

Probability-based storylines of unprecedented tropical cyclones impacting Southern Africa

Elizabeth Kendon

`elizabeth.kendon@metoffice.gov.uk`

Met Office Hadley Centre <https://orcid.org/0000-0003-1538-2147>

Joshua Macholl

UK Met Office

Daniel Green

University of Bristol <https://orcid.org/0009-0009-6262-5659>

Helen Titley

Met Office

Mikki Korodimou

Red Cross Red Crescent Climate Centre

Alexander Baker

University of Reading <https://orcid.org/0000-0003-2697-1350>

Rachel James

University of Bristol

Alan Kennedy-Asser

University of Bristol <https://orcid.org/0000-0001-5143-8932>

Genito Maure

Eduardo Mondlane University

Percy Muofhe

University of Witwatersrand

Bernardino Nhantumbo

Mozambique National Institute of Meteorology

James Pagona

Department of Climate Change and Meteorological Services

Zo Rakotomavo

Meteo Madagascar

Jessica Steinkopf

University of the Witwatersrand <https://orcid.org/0000-0003-2782-9049>

Charles Vanya

Department of Climate Change and Meteorological Services

Francois Engelbrecht

Article

Keywords:

Posted Date: October 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11284807/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: There is **NO** Competing Interest.

Abstract

Southern Africa is highly vulnerable to tropical cyclones, with Cyclones Idai and Freddy in 2019 and 2023 leading to over 1000 deaths, never seen previously in African history. However, how tropical cyclones will change in the region is uncertain due to relatively few studies and the coarse resolution of conventional climate models. Here, we provide the first comprehensive assessment of future changes in tropical cyclones in Southern Africa, considering multiple lines of evidence, including an ensemble of very high-resolution climate projections. At the km-scale, climate models are for the first time able to represent the most intense Category 5 storms. A number of storylines have been developed illustrating plausible outcomes from the assessment, including tropical cyclone landfall as far south as Durban and landfall of a Category 5 cyclone, both unprecedented in the historical record. Each storyline is associated with a likelihood that changes with time, supported by the formal assessment. This likelihood framing is critical for storylines to appropriately inform decision making and yet is typically missing in current approaches. The storylines promote increased understanding of climate risk; and through stress testing operational plans, they can help identify adaptation options to reduce vulnerabilities to unprecedented events of the future.

Introduction

Recent years have seen tropical cyclones of unprecedented impact in Southern Africa. Tropical cyclone (TC) Idai in March 2019 became the first recorded system to lead to the loss of more than 1000 lives in Africa, and then TC Freddy in February 2023 became the second to reach such a death toll (Engelbrecht et al. 2021; WMO, 2024). TC Freddy was the world's longest-lived cyclone (Earl-Spurr et al 2024), reaching the most intense (Category 5, see Methods for definition) status over the Indian Ocean. After impacting Madagascar (Category 2) and Mozambique (Category 1), it unexpectedly recurved back to make a second landfall in Mozambique, leading to severe flooding in Malawi, with over 200,000 ha of crops flooded. The devastation caused by TCs such as Idai and Freddy has led to the perception that TCs in the region are becoming more intense and destructive.

Globally TCs are expected to increase in intensity in a warmer world and decrease or remain constant in frequency, with the fraction of Category 4 and 5 systems increasing (Seneviratne et al., 2021). However, despite the vulnerability of the region, there have been relatively few published studies specifically assessing changes in southern Africa. Previous studies for Southern Africa have indicated an overall future decrease in tropical cyclone frequencies (Trisos et al 2022), however there is considerable uncertainty about changes for the most intense cyclones. This is partly a consequence of the coarse resolution global climate models used in previous assessments, which are unable to capture the most intense TCs (Roberts et al, 2020a; Thompson et al 2021; Pall et al 2024).

In general, higher resolution models are able to better represent small scale processes (e.g. in the eye wall of tropical cyclones), which help drive the intensification of cyclones (Vanniere et al 2020). At 25 km resolution, global climate models give improvements in the representation of TCs, including the spatial

distribution, but still struggle to capture the most intense TCs of Category 4 and above (Roberts et al 2020a). New km-scale projections, which are being developed and explored under the Resilience and Preparedness to Tropical Cyclones over Southern Africa (REPRESA) project, represent a step change in modelling capability. At these resolutions (< 5km grid spacing) models are termed ‘convection-permitting’ – convection can be explicitly represented without the need for a parameterisation scheme, but smaller showers and updrafts are not fully resolved. Importantly, at km-scale, the most intense Category 5 (wind speeds in excess of 252 km/h) storms are produced (Macholl et al submitted, Baker et al 2024), with a more realistic representation of fine-scale TC intensification processes (Green et al submitted) and associated extreme rainfall (Hooker et al 2026).

In this paper we provide the first synthesized Intergovernmental Panel on Climate Change (IPCC) – style assessment of future changes in tropical cyclones in southern Africa, spanning a range of different impact-relevant characteristics (including intensity, frequency, track, rate of intensification and associated rainfall). We include multiple lines of evidence, including observed trends, previous assessments based on Coupled Model Intercomparison Project (CMIP6) projections, the latest high resolution global models (Roberts et al 2020b, Chu et al, 2026, Green et al 2026) and new results emerging from the first convective-scale (grid spacing <5km) ensemble projections for Africa (Green et al submitted, Macholl et al submitted).

From this synthesized assessment, a number of storylines have been developed, that draw out the key messages, providing narratives on plausible TCs of the future. We provide a perspective on the value of these storylines, and how they complement the overarching assessment. Storylines have previously been used to explore uncertainty in climate projections, imagining possible futures to help motivate and inform adaptation actions (Baulenas et al 2023, Shepherd et al 2018). However, typically, they do not directly relate to an underlying quantitative assessment, with no specific likelihoods assigned to given narratives (Jack et al 2020). By contrast in this paper, we specifically view the storylines in the context of the evolving envelope of plausible projections, and thus associate each with a likelihood that changes with time. Without knowing how likely an outcome is, it is not possible to evaluate the benefit of mitigation and adaptation strategies to avoid its occurrence or lessen its impact. Thus, we argue that framing storylines within likelihood assessments is critical, and that this approach should extend beyond the case of tropical cyclones.

Results

REPRESA synthesized assessment

Here we present a comprehensive assessment of changes in tropical cyclones over southern Africa, drawing on multiple lines of evidence and using our collective expert judgement to assign a confidence level. *High confidence* indicates a high level of agreement across multiple sources of high-quality evidence; *low confidence* indicates a low level of agreement and/or limited evidence. For future

projection likelihood assessments, we also make use of the IPCC probability categories (Table 1). For further details on approach, see Methods.

For the assessment, we draw on published literature but also augment this with new analysis of the first ensemble of convection-permitting (km-scale) climate projections for Africa (CP4A, see Methods). Due to the more realistic representation of TC intensification (Green et al, submitted) and the ability to capture the most intense TCs (Macholl et al, submitted), we place greater confidence in projected changes in the most intense TCs from the km-scale model than from coarser resolution models. However, there are caveats relating to the lack of ocean coupling in CP4A, the close proximity of Madagascar to the model boundary and the small ensemble size (see Methods). For the assessment, we focus on higher Global Warming Levels (GWLs) of 2°C and higher as these allow a more robust identification of the climate change signal above natural variability, and are sampled by the available CP4A projection data (end-of-century under a high emissions scenario SSP5-8.5, see Methods).

TC frequency and intensity

For the frequency and intensity of tropical cyclones in the SWIO, there is *low confidence* in observed trends due to the heterogeneity of observed records (Walsh et al 2016), including changes in remote-sensing instrumentation (Leroux et al., 2018, Kossin et al., 2020) and a limited number of studies (Leroux et al 2018). For projected changes in frequency and intensity in the SWIO basin as a whole, there is consistency in the findings based on both previous CMIP6-assessments (Ranasinghe et al., 2021) and CORDEX regional downscaling experiments (Muthige et al 2018) and new information emerging from the latest high-resolution global climate models (Green et al, 2026, Roberts et al 2020b, Cattiaux et al., 2020) and km-scale models (Green et al submitted, Macholl et al submitted). Importantly, however, there is model disagreement in the sign of the change in TC frequency at local scale in the Mozambique Channel, including changes in landfall (Roberts et al 2020b, Pall et al 2024, Chu et al 2026).

Observed changes in TC frequency and intensity

- For the SWIO region as a whole, there is no detectable trend in the frequency of TCs, including intense and very intense TCs (Regional Specialized Meteorological Centre RSMC scale, see Methods) in observations from 1990-2023 (*low confidence*) (Fig 1; Klotzbach et al., 2022, Chand et al., 2022; Emanuel, 2024, Trisos et al., 2022, Tu et al 2024, Ayob et al 2026).
- There is an increasing trend in the intensity of the more-intense TCs in the SWIO from 1990-2023 (*low confidence*) (Elsner, 2020; Elsner et al., 2008, Ayob et al 2026). Consistent with this, TCs are spending a greater proportion of their life cycle in the intense or very intense category (*low to medium confidence*) (Fig 1; Kossin et al., 2020).

Modelled future changes in TC frequency and intensity

- Decreasing TC frequencies are *likely* (66-100% probability, see Table 1) for the SWIO region, under higher GWLs (Fig 2; Camargo et al 2023, Cattiaux et al 2020, Roberts et al 2020b, Muthige et al

2018, Bell et al 2019, Trisos et al 2022, Leroux et al 2024, Knutson et al 2020, Chu et al 2026). For the Mozambique Channel itself, there is *low to medium confidence* in the evidence available to assess the likelihood of changes, with considerable uncertainty around localised changes (Green et al, 2026).

- It is *very likely* (90-100% probability) that the proportion of TCs that are intense to very intense will increase under higher GWLs for the SWIO and Mozambique Channel, but whether there is an increase in the absolute number of intense to very intense TCs is *about as likely as not* (33-66%) (Fig 2; Camargo et al 2023, Knutson et al 2019, Green et al 2026, Cattiaux et al 2020, Leroux et al 2024, Trisos et al 2022).
- The first recorded Category 5 (see Methods) TC landfall in Madagascar or Mozambique will *very likely* occur at higher GWLs. The occurrence of such an event in the next ten years is *about as likely as not* (Fitchett et al 2018; Fig 6).

TC rapid intensification

Operationally, tropical cyclones are classified as ‘rapidly intensifying’ when maximum sustained surface winds increase by at least 30 knots (15.4 m/s) within a 24-hour period (Kaplan and DeMaria, 2003). Their rapid development means that there may be limited warning time of imminent TC hazards, impacting the ability of people to prepare. Changes in rapid intensification are consistent across multiple lines of evidence including theory, observations and the latest km-scale climate projections (Green et al submitted).

Observed changes in TC rapid intensification

- Rapid intensification is strongly associated with the development of tropical cyclones that reach the very intense TC category globally (*high confidence*) (Lee et al 2016).
- There is an increasing trend in the proportion of TCs that rapidly intensify in regions of the SWIO and Mozambique Channel from 1990-2023 (*low-medium confidence*) (Wang et al 2025, Li et al 2023, Ayob et al 2026).

Modelled future changes in TC rapid intensification

- It is *likely* that rapidly intensifying TCs will occur relatively more frequently at higher GWLs (Fig 3; Green et al submitted).

TC tracks and landfall

For any changes in the tracks TCs take, and hence the position of landfall and countries impacted, there is *low confidence* in observed trends, due to the heterogeneity of the observational record (Walsh et al 2016), including changes in remote-sensing instrumentation (Leroux et al., 2018, Kossin et al., 2020), the relative rareness of landfalling TCs, and multi-decadal climate variability. There is some evidence from global models (Green et al 2026, Cattiaux et al 2020) and new km-scale projections (Green et al

submitted) of a projected southerly shift in tracks in the SWIO, but there is *low confidence* in this evidence due to lack of consistency across all ensemble members and the relative rareness of events.

Observed changes in TC tracks and landfall

- There is some evidence in observations (1990-2023) of increases in TC activity with the potential to impact Madagascar, Mozambique and Malawi, including increases in landfall (*low confidence*) (Fig 1; Chichava et al., 2024; Cao et al 2024; Studholme et al 2022).

Modelled future changes in TC tracks and landfall

- An increase in intense and very intense TCs following more southerly tracks in the SWIO, including the southern Mozambique Channel, is *more likely than not* at higher GWLs (Fig 2; Cattiaux et al 2020, Leroux et al 2024, Green et al 2026, Green et al submitted, Chu et al 2026).
- Landfall at southerly latitudes (i.e. at the latitude of Maputo and further to the south) in any given year remains *unlikely* even under high GWLs (Fig 2, cf. Fig 7).

TC rainfall

For changes in rainfall, we consider both annual totals and the rainfall associated with TCs (defined as rain occurring within 500km of the TC centre, following Lavender & McBride, 2021). TCs contribute significantly to annual rainfall totals in southeast Africa and substantially more in Madagascar (Mawren et al 2023). There is *high confidence* that the rainfall brought by individual TCs will increase in future, as this is consistent with theoretical expectations of increased atmospheric moisture in a warmer climate, evident in observations and consistently seen in climate model projections (Camargo et al 2023; Knutson et al 2019, 2020). There is *low confidence* in the evidence around changes in annual and seasonal mean rainfall in some parts of southeast Africa due to multiple driving factors, including high natural climate variability, differences between climate models in how the tropical circulation responds to global warming, and the varying role of TC contribution to overall totals, which contributes to the lack of model agreement (Kennedy-Asser et al. 2026).

Observed changes in TC rainfall

- The rain rates of TCs in the SWIO have increased over the last two decades (*medium confidence*) (Guzman and Jiang, 2021)

Modelled future changes in TC rainfall

- Decreases in annual mean rainfall are *likely* across southern Africa as a whole (south of 10°S) at higher GWLs, this is especially for western parts of southern Africa with uncertainty in changes in eastern regions. Rainfall decreases are *about as likely as not* over the east coast of South Africa and the escarpment areas to the west, western Madagascar and the most northern parts of southern Africa (Ranasinghe et al 2021, Engelbrecht et al., 2024, Kennedy-Asser et al. 2026, Fig 4).

- TCs of a given storm intensity are *very likely* to bring more rainfall individually at higher GWLs (Camargo et al 2023; Knutson et al 2019, 2020, Chu et al 2026, Titley et al submitted).
- The overall contribution of tropical cyclones to seasonal mean rainfall is *likely* to decrease at higher GWLs over Madagascar and northern Mozambique (Chu et al 2026; Fig 5), conditional on a projected decrease in TC frequency.

Wind and storm surge

Changes in wind and storm surge hazard in the SWIO are associated with *high confidence*. TC intensity directly translates to maximum wind speed; storm-surge hazard reflects TC wind speed, but also TC size, propagation speed, proximity to the coast, bathymetry and mean sea-level (Gori et al 2023).

Observed changes in TC storm surge

- There is an observed increase in tropical cyclone storm surge over the SWIO over recent decades, linked to the poleward migration of TCs, but uncertainty whether this is a forced trend (*low confidence*) (Guo et al 2026, Zhou et al 2026).

Modelled future changes in TC storm surge

- The more-intense TCs (Category 3 to 5 storms) are *very likely* to get more intense when they do occur at higher GWLs. This translates to an increase in wind and storm surge hazard when TCs form in a warmer world (*high confidence*), as seen in other regions (Needham & Keim, 2014; Chen et al, 2020).
- Sea-level rise is a contributing factor to higher storm-surge hazards along the coasts of Madagascar and Mozambique in a warmer world (*high confidence*) (Huang et al, 2024).

Term	Likelihood of the outcome
<i>Virtually certain</i>	99-100% probability
<i>Very likely</i>	90-100% probability
<i>Likely</i>	66-100% probability
<i>More likely than not</i>	>50% probability
<i>About as likely as not</i>	33-66% probability
<i>Unlikely</i>	0-33% probability
<i>Very unlikely</i>	0-10% probability
<i>Exceptionally unlikely</i>	0-1% probability

Table 1: IPCC probability categories

We have developed five storylines (Table 2) that highlight the main messages of changes to TC characteristics from our formal assessment above, with the aim of making this more accessible to a broader audience. They were developed through stakeholder engagement sessions in Madagascar, Malawi and Mozambique, where the scientific findings were exposed to the local contexts and different user lenses. They span a range of possible likelihoods, which are estimated for the immediate-future defined as 2026-2035 and end-of-century defined as 2086-2095 under low mitigation (corresponding to a model-dependent global warming level $\text{GWL} \geq 3^{\circ}\text{C}$; $3.3^{\circ}\text{C} - 5.8^{\circ}\text{C}$ for the CMIP6 models assessed here, see Methods). For the meaning of these likelihoods, see Table 1.

Importantly in this framing, the storylines relate to a specific outcome, where the likelihood of this is a function of time, meaning that the storyline sits in a time-evolving envelope of plausible outcomes. This can include outcomes that are becoming more likely or less likely, or where likelihood does not change monotonically with time. The likelihood values stated directly relate to those in the formal assessment, however, below we additionally provide illustrative worked examples of estimating these likelihoods for Storylines 4 and 5 using the CP4A ensemble data. It should be noted that these examples do not provide a comprehensive assessment of the full range of likely outcomes as they are based on a single km-scale ensemble sampling 5 different CMIP6 models. They form only one component of the contributing evidence that we draw on to assess the storyline likelihoods but are highlighted here as they provide visual illustration of the storylines contextualised in an evolving probability envelope.

Storyline #	Narratives of tropical cyclone outcomes over Southern Africa	Likelihood for immediate-future (2026-2035) & end-of-century (2086-2095, $\geq 3^{\circ}\text{C}$ GWL)
1	Decreased annual rainfall across southern Africa as a whole, with decreasing overall contribution from TCs	<i>about as likely as not</i> , becoming <i>likely</i>
2	Of the tropical cyclones that do form, a greater proportion will be higher intensity (Category 3-5) with stronger winds and more intense rainfall	<i>likely</i> , becoming <i>very likely</i>
3	A greater frequency of rapid intensification, which results in less warning time	<i>more likely than not</i> , becoming <i>likely</i>
4	The occurrence of at least one tropical cyclone landfall at latitude of Maputo or further south that has not historically experienced cyclones	<i>very unlikely</i> , becoming <i>unlikely</i>
5	The occurrence of at least one Category 5 landfall, unprecedented in the historical record	<i>about as likely as not</i> , becoming <i>likely</i>

Table 2. REPRESA storylines of changing tropical cyclone attributes and their likelihood

Storyline 5 – Category 5 landfall

Fig 6 illustrates the changing likelihood of a Category 5 tropical cyclone in an ensemble of km-scale climate projections for Africa (CP4A, see Methods). It should be noted that here we are considering all storms west of 55°E, and not only those that make landfall. For the historical climate, the observations show that the most likely outcome is zero Category 5 TCs in a 10y period, with the probability of at least one Category 5 TC being 59%, corresponding to the *more likely than not* category (Table 1). For the observations, such high intensity TCs are confined to the east of Madagascar. The CP4A ensemble overestimates the number of Category 5 TCs compared to observations, however there is considerable ensemble spread with the number of Category 5 TCs in the historical 10-year period varying from 0 to 3 depending on member. Given the small numbers of events, and the considerable model variability (Fig 6), it is difficult to assess the significance of any model bias. However, some overestimation of TC intensity is expected given that the CP4A model is atmosphere-only (see Methods) and therefore does not capture the cold wake of a TC in SST, which acts to reduce the maximum intensity reached. Although we note that the size of this impact is a similar magnitude to the impact on the strongest TC intensities of sampling different SST biases across the driving CMIP6 models (Macholl et al, submitted).

CP4A shows an increase in the likelihood of Category 5 cyclones from the historical to future climate, with the probability of at least one Category 5 TC in the region (west of 55E) in the 10-year future period increasing to 99% i.e. such an occurrence is *virtually certain*, if we can assume the model results provide a perfectly reliable description of the future. In CP4A, the majority of these Category 5 TCs come within 250 km of the coastline (with the potential for impact over land), whilst one third or more come within 100 km of the coastline (i.e. make direct landfall). We would therefore expect the probabilities calculated to be lower for an actual Category 5 landfall. For the future simulations, there are 8 Category 5 TCs that come within 100 km of land in the 45-year dataset (corresponding to at least one Category 5 landfall being *likely* in a 10-year period, increasing to *very likely* for longer periods).

It should be noted that these probability values are just from a single model ensemble, with the numbers of landfalling Category 5 TCs in the CP4A dataset too small to allow a robust assessment, and that structural uncertainties in the model simulations (e.g. use of parametrisations that provide a simplified representation of sub-grid scale processes) remain. They form just one component of the evidence leading to the assessed likelihood of Storyline 5 being *about as likely as not* in the immediate future, becoming *likely*. In particular this assessment draws on multiple lines of evidence including the recent emergence of Category 5 TCs in the SWIO (Fitchett 2018), recorded near-misses of a Category 5 landfall (TCs Gafilo in 2004 and Hary in 2002 were potential Category 5 landfalls on the east coast of Madagascar), our mechanistic understanding of intensifying TCs in a warmer world, and future projected changes from the CP4A ensemble (Figs 3 & 6) and global high resolution climate models (Green et al 2026). On this basis we expect an increase in likelihood of very high intensity TCs even for the immediate-future compared to the historical period, with such an occurrence being *very likely* at higher GWLs (reduced to *likely* for a specific 10y end-of-century period).

Storyline 4 – Southern latitude landfall

Fig 7 illustrates the changing probabilities of the latitude and maximum intensity relationship. The probability of a TC having a maximum intensity in the middle of the Category 3 range (50-58 m/s) at the latitude of Durban, South Africa (30°S) is marked in 2D-space. Durban is chosen as a key city south of Maputo. We use this to calculate the expected number of TCs that satisfy this condition in the historical and future climate, taking into account the projected future decrease in overall TC numbers (see below). In general, we see that high intensity TCs (in particular Category 5 storms) are relatively more common in the future and there is a southward shift of the latitude of maximum intensity across all TC categories. It should be noted that here again we are considering all storms west of 55E, and not just landfalling TCs, with Category 5 TCs seen in both the observational and modelled historical distributions (Fig 7 top). From the 1D pdf for storm category (top panel insert), it can be seen that the model well captures the intensity distribution of storms, giving good agreement in the relative proportion of TCs in each of the intensity categories. There is some evidence that tropical cyclones tend to occur slightly too far north in CP4A, compared to the observations, although in both cases tropical cyclones as far south as 30S are outside the 10% probability level. These model biases are discussed in more depth in Macholl et al (submitted).

The relative probability of a TC having Category 3 intensity at the latitude of Durban is similar in the IBTrACS observations to the CP4A historical climate simulations, occurring at the 2% and 1% probability levels respectively. The projected future probability increases to 8%. Taking into account the numbers of Category 1+ TCs in the 45-years of data for each of the datasets (105 IBTrACS, 217 CP4A historical, 148 CP4A future), the expected number of TCs with a Category 3 maximum intensity at Durban latitude (in 45 years) is 2, 2 and 12 in the IBTrACS, CP4A historical and CP4A future respectively (to the nearest integer). Using a Poisson distribution (see Methods) we convert this to the likelihood of at least one event occurring in a 10-year period. This gives a likelihood value of 38% corresponding to *about as likely as not* for the historical period (both for CP4A and IBTrACS), increasing to 93%, i.e. *very likely*, for the future end-of-century period. We emphasize that this conversion of probabilities to IPCC-style likelihoods is only robust where we use large multi-model ensembles constrained by observations (and other emerging lines of evidence). Here we are illustrating this conversion but just for a single small ensemble.

For a TC actually making landfall at Maputo or further south (including Durban) (Storyline 4), this is unprecedented in the historical climate (i.e. there are no storms in the observations or historical CP4A simulations). In the future CP4A ensemble, there are two TCs that make landfall at Durban: one at Category 2 status and one at Category 3 for the 45 years of data. This gives a probability of at least one Category 3+ landfall in Durban in the 10y end-of-century period of 20% (corresponding to *unlikely*). This is one component of the evidence leading to the assessed likelihood for Storyline 4 of *very unlikely* (immediate-future), becoming *unlikely* (end-of-century). The other contributing evidence includes an understanding of the environmental conditions conducive to TC landfall at southern latitudes in a future climate which increases our confidence in the credibility of the CP4A projections; and evidence of a

projected southerly shift in tracks in high resolution global models (Green et al 2026, Cattiaux et al 2020) although with a lack of consistency across all ensemble members.

In Fig 7 we have chosen to consider the maximum intensity and its latitude of occurrence for all TCs in the region, rather than considering actual landfall intensity and location. This is because the number of TCs which make landfall is significantly lower, particularly as the westerly flow tends to steer TCs away from Mozambique and South Africa when exiting the Mozambique Channel. Considering all TCs gives more robust values and provides an illustrative example of a time-evolving probabilistic envelope relevant to Storyline 4. It should also be noted that whilst the latitude of maximum intensity may occur further north, impacts of the storm can still be felt further south, depending on the subsequent track of the storm and its rate of decay. Two important examples of such systems are tropical storm Domoina, which made landfall in southern Mozambique before causing extensive loss of life in South Africa's KwaZulu-Natal Province in January 1984 as a tropical depression (Jury et al., 1993), and TC Eloise, which made landfall in southern Mozambique in January 2021 as a Category 2 system before impacting in northeastern South Africa as a tropical storm and then tropical depression.

Link to impacts

High impact high likelihood events are of the greatest concern. Storyline 5 is an example of such an event, associated with high likelihood at $\geq 3^\circ$ GWL and high impact. The landfall of a Category 5 tropical cyclone is associated with winds in excess of 252 km/h, very heavy rainfall and depending on location a significant storm surge, leading to destruction of homes and infrastructure, damage to people's livelihoods including livestock and crops (Ortiz et al 2023; Bundy et al 2023), and significant loss of life (Kelder et al, 2025; Shultz et al 2020; Young & Hsiang, 2024). We note that lower likelihood outcomes are also important to understand and prepare for, especially where these may lead to high impact. Storyline 4 is an example of such an outcome. We may expect greater vulnerabilities to events where these are unprecedented, such as tropical cyclone landfall in new locations, as infrastructure is not adapted and/or evacuation procedures are not in place (Coughlan de Perez et al 2026). In general, the storylines presented here (Table 2) only consider the physical hazard, but can be extended to consider their associated impact, using information on exposure (e.g. the number of people affected) and vulnerability (e.g. the extent to which homes can withstand the hazard). These factors will vary with location and may also vary with time, alongside the likelihood of the hazard.

Discussion

In this paper we have produced storylines of specific plausible outcomes, that are rooted in the broader assessment of future changes in tropical cyclone attributes over southern Africa. Storylines have been gaining increasing popularity within the scientific community, as they help us to explore and communicate uncertainty, for example in the context of regional climate outcomes where there is no model consensus in changes to large-scale circulation patterns (Shepherd et al 2018; Zappa & Shepherd 2017). However, they can also be used to make the main messages and findings of a formal assessment

more accessible to a broader audience, whether the assessment yields low or high likelihood in the projected changes. They can be of immense value for highlighting the urgency of action, by bringing scientific findings into stories that people can more easily relate to. They can also assist in understanding the complexity of climate risk, exploring projected changes in the wider socio-ecological context, where multiple things can be occurring at once that may reduce or amplify the impact. They can facilitate dialogues between people of different disciplines and experiences, including the integration of local lived experience and knowledge with scientific findings. Importantly, community engagement should shape the process of storyline development (as was done here in the development of the REPRESA storylines via stakeholder engagement sessions) enriching and substantiating the storylines, and helping to achieve buy-in, trust and the uptake of information in decision making.

Storylines however typically have not been quantified in terms of their likelihood. Storylines are often used to explore worse-case outcomes, that are not grounded in scientific probabilistic assessments, and much less often the most likely outcomes. If storylines primarily illustrate extreme scenarios, then there is a risk they can lead to maladaptation (e.g. costly over-engineering of flood defences), unless the likelihood of such events occurring is clearly communicated. When presented with multiple “climate risk narratives” with no probabilities, people often choose one and would like to know which is more likely (Craig et al, submitted). Opposing storylines e.g. increasing flooding and increasing drought, although both plausible consequences of a changing climate in some regions, can be confusing and give the impression that there is greater uncertainty than in the formal assessment. Therefore, while there is much value in using storylines to explore high-impact outcomes that may be poorly represented by conventional probabilistic approaches, their use requires transparent communication of the evidence, confidence and plausibility underlying each storyline.

Here we argue that assigning likelihood to storylines is critical for these to properly inform decision-making, with the storylines having their roots in the scientific assessment. We acknowledge that this can lead to people focussing on the more likely outcomes and disregarding the others. Likelihood directly links to the global warming level, or time for a given emissions scenario. Knowledge of this evolving likelihood for each given storyline provides valuable information on the benefit and urgency of action. What is a current high-impact low-likelihood outcome in the present-day may evolve to become a high-impact high-likelihood outcome by the end-of-the-century, especially if there is limited mitigation. This has implications for the relevance of end-of-century projections, not only for mitigation decisions, but also adaptation measures to reduce vulnerability in the short term. That is, it is important for the use of storylines to assume the dimension of time and/or GWL.

Within the REPRESA project, the storylines have been used to stress test organisational procedures and plans. This involves exposing systems (e.g. anticipatory action protocols) to the storyline(s) and working with a range of actors to identify stressors and failure points, and then co-develop solutions (RCCC, 2025). This participatory approach is a key route to pull through scientific knowledge into decision making, and ultimately achieve increased preparedness and resilience to severe weather and unprecedented events of the future.

Methods

Model data

In this paper we have analysed a new ensemble of convection-permitting climate projections for Africa (CP4A) to provide additional evidence on changes in tropical cyclones, augmenting available published literature. The CP4A model has a resolution of 4.5km and spans the entire African subcontinent. It is termed “convection-permitting” because at this resolution it is possible to switch off the convection scheme, with convection represented explicitly on the model grid, although smaller convective plumes and updrafts are still not fully resolved. The CP4A ensemble builds on the first-ever climate projection simulation at such high resolution for Africa (Kendon et al 2019) carried out for just a single member and with an older version of the Met Office Unified Model. The new CP4A model uses the RAL3 model configuration (Bush et al 2025), with a number of important changes to the model physics compared to the original CP4A model. It includes a new land-surface scheme, bimodal cloud and new CASIM microphysics, and the Flake model to represent inland lakes. In addition more realistic soil properties, derived from the SoilGrids database, are used compared to the specification of sandy soils everywhere in the original CP4A climate simulation (Stratton et al 2018). A detailed description of the new CP4A model and evaluation of its performance compared to the original model is provided in Tucker et al (submitted). Overall, the new CP4A model performs better with reduced cold temperature biases in the north of Africa, and a reduction in rainfall intensity in better agreement with observations.

The new ensemble consists of five members downscaling five different CMIP6 global models, allowing us to provide a preliminary assessment of uncertainty in future changes at local scale. The downscaled global models (respective resolution) were chosen as HadGEM3-GC31-MM ($0.8^\circ \times 0.6^\circ$), MRI-ESM2-0 ($1.1^\circ \times 1.1^\circ$), TaiESM1 ($1.25^\circ \times 0.9^\circ$), MPI-ESM1-2-LR ($1.9^\circ \times 1.9^\circ$) and CanESM5 ($2.8^\circ \times 2.8^\circ$), with grid-spacings ranging from approximately 100-300 km. This choice was made based firstly on a validation of seasonal mean temperature, precipitation and sea-surface temperatures. CMIP6 models with large biases were ruled out, whilst models with smaller biases were given warnings. As a second step, projected climate changes in seasonal mean temperature and precipitation were examined, and CMIP6 models with a large number of warnings were ruled out unless excluding them resulted in not sampling the full range of changes seen in the CMIP6 ensemble. As a final step, more in-depth evaluation of some bespoke metrics important for African climate, including the African Easterly Jet, Central African Easterlies, Turkana Jet, West African Heat Band and West African Westerly Jet (James et al, 2018) was carried out. Performance for tropical cyclones was not specifically considered in the model selection. It should be noted that the subset of five CMIP6 models that were downscaled have more of a tendency for future increases in annual mean rainfall over southeastern Africa than the full ensemble of all CMIP6 models (Fig 4).

The selected CMIP6 models span a range of climate sensitivities, with equilibrium climate sensitivity values as follows: HadGEM3-GC31-MM (5.4°C), MRI-ESM2-0 (3.1°C), MPI-ESM1-2-LR (3.0°C), CanESM5 (5.6°C) and TaiESM1 (4.4°C). This results in a range of GWLs being sampled at the end-of-century, under

a low mitigation scenario (SSP5-8.5), ranging from 3.3°C (MPI-ESM1-2-LR) to 5.8°C (CanESM5). The horizontal resolution of the CMIP6 models ranges from 100km to 500km, and hence a 25km resolution regional model is used as an intermediate nest: the CMIP6 model drives the 25km regional model, which in turn provides lateral boundary data for CP4A. The domain of the 25km model is slightly larger than CP4A (Macholl et al, submitted) extending into the Indian ocean to facilitate the spin up of cyclones before they enter the CP4A domain. Sea surface temperatures in both the 25km regional model and CP4A are prescribed from the parent CMIP6 model.

For each CP4A ensemble member there is a historical simulation (1997-2007) and a future simulation (2079-2089), with the first few months of simulation discarded as spin-up. For the future, we use the SSP5-8.5 scenario in order to increase the signal to noise ratio and aid identification of the climate change response of local weather extremes. This high emissions scenario provides information on the upper-end of changes for precautionary planning, and we can interpolate results to lower emissions scenarios using scaling approaches (whilst the reverse of extrapolating from low to high emissions is not scientifically robust).

Overall, the CP4A ensemble provides nine decades of data at km-scale resolution, consisting of 45 seasons of TC activity in the historical and future periods respectively. This allows us for the first time to assess future changes in the climatological characteristics of TCs in a convection-permitting model. Macholl et al (submitted) provide an evaluation of CP4A's simulation of TCs showing evidence of too many weak tropical storms, but the ability to capture the most intense (Category 5) TCs. Green et al (submitted) shows that CP4A is able to capture TC intensification rates seen in observations, unlike coarser resolution models, responding realistically to favourable local storm environmental conditions and storm structures. There are caveats to the use of CP4A: the km-scale model is atmosphere-only and the lack of coupling to the ocean means it is likely to overestimate TC intensity; the close proximity of Madagascar to the lateral boundary of CP4A means there are some effects related to the spin-up of small-scale features entering the domain; the ensemble size is small (5 members) and therefore does not comprehensively sample uncertainty in future changes; and the simulation periods are relatively short (10-year present-day and 10-year future, for each member) and hence subject to inter-annual variability. However, overall, historical evaluation studies support the use of CP4A for projecting future changes to TCs over southern Africa (Macholl et al, submitted).

Tropical cyclone tracking

Tropical cyclones in the CP4A data were tracked and classified using the System for Classification of Low-Pressure Systems (SyCLOPS) approach (Han and Ullrich, 2025). This framework detects and tracks low-pressure systems (LPSs) using TempestExtremes (Ullrich and Zarzycki, 2017; Ullrich et al., 2021) and then classifies the different low-pressure types (e.g., Tropical Cyclone, Tropical Depression, Polar Low) at each data point. It has the benefit over other trackers in that it allows us to explore the full lifecycle track of a tropical cyclone from its genesis as a low-pressure system, intensification into a tropical cyclone and then decay.

One advantage of the TempestExtremes/SyCLOPS framework is the flexibility it provides through a wide range of tuneable parameters, allowing detection and tracking criteria to be adapted to the specific characteristics of the dataset and research question. In the detection step of TempestExtremes, we required a minimum closed-contour delta of 40 Pa in MSLP, a threshold chosen to balance sensitivity to weaker systems with robustness against noise. For the tracking step, we applied a maximum linkage distance of 4°, a minimum track duration of 18 hours, and a minimum great-circle track length of 8°, helping to suppress short-lived or poorly resolved features and reduce abrupt jumps between unrelated systems; the 4° linkage threshold over a 6 hour timestep is also consistent with plausible upper-end propagation speeds of tropical cyclones at the latitudes considered here.

We then applied additional filters to the SyCLOPS output to focus on the full lifetime tracks of tropical cyclones in our region of interest. Specifically, we (i) excluded track points within 1° of the model boundary to avoid edge effects; (ii) removed LPS feature types unlikely to be associated with tropical cyclones life-cycles (e.g. thermal lows); (iii) split tracks where consecutive points were separated by more than 4° or 24 hours, and discarded resulting segments with fewer than three points to remove fragmented tracks; and (iv) retained only tracks containing at least two points classified as tropical cyclones. Together, these filtering steps are designed to ensure coherent cyclone life-cycle tracks, minimising both spurious detections and unrealistic track linkages. The tracking settings and filtering steps were selected following sensitivity testing to provide an optimum representation of cyclone tracks in the model data.

Observational track data

We use observational track data from version 4r01 of the International Best Track Archive for Climate Stewardship (IBTrACS) database (Knapp et al 2010; Gahtan et al 2024). TC position and intensity data were taken from RSMC La Réunion and the US Navy's Joint Typhoon Warning Center (JTWC).

For Fig. 1, we assess observed trends using data from the RSMC and JTWC as individual subsets of the IBTrACS data. This provides a measure of the uncertainty in the location and intensity of TCs. Data from the RSMC subset is limited from the 2000 TC season onwards (2000-2024), consistent with Leroux et al. (2018). We extend the JTWC dataset back to the 1990 season, due to the reduction of missing data in the 1990s, compared to the 1980s (Knapp & Kossin, 2007) (1990-2024). We convert 1-minute sustained winds from JTWC to 10-minute using a conversion factor of 0.88 (Harper et al., 2010) and identify TCs in IBTrACS where the following criteria are satisfied:

- A TC reaches 17.4m/s (RSMC Tropical Storm threshold) between 30°E - 90°E, 30°S-5°S, whilst designated as a Tropical Depression (TD), Tropical Storm (TS) or Tropical Cyclone (TC) by the nature flag in the IBTrACS data. In JTWC, we use those designated as a TD, TS and TC, or the WMO Tropical designation if this is not available. In the RSMC TC track data, we use the classifications of 02, 03 or 04.
- The TC must last at least 2 days in duration.

- Genesis (defined as the first timestep of the track) must occur between October-May.

For storylines 4 and 5 analysis, we collated records from both centres, prioritising 1-minute sustained wind speed data from JTWC given our choice to adopt the Saffir Simpson intensity classification scale. Where a storm featured in the RSMC records but not JTWC, its intensities were converted from 10 to 1-minute sustained wind speeds using a conversion factor of 1.136 (Harper et al., 2010). We used 45 years of data from IBTrACS corresponding to the period Aug 1979 to Aug 2024, so that we have a similar data record length to the 45 years of model data for each of the historical and future periods.

Tropical cyclone categorisation

In this paper we use the widely used Saffir-Simpson scale to categorise the intensity of TCs, as this will be most familiar to readers. This is typically based on maximum wind speeds, with the strongest Category 5 TCs associated with wind speeds in excess of 70m/s (252 km/h) (Table 3). The wind-speed thresholds are used for categorisation within IBTrACS observations, whilst minimum sea level pressure (MSLP) is typically used for categorisation in coarser resolution climate models that are unable to represent the high wind speeds (Roberts et al, 2020a). For CP4A, we use both the max wind speed and min sea level pressure categorisation approaches. We use instantaneous max wind speed outputs, that are sampled every model timestep (of 75sec). The Saffir-Simpson categories are not used operationally in the SWIO, with the RSMC La Reunion scale used instead (Table 3, WMO, 2021). It is worth noting that the two scales use different averaging periods (10-minute average maximum sustained wind speeds for RSMC La Reunion versus 1-minute maximum sustained winds for the Saffir-Simpson scale).

Saffir-Simpson classification			RSMC La Reunion scale	
Category	Max wind speed (m/s)	Min sea level pressure (hPa)	Category	Max wind speed (km/h)
Tropical depression	<17.5		Tropical depression	51-62
Tropical storm	17.5 – 33	>= 994	Moderate tropical storm	63-88
			Severe tropical storm	89-117
Category 1	33 – 43	980 – 994	Tropical cyclone	118-165
Category 2	43 – 50	965 – 980	Intense tropical cyclone	166-212
Category 3	50 – 58	945 – 965		
Category 4	58 – 70	920 – 945	Very intense tropical cyclone	> 212
Category 5	>= 70	< 920		

Table 3: Tropical cyclone intensity classification. (left) Categories defined from the official Saffir-Simpson 1-min sustained wind speed classification, alongside categories as measured by minimum sea level pressure thresholds (following Roberts et al 2020a). (right) RSMC La Reunion scale used operationally in the SWIO (WMO, 2021).

Assigning likelihood and confidence in synthesized assessment

We focus our assessment on the Southwest Indian Ocean (SWIO, 30°E - 90° E, 0°S - 40°S), over the Mozambique Channel (30°E - 52.5°E, -5°S - 30°S), and on Malawi, Mozambique and Madagascar.

We use confidence levels for statements relating to observed trends (and for some statements around the quality of evidence for future changes), whilst likelihood assessments are used for future projections themselves, as they encompass fundamentally different sources of uncertainty. For observational trends, confidence is determined by the availability, length and quality of observed records, augmented by our physical understanding of the underlying processes needed to distinguish anthropogenically forced trends from multi-decadal variability. For future projections, we are dealing with unseen future outcomes using imperfect models, and so results are subject to modelling (structural) uncertainty, with different models having different levels of credibility. They are also subject to sampling uncertainty, i.e., model projections may not be sufficiently long to extract the climate change signal from multi-annual and decadal natural variability. There is uncertainty regarding our future emissions pathway, but here statements are conditional on a given global warming level, and so we do not explicitly consider this uncertainty (following Seneviratne et al, 2021). To provide a likelihood estimate, we draw on multiple lines of evidence, assessing the quality of the information and the level of agreement across independent studies. The reliability of different model projections is assessed using our understanding of the underlying processes and how well these are represented in the models, as well as observational constraints. This can be represented using model weights for combining different model projections to produce a quantitative probabilistic envelope of future outcomes (Räisänen et al 2010).

Storyline analysis methods

In this paper we provide some illustrative examples of storylines visualised within the probabilistic distribution of TCs from a km-scale model ensemble, where all ensemble members are considered equally credible. These are simply illustrative and do not provide a comprehensive assessment of the full probabilistic envelope as they are based on a single ensemble sampling 5 different CMIP6 models. They form just one component of the contributing evidence that we draw on to assess the storyline likelihoods.

For Storyline 5, we identified all tracks in CP4A historical and future simulations west of 55°E that reach Category 5 for at least one timestep. This provided numbers of Category 5 TCs in each 45-year dataset for the historical and future periods (15 and 22 TCs respectively). The likelihood of at least one Category 5 TC in a 10-year period was calculated using a Poisson distribution, assuming events are randomly

distributed across years (Fig 6). For landfalling Category 5 TCs, all TCs that were Category 5 status within 100km of the coastline of Mozambique or Madagascar were counted. We also repeated this process for observational track data from IBTrACS.

For Storyline 4, the maximum intensity (wind speed in m/s) reached by each TC and the latitude at which this occurred was identified in each of the IBTrACS, CP4A historical and future datasets, for all tropical cyclones (Category 1+) in the Southwest Indian Ocean and Mozambique Channel (defined as the region west of 55°E). The tropical cyclones in each dataset were then binned according to the values of maximum intensity and latitude, with the numbers in each bin normalised by the total number of tropical cyclones, to give a 2D probability density function (Fig 7). From this 2D probability density function, the probability of a given TC reaching a maximum intensity of Category 3 south of Durban (30°S) can be assessed. The expected number of TCs satisfying this condition was then given by this probability multiplied by the total number of TCs in each of the 45-year datasets (total number of TCs = 105 IBTrACS, 217 CP4A historical, 148 CP4A future). Again a Poisson distribution was used to convert the expected number of TCs to the probability of at least one TC satisfying the condition in a 10-year period.

We note that we can construct similar figures for the other storylines illustrating their occurrence within time-evolving probabilistic envelopes. For Storyline 1, the appropriate axes would be the change in annual rainfall versus the change in TC contribution to annual rainfall, across ensemble members (and ideally across a large multi-model ensemble). Similarly for Storylines 2 and 3, we are considering changes in a TC characteristic (a greater proportion of high intensity TCs or a greater frequency of rapidly intensifying storms, respectively). These storylines are quite different to Storylines 4 and 5, where we are considering the occurrence of a specific event within a given period of time. Natural variability has a much greater contribution to uncertainty in the occurrence of a specific extreme event than for a change in a mean climate state (or climatological TC characteristic). For the former, this is captured by sampling all individual TC tracks, across all ensemble members, in the construction of probabilities (although again with the caveat here that we only have a single km-scale model ensemble, and 9 TC seasons for each member, totalling 45 seasons).

Declarations

Competing interests

The authors declare no competing interests.

Author contributions

EJK and FAE conceived the idea. EJK wrote the manuscript. JDM and EJK carried out TC tracking and designed the storyline methodology. HAT developed code for rainfall analysis and post-processing of TC tracks. EJK, JDM, DRG & AKA produced the figures. MK helped with the storyline development. All authors contributed to the synthesized assessment, evaluating multiple lines of evidence and agreeing likelihood statements. All authors reviewed, edited and commented on the manuscript.

Acknowledgements

The REPRESA project was funded by the Foreign, Commonwealth and Development Office in the UK and the International Development Research Council in Canada under the Climate Adaptation and Resilience program. EJK is additionally supported by the Met Office Hadley Centre Climate Programme funded by the UK Department for Business, Innovation, Science and Trade. DRG thanks the University of Bristol for providing doctoral training funding. RAJ and AKA were supported by UK Research and Innovation (UKRI) through a Future Leaders Fellowship project, SALIENT [grant number MR/W013223/1]. HAT was supported by the Met Office Weather and Climate Science for Service Partnership (WCSSP) South Africa project, supported by the International Science Partnerships Fund (ISPF) from the UK's Department for Science, Innovation and Technology (DSIT).

Data availability

Tropical cyclone track and climate model data from the new CP4A ensemble simulations are available from the authors upon reasonable request and can be accessed through the JASMIN platform. There are plans to make these datasets openly available at a later date.

References

1. Ayob, N.N., Sharoni, S.M.H. & Lim, H.S. 2026: Multiple perspectives on global tropical cyclone intensity trends (1980–2024) using IBTrACS dataset. *Clim Dyn* **64**, 286.
<https://doi.org/10.1007/s00382-026-08248-3>
2. Baker, A. J., B. Vanniere, and P. L. Vidale, 2024: On the realism of tropical cyclone intensification in global storm-resolving climate models. *Geophys. Res. Lett.*, 51, e2024GL109841,
<https://doi.org/10.1029/2024GL109841>
3. Baulenas, E., G. Versteeg, M. Terrado, J. Mindlin, D. Bojovic, Assembling the climate story: use of storyline approaches in climate-related science. *Global Challenges* 2023, 7, 2200183.
<https://doi.org/10.1002/gch2.202200183>
4. Bell, S. S., Chand, S. S., Tory, K. J., Dowdy, A. J., Turville, C., & Ye, H. (2019). Projections of southern hemisphere tropical cyclone track density using CMIP5 models. *Climate Dynamics*, 52(9), 6065-6079. <https://doi.org/10.1007/s00382-018-4497-4>

5. Bundy, L.R., V. A. Gensini, M. S. Van Den Broeke (2023) Tropical cyclone impacts on crop condition ratings and yield in the Coastal Southern United States, *Agricultural and Forest Meteorology*, 340, <https://doi.org/10.1016/j.agrformet.2023.109599>
6. Bush, M., et al, 2025: The third Met Office Unified Model-JULES regional atmosphere and land configuration, *RAL3. Geoscientific Model Development*, 18, 3819–3855, <https://doi.org/10.5194/gmd-2024-201>
7. Camargo, S. J., and Coauthors, 2023: An update on the influence of natural climate variability and anthropogenic climate change on tropical cyclones. *Trop. Cyclone Res. Rev.*, 12, 216–239, <https://doi.org/10.1016/j.tccr.2023.10.001>
8. Cao X et al 2024: Westward shift of tropical cyclogenesis over the southern Indian Ocean, *Environ. Res. Lett.* **19** 034016
9. Cattiaux, J., Chauvin, F., Bousquet, O., Malardel, S., & Tsai, C.-L. (2020). Projected Changes in the Southern Indian Ocean Cyclone Activity Assessed from High-Resolution Experiments and CMIP5 Models. *Journal of Climate*, 33(12), 4975-4991. <https://doi.org/https://doi.org/10.1175/JCLI-D-19-0591.1>
10. Chand, S. S., Walsh, K. J. E., Camargo, S. J., Kossin, J. P., Tory, K. J., Wehner, M. F., Chan, J.C.L., Klotzbach, P.J., Dowdy, A. J., Bell, S. S., Ramsay, H.A., & Murakami, H. (2022). Declining tropical cyclone frequency under global warming. *Nature Climate Change*, 12(7), 655-661. <https://doi.org/10.1038/s41558-022-01388-4>
11. Chen, J., Wang, Z., Tam, CY. et al. (2020) Impacts of climate change on tropical cyclones and induced storm surges in the Pearl River Delta region using pseudo-global-warming method. *Sci Rep* **10**, 1965. <https://doi.org/10.1038/s41598-020-58824-8>
12. Chichava, D., Yu, J. H., King’uza, P. H., & Ekwacu, S. (2024). Change in the Number of Tropical Cyclone Landfall and Approach over Mozambique from 1980 to 2020. *Journal of Geoscience and Environment Protection*, 12, 1-20. <https://doi.org/10.4236/gep.2024.1210001>
13. Chu, W., García-Franco, J.L., Camargo, S.J., Lee, C.Y., Tippet, M.K., Murakami, H., Baldwin, J.W. and Frucht, S., 2026. Historical and projected tropical cyclone characteristics in SPEAR large ensemble simulations. *Earth's Future*, 14(6). <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2025EF007720>
14. Coughlan de Perez, E., L. Artur, D. Heinrich, M. Lagmay, G. I. T. Masukwedza, B. Nhantumbo, E. Stephens (2026) Unseen but increasing: recent changes in risk of extreme precipitation over Southern Africa and Southeast Asia, *Weather and Climate Extremes*, 52, <https://doi.org/10.1016/j.wace.2026.100910>
15. Craig, A., James, R. A., Kennedy-Asser, A. T., Daron, J., Jones, R., McClure, A, Shaw, S., Stephens, E., Steynor, A., Taylor, A., Vincent, K., submitted: Testing future climate risk communications with adaptation and disaster risk reduction professionals, submitted to *Climate Services*
16. Earl-Spurr, C., and Coauthors, 2024: New WMO Certified Tropical Cyclone Duration Extreme: TC Freddy (04 February to 14 March 2023) Lasting for 36.0 Days. *Bull. Amer. Meteor. Soc.*, **105**, 845–

- 849, <https://doi.org/10.1175/BAMS-D-24-0071.1>
17. Elsner, J. B. (2020). Continued Increases in the Intensity of Strong Tropical Cyclones. *Bulletin of the American Meteorological Society*, 101(8), E1301-E1303. <https://doi.org/10.1175/BAMS-D-19-0338.1>
 18. Elsner, J., Kossin, J. & Jagger, T., (2008) The increasing intensity of the strongest tropical cyclones. *Nature* **455**, 92–95. <https://doi.org/10.1038/nature07234>
 19. Emanuel, K., (2024). Limitations of reanalyses for detecting tropical cyclone trends. *Nature Climate Change*, 14(2), 143-145. <https://doi.org/10.1038/s41558-023-01879-y>
 20. Engelbrecht, F.A. and Vogel, C.H., (2021). When early warning is not enough. *One Earth*, 4, 1055-1058. <https://doi.org/10.1016/j.oneear.2021.07.016>.
 21. Engelbrecht, F.A., Steinkopf, J., Padavatan, J., Midgley, G.F. (2024). Projections of Future Climate Change in Southern Africa and the Potential for Regional Tipping Points. In: von Maltitz, G.P., *et al.* Sustainability of Southern African Ecosystems under Global Change. Ecological Studies, vol 248. Springer, Cham. https://doi.org/10.1007/978-3-031-10948-5_7
 22. Fitchett, J. M., (2018). Recent emergence of CAT5 tropical cyclones in the South Indian Ocean. *South African Journal of Science*, 114(11-12), 1-6. <https://doi.org/10.17159/sajs.2018/4426>
 23. Gahtan, J., K. R. Knapp, C. J. Schreck, H. J. Diamond, J. P. Kossin, M. C. Kruk (2024) International Best Track Archive for Climate Stewardship (IBTrACS) Project, Version 4r01. The since 1980 subset was used in this analysis. NOAA National Centers for Environmental Information. doi:10.25921/82ty-9e16 [accessed September 2026]
 24. Gori, A., Lin, N., Schenkel, B., & Chavas, D. (2023). North Atlantic tropical cyclone size and storm surge reconstructions from 1950-present. *Journal of Geophysical Research: Atmospheres*, 128, e2022JD037312. <https://doi.org/10.1029/2022JD037312>
 25. Green, D. R., James, R. A., Kendon, E. J., Mitchell, D., & Roberts, M. J. (2026). Projected changes to tropical cyclones in the southwest Indian Ocean using high-resolution global climate models. *Earth's Future*, 14, e2025EF007484. <https://doi.org/10.1029/2025EF007484>
 26. Green, D. R., James, R. A., Kendon, E. J., Blamey R.C., Reason C.J.C., Macholl J.D., Tucker S. and Mitchell, D. (submitted) Greater likelihood of rapidly intensifying Tropical Cyclones in the Mozambique Channel under a high-emission scenario, submitted to *Earth's Future*
 27. Guo, Y. & Z. Tan, Enhanced global storm surges by tropical cyclone poleward migration, *Proc. Natl. Acad. Sci. U.S.A.* 123 (24) e2535524123, <https://doi.org/10.1073/pnas.2535524123> (2026).
 28. Guzman, O., and H. Jiang, 2021: Global increase in tropical cy clone rain rate. *Nat. Commun.*, 12, 5344, <https://doi.org/10.1038/s41467-021-25685-2>
 29. Han, Y., & Ullrich, P. A. (2025). The System for Classification of Low-Pressure Systems (SyCLOPS): An All-In-One Objective Framework for Large-Scale Data Sets. *Journal of Geophysical Research: Atmospheres*, 130(1), e2024JD041287. <https://doi.org/10.1029/2024JD041287>
 30. Harper, B., Kepert, J., & Ginger, J. (2010). Guidelines for converting between various wind averaging periods in tropical cyclone conditions, WMO/TD-No.1555, 54p., August 2010, WMO, Geneva.

31. Huang, L., Zhuang, W., Lu, W., Zhang, Y., Edwing, D., & Yan, X.-H. (2024). Rapid sea level rise in the tropical Southwest Indian Ocean in the recent two decades. *Geophysical Research Letters*, 51, e2023GL106011. <https://doi.org/10.1029/2023GL106011>
32. Helen Hooker, Jessica Steinkopf, Charles Langton Vanya, Genito Maure, Bernardino Nhantumbo, Francois Engelbrecht, Hannah Cloke, Elisabeth Stephens (2026) Extreme Rainfall from Tropical Cyclones is Revealed by Kilometer-Scale Downscaling in Southeast Africa, *J of hydrometeorology*, <https://doi.org/10.1175/JHM-D-25-0179.1>
33. Jack, C. D., R. Jones, L. Burgin, J. Daron (2020) Climate risk narratives: An iterative reflective process for co-producing and integrating climate knowledge, *Climate Risk Management*, 29, <https://doi.org/10.1016/j.crm.2020.100239>
34. James, R., Washington, R., Abiodun, B., Kay, G., Mutemi, J., Pokam, W., Hart, N., Artan, G., & Senior, C. (2018). Evaluating Climate Models with an African Lens. *Bulletin of the American Meteorological Society*, 99(2), 313–336. <https://doi.org/10.1175/BAMS D-16-0090.1>
35. Jury, M.R., Pathack, B., Wang, B., Powell, M. and Raholijao, N. (1993). A destructive tropical cyclone season in the SW Indian Ocean: January-February 1984. *South African geographical journal* 75 53-59. <https://doi.org/10.1080/03736245.1993.10586405>
36. Kaplan, J., and M. DeMaria, 2003: Large-Scale Characteristics of Rapidly Intensifying Tropical Cyclones in the North Atlantic Basin. *Wea. Forecasting*, **18**, 1093–1108, [https://doi.org/10.1175/1520-0434\(2003\)018<1093:LCORIT>2.0.CO;2](https://doi.org/10.1175/1520-0434(2003)018<1093:LCORIT>2.0.CO;2)
37. Kelder, T., Heinrich, D., Klok, L. et al. 2025: How to stop being surprised by unprecedented weather. *Nat Commun* **16**, 2382. <https://doi.org/10.1038/s41467-025-57450-0>
38. Kendon, E. J., Stratton, R. A., Tucker, S., Marsham, J. H., Berthou, S., Rowell, D. P., & Senior, C. A. (2019). Enhanced future changes in wet and dry extremes over Africa at convection-permitting scale. *Nature Communications*, 10(1), 1–14. <https://doi.org/10.1038/s41467-019-09776-9>
39. Kennedy-Asser, A.T., James, R.A., Daron, J. et al. Do climate models agree on seasonal rainfall patterns and future changes over Southern Africa?. *Climatic Change* **179**, 22 (2026). <https://doi.org/10.1007/s10584-025-04073-5>
40. Klotzbach, P. J., Wood, K. M., Schreck III, C. J., Bowen, S. G., Patricola, C. M., & Bell, M. M. (2022). Trends in Global Tropical Cyclone Activity: 1990–2021. *Geophysical Research Letters*, 49(6), e2021GL095774. doi.org/10.1029/2021GL095774
41. Knapp, K. R., & Kossin, J. P. (2007). New global tropical cyclone data set from ISCCP B1 geostationary satellite observations. *Journal of Applied Remote Sensing*, 1(1), 013505. <https://doi.org/10.1117/1.2712816>
42. Knapp, K. R., M. C. Kruk, D. H. Levinson, H. J. Diamond, and C. J. Neumann, 2010: The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. *Bulletin of the American Meteorological Society*, 91, 363-376. [doi:10.1175/2009BAMS2755.1](https://doi.org/10.1175/2009BAMS2755.1)
43. Knutson, T., and Coauthors, 2019: Tropical cyclones and climate change assessment: Part I: Detection and attribution. *Bull. Amer. Meteor. Soc.*, 100, 1987–2007, <https://doi.org/10.1175/BAMS->

44. Knutson, T., and Coauthors, 2020: Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bull. Amer. Meteor. Soc.*, 101, E303–E322, <https://doi.org/10.1175/BAMS-D-18-0194.1>
45. Kossin, J. P., Knapp, K. R., Olander, T. L., & Velden, C. S. (2020). Global increase in major tropical cyclone exceedance probability over the past four decades. *Proceedings of the National Academy of Sciences*, 117(22), 11975-11980. <https://doi.org/doi:10.1073/pnas.1920849117>
46. Lavender, S. L., & McBride, J. L. (2021). Global climatology of rainfall rates and lifetime accumulated rainfall in tropical cyclones: Influence of cyclone basin, cyclone intensity and cyclone size. *International Journal of Climatology*, 41, E1217-E1235.
47. Lee, CY., Tippett, M., Sobel, A. et al. Rapid intensification and the bimodal distribution of tropical cyclone intensity. *Nat Commun* 7, 10625 (2016). <https://doi.org/10.1038/ncomms10625>
48. Leroux, M.-D., Meister, J., Mekies, D., Dorla, A.-L., & Caroff, P. (2018). A Climatology of Southwest Indian Ocean Tropical Systems: Their Number, Tracks, Impacts, Sizes, Empirical Maximum Potential Intensity, and Intensity Changes. *Journal of Applied Meteorology and Climatology*, 57(4), 1021-1041. doi.org/10.1175/JAMC-D-17-0094.1
49. Leroux, M.D., Bonnardot, F., Somot, S., Alias, A., Kotomangazafy, S., Ridhoine, A. O. S., Veerabadren, P., & Amelie, V., (2024). Developing climate services for vulnerable islands in the Southwest Indian Ocean: A Combined statistical and dynamical CMIP^ downscaling approach for climate change assessment. *Climate Services*, 34, 100491. <https://doi.org/https://doi.org/10.1016/j.cliser.2024.100491>
50. Li, Y., Tang, Y., Wang, S., Toumi, R., Song, X., & Wang, Q. (2023). Recent increases in tropical cyclone rapid intensification events in global offshore regions. *Nature Communications*, 14(1), 5167. <https://doi.org/10.1038/s41467-023-40605-2>
51. Macholl, J. D., E.J. Kendon, P. L. Vidale , E. Stephens, M. J. Roberts, H. A. Titley, C. Scullion & S. O. Tucker (submitted) Km-scale modelling of tropical cyclones in southern Africa, submitted to *Weather and Climate Extremes*
52. Mawren, D., R. Blamey, J. Hermes, and C. J. C. Reason, 2023: On the importance of the Mozambique Channel for the climate of southeastern Africa. *Climate Dyn.*, 60, 279–299, <https://doi.org/10.1007/s00382-022-06334-w>
53. Muthige, M. S., Malherbe, J., Engelbrecht, F., Grab, S., Beraki, A., Maisha, T. R., & Van der Merwe, J. (2018). Projected changes in tropical cyclones over the South West Indian Ocean under different extents of global warming. *Environmental Research Letters*, 13(6), 065019. <https://doi.org/10.1088/1748-9326/aabc60>
54. Needham, H. F., and B. D. Keim (2014) Correlating Storm Surge Heights with Tropical Cyclone Winds at and before Landfall. *Earth Interact.*, 18, 1–26, <https://doi.org/10.1175/2013EI000527.1>.
55. Ortiz AMD, Chua PLC, Salvador D Jr, Dyngeland C, Albao JDG Jr, Abesamis RA (2023) Impacts of tropical cyclones on food security, health and biodiversity. *Bull World Health Organ.* 101(2):152-154.

doi: 10.2471/BLT.22.288838.

56. Pall, P., Gagnon, A. S., Bollasina, M. A., Zarzycki, C. M., Huang, Y., S. Beckett, C. T., Ramanantoanina, H., & S. Reynolds, T. P. (2024). Assessing South Indian Ocean tropical cyclone characteristics in HighResMIP simulations. *International Journal of Climatology*, 44(13), 4792-4808.
<https://doi.org/10.1002/joc.8609>
57. Räisänen, J., Ruokolainen, L. & Ylhäisi, J. Weighting of model results for improving best estimates of climate change. *Clim Dyn* **35**, 407–422 (2010). <https://doi.org/10.1007/s00382-009-0659-8>
58. Ranasinghe, R., A.C. Ruane, R. Vautard, N. Arnell, E. Coppola, F.A. Cruz, S. Dessai, A.S. Islam, M. Rahimi, D. Ruiz Carrascal, J. Sillmann, M.B. Sylla, C. Tebaldi, W. Wang, and R. Zaaboul, 2021: Climate Change Information for Regional Impact and for Risk Assessment. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1767–1926, doi: 10.1017/9781009157896.014.
59. RCCC, 2025: Module 6: Stress testing for anticipatory action: identifying risk multipliers, in *Toolkit for anticipatory action in fragile, conflict- and violence-affected settings (FCV)*, Red Cross Red Crescent Climate Centre; Anticipation Hub; International Water Management Institute. March 2025. Available from <https://www.anticipation-hub.org/download/file-4844>
60. Roberts, M. J., Camp, J., Seddon, J., Vidale, P. L., Hodges, K., Vanniere, B., Mecking, J., Haarsma, R., Bellucci, A., Scoccimarro, E., Caron, L., Chauvin, F., Terray, L., Valcke, S., Moine, M., Putrasahan, D., Roberts, C., Senan, R., Zarzycki, C., & Ullrich, P. (2020a). Impact of Model Resolution on Tropical Cyclone Simulation Using the HighResMIP–PRIMAVERA Multimodel Ensemble. *Journal of Climate*, 33(7), 2557-2583. <https://doi.org/10.1175/JCLI-D-19-0639.1>
61. Roberts, M. J., Camp, J., Seddon, J., Vidale, P. L., Hodges, K., Vannière, B., Mecking, J., Haarsma, R., Bellucci, A., Scoccimarro, E., Caron, P., Chauvin, F., Terray, L., Valcke, S., Moine, P., Putrasahan, D., Roberts, C. D., Senan, R., Zarzycki, C., . . . Wu, L. (2020b). Projected Future Changes in Tropical Cyclones Using the CMIP6 HighResMIP Multimodel Ensemble. *Geophysical Research Letters*, 47(14), e2020GL088662. <https://doi.org/10.1029/2020GL088662>
62. Shultz J. M., D. E. Sands, J. P. Kossin, S. Galea, 2020: Double Environmental Injustice — Climate Change, Hurricane Dorian, and the Bahamas, *New England Journal of Medicine*, 382, 1-3, <https://www.nejm.org/doi/full/10.1056/NEJMp1912965>
63. Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A. Di Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou, 2021: Weather and Climate Extreme Events in a Changing Climate. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R.

- Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766, doi:10.1017/9781009157896.013.
64. Shepherd, T.G., Boyd, E., Calel, R.A. *et al.*, 2018: Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Climatic Change* **151**, 555–571. <https://doi.org/10.1007/s10584-018-2317-9>
 65. Stratton, R. A., Senior, C. A., Vosper, S. B., Folwell, S. S., Boutle, I. A., Earnshaw, P. D., Kendon, E., Lock, A. P., Malcolm, A., Manners, J., Morcrette, C. J., Short, C., Stirling, A. J., Taylor, C. M., Tucker, S., Webster, S., & Wilkinson, J. M. (2018). A Pan-African convection-permitting regional climate simulation with the met office unified model: CP4-Africa. *Journal of Climate*, 31(9), 3485–3508. <https://doi.org/10.1175/JCLI-D-17 0503.1>
 66. Studholme, J., Fedorov, A.V., Gulev, S.K. *et al.* Poleward expansion of tropical cyclone latitudes in warming climates. *Nat. Geosci.* **15**, 14–28 (2022). <https://doi.org/10.1038/s41561-021-00859-1>
 67. Thompson, C., Barthe, C., Bielli, S., Tulet, P. & Pianezze, J. (2021) Projected characteristic changes of a typical tropical cyclone under climate change in the Southwest Indian Ocean. *Atmosphere*, 12, 232. Available from: <https://doi.org/10.3390/atmos12020232>
 68. Titley H., E. J Kendon, J. D. Macholl (submitted) Insights from high-resolution climate models into projected changes in tropical cyclone rainfall in the South West Indian Ocean, submitted to *International Journal of Climatology*
 69. Trisos, C. H., Adelekan, I. O., Totin, E., Ayanlade, A., Efitre, J., Gemed, A., Kalaba, K., Lennard, C., Masao, C., & Mgaya, Y. (2022). Africa. In *IPCC Climate Change 2022: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1285-1455). Cambridge University Press.
 70. Tu, S., Hu, Z., Liang, M., Zhou, W., Chan, J. C. L., & Xu, J. (2024). Decreasing trend in destructive potential of tropical cyclones in the South Indian Ocean since the mid-1990s. *Communications Earth & Environment*, 5(1), 543. <https://doi.org/10.1038/s43247-024-01683-2>
 71. Tucker S., E. J. Kendon, C. J. Short and J. D. Macholl (submitted) A New Convection Permitting Climate Model for Africa, submitted to *Journal of Climate*
 72. Ullrich, P. A., & Zarzycki, C. M. (2017). TempestExtremes: A framework for scale-insensitive pointwise feature tracking on unstructured grids. *Geoscientific Model Development*, 10(3), 1069–1090. <https://doi.org/10.5194/gmd-10-1069-2017>
 73. Ullrich, P. A., Zarzycki, C. M., McClenny, E. E., Pinheiro, M. C., Stansfield, A. M., & Reed, K. A. (2021). TempestExtremes v2.1: A community framework for feature detection, tracking, and analysis in large datasets. *Geoscientific Model Development*, 14(8), 5023–5048. <https://doi.org/10.5194/gmd-14-5023-2021>
 74. Vannière, B., Roberts, M., Vidale, P. L., Hodges, K., Demory, M., Caron, L., Scoccimarro, E., Terray, L., & Senan, R. (2020). The Moisture Budget of Tropical Cyclones in HighResMIP Models: Large-Scale

- Environmental Balance and Sensitivity to Horizontal Resolution. *Journal of Climate*, 33(19), 8457-8474. <https://doi.org/10.1175/JCLI-D-19-0999.1>
75. Walsh, K.J.E., McBride, J.L., Klotzbach, P.J., Balachandran, S., Camargo, S.J., Holland, G., Knutson, T.R., Kossin, J.P., Lee, T.-c., Sobel, A. and Sugi, M. (2016), Tropical cyclones and climate change. *WIREs Clim Change*, 7: 65-89. <https://doi.org/10.1002/wcc.371>
76. Wang, Q., Guan, S., Luo, C., Zhao, W., Zhang, L., & Yang, S. (2025). Record-breaking lifespan, rapid intensification, and long-lasting coastal activity of tropical cyclone Freddy (2023) in the South Indian Ocean. *Environmental Research Letters*, 20(6), 064038.
77. WMO (2021) Tropical cyclone operational plan for the South-West Indian Ocean, TCP-12, WMO-No. 1178, 70p., Geneva, <https://library.wmo.int/idurl/4/42996>
78. WMO (2024) Tropical Cyclone Freddy is the longest tropical cyclone on record at 36 days: WMO. <https://wmo.int/news/media-centre/tropical-cyclone-freddy-longest-tropical-cyclone-record-36-days-wmo> [accessed 6 July 2026]
79. Young, R., Hsiang, S. (2024) Mortality caused by tropical cyclones in the United States. *Nature* **635**, 121–128. <https://doi.org/10.1038/s41586-024-07945-5>
80. Zappa, G., and T. G. Shepherd, 2017: Storylines of Atmospheric Circulation Change for European Regional Climate Impact Assessment. *J. Climate*, **30**, 6561–6577, <https://doi.org/10.1175/JCLI-D-16-0807.1>.
81. Zhou, W., Leung, L.R., Chang, CC. *et al.* (2026) Poleward migration of tropical cyclones over 1980–2024 is dominated by Pacific variability. *Nat. Geosci.* **19**, 42–51. <https://doi.org/10.1038/s41561-025-01866-2>

Figures

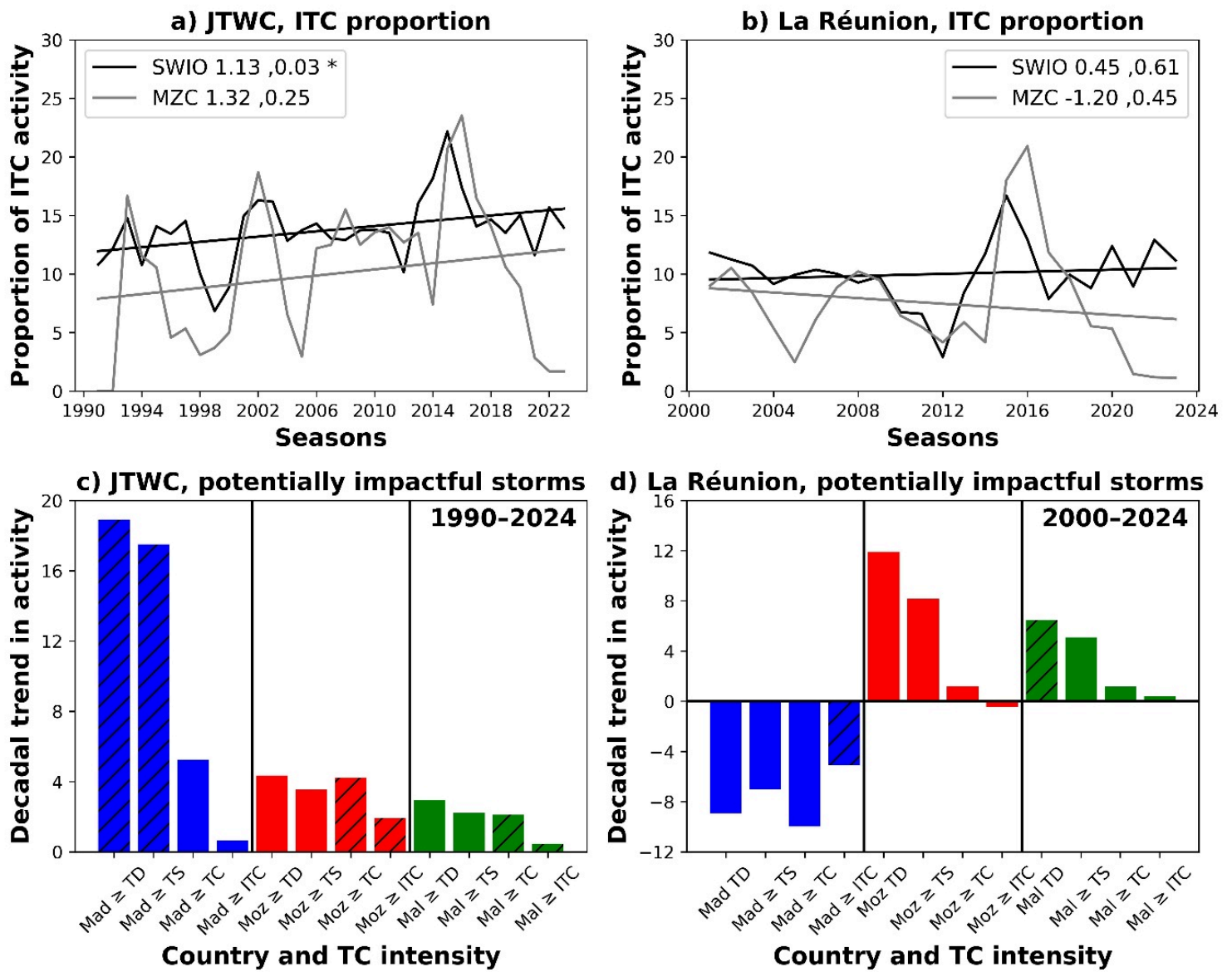


Figure 1

Observed decadal trends in tropical cyclones. (top) Observed decadal trend in the proportion of intense TC activity (ITC, defined as total activity $\geq 46.3\text{m/s}$ $\div$ total activity $\geq 17.4\text{m/s}$, following Leroux et al 2018) in the SWIO (30°E - 90°E, 40°S - 0°S) and Mozambique Channel (MZC, 30°E - 52.5°E, 30°S - 5°S). (bottom) Observed decadal trend in tropical storms, categorised by TC intensity, within 500km of Madagascar (Mad), Mozambique (Moz) and Malawi (Mal). Results are shown from JTWC (left) over 1990 - 2024 and RSMC La Réunion (right) over 2000 - 2024. TD refers to systems with Tropical Depression intensity (13.9m/s). Hatching denotes where a trend is statistically significant. We compute the trends over 3-year triads, i.e for the 2001 season, we analyse the 2000-2002 period, due to the relatively low frequency of TCs in the Mozambique Channel. Trend analysis is conducted using a linear least-squares regression and statistical significance (p-value < 0.05) tested using a Wald test.

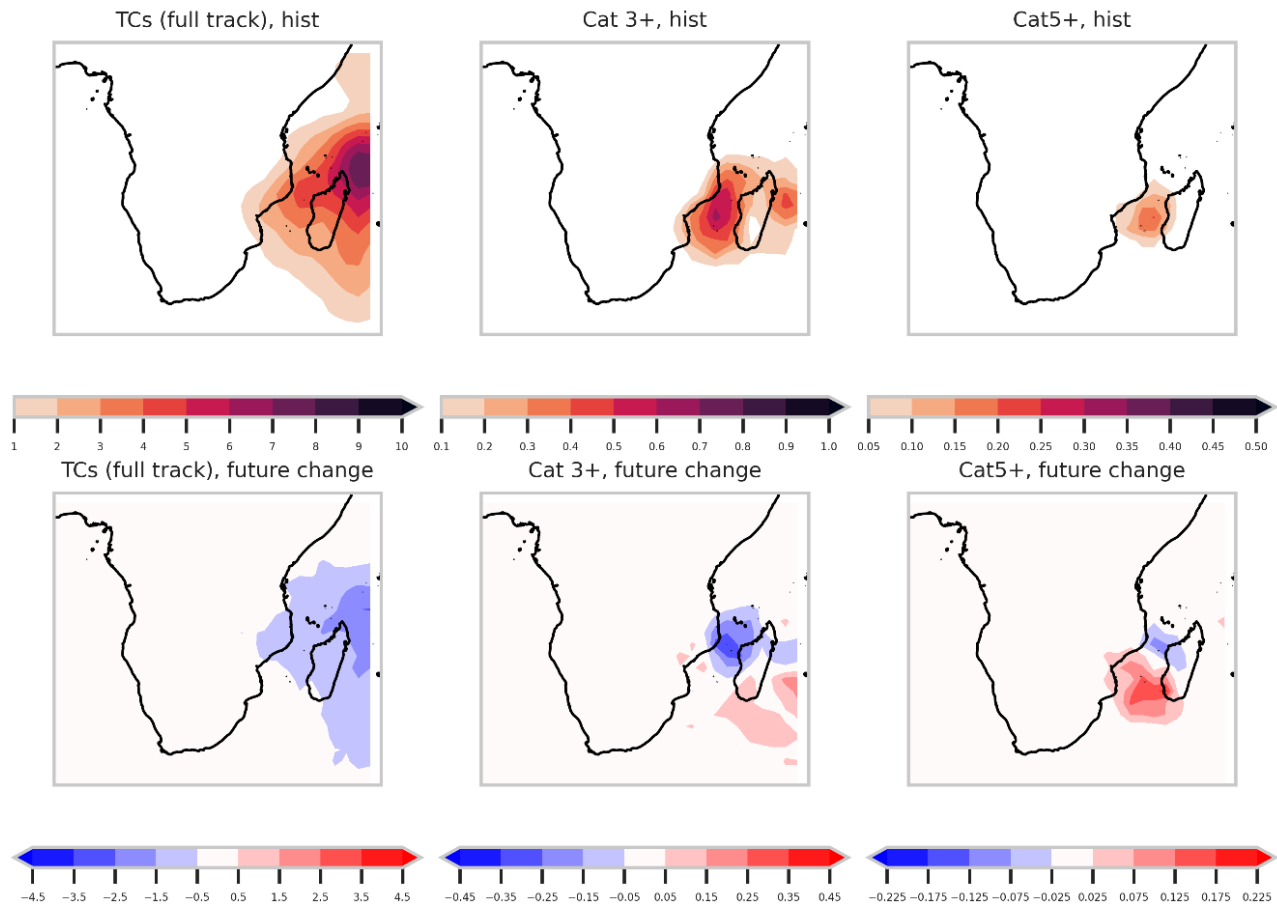


Figure 2

Tropical cyclone track density and its future change. (top) Historical track density and (bottom) future change for (left) all tracks that reach tropical cyclone intensity, with all phases of track from tropical depression to tropical storm and tropical cyclone shown (centre) only the portions of the track that are Category 3 and above; and (right) only the portions of the track that are Category 5. Historical corresponds to 1997-2007 and future to 2079-2089, SSP5-8.5, with results averaged across the five member CP4A ensemble.

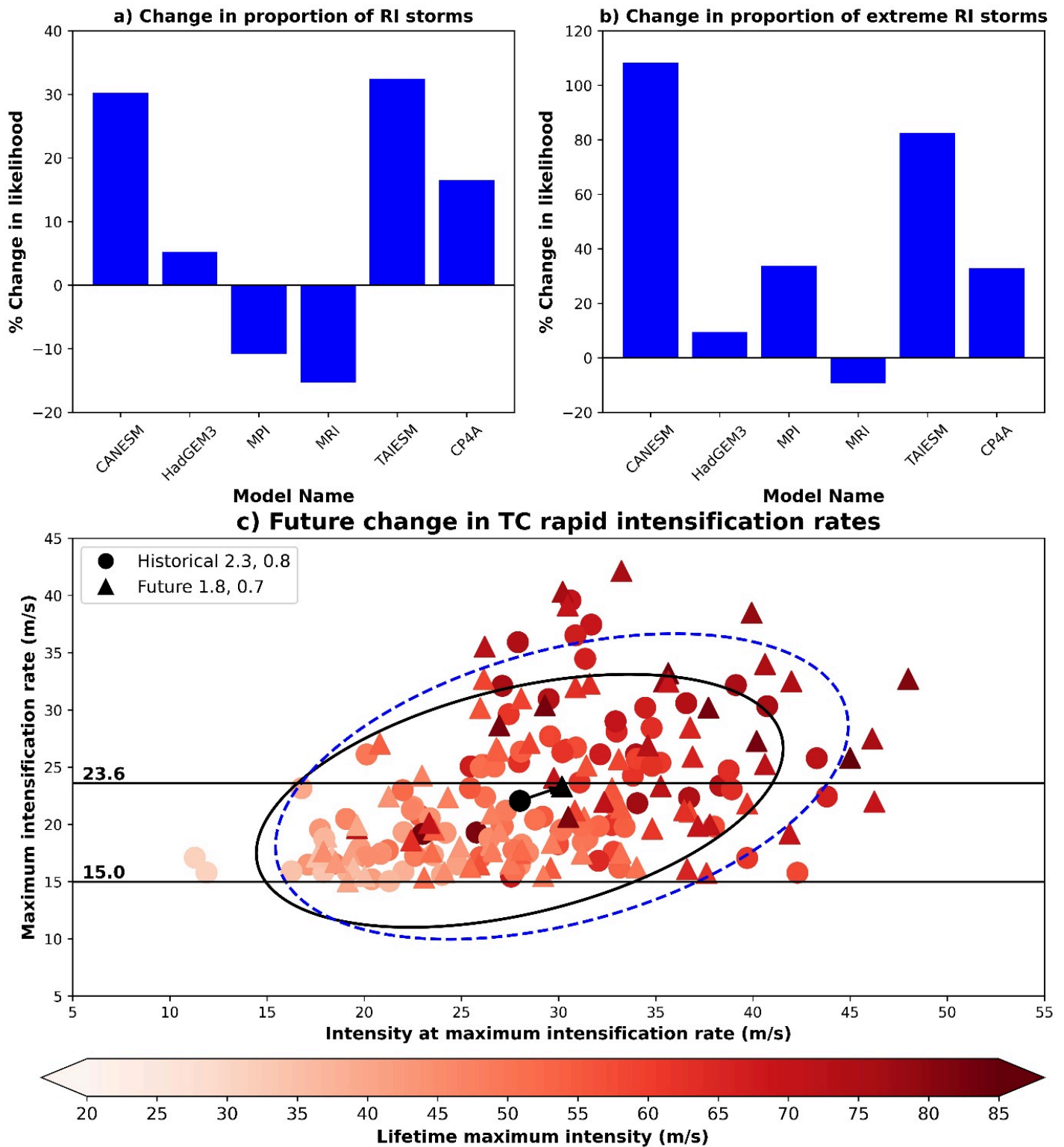


Figure 3

Future changes in TC rapid intensification. Future changes (%) in the proportion of storms that (a) rapidly intensify (defined as exceeding 95th percentile of all 24-hour TC intensity changes) and (b) undergo extreme rapid intensification (defined as exceeding 99th percentile of all 24-hour TC intensity changes), across the CP4A ensemble. Intensification thresholds are defined by the percentile value for each individual ensemble member, whilst for 'CP4A' it is based on the aggregated ensemble. (c) Maximum

intensification rate and its intensity at occurrence for Tropical Cyclones (TC) that undergo rapid intensification (RI). In panel c, circles indicate historical TCs and triangles future TCs; the shading colour denotes the lifetime maximum intensity of the TC; the ellipse contour indicates the values within two standard deviations of the joint bivariate distribution, with a black line for the historical range and the dashed blue the future. Black markers indicate the mean historical (circle) and future (triangle) values, with the arrow indicating the direction of change. The RI rate and extreme RI rate for the aggregated CP4A ensemble, corresponding to values of 15.0m/s and 23.6m/s respectively, are shown as horizontal lines. Noted in the legend is the number of storms per TC season that undergo RI and extreme RI in the historical and future periods.

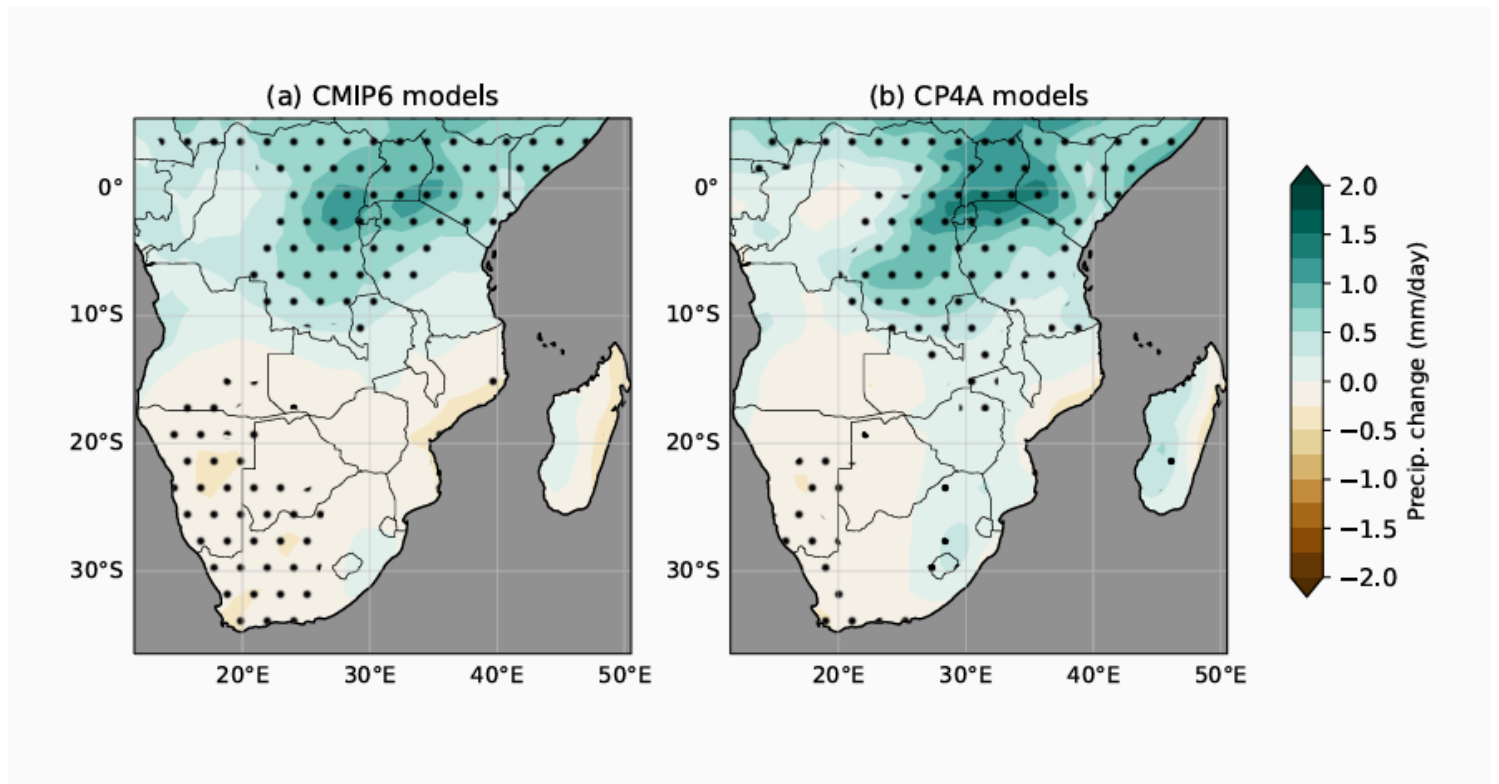


Figure 4

Future changes in annual mean rainfall over southern Africa in (a) all CMIP6 models and (b) the subset of five CMIP6 models that were downscaled by CP4A. Shown is ensemble mean future change between 1985-2014 and 2070-2099 according to SSP5-8.5, with stippling to indicate where > 80 % of models agree on the direction of change.

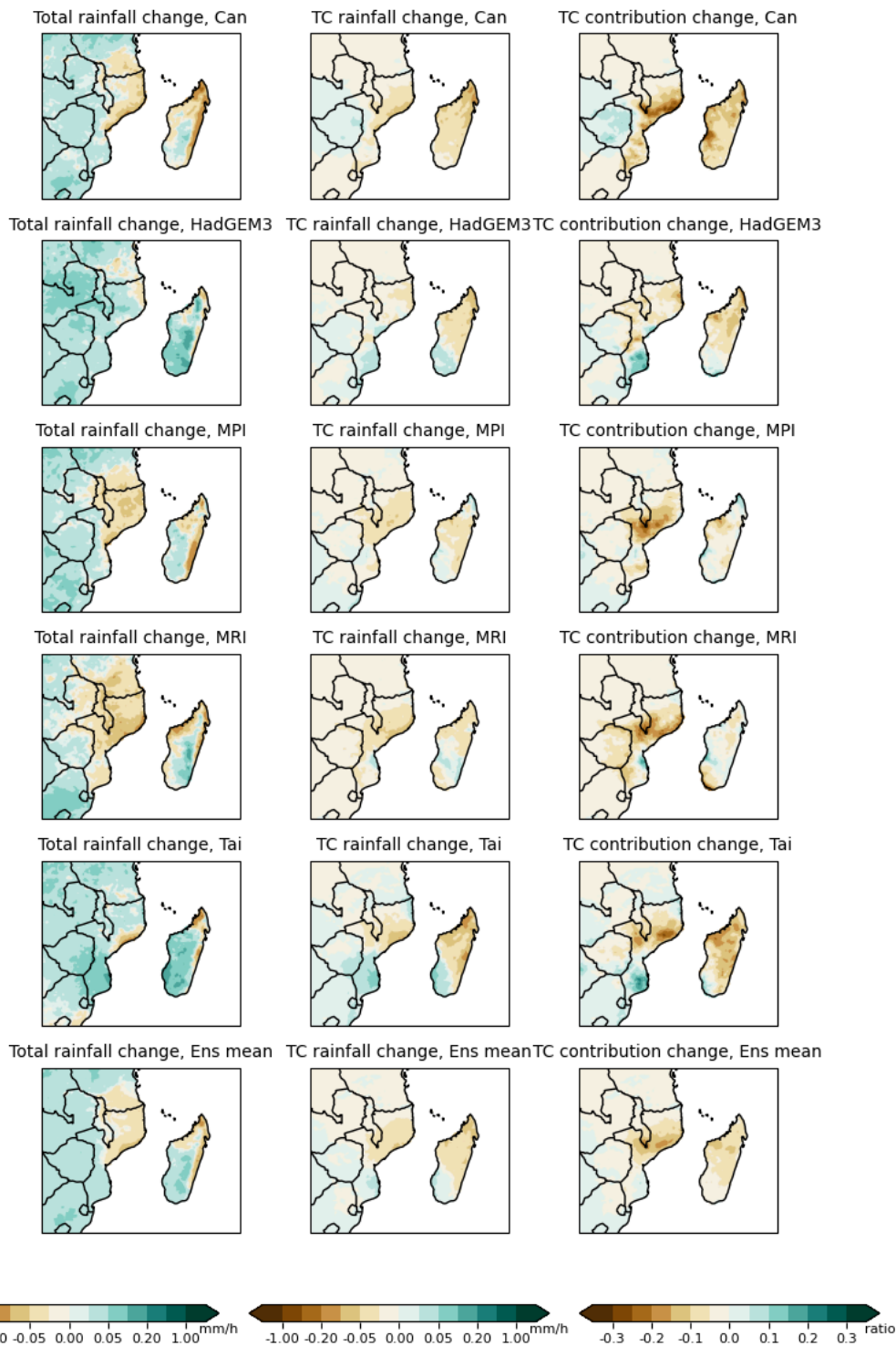


Figure 5

Future changes in mean rainfall during the tropical cyclone season (November to April) and the TC contribution to this. Shown is future change in (left) seasonal mean rainfall, (centre) mean rainfall from tropical cyclones and (right) TC contribution to seasonal mean rainfall, defined as the ratio of TC to total precipitation, in the CP4A ensemble. Results are shown for the individual ensemble members (driven by Can-ESM, HadGEM3, MPI, MRI and TaiESM) and also (bottom) the average across the ensemble.

Historical corresponds to 1997-2007 and future to 2079-2089, SSP5-8.5. Seasonal mean rainfall increases over much of southeastern Africa in the CP4A ensemble, consistent with the tendency for wetting in the subset of driving CMIP6 models (Fig 4). Precipitation occurring within 500km of the cyclone centre is designated as being associated with the TC. All members agree on a decrease in the contribution of TCs to seasonal mean rainfall over Madagascar and northern Mozambique.

Likelihood of TC with Category 5 wind speeds west of 55E

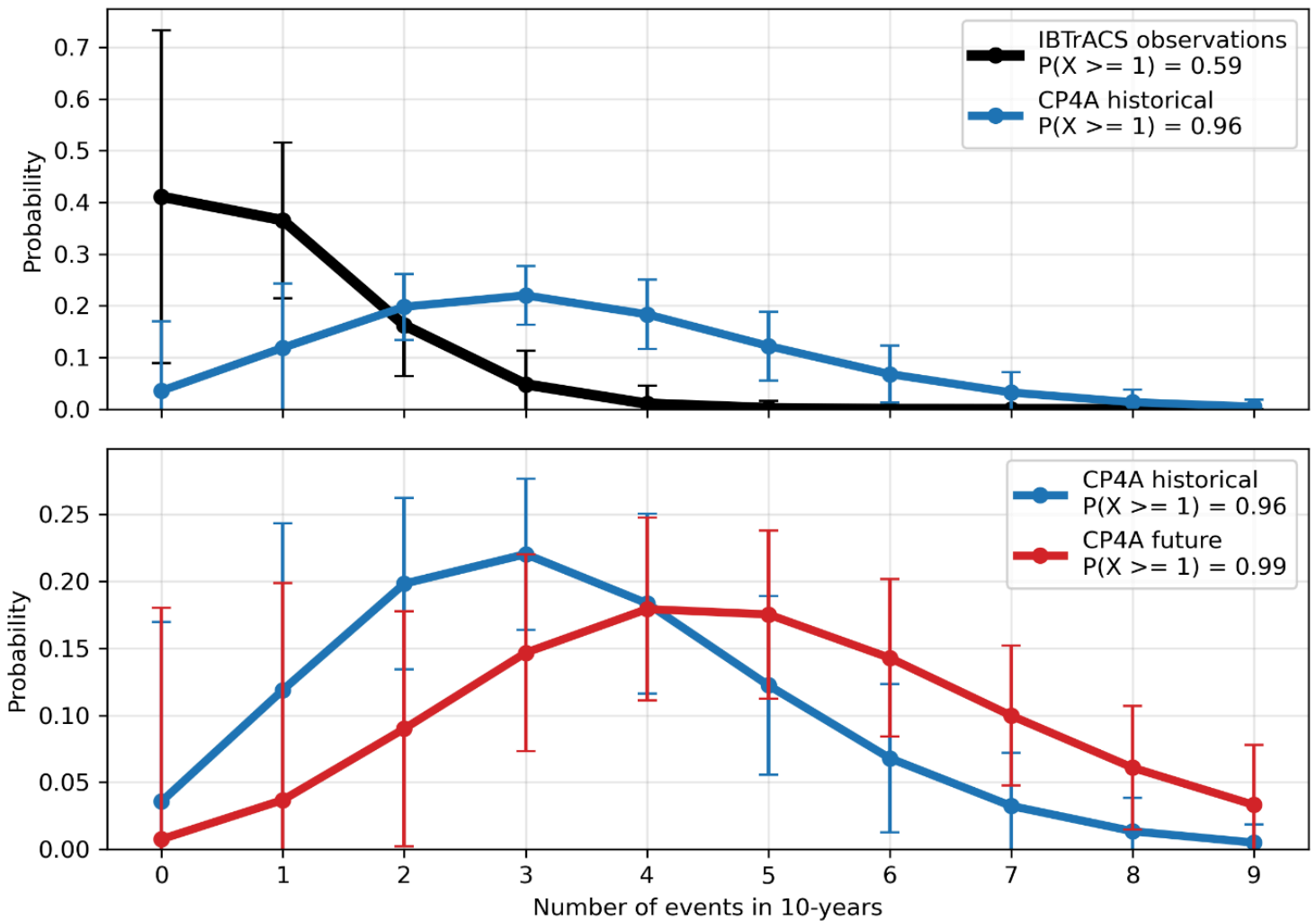


Figure 6

Likelihood of Category 5 TC occurring west of 55°E in Southern Africa. Plotted is probability of different numbers of events, with the probability of at least one event occurring shown in the legend, for (top) historical (1997-2007) and (bottom) future (2079-2089, SSP585) climate. The distribution is generated fitting a Poisson distribution to the numbers of Category 5 events in 45 years of data from each of the IBTrACS observations (black), CP4A historical (blue) and CP4A future (red) simulations, assuming events are randomly distributed across years. The error bars indicate the standard deviation of the probability values considering decadal variability in IBTrACS (showing uncertainty due to natural

variability), and uncertainty sampled by the different CP4A ensemble members in the historical and future.

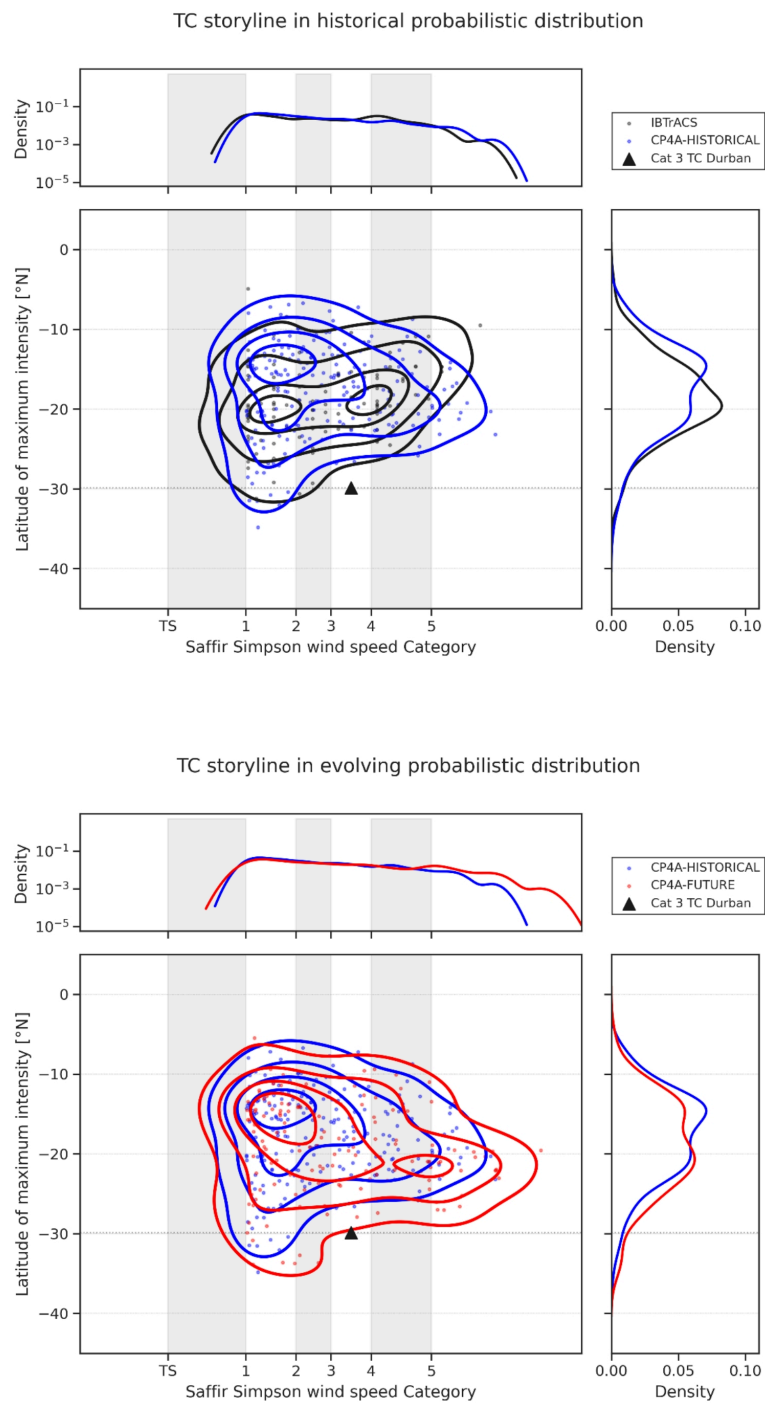


Figure 7

Occurrence of a Category 3+ cyclone at latitudes as far south as Durban (30°S), in context of the evolving probabilistic distribution of tropical cyclones. Plotted is 2D pdf of latitude of maximum intensity

(°N) against tropical cyclone wind speed category, for all tropical cyclones west of 55°E. Probability space is contoured with lines at 90%, 66%, 33%, 10% probabilities. (Top) shows the historical probability distribution comparing the CP4A model (blue) with IBTrACS observations (black); (bottom) shows the future change in the probability distribution with blue lines for historical (1997-2007) and red lines for future (2079-2089, SSP5-8.5). Inserts show the 1D pdfs for latitude and windspeed category at maximum cyclone intensity, respectively. Data from all 5 CP4A ensemble members are concatenated into a single dataset, corresponding to 45 years of data for each period.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [REPRESApaperstorylinesSupplementarycodefile.docx](#)