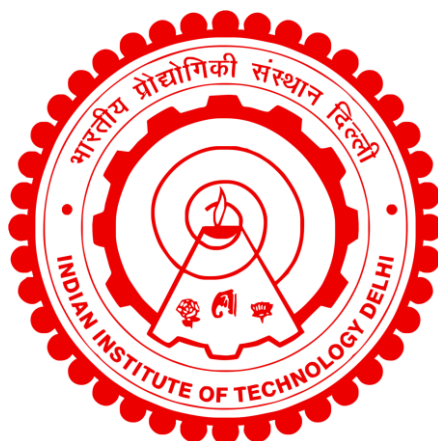


RESPONSE OF AFRICAN EASTERLY WAVES TO A CHANGING CLIMATE

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RESPONSE OF AFRICAN EASTERLY WAVES TO A CHANGING CLIMATE

by

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DEDICATION

I humbly dedicate this thesis to God Almighty, my immediate family, my parents and my teachers

CERTIFICATE

This is to certify that the dissertation entitled “**Response of African Easterly Waves to a Changing Climate**” which is being submitted by **Mr. Tomviezibe Cephas Dombo** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a record of bonafide work carried out by him under our guidance and supervision. The dissertation has reached the standard of fulfilling the requirements of the regulations relating to the degree. The results embodied in the dissertation have not been submitted to any other university or institution for the award of any degree or diploma.

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ABSTRACT

The northward migration of the Intertropical Convergence Zone (ITCZ) is a significant feature of the West African (WA) monsoon. An accurate simulation of ITCZ migration is essential for the realistic representation of WA precipitation in global coupled models. This study employs the energetics and dynamics framework with a subset of Coupled Model Intercomparison Project Phase VI (CMIP6) models to investigate the bias in the simulated WA precipitation. Models were found to simulate more local positive (negative) shortwave cloud radiative forcing (SWCRF) in the Southeastern Atlantic Ocean (over the African continent). The effect of the excess local SWCRF is linked to the stagnation of the ITCZ latitudinal migration and the associated biases in the asymmetry index of precipitation. In the models, there is more (less) moist static energy in the lower (mid and upper) troposphere than in the reanalysis. The worst models have a stronger bias, especially over land. The vertical transport of moisture is confined to the boundary layer in the worst model ensemble. In most cases, the high-resolution coupled models show substantial northward migration of the ITCZ compared to the low-resolution models. Furthermore, the best performing models capture local circulation and energetic processes more accurately than the worst-performing models.

Chapter 3 investigates the contribution of African easterly waves (AEWs) to precipitation in the current climate. AEW influences the precipitation variability over West and Central Africa, as seen from the study. This makes the tracking of AEW an important feature to estimate, using dynamical means and quantifying its current and future variability. An ideal threshold for tracking AEW in climate models and reanalysis is proposed as the 90th percentile of vorticity values. With these threshold values, the Lagrangian technique successfully identifies AEW, which is reliable and comparable to previous methods. The AEW tracks using the Lagrangian tracking method were found to be comparable with the archives of Belanger, the reference tracked datasets in this study. Using the three skills score criteria, the results of the Lagrangian method were found to match about 60-70% with ERA5 tracks, 85-98% with MERRA2 tracks, and ERA-Int with ~98% from all three tracking levels.

Though the study quantified matches between the archived tracks, nonmatches are not quantified since the algorithm significantly captures AEW evolution and propagation characteristics in both reanalysis and CMIP6 models. These results suggest high confidence in the applicability of the algorithm for tracking point-wise atmospheric synoptic features such as AEW from all kinds of datasets with varying temporal and horizontal resolutions. The similarity in the evolution of waves in CMIP6 models compared to ERA5 composites indicates an improvement in the dynamical coupling of convection with AEW in most of the high-resolution CMIP6 models, except for the low-resolution models. However, the simulated convection in the high-resolution models appears to be weaker than that in ERA5, as seen in the days before day-0 composites, and overestimated in the low-resolution models. The precipitation rate is higher in the tracks at 600 hPa (Southern tracks) than in the tracks at 850 hPa (Northern tracks), in agreement with previous studies. The tracks at 700 hPa and 850 hPa from the bandpass filtering method suggest that the waves may not be specifically different from each other, instead, they may be a feature of the same wave that merges or splits.

The response of AEW to climate change and their contribution to future extreme precipitation using CMIP6 models are investigated. First, the future changes in precipitation characteristics are quantified before investigating the changes in the AEW tracks and their influence on future precipitation and extremes. The median and maximum ITCZ positions are projected to migrate northward in the future, with the median at $\sim 7.7^\circ\text{N}$ and the maximum at $\sim 7.9^\circ\text{N}$, respectively. The tendency for a northward shift of the ITCZ in response to climate change suggests future changes in precipitation patterns. During the JJAS season, the interhemispheric asymmetry (IA) in the models is projected to broaden, while future trends in the precipitation asymmetry index (PAI) do not show significant changes from the historical patterns. Secondly, the counts of AEW in the future are higher in the 600 hPa than in the 700 hPa and 850 hPa levels, respectively. The percentage increase in future AEW counts varies among the models. For instance, the percentage change in AEW counts ranges from 12% to 50% in most models except for MRI-

ESM2-0, with a 20% decrease in July, while MIROC6 simulates a more than 100% increase in June. In the future climate, the complex interaction between hydrological processes and atmospheric dynamics may be impacted by changes in the AEW in the region. Models project an increased lifetime and decreased phase speed in the future climate. The projected decrease in the phase speed of AEW may have potential implications for the formation and intensity of the waves in the future over the continent. When the AEW slows down, the momentum and energy of the waves decrease, leading to less organized and weaker intensities of the waves as they propagate. This may have potential implications for the representation of weather patterns such as localized onset and cessation of rainfall and even extreme events such as heavy precipitation and flooding.

KEYWORDS: African Easterly Waves, Monsoon, Climate change, Lagrangian tracking method, Intertropical convergence zone, precipitation extremes

सारांश

West African (WA) मानसून की एक महत्वपूर्ण विशेषता है Intertropical Convergence Zone (ITCZ) का उत्तर की ओर प्रवासन। ITCZ प्रवासन का सही-सही अनुकरण वैश्विक जुड़ा हुआ मॉडल्स में WA वर्षा के वास्तविक प्रतिनिधित्व के लिए आवश्यक है। यह अध्ययन CMIP6 (Coupled Model Intercomparison Project Phase VI) मॉडल्स के एक उपसेट के साथ ऊर्जा और गतिशास्त्र ढांचे का उपयोग करके WA वर्षा में अनुकरणीय बायस की जांच करता है। मॉडल्स ने पाया कि वे दक्षिण-पूर्वी अटलांटिक महासागर (अफ्रीकी महाद्वीप पर) में अधिक स्थानीय सकारात्मक (नकारात्मक) shortwave cloud radiative forcing (SWCRF) का अनुकरण करते हैं। अतिरिक्त स्थानीय SWCRF का प्रभाव ITCZ के अक्षांशीय प्रवासन की रुकावट और वर्षा के विषमता सूचकांक में संबंधित बायस से जुड़ा हुआ है। मॉडल्स में, निचले (मध्य और ऊपरी) ट्रोपोस्फीयर में अधिक (कम) आर्द्र स्थैतिक ऊर्जा पाई जाती है, जो पुनः विश्लेषण में अधिक है। सबसे खराब मॉडल्स में बायस मजबूत पाया गया है, विशेष रूप से भूमि के ऊपर। सबसे खराब मॉडल एन्सेम्बल में आर्द्रता का ऊर्ध्वाधिकार परिवहन केवल सीमा परत तक सीमित है। अधिकांश मामलों में, उच्च-रिज़ॉल्यूशन वाले जुड़े हुए मॉडल्स ITCZ के उत्तर की ओर प्रवासन में अधिक महत्वपूर्ण दिखते हैं, जो निम्न-रिज़ॉल्यूशन मॉडल्स की तुलना में। इसके अलावा, सबसे अच्छा प्रदर्शन करने वाले मॉडल्स स्थानीय परिसंचरण और ऊर्जा प्रक्रियाओं को सबसे खराब प्रदर्शन करने वाले मॉडल्स की तुलना में अधिक सटीकता से पकड़ते हैं।

अध्याय 3 वर्तमान जलवायु में African easterly waves (AEWs) के योगदान की जांच करता है। AEW पश्चिम और केंद्रीय अफ्रीका में वर्षा परिवर्तनशीलता को प्रभावित करता है, जैसा कि अध्ययन से देखा गया है। यह AEW का ट्रैकिंग करना एक महत्वपूर्ण विशेषता बनाता है, जिसे गतिशास्त्रीय तरीकों का उपयोग करके अनुमानित किया जा सकता है और इसकी वर्तमान और भविष्य की परिवर्तनशीलता को मापा जा सकता है। AEW का ट्रैकिंग करने के लिए एक आदर्श सीमा वर्तिसिटी मानों का 90वां पर्सेंटाइल प्रस्तावित किया गया है। इन सीमा मानों के साथ, लैंग्रेजियन तकनीक ने AEW को सफलतापूर्वक पहचाना, जो विश्वसनीय और पिछले तरीकों के साथ तुलनीय है। लैंग्रेजियन ट्रैकिंग विधि का उपयोग करके AEW ट्रैक्स को बेलेंजर के आर्काइव्स के साथ तुलनीय पाया गया, जो इस अध्ययन में संदर्भ ट्रैक डेटासेट्स हैं। तीन कौशल स्कोर मापदंडों का उपयोग करते हुए, लैंग्रेजियन विधि के परिणामों को ERA5 ट्रैक्स के साथ 60-70% तक, MERRA2 ट्रैक्स के साथ 85-98% तक, और ERA-Int के साथ लगभग 98% तक मेल खाते हुए पाया गया। हालांकि, अध्ययन ने आर्काइव्स ट्रैक्स के बीच मेल का मात्राकरण किया, गैर-मेल को मापित नहीं किया गया क्योंकि एल्गोरिदम ने AEW के विकास और प्रसार लक्षणों को पुनः विश्लेषण और CMIP6 मॉडल्स में महत्वपूर्ण रूप से कैप्चर किया। ये परिणाम इस एल्गोरिदम की सभी प्रकार के डेटासेट्स के साथ पॉइंट-वाईज़ एटमोस्फेरिक सिनॉप्टिक फीचर्स जैसे AEW को ट्रैक करने के लिए उच्च विश्वास

का संकेत देते हैं। CMIP6 मॉडल्स में लहरों के विकास में ERA5 समग्रों के साथ समानता यह संकेत देती है कि उच्च-रिज़ॉल्यूशन CMIP6 मॉडल्स में कन्वेक्शन के AEW के साथ गतिशास्त्रीय जुड़ाव में सुधार हुआ है, सिवाय निम्न-रिज़ॉल्यूशन मॉडल्स के। हालांकि, उच्च-रिज़ॉल्यूशन मॉडल्स में अनुकरणित कन्वेक्शन ERA5 के मुकाबले कमजोर दिखता है, जैसा कि दिन-0 समग्रों से पहले के दिनों में देखा गया, और निम्न-रिज़ॉल्यूशन मॉडल्स में अधिक आंका गया है। वर्षा दर 600 hPa (दक्षिणी ट्रेक्स) पर 850 hPa (उत्तरी ट्रेक्स) के ट्रेक्स की तुलना में अधिक है, जैसा कि पिछले अध्ययनों से मेल खाता है। बैंडपास फिल्टरिंग विधि से 700 hPa और 850 hPa के ट्रेक्स यह सुझाते हैं कि लहरें एक-दूसरे से विशिष्ट रूप से भिन्न नहीं हो सकतीं, बल्कि यह एक ही लहर की विशेषता हो सकती हैं जो मिलती या बंटती हैं।

CMIP6 मॉडल्स का उपयोग करके AEW की जलवायु परिवर्तन के प्रति प्रतिक्रिया और भविष्य की चरम वर्षा में उनका योगदान जांचा गया है। पहले, भविष्य की वर्षा लक्षणों में बदलावों का मात्राकरण किया गया, फिर AEW ट्रेक्स में बदलावों और भविष्य की वर्षा और चरम घटनाओं पर उनके प्रभाव की जांच की गई। ITCZ की मध्य और अधिकतम स्थिति भविष्य में उत्तर की ओर प्रवासित होने का अनुमान है, जिसमें मध्य स्थिति $\sim 7.7^\circ\text{N}$ और अधिकतम स्थिति $\sim 7.9^\circ\text{N}$ होगी। जलवायु परिवर्तन के उत्तर की ओर ITCZ की प्रवृत्ति वर्षा पैटर्न में भविष्य के बदलावों का संकेत देती है। JJAS मौसम के दौरान, मॉडल्स में interhemispheric asymmetry (IA) का अनुमान है कि यह चौड़ा होगा, जबकि भविष्य के precipitation asymmetry index (PAI) में ऐतिहासिक पैटर्न से महत्वपूर्ण बदलाव नहीं दिखाए गए हैं। दूसरा, भविष्य में AEW की गिनती 600 hPa में 700 hPa और 850 hPa स्तरों की तुलना में अधिक होगी। भविष्य में AEW की गिनती में प्रतिशत वृद्धि मॉडल्स में भिन्न होती है। उदाहरण के लिए, AEW की गिनती में प्रतिशत बदलाव 12% से 50% के बीच होता है, अधिकांश मॉडल्स में, सिवाय MRI-ESM2-0 के, जिसमें जुलाई में 20% की कमी होती है, जबकि MIROC6 जून में 100% से अधिक वृद्धि का अनुमान करता है।

भविष्य की जलवायु में, जलवायु प्रक्रियाओं और वायुमंडलीय गतिशास्त्र के बीच जटिल इंटरएक्शन को AEW में बदलावों द्वारा प्रभावित किया जा सकता है। मॉडल्स भविष्य की जलवायु में AEW के जीवनकाल में वृद्धि और फेज स्पीड में कमी का अनुमान लगाते हैं। AEW के फेज स्पीड में अनुमानित कमी भविष्य में महाद्वीप पर लहरों के गठन और तीव्रता पर संभावित प्रभाव डाल सकती है। जब AEW धीमा होता है, तो लहरों की संवेग और ऊर्जा में कमी होती है, जिसके कारण वे कम संगठित और कमजोर होते हैं जब वे फैलते हैं। यह संभावित रूप से मौसम पैटर्नों जैसे वर्षा की स्थानीय शुरुआत और समाप्ति और यहां तक कि चरम घटनाओं जैसे भारी वर्षा और बाढ़ को प्रभावित कर सकता है।

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ABBREVIATIONS

<i>AEJ</i>	<i>African Easterly Jets</i>
<i>AEW</i>	<i>African Easterly Waves</i>
<i>AMRB</i>	<i>African Monsoon Rain-Belt</i>
<i>BMMM</i>	<i>Best Multi-Model Mean</i>
<i>CERES-EBAF</i>	<i>Clouds and the Earth's Radiant Energy Balanced and Filled</i>
<i>CDAT</i>	<i>Climate Data Analysis Tool</i>
<i>CORDEX</i>	<i>Coordinated Regional Climate Downscaling Experiment</i>
<i>CGCM</i>	<i>Coupled General Circulation Models</i>
<i>CMIP6</i>	<i>Coupled Model Inter-comparison Project Phase 6</i>
<i>EKE</i>	<i>Eddy Kinetic Energy</i>
<i>EOF</i>	<i>Empirical Orthogonal Function</i>
<i>ECMWF</i>	<i>European Centre for Medium Range Weather Forecasting</i>
<i>ERA5</i>	<i>ECMWF Re-Analysis fifth generation</i>
<i>GCM</i>	<i>General Circulation Models</i>
<i>GHG</i>	<i>Green House Gases</i>
<i>IPCC</i>	<i>Inter-governmental Pannel on Climate Change</i>
<i>ITCZ</i>	<i>Intertropical Convergence Zone</i>
<i>LLEJ</i>	<i>Low Level Easterly Jet</i>
<i>LPS</i>	<i>Low Pressure Systems</i>
<i>MCS</i>	<i>Mesoscale Convective Systems</i>
<i>MTJ</i>	<i>Mid-Tropospheric Jets</i>
<i>MSE</i>	<i>Moist Static Energy</i>
<i>MMM</i>	<i>Multi Model Mean</i>
<i>PCC</i>	<i>Pattern Correlation Coefficient</i>
<i>PAI</i>	<i>Precipitation Asymmetry Index</i>
<i>PDF</i>	<i>Probability Density Function</i>

<i>POD</i>	<i>Probability of Detection</i>
<i>RCM</i>	<i>Regional Climate Model</i>
<i>RCP</i>	<i>Representative Concentration Pathway</i>
<i>RMSE</i>	<i>Root Mean Squared Error</i>
<i>SAL</i>	<i>Saharan Air Layer</i>
<i>SST</i>	<i>Sea Surface Temperature</i>
<i>SSP</i>	<i>Shared Socioeconomic Pathways</i>
<i>SWCRF</i>	<i>Shortwave Cloud Radiative Forcing</i>
<i>SETAO</i>	<i>SouthEastern Tropical Atlantic Ocean</i>
<i>STD</i>	<i>STandard Deviation</i>
<i>SPI</i>	<i>Standardized Precipitation Index</i>
<i>TEJ</i>	<i>Tropical Easterly Jet</i>
<i>VIMSE</i>	<i>Vertically Integrated Moist Static Energy</i>
<i>WAM</i>	<i>West African Monsoon</i>
<i>WMMM</i>	<i>Worst Multi Model Mean</i>