional surge models where available and highlighted the need to develop higher resolution global coastal models. Understanding of the lead time dependent thresholds of Zsoter et al. (2020) illustrated in (Section 3.6.3) improved the usability of GloFAs forecasts. Further work by Titley et al. (2023) analyses the link between cyclone track and flood forecast skill for Iota. Ongoing updates to the flood hazard model at Fathom and UoB (e.g. Bates et al., 2021; Neal et al., 2021; Zhao et al., 2021) bring regular incremental improvements in accuracy, and joint work with ECMWF as part of this project enabled the inundation maps to be based on the full GloFAS ensemble rather than percentage chance of exceeding a threshold.

One of the challenges of using global flood models in this context is that the existing skills metrics do not necessarily reflect the criteria that are important to decision makers (see Section 4.5). A real time expert assessment of confidence should therefore be included in forecast bulletins based on the predictability of the meteorological situation (Harrigan, Cloke, & Pappenberger, 2020; Lavers et al., 2021; Titley et al., 2021) and understanding of how well the model represents hydrological processes (Alfieri et al., 2013) for the region of interest, the consistency of the forecast over time (Section 3.3.1), and any observations on how the model forecasts compare to observed flows or real time impacts (Section 3.3.3).

Whilst the bulletins have attempted to communicate this assessment, the process was ad hoc and much of the expertise remains tacit. The depth of understanding of GloFAS contained within the team, alongside active involvement in ongoing joint research on the operational use of GloFAS (e.g. Budimir et al., 2022; Coughlan de Perez et al., 2016; Emerton et al., 2020; Ficchì et al., 2021; Hirpa, Pappenberger, et al., 2018; Hossain et al., 2023; Robbins et al., 2022) and global flood modelling (e.g. Emerton et al., 2016; Harrigan et al., 2023; Harrigan, Zoster, et al., 2020; Lavers et al., 2020; Towner et al., 2019; Zsoter et al., 2020) enabled valuable expert interpretation. This contrasts to other areas of hydro-meteorology where models are more developed and there are limits to how much additional value forecast translators can add to model output using their own expertise compared to the inbuilt skill of the forecast models (Pagano et al., 2016). However, the small group of experts that currently process this knowledge limits the number of events that forecast bulletins can be produced for and potentially acts as a gatekeeping process for the wider effective use of global models by decision makers. Therefore, research that has been shown to have operational impact should be communicated widely and prioritised in model updates.

Funding for future model developments is contingent on evidence of impact. The increasing use of global models to support decision making provides an opportunity to identify this. By combining available data (Section 4.3) with focused user feedback (Section 4.1) and emerging best practice on methodologies for post event reviews in data sparse contexts (HiWeather, 2022; Magnusson, 2019; Venkateswaran et al., 2020), a valuable learning database is developing which will help build confidence and skills in the use of global forecasts for decision making.

4.5 | Develop action-based forecast skill assessment to support improved decision making

The applied nature of the bulletin development has offered a unique opportunity to identify directions for future research informed by operational needs. The most significant is the need to develop an operationally informed forecast skill assessments in regions with limited data.

The decision to trust available global forecasts would be easier if users could easily compare the output and skill of different approaches (Alfieri et al., 2018; Towner et al., 2019, and Section 4.2). A major limitation of global models such as GloFAS is that although they have been calibrated for hundreds of river catchments covering a range of global climates (Hirpa, Salamon, et al., 2018), they have not been calibrated for all countries where a humanitarian response might be activated as observation data are not easily available (Lavers et al., 2019). Where data are available, attempts have been made to assess global skill (Harrigan et al., 2023; Harrigan, Zoster, et al., 2020) and skill metrics are published on the GloFAS website (ECMWF, 2021). However, these global skill assessments often focus on the skill of the forecast model over the full range of flows from droughts to floods and can be of limited value to assess the skill during large flood events. Global flood models are increasingly being used by humanitarians to support the development of Early Action Protocols (Coughlan de Perez et al., 2015, 2016; Nauman et al., 2021). In these situations, a decision-based skill assessment for the country or location of interest is undertaken (Coughlan de Perez et al., 2016; Ficchì et al., 2021; Hossain et al., 2023; Lala et al., 2021; Lopez et al., 2020).

Impact based forecasts require linking hydrological and coastal models with flood inundation models to simulate hazard. As such flood forecast inundation maps embody multiple sources of uncertainty, one specific example is the downscaling of GloFAS to the 90 m resolution used in the inundation mapping to provide information at a decision relevant scale (see Appendix A). The performance of inundation models is often very site specific and building up a representative sample of events to make general statements on model performance is a long and ongoing process (see Bernhofen et al., 2018; Hawker et al., 2020; Trigg et al., 2016).

The continued development of pragmatic solutions to assess the suitability of global models for countries of interest in the absence of observation data will require collaboration (see Section 4.1). Any such assessment should consider forecast skill from a user perspective (Parker, 2020), covering aspects of consistency, quality and value (Murphy, 1993) and considering how the derived metric could be used to improve decision making during events (Lopez et al., 2020; Werner et al., 2016). Such an assessment is further complicated by the need to assess the skill of both the hydro-meteorological components and the inundation and exposure assessments. This is especially challenging as there is no systematic approach to impact reporting on a global scale (Robbins & Titley, 2018). Recent innovations (e.g. Mitheu et al., 2022) are starting to use historical re-forecasts and observed flood reports to evaluate skill for past events in ungauged basins for both the flood and inundation model components for specific locations. These approaches should be modified for use in global models.

5 | CONCLUSIONS

In the absence of global hydrological observations, it continues to be difficult to evidence the skill of global flood models. The case studies presented here for Tropical Cyclones Iota and Eloise, as well as the previous experience of producing flood bulletins from Idai and Kenneth

(Emerton et al., 2020), show that despite their well-documented limitations, global flood models are a valuable resource for humanitarians. The access to computationally expensive probabilistic information and increased lead time with respect to local models is appreciated by decision makers and FCDO reported that humanitarian colleagues are appreciative and excited by the expertise and insight this pilot project has enabled during TC flooding events.

The effective use of global models currently requires understanding of their strengths and weakness in conjunction with access to local data to provide information at a scale that can support local humanitarian action. Long term funding is required to support the development of close research and operational collaborations to improve the linkages between expert knowledge and forecast interpretation. The increasing use of global forecasting systems highlights an urgent need for innovative development of user relevant metrics to assess the skill and value of global models, particularly in ungauged catchments.

Multiple global models are available (Emerton et al., 2016), they are a valuable resource and should be used more effectively. With continued communication and co-ordination between people, organisations, models and data, global forecasting systems can improve humanitarian decision making. And in turn, the increased use of such systems will inform and motivate further development of forecasting capabilities at local and global scales. To achieve this, reliable funding to support the long-term development of the skillsets, partnerships and tools advocated in this paper is required.

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DATA AVAILABILITY STATEMENT

Real-time GloFAS forecast products are freely available at www.globalfloods.eu, and GloFAS data can be obtained through the Copernicus Emergency Management Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/provider/provider-cems-without?tab=overview). ECMWF ENS forecast data are available through the TIGGE archive (https://www.ecmwf.int/en/research/projects/tigge). The Global TELEMAC-2D model is open source (http://www.opentelemac.org/). The IMERG satellite rainfall data can be downloaded from NASA (https://gpm.nasa.gov/data/imerg) and the observed tropical cyclone data from IBTrACS (https://www.ncdc.noaa.gov/ibtracs/). The LISFLOOD-FP code is freely available from http://www.bristol.ac.uk/geography/research/hydrology/models/lisflood/, and the global flood inundation maps used in this study are available upon request from Dr Jeffrey Neal or Dr Laurence Hawker. WorldPop data is available from https://www.worldpop.org/.

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ENDNOTES

[1] DNGRH stands for Direcção Nacional de Gestão de Recursos Hídricos, the National Directorate of Water Resources Management in Mozambique

[2] The GloFAS version used during the case studies was v2.2. GloFAS was subsequently upgraded to v3.1 in May 2021 and v4.0 in July 2023

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APPENDIX A: FORECAST METHODS

A.1 | Coastal forecasts of storm surge

Since the original bulletin production for Cyclones Idai and Kenneth in 2019 (Emerton et al., 2020), an approach for storm surge modelling was added to the procedures in response for the subsequent need for coastal flooding information for Cyclone Amphan which affected India and Bangladesh in 2020 (Table A1).

The surge forecast uses the open-source hydrodynamic model, TELEMAC-2D (Hervouet, 2007, www.opentelemac.org). The model is forced with wind and pressure fields generated from cyclone track forecasts produced by relevant meteorological agencies such as the Joint Typhoon Warning Centre (JTWC) and Regional Specialized Meteorological Centers: the National Hurricane Center in Miami, Météo France in La Réunion and the Indian Meteorological Department in New Delhi. For regional models, tidal water levels and currents are applied at the boundaries of the model. Internal forcing

TABLE A1 Data sets used in forecast models.

Source	Used in	Description	Spatial resolution	Further information
GloFAS	Fluvial flooding forecast	Produced by ECMWF on behalf of the EU Copernicus service, hydro-meteorological forecasts force a global river routing model	0.1° × 0.1° (~10 km)	https://www.globalfloods.eu/
ECMWF IFS forecast model	Fluvial flooding forecast and meteorological summary	51 member numerical weather prediction ensemble used in GloFAS and meteorological summary	~18 km	https://www.ecmwf.int/en/publications/ifs-documentation https://www.ecmwf.int/en/forecasts/documentation-and-support
GEBCO bathymetry	Coastal surge modelling	Ocean bathymetry used in surge model	15′ × 15′ (~500 m)	https://www.gebco.net/ GEBCO (2020)
Topography	Coastal and fluvial flood modelling	Global elevation data from MERIT DEM	90 m	http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/ Yamazaki et al. (2017)
JTWC cyclone track forecasts	Coastal surge modelling	Forecast cyclone tracks in Indian Ocean and western Pacific Ocean	-	https://www.metoc.navy.mil/jtwc/jtwc.html
NHC hurricane track forecasts	Coastal surge modelling	Forecast cyclone tracks in North Atlantic, Caribbean, eastern and central Pacific	-	https://www.nhc.noaa.gov/
MeteoFrance cyclone track forecasts	Coastal surge modelling	Forecast cyclone tracks in southeast Indian Ocean	-	http://www.meteofrance.re/cyclone/activite-cyclonique-en-cours
Fathom Global 2.0	Fluvial flooding forecast	Flood hazard layers used to predict inundation extent	~90 m	https://www.fathom.global/fathom-global
WorldPop (Constrained 2020)	Flood exposure analysis	Population per 100 m grid-cell, constrained by building footprint. Global coverage	3 arc second (~90 m)	https://www.worldpop.org/geodata/listing?id=78
Humanitarian OpenStreetMap	Flood exposure analysis	Geographic data on infrastructure (e.g. roads) and key amenities (e.g. health facilities)	Vector data	https://www.hotosm.org/
Humanitarian Data Exchange	Flood exposure analysis	Geographic data on infrastructure (e.g. roads) and key amenities (e.g. health facilities)	Variable	https://data.humdata.org/

from the gravitational effects of the moon and sun is also included.

A.2 | Fluvial forecasts

The fluvial flood forecast uses the Global Flood Awareness System (GloFAS,[2] www.globalfloods.eu), an early warning component of the European Commission Copernicus Emergency Management Service (emergency.copernicus.eu). Using a 51-member forecast ensemble from the ECMWF Integrated Forecast System (IFS), the GloFAS web interface produces a probability of exceeding three different flood severity thresholds corresponding to the 2-, 5-and 20-year return period (referred to as medium, high and severe respectively) at every grid point along the global river network out to 30 days ahead (Alfieri et al., 2013). GloFAS is designed to simulate large scale hydrological systems, predictions for smaller catchments (generally consider to be less than 1000 km^2) should be evaluated with caution due to limited calibration (Hirpa, Salamon, et al., 2018). Skill is also known to be lower in areas where large amounts of water can be stored naturally within the river system (e.g. in flat waterlogged areas, rivers with inner deltas and braided channels), in arid regions (Alfieri et al., 2013) and where water management features such as dams are utilised (Zajac et al., 2017).

A.3 | Inundation modelling

A global flood inundation model framework (Sampson et al., 2015) estimates riverine flooding at ~90 m resolution for all basins with an upstream area >50 km^2 using a sub-grid hydrodynamic model within the LISFLOOD-FP code (Neal et al., 2012). The inundation model has been updated from the original reference by using MERIT DEM (Yamazaki et al., 2019) and MERIT HYDRO (Yamazaki et al., 2019) and most recently FABDEM (Hawker et al., 2022). A regionalised flood frequency analysis (Smith et al., 2015) provides model boundary conditions to produce flood hazard maps for different return periods.

For river flooding direct coupling of GloFAS with the flood inundation model is not possible given the large spatial area and short-time frames needed to produce results. As such, the inundation analysis selects a range of return period(s) inundation maps to align with the spread of estimates produced by the GloFAS ensemble, thus keeping the value of this probabilistic information. To estimate storm-surge flooding water levels along the affected coast are extracted from TELEMAC2D model and then applied to the boundary of the LISFLOOD-FP inundation model.

Dams, flood defences and wetland processes are not included in the inundation model as reliable data on these are difficult to obtain at large scale (Hawker et al., 2020). The flood inundation model struggles to model frequent flood events (return periods <20 years) as it is difficult for the model to capture anthropogenic change, and the model has a greater sensitivity to discharge, channel conveyance and topography errors for smaller flood events (Quinn et al., 2019).

A.4 | Exposure analysis

Leyk et al. (2019) describe the various available gridded population datasets available and their differences. The techniques to distribute population onto grids have improved markedly in recent years (Leyk et al., 2019; Stevens et al., 2015), especially with the addition of building footprints. For the bulletins, we used the WorldPop Constrained 2020 UN (WorldPop, Stevens et al., 2015; Bondarenko, Kerr, Sorichetta, & Tatem, 2020; Bondarenko et al., 2020) dataset, chosen as the most up-to-date global dataset constraining population to building footprints, which results in a better estimate of exposure, especially in rural areas (Smith et al., 2019). Despite the latest census data being used, the dataset is limited by the timeframe of the census data (e.g. Mozambique uses 2017 census data), and thus may not take into account the latest population movements, which can contain some of the most vulnerable people that have been displaced.

Population exposure due to fluvial flooding is estimated by combining GloFAS forecast probabilities of exceeding the flood alert thresholds, with flood inundation and population information, following the method developed for Cyclone Idai (Emerton et al., 2020). Population exposed due to coastal flooding is calculated by intersecting population data with a binary flood map from the coastal flood simulation.