How Well Do CMIP6 Models Simulate the Influence of the West African Westerly Jet on Sahel Precipitation?

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Abstract

The West African westerly jet (WAWJ) plays a crucial role in Sahel precipitation, yet there is no information on how well climate models simulate the jet and its contribution to Sahel precipitation. This study examines the capabilities of Coupled Model Intercomparison Project (version six; CMIP6) models in simulating the WAWJ and its influence on Sahel precipitation. For the study, we combine the Climate Research Unit (CRU) observation with the European Centre for Medium-Range Weather Forecast (ECMWF) Atmospheric Reanalysis (ERA5) to evaluate 26 CMIP6 simulation datasets. Defining the WAWJ as a low-level westerly jet over the eastern Atlantic and the West African coast, we extracted the characteristics of the WAWJ in the CMIP6 simulations and compared them with those from the ERA5 reanalysis. The results show that the majority of the CMIP6 models agree with ERA5 on the structure and location of the jet, except the jet forms earlier and are stronger in CMIP6 models than in ERA5. While most of the CMIP6 simulations capture the link between the jet and temperature distribution over West Africa, they struggle to reproduce the relationship between the jet and precipitation distribution over the sub-continent, especially over the Sahel. Most simulations failed to replicate the increase in the moisture transport (i.e., the eastward and north-eastward transports) associated with the stronger WAWJ as shown by ERA5. Some simulations capture the increased moisture transport but do not translate it to increased precipitation over the Sahel. This study contributes towards better simulations of Sahel precipitation in climate models.

1. Introduction

The high interannual variability of rainfall in the Sahel is a bottleneck to socio-economic development in the region. The variability fuels extreme climatic events like droughts and floods that usually degrade the environment, damage water resources, induce disease epidemics (e.g., malaria, meningitis), destroy agricultural products (e.g., crops and pasture), and threaten food security (Jnr, 2014; Geist and Lambin, 2004). The Sahel region has a long history of climatic stress from extreme events, including the wet period of the 1930s, 1950s, and 1960s (Giannini et al., 2008; Tschakert et al., 2010) and the droughts of the 1960s–1990s (Balme et al., 2006). For instance, the Sahelian droughts of 2010 deteriorated soil quality and destroyed vegetation (Jnr, 2014), putting approximately 10 million people at risk of acute hunger and resulting in more than 25% of refugee children in Chad becoming malnourished (Vogel, 2010).

In addition to its direct effect on human subsistence, the high rainfall variability devastates planning and management across many socio-economic sectors, including agriculture, water resources, health services, and sporting activities. For instance, any variability in the characteristics of the rainy season (e.g., the amount, onset, cessation, and duration) usually impacts agricultural practices by influencing things such as seed sowing, germination, and overall crop production. Meanwhile, about 85% of the Sahelian population depends on rain-fed agriculture for their livelihood (Jnr, 2014; Monerie et al., 2020) and rain-fed agriculture contributes at least 35% to the GDP of nations whose borders span the Sahel region (Ben Mohamed et al., 2002). However, despite its massive economic importance, trying to predict rainfall variability over the Sahel remains a major challenge when it comes to accurate simulation for many climate models (Roehrig et al., 2013; Vellinga et al., 2016). This difficulty in modelling rainfall variability is a direct result of the complex interactions between various atmospheric features in West Africa, which climate models generally struggle to simulate accurately (Cook and Vizi, 2006; Biasutti, 2013; Roehrig et al., 2013). Therefore, any improvement in the simulation and prediction of Sahelian rainfall variability could go a long way towards reducing the negative socio-economic impacts that occur as a result of unpredictable rainfall in the region. However, any such improvement first requires a better understanding of how well the contemporary climate models represent the rainfall-producing features in West Africa.

The WAWJ, a low-level westerly jet over the eastern Atlantic and West African coast, is one of the atmospheric features that modulates precipitation over the Sahel. Several studies (e.g., Grodsky, 2003; Pu and Cook, 2010 and 2012; Liu et al., 2019; Leslie et al., 2016) have documented the characteristics of the WAWJ and its moisture transports to West Africa. For instance, Pu and Cook (2010) have shown that the WAWJ is formed through the superposition of the westward extension of the continental thermal low (i.e., the West African Heat Low, hereafter WAHL) and the Atlantic marine Intertropical Convergence Zone (ITCZ). The climatological WAHL migrates north-westward from its winter position (between November and March) to over the Sahara (where it is referred to as the Saharan Heat Low, hereafter SHL) during the summer months (June–September), just before the onset of the climatological monsoon (Lavaysse et al., 2009). The westward extension of the SHL creates a pressure gradient between 9°–10°N and 20°–30°W that speeds up the zonal wind to the east of the region. Simultaneously, the superposition of the large-scale meridional convergence associated with the ITCZ inhibits the formation of meridional acceleration. The zonal acceleration manifests as the WAWJ.

Pu and Cook (2010) have also clearly distinguished the WAWJ from the West African monsoon (WAM) flow and showed that the jet forms in June and persists into September, reaching a maximum velocity that exceeds 5.5 ms^{-1} in August. However, Grodsky et al. (2003) showed that in 1999, the jet speed exceeded 15 ms^{-1} at some locations, as well as cooling the sea surface temperature (SST) by about 0.3°C through entrainment and latent heat loss. Liu et al. (2020) and Pu and Cook (2012) showed that the WAWJ transports moisture from the eastern Atlantic onto the subcontinent (especially at 8°–11°N) and has a strong correlation with the interannual variability of the Sahelian rainfall. Liu et al. (2019) also found a strong relationship between the jet and West African precipitation at seasonal and diurnal timescales. Finally, Pu and Cook (2010) argued the WAWJ plays a crucial role in the atmosphere-ocean-land surface interactions in West Africa.

In light of the complex interaction of various climatic factors, as well as the variation in results of the studies cited above, it is clear that any reliable simulations and predictions of rainfall in the Sahel would greatly benefit from an adequate simulation of the WAWJ by global climate models (GCMs). However, there is a dearth of information relating to how well contemporary GCM simulations (e.g., CMIP6) represent the WAWJ and its influence on precipitation over the Sahel.

Several studies have discussed the biases of CMIP6 ensembles in simulating the characteristics of precipitation over West Africa (e.g., see Foltz et al. 2019; Almazroui et al., 2020; Monerie et al., 2020; Klutse et al., 2021). Specifically, Iyakaremye et al. (2021) showed that while the majority of CMIP6 models reasonably simulate observed temperature over West Africa, only 20% of these models have a very strong correlation with observed monthly mean temperature over the Sahel region. The authors attribute the temperature bias (which is up to 3.0°C over the Sahel region) in the models to the inability of the model to adequately represent the complex topography in West Africa. Similarly, Monerie et al. (2020) showed the CMIP6 models do not simulate the monsoon system to propagate northward enough over West Africa and used that to why the models underestimate precipitation over the Sahel. Foltz et al. (2019) also found similar shortcoming in CMIP5 models and attributed it to a warm bias over the Atlantic cold tongue and a cold bias in the Sahara (Foltz et al., 2019). Although the majority of the CMIP6 models perform well in simulating the mean maximum length of dry spells and wet days over West Africa (Klutse et al., 2021), more than 95% overestimated the mean maximum length of wet spells. Some of the models were also found to overestimate the mean maximum length of dry spells over the Sahel and Sahara. However, there is a notable gap in the research relating to how well contemporary GCMs capture the structure and temporal variations of the WAWJ. Such information is necessary for improving the climate projection over the Sahel.

The aim of this study is to examine how well CMIP6 models simulate the characteristics of the WAWJ and its influence on Sahel precipitation. The remainder of the paper is structured as follows: Section 2 presents the methodology, including the description of the study domain, datasets, and data analysis methods; Section 3 presents and discusses the results of the analysis; and Section 4 provides our concluding remarks.

2. Methodology

2.1 Study domain

The region of study for this paper is West Africa (13.5°N, 2.5°W) with a focus on the Sahel (19.1°N, 13.5°E) (Fig. 1). The Sahel, a semi-arid region in West Africa, stretches from the Atlantic Ocean eastward through northern Senegal, southern Mauritania, the great bend of the Niger River in Mali, Burkina Faso (formerly Upper Volta), southern Niger, north-eastern Nigeria, south-central Chad, and into Sudan (Britannica, 2020). It forms a transitional zone between the arid Sahara (desert) to the north and the belt of humid savannas to the south. The climate of the Sahel is arid and hot, with strong seasonal variations in temperature and rainfall. The Sahel monthly mean temperatures vary from a maximum of 33–36°C to a minimum of 18–21°C. During the winter, hot dry Harmattan winds off the Sahara can bring sand and dust storms. The Sahel receives a yearly rainfall of approximately 200–600 mm, which falls mostly in the May to September monsoon season. The rainfall is generally higher in the south, declining rapidly as one reaches the northern edge of the Sahel. However, the rainfall is characterised by great variation from year to year and from decade to decade. On interannual and decadal time scales, Sahelian rainfall is known to be affected by a variety of regional and global sea surface temperature (SST) anomaly patterns (Buontempo et al., 2012).

2.2 Data

This study analysed monthly climate simulations, reanalysis, and observational datasets. The simulation datasets consist of twenty-six (26) GCM simulations from the CMIP6, downloaded from the Earth System Grid Federation (ESGF) website under the CMIP6 search (<https://esgf-node.llnl.gov/search/cmip6/>). These GCM datasets were chosen based on model resolutions and availability of the atmospheric variables needed in the study. Only two GCM datasets used in this study have a 250 km resolution; the rest have a resolution of 100 km.

The variables used in the analysis were temperature, precipitation, wind (zonal and meridional components), vertical velocity, geopotential height, and specific humidity. The reanalysis dataset is the fifth generation of the European Centre for Medium-Range Weather Forecast (ECMWF)'s Atmospheric Reanalysis (ERA5). It is the ECMWF's latest high-resolution reanalysis dataset that combines vast amounts of historical observations into global estimates using advanced modelling and data assimilation systems. The observation dataset is the precipitation dataset from the CRU TS v4.03 (<https://crudata.uea.ac.uk/cru/data/hrg/>). The CRU and ERA5 datasets were used to evaluate the GCM datasets over West Africa. For the evaluation, all datasets were regridded to 0.5° x 0.5° horizontal resolution and analysed for a 35-year period (1980–2014).

2.3 Method

Following previous studies (Pu and Cook, 2010 and 2012; Lui et al., 2019), this study defined the WAWJ as a low-level westerly jet over the eastern Atlantic and the West African coast. Using this definition, we identified and compared the characteristics of the WAWJ in ERA5 reanalysis and CMIP6 simulation datasets over a period of 35 years. The analysis focused on the climatological structure and interannual variability of the jet, as well as the relationship of the jet with other climatic variables over West Africa. We define the core area (averaging region) of the jet as a 7° x 2° (longitude x latitude) area over the WAWJ region. This box area encompasses the core of the jet without extending outside the jet region. While the size of the area is the same for all the datasets, the specific location of the area differs.

For the climatological structure, we considered the vertical, horizontal, and annual structure of the jet. In the vertical structure analysis, we examined the vertical profile, as well as the longitude-vertical and latitude-vertical distributions of the jet using the jet core area as the averaging region. In the annual variation analysis, we obtained data for the maximum zonal wind over the core area of the jet for all months of the year. In the horizontal analysis, we obtained data for the zonal wind greater than or equal to 2 ms^{-1} and the continent was masked out. The capability of the CMIP6 simulations to reproduce the spatial pattern in the reanalysis was quantified with correlation, and percentage bias was calculated. For ERA5 and the majority of CMIP6 simulations, the jet core is at 925 hPa and its maximum strength is in August. Therefore, for most of the analyses reported in this paper; 925 hPa was used as the default level; August as the default month; and the average zonal wind over the core area as the WAWJ strength.

For each dataset, we obtained the interannual variability of the WAWJ and compared it with that of Sahel precipitation. The interannual variability of the WAWJ is represented using the anomalies of the WAWJ strength (at 925 hPa in August), while the interannual variability of Sahel precipitation is designated with the standardised precipitation over the Sahel (averaged over 18°W – 30°E , 10° – 20°N in August). The characteristics of the WAWJ time-series (the WAWJ strength) were quantified with trend and standard deviation, while the relationship between the WAWJ and precipitation time-series was quantified with correlation coefficient. Finally, the capability of the CMIP6 simulations to reproduce the WAWJ interannual variability, as well as the influence of the variability on Sahel precipitation were examined.

To examine the relationship between the WAWJ and the spatial distribution of climate variables (i.e., temperature and precipitation) over West Africa, we analysed correlation between the jet strength and the climate variables at each grid point over West Africa in August at 925hPa for each year between 1980–2014. The spatial distribution of the correlation coefficient obtained for each CMIP6 simulation dataset was compared with the one obtained for the ERA5 dataset. The comparison was then quantified with correlation analysis. To explain the relationship between the jet and climate variables, we obtained the spatial distribution of the difference between the composites of climate variables (precipitation, temperature, and moisture flux) during the WAWJ positive and negative modes (i.e., positive modes minus negative modes). For each dataset, the WAWJ positive modes are the three years with the highest WAWJ strength anomalies, while the negative modes are the three years with the lowest WAWJ strength anomalies.

3. Results And Discussion

3.1 Temporal structure

The ERA5 reanalysis reproduces the annual cycle of the WAWJ (Fig. 2), including the five-stage evolution of the jet as reported in Pu and Cook (2010). The jet has a core speed of about 2.5 ms^{-1} in Stage 1 (June), intensifies steeply as its core speed increases from 2.5 ms^{-1} to 4.3 ms^{-1} in Stage 2 (June–July), attains its peak strength of about 5 ms^{-1} in Stage 3 (August), and weakens as its core speed reduces to about 2.7 ms^{-1} in Stage 4 (September). Despite the differences in the temporal resolution of the data used in Pu and Cook (2010) (i.e., daily) and the present study (i.e., monthly), the strength of the jet obtained here agrees with that reported in Pu and Cook (2010) at each stage. This implies that the characteristics of the jet can be described with monthly datasets.

The majority of the CMIP6 simulations depict the five-stage evolution and the peak of the jet (Fig. 2). However, there are notable biases in the results. Firstly, the jet develops too fast in the models. For example, the jet already attains Stage 3 (speed ≥ 4.0) in February in 6 models (23%); in March in 7 models (27%); in April in 8 models (31%); and in May in 2 models (8%). Only 3 models (ECE-A&B and CIESM) simulate Stage 3 in August as depicted in ERA5 results. Second, the jet is too strong in most models. The peak strength of the jet is more than 5 ms^{-1} in 15 models (58%) and even more than 8 ms^{-1} in 8 models (31%). Third, the weakening of the jet (Stage 4; speed $< 4.0 \text{ ms}^{-1}$) is prolonged in most models. Only 5 models (19%) simulate Stage 4 of the jet in September; 12 models (46%) simulate it in October; and 2 (8%) feature it in November. Four models (CASE, HADGE, INM-A&B, and MRIES) fail to simulate the temporal structure of the jet as in ERA5. For instance, in MRIES, the jet first features in March (instead of June), intensifies steeply and reaches maximum speed in April (instead of August), and disappears in August (instead of September).

3.2 Spatial structure

The ERA5 reanalysis also captures all the spatial structures of the WAWJ in August (Fig. 3) as in Pu and Cook (2010). In ERA5, the WAWJ extends from 6° – 12°N and from 5° – 35°W , but the jet core is located around 8°N and 20°W . The jet is associated with an offshore extension of the thermal low, as indicated by the trough (i.e., 780-gpm contour) extending from over the continent to around 30°W over the ocean. Most CMIP6 models produce a westerly jet off the coast of West Africa but the capability of the models to replicate the spatial structure varies, as depicted by the spatial correlation (r) of the simulated structure with the reanalysis and by associated simulation bias (i.e., percentage bias or 'PBIAS'), indicated in the bottom left panels of Figure 3. While 9 models (35%) feature a strong to very strong positive correlation ($r \geq 0.7$) with the ERA5 reanalysis, 8 models (31%) have a weak positive correlation ($0.4 \leq r \leq 0.6$), and 9 models (35%) show poor correlation ($-0.3 \leq r \leq 0.3$). Most models overestimate area coverage and the core strength of the jet. Their PBIAS range from 1% (in ECE-A) to 57% in (CES-C). For example, in CES-C (which shows the highest PBIAS), the jet stretches from 5° – 14°N and 15° – 40°W with a core strength of more than 8 ms^{-1} . Only 4 models (GISSE, INM-A & B, and MRIES) feature negative PBIAS (-27% to -8%). In MRIES (which has the largest negative bias) the jet only stretches from 7° – 11°N and 15° – 23°W with a core strength of less than 4 ms^{-1} .

3.3 Vertical structure

The latitude-height cross-section of the zonal wind along the jet's longitudes in August further confirms the agreement between the ERA5 and Pu and Cook (2010) results (Fig. 4). In both, the jet extends from the surface to about 750 hPa but the core of the jet (about 4 ms^{-1}) is at 925 hPa (Fig. 4). The African easterly jet (AEJ) core is located above (600 hPa) and north (centred on 16°N) of the WAWJ. This agrees with the finding of Grist and Nicholson (2001) that equatorial westerlies (including the WAWJ) displace the AEJ (and its associated disturbances) northward and modulate the interannual variability of the AEJ. The study also found that the northward displacement of the AEJ coincides with wet years in the Sahel because it enhances both the horizontal and vertical wind shear over the Sahel. The majority of the models capture the vertical structure of the jet as in the ERA5 reanalysis and the seasonal northward shift of the AEJ. However, the models show different capabilities in simulating the vertical extent of the WAWJ and the associated northward shift of the AEJ. The jet extends to 750 hPa (or above) in only 13 models (50%) and to 800 hPa in 6 models (23.1%). However, one model (MRIES, which simulates the weakest WAWJ) features the jet below 900 hPa and puts the jet core at 1000 hPa.

The longitude-height cross-section of the zonal wind speed along the jet's latitudes in August shows the jet core (4 ms^{-1}) between 25° – 15°W in the ERA5 (Fig. 5), which is 2 ms^{-1} weaker and extends more westward than in Pu and Cook (2010). This small discrepancy could be because this study used averaged values over 8° – 10°N , whereas Pu and Cook (2010) used values along a single latitude (9.5°N). However, as in Pu and Cook (2010), the ERA5 result distinguishes the WAWJ from the WAM westerly component maxima over land. While the WAWJ core is located between 15° – 25°W , the WAM core is located between 9° – 15°E . Some of the models capture the vertical structure of the jet in the longitudinal cross-section. However, the majority of the models fail to clearly distinguish the WAWJ from the WAM. For instance, the CES-C model features the westerly flow maxima from about 28°W – 12°E overland without any distinction. The INM-A model failed to capture the WAWJ at all and only features a westerly flow maximum at 10°E .

3.4 Inter-annual variability of the WAWJ

The capability of CMIP6 simulations to reproduce the interannual variability of the WAWJ as in ERA5 differs (Fig. 6). ERA5 shows a strong positive trend ($\text{tr} = 0.04 \text{ ms}^{-1}\text{yr}^{-1}$) in the interannual variability of the jet. This positive trend is related to the partial recovery of precipitation in the Sahel that began in the 1990s (Hagos & Cook, 2008; Pu & Cook, 2010 and 2012). The majority of the models capture the positive trend of the jet ranging from $0.01 \text{ ms}^{-1} \text{ yr}^{-1}$ (in INM-A) to $0.05 \text{ ms}^{-1} \text{ yr}^{-1}$ (in ECE-A and CES-B). However, 3 models (CAMSC, E3S-A, E3S-C) show a negative trend ($\text{tr} \leq -0.017 \text{ ms}^{-1}\text{yr}^{-1}$) of the jet. The jet in these models also shows a weak positive correlation with precipitation over West Africa, particularly over the Sahel. The standard deviation of the simulated WAWJ variability varies from 0.42 (in INM-A) to 1.5 (CES-C, E3S-C), with 16 models (61.5%) underestimating the variability. In ERA5, the interannual variability of the WAWJ is strongly correlated with that of the Sahelian rainfall ($r = 0.76$). While some 15 models (57.7%) agree with ERA5 on the correlation (i.e., $r > 0.5$), 11 models (42.3%) disagree. Hence, the correlation of the WAWJ and Sahelian rainfall ranges from 0.1 (in INM-A, which features the lowest interannual variability of the WAWJ) to 0.83 (in CIESM).

3.5 WAWJ and the spatial distribution of climate variables over West Africa

Observation (ERA5 with CRU) shows that there is a strong relationship between the WAWJ strength and spatial distribution of climate variables (i.e., precipitation and temperature) in West Africa (Figs. 7 and 8). The jet features a strong correlation ($r > 0.6$) with precipitation over the Savanna and Sahel zones (10° – 30°N and 20°W – 25°E ; Fig. 7). However, the peak correlation ($r \approx 0.8$) obtained in this study is higher than that which is reported in PC2012 ($r \approx 0.6$). The jet also has a strong dipole correlation with the surface temperature (Fig. 8), featuring a positive correlation ($r \approx 0.6$) north of 20°N but a negative correlation ($r \approx -0.7$) between 8° – 20°N . While the positive correlation can be attributed to the role of the Saharan heat-low in the formation of the WAWJ (as discussed by PC2012 and reviewed in our introduction), the negative correlation (between 8° – 20°N) is due to the influence of the jet on the temperature field through precipitation. Hence, the ERA5 (with CRU) results suggest that the stronger the intensity of the Saharan heat-low (i.e., the higher the temperature north of 20°N), the stronger the WAWJ (due to associated stronger pressure gradient force between the continent and the Atlantic Ocean).

The stronger WAWJ transports more moisture eastward into the continent within the 5° – 10°N band (Fig. 9). Figure 9 shows more transport of moisture from this band (5° – 10°N) in the northeast direction in the Sahel (north of 10° – 20°N). This suggests that the increase in the eastward transport of moisture by the WAWJ provides more moisture for the north-eastward transport of moisture by the monsoon flow. The increase in moisture transport into the sub-continent increases precipitation and soil moisture, which results in lower temperatures within the 8° – 20°N band (Fig. 8). These results agree with previous studies (i.e., PC2012) that linked the yearly variation in the WAWJ strength to interannual variability of precipitation in the Sahel.

It is worth noting that not all the CMIP6 models capture the relationship between the jet and spatial distribution of the climate variables as depicted in ERA5 (Figs. 7 and 8). While most models reproduce the observed strong correlation between the jet and climate variables, the pattern and magnitude of the correlation differ from ERA5. For instance, on the relationship between the jet and precipitation (Fig. 7), only 7 models (26.9%) feature a comparable pattern ($r \geq 5$; shown at the bottom left corner of Fig. 7) with the correlation map of ERA5, namely: ECE-A ($r = 0.5$), ECE-B ($r = 0.5$), GFDLC ($r = 0.5$), CES-B ($r = 0.5$), CIESM ($r = 0.6$), MPIES ($r = 0.5$), and TAIES ($r = 0.5$). All these models (except TAIES) agree with ERA5 that the

positive phase of the WAWJ produces a stronger eastward transport of moisture within the 8°–20°N band (from the west coast up to 25°E), a more north-eastward transport of moisture (from the band to north of 20°N), and higher precipitation over the sub-continent (north of 8°N). However, the north-eastward transport of moisture is weaker in these models than in ERA5, suggesting that their coupling of the WAWJ eastward transport of moisture and monsoon north-east transport of moisture may be weak in the models (Aadhar & Mishra, 2020; Hourdin et al., 2015; Li et al., 2021; Stouffer et al., 2017). That may explain why the increase in precipitation during the stronger WAWJ is limited to south of 15°N in these models (Fig. 9). The remaining models (73.1%) have a weak agreement with ERA5 on the relationship between the WAWJ and spatial distribution of precipitation; their correlation with ERA5 ranges from 0.1 (E3S-A and E3S-B) to 0.4 (FIOES). While some of these models (e.g., AWICM, CASES, and MPIES) capture the two distinct increases in moisture transports (i.e., the eastward and north-eastward transports) during the stronger WAWJ, the moisture increase does not translate to a commensurable increase in precipitation north of 10°N, as in ERA5. Other models fail to simulate the two distinct increases in moisture transports altogether. For instance, with the increase in the WAWJ, some models (e.g., CES-C and UKESM) simply produce an increase in the eastward transport of moisture, while others (e.g., BCCCS, INM-A, and CMCC) simulate the increase in the north-eastward transport over the whole of West Africa. Three models (E3S-A, E3S-B, and E3S-C) do not produce any coherent pattern in moisture transport over the domain at all (see Fig. 9). It is important to note that the latitudinal location of the jet and its core does not have any influence on the performance of these models.

The simulation performs better at linking the jet with the spatial distribution of temperature than with the spatial distribution of precipitation (Fig. 8). Only 6 models (23.1%) show a weak agreement ($r < 0.5$) with ERA5 results, namely: FIOES ($r = -0.1$), INM-A ($r = 0.1$), CAMSC ($r = 0.2$), CES-C ($r = 0.2$), HADGE ($r = 0.2$), and E3S-C ($r = 0.4$). While HADGE and INM-A show a positive correlation between the jet and the spatial distribution of temperature over most parts of the domain, E3S-C shows a positive correlation. CAMSC features a dipole correlation, but it features some positive correlations north of 20°N in contrast to the ERA5 result. Not all the models that have good agreement with ERA5 (i.e., $0.5 \leq r \leq 0.7$) reproduce the dipole correlation pattern as in ERA5. For instance, 6 models (AWICM, FGOAL, GISSE, E3S-A, E3S-C, SAMUN, and TAIES) show very weak positive correlations ($r < 0.3$) between the jet and temperature north of 25°N. This suggests that these models may underestimate the link between the WAWJ and the SHL. However, ECE-A and ECE-B show the best agreement with ERA5 on the relationship between the WAWJ and spatial distribution of climate variables over the sub-continent.

4. Conclusion

As part of the ongoing efforts to improve the simulation and projection of precipitation in the Sahel, this study evaluated the capability of CMIP6 simulations in replicating the WAWJ and its influence on precipitation across the Sahel. The study analysed the CRU, ERA5, and 26 CMIP6 datasets over a period of 35 years. The study, which defined the WAWJ as a low-level westerly jet over the eastern Atlantic and the West African coast, compared the characteristics of the WAWJ in ERA5 and the CMIP6 simulations and used standard statistical metrics to quantify the comparison. It also quantified the relationship between the jet and climate variables in the datasets with correlation analysis and used composite analysis of the climate variables during the positive and negative modes of the WAWJ to investigate the relationship. The results of the study are summarised below:

- ERA5 shows that the WAWJ has its core at 925 hPa and attains its maximum speed in August. Most CMIP6 simulations capture the vertical and temporal structure of the jet but produce jets that develop too fast and are too strong with reference to ERA5 results.
- While most CMIP6 models agree with ERA5 on the spatial structure of the WAWJ (covering 6°–12°N, 15°–35°W with the core around 8°N and 20°W), more than 38% disagree with ERA5 on the spatial structure.
- The majority of the models reproduce a positive trend in the interannual variability of the WAWJ (as in ERA5 results), but some models show a negative trend in the interannual variability.
- In ERA5, the WAWJ has a strong positive correlation with precipitation over West Africa (especially over the Sahel) and a dipole correlation pattern with temperature over the sub-continent. Most CMIP6 simulations capture the correlation between the jet and temperature, but only a few of them capture the correlation between the jet and precipitation.
- Not all the CMIP6 simulations feature the two distinct increases in the moisture transports (i.e., the eastward and north-eastward transports) during the years exhibiting a stronger WAWJ, as in ERA5 results. Some of those that capture it do not translate the increase in moisture transport to a commensurable increase in precipitation north of 10°N.

While instructive, the results of this study could be improved in various ways. For example, this study evaluated how well the models capture the WAWJ. The relative performance of the models may depend on the model horizontal resolution. While the formation of the WAWJ is closely related to the strength and westward extension of the SHL, improvement in the simulation of the SHL is linked to an adequate representation of the complex topography of Africa. Hence, changes in model resolution may improve the performance of models in simulating the WAWJ. In addition, the biases identified in some of the models in this study could be related to physics parameterisation. For example, the inability of some of the models to translate the moisture transport by the jet to commensurable precipitation suggests that the convective parameterisation schemes in the models might be too weak. Therefore, future studies could evaluate different physics parameterisation schemes in those models. Lastly, while this study has helped to confirm that the jet does transport moisture into the region, this may not be sufficient criteria for rainfall occurrence.

Investigating how well the simulations simulate various processes that trigger deep convection in relation to the westerly moisture flux over West Africa would therefore be very useful. Ultimately, the present study has shown that most of the CMIP6 models do not adequately capture the WAWJ and its interannual variability. Furthermore, it has further established the relationship of the jet with precipitation and moisture transport over the Sahel, thereby providing a useful platform for future climatic simulations of the influence of the WAWJ on Sahelian precipitation.

Declarations

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Code Availability

The code for the diagnostic is made available at <https://github.com/Priority-on-African-Diagnostics/LaunchPAD>

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Contributions

All authors contributed to the study conception and methodology. The first author prepared the material, collected the data and performed the analysis under the supervision of the second author. The first draft of the manuscript was written by the first author and all other authors were responsible for reviewing and editing previous versions of the manuscript. All authors read and approved the final manuscript.

Conflicts of interest

We declare that none of the authors have conflicting nor competing interest.

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Tables

Table 1
Simulation aliases, model names, and key references of CMIP6 models used in this study. All simulations have ~100 km horizontal resolution except GISS (250 km) and UKESM (250 km).

Simulation	Model Name	Variant	Reference
AWICM	AWI-CM-1-1-MR	r1i1p1f1	Semmler et al. (2018)
ECE-A	EC-Earth3	r1i1p1f2	EC-Earth (2019)
ECE-B	EC-Earth3-Veg	r1i1p1f3	EC-Earth-Veg (2019)
BCCCS	BCC-CSM2-MR	r1i1p1f4	T. Wu et al. (2018)
FGOAL	FGOALS-f3-L	r1i1p1f5	Yu (2019)
CAMSC	CAMS-CSM1-0	r1i1p1f6	Rong (2019)
FIOES	FIO-ESM-2-0	r1i1p1f7	Z. Song et al. (2019)
CASES	CAS-ESM2-0	r1i1p1f8	Chai (2020)
GFDLC	GFDL-CM4	r1i1p1f9	Guo et al. (2018)
CES-A	CESM2	r1i1p1f10	Danabasoglu (2019b)
CES-B	CESM2-WACCM	r1i1p1f11	Danabasoglu (2019a)
CES-C	CESM2-WACCM-FV2	r1i1p1f12	Danabasoglu (2019a)
GISSE	GISS-E2-1-G	r1i1p5f1	NASA-GISS (2018)
HADGE	HadGEM3-GC31-LL	r1i1p1f3	Ridley et al. (2019)
INM-A	INM-CM4-8	r1i1p1f1	Volodin et al. (2019a)
INM-B	INM-CM5-0	r1i1p1f2	Volodin et al. (2019b)
CIESM	CIESM	r1i1p1f3	W. Huang (2019)
CMCCC	CMCC-CM2-SR5	r1i1p1f4	Lovato & Peano (2020)
MPIES	MPI-ESM1-2-HR	r1i1p1f5	Jungclaus et al. (2019)
E3S-A	E3SM-1-0	r1i1p1f6	Bader et al. (2019a)
E3S-B	E3SM-1-1	r1i1p1f7	Bader et al. (2019b)
E3S-C	E3SM-1-1-ECA	r1i1p1f8	Bader et al. (2020)
MRIES	MRI-ESM2-0	r1i1p1f9	Yukimoto et al. (2019)
SAMUN	SAM0-UNICON	r1i1p1f10	Park & Shin (2019)
TAIES	TaiESM1	r1i1p1f11	Lee & Liang (2020)
UKESM	UKESM1-0-LL	r9i1p1f2	Tang et al. (2019)

Figures

Figure 1

West African domain showing the topography (in meters) and the climatic zones (Sahel, Savannah, and Guinea) as used in the study.

Figure 2

The magnitude and annual cycle of WAWJ core climatology from 1980-2014 at 925 hPa

Figure 3

The spatial distribution of WAWJ (shading) climatology (1980 - 2014) and the associated ITCZ (Red), geopotential heights (contour), and wind patterns (vector) in August at 925 hPa.

Figure 4

Cross-sections of zonal wind speed (ms^{-1} ; contours; westerlies shaded) with vectors of meridional and vertical winds (scaled by 10^2). The averaging regions used are shown (the white box) in Fig. 3.

Figure 5

Cross-sections of zonal wind speed (ms^{-1} ; contour; westerlies shaded) with vectors of zonal and vertical winds (scaled by 10^2). The averaging regions used are shown in Fig. 3.

Figure 6

The temporal variation of WAWJ (anomaly, $m s^{-1}$) and Sahelian (domain; 10° - 20° N, 18° W - 30° E) precipitation (standardized anomaly) in August as depicted by ERA5 (with CRU) and CMIP6 models.

Figure 7

The spatial distribution of correlation between WAWJ and precipitation (mm/month) over West Africa in August (1980 - 2014), as observed by ERA5 (and CRU) and simulated by the CMIP6 models. The similarity between the simulated and observed patterns is quantified and indicated with a correlation value in each panel.

Figure 8

The spatial distribution of correlation between WAWJ and temperature (°C) over West Africa in August (1980 - 2014), as observed by ERA5 (and CRU) and simulated by the CMIP6 models. The similarity between the simulated and observed patterns is quantified and indicated with correlation in each panel.

Figure 9

Difference of the composite of precipitation (mm/month; shade), temperature ($^{\circ}\text{C}$; contour), and moisture flux (arrow) anomalies during positive and negative modes of WAWJ (1980 - 2014).