

Title: Modelling temperature-precipitation pressures on African timber heritage

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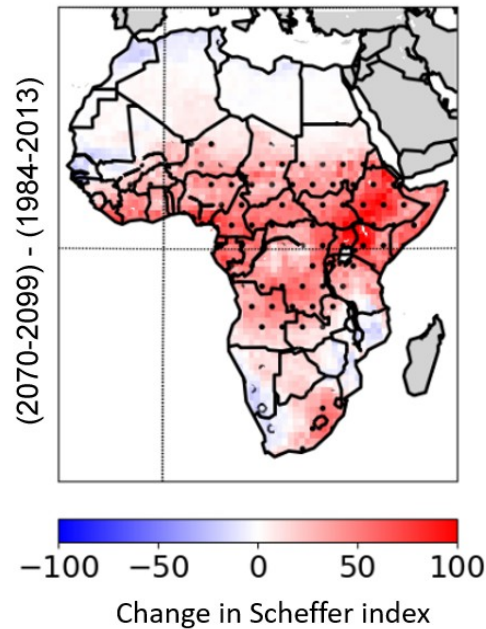
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ABSTRACT: Climate parameters can be refined for use in a heritage context to capture climate-based deterioration processes occurring on buildings and sites. The Scheffer index, which combines temperature and rainfall components, is commonly used as a metric of wood decay risk. Understanding how the index is likely to change is important for developing effective conservation strategies for timber heritage. However, there has been limited research assessing the agreement between climate model outputs for such heritage-based metrics. This is especially important where capturing projected rainfall is known to be problematic, such as over regions of Africa. We address the following questions: to what extent is there model agreement over continental Africa for (i) the magnitude of the Scheffer index and (ii) the direction of change of future Scheffer indices. A multi-model ensemble (MME) approach was used utilising 13 CMIP6 models under the SPS585 scenario. Results showed that rainfall was important in determining the magnitude of the index. In regions where rainfall systems are not well captured by climate models, such as in eastern Africa, there was a large range in projected Scheffer values. To help with the transferability of the index to regions with a tropical climate, we suggest the addition of a Scheffer threshold for a very-high risk of deterioration. Projections of future change to the index were found to be predominantly driven by changes in temperature, rather than rainfall. While there was considerable disagreement in the simulated magnitude of the Scheffer index, there was good agreement between models over the direction of change across Equatorial Africa, where the Scheffer index is greatest. Such agreement between models suggests that heritage decision makers can utilise the direction of change projected by models when shaping future conservation plans.

GRAPHICAL ABSTRACT

Scheffer indices are used to assess risk of wood decay in timber heritage. The index consists of a rainfall and temperature component. We used a CMIP6 MME to assess model agreement in the magnitude of indices and direction of future change. Results showed the magnitude of indices varied within the MME, particularly where climate models struggle to capture rainfall correctly. Future change was driven by changes in temperature, with good model agreement within the MME.



Keywords: Climate change, heritage climatology, temperature, rain days, high emission scenario, multi-model ensemble

1. INTRODUCTION

Weather and climate processes play important roles in driving the deterioration of historic buildings and archaeological sites (e.g., Grossi et al., 2007; Sabbioni et al., 2010; Sesana et al., 2021; Taye et al., 2022). Over the last few decades there has been much interest in the way in which climate change is likely to affect tangible heritage, with a particular focus on built heritage (Bonazza et al., 2009; ICOMOS, 2021; Leissner et al., 2015; Orr et al., 2021). This concern has recently been addressed in the Intergovernmental Panel on Climate Change (IPCC) AR6 Working Group II report (Pörtner et al., 2022). The report states that there is a high confidence that both tangible and intangible heritage are being lost due to changes in climate, and such losses can threaten the adaptive capacity of affected communities. In particular, cultural heritage in areas including Africa, the Arctic and Small Island Developing States are already being affected by risks from climate change (Pörtner et al., 2022). Furthermore, in low and middle-income countries, Simpson et al. (2022) argue that climate change is exacerbating “existing risks to heritage” as “vulnerability to climate change is generally high and adaptation capacity low” (p210).

We need to understand how changes in the climate system will affect processes that deteriorate heritage if policy makers are to effectively address climate change risks to heritage.

Conventional climate parameters, such as average annual temperature, do not capture the risk that climate poses to heritage, as wood or stone would not be damaged by slow changes of a few degrees alone. Instead, we need climate parameters to be refined for a heritage context to capture the likely threat when small changes are amplified by rapid fluctuations, phase changes or biology (Brimblecombe, 2014). These heritage climate parameters (Brimblecombe, 2010) can combine or adjust conventional meteorological variables and are used to assess past, present and future risks to heritage (e.g., Grossi et al., 2011; Curling and Ormondroyd, 2020; Richards et al., 2020).

Such heritage climate parameters are not commonly included within most climate research. Therefore, the uncertainties associated with modelled heritage climate parameters, and how this uncertainty could influence decision-making processes, has yet to be assessed. These are particularly important to understand for regions such as Africa that have a rich and diverse

heritage, but where climate models are known to struggle in capturing some of the key aspects of its climate, e.g., the Congo Basin, the Sahel and east Africa (Dosio et al., 2021). The contribution of Africa to anthropogenic forcing of climate change is low, yet the continent will be affected severely by its impact (Collier et al., 2008). While uncertainties in modelling African climate have been a focus for climate science, research into the impacts of climate change on heritage has predominantly addressed Europe and North America, with few papers examining heritage in Africa (Orr et al., 2021).

Water can pose substantial risks to heritage, and in particular, timber heritage is sensitive to moisture (Sabbioni et al., 2010). Changes in temperature and moisture can influence rates of fungal growth (Choidis et al., 2021), insect attack (Brimblecombe and Lankester, 2013; Pournou, 2020), as well as causing physical stress on the material through processes such as wetting and drying and salt crystallisation (e.g., Blanchette et al., 2002). Therefore, the risk of climate to timber heritage has been found to be high in areas with a high number of annual rain days, such as west Africa and the Congo Basin (Brimblecombe and Richards, 2022; Richards and Brimblecombe, 2022).

Heritage in Africa is affected by its climatological context. Areas with the greatest number of rainfall days are found roughly between 20°N and 20°S, with some areas of the eastern Democratic Republic of Congo having more than 250 days of rain a⁻¹ (Figure 1). There is a reasonable agreement with mean rainfall amount as shown in supplementary material (Fig. S1). Deep convection within the inter-tropical convergence zone, ITCZ (Waliser and Gautier, 1993) over the Indian Ocean (Dyer et al., 2017; Sorí et al., 2017; Van Der Ent and Savenije, 2013) is one of the major sources of water vapour. Easterly trade winds interacting with the complex topography of the East African Rift System (EARS) are thought to play an important role in the formation of nocturnal easterly low-level jets (LLJ), such as the Turkana (Kinuthia and Asnani, 1982; Munday et al., 2022), Limpopo (Rife et al., 2010; Spavins-Hicks et al., 2021; Zunckel et al., 1996), Zambezi, Rufiji and Malawi LLJs (Munday et al., 2021). The LLJs form in topographic channels in between the highlands and are thought to transport more than 200 000 t s⁻¹ (i.e. Mg s⁻¹) of water vapour towards the Congo Basin (Munday et al., 2021). In the southern Atlantic Ocean, low-level trade winds are redirected by the Coriolis force towards the northeast

once they cross the equator, transporting water vapour towards the Congo Basin (Cook and Vizy, 2016; Pokam et al., 2014) and the Sahel region (Figure 1). The subtropical high-pressure belts around 30°N and 30°S, associated with the downward branches of the Hadley cells, suppress moist convection and rainfall development in those regions maintaining the arid to hyper-arid desert environments associated with the Sahara (northern hemisphere) and the Kalahari and Namib desert (southern hemisphere). The annual mean number of days with more than 0.3 mm of rain is often extremely low in those deserts (Figure 1) with mean rainfall rates are below 100 mm a⁻¹ (Figure S1). Long term mean ERA5 2m air temperature often shows values in excess of 30°C (Figure 1). The diversity of climate across continental Africa means that the type and magnitude of climate risks facing heritage are highly varied.

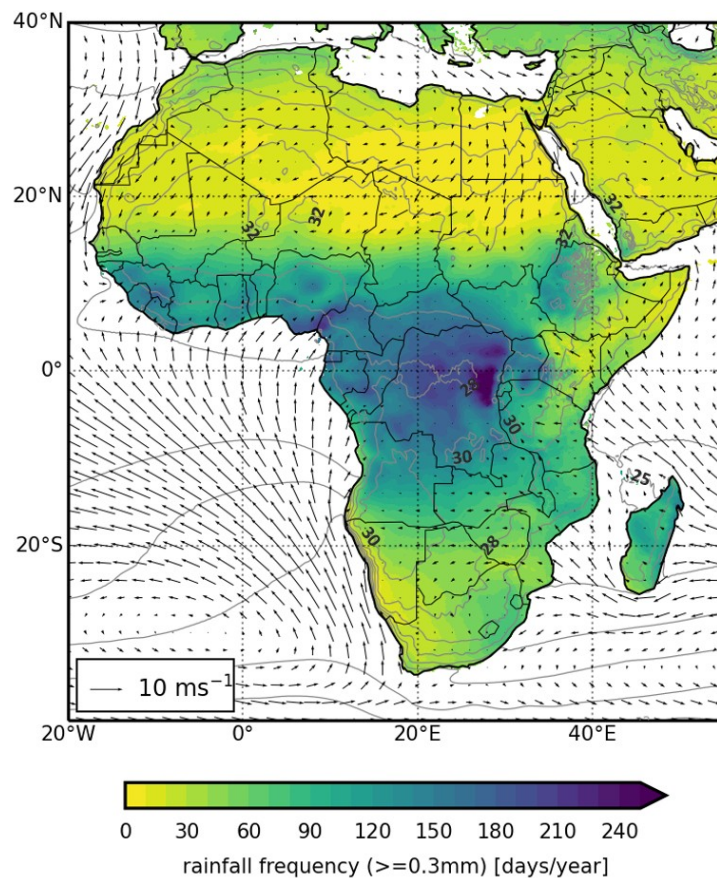


Figure 1: Long term (1981-2022) annual mean number of rain days ≥ 0.3 mm using CHIRPS v2 (Funk et al., 2015) rainfall (filled contours) and long term (1979-2019) mean ERA5 1000 hPa air temperature (line contours) and wind vectors.

The Scheffer index (Scheffer, 1971) has been found to be useful for assessing the current and future threat to timber heritage (Brimblecombe and Richards, 2022; Brischke and Selter, 2020; Curling and Ormondroyd, 2020; Lisø et al., 2007; Richards and Brimblecombe, 2022). The index combines conventional temperature and rainfall parameters (average monthly temperature and monthly rain days) into an annual metric, i.e., one index value is calculated per year, to represent the risk of timber decay, and so does not capture seasonal variability. It was originally developed for fungal attack in the United States of America, though now used more internationally (e.g. Hygen et al., 2011; Kim et al., 2011). The index can represent a range of mechanisms that damage timber including softening and termite attack. Index values below 35 and above 65 are typically associated with low and high risk (Scheffer, 1971). The simplicity of the index explains its wide use, although modifications have been proposed, which for example include the addition of a term to account for high levels of condensation or dew during the morning (Fernandez-Golfin et al., 2016). More elaborate models are available that focus on moisture content, but challenges remain in using them to predict the service life of timber (Niklewski et al., 2021).

Heritage research on the effect of climate on sites and historic materials has typically employed the output from single models, particularly in regional scale and high spatial resolution studies (Grossi et al., 2007; Lankester and Brimblecombe, 2012; Richards and Brimblecombe, 2022). Richards and Brimblecombe (2022) used a single model, HadGEM3-GC31-MM, from the Climate Model Intercomparison Project Phase 6, CMIP6 (Eyring et al., 2016), to show that the Scheffer index is projected to increase across many regions of Africa. However, as only one model was used, confidence in the interpretation of the Scheffer projections remains low because numerical climate models differ in the way they represent the climate system (for instance, the level of complexity, model resolution and the parameterisation of processes). Using multiple model ensembles (MMEs) allows the level of uncertainty to be assessed (Parker, 2013) by identifying where model output shows agreement or disagreement (for instance, for regions variables). In African climate research the use of MMEs, such as CMIP5 and CMIP6, are common (e.g., Creese and Washington, 2018; Almazroui et al., 2020). Studies of the climate change impact on heritage is often limited to regional climate models that target specific heritage sites (e.g., Bonazza et al., 2021; Kotova et al., 2023), cities (e.g., Vandemeulebroucke et al., 2021), countries (e.g., Orr et al., 2018; Hedayatnia et al., 2021) or continents (Sabbioni et al.,

2010). There has been some engagement with reanalysis datasets such as ERA5 (e.g., Choidis et al., 2021; Nikolova et al., 2021; Vyshkvarkova and Sukhonos, 2023) and MERRA2 (e.g., Rosu et al., 2020) to study the potential pressures of changing climate on heritage, but these datasets relate only to past climate.

In this paper, we use a MME approach, employing CMIP6 global climate model (GCM) simulations, to address the following research questions. To what extent is there model agreement over continental Africa for (i) the *magnitude* of the Scheffer index and (ii) the *direction of change* of projected Scheffer indices? This will help us to understand how some uncertainties in model outputs may propagate from the initial climate parameters to affect heritage management decisions.

2. METHOD

We use an ensemble approach combining outputs from multiple models from CMIP6 (Eyring et al., 2016) to assess the Scheffer index for continental Africa. Daily fields of CMIP6 2 m surface temperature and precipitation were obtained from the Centre for Environmental Data Analysis (CEDA) archive [<https://catalogue.ceda.ac.uk/uuid/b96ce180077f4810abc4eef0e48901d9>] accessed in October 2022, for the CMIP6 historical period (CMIP experiment) and future projections scenario SSP585 (ScenarioMIP experiment). Future projections following the SSP585 pathway were chosen to illustrate a worst-case scenario. Only model runs of the variant r1i1p1f* were used. Models included within this study were required to have: (i) daily precipitation and 2m surface temperature (Brimblecombe and Richards, 2023) and (ii) outputs for the years 1984-2013 (past); 2035-2064 (mid-century); 2070-2099 (end-century). Where multiple models were available from the same modelling group, only one model was retained for analysis (typically the model with higher spatial resolution) to reduce the risk of model structural biases introduced by model interdependencies (Knutti et al., 2013; Kuma et al., 2023). Thus, we included 13 models in our analysis (Table 1). To facilitate the comparison between models, we followed Creese and Washington (2018), so all model outputs within the study domain of 20°W-53°E, 35°S-40°N were interpolated onto a common 1° x 1° grid.

Table 1: The CMIP6 models included within this analysis

Model	Institute	Spatial model resolution /km
ACCESS-ESM1-5	Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology Australia (CSIRO–BoM)	140
CanESM5	Canadian Centre for Climate Modelling and Analysis (CCCma)	250
CESM2	National Center for Atmospheric Research (NCAR)	100
CMCC-CM2-SR5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CNRM–CERFACS)	100
FGOALS-g3	State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG) and Institute of Atmospheric Physics (IAP)	190
HadGEM3-GC31-MM	Met Office Hadley Centre (MOHC)	60
MIROC6	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (MIROC)	250
MPI-ESM1-2-HR	Max Planck Institut für Meteorologie (MPI-M)	80
MRI-ESM2-0	Meteorological Research Institute (MRI)	100
NESM3	Nanjing University of Information Science and Technology (NUIST)	170
NorESM2-MM	Norwegian Climate Centre (NCC)	100
TaiESM1	Research Center for Environmental Changes (AS-RCEC)	100
UKESM1-0-LL	Met Office Hadley Centre (MOHC)	140

We compare the performance of the CMIP6 ensemble to the Scheffer index calculated using the ERA-5 reanalysis and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) Version 2 (hereafter referred to as *observed*) over the period 1984-2013 (Funk et al.,

2015). The daily mean 2m surface temperature from ERA-5 and rainfall from CHIRPS were used. Both datasets were interpolated onto a common 0.25° x 0.25° grid.

The Scheffer index was calculated using daily 2m surface temperature and precipitation data provided by the CMIP6 models (Table 1), for each year in the periods 1984-2013; 2035-2064; 2070-2099:

$$Sch = \sum_{Jan}^{Dec} [(T_m - 2)(D - 3)] / 16.7 \quad (1)$$

where T_m is the monthly mean temperature and D the number of days in the month with ≥ 0.3 mm of precipitation (Lisø et al., 2007; Scheffer, 1971). In addition, we calculated individual contributions to the index, retaining the conversion factor 16.7, for the temperature component:

$$T_{Sch} = \sum_{Jan}^{Dec} [(T_m - 2)] / 16.7 \quad (2)$$

and the rainfall component:

$$D_{Sch} = \sum_{Jan}^{Dec} [(D - 3)] / 16.7 \quad (3)$$

For each 30-year period, the median value of the index was taken for each grid cell. The median was chosen because the indices in each cell were not normally distributed in the majority (84%) of cases. The MME average was also determined using the median, along with the range and interquartile range (IQR) of indices.

The direction of future change in Sheffer indices was calculated by subtracting past indices from mid- and end- century indices. Stippling was used to indicate where ≥ 12 models agreed on the direction of change, with closed and open dots representing agreement of a positive and negative change.

3. RESULTS

3.1 Magnitude of Scheffer index: past (1984-2013)

Over the period 1984-2013, the model-based Scheffer index for Africa ranged from 0 to over 450 (Fig. 2). The output from all models included in our ensemble show similar spatial variability, with: (i) low indices in the Sahara; (ii) high values around the equatorial region; notably over the Congo Basin and (iii) moderate values in southern Africa; generally decreasing from east to west. There is some inter-model variability, e.g., the MPI-ESM1 model (Fig. 2h) yields much lower values for southern Africa than other models, such as TaiESM1 (Fig. 2l). The greatest dispersion of indices is found in eastern Africa, extending south along the East African Rift System (Fig. 3).

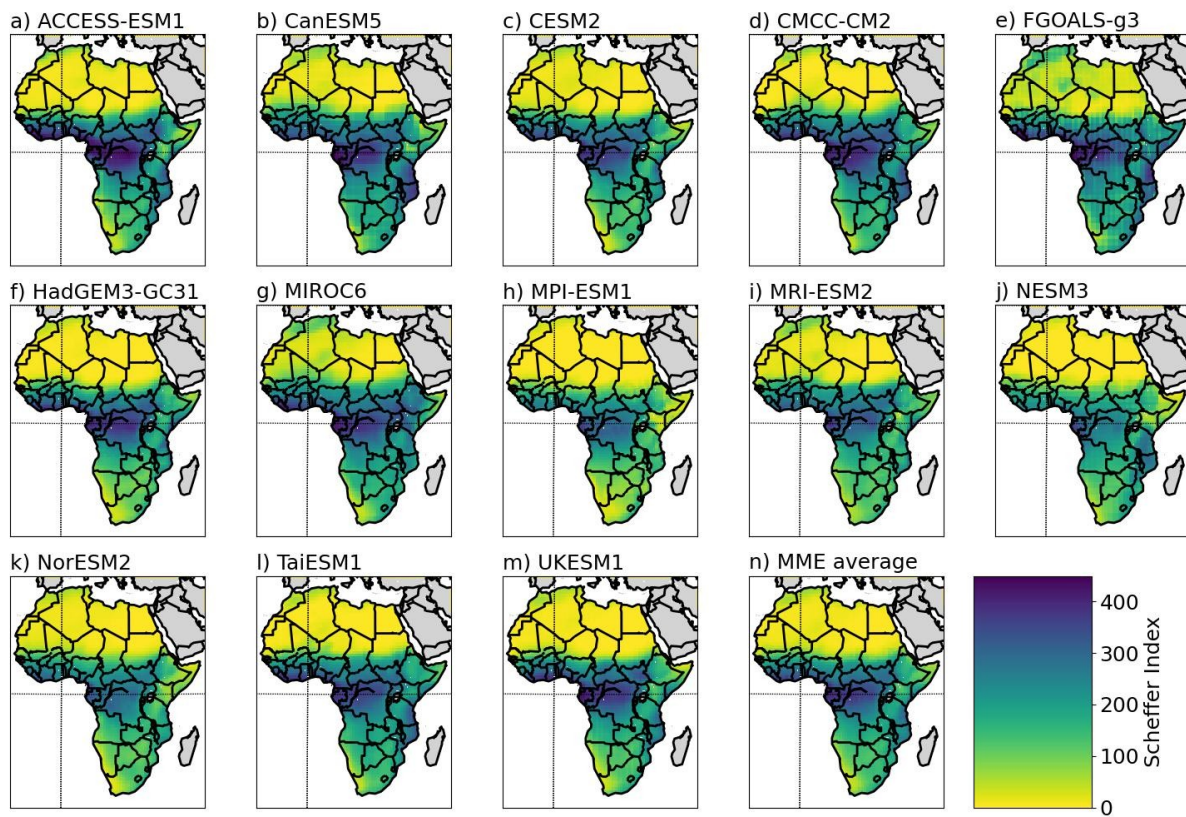


Figure 2: Scheffer indices for the period 1984-2013 for (a-m) each model used in this ensemble and (n) the MME average (i.e., median).

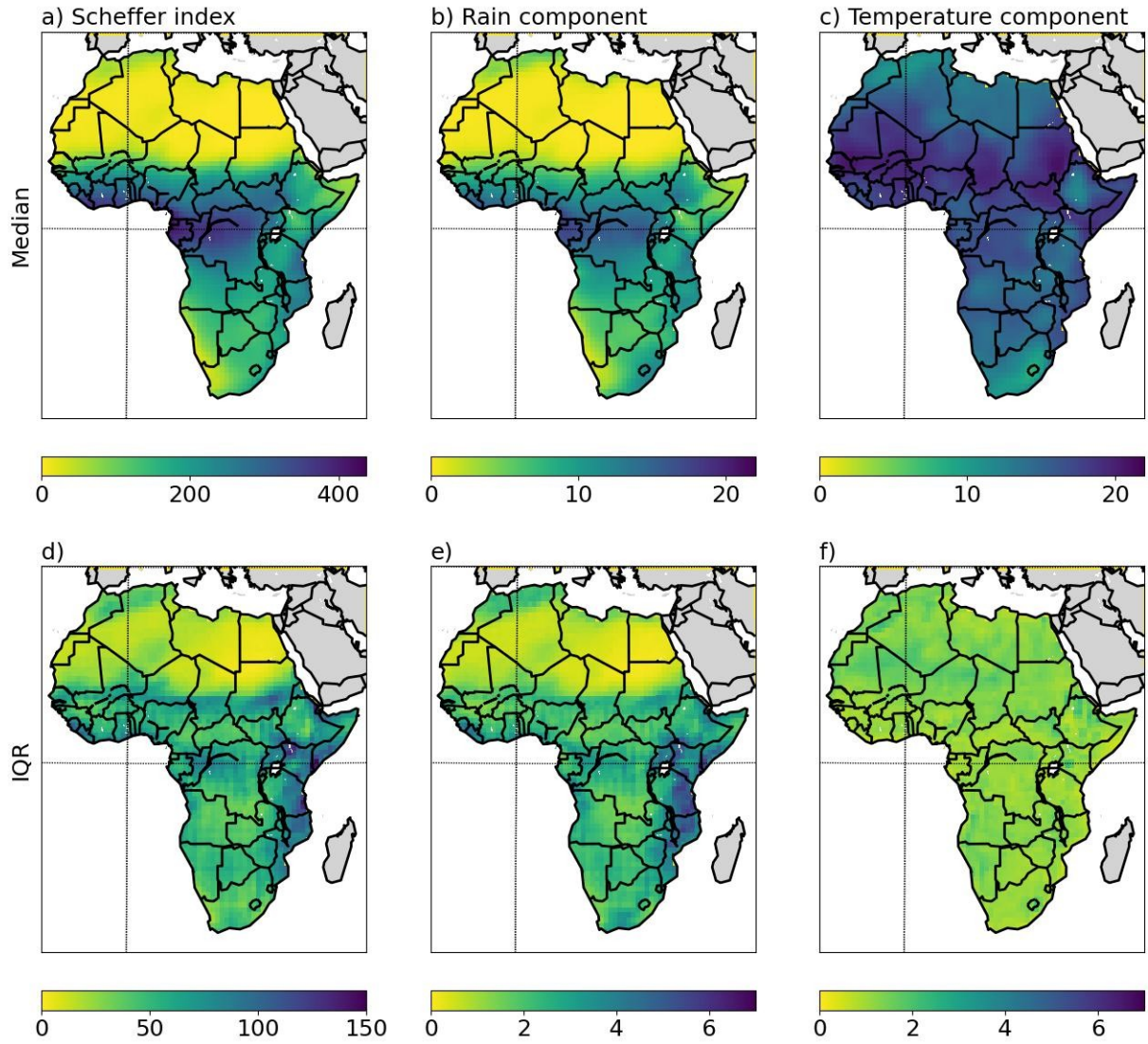


Figure 3: MME (a-c) median and (d-f) inter quartile range (IQR) for the (a, d) Scheffer index, (b, e) rainfall component (D_{Sch}) and (c, f) temperature component (T_{Sch}) for the period 1984-2013.

Figure 3 shows the rainfall (D_{Sch}) and temperature (T_{Sch}) components of the Scheffer indices (see supplementary information, Fig. S2 and S3 for individual model results). The spatial patterns of D_{Sch} and T_{Sch} are notably different. The temperature component, T_{Sch} , is broadly homogeneous across the continent, with a median T_{Sch} value and IQR of 16.3 and 1.2, indicating little variability between the models (Fig. 3c,f).

The median value of the rainfall component, D_{Sch} , is 6.0 (Fig. 3b). There is a notable similarity between the spatial distribution of the rainfall component and the Scheffer index, with highest values occurring in the tropics ($D_{Sch} > 15$), and lowest over the Sahara ($D_{Sch} = 0$). Compared to the temperature component, the rainfall component shows greater variability within the MME, with a median D_{Sch} IQR of 2.0 (Fig. 3e). The variability of the rainfall component is greatest over eastern Africa (D_{Sch} IQR > 5), while in arid areas, such as over the Sahara Desert, variability is low (D_{Sch} IQR < 1 , Fig. 3e).

3.2 Comparison of observed and modelled Scheffer Index

The Scheffer index calculated from the CHIRPS rainfall data and the ERA-5 reanalysis dataset showed similar spatial patterns across Africa compared to the CMIP6 data (Fig. 4a, b). The greatest indices were found in the Congo basin, while the Sahara and southern Africa were associated with low values. However, the Scheffer index calculated using the CMIP6 datasets were notably higher than those using ERA-5 and CHIRPS, with differences of more than 200 found in areas of the Congo basin, the Sahel and western Africa (Fig. 4c). The smallest differences were found in areas associated with a low value (e.g. the Sahara). All models within the CMIP6 ensemble were found to give calculated Scheffer indices that were higher than those from observations and reanalysis (Supplementary material Fig. S4). This was especially notable for ACCESS-ESM1, CanESM5, CMCC-CM2 and MIROC6, while MPI-ESM1-2-HR, NESM3 and NorESM2-MM had smaller positive biases.

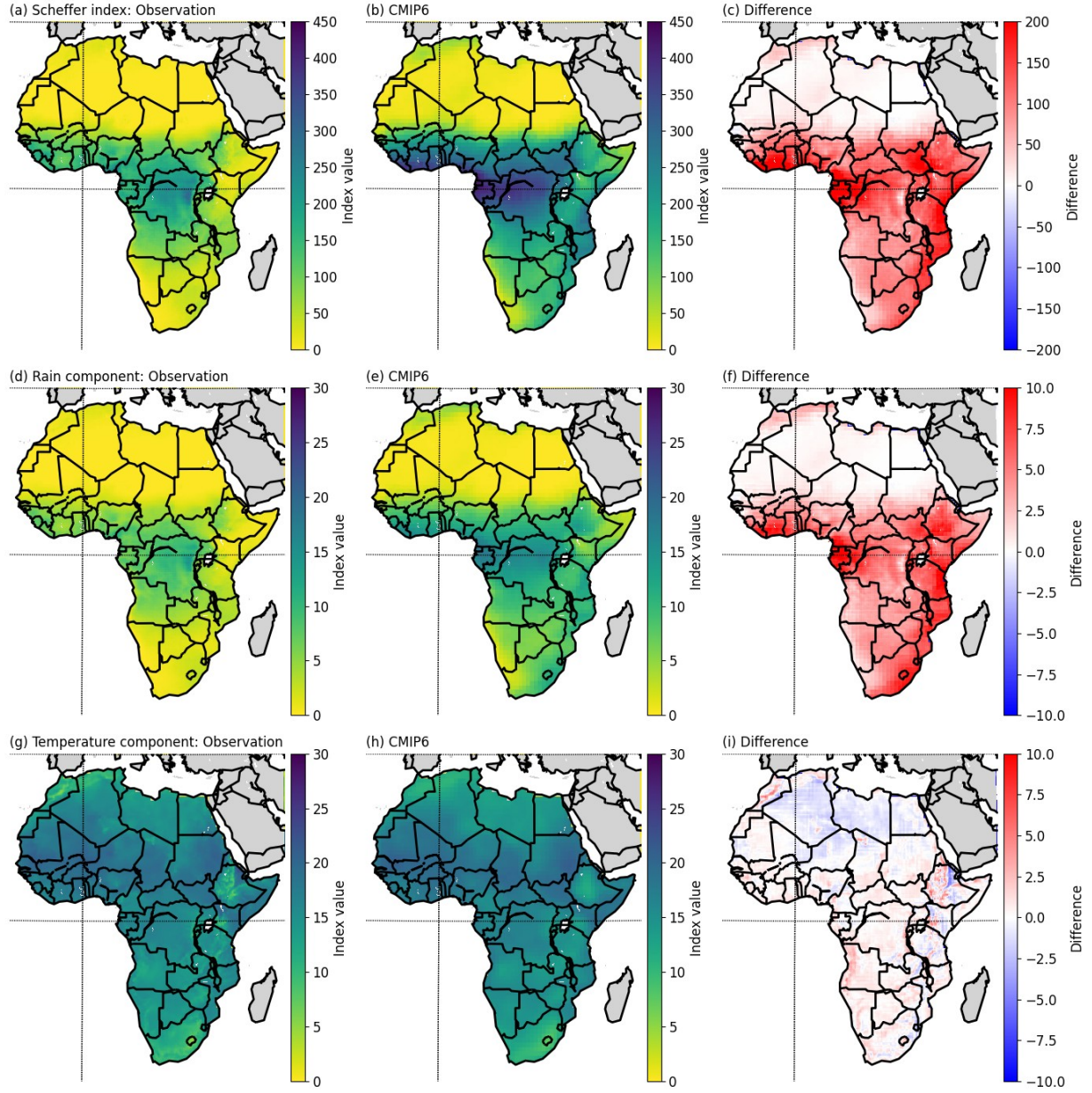


Figure 4: (a-c) The Scheffer index; (d-f) rainfall component of the Scheffer index (D_{Sch}); and (g-i) temperature component of the Scheffer index (T_{Sch}) calculated using (a,d,g) CHIRPS/ERA-5 data and the CMIP6 ensemble average. (c,f,i) show the difference between the CMIP6 and CHIRPS/ERA-5 outputs. A positive value indicates that the CMIP6 value was greater.

Only small differences were found in the temperature component of the Scheffer index (T_{Sch}) between the CMIP6 and ERA-5 datasets (Fig. 4 d-f). Some localised areas with differences >4 were found, typically in mountainous regions such as the Ethiopian highlands (Fig. 4 f). Within

the CMIP6 ensemble, most models had lower T_{Sch} over the Sahara and higher T_{Sch} in the Congo Basin (Supplementary material Fig. S5). The MIROC6 model was found to have a higher T_{Sch} in all areas except in Congo Basin.

Large differences were found between the rainfall component of the Scheffer index (D_{Sch}) calculated using CMIP6 and CHIRPS (Fig. 4 g-i). D_{Sch} was notably greater in the CMIP6 dataset across almost all of central and southern Africa (Fig. 4i), with areas of Cote de Ivoire, Gabon, Tanzania and Ethiopia having a particularly large difference, i.e. >7.5 . The CMIP6 models with D_{Sch} values closest to those produced by CHIRPS were MPI-ESM1-2-HR, and NorESM2-MM, but even these two models showed positive biases across large areas of central and southern Africa (Supplementary material Fig. S6).

3.3 Projected change in Scheffer index (2035-2064 and 2070-2099)

The majority of models within the MME indicate an increase in the Scheffer index across Equatorial Africa ($\pm 10^\circ$ latitude) over the 21st century (Fig. 5; see supplementary information: Fig. S7-S19 for individual model results for mid- and end-century). There are notable differences between models in terms of the magnitude of change. For example, models such as MIROC6 indicate end century increases of 0 to 30 in the Sahel region (Fig. 5g), while CanESM5 showed increases of >100 (Fig. 5b). There is also variation between models as to the northward extension of increased Scheffer index values. In CanESM5 and CMCC-CM2 notable increases are seen across the whole of Sudan, Chad and Niger (Fig. 5c,d), while for NorESM2 and FGOALS-g3 increases are smaller in magnitude and limited to the south of these countries (Fig. 5e,k).

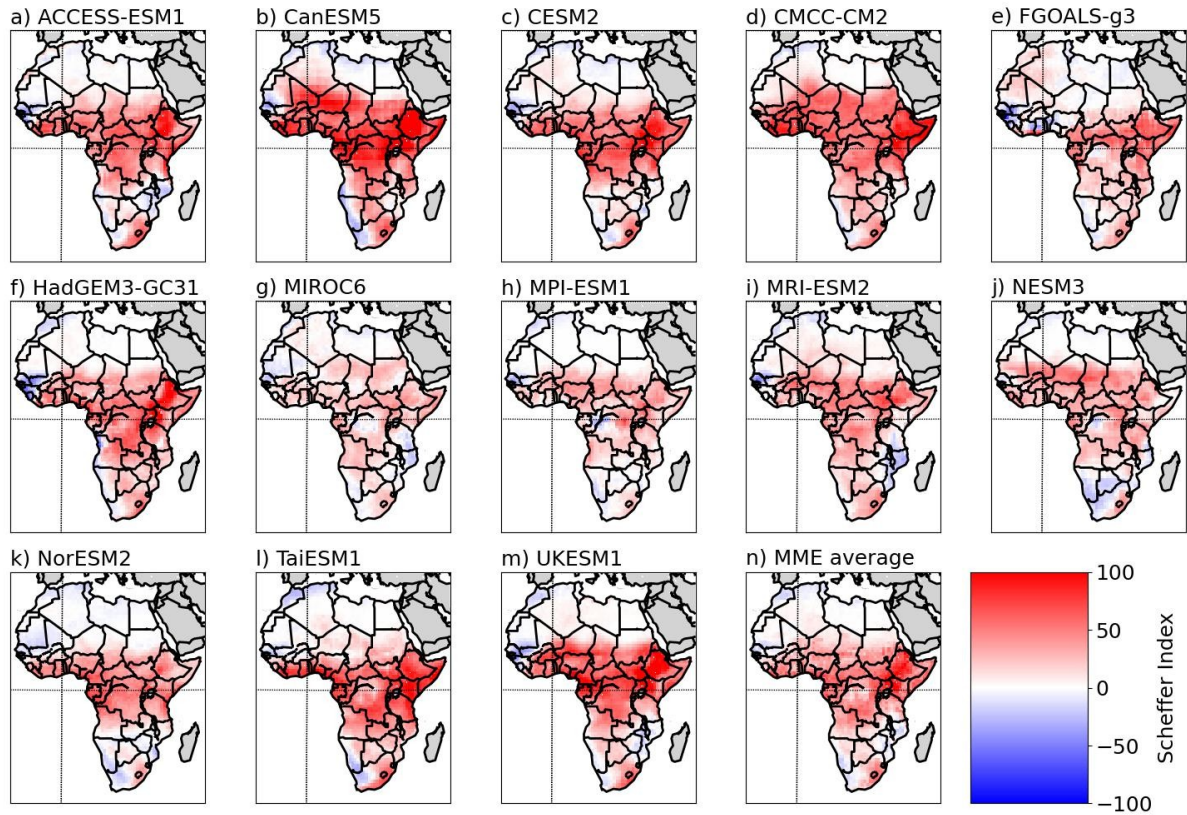


Figure 5: Difference in Scheffer indices for the period 2070-2099 compared to 1984-2013 for (a-m) each model used in this ensemble and (n) the MME average (median). A positive value indicates an increase.

There is less consensus regarding the regions that are projected to experience a decrease in the Scheffer index (Fig. 4). Several models indicate a small decrease over the Congo Basin (MIROC6, MPI-ESM1, NESM3) while others indicate a large increase (>100). A lack of consensus among models means that some localised areas projected to have a decrease in Scheffer index are not captured in the MME average (median; Fig. 5n).

Figure 5 shows where ≥ 12 of the 13 models agree in the direction of change of the Scheffer index mid- (Fig. 6a-c) and end-century (Fig. 6d-f). In the equatorial regions, there is widespread agreement within the ensemble that the Scheffer index will increase by mid- and end- century. However, there is less agreement elsewhere, for example Ghana, Côte d'Ivoire, Liberia and Sierra Leone.

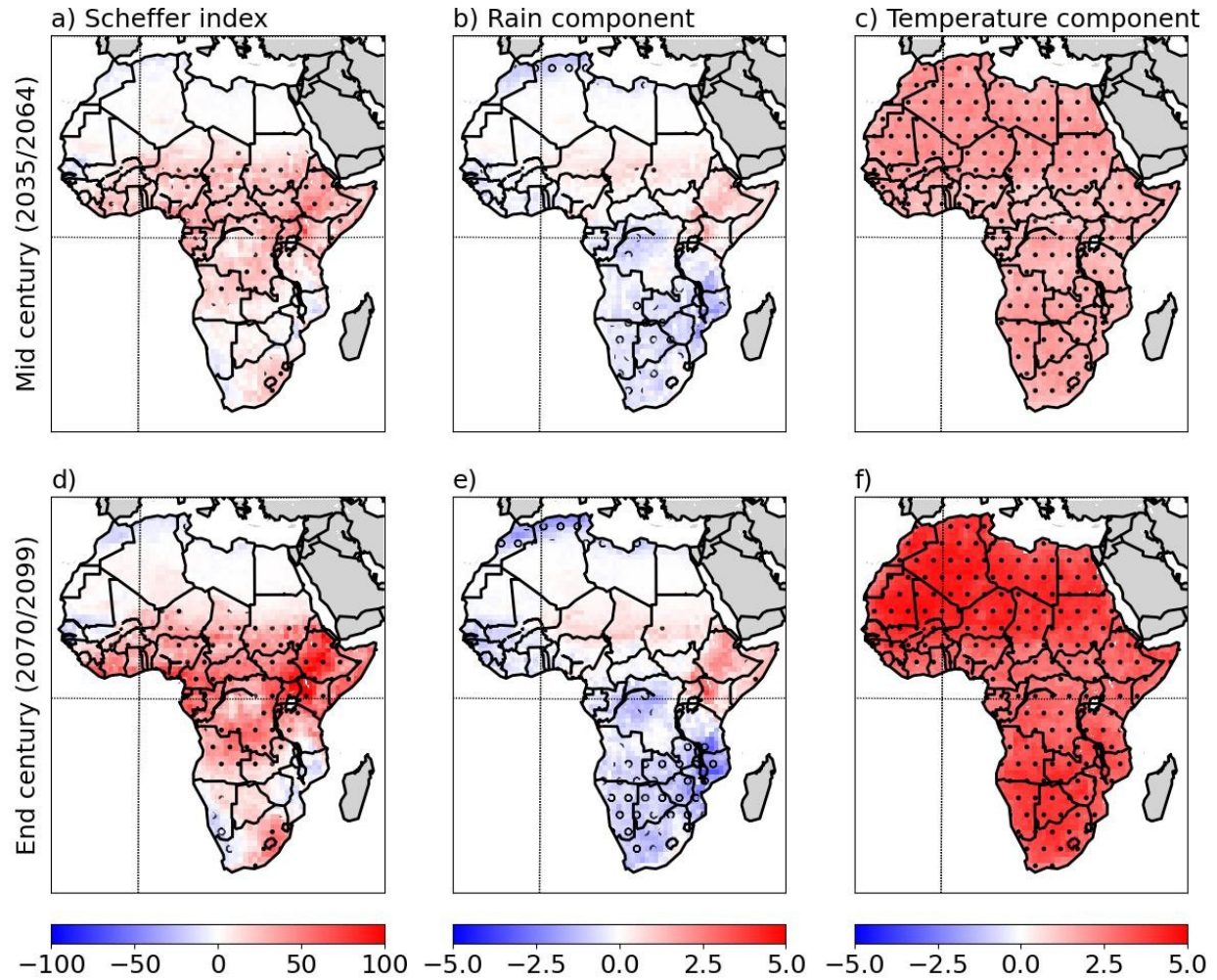


Figure 6: Change in values: (a-c) mid-century (2035-2064); and (d-f) end-century (2070-2099) values compared to the recent past for the (a,d) Scheffer index, (b,e) rain component (D_{Sch}) and (c,f) temperature component (T_{Sch}). Stippling as open (increase) and closed circles (decrease) indicates areas of model agreement as outlined in Section 2.

The rain component of the Scheffer index (D_{Sch}) is projected to decrease along parts of the Mediterranean coast (for instance, Atlas Mountains), western Africa and southern Africa, with models generally agreeing for northern and southern Africa (Fig. 6b,e). Areas from Niger across to Ethiopia and Kenya are on average projected to increase, but there is a lack of agreement between models in the direction of change. The change in the temperature component (T_{Sch}) is relatively homogeneous across the African continent, showing a median increase of 1.6 and 3.4 mid- and end- century (Fig. 6c,f). There is model agreement in the direction of change across the entire continent for both mid- and end- century.

4. DISCUSSION

4.1 Magnitude of the Scheffer index

The MME outputs of the Scheffer index show that the risk of climate-induced wood decay varies greatly across Africa. The highest indices are found in equatorial regions associated with warm temperatures and a high number of rain days, and the lowest indices in arid regions with a low number of rain days (Fig. 2). This result corroborates findings from Richards and Brimblecombe (2022), who showed similar spatial patterns in the Scheffer index over continental Africa when using a single CMIP6 model (HadGEM3-GC31-MM).

However, the indices calculated from the ERA-5 and CHIRPS datasets suggest that the magnitude of the Scheffer index is overestimated by CMIP6 models, particularly in areas with high indices, such as the Congo Basin (Fig. 4). The difference was primarily driven by the rainfall component of the index as there are high values of D_{Sch} in the CMIP6 model (Fig. 4g-i). The parameterisation of rainfall within GCMs means that low intensity rainfall events are simulated too frequently (Dai, 2006; Berg et al., 2013; Kim et al., 2019) these models commonly over-estimate the number of small rainfall events. As the Scheffer index threshold for a rain day is only 0.3mm, this makes the index sensitive to the ability of GCMs to effectively capture rainfall. To reduce this sensitivity the either: (i) only use models which best capture the D_{Sch} values within the ensemble, but even these models are still likely to overestimate the rainfall component of the index or (ii) recalculate the Scheffer index using a higher rain day threshold. A higher threshold could exclude the artificially high number of low rainfall events experienced in some areas, but would reduce the effectiveness of the index in capturing surface dampness caused by small amounts of rainfall.

4.1.1 Risk thresholds

Richards and Brimblecombe (2022) also showed that Scheffer indices could be substantially higher than the values associated with the traditional thresholds of risk determined for the United States of America: <35 = low risk and >65 = high risk (Scheffer, 1971). For example, regions of continental Africa were found to have Scheffer indices >250 in all 13 models (Fig. 2). If the US

thresholds were applied, it would suggest that 67% of continental Africa had high risk between 1984-2013 based on the CMIP6 data or just under 20% if based on the observational data. This masks the fact that many areas have Scheffer indices notably higher than 65 and highlights how science developed within a national setting, can result in challenges when applied outside its borders.

We suggest that the Scheffer index thresholds can be made more relevant for countries with tropical climates by defining a new *very high risk* category. This could help account for the impact of tropical climates on wood risk without altering the existing index. However, the original Scheffer risk was established for decay-susceptible of the wood species such as hemlock, fir and pine (Scheffer, 1971), so the applicability to dense resistant African timbers is a matter for further research. It should also be noted, that in a global economy softer woods are used more widely as they may be more affordable and easier to work. Here, we have taken a more probabilistic approach focusing on the CMIP6 results due to their ability to provide future projections. We set an index value threshold of 200 for the *very high risk* category, which results in 50% of areas currently classified as *high risk* remaining as *high risk* and the other 50% classed as *very high risk* (Fig. 7a). We realise that by using the CMIP6 data to construct these thresholds, some areas may be assigned a classification which over states the risk. However, this is still a useful exercise to undertake to understand how the spatial patterns of risk may change in the future.

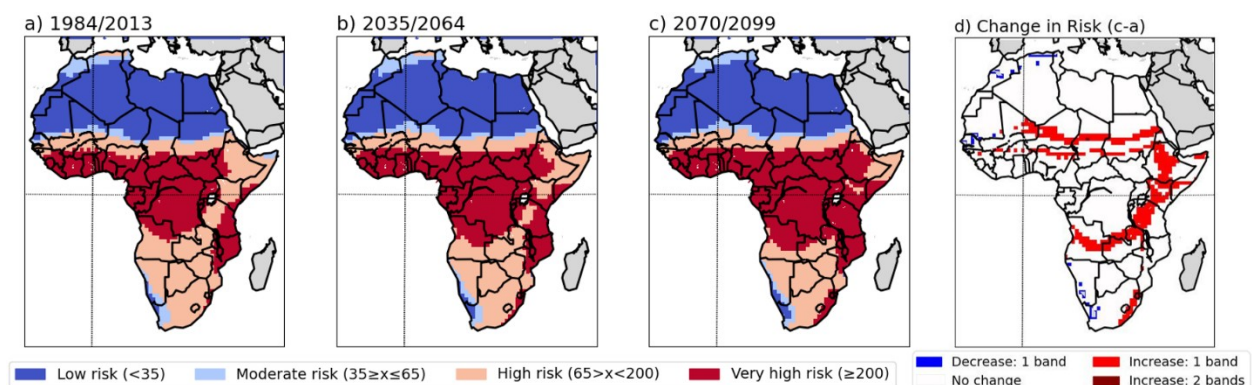


Figure 7: The spatial distribution of risk associated with the Scheffer index in (a) 1984-2013; (b) 2035-2064 and (c) 2070-2099 and (d) areas with changed risk.

Areas at very high risk are predominantly in equatorial regions of Africa, suggesting that there are substantial climate threats to timber heritage such as the boardhouses in Freetown, Sierra Leone (Basu and Sam, 2016), or the architecture of Kisangani (formerly Stanleyville). Areas associated with a very high risk are seen to expand south along the eastern coast of South Africa and the East African Rift System (EARS), including parts of Ethiopia, Kenya and Tanzania over the 21st Century (Fig. 7b,c), along with the change in risk (Fig. 7d).

4.1.2. Spatial variability

There is similar spatial variability between models in the MME for the past Scheffer index (1984-2013). However, a notable spread in the magnitude of modelled indices was found for large parts of sub-Saharan Africa, with particularly high inter-model variability (roughly $IQR > 75$) along the EARS, the Congo Basin and parts of the northern Sahel (Fig. 3a,d). This spread is driven primarily by uncertainties in modelling rainfall as shown by the rainfall component of the Scheffer index (Fig. 3b,e). Rainfall within the ITCZ is primarily driven by deep convection, which cannot be simulated explicitly in GCMs due to their relatively coarse resolution. The parameterisation schemes used in the models to estimate convective rainfall struggle to simulate the timing, magnitude and spatial distribution of rainfall correctly (Kendon et al., 2018). Coarse resolution models also fail to represent key characteristics of water vapour transported by low level jets in eastern Africa, leading to biases in rainfall simulations across large parts of the continent (Munday et al., 2021, 2023). Rainfall projections in eastern Africa are also uncertain because of an observed drying trend in the long rains (March, April and May) between the 1980s and late 2000s (Liebmann et al., 2017; Lyon, 2014) that is contrasted by a projected increase under future global warming scenarios termed the East African Climate Paradox (e.g., Rowell et al., 2015; Wainwright et al., 2019; King et al., 2021).

In the western and central Sahel, the projected change in rainfall (Monerie et al., 2020) maps onto the projected change in Scheffer index. These regions, located at the northern fringes of the ITCZ, have experienced extended periods of multi-year to decadal drought in the late 20th and early 21st century (Held et al., 2005). These are thought to be linked to changes in sea surface temperatures that impact the west African monsoon system, as well as the complex interplay of land-atmosphere feedbacks, anthropogenic climate change and land degradation (e.g., Courel et al., 1984; Nicholson, 2000; Giannini et al., 2003; Held et al., 2005; Lu and Delworth, 2005; Yu

et al., 2017). A primary source of uncertainty in projections of rainfall in the Sahel is thought to be related to the ways in which models simulate shifts in the atmospheric circulation in response to global warming, with MMEs such as CMIP5 and CMIP6 showing similar results (Monerie et al., 2020). Large uncertainties in Sahel rainfall projections remain (e.g., Giannini et al., 2003; Monerie et al., 2017; Schewe and Levermann, 2017); also causing uncertainty in future projections of the Scheffer index over this region. Ongoing climatological research with the aim to better understand the sources of model rainfall biases across Africa will help guide the interpretation of modelled Scheffer index.

Our results suggest that uncertainties in modelling African rainfall have permeated into our understanding of future projections of the Scheffer index (Fig. 3). Consequently, for regions where rainfall is not captured well, the risk levels mapped in Fig. 7 should be seen as indicative, rather than exact, due to model variability and the over representation of low intensity rainfall events in GCMs, caused by convection parameterisation that results in the overestimation of low precipitation events and underestimation of high intensity events (Berg et al., 2013; Dai, 2006; Kim et al., 2019; Stephens et al., 2010). It also shows that contemporary challenges in realistically capturing African rainfall in climate models extend beyond climate science, affecting the understanding of processes relevant to heritage science.

4.2 Direction of future change

Our results show an increase in Scheffer indices across large areas of central and southern Africa (Fig. 6), correspond with previous projections for future African Scheffer index (Richards and Brimblecombe, 2022). Moreover, they also align with previous findings highlighting the importance of temperature as a driver of Scheffer indices in regions between 60° N/S of the equator (Brimblecombe and Hayashi, 2018; Richards and Brimblecombe, 2022).

Our MME approach shows a good agreement within our ensemble to the modelled direction of future changes in the Scheffer index. The agreement is particularly strong in areas that are likely to experience the greatest change (Fig. 6). This finding is useful for heritage managers and policy makers, as it shows, in spite of uncertainties in modelling precipitation over Africa, changes to future threat to timber heritage, as expressed through the Scheffer index, can be assessed with reasonable certainty. It also suggests that a smaller ensemble of models could be used to

determine the direction of change. If this was implemented, model inclusion should be determined on the ability for the model to capture observed Scheffer index values.

While the impact of climate change on heritage is being discussed within the IPCC context, it should be noted that in Working group II Summary for Policy Makers the word ‘heritage’ is not mentioned (IPCC, 2021). The robust nature of our projections legitimises the use of heritage specific climate parameters within policy documents and decision making. We hope that our interdisciplinary approach that uses climate parameters tuned to a heritage context can enable more useful and informed decision making.

5. CONCLUSIONS

The Scheffer index is an important metric for assessing wood decay risk. This study investigates the extent of agreement in modelled Scheffer indices over continental Africa for: (i) the *magnitude* and (ii) the *direction of future change* of Scheffer indices. Good model agreement is found in the spatial distribution of Scheffer values. The highest values are found in central regions, while the lowest values are in the Saharan regions, although the over representation of low intensity rainfall events in CMIP6 models result in the simulated Scheffer index being higher than the observed. In areas with high indices, we propose a new threshold, to reflect the very high level of risk associated with the Scheffer index in tropical climates. However, the exact magnitude of the modelled values varied between models, particularly in regions where climate models often fail to represent rainfall accurately (e.g., eastern Africa). Convection-resolving models might improve the capture of the rainfall component of the Scheffer index, but these models would need to be run over time scales that are currently not feasible.

Future change to indices was found to be driven primarily by increases in temperature across the continent. There was good model agreement particularly in areas projected to experience the greatest increases. Our result is useful for heritage managers and policy makers, who tend to rely more on the direction of significant change, than its magnitude. It is important that the direction of change in the Scheffer index, and thus the threat to timber heritage can be projected with some certainty, despite uncertainties in modelling precipitation over Africa.

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