

1 **The Effect of Pseudo-Global Warming on the**
2 **Weather-Climate System of Africa in a**
3 **Convection-Permitting Model**

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6 **Key Points:**

- 7 • The weather-climate system of Africa is explored with the novel use of a convection-
- 8 permitting model and the pseudo-global warming method.
- 9 • The African easterly jet and areas of monsoon flow will intensify in a warming cli-
- 10 mate scenario together with increased monsoon moisture.
- 11 • An increase in precipitation is expected in a future warming climate scenario over
- 12 the monsoon, high topography, and the eastern Atlantic.

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Abstract

The weather-climate system of Africa encompassing the African easterly jet (AEJ) and the West African Monsoon (WAM) can largely modulate high-impact weather over Africa and the tropical Atlantic. How the weather-climate system of Africa will change with a warming climate is just starting to be addressed due to global climate model limitations in resolving convection. We employ a novel atmospheric convection-permitting model regional setup alongside the pseudo-global warming (PGW) approach to address climate change impacts on the weather-climate system of Africa. Our findings indicate that the AEJ and areas of monsoon flow intensify in a future warming climate scenario together with an increase in monsoonal moisture. Moreover, precipitation will increase over high topography and shift southward due to a latitudinal expansion and increase of deep convection closer to the equator. This has relevant ramifications for the livelihood of communities that depend on water-fed crops in tropical Africa.

Plain Language Summary

The weather-climate system of Africa is closely linked to high-impact weather events, such as storms and African easterly waves, which can lead to tropical cyclones. Studying how the weather-climate system of Africa will change with a warming climate is a recent research focus. In our study, we use a novel weather model to investigate these changes. By adjusting the model to reflect a future warming climate scenario, we discover that the African easterly jet, convection, and West African Monsoon will become stronger. Additionally, rainfall will increase in the monsoonal region and shift southward. This information is vital, as it significantly affects communities relying on water-fed crops.

1 Introduction

The weather-climate system of Africa comprises of the African easterly jet (AEJ) sustaining African easterly waves (AEWs), the West African Monsoon (WAM), and associate convection. The AEJ arises from thermal wind balance over the northern summer months due to the very warm and dry Saharan desert over North Africa and the relatively cooler and moist conditions south of it (Pytharoulis & Thorncroft, 1999). The interactions between the AEJ and the WAM can dictate monsoonal precipitation patterns (Diallo et al., 2013; Sylla et al., 2013; Pytharoulis & Thorncroft, 1999; Hsieh & Cook, 2007; Bercos-Hickey et al., 2020), and the formation, growth, and propagation of mesoscale

44 convective systems (MCSs) and AEWs which can serve as tropical cyclone (TC) precur-
45 sors (Landsea, 1993; Núñez Ocasio et al., 2021, 2020b; Rajasree et al., 2023). Both AEWs
46 and MCSs are high-impact weather events embedded within the complex African weather-
47 climate system.

48 Few studies have specifically addressed how the AEJ-AEW system and WAM may
49 change in a warming climate (Skinner & Diffenbaugh, 2014; Hannah & Aiyyer, 2017; Bran-
50 nan & Martin, 2019; Kebe et al., 2020; Bercos-Hickey & Patricola, 2021; Bercos-Hickey
51 et al., 2023). This is largely due to global climate models (GCMs) and regional models
52 with deep convection parameterized not properly resolving the complex moisture-convective
53 feedbacks and the multi-spatial nature of the weather-climate system of Africa (Cornforth
54 et al., 2009; Janiga & Thorncroft, 2013; Tomassini et al., 2017; Núñez Ocasio et al., 2020a;
55 Núñez Ocasio & Rios-Berrios, 2023).

56 For example, Kebe et al. (2020) found a future intensification and southern shift
57 of the AEJ related to a shift in the meridional temperature gradient causing a decrease
58 in AEW activity. Skinner and Diffenbaugh (2014) found an intensification of the merid-
59 ional temperature gradient and the AEJ although they did not establish a consistent move-
60 ment of the location of the jet. They also found an increase in low-level westerly flow
61 beneath the jet and in AEW activity. Using a regional WRF configuration with a rel-
62 atively coarse resolution of 27 km and parameterized convection, Bercos-Hickey and Patri-
63 cola (2021) found that the AEJ weakens, shifts poleward, and is located at a higher al-
64 titude in the future climate with increased precipitation and low-level westerlies over the
65 Sahel region. They also show an increase in the strength of the meridional temperature
66 gradient. These results are similar to Núñez Ocasio et al. (2024) moisture sensitivity ex-
67 periments except that they show that the AEJ is more intense in a moister environment.
68 Noteworthy is that Núñez Ocasio et al. (2024) study uses a novel convection-permitting
69 regional setup using the Model for Prediction Across Scales-Atmosphere (MPAS-A). Al-
70 though moisture-sensitivity experiments like these cannot be directly related to climate
71 projection experiments for which the role of temperature and anthropogenic sources are
72 considered, the comparison can help elucidate the role of moist-convective processes in
73 the weather-climate system of Africa and their connection to AEWs. These few stud-
74 ies present conflicting findings regarding the future trajectory of the AEJ, the meridional
75 temperature gradient over North Africa, and, consequently, precipitation patterns, as well
76 as the intensity and frequency of AEWs.

77 To capture the effect of thermodynamic changes due to anthropogenic-induced warm-
78 ing, this study applies a pseudo-global warming (PGW) method over a several day pe-
79 riod of high-impact weather in Africa in convection-permitting simulations. The PGW
80 method adds a perturbation representative of a future climate state to reanalysis data
81 to understand how today’s weather will change under warmer and moister conditions (Schär
82 et al., 1996). While the PGW method has been applied in the mid-latitudes to study re-
83 gional climate change impacts at convection-permitting scales on convection (Prein et
84 al., 2017; Rasmussen et al., 2020; Dougherty et al., 2023), heavy rainfall (Schär et al.,
85 1996; Kawase et al., 2009; Lackmann, 2013; Ban et al., 2015; Dougherty & Rasmussen,
86 2020), and atmospheric rivers (Mahoney et al., 2013; Dougherty et al., 2020), very few
87 studies have utilized this approach to study climate change impacts on tropical precip-
88 itation, aside from Heim et al. (2023) and Bercos-Hickey and Patricola (2021). However,
89 even studies that have applied the PGW method to the tropics use the WRF model, whereas
90 this is the first study to apply it to the MPAS-A model.

91 Understanding how the weather-climate system of Africa evolves with climate change
92 using convection-permitting modeling can enhance our ability to assess the critical im-
93 plications of environments conducive to high-impact weather such as tropical cyclones
94 and AEWs. This is the first study to the authors’ knowledge that applies the PGW method
95 to a Model for Prediction Across Scales-Atmosphere (MPAS-A) regional variable-resolution
96 configuration introduced in Núñez Ocasio et al. (2024) that is capable of simulating pro-
97 cesses at convection-permitting scales.

98 This study aims to answer the following scientific question:

99 Q: What are the short-term changes to the African weather-climate system in a fu-
100 ture warmer climate scenario?

101 **2 Methods and Data**

102 **2.1 MPAS Configuration**

103 The Model for Prediction Across Scales-Atmosphere (MPAS-A) version 8.0.1 with
104 the Limited-Area configuration was used for this study (Skamarock et al., 2012; Núñez Oca-
105 sio & Dougherty, 2024) to simulate the period of 1200 UTC 8 September–1800 UTC 13
106 September 2006 as in Núñez Ocasio and Rios-Berrios (2023); Núñez Ocasio et al. (2024).

107 Various features were active during this period including AEWs, MCSs, WAM, and ITCZ,
108 all while during field campaigns NAMMA and AMMA (Zipser et al., 2009). In addition
109 to initializing the model at 1200 UTC on 8 September, two other sets of experiments were
110 completed: initializing the model at 00 UTC on 5 September and initializing at 00 UTC
111 on 6 September. In incorporating three sets of experiments, we can account for spinup
112 and the sensitivity to small perturbations for precipitation details given the short inte-
113 gration period.

114 The Limited-Area domain is from 30°S to 51°N and 65°W to 59°E depicted in Núñez Oca-
115 sio and Dougherty (2024)(and in Núñez Ocasio et al. (2024) their Figure 1). A 15-km–
116 3-km variable-resolution mesh was used with the 3-km high-resolution refinement region
117 elliptically shaped. The mesh was rotated over North Africa and the eastern Atlantic
118 to ensure the track of AEWs and the inclusion of the ITCZ, AEJ, and WAM within the
119 refined region.

120 The “convection permitting” physics suite was used here as in Núñez Ocasio et al.
121 (2024). The scale-aware Grell-Freitas convection parameterization scheme (Grell & Fre-
122 itas, 2014) changes from parameterized deep convection at the hydrostatic scales (pa-
123 rameterized grid is at 15 km) to only parameterize shallow convection in the refined 3-
124 km region. At 3 km, deep convection was explicitly resolved. The rest of the schemes
125 include RRTMG shortwave and longwave radiation (Iacono et al., 2008), Xu-Randall sub-
126 grid cloud fraction (Xu & Randall, 1996), MYNN boundary-layer and surface-layer schemes
127 (Nakanishi & Niino, 2004), Noah land-surface scheme (Niu et al., 2011), and Thompson
128 microphysics (Thompson et al., 2008).

129 The model was configured to run with 55 levels. Model outputs in the native un-
130 structured grid were hourly. Native model output was vertically interpolated to obtain
131 isobaric variables with 27 isolevels. The model output was spatially interpolated to a lat-
132 itude and longitude grid equivalent of a $0.25^\circ \times 0.25^\circ$ horizontal resolution. The inter-
133 polation used a first-order conservative Gaussian grid (Jones, 1999) as done in Núñez Oca-
134 sio and Rios-Berrios (2022); Núñez Ocasio (2023).

135 **2.2 Pseudo-global Warming Experiment**

136 The ECMWF reanalysis 5th Generation (ERA5; Hersbach et al., 2020) was used
137 to initiate the model and provide lateral boundary conditions hourly for the control (CTRL)

138 simulations. The PGW experiments are the same as the CTRL experiments, except a
 139 delta signal representative of a future climate state is added to the ERA5 forcing data
 140 at the lateral boundaries:

$$CTRL = ERA5 \quad (1)$$

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$$PGW = ERA5 + \Delta LENS2 \quad (2)$$

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where Δ is given by the following:

$$\Delta = (2070 - 2100) - (1991 - 2021) \quad (3)$$

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The PGW experiment takes the 100-member ensemble mean difference of the Com-
 munity Earth System Model (CESM) Large Ensemble (LENS) version 2 (LENS2; Rodgers
 et al., 2021) at the end-of-century (2070-2100) under the SSP3-7.0 future radiative forc-
 ing scenario from the historical period (1991-2021). The perturbed variables from LENS2
 added to ERA5 include temperature, geopotential height, horizontal winds, relative hu-
 midity, sea surface temperature, soil temperature, and pressure. Perturbing pressure, geopo-
 tential height, and winds, alongside temperature and humidity, ensure balance is main-
 tained in the atmosphere (Brogli et al., 2023). This method thus simulates similar weather
 patterns as the current day but under warmer and moister conditions. Using the ensem-
 ble mean from LENS2 also assures that this response is a robust climate change signal,
 and not due to the internal variability of the model (Huang et al., 2020).

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A limitation of the study is that it uses only one future projection scenario and one
 climate model for simulations of short integration time. Nonetheless, the main differences
 between the CTRL and PGW simulations in three experiments with different initializa-
 tions are noteworthy and consistent across experiments, providing confidence that our
 results are not just artifacts of spin-up time. The variability across the three experiments
 initialized at different times is also noted in the study. This demonstrates that this kind
 of framework can be applied to multiple future climate scenarios and longer simulations.
 The objective of this study is on how future climate projections will affect the weather-
 climate system of Africa at short time scales, and thus, the focus is on a short period.

3 Results

To validate our regional convection-permitting PGW approach, we first assess the effects of the future warming on convection and precipitation associated with the ITCZ over the eastern Atlantic and the WAM over land. The differences across CTRL and PGW simulations (Figure 1g, Figure S1g, and Figure S2g) shows higher precipitation rates in the future climate. Specifically, precipitation rates are greater in the PGW scenario over the eastern Atlantic offshore waters (part of the ITCZ and West African offshore rainfall maximum), the Guinea Highlands, Cameroon Mountains, and the offshore waters of the Bight of Benin following the coast of Nigeria, Cameroon, Equatorial Guinea, and Gabon.

Although there is a slight increase in precipitation over the Sahel in the future climate agreeing with Bercos-Hickey and Patricola (2021) findings, the more prominent increases in precipitation here are located south of 10°N . Moisture-sensitivity experiments by Núñez Ocasio et al. (2024) also show these distinct peaks in precipitation over the region of the west African coast rainfall maximum, Guinea Highlands, and over the coast of the Bight of Benin with maxima over the Cameroon Mountains. The similarities across the PGW experiment here and moist-sensitivity experiments in Núñez Ocasio et al. (2024) may suggest a key role of water vapor in modulating future precipitation extreme patterns over the ITCZ and African monsoonal belt over tropical Africa.

With respect to the WAM, it is evident from Figure 1 (second column and in S1 and S2 for the additional experiments) that monsoonal moisture will increase in the future climate scenario both over land and water consistent with the increase in precipitation. There is variability across experiments on the location and intensity of the WAM confluent zone over the continent (Figure 1i, S1i, and S2i). However, the southwesterly monsoonal flow over the Gulf of Guinea and the embedded Bight of Benin consistently shows a strengthening across all experiments in the future climate. Over the western coast of Africa a prominent cyclonic feature also exhibits intensification in the future. This feature can be a signal of both intensifying AEWs and ITCZ.

Figure 2 (as well as S3 and S4) shows a time-average latitude analysis over a longitudinal average defined as the WAM box from 15°W to 25°E . More precipitable water content across the monsoonal region is to be expected in the future climate due to moisture increases following the Clausius-Clapeyron relationship and consistent with the

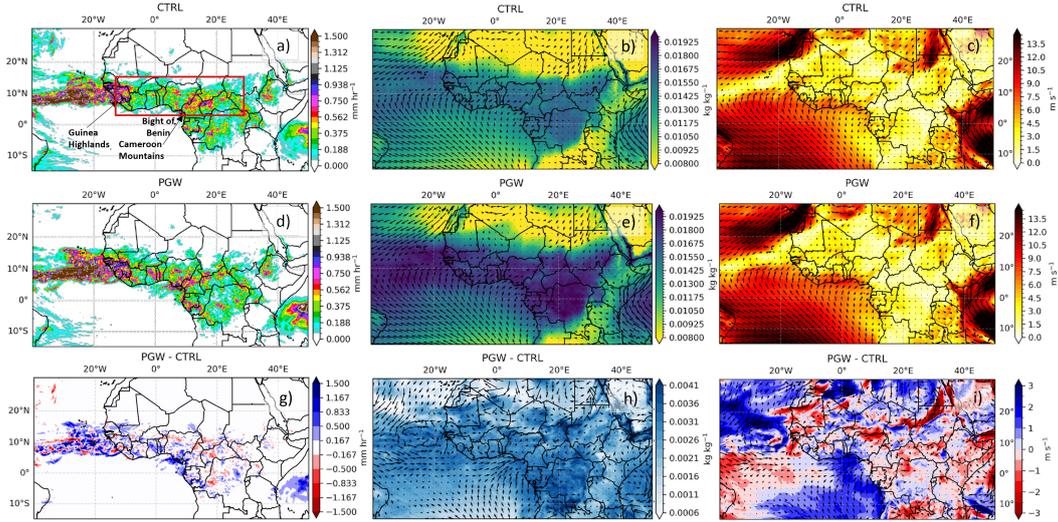


Figure 1. Time-averaged precipitation rates, 950-hPa water vapor mixing ratio (shade), and 950-hPa total winds (vectors and shade) removing the first 24 hours of the simulation for CTRL in (a), (b), and (c), respectively. The same from (d-f) for PGW and from (g-i) for the differences. Labels for Guinea Highlands, Bight of Benin, and the Cameroon Mountains are included in (a) for reference. The red square denotes the region that will be named WAM box hereon from 15°W to 25°E and 4°N to 15°N.

195 increase in monsoonal moisture (Figure 2; precipitable water). However, the average pre-
 196 cipitation rate over the domain increases at less than the Clausius-Clapeyron rate of 7
 197 % K^{-1} , with an increase of 4.8 % K^{-1} . This rate of increase is possible because we con-
 198 sider all precipitation, not just precipitation extremes or convection specifically, where
 199 precipitation rates are expected to increase at or above the Clausius-Clapeyron rate (Prein
 200 et al., 2017; Loriaux et al., 2013).

201 Convection is also deeper between 5°S and 7.5°N (Figure 2; OLR) in the future cli-
 202 mate. Related to the deeper ITCZ and monsoonal convection in the PGW scenario, re-
 203 gions of peak precipitation rates are to expected to have even higher rates and the peaks
 204 will be shifted equatorward (Figure 2; precipitation rates) as was evident from Figure 1.
 205 Heim et al. (2023) similarly saw a southward shift in the precipitation maximum near
 206 the equator and intensification of the ITCZ.

207 Cross sections of time-average diabatic heating rates show where the maximum of
 208 moist convection for each simulation is located (Figure 3, and S5). The majority of the

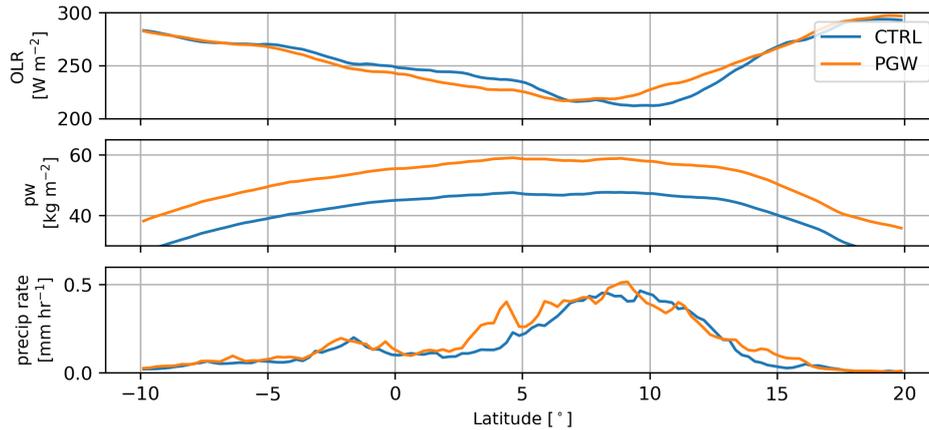


Figure 2. Latitude analyses of time-averaged, zonally averaged (top) OLR, (middle) precipitable water (pw), and (bottom) precipitation rate removing the first 24 hours of the simulation for CTRL (blue lines) and PGW (orange lines). Longitude average is taken for the WAM box.

209 monsoonal moist convection is located between 5°N and 15°N in the CTRL scenario with
 210 maximum between 10°N and 12°N. The future scenario exhibits a latitudinal expansion
 211 of the convection with deeper (top-heavy signature reaching above 250 hPa). Although
 212 there is variability across experiments as to where the maximum of diabatic heating dif-
 213 ference lies (compare maxima locations in Figure 3c, S5c, and S5f) there is consistency
 214 across experimenters that deeper and more intense convection shifts to the south of 10°N
 215 in the PGW simulations. This diabatic heating signature agrees with the expected south-
 216 ward shift of the ITCZ and monsoonal precipitation shown in the previous figures.

217 Such a deepening of diabatic heating is expected in a warmer climate in the trop-
 218 ics, fitting with the fixed anvil temperature (FAT) hypothesis (Hartmann & Larson, 2002),
 219 whereby anvils rise in a warmer climate and thereby remain at the same temperature.
 220 Interestingly, the widening of diabatic heating contrasts the idea of a “deep-tropics squeeze”
 221 (Lau & Kim, 2015) that suggests a narrowing of the ITCZ. Similar to this idea is the
 222 “warming-induced contraction of tropical convection” hypothesis by a GCM climate change
 223 study over the tropics (Zhang, 2023), though the PGW convection-permitting simula-
 224 tions from Heim et al. (2023) also do not find such a pronounced narrowing of the ITCZ.

225 Within the weather-climate system of Africa is the AEJ which serves as an energy
 226 source for both AEWs and MCSs and plays a major role in dictating the high-impact
 227 weather over the region. Previous climatology studies have shown that the AEJ is weaker

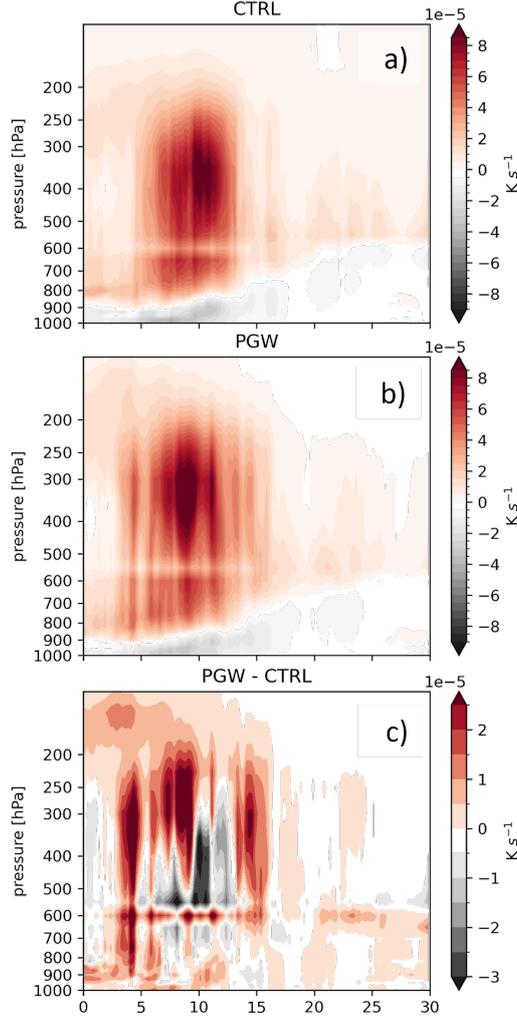


Figure 3. Vertical cross-section of the time-averaged diabatic heating rates from microphysics scheme removing the first 24 hours of the simulation for (a) CTRL, (b) PGW, and (c) the difference. Longitude average taken for WAM box. Y axis is in log scale.

228 and farther north during wet years (Newell & Kidson, 1984; Sylla et al., 2013; Diallo et
 229 al., 2013; Bercos-Hickey et al., 2020). In Bercos-Hickey and Patricola (2021) they found
 230 a weaker, more northward-positioned AEJ located at a higher altitude in the future cli-
 231 mate. Similarly, the difference between PGW and CTRL here in Figure 4c (as well as
 232 in S6e and S7e) show an AEJ shifted northward in the future climate with core greater
 233 than 13 m s^{-1} located at or slightly above 15°N at 600 hPa. However, unlike Bercos-
 234 Hickey and Patricola (2021), the core of the AEJ here is more intense in the future sce-
 235 nario than the CTRL experiment. A stronger more northward AEJ and wetter condi-
 236 tions were also found in Núñez Ocasio et al. (2024) moisture-sensitivity experiments al-

237 luding again to the role of water vapor on high-impact weather events. With the AEJ
238 strengthening and being positioned more northward relative to the WAM confluent zone
239 over the continent in the future climate, is less likely for the AEJ to interact with the
240 southwesterly monsoonal flow sufficiently. This in turn inhibits significant shear produc-
241 tion and limits the likelihood of barotropic and baroclinic energy exchanges ultimately,
242 affecting the intensity of AEWs and the AEJ-AEW system (i.e., Núñez Ocasio et al., 2024).
243 How the AEJ-AEW system, as well as how the intensity and frequency of AEWs and
244 MCSs will be affected in the changing climate is out scope of this study. However, it is
245 currently being explored and is the topic of a follow-up study.

246 At the larger scales, the upper-level jets such as the tropical easterly jet (TEJ) with
247 a maximum of around 250 hPa will strengthen while the subtropical jet with the core
248 at about 200 hPa, will weaken in the future climate scenario. The strengthening of the
249 AEJ in the future climate scenario is related to the low-level meridional potential tem-
250 perature gradient. Additionally, the stronger TEJ is consistent with a strengthening of
251 jet stream wind projected by GCMs globally, due to an increase in the meridional hu-
252 midity gradient under climate change that impacts the thermal wind via density gradi-
253 ents (Shaw & Miyawaki, 2023).

254 Within the weather-climate system of Africa, the meridional temperature gradi-
255 ent during the northern summer months gives rise to the AEJ through thermal wind bal-
256 ance. Skinner and Diffenbaugh (2014) and Bercos-Hickey and Patricola (2021) found an
257 increase in the strength of the meridional temperature gradient. Agreeing with these stud-
258 ies, it is evident that in the future climate scenario here, the strength of the meridional
259 potential temperature gradient increases across the atmospheric column (Figure 4f, S6f,
260 and S7f). This stronger meridional potential temperature gradient relates to an increase
261 in precipitation and monsoon intensity. The stronger meridional potential temperature
262 gradient at the surface directly relates to the meridional potential vorticity (PV) rever-
263 sal at the mid-levels that exists over the African continent during the northern summer
264 months and satisfies the Charney-Stern criterion for dynamical instability (Pytharoulis
265 & Thorncroft, 1999). This PV meridional gradient is also strengthened in the PGW sce-
266 nario (not shown). Finally, given the evident increase in precipitation over high topog-
267 raphy shown here in the future climate, it is noteworthy that topography like the Cameroon
268 Mountains and the Guinea Highlands can influence the low-level meridional potential

269 temperature gradient over Africa. This, in turn, can affect precipitation as we see here
 270 and AEW energetics (i.e., Hamilton et al., 2020, 2017).

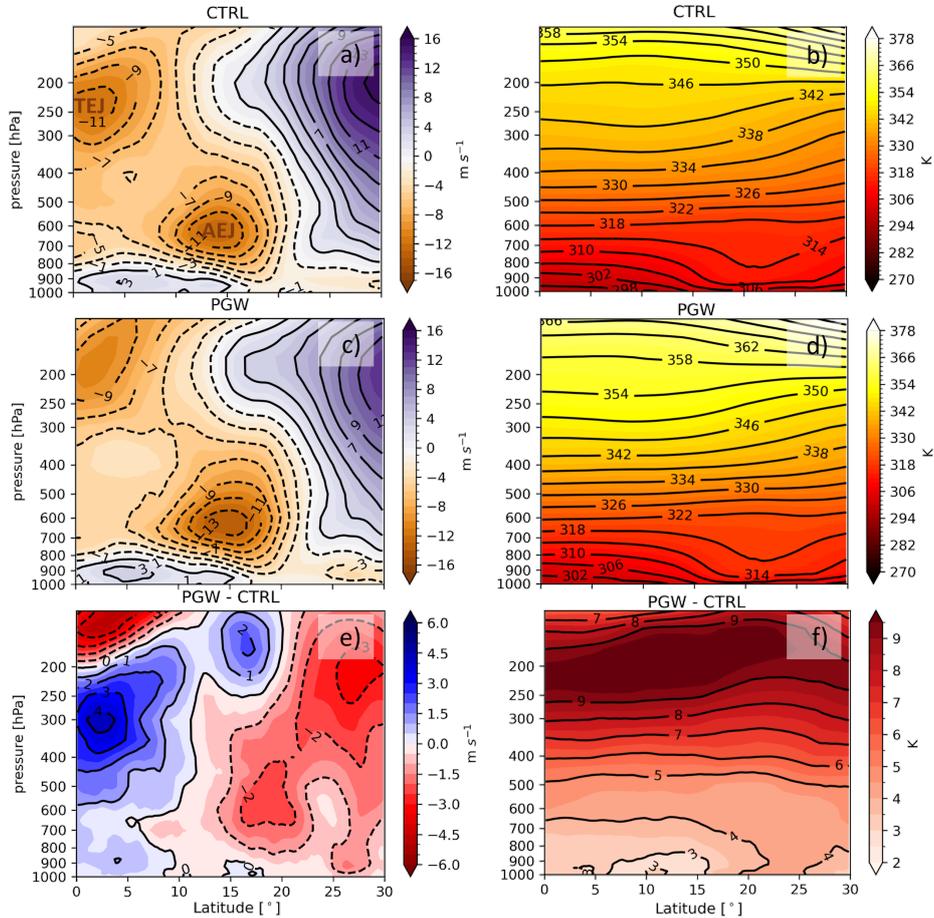


Figure 4. Vertical cross-section of the time-averaged zonal wind and potential temperature removing the first 24 hours of the simulation for CTRL in (a) and (b), respectively. The same from (c-d) for PGW, and from (e-f) for the differences. Longitude average taken for the WAM box. Y axis is in log scale. The AEJ and TEJ are labeled in (a).

271 **4 Conclusions**

272 Through a novel convection-permitting framework that applies the PGW method,
 273 we have addressed the question of what are the short-term changes to the weather-climate
 274 system of Africa in a future warming climate scenario. Using a convection-permitting model
 275 alongside the PGW method, we can better assess climate changes in a more realistic model

276 setup to be able to compare our results to past studies that used GCMs and/or param-
277 eterized convection.

278 Although some variability is evident across the three experiments initialized at dif-
279 ferent times while using the same future climate scenario, consistent patterns emerge of
280 how the weather-climate system of Africa will change with the changing climate. Dif-
281 ferent from past studies we find that the AEJ intensifies and shifts poleward in the fu-
282 ture climate scenario. The ITCZ over the eastern Atlantic will intensify in a future cli-
283 mate scenario. An increase in precipitation rates related to a monsoonal increase in mois-
284 ture is also to be expected in the future climate, especially south of 10°N . This south-
285 ern shift of the precipitation is consistent with deeper and more intense convection shift-
286 ing to the south of 10°N . In the future climate scenario, the southwesterly monsoonal
287 flow over the Gulf of Guinea and the embedded Bight of Benin intensifies. Agreeing with
288 past studies, we show an increase in the strength of the meridional temperature gradi-
289 ent. This strengthening is related to the intensification of both the AEJ at the mid-levels
290 and of the TEJ.

291 The AEJ serves as an energy source for AEWs, and the WAM and ITCZ provide
292 a moisture-favorable environment for both AEW and MCSs to grow and propagate. How
293 the intensity and frequency of AEWs and MCSs will be affected in the changing climate
294 is the topic of a follow-up study that will use the simulations introduced here. Additional
295 future work will focus on longer and multiple future climate scenarios to asses whether
296 the short-term changes in the weather-climate system of Africa presented here are rep-
297 resentative of changes in long-term simulations or a consensus of climate model simu-
298 lations.

299 Finally, we call upon communities whose livelihoods depend on water-fed crops to
300 prepare and adapt for the possibility of more intense monsoonal rainfall extremes to be
301 located near the Guinea Highlands, the Cameroon Mountains, and coastal countries shar-
302 ing the Bight of Benin coast. Forecasting centers and risk management agencies should
303 assess the impact and implication of such changes, and take the necessary actionable steps
304 toward mitigating loss of life and property.

5 Open Research

Post-processed model outputs and the namelists for the MPAS-A simulations can be accessed at <https://doi.org/10.5065/wfzv-nx43> (Núñez Ocasio & Dougherty, 2024). The modified MPAS-A code to output isobaric variables following MPAS developers can be found in the first author's Github: <https://github.com/knubez/MPAS-Model>. Please reference this paper that uses this code and/or the one mentioned on GitHub. The ERA5 (<https://rda.ucar.edu/datasets/ds633.0/>) and LENS2 (<https://www.cesm.ucar.edu/community-projects/lens2>) for initial and lateral boundary conditions were accessed via the NSF NCAR Research Data Archive via the Computational and Information Systems Laboratory (CISL).

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