School of Geography and the Environment

Options Extended Essay

Essay Title: Assessing the representation of the Tropical Easterly Jet in CMIP5 models, and the relationship with rainfall simulations over the Sahel.

Option title: Climate Change and Variability

Word count: 4495

Abstract

This study evaluates 20 CMIP5 models in their ability to represent the Tropical Easterly Jet in historical simulations and determine whether this ability of the models is related to their ability to simulate rainfall over the Sahel region. The study also considers projected changes in the jet in the future and explores whether models that simulate the jet better in the present-day have significantly different projected future rainfall compared to the multi-model mean and models that simulate the jet poorly.

The results of the study show the three models that represented the Tropical Easterly Jet best were able to simulate the majority of rainfall over the Sahel accurately, however they failed to simulate the rainfall peaks over the coasts of Guinea and Nigeria. Meanwhile, the three models that represented the TEJ least well struggled with parts of the pattern and spatial extent of the rainfall over the Sahel region and had too wide a range of rainfall values, but were able to simulate the rainfall peaks over the identified coastal areas. The multi-model mean was able to produce the most accurate simulation of rainfall over the Sahel, with the spatial extent, general rainfall levels and peak rainfall levels all being similar to those seen in the satellite data. This was a significant finding as it increases trust in the multi-model mean when looking at the TEJ and its relationship with rainfall. The future projections of the TEJ and rainfall over the Sahel indicated the ability of the models to represent the TEJ in the historical simulations had an impact on model projections of future rainfall.

KEYWORDS

Tropical Easterly Jet - Sahel Rainfall - Process-Based Analysis - CMIP5

1. Introduction

The Tropical Easterly Jet (TEJ) is a key feature of the atmospheric general circulation in the tropics. The jet plays an important role in the Indian monsoon, whereby a stronger jet is correlated with anomalously high monsoon rainfall levels (Pattanaik and Satyan, 2000). The jet also has a relationship with rainfall over Africa. In the literature, links have been made between the strength of the TEJ and rainfall over the Sahel (e.g., Nicholson and Klotter (2020)). The Sahel is highly vulnerable to rainfall variability, and therefore the influence of the jet on rainfall in the region is important for climate science and adaptation decisions. The TEJ influences the climate on a wide scale and across multiple continents, however, this study will focus solely on rainfall over the Sahel as studies of the jet over Africa are limited (Chen and Yen, 1993) and improved understanding of the TEJ in the Sahel is likely to be beneficial for policymakers.

Sahel rainfall is highly variable on interannual and interdecadal timescales. The socio-economic status of regions in the Sahel is highly dependent on this rainfall variability. In the 1970/80s the Sahel experienced a severe drought which saw a 30% reduction in rainfall compared to pre-drought levels (Nicholson and Grist, 2002). As well as the drought representing some of the highest levels of rainfall variability in the world (Trenberth et al., 2007), it also had serious humanitarian consequences. Of the 50 million people who lived in the region, 1 million were on food aid and 100,000 died (AMCEN Secretariat, 2002). The Sahel drought is evidence that the livelihood of the Sahel population is dependent on regional rainfall levels. Therefore, it is important that climate models can accurately simulate both this rainfall and the individual features that influence it. However, global climate models, such as those associated with CMIP5, have a number of limitations, especially when investigating the regional climate over tropical Africa (Vashisht et al., 2021). These include biases in model simulations and parameterisations which cause high levels of uncertainty (IPCC, 2013). For example, Monerie et al. (2020) highlight the Northern hemispheric temperature gradient as a major source of inter-model spread in CMIP5 and CMIP6 Sahel rainfall simulations. Process-based analysis is one way to overcome these limitations by looking to understand the processes underlying model simulations and assess their accuracy to reality (e.g., James et al. (2018)). This enables constraints to be placed on extreme projections and guides model improvements. Nicholson and Klotter (2020) recently used this approach to assess the representation of the TEJ and its relationship with rainfall over the Sahel in reanalysis products. This study will expand on this by using the concept of process-based analysis to assess CMIP5 model simulations of the TEJ and Sahel rainfall.

This study aims to evaluate CMIP5 models' abilities to accurately simulate the TEJ and determine whether this ability of the models is related to their ability to simulate rainfall over the Sahel. The study will then go on to consider projected changes in the TEJ in the future and explore whether models that simulate the jet better in the present-day have significantly different projected future rainfall compared to the multi-model mean and models that simulate the jet poorly.

This study is organised into 5 further sections. Section 2 provides a background to the TEJ and its relationship with rainfall over the Sahel. Section 3 evaluates the ability of CMIP5 models to simulate the jet and how this impacts the simulation of rainfall. Section 4 assesses future projections of rainfall over the Sahel based upon the evaluation of models in Section 3. Section 5 summarises the main conclusions of the study.

2. Background

2.1 Overview of the TEJ

The TEJ is an upper-tropospheric jet present in the boreal summer (Hastenrath, 1988) that originates over the Bay of Bengal and extends to West Africa (Nicholson et al., 2007; Salunke and Mishra, 2019). The jet forms in the South Asian monsoon system as a result of convective heating over the Himalayan Tibetan Plateau and North Indian Ocean (Gill, 1980; Lemburg et al., 2019). The jet was first discovered in the 1950s by Rao (1952) and Koteswaram (1958). As shown in Figure 1B, the jet is present at 100-250 hPa and lies between 0° and 20°N. The core of the jet typically sits over the Indian Ocean at approximately 10°N and can reach speeds of 35 ms^{-1} (Figure 1A).

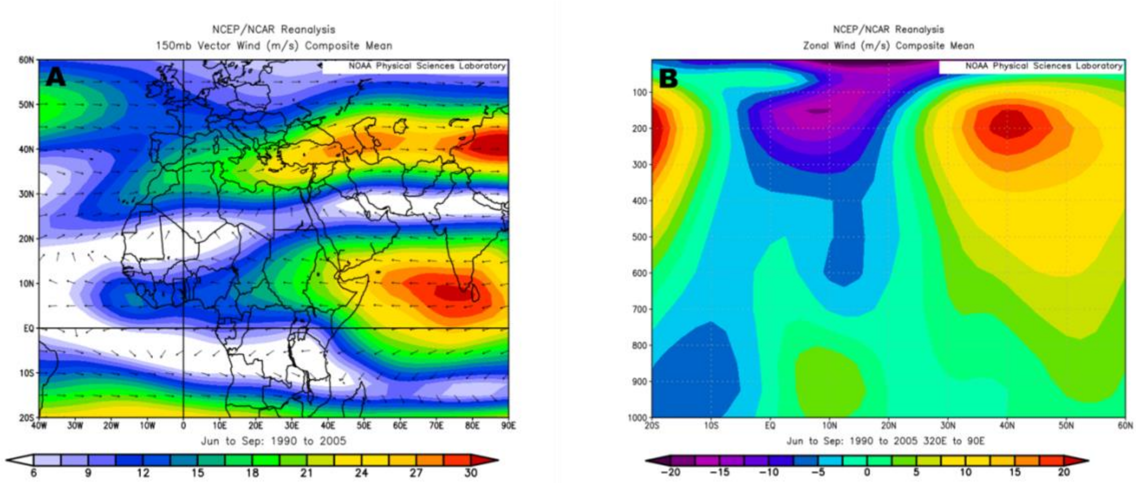

Figure 1 – A) Wind vector (ms^{-1}) plot at 150 hPa for JJAS showing the TEJ over the Indian Ocean and across Africa. B) Zonal wind (ms^{-1}) latitudinal cross section plot for JJAS with the TEJ evident at 100-250 hPa between 0° and 20°N. For plot (B) negative values show easterly winds and positive values show westerly winds. Plots use NCEP/NCAR reanalysis data to show composites for the period 1990-2005.

The TEJ has a distinct seasonal cycle (Figure 2). In June the jet emerges over the Indian Ocean with core winds at 5-10°N of 25 ms^{-1} and begins to build in strength. By July and August, the jet is at its strongest with core winds of 35 ms^{-1} and the feature has extended across West Africa and into the Atlantic. The jet remains present in September, but the strength decreases back to the levels seen in June and the jet has retreated to predominantly sit over the Indian Ocean. From late October to May the jet is not present and instead the main circulation feature over the region is the subtropical jet that extends over north Africa and the southern Himalayas.

The strength of the TEJ can be altered by a number of factors. Interannual variability of the jet can result from diabatic heating anomalies which are strongly associated with modes of sea surface temperature variability (Lemburg et al., 2019). For example, La Nina events have been shown to strengthen the jet while El Niño events can weaken it (Huang et al., 2019). Interdecadal variability is also apparent, with the jet being projected to change in the future under global warming. Salunke and Mishra (2019) suggest that by the end of this century the TEJ will be stronger. However, the characteristics and magnitudes of these changes are still largely uncertain (Huang et al., 2020).

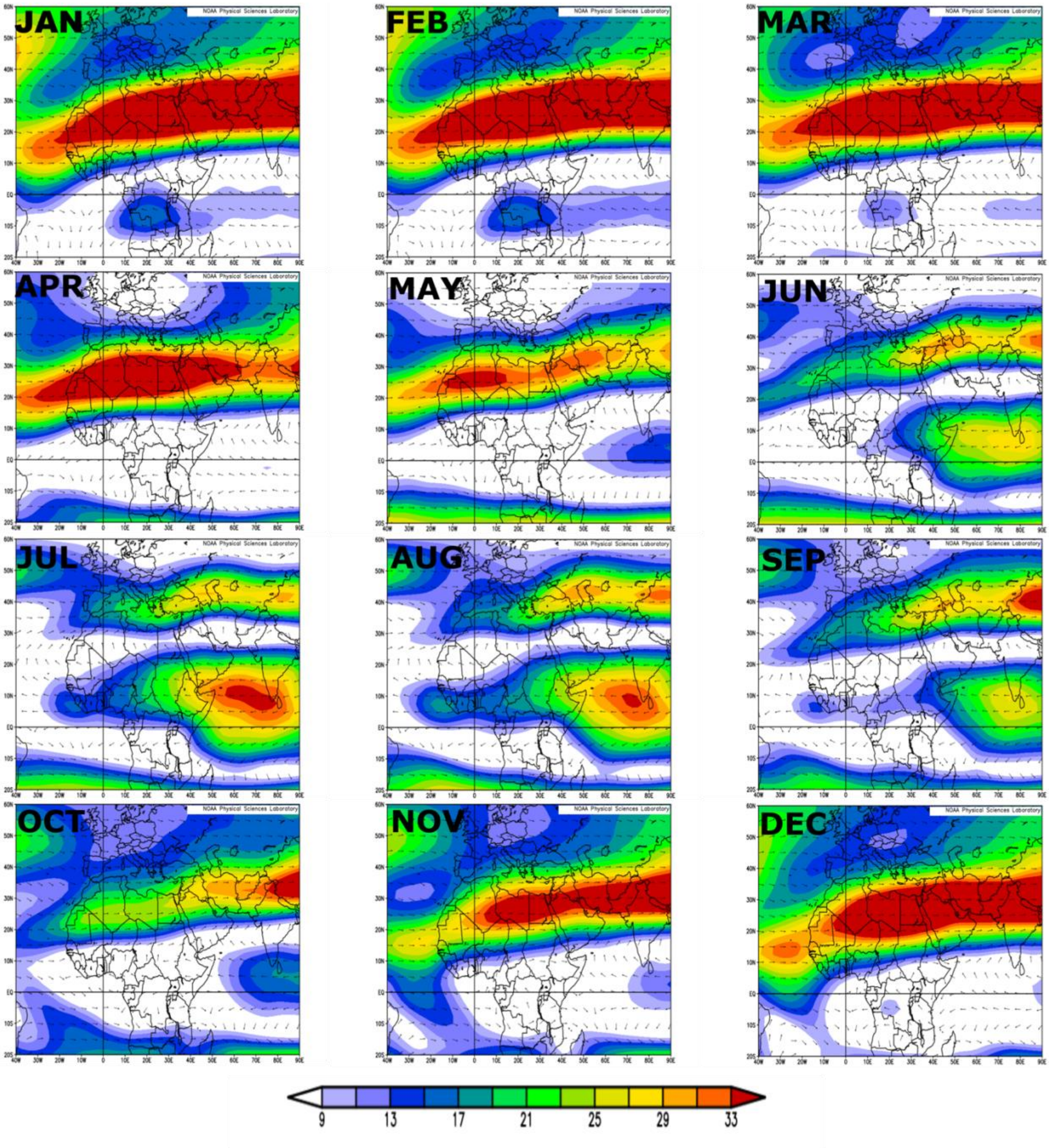

Figure 2 – Monthly wind vector (ms^{-1}) plots at 150 hPa for JJAS using NCEP/NCAR reanalysis data. Plots show composites for the period 1990-2005.

2.2 The relationship between the TEJ and rainfall over the Sahel

The Sahel experiences significant rainfall variability. The West African Monsoon is the main control on interannual rainfall and provides rains from June to September which amounts to 90% of the Sahel's annual rainfall. Figure 3 outlines the vertical profile of the monsoon and demonstrates that the TEJ plays a major role in determining the summer rainfall's northward extent and intensity. The population of the region is heavily reliant on the summer rains for agriculture, and therefore rainfall variability has significant socio-economic consequence.

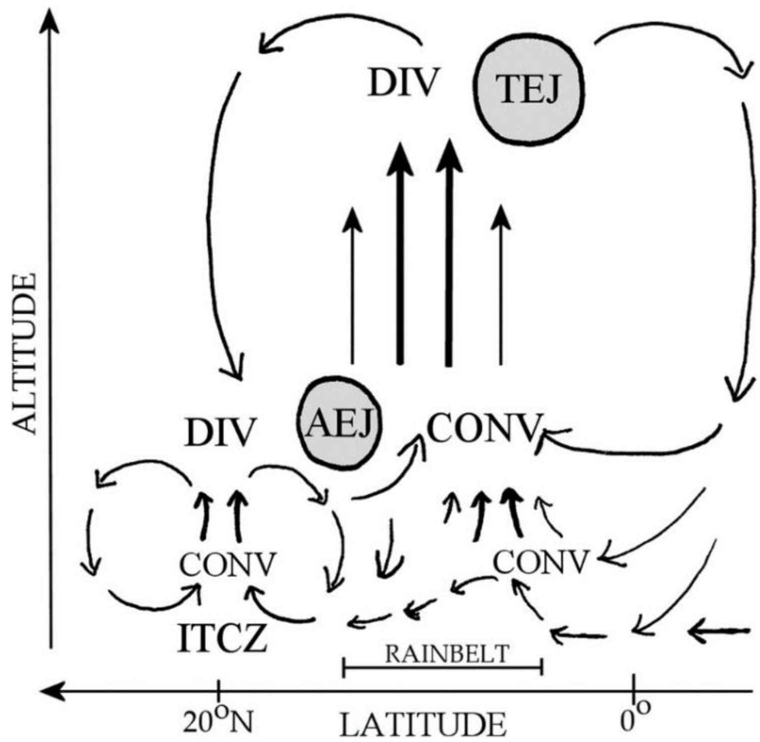

Figure 3 – A schematic showing the vertical profile of the West African Monsoon, and the role of the TEJ on summer rainfall over West Africa (Nicholson, 2009).

There is a large body of literature that shows a consistent causal relationship between the TEJ and rainfall over the Sahel in the boreal summer. This relationship is displayed in Figure 4 by showing the levels of higher rainfall (up to 16 mm day^{-1}) over the Sahel largely correspond to the area of West Africa covered by the extent of the TEJ. Hermann Flohn (1964) produced some of the earliest work showing the influence of the TEJ on African rainfall. Flohn (1964) used jet-streak theory to suggest that patterns of upper-level divergence in the exit regions of the TEJ can explain the rainy seasons over the Sahel. Much other literature is consistent with this theory (e.g., Chen and Yen (1993) and Nicholson (2008)) and further mechanisms have been theorised to suggest that strong upper-level divergence increases rainfall by encouraging ascent below the core of the jet (Grist and Nicholson, 2001). Since the 1980s Sahel drought, African rainfall and the relationship with the TEJ has seen increased attention. In general, a link between a weakened TEJ over Africa and the Sahel drought has been determined (Kidson, 1977; Kanamitsu and Krishnamurti, 1978; Newll and Kidson, 1984; Grist and Nicholson, 2001; Yang et al., 2018; Lemburg et al., 2019a), with the speed of the TEJ over West Africa in wet years being nearly double that seen in dry years (Nicholson and Klotter, 2020).

While numerous studies have shown there is a consistent relationship between the strength of the TEJ and rainfall over the Sahel, the underlying mechanisms are not yet fully understood. Furthermore, in the years following the Sahel drought some recovery has been seen in the rainfall regime, yet the jet has stayed at a relatively weak intensity (Nicholson and Grist, 2001; Nicholson et al., 2018). This has led to debate among the literature regarding the relationship. Questions arise concerning whether the TEJ is independently associated with Sahel rainfall variability, and whether the relationship is coincidental (Nicholson and Klotter, 2020). To begin to address these questions it is important to evaluate how models simulate the relationship between the TEJ and Sahel rainfall, and to understand the processes underlying these simulations.

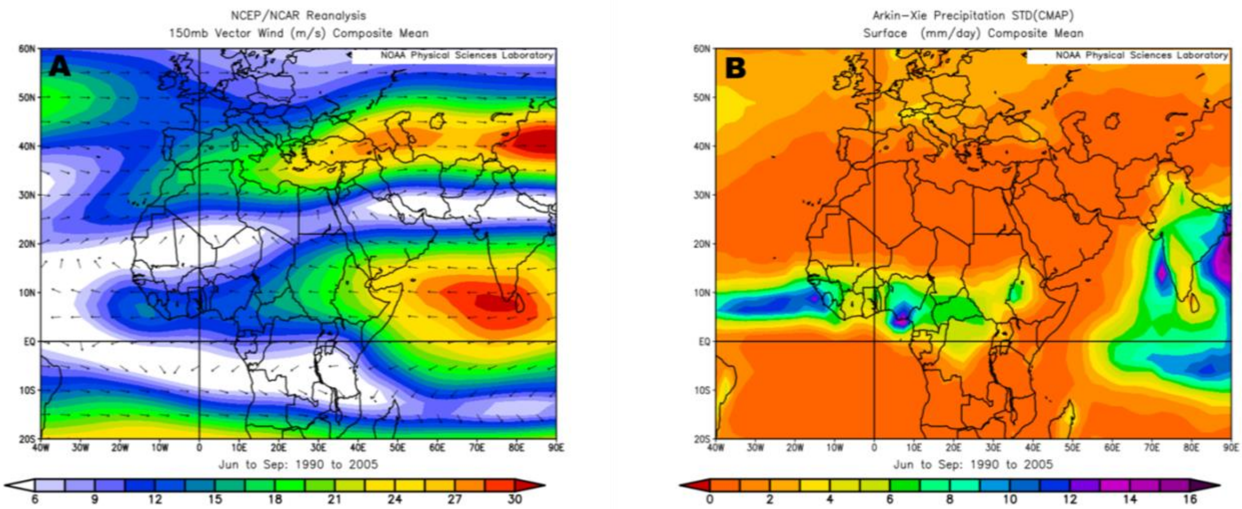

Figure 4 - A) Wind vector (ms^{-1}) plot at 150 hPa for JJAS using NCEP/NCAR reanalysis data. B) Surface precipitation (mm day^{-1}) plot for JJAS using Arkin-Xie/CMAP satellite data. Plots show composites for the period 1990-2005.

3. How well do CMIP5 models represent the TEJ and how does this relate to the simulation of rainfall over the Sahel?

In this section, 20 CMIP5 models (Table 1 in the Appendix) will be assessed to determine their ability to simulate the TEJ and whether this ability correlates with the ability to simulate rainfall over the Sahel accurately. For this, mean eastward wind speeds at 150 hPa for June-September (JJAS) have been plotted over the historical period of 1990-2005. JJAS mean precipitation has also been plotted over this period. This historical period corresponds to the period used in the reanalysis plot for vector wind (Figures 1A and 4A) and the CMAP/Arkin-Xie satellite data plot (Figure 4B) to allow comparisons between the models and reanalysis/satellite data to be made. In the 1970s satellite data was integrated into the NCEP/NCAR reanalysis (Sterl, 2004), which makes the reanalysis data a more reliable source to compare to determine accurate representations.

3.1 How well do CMIP5 models represent the TEJ?

In general, the CMIP5 models perform well in simulating the TEJ. This is evident in Figure 5. All models capture the jet; however, differences occur regarding its intensity and spatial extent. The best simulations were produced by BNU-ESM, GFDL-CM3 and inmcm4. These models represent a jet extending across Africa, over the Sahel region and decaying over the tropical Atlantic. The models show a maximum wind speed of 31 ms^{-1} at the core of the jet over the west Indian Ocean. Over the Sahel region this wind speed is reduced to approximately 15 ms^{-1}. This is very similar to that seen by the reanalysis vector winds, which show the jet extending across Africa and over the tropical eastern Atlantic along a latitude of 0-10°N, with wind speeds of 30 ms^{-1} at the core and 12-15 ms^{-1} over the Sahel region.

The worst simulations were displayed by CMCC-CESM, CMCC-CM and MRI-CGCM3. In these models, the TEJ fails to fully extend across Africa and over the Sahel region, with wind speeds over the Sahel reaching a maximum of 1-5 ms^{-1} and at the core of the jet speeds only reaching 21-23 ms^{-1}. In comparison to the reanalysis plots, these models represent a TEJ with wind speeds that have approximately a 27% reduction at the core of the jet and a 78% reduction over the Sahel region. Furthermore, in MRI-CGCM3, the core of the jet is shifted eastward by approximately 10° compared to the reanalysis plot.

Here, the three best and three worst models at representing the TEJ have been identified. To determine whether there is a correlation between the ability of models to represent the TEJ and their ability to accurately simulate rainfall over the Sahel it is necessary to compare the JJAS precipitation of these two groups of models to each other and to the precipitation multi-model mean. This method of model selection as part of a process-based analysis approach has been seen in other papers, for example Cook and Vizy (2006).

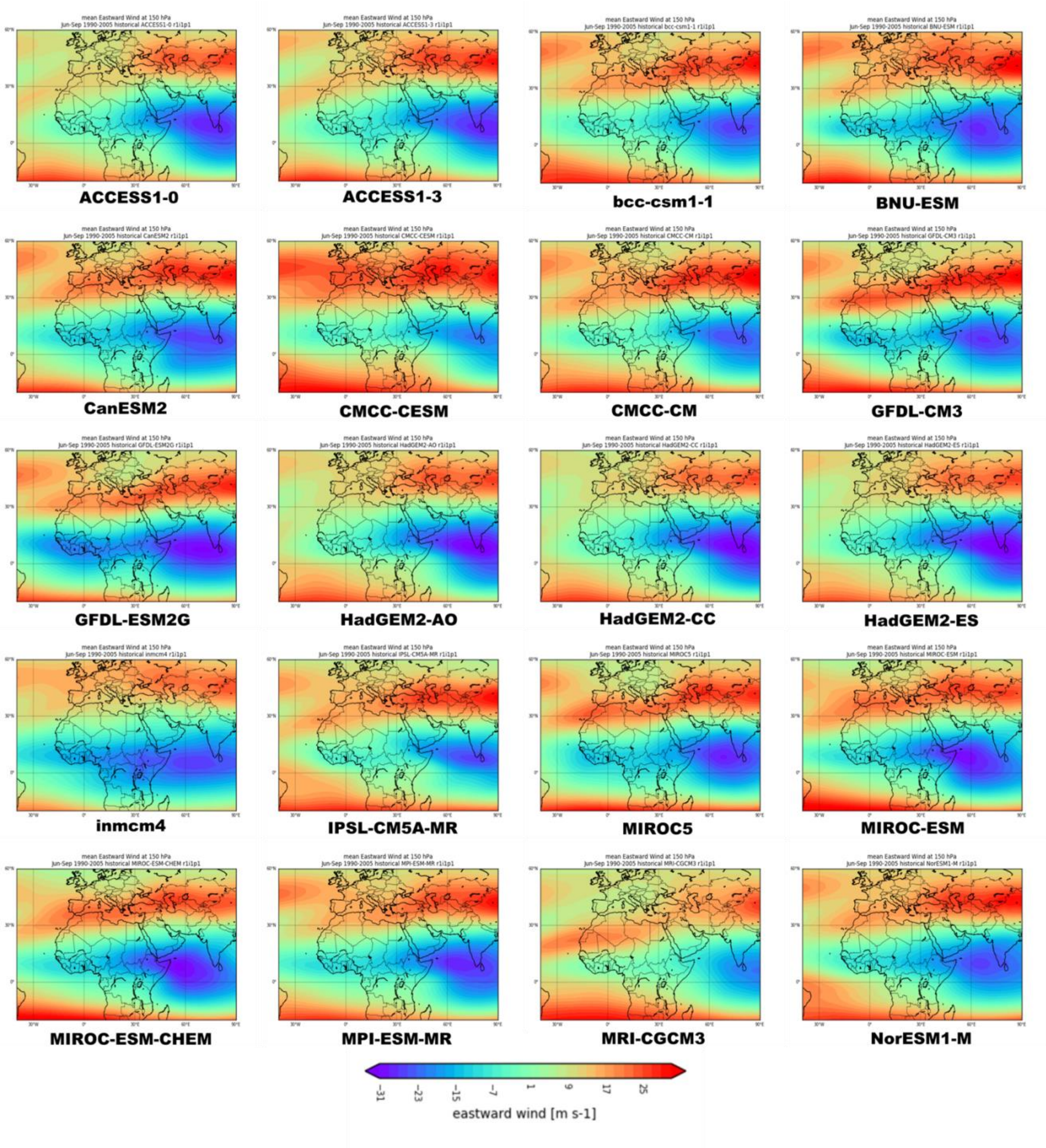

Figure 5 – Composites of mean eastward wind speed (ms^{-1}) at 150 hPa for 20 CMIP5 historical simulations for JJAS over the period 1990-2005. (Source of CMIP5 simulations: Climate Research Lab, OUCE, University of Oxford).

3.2 Do models' abilities to represent the TEJ correlate with their ability to simulate rainfall over the Sahel accurately?

Figure 6 investigates whether the ability of the models to represent the TEJ correlates with their ability to accurately simulate rainfall. The three models that best represent the jet simulate rainfall over the Sahel region of 6-12 mm day^{-1}. This maps on reasonably well to the precipitation levels seen in the satellite data of 6-14 mm day^{-1}, although these models tend to underestimate the maximum rainfall. These models manage to capture a similar spatial extent and pattern of rainfall as seen in the satellite data, with rainfall values of approximately 6-10 mm day^{-1} being seen from 5°S to 15°N and extending across the entire Sahel region. Meanwhile, the three models that worst represent the TEJ simulate rainfall over the Sahel of 2-14 mm day^{-1}. This spread of rainfall is larger than seen in the satellite data, and the spatial pattern is less extensive with higher rainfall only being evident from approximately 2°S to 10°N.

The satellite data shows peak rainfall levels of 10-14 mm day^{-1} over the coast of Guinea and the coast of Nigeria. Interestingly, the three best models simulate the higher levels of rainfall on the coast of Guinea (although these levels are slightly underestimated to 10-12 mm day^{-1}), but fail to produce the rainfall peak over the coast of Nigeria. Whereas the three worst models simulate rainfall peaks at both coasts, and with similar values of 12-14 mm day^{-1} being seen. Comparing the multi-model mean to the satellite data, a reasonably accurate simulation is produced. The pattern and spatial extent of the rainfall is largely similar, with an accurate width of the rainfall band. The simulation of peak rainfall levels of approximately 12-14 mm day^{-1} are also evident over the coasts of Guinea and Nigeria.

Overall, this section has shown the three models that represent the TEJ best simulate the majority of rainfall over the Sahel accurately, however they fail to simulate the rainfall peaks over the coasts of Guinea and Nigeria. Meanwhile, the three models that represent the TEJ least well struggle with parts of the pattern and spatial extent of the rainfall over the Sahel region and have too wide a range of rainfall values, but do simulate the rainfall peaks over the identified coastal areas. The multi-model mean is able to produce the most accurate simulation of rainfall over the Sahel, with the spatial extent, general rainfall levels and peak rainfall levels all being similar to those seen in the satellite data. This suggests the majority of models represent the TEJ well enough to provide an accurate simulation of rainfall over the Sahel. This is a significant finding as it increases trust in the models when looking at the TEJ and its relationship with rainfall. The following section will explore how the future projections of the TEJ and rainfall over the Sahel differ between the three best models, three worst models and multi-model mean.

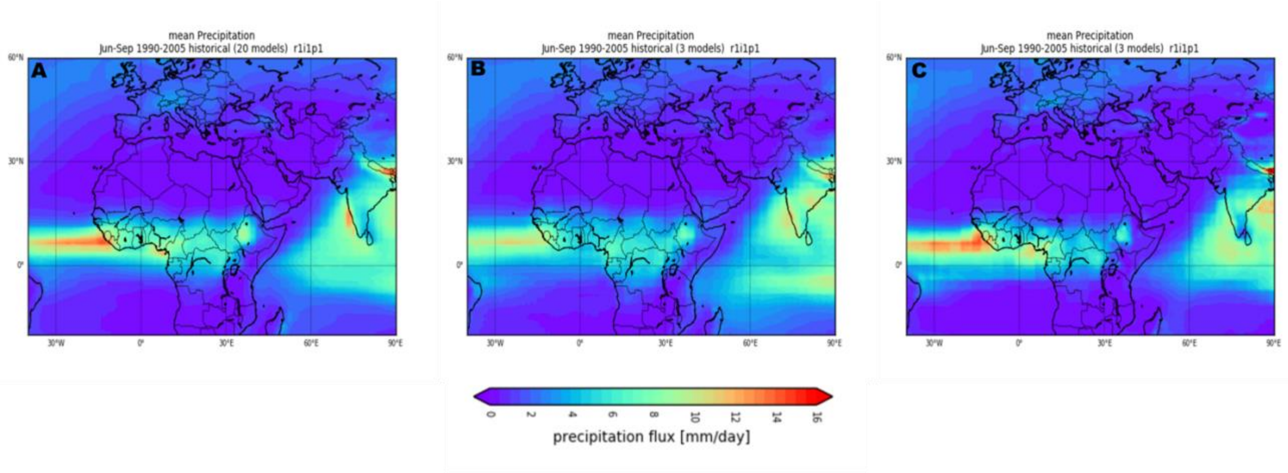

Figure 6 – Composites of mean precipitation (mm day^{-1}) for JJAS over the period 1990-2005. A) a historical simulation of the multi-model mean of 20 CMIP5 models. B) a historical simulation of the 3 CMIP5 models that best represent the TEJ. C) a historical simulation of the 3 CMIP5 models that worst represent the TEJ. (Source of CMIP5 simulations: Climate Research Lab, OUCE, University of Oxford).

4. How are the TEJ and rainfall over the Sahel projected to change in the future in CMIP5 models?

Section 3 has identified the three best and three worst models that represent the TEJ. Using these model groupings, as well as the multi-model mean, this section will investigate future projections of the TEJ and rainfall over the Sahel. In doing this, the section aims to determine whether there are significant differences in the future changes based upon the historical representations of the TEJ. The models are forced with the RCP8.5 pathway, which results in a radiative forcing of 8.5 W m^{-2} at 2100 relative to pre-industrial conditions (IPCC, 2013), for the future period of 2085-2100.

Since the end of the Sahel drought, rainfall in the region has experienced a recovery period (Nicholson et al., 2018). Determining whether this increase in rainfall is a result of global warming, and how this trajectory is likely to play out into the future, is important for advancing the science of the West African climate as well as for policymakers and adaptation planners. In the literature, rainfall projections over the Sahel are highly uncertain (Biasutti et al., 2008). Monerie et al. (2016) used thirteen CMIP5 models to analyse the West African Monsoon and project a strengthening and northward shift of the monsoon, which leads to more rainfall in the Sahel during the summer months. Meanwhile, James et al. (2015) used a process-based analysis approach and both global and regional models to project a strong drying trend over West Africa and a strong wet signal over the eastern Sahel. The future projections of the TEJ are also highly uncertain. Huang et al. (2020) project a decrease in intensity of the jet by 11% toward the end of the 21st century. Meanwhile, Salunke and Mishra (2019) project a stronger TEJ by 2100, with the maximum speed of the jet increasing by approximately 8 ms^{-1}. High levels of uncertainty in projections of both rainfall and the TEJ emphasise the importance of a process-based analysis approach which looks to incorporate assessing the ability of models to represent individual circulation features into future projections. Hence, this section will look to see if the TEJ representation in CMIP5 model historical simulations alters the future projections of rainfall over the Sahel.

Figure 7 displays anomaly plots for the future simulations of the TEJ eastward wind speed at 150 hPa and anomaly plots of future rainfall over the Sahel region. A number of varying changes in the TEJ are evident across the three groups. Looking at the three models that represent the jet best in the historical period, the future projection shows a decrease in the strength of the jet at its core over the Indian Ocean of approximately 3.5 ms^{-1}. Furthermore, a significant increase in westward wind of over 4.5 ms^{-1} is evident along the equator over the tropical Atlantic, which suggests an expansion of the TEJ southwards. Across the Sahel region the strength of the jet increases by 1.5-3 ms^{-1}. Very different results are shown by the three models that worst represent the jet in the historical period. These models simulate a decrease in the strength of the jet of 4.5 ms^{-1} at its core as well as a substantial decrease of 7.5 ms^{-1} over the tropical Atlantic between 10° and 20°N. Furthermore, a decrease in wind speed of 4-6 ms^{-1} is seen over the Sahel region. The multi-model mean simulation shows similar results to that shown by the three best models. The core of the jet over the Indian Ocean shows a reduction in strength of 5 ms^{-1}, while over the equator and the tropical Atlantic the strength of the TEJ increases by 2.5-4.5 ms^{-1}. However, unlike the three best models, the multi-model mean shows a decrease in wind speed of 1.5-3 ms^{-1} over the Sahel region.

All the model groups project a similar pattern of change in rainfall simulations, with an increase in rainfall over the Atlantic from 5-10°N and over some inland areas of the Sahel region, and a decrease in rainfall along the coastal area below the Sahel, including the coasts of Guinea and Nigeria. This is an interesting result because in the satellite data the coasts of Guinea and Nigeria are shown to be areas of relatively high rainfall levels. However, these projected changes vary in magnitude between the model groupings. Looking at the simulation using the three models that best represent the TEJ in the historical period, some slight changes in rainfall can be seen. Over the central Sahel region rainfall is projected to increase by 1-2 mm day^{-1}. An increase is also evident over the tropical Atlantic of up to 2.6 mm day^{-1}. A decrease in rainfall of 1-2 mm day^{-1} is seen along the coastal areas in the southern Sahel region. The three models that represent the TEJ the worst in the historical period simulate a slightly different pattern. The simulation shows large rainfall increases of over 3.5 mm day^{-1} over the tropical Atlantic, and slight increases of 1-2 mm day^{-1} over the coasts of Guinea and Nigeria. This increase also extends into the inland southern Sahel region. Rainfall decreases of 2-2.8 mm day^{-1} are seen off the coast of the southern Sahel region and over Senegal. Meanwhile, there is virtually no change in rainfall over the central Sahel region. The multi-model mean shows a similar pattern to that shown by the three best models but with changes of a lower magnitude. An increase in rainfall of approximately 1 mm day^{-1} is evident over the inland Sahel region and a decrease in rainfall of approximately 0.5-1 mm day^{-1} is seen along the majority of the southern Sahel coastline.

Overall, it is clear the ability of the models to represent the TEJ in the historical simulations has an impact on model projections of future rainfall. The simulation using the three best models shows similar patterns to the multi-model mean but with changes of a greater magnitude, but shows quite different results to those seen in the simulation using the three worst models. The mechanisms for these differences remain unknown, but it appears that future increases in the strength of the jet over the Sahel region could be related to increased rainfall over the Sahel. The rainfall projection simulated by the multi-model mean does show differences compared to the simulation using the three best models. But importantly, the similarities between the two groups suggest some level of reliability of the multi-model mean projection. This shows that assessing how well models can simulate the TEJ is a powerful approach to improve the understanding of the reliability of model projections.

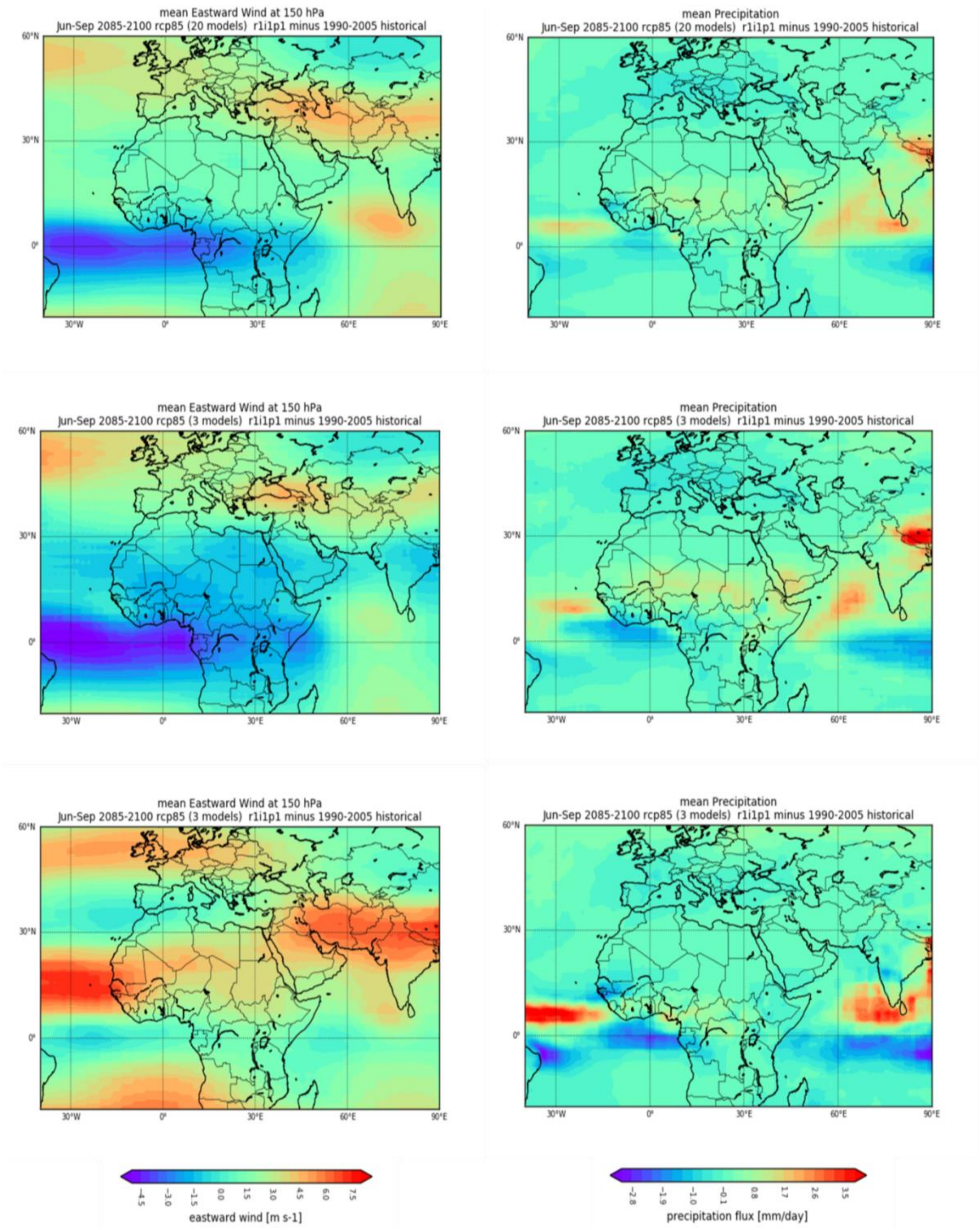

Figure 7 – Anomaly projections of mean eastward wind speed (ms^{-1}) at 150 hPa (left column) and mean precipitation (mm day^{-1}) (right column) for JJAS over the period 2085-2100 with respect to the wind speed and precipitation in 1990-2005. The top row shows the multi-model mean of 20 CMIP5 models. The middle row shows the 3 CMIP5 models that best represent the TEJ in the historical simulations. The bottom row shows the 3 CMIP5 models that worst represent the TEJ in the historical simulations. All simulations are forced with the RCP8.5 pathway. (Source of CMIP5 simulations: Climate Research Lab, OUCE, University of Oxford).

5. Conclusions

This study has expanded upon the recent work of Nicholson and Klotter (2020) to provide a process-based analysis of the TEJ in CMIP5 models. It is clear the TEJ has a relationship with rainfall over the Sahel, an area highly vulnerable to rainfall variability, and therefore studying this circulation feature is important for climate scientists and policymakers. Furthermore, increasing understanding of individual climate features helps to advance the science on the African climate.

The abilities of 20 CMIP5 models were assessed for their representation of the TEJ over Africa by simulating mean eastward wind speed at 150 hPa for June-September over the period of 1990-2005. These simulations were compared to NCEP/NCAR reanalysis data of vector winds at the same atmospheric level. All models captured the jet; however, differences occurred regarding its intensity and spatial extent. Three models, BNU-ESM, GFDL-CM3 and inmcm4, produced the best simulations. These models showed wind speeds of up to 31 ms^{-1} at the core of the jet and 15 ms^{-1} over the Sahel region, which match up well with the reanalysis data. Meanwhile, CMCC-CESM, CMCC-CM and MRI-CGCM3 simulated the jet the most poorly. These models struggled to represent the full extent of the jet across Africa and over the Sahel region, and showed wind speeds that have approximately a 27% reduction at the core of the jet and a 78% reduction over the Sahel region compared to reanalysis data.

The study went on to determine whether there was a correlation between the ability of models to represent the TEJ and their ability to accurately simulate rainfall over the Sahel. Overall, the three models that represented the TEJ best were able to simulate the majority of rainfall over the Sahel accurately, however they failed to simulate the rainfall peaks over the coasts of Guinea and Nigeria. Meanwhile, the three models that represented the TEJ least well struggled with parts of the pattern and spatial extent of the rainfall over the Sahel region and had too wide a range of rainfall values, but were able to simulate the rainfall peaks over the identified coastal areas. The multi-model mean was able to produce the most accurate simulation of rainfall over the Sahel, with the spatial extent, general rainfall levels and peak rainfall levels all being similar to those seen in the satellite data. This was a significant finding as it increases trust in the models when looking at the TEJ and its relationship with rainfall.

Lastly, the future projections of the TEJ and rainfall over the Sahel were explored to determine whether there were significant differences in the future changes based upon the historical representations of the TEJ. Using the identified groups of the three best models, the three worst models, and the multi-model mean, it was clear the ability of the models to represent the TEJ in the historical simulations had an impact on model projections of future rainfall. The simulation using the three best models showed similar patterns to the multi-model mean but with changes of a greater magnitude. Whereas quite different results were seen in the simulation using the three worst models. Importantly, the similarities between the simulation using the three best models and the multi-model mean suggested some level of reliability of the multi-model mean projection.

Assessing the ability of models to simulate the TEJ has improved our understanding of the reliability of model projections, and in this instance has increased our trust in the multi-model mean projections of the jet. Evaluating the multi-model mean projection by comparing it to an identified subgroup of models that are based on their robust ability to simulate dynamics is an important approach when there is high uncertainty among model simulations. Future research should look to develop on this assessment by using the newly available CMIP6 data, as well as increase the understanding of the dynamics underlying the relationship between the TEJ and rainfall over the Sahel through further investigation.

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7. Appendix

Model Name	Institution and Location
ACCESS1-0	Commonwealth Scientific and Industrial Research, Organisation and Bureau of Meteorology, Australia
ACCESS1-3	Commonwealth Scientific and Industrial Research, Organisation and Bureau of Meteorology, Australia
BCC-CSM1-1	Beijing Climate Centre, China Meteorological Administration, Beijing, China
BNU-ESM	College of Global Change and Earth System Sciences, Beijing Normal University, Beijing, China
CanESM2	Canadian Centre for Climate Modelling and Analysis, Victoria, BC, Canada
CMCC-CESM	Centro Euro- Mediterraneo per I Cambiamenti Climatici, Lecce, Italy
CMCC-CM	Centro Euro- Mediterraneo per I Cambiamenti Climatici, Lecce, Italy
GFDL-CM3	Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, NJ, USA
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, NJ, USA
HadGEM2-AO	Met Office Hadley Centre, Exeter, UK
HadGEM2-CC	Met Office Hadley Centre, Exeter, UK
HadGEM2-ES	Met Office Hadley Centre, Exeter, UK
inmcm4	Russian Institute for Numerical Mathematics
IPSL-CM5A-MR	L'Institut Pierre-Simon Laplace, Paris, France
MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Tsukuba, Japan
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Tsukuba, Japan
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Tsukuba, Japan
MPI-ESM-MR	Max Planck Institute for Meteorology, Hamburg, Germany
MRI-CGCM3	Meteorological Research Institute, Tsukuba, Japan
NorESM1-M	Norwegian Climate Centre, Bergen/Oslo, Norway

Table 1 – List of CMIP5 models used in this study.