Weather and Climate Extremes 36 (2022) 100462

Contents lists available at ScienceDirect

Weather and Climate Extremes

journal homepage: www.elsevier.com/locate/wace

High-impact weather and urban flooding in the West African Sahel – A multidisciplinary case study of the 2009 event in Ouagadougou

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ARTICLE INFO

Keywords:
West african sahel
Ouagadougou
High-impact weather
Flood
Urban
Multidisciplinary

ABSTRACT

On September 1st 2009 an extreme high-impact weather event occurred in Burkina Faso that had significant impacts upon the capital city Ouagadougou and its inhabitants. Subsequent reporting and research has however not focused on the contributing socio-economic and hydrological factors and the role of global warming and climatic change remains uncertain. This reflects a paucity of evidence attributing such extreme weather events to climate change for the West Africa region and limits the knowledge base for urban planning to climate-related risks which pose serious threats. This case study provides a holistic assessment of the most extreme urban hydrometeorological event recorded in the West African Sahel, that links synoptic conditions to climate change and through to hydrological impacts on vulnerable urban populations. The intention is to inform regional decision-makers on climate change and flood-generating high-impact weather events at the urban scale and to bridge the gap between what scientists understand as useful and decision-makers view as useable at the city scale by providing interdisciplinary answers to key questions raised by local stakeholders.

Such an approach was shown to foster enhanced dialogue and engagement with stakeholders, while also providing a focus for communicating science at variable time- and spatial scales and between disciplines to improve understanding of how global processes have localised consequences. This reveals that Ouagadougou remains vulnerable to climate change and that such extreme weather events will become more frequent. But it is also demonstrated the complexity of attributing extreme events at such localised 'urban' scales to atmospheric phenomena affected by global climate change. Regional climate models are evolving and becoming more able to represent such extreme weather phenomena at suitable scales, enabling improved representation of climate-driven changes on such events, improving the ability for short-range forecasts in the future. Frameworks for managing flood risks however remain weak and under-resourced and there is limited capacity to manage flood risk from such events, particularly when rapid urbanisation amplifies vulnerability concerns. Recommendations are made to improve flood-resilience to future storms.

1. Introduction

There has been increasing attention paid to the rising impact of floods on lives and livelihoods in Africa during the latter part of the 20th century and into the 21st century (Jonkman, 2005; Di Baldassarre et al., 2010; Giugni et al., 2015). The West African Sahel is emerging as under particular threat as a tropical semi-arid region with recent changes in rainfall regimes and land-use being linked to hydrological and related socio-economic impacts (Mahe et al., 2005; Panthou et al., 2018).

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https://doi.org/10.1016/j.wace.2022.100462
Received 21 September 2021; Received in revised form 28 April 2022; Accepted 29 April 2022

Abbreviations

HIW	High-impact weather
AMMA-2050	African Monsoon Multidisciplinary Analysis
MCSs	Mesoscale convective systems
WAM	West African Monsson
AEWs	African Easterly Waves

Regional increases in flood magnitude and frequency (Wilcox et al., 2018) have been linked to changes in extreme rainfall (Panthou et al., 2014) that could well explain such trends (Nka et al., 2016) alongside land use and cover changes (Gal et al., 2017). Urban areas are particularly vulnerable to such extreme high-impact weather (HIW) events, particularly informal settlements situated in areas that are natural flood basins with little hydraulic infrastructure to manage storm runoff (Douglas, 2017). A projected tripling of the regional urban populace (UN, 2018) coupled with projected future increases of extreme rainfall frequency and magnitude (Sylla et al., 2015; Akinsanola and Zhou, 2018) pose serious threats for urban inhabitants in West Africa.

Enabling climate information to be useful, useable and used requires addressing constraints in accessibility, scale and institutional practices (Boaz and Hayden, 2002). This requires active engagement of both producers and users of the information (Cash et al., 2003) and multi-disciplinary approaches synthesising interdisciplinary knowledge (Hewitt et al., 2020). Case studies of HIW events, linking hazard to impacts, are one way of addressing the ‘usability gap’ (Lemos et al., 2012). HIW events enable scientists to consider a range of drivers interacting to create a specific hazard, while also enabling decision-makers to better understand the role of climate-change at relatable scales (Stott et al., 2016).

Ouagadougou, capital of Burkina Faso, is characteristic of the HIW challenges faced by rapidly developing regional cities. A record 24hr rainfall of 263 mm on September 1st 2009 (Lafore et al., 2017a) caused widespread flooding and loss of life (Dos Santos et al., 2019). Studies at the urban scale of Ouagadougou have considered the event from flooding (e.g CLUVA project: Giugni et al., 2015), meteorological (e.g. Lafore et al., 2017a; Engel et al., 2017), and disaster response perspectives (e.g. UNDP, 2010; PRISE, 2017). However, these localised urban and event-scale hazards and impacts have not been considered collectively or involved consideration of regional warming (e.g. Taylor et al., 2017; Panthou et al., 2018). This reflects a paucity of evidence attributing such HIW events to climate changes for the region (Stott et al., 2016). This, in turn, limits the knowledge base to draw upon for urban planning for decision-makers who require useable climate information that can ‘fit’, or appropriately inform, climate risk management and adaptation planning (Lemos et al., 2012). A HIW case study focused on such an urban location in the West African Sahel provides a context for scientists and decision-makers to consider possible ways for strengthening management of regional flood risk and for framing climate change projections of extreme weather within a relatable framework of local experience.

This case study on the 2009 event was undertaken by the African Monsoon Multidisciplinary Analysis (AMMA-2050) project (AMMA 2050.org) consortium and provides a holistic assessment of one of the most extreme urban hydrometeorological events recorded in West Africa. It was borne out of project inception meetings with regional project partners who highlighted local knowledge needs on HIW floods events such as the 2009 flood, particularly in urban areas, to inform planning. Furthermore, through a series of workshops and meetings (https://www.amma2050.org/content/meetings) with local decision makers and engineers spanning 2014–2019 (including from: Mayor’s office, Ministry of Urbanism, and Directorate General of Water Resources) it was clear the 2009 event remained the basis for flood planning and that multidisciplinary information for capacity building on HIW events was required (e.g. Visman et al., 2016; Karimbiri et al., 2018). These information needs were wide ranging, but particular questions and discussions concerning local climate change, flooding, and the 2009 event, that were raised included: i) the rarity of the event, ii) the role of climate change, iii) forecasting, iv) past and current preparedness, and v) future climate change, vi) knowledge gaps, and vii) actions needed.

This paper takes an interdisciplinary view of the 2009 event, its impacts and its climatic context. We integrate published evidence in different specialist fields with new data to support interdisciplinary links. The aim is to inform regional decision-makers on climate change and flood-generating HIW events at the urban scale in the West African Sahel. There are four objectives to support this aim: i) contextualize meteorological drivers with respect to observed regional climate, ii) assess the hydrological response: iii) consider the socio-economic impacts and urban context, and, iv) consider the role of projected climate change. For each objective, the paper seeks to outline possible links between regional and local factors, and to consider the current state of knowledge and adaptation. The paper then synthesizes our understanding from these interdisciplinary contexts to address certain questions, listed above, that emerged during the stakeholder engagement process.

2. Meteorological context

Ouagadougou is located in the southern Sahelian region that experiences most rainfall during the West African Monsoon (WAM) season (June–September) when the northward migration of the rain band and associated weather conditions provide favourable conditions for intense storms to develop (Fig. 1). A major feature of the WAM is the large meridional gradient of climate between the dry, hot, Sahara to the north and the more humid, cooler, Guinea coast to the south – and in between lies the Sahel where the gradient of temperature and water vapour is the greatest (Thorncroft et al., 2011). The gradient maintains a mid-level jet, named the African Easterly Jet (AEJ), which is the main stream for convective development (Parker et al., 2005). The AEJ maintains the growth of the major synoptic-scale (4–7 days, a few thousand km) disturbances over West Africa, namely African Easterly Waves (AEWs) (Leroux and Hall, 2009). During the WAM most rainfall in the Central Sahel rainfall domain (Fig. 1) comes from large convective storms, referred to as mesoscale convective systems (MCSs). MCSs correspond to the aggregation of several deep convective cells into a single cloud system characterized by rainfall over a large area that can last from several hours to more than a day and typically propagate westward (Mathon et al., 2002). MCS are often embedded within AEWs developing along the AEJ as these waves provide favourable atmospheric conditions (wind shear and vertical velocity) for the development of MCSs (Poan et al., 2015) and precipitation arrival can further be modulated by large-scale atmospheric circulations and oceanic conditions (eg. Rowell, 2001).

Rainfall records for the Sahelian region suggest a rebound in mean annual rainfall during the 1980’s that arrested a period of falling annual totals since the wet 1950–1960’s decades (Panthou et al., 2018). Taking a more localised perspective Fig. 2 illustrates the temporal trends in the mean annual rainfall and extreme rainfall (defined as daily rainfall that occurs on average two times a year) as a proportion of annual rainfall over the Central Sahel during the 1950–2014 period, based on an reanalysis of 26 daily raingauges within a local context using methods detailed by Panthou et al. (2014, 2018). Since circa 2000 evidence suggests extreme rainfall as a proportion of annual rainfall has been increasing steadily. This shows that an important change in rainfall regime recently occurred in which extreme events are becoming more intense, and that since 2005 such intense events have consistently occurred each year.

The 2009 storm event in Ouagadougou corresponds to the most

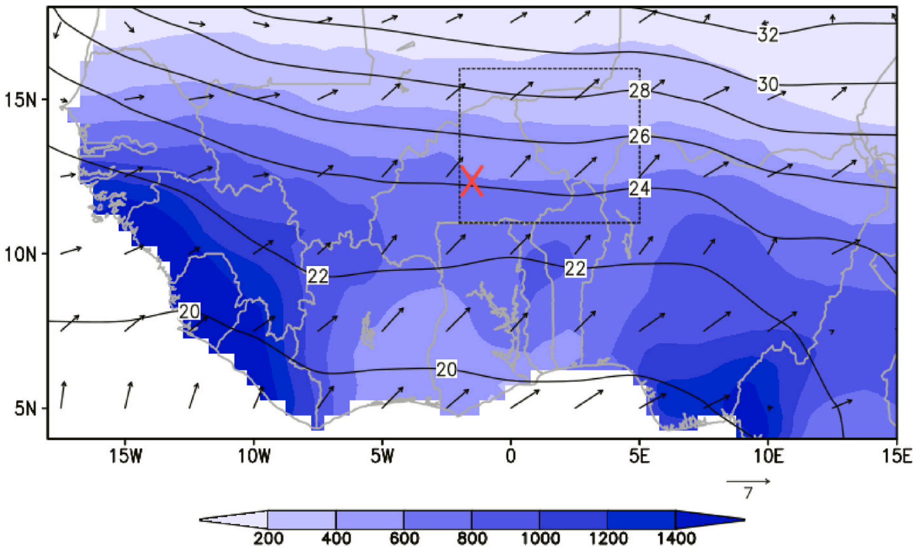

Fig. 1. Annual mean rainfall [shading; mm] from the Climate Research Unit, University of East Anglia. Contours and vectors depict June–September mean temperature [°C] and wind at 925 hPa according to ERA5 reanalysis. The location of Ouagadougou is marked with an X, and the dashed rectangle shows the Central Sahel rainfall domain.

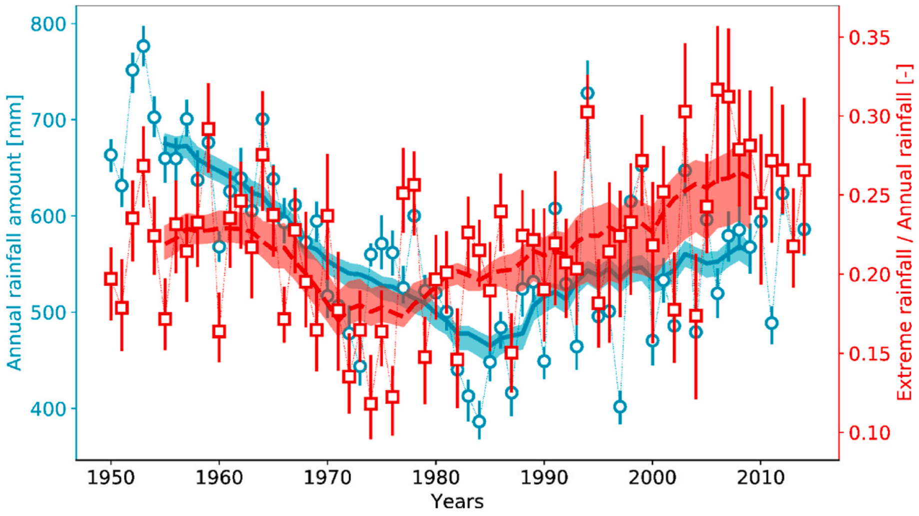

Fig. 2. Mean annual rainfall (left axis) and extreme rainfall (defined as daily rainfall that occurs on average two times a year) as a proportion of annual rainfall (right axis) over the Central Sahelian box [11–16°N, 2°W-5°E: see Fig. 1] during the 1950–2014 period (red symbols and corresponding 11-year moving mean shown with a red line; the cyan symbols and lines indicate the annual rainfall amounts). Data and method is from Panthou et al. (2014, 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

extreme rainfall event of the last fifteen years (with 263mm/24h) over the Sahel, and the third maximum daily rainfall recorded over the Sahel since the 1950s (Panthou et al., 2014). The extreme nature of the 2009 event, and the lack of suitable continuous records, complicates analysis of event rarity, a familiar regional situation (Tazen et al., 2018). An estimate of event rarity is provided here based on Generalized Extreme Value distributions fitted on both regional (Central Sahel) and local (Ouagadougou) series of rainfall annual maxima over the period 1950–2014 (see Panthou et al. (2012) for methodological details). Considering the range of uncertainty in derived values it is likely that the return period is between 500 and 5000 years and that it is in the region of around 1000 years.

From a meteorological perspective, the event was characterised by an intense MCS which evolved into a slow-moving moist vortex within only a few hours, between 31 August 2100 UTC and 1 Sept 0600 UTC (Lafore et al., 2017a). This is in contrast to much faster-moving systems which usually dominate the seasonal rainfall of this part of the Sahel (Lafore et al., 2017b). The slow movement of the 2009 event certainly contributed to the high accumulated rainfall and Fig. 3 illustrates the scale and intensity of the event as the MCS reaches Ouagadougou around 0600 UTC using 3-hourly satellite data available to weather-forecasters. It is noticeable that it displays a more circular shape than frequently observed for fast-moving Sahelian squall lines (Lafore et al., 2017b). The atmospheric conditions driving the 2009 event have been analysed in detail using meteorological re-analyses (the best estimate of the atmospheric three dimensional winds, temperature and humidity) and available satellite and ground observations by a number of authors (Lafore et al., 2017a; Engel et al., 2017; Beucher et al., 2019). They concluded that the very large rainfall amount (263 mm) recorded at Ouagadougou involved a combination of factors acting at different space and time scales. The vortex developed along an AEW train at synoptic scale (5,000 km) and evolved within a moister than usual air mass over a large area, thanks to a combination of large scale tropical waves (10, 000 km). The strong vortex combined with the prevailing moist air helped the MCS develop into a slowly moving storm able to generate heavy accumulated rainfall.

A composite analysis of extreme rainfall events recorded in Ouagadougou over the last 20 years further emphasizes that a similar co-occurrence of atmospheric phenomena (i.e. an intense southerly monsoon coincident with strong African easterly waves and large-scale

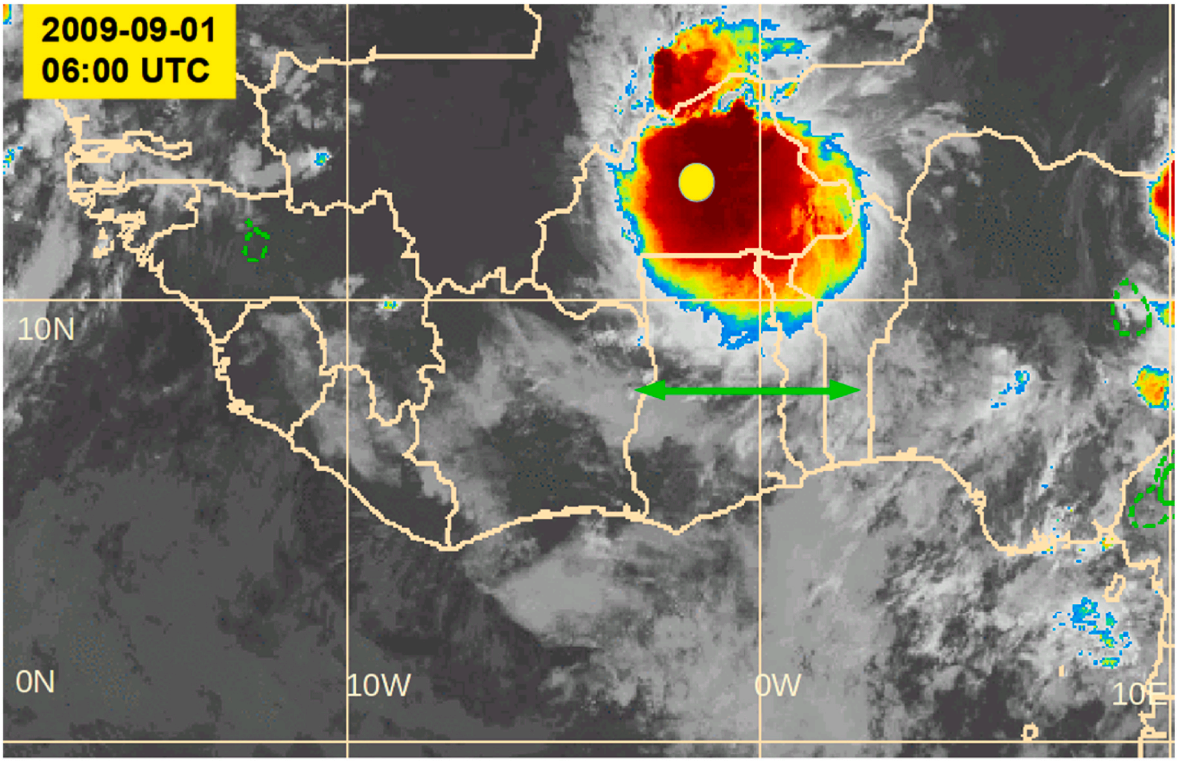

Fig. 3. Cloud organisation during the 2009 event illustrated using Meteosat Infra-red 10, 8 (colour) and visible channels for 06:00 UTC at the storm peak. For Infra-red channel, a brightness temperature threshold - Tb < 240K - is applied to isolate the coldest clouds. Ouagadougou is located by the yellow dot and the green arrow indicates 500 km scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

moisture anomaly) is at play. It occurs at least once a year and leads to a daily precipitation amount above the 1% (lower bound) most intense observed rainfall in Ouagadougou, (~50mm/24h) (Vischel et al., 2019). While it is clear that the atmospheric conditions of the 2009 case study stand out, it remains difficult to identify what caused this HIW event to differ so significantly from other (less extreme) events associated with similar atmospheric phenomena. Other studies certainly indicate the frequency of MCSs and AEW involved in the 2009 event are highly influenced by natural variability in the Sahelian rainfall regime, driven by factors such as ENSO, La Niña and sea temperatures (Diakhate et al., 2019).

In terms of event forecasting, numerical weather prediction (NWP) for West African storms has very poor skill for precipitation, and does not provide forecasters with reliable guidance on the rainfall intensity (Vogel et al., 2018). However, in this case it should have been possible to note that large-scale conditions were conducive to the occurrence of very heavy rain. Once a storm is established, MCS are usually 'now-casted' using satellite imagery and in the event, weather forecasters likely noticed that the MCS had slowed down and intensified, and therefore that accumulated rain would be heavy, in the range 50–100 mm/24h. However, no indicator could have helped them to anticipate the unusual amount of precipitation generated by the storm. An intense MCS occurring at night is a common phenomenon during the rainy season in Burkina Faso (~1 event/2 weeks) but what was unlikely, and very hard to forecast, is the MCS trajectory over Ouagadougou and the huge precipitation that fell on this specific location. It is possible that the next generation of convection-permitting NWP models will improve the reliability of rainfall information available to forecasters (Woodhams et al., 2018), but for now, their forecasts need to be based mainly on "situational awareness" of the large-scale conditions, and nowcasting of the storms while they are actually happening.

3. Hydrological context

River flows in West African rivers within the Sahel are closely related to rainfall seasonality, which in turn is controlled primarily by the West African Monsoon (WAM) (Wilcox et al., 2018). In Burkina Faso, floods typically occur between August and September as a result of intense rainfall from the WAM (Tazen et al., 2018). Evidence suggests an increasing trend in flood magnitude and frequency in Sahelian catchments mirrors trends shown in extreme rainfall (Nka et al., 2016; Wilcox et al., 2018) but has also been linked to change in land use and land management (Mahe et al., 2005; Descroix et al., 2012). For Burkina Faso the frequency of floods has increased substantially from around 1 event per year during the period 1986–2005 to 5 events during 2006–2010 and highlights a recent period of increasing flood frequency (Tazen et al., 2018).

Situated on a minor tributary of the Massili river system (Fig. 4a) with a contributing catchment area to the central dam system of around 420 km^2 Ouagadougou was built on a marshy site on soils with limited capacity for water infiltration during the rainy season (Les Ateliers, 2019). Localised intense storm rainfall drives flooding, in contrast to other large Sahelian cities (e.g. Bamako, Niamey) where floods come from large drainage areas within the river Niger catchment. Flows are highly altered from natural states by a combination of urbanisation, abstraction and impoundment. The upper catchment area to the west of the city is low lying savannah and bush. The lower urbanized areas are characterized by a gradient of development from formally planned centralized areas with paved roads and associated concrete drainage channels to more informal developments with bare earth roads and no overall storm drainage provision. The main channel passing through Ouagadougou is intermittent and without clear channel form and evident erosion and instability leading to channel movement and reformation. The flow of storm water through the city was highly affected by bridge structures limiting flow during heavy rains.

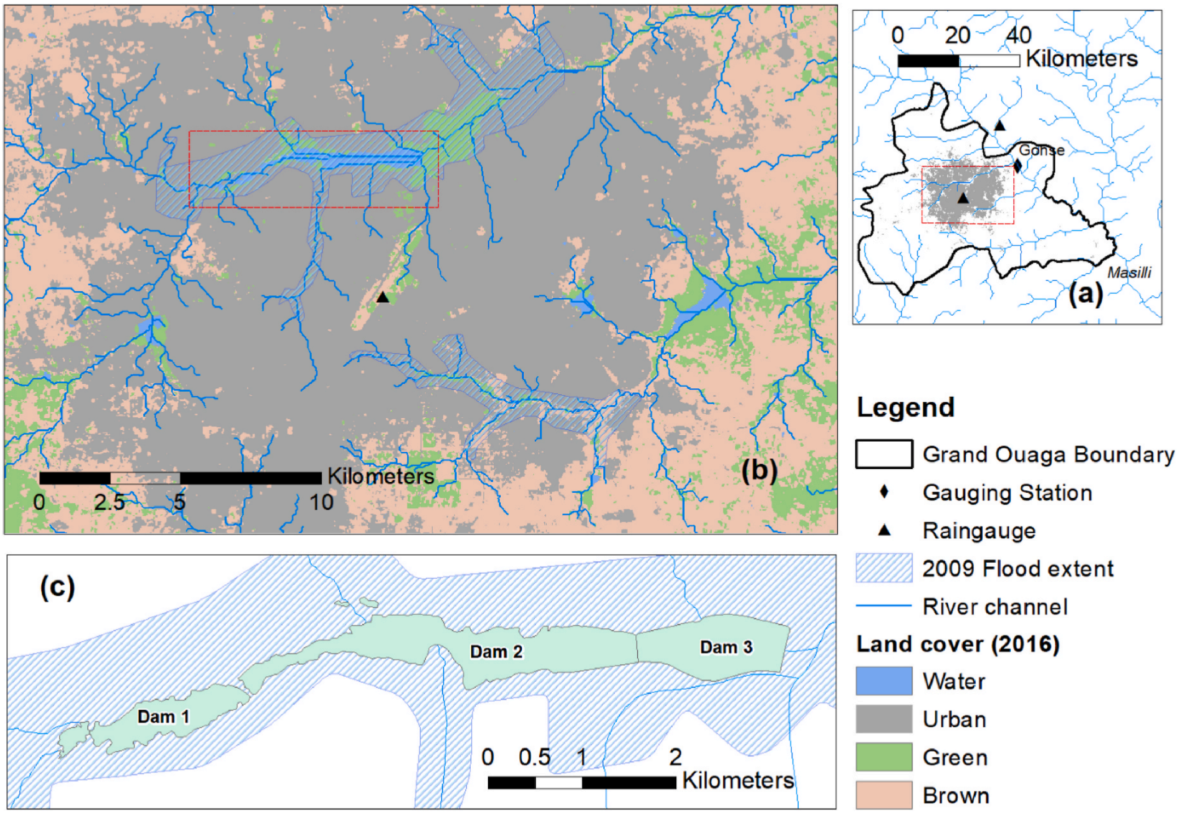

Fig. 4. (a) Ouagadougou location with regard to the Massili River system and local dams and the 'Grand Ouaga' administrative boundary, (b) Ouagadougou city and local land cover – showing flood extent of 2009 event based on Map Action (2011), (c) central system of dams and local flood extent.

Interviews with city planners and hydrologists indicate the city hydraulic system in 2009 was complex and characterized by the poor design and quality of water infrastructure, with urban tributaries converted to large concrete channels. A linked-chain of centrally located silted-up dams (Fig. 4c) would rapidly fill and had no active sluice control for storage and release – with flood levels fully exceeding the release sluice.

Local hydro-meteorological data for 2009 were minimal and patchy given the heterogeneity of land-use and capital city status. The city was served by only two hourly raingauges, one localized flow gauging station (Gonse - an autographic water level recorder), and one manually recorded staff gauge (Dam 1) (Fig. 4). In the absence of hydrometric data, media reporting of floods across Burkina was collated into a flood database and reveals that Ouagadougou experiences around one major flood event per year since the year 2000 (Fowe et al., 2018). A number of these events are not associated with extreme rainfall and highlight that the flooding in Ouagadougou is also a result of unplanned urban development and malfunctioning or blocked drainage (Tazen et al., 2018; Schlef et al., 2018).

September 1st, 2009 was the most destructive flood in Ouagadougou's recent history. The 263 mm of rainfall represented a national record over 115 years, exceeding the next largest amount recorded in Burkina Faso by over 100 mm. Estimates of flood flows and extent for the 2009 flood are unavailable due the lack of suitable hydrometric data, with the only local gauging station destroyed before the 2009 flood and the staff board inundated during the event. The general flood extent was mapped by (MapAction, 2011) (mapaction.org) and replicated by De Risi et al. (2018) using satellite imagery data collected on 3 September 2009 – reproduced in Fig. 4b. This mapping, alongside reporting on the flood impacts (UN Habitat, 2010), suggests the majority of flooded properties were located near central dams and contributing drainage channels (Fig. 4c).

There have been no substantial improvements to the local hydrometric network since 2009, but Gonse is operational. Infrastructure is slowly improving but many large channels remain in poor condition and have flows constrained by improper bridge structures or waste blockages (PRISE, 2017). Works in 2016 started on a large new transport junction passing over the dams and involves significant hydraulic works to facilitate the flow of water from the upstream, but observations indicate no planning for environmental objectives or flood control. City surveys show flood storage and improved drainage in flood hit areas, alongside stronger zonal planning, also evidence of widespread upgrades to major road drainage systems. Despite the event, however, there is still no formal map of flood risk for the city and little evidence that climate change or urban densification is being considered in hydraulic engineering design. Between 10% and 40% of residential population may be affected by flooding (De Risi et al., 2018).

4. Socio-economic and urban context

Ouagadougou is a crossroads city in West Africa subject to significant population growth since the 1960s, a 5.6% annual growth rate since 2000, and projections suggesting annual growth of 4.7% to around 4.4 million by 2030 (UN, 2018). By 2100 some projections estimate the city could be the 38th largest city on earth and have a population of 20.6 million (Hoornweg and Pope, 2014). The country in 2009 was considered a peaceful moderate regional country, with growth supported by effective governance (Söderström et al., 2012). However, the city was also characterized by unplanned urban-sprawl for large areas of unzoned informal settlements, often located in flood-prone areas (Boyer and Delaunay, 2009). Self-constructed 'mud–walled' homes in unplanned areas were most at risk of flood damage in 2009, leading to the type of socio-economic and spatial segregation that puts the vulnerable at most risk of natural disasters (Dos Santos et al., 2019).

Estimates of those affected by the Ouagadougou 2009 flood vary but indications suggest 9 lives lost, 12,000 to 33,000 households directly affected, and widespread damage to property and infrastructure in flood prone areas (Tazen et al., 2018; UNDP, 2010; PRISE, 2017). Dos Santos et al. (2019) identified that the majority of impacts were felt by the most vulnerable and in areas that had not been subject to formal planning and where access to sanitation was minimal. A post disaster needs assessment by the government with the UNDP World Bank put national losses and damages at around $140 million (UNDP, 2010).

To develop an understanding of the decision-making context, AMMA2050 developed a baseline assessment based on desk-based review of key policies, programmes and research and key informant interviews (Visman et al., 2016). This highlighted that the institutions concerned with urban planning, water resources and emergency support and rehabilitation base their work on current understanding of flooding rather than employing scientific understandings of future climate risks, with decision-makers' having limited access to climate information to support medium-term planning. Moreover, policies seeking to prevent flood risks amongst at-risk population settlement close to dams remain largely un-operational. Echoing baseline findings, unpublished mapping of key institutions' current access to and use of weather and climate information highlighted the lack of both information at relevant geographic and temporal scales required for urban planning, and limited ongoing engagement between providers and users of climate information. Focusing on the national Ministry of Urbanism and the mayors of Ouagadougou, AMMA2050 held a series of engagements, including participatory workshops, informal meetings and annual key informant interviews (https://www.amma2050.org/content/meetings) to track changes in decision-makers' perceptions of AMMA2050 products and activities.

Interviews were also conducted in 2016 with 220 heads of households in flood risk areas to determine the extent and depths experienced (Bologo and Traore, 2017), with 61% reporting flood levels between 0.5 and 1 m during the event. Results have been used to plot water levels across the city (Fig. 5) as a proxy for flood depths in the absence of hydrometric data. This highlighted the significant number of households that experienced flooding across a large area, with depths that would have certainly caused damage to buildings and contents. There was a common perception amongst those interviewed that inadequate or blocked local drainage combined with poor urban planning was the primary cause of flooding, rather than the extreme nature of the event. This suggests a lack of communication from authorities on the extreme nature of the meteorological conditions.

No formal early warning system existed on September 1st 2009 and government response was limited to coordinating the emergency response between agencies. UN-Habitat (2010) reported that not all agencies were working together optimally, with the meteorological directorate having no role in any disaster prevention and management. PRISE (2017) suggest this demonstrates communication and coordination challenges within and across government agencies. The National Emergency Relief and Rehabilitation Council (CONASUR) led relocation and management of those affected by the flood, with rehabilitation sites established in Yagma and Bassinko outside (~10 km) of the core city. The Yagma site alone welcomed 24,000 households onto a 900 ha area, but many people have subsequently returned to informal flood-prone sites due to lack of services and opportunities in relocation sites (Dos Santos et al., 2019). Interviews found well established householders also chose to remain in areas of flood risk.

Despite scaling up disaster risk management (DRM) efforts since 2009 and the United Nations Development Program (UNDP) strengthening of government agencies' capacity to manage current and future flood events, operational progress has been slow, and there remains a recognized need to strengthen decision-makers understanding and confidence in appropriately applying climate information, particularly at sub-national level (Visman and Tazen, 2019). Planned reporting and flood mapping was pending in 2019 due to lack of financial support and

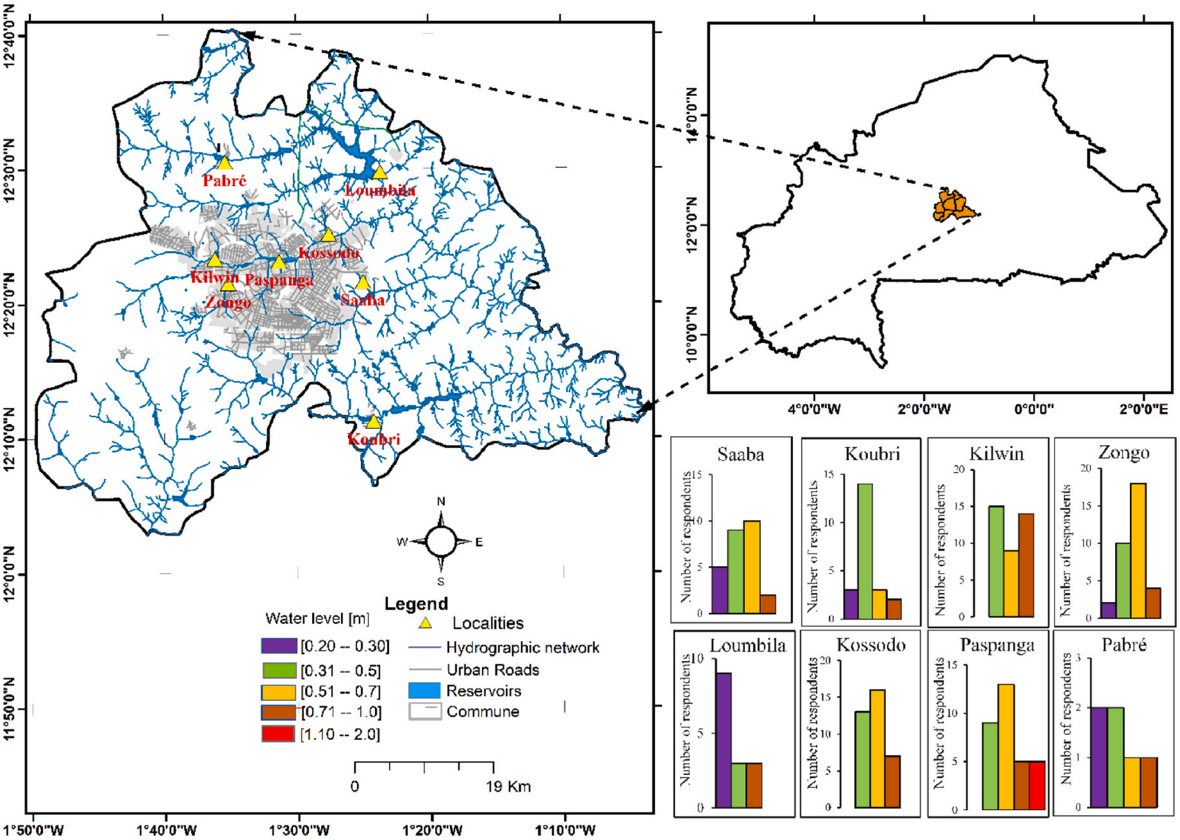

Fig. 5. Water levels reported across the city during the Ouagadougou 2009 flood in Burkina Faso. Inset shows location of Grand Ouaga administrative boundary in relation to Burkina Faso. Data from Bologo and Traore (2017)

refusal of populations to accept relocation (PRISE, 2017) but recent progress is being made on the ground. Markers indicating flooded areas are in place and important planning was set up to manage primary canals and planning of flood prone areas. This has resulted in visible large-scale hydraulic infrastructure development being built between 2016 and 2019, and improved urban drainage along transport routes being implemented since 2019.

The wider issue is a lack of citywide coordination and planning that incorporates flood risk alongside climate change and population projections. Little evidence exists that the range of storm water infrastructure currently being implemented has any consideration of climate change or future densification. The current master plan for development of Ouagadougou is the 'Grand Ouaga Master Plan' but meetings with stakeholders during AMMA-2050 workshops in Ouagadougou have highlighted limited coordination and inclusive consultation in future planning for Ouagadougou. The Ministry of Urbanism and Housing (MUH) has recognized the lack of local climate data to support the plan, and many agencies consider the plan outdated and insufficient. Such climate information is vital given the scale of planned projects that are accelerating urban growth in Ouagadougou.

5. Climate change context

In this section, we place the 2009 event in the context of recent and projected climate change and its impacts on extreme rainfall. We begin by considering historical trends in MCSs, and their relationships with rainfall totals and floods. Using satellite data Taylor et al. (2017) found that more than 85% of intense Sahelian rain could be associated with MCSs. Crucially, they showed that averaging across the entire Sahel, the most intense MCSs have tripled in their frequency over 35 years (1982–2016). Storms that occurred typically every 5 days are now observed on 3 days out of 5. More intense MCSs over this period implies a stronger contribution of the heaviest rain days in the year to the total rain, consistent with the gauge-based analysis of Panthou et al. (2018).

In Fig. 6 we present statistics of intense MCSs, extreme rain events, and reported flood events across Sahelian Burkina Faso (defined here as 12–15°N) which have previously been published over larger regions. Using the same satellite dataset and methodology as Taylor et al. (2017), we find a strong upward trend in the frequency of intense MCSs, amounting to an increase of 106% of the mean over 35 years. Analysing the 15 rain gauges within the domain used by Panthou et al. (2014), we also find a clear increase in extreme daily rain (defined as exceeding the 98th centile). Note that the presence of an intense MCS in the region does not imply that intense rain occurs at one of the gauges, and the frequency of the former exceeds the latter by a factor of 6.8. Fig. 6 also presents reported flood event data within Sahelian Burkina Faso from Tazen et al. (2018), indicating an average number of flood days per year of 1.7. There are several reasons for the noisy nature of the flood time series, including the infrequent nature of recorded floods, and that intense rain falling in much of the region may not produce extensive flooding and often will go unreported. It is also possible that over time, the likelihood of a flood being reported has increased. At the same time however, it is evident from both gauge and satellite data that intense storms have become substantially more frequent over this period, particularly since 2003. This would appear to be an important driver of the trend in recorded floods, with floods recorded every year since 2005.

Interannual and decadal variability in seasonal mean rainfall affects the statistics of intense storm frequency, and the Sahelian drought of the 1970s and 1980s, will therefore have played an important role in the frequency trends evident in Fig. 6. However, trends in the intensity of both the hydro-climatic regime (from gauges; Panthou et al., 2018) and individual storms (from satellites; Taylor et al., 2017) are less sensitive to interannual rainfall fluctuations, such that "the intensification signal emerges above the strong decadal variability of total rainfall in this region" (Taylor et al., 2017). That study linked the intensification in Sahelian storms to global warming, and its impact on temperature gradients across North Africa. Increased concentrations of greenhouse gases tend to produce enhanced warming over more arid regions at low latitudes (so-called "desert amplification"; Zhou, 2016). Indeed Cook and Vizy (2015) reported that temperatures in the Sahara have been rising more rapidly than in the rest of Africa. The north-south temperature gradient across the Sahel has thus been increasing (Fig. 7), and climate

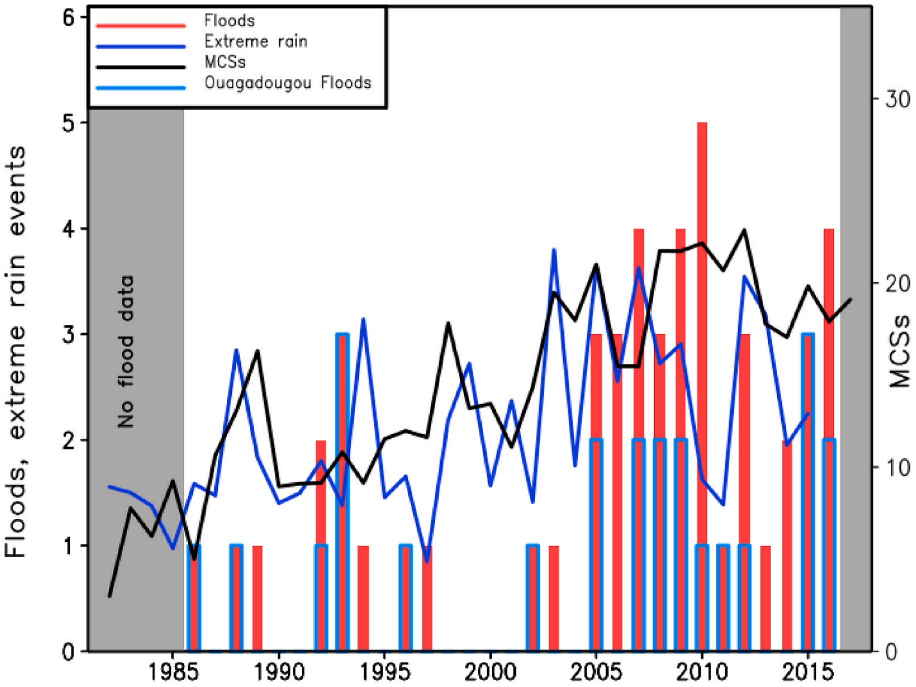

Fig. 6. Frequency of days in June–September with recorded floods (red bars), extreme rainfall (blue), and intense MCSs (temperature threshold of −70 °C; black) across Sahelian Burkina Faso (12–15°N). Pale blue bars denote those flood-days which affected Ouagadougou. Data and methods from: Taylor et al. (2017), Panthou et al. (2014), Tazen et al. (2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

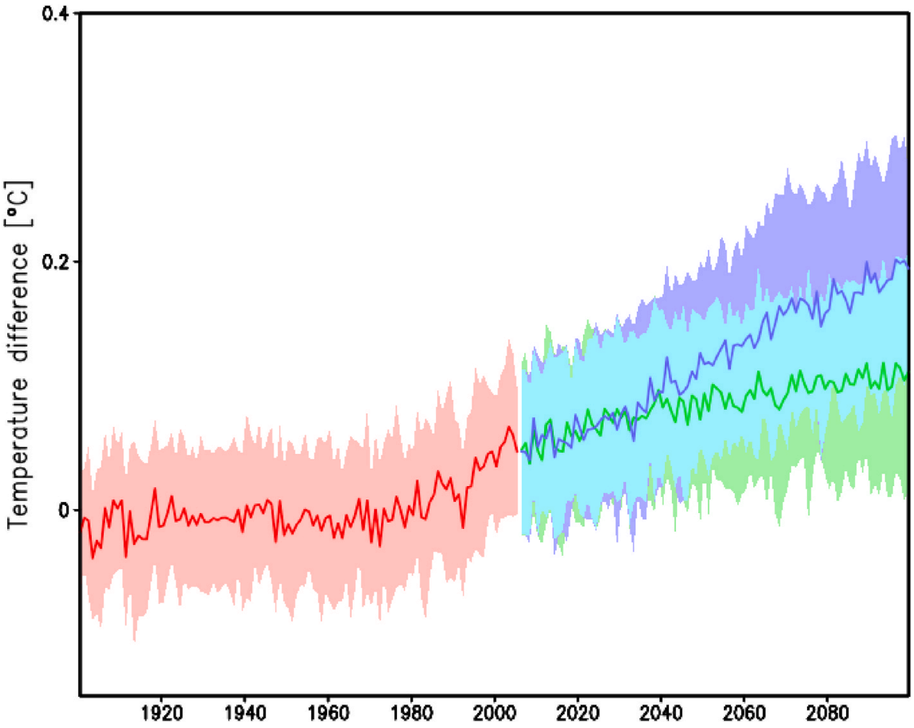

Fig. 7. Mean historical (red) and projected future evolution of the temperature difference across the Sahel from CMIP5 models (Taylor et al., 2017) under RCP4.5 (green) and 8.5 (purple) emissions scenarios. Shading indicates the spread of each ensemble. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

models show that this is due primarily to greenhouse gas emissions The temperature gradient affects several key aspects that control Sahelian weather systems. In particular, a stronger gradient changes the way that winds vary with height. This enhanced wind shear allows MCSs to process the moisture in the atmosphere more effectively, producing more intense rainfall, an effect that has since been shown to also drive trends at sub-Sahelian latitudes (Taylor et al., 2018; Klein et al., 2021a). Moreover, a stronger temperature gradient is expected to amplify the African Easterly Waves in which MCSs are embedded (Cornforth et al., 2017).

Considering the above, an important question for stakeholders is the extent to which climate change may have contributed to the Ouagadougou flood event. However, we are not currently in a position to provide a clear answer. As noted in Section 2, the storm was the result of a combination of atmospheric features, with a structure distinct from the more typically observed intense MCSs. On the other hand, we can use physically-founded arguments to say that global warming has likely contributed to the strong intensification of Sahelian storms seen in recent decades, with an increasing temperature gradient across the region favouring more volatile weather systems. Such changes affect the statistics of intense rain, including in the extreme tail of the rainfall distribution, where the Ouagadougou event sits.

As greenhouse gas concentrations continue to rise over the coming decades, climate models robustly project continuing enhancements to the temperature gradient across the Sahel (Fig. 7), accompanied by global increases in atmospheric moisture (Rowell et al., 2021). Both of these factors drive more intense rain events. Whilst annual rainfall will continue to fluctuate from year to year and decade to decade, we can be quite confident that on average, future storms will tend to become more intense, and pose a greater flash flooding hazard. For a more quantitative perspective on rainfall intensification, we rely on projections from climate models. Whilst models all agree that the Sahel will warm over the course of the century, there is no consensus on the sign of projected changes in annual rainfall from different models. Moreover, climate models are unable to simulate realistic statistics of rainfall in the present day, with a strong tendency to under-estimate the higher end of the rainfall distribution. Broadly speaking, the models project increases in intense rain in the tropics in line with the Clausius-Clapeyron scaling (that is, an increase of 6–7% per degree Celsius, O'Gorman, 2012). However a new, more spatially detailed generation of climate models is starting to be applied over Africa, with much more realistic depictions of rainfall statistics (Senior et al., 2021). Analysis over the Sahel suggests that traditional climate models may substantially underestimate the intensification of the most extreme storms compared to these new models (Berthou et al., 2019; Klein et al., 2021b). Under a strong global warming scenario by 2100, Berthou et al. (2019) suggests an increase in the most extreme (>99.99th centile) rain rates by a factor of between 5 and 10 in West Africa, driven primarily by large increases in atmospheric humidity (Fitzpatrick et al., 2020). In spite of uncertainties about how often Sahelian storms will occur in the future, linked to changes in inter-annual and decadal rainfall variability, it is clear that when they do occur, they will tend to get more intense by the decade.

6. Discussion

The discussion focuses upon drawing together the various interacting factors that came together in the 2009 flood, and developments in science and management since 2009, to answer key questions raised by decision-makers at national and city levels in relation to HIW events and climate change.

6.1. How rare was the 2009 event?

This paper estimates the observed rainfall of 263 mm as having a return period around 1000 years - a 0.1% chance of being exceeded in any one year. This suggests that while highly unlikely to occur there is around a 3% chance of the 1000-year event occurring any time in the next 30 years, assuming its probability doesn't change over that time. Yet it is clear that estimates can vary considerably based on the data available and method used, and this estimate assumes that the analysed rainfall series are statistically stationary over time. Given global warming intensifies the water cycle leading to more precipitation extremes (Cheng et al., 2014) and regional evidence (Taylor et al., 2017; Panthou et al., 2018) already indicates an increase in MCS and rainfall intensity, this suggests such large HIW events will need to be considered in a non-stationary statistical assessment. Another consequence of non-stationarity will be the need to find better indicators of frequency than the usual 'return period' which assumes climate stationarity (e.g. Sarhadi and Soulis, 2017).

Additionally, the difficulty in estimating rarity for this event is complicated by the complexity of the driving meteorological factors discussed. The complexity originates from the fact we tend to classically mix all rainfall extremes in the sample, but extremes might belong to different families of extremes according to their meteorological origin (Blanchet et al., 2018). Here an MCS had ceased propagating due to a vortex within the AEWs, a phenomenon that seems to be a frequent marker of the most intense MCSs over Ouagadougou (Vischel et al., 2019). However, it differs from the behaviour identified by Taylor et al., (2017) on the entire Sahelian band, in which MCSs appear to be more propagative. If, on the basis of different identified atmospheric mechanisms, a distinction in the typology of extremes were confirmed (which is not yet proven), the assessment of rarity would have to be re-evaluated according to the typology. This could lead to a revision of the estimate of the return period.

In summary, estimating the return period assessment of this outlier is extremely challenging, complicated by the most adequate statistical method to use, and in terms of meteorological situation. Estimates of around 1000 years, while indicative of its extreme nature, use stationary assumptions that are likely unsuitable given recent changes to intense rainfall. Given our understanding of increased frequencies of extremes in the observational record (non-stationarity), this could imply an overestimate of the true return period.

6.2. *Was the 2009 event due to anthropogenic global warming?*

Attributing the intensity of such an extreme single localised event to global or regional climate change, or providing an estimate of rarity, is problematic, due to a number of factors. As Stott et al. (2016) notes it remains difficult to isolate causal factors within the causal chain linking large weather variability to climate, particularly where there are limited observations or unsuitable climate models. This is the situation faced in considering the Sept 1st 2009 event in Ouagadougou, whereby the evidence suggests the event was a result of multiple interacting meteorological factors at various scales (Lafore et al., 2017a; Engel et al., 2017) and climate models have not been suitable for modelling convective storms (Berthou et al., 2019). Despite a growing number of attribution studies attempting to assess the role of climate change in observed extreme precipitation, evidence for human influences remains mixed across globally diverse locations (Trenberth et al., 2015) and limited for Africa (Stott et al., 2016). What we can say, is that while the structure was distinct from frequently observed intense MCSs, it is reasonable to propose that the recently observed rise in frequency of extreme precipitation, being driven by more intense MCSs as a result of a warming Sahara, is likely to have affected the underlying meteorological conditions controlling the development of such a "perfect storm".

6.3. *Could city authorities have been more prepared?*

The complex meteorological phenomena and overall rarity, coupled with forecasting difficulty, suggests the city authorities or local population could not have expected or been prepared for such an unprecedented event even with advanced knowledge of historical flood-risk and an operational early warning system. Only a regular storm was expected when precipitation started that day so even with such a system there would have been little time to alert the population. Further, many areas of the city in 2009 were relatively new and would have been built during what evidence has shown was relatively dry period before 2000 with few floods (Tazen et al., 2018). This lack of perceived risk may well have contributed to limited flood-risk management capacity at the time and the lack of flood-risk management or warning in Ouagadougou was typical of other West African cities during this period (Douglas, 2017). Coupled with the extreme nature of the event, this leads us to conclude authorities had limited capacity or information in 2009 on which to prepare for such an unprecedented event.

6.4. *Is the city now more prepared for HIW flooding?*

Resilience and preparedness to floods is reducing across Sub-Saharan African cities as a result from risks rooted in inequality and environmental degradation, amplified by recent rapid unplanned urbanization (Fraser et al., 2017). Ouagadougou is typical of this trend and highlights the limitations of not having suitable hydrometric data and flood mapping to support effective planning for flood-resilience. It is over 10 years since the event and while limited flood mitigation measures continue to be implemented, such as urban drainage, there is no holistic flood management plan for the city, the 'Grand-Ouaga' plan does not consider climate or flooding, and stakeholder feedback suggests the centralised measures will not benefit the majority of unplanned plots across the city, leaving the most vulnerable at risk. Further, increased frequency of storm events and rainfall intensities resulting from climate change will further stress the design limits of existing and planned measures.

More promising are efforts to strengthen climate information and early warning in Burkina Faso. Collaborations between Météo-France and Met-Burkina Faso (ANAM: Agence Nationale de la Météorologie) have emerged since 2009 to improve the forecast of such events, and the WMO and World Bank have funded the Climate Risk & Early Warning Systems (CREWS) project in Burkina Faso with the goal of improving the existing structure of forecast communication. The UK-led African Science for Weather Information and Forecasting Techniques (African SWIFT) project is proposing to make new nowcasting products available to better inform responses on the event timescale. Projects such as AMMA-2050, provide a means for improving upon what the Global Facility for Disaster Reduction and Recovery (GFDDR) identified as being a lack of necessary frameworks and technical capability within the country required to ensure sustainable planning for hazards such as floods (GFDRR, 2017). Also the national raingauge network as of 2020 includes more than 180 stations. Taken together, these improvements provide the capacity to forecast the atmospheric situation favourable to MCS several days ahead.

Qualitative and quantitative questions designed to baseline and monitor key areas of change over the course of the project through scorecards reveal the project has 'sensitised decision-makers to climate change issues such that they are asking for specific products, such as IDF curves and flood maps' (Visman et al., 2016). But while awareness may be growing, there remains an urgent need for increased investment in efforts to strengthen flood preparedness and resilience across timeframes, and to ensure that this investment is continued, including within contexts of ongoing and increased insecurity. In the near-term, it is unlikely the city is more prepared, particularly as flood mitigation and planning measures have not kept pace with the rapid population growth since 2009.

6.5. *Will this happen more frequently as a result of climate change?*

Prediction of further changes in the frequency of intense MCS events depends in part on large-scale climate models, which are unable to explicitly model MCS development but are to some extent able to capture the relevant regional and global scale processes. First, atmospheric moisture content increases with global warming, and this is extremely likely to continue apace until international negotiations and action succeed in reducing anthropogenic carbon emissions and concentrations. Second, enhanced Saharan warming is also physically wellunderstood and expected to continue with rising concentrations of CO_2 and other greenhouse gases (Zhou 2016). Both of these changes are seen to lead to an intensification of extreme storms, or at least the proportion of seasonal rain falling as intense events. However, the precise magnitude of long-term increases in regional moisture content and differential warming is highly uncertain due to variations in model formulation (Rowell et al., 2021), natural climate variability, and the rate of global transition to green economies.

On the other hand, the remote and regional drivers that determine seasonal rainfall are also relevant to storm development, and even the sign of change for this factor is not robust amongst models. So although it is accepted that a larger proportion of the seasonal mean rain will fall as intense events (so with longer intervening dry spells), due to the moisture and temperature gradient changes, it cannot be ruled out that other processes may cause seasonal rainfall to decline to such an extent that the frequency of intense events exceeding a given intensity threshold also declines. The possibility of such an outcome is perhaps a little higher in the western Sahel than in the Ouagadougou region (e.g. Biasutti 2013; Rowell et al., 2016).

Determining future prospects for the frequency of MCS-related flooding is also complicated by the limitation highlighted in this study that standard climate models are unable to explicitly capture convective storms and MCSs, along with their response to the above large-scale forcing. Nevertheless, progress is being made with the development of 'convection-permitting models' capable of simulating these dynamics (Berthou et al., 2019; Kendon et al., 2019) and understanding their impact on MCS development (Fitzpatrick et al., 2020; Klein et al., 2021a, 2021b). As computing power increases, we can expect more such models to become available. A second complicating factor is that the socio-economic scenarios used to force climate models do not adequately represent uncertainties in national air quality policies. These in turn determine concentrations of atmospheric aerosols that affect remote climate, in regard to which the Sahel is a particularly sensitive region (e.g. Ackerley et al., 2011). Improved monitoring and modelling of these effects has the potential to reduce such uncertainties (Scannell et al., 2019).

Despite the sign of changes in seasonal mean rainfall remaining uncertain, observational analyses of drivers of intense rain are consistent with well-established theories of organised convection, and future upward trends in those drivers are projected robustly across climate models (Klein et al., 2021a; 2021b). This suggests confidence that the *proportion* of seasonal rain falling as extreme events will likely continue to increase. On this basis, it seems more likely than not that the frequency of intense MCSs and their associated flooding will continue to increase through the 21st century across the Central Sahel. This picture is less clear in the western Sahel, and in both regions, the magnitude of future change is unclear. The uncertainty surrounding this extreme event is whether situations of MCS blockage similar to 2009 become more frequent in the future. With current understanding we can only suggest recurrence of storms that parallel the exceptional 2009 event studied here will remain extremely unusual, albeit somewhat less so.

6.6. What are the key gaps in understanding future flood-risks for Ouagadougou?

This case study highlights the concerning lack of detailed hydrometeorological data and associated research at the city scale in West Africa Sahel. Such data and research are key limiting factors for understanding current and future flood risk. Regional hydrometric data is generally limited, patchy, and monitoring networks require updating (Nka et al., 2016). Current systems in Ouagadougou are not suitable for providing the detailed surveys and modelling required to provide useable flood-risk mapping of the city. This lack of flood mapping limits the ability for authorities to provide suitably zoned flood planning and mitigation. Further, this limits public awareness of the need to employ more suitable building materials. All these issues are further compounded by an overall lack of suitable climate models and detailed climate research at the city scales, particularly in sub-Saharan Africa (Stott et al., 2016) or tools to operationalize such knowledge in a risk-based context given the significant modelling uncertainties (Giugni et al., 2015). Serious data limitations for understanding flood-risk in Ouagadougou under current and future scenarios of growth and climate change remain, with detailed flood risk maps incorporating climate projections a priority.

6.7. What are the key recommendations to improve flood-resilience to future storms?

In agreement with Schlef et al. (2018), there are a range of actions common to many urban cities in West Africa required to reduce flood risk and improve resilience in Ouagadougou: planning enforcement, improved drainage, waste management, risk education, mitigation options for at-risk populations, improved flood risk management, early warning systems, improved scientific data on current and future flood-risk insurance. Specifically, there is a need to consider the impacts of a rapidly increasing population and long-term regional climate change, based on suitable hydrometric data and modelling of these drivers. Such data will be invaluable for the development of the tools required for decision makers to consider strengthening resilience to such events.

What has been shown in this case study is that at present such data are limited and the climate science is evolving. Even if forecasts and climate information are improved, there remains a need to strengthen decision-makers' understanding and confidence in appropriately applying key climate information in planning considerations, including the probabilistic nature of climate information. A key recommendation to enable this is to ensure knowledge co-production with local stakeholders, which as part of this case study has accelerated awareness and willingness to engage with climate information across sectors. Further, in agreement with Dos Santos et al. (2019) we highlight the benefit of applying a decision-first approach, using *trans*-disciplinary science working with decision-makers to meet their longer-term needs.

Many of the more focused recommendations and tools to support decision makers in the region are outlined in technical reports (https://www.amma2050.org/content/technical-reports).

7. Conclusions

The West African Sahel has been undergoing rapid changes in regional climate and population growth, leading to significant issues concerning High Impact Weather (HIW) events such as the Sept 1st 2009 event in Ouagadougou. This was the largest event from observed data and had the greatest flood impact on the city in living memory. This case study set out to bridge the gap between what scientists understand as useful and decision-makers view as useable at the city scale by providing interdisciplinary answers to key questions raised by local stakeholders. By undertaking an urban event-scale interdisciplinary case study of a recent HIW event, this provides a more relatable form of evidence than many top-down science focused papers from which it is hard to relate elements like trends or regional climate models to local urban-scale impacts and planning decisions. Along with fostering enhanced dialogue and engagement with stakeholders, the case study has also provided a focus for communicating science at variable time- and spatial scales and between disciplines to improve understanding of how global processes have localised consequences.

Certain detailed linkages between climate, weather and flooding are specific to the Sahelian location of this case-study HIW event and local decision-makers. These specific linkages include our finding that the observed rise in frequency of extreme precipitation as a result of a warming Sahara is likely to have affected the underlying meteorological conditions controlling the development of the 2009 event. While certainly rare in the combination of atmospheric features occurring above, and being recorded within, an urbanized location in the Western Sahel, estimating the current and future-climate likelihood of an event of this magnitude remains challenging and uncertain, and is dependent on the geographic and climatological location. Indeed, it is important to acknowledge to decision-makers that physical science cannot easily provide measures of how likely such events will be in the future, beyond a general understanding that their likelihood has increased over recent years and will further increase in the coming decades. Despite this uncertainty about the likelihood of such future events, it is clear that the event forms an important basis for local knowledge on flood extents, and that without more robust planning that incorporates climate change, Ouagadougou remains vulnerable to such HIW events which could become more frequent with climate change.

More general lessons and insights for regional decision-makers in the Sahel and other parts of Africa can be drawn from other interdisciplinary findings. We have shown attribution of extreme events at such a localised scale to atmospheric phenomena affected by global climate change is complex but the evidence suggests such HIW events will become more frequent in the region – requiring reassessment of future flood risk. Further, while there is an overall lack of suitable climate models and detailed climate research at the city scales, we have shown regional climate models are beginning to represent MCS phenomena, enabling improved representation of climate-driven changes on HIW events at urban scales. Likewise, knowledge is building on the underlying meteorological phenomena providing an enhanced ability for short-range forecasts of such events in the future, which combined with effective early warning systems, could significantly reduce the risk of future flooding and/or its risk to life. To enable such advancements to have impact it is clear that users require information and tools in useable formats that meet their needs. Co-production of such information with local stakeholders, being part of this case study, accelerates awareness and willingness to engage with climate information across sectors. This fosters the type of engagement required to disseminate project findings to those with knowledge needs, demonstrated in the AMMA-2050 project training workshop held in Ouagadougou, December 2021 (Karimbiri et al., 2021).

Author statement

James Miller led case study development, paper writing, led hydrological analysis in section 3 and provided Fig. 4. Chris Taylor led analysis of section 5, provided Figs. 1, 6 and 7, and was involved in overall paper writing. Francoise Guichard and Douglas J Parker were involved in developing the case study and were involved in section 5 and overall paper writing. Phillippe Peyrillé led analysis of meterological evidence in section 2. Theo Vischel and Geremey Panthou undertook analysis of rainfall and return periods for section 2, provided Fig. 2, and were involved in overall paper writing. Tazen Fowe contributed to writing of section 3 and data for Fig. 6 and overall paper writing. Emma Visman contributed to section 5 and overall paper writing. Maimouna Bologo and Karim Traore provided data contributed to writing section 4 and provided Fig. 5. Gnenakantanhan Coulibaly contributed to section 3. Nicolas Chapelon provided Fig. 3. Florent Beucher contributed to section 2. David P Rowell contributed to section 5 and overall paper writing.

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.

Acknowledgements

The research leading to these results received funding from the UK's National Environment Research Council (NERC)/Department for International Development (DFID) Future Climate For Africa programme, under the AMMA-2050 project (grant numbers NE/M020428/1, NE/M019969/1, NE/M019950/1, NE/M020126/1 and NE/M019934/1). The case study has benefitted from input from across the AMMA-2050 project consortium and draws on consultations with a range of stakeholders from across sectors in Ouagadougou during 2015–2019. Additional support was provided by the GCRF African SWIFT project (NE/P0201077/1). We would like to dedicate this article to our co-author and friend Francoise Guichard who sadly passed during the writing of this paper.

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