Atlantic zonal mode-monsoon teleconnection in a warming scenario

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Abstract
The dominant interannual SST variability in the eastern equatorial Atlantic is referred to as the Atlantic Zonal Mode (AZM), which peaks in boreal summer impacts global weather patterns. The cold (warm) phase of this ocean-atmospheric coupled phenomenon enhances (weakens) the intensity of the Indian Summer Monsoon Rainfall (ISMR). Observational studies show a strengthening relationship between AZM and ISMR in recent decades, providing a predictive signal for the ISMR. However, a suite of Coupled Model Intercomparison Project Phase 6 (CMIP6) model simulations in the highest emission scenario (SSP58.5) show a weakening relationship between ISMR and AZM in the future (2050–2099). The strengthening of atmospheric thermal stability over the tropical Atlantic in the warming scenario weakens the associated convection over the eastern equatorial Atlantic in response to the warm phase of AZM. This leads to weakening velocity potential response over the Indian subcontinent, resulting in a weak AZM–ISMR relationship. There is no convincing evidence to indicate that either the tropical Atlantic SST bias or the AZM–ISMR teleconnection bias plays a crucial role in the potential weakening of this relationship. These results imply that ISMR prediction will become more challenging in a warming scenario as one of the major external boundary forces that influence monsoon weakens.

Keywords Indian summer monsoon · Atlantic Zonal Mode · AZM-Monsoon Teleconnection · CMIP6 models · Global warming

1 Introduction
India receives ~80% of its annual rainfall during boreal summer months. A large majority of people in an agrarian-based society like India depend on seasonal rainfall. The year to year variability of the seasonal quantum of rainfall is significant as the country’s economy and gross domestic product (GDP) are dependent on the amount of rainfall received during this period (Gadgil and Gadgil 2006). This inter-annual variability (IAV) in the Indian summer monsoon rainfall (ISMR) is partly controlled by slowly varying modes of variability in the tropical ocean (Ajayamohan and Goswami 2000; Goswami and Ajayamohan 2001a; Krishnamurthy and Shukla 2007). The El Niño-Southern Oscillation (ENSO) in the tropical Pacific (Rasmusson and Wallace 1983; Shukla 1987; Philander 1990), the Indian Ocean Dipole (IOD) in the tropical Indian Ocean (Saji et al. 1999; Ashok et al. 2001) and the Atlantic Zonal Mode (AZM) in the tropical Atlantic (Kucharski et al. 2008; Losada et al. 2010; Kucharski and Joshi 2017; Sabeerali et al. 2018, 2019) are the major SST modes of variabilities that influences the IAV of ISMR. In addition to these tropical SST variabilities, the SST variations in extra-tropical Pacific and Atlantic Ocean also affects the IAV of ISMR. The seasonal mean ISMR forecasts consequently rely on the skillful prediction of these interannual modes in the tropical ocean and their associated teleconnections.

Recently, Sabeerali et al. (2018) show that the prediction skill of ISMR improves significantly by correcting the biases in the simulation of tropical Atlantic Zonal Mode (also known as the Atlantic Niño) variability in a coupled model (NCEP-CFSv2). Further, observations indicate that the teleconnection between AZM and ISMR has
strengthened in recent decades (Sabeerali et al. 2019). These studies highlight the significance of a realistic simulation of tropical Atlantic variability for the skillful prediction of ISMR. Considering the importance of these teleconnections in predicting ISMR in the present (historical) scenario, it will be intriguing to see how these variabilities change in a warming scenario. The future changes in the ENSO–ISMR teleconnection and IOD–ISMR teleconnections are explored in previous studies (Li and Ting 2015; Azad and Rajeevan 2016; Yeh et al. 2018; Roy et al. 2019; Zheng et al. 2013). However, little attention has been paid to the AZM–ISMR teleconnection and its changes in the future. Here, we analyze the AZM–ISMR teleconnection in the future scenario using a suite of CMIP6 coupled models that realistically simulates this association in the historical simulations.

The AZM is primarily driven by the Bjerknes feedback mechanism (Bjerknes 1969) akin to the dynamics responsible for the evolution of ENSO in the tropical Pacific (Zebiak 1993; Carton and Huang 1994; Keenlyside and Latif 2007; Ding et al. 2010; Foltz and McPhaden 2010; Lübbecke et al. 2010). The SST variability over the eastern equatorial Atlantic exerts a profound impact on the Indian summer monsoon (Kucharski et al. 2008; Pottapinjara et al. 2014, 2016; Kucharski and Joshi 2017; Sabeerali et al. 2018, 2019). A cold (warm) phase of AZM contributes to enhanced (reduced) rainfall over central India and the Western Ghats. Sabeerali et al. (2019) attributed the strengthening of AZM–ISMR teleconnection in recent decades to the increase in the interannual variability of eastern tropical Atlantic SST. The AZM is also found to influence the characteristics of ENSO in the Pacific (Janssen et al. 2009; Wang et al. 2009; Rodríguez-Fonseca et al. 2009; Ding et al. 2012; Keenlyside et al. 2013; Ham et al. 2013; Yang et al. 2018). A few CMIP5 models show a weakening of the AZM-Pacific Ocean teleconnection under global warming (Jia et al. 2019). They attributed the AZM–ENSO weakening to the increase in the thermal stability of the atmosphere in the warming scenario. A recent study discusses the characteristic change in the equatorial Atlantic SST mode (AZM) in a warming scenario (Mohino and Losada 2015). Here, we examine the AZM–ISMR relationship in a warming scenario by analyzing the state-of-the-art coupled climate model outputs from the CMIP6 archive.

In general, the coupled models show a large bias in simulating and predicting the AZM and its associated teleconnection (Stockdale et al. 2006; Kucharski and Joshi 2017; Sabeerali et al. 2018). Kucharski and Joshi (2017) show that about half of the CMIP5 models analyzed (16 out of 32 models) fail to capture the observed AZM-monsoon teleconnection. The large eastern equatorial Atlantic warm SST bias in coupled models limit the proper simulation of interannual variability of SST (Richter and Xie 2008; Wahl et al. 2011; Wang et al. 2014; Ding et al. 2015a, b). This SST bias is closely related to the boreal spring tropical Atlantic westerly wind stress and associated deepening of thermocline in eastern equatorial Atlantic (Chang et al. 2007; Richter and Xie 2008; Tozuka et al. 2011). A significant improvement in the mean SST bias is not evident in the CMIP5 models (Richter et al. 2014). To a certain extent, the AZM prediction skill in coupled models can be improved by correcting these mean SST biases (Ding et al. 2015b). The latest version of coupled models in the Coupled Model Intercomparison Project Phase 6 (CMIP6) offers new opportunities for a more detailed evaluation of AZM and its associated teleconnection in both historical and future simulations. A one-to-one comparison between CMIP5 and CMIP6 models on the AZM–ISMR teleconnection is essential to understand how the AZM–ISMR relation has changed from CMIP5 to CMIP6 models. Most of the models participating in CMIP6 are new. Hence, it is practically not possible to make a one-to-one comparison between CMIP5 and CMIP6 models due to unavailability of CMIP5 data corresponding to the new CMIP6 models.

The predictability of weather (or the instantaneous state of the atmosphere) is limited to about two weeks due to the inherent instability and nonlinearity of the system (Lorenz 1965, 1982). The atmosphere possesses significant low-frequency variability. If the low-frequency variations of the monthly and seasonal means were entirely governed by scale interactions of the higher frequency chaotic weather fluctuations, the time averages would be no more predictable than the weather disturbances themselves. However, it appears that a large fraction of the low-frequency variability, especially in the tropics, maybe forced by slowly varying boundary conditions such as the sea surface temperature (SST) and soil moisture variations. Hence, the predictability of climate (e.g., space-time averages) is determined partly by chaotic internal processes and partly by slowly varying boundary forcing (Goswami and Ajayamohan 2001a, b). The predictability of tropical climate depends on the relative contributions of “internal” dynamics and “external” slowly varying forcing to the inter-annual variability. The contributions from “external” variability such as solar forcing or slow coupled ocean-atmosphere oscillations (e.g., El Niño Southern Oscillation (ENSO), IOD, AZM, etc.) are less sensitive to initial conditions and hence more predictable. The contributions from “internal” variability are sensitive to initial conditions and therefore are not predictable months in advance. The “internal” variability of the monsoon can arise from a number of processes, such as nonlinear interaction between high-frequency oscillations, the interaction between organized convection and dynamics, and interaction between flow and orography. The chaotic nature of internal variability limits the predictability of the monsoon. Hence, the influence of slowly varying SST forcing like ENSO and AZM on Indian Summer Monsoon Rainfall (ISMR) makes the system
more predictable. More knowledge of these slowly varying external drivers and their associated teleconnection helps for better monsoon prediction.

As mentioned above, the long-term observational datasets show a strengthening relationship between AZM and monsoon in recent decades (Sabeerali et al. 2019). The AZM–ISMR teleconnection provides an additional source of memory for monsoon prediction, a season in advance. The correct representation of AZM and its teleconnection with ISMR in coupled models markedly improves the prediction skill of ISMR (Sabeerali et al. 2018). Hence, how the AZM–ISMR relationship change in future warming scenario is not only a scientific problem but also very relevant for the operational forecasting of monsoon rainfall over India. This study is organized as follows. In Sect. 2, a brief introduction of CMIP6 model experiments and the data used in this study is enlisted, followed by the methodology used. The simulation of AZM and its associated teleconnection with ISMR in the historical simulations is described in Sect. 3. Section 4 details the projected changes in AZM–ISMR teleconnection in the future. The underlying dynamics causing these changes are also discussed. A brief summary and concluding remarks are provided in Sect. 5.

2 Data and methods

2.1 CMIP6 data

In this study, we use the monthly outputs of historical simulations for the period 1965-2014 to represent the present-day climate. For the future climate (2050-2099), Shared Socioeconomic Pathways (SSPs) scenario SSP5-8.5 simulations are used. One ensemble member (r1i1p1f1) from 23 models (see Table 1) from the CMIP6 archive (Eyring et al. 2016; O’Neill et al. 2016, 2017) is used for the analysis. In the historical simulations, models are forced with time-dependent observations to simulate the climate of the period 1850-2014 (Eyring et al. 2016). The SSP5-8.5 represents the highest emission scenario (comparable to business as usual RCP8.5 scenario of CMIP5) where the radiative forcing reaches 8.5 W m$^{-2}$ by the end of the century (2100) (O’Neill et al. 2016).

All the model data is regridded to a common 1° x 1° regular grid for ease of comparison. The linear trend has been removed from the model data prior to the analysis. The observed monthly SST data originates from the

Table 1 Details of CMIP6 models used in this study

| Model          | Institution                                         | Resolution (km) |
|----------------|-----------------------------------------------------|-----------------|
| ACCESS-CM2     | Commonwealth Scientific and Industrial Research Organisation-ARCCSS (CSIRO-ARCCSS) | 250             |
| ACCESS-ESM1-5  | Commonwealth Scientific and Industrial Research Organisation (CSIRO)              | 250             |
| BCC-CSM2-MR    | Beijing Climate Center (BCC)                        | 100             |
| CAMS-CSM1-0    | Chinese Academy of Meteorological Sciences (CAMS)  | 100             |
| CanESM5        | Canadian Centre for Climate modelling and Analysis (CCCma) | 500             |
| CESM2          | National Center for Atmospheric Research (NCAR)     | 100             |
| CESM2-WACCM    | National Center for Atmospheric Research (NCAR)     | 100             |
| EC-Earth3      | A European community Earth-System Models (EC-Earth-Consortium)              | 100             |
| EC-Earth3-Veg  | A European community Earth-System Models (EC-Earth-Consortium)              | 100             |
| FGOALS-g3      | Institute of Atmospheric Physics, Chinese Academy of Sciences (CAS)           | 250             |
| FGOALS-f3-L    | Institute of Atmospheric Physics, Chinese Academy of Science (CAS)            | 100             |
| GFDL-ESM4      | Geophysical Fluid Dynamics Laboratory (NOAA GFDL)   | 100             |
| INM-CM4-8      | MARCHUK Institute of Numerical Mathematics of the Russian Academy of Sciences (INM) | 100             |
| INM-CM5-0      | MARCHUK Institute of Numerical Mathematics of the Russian Academy of Sciences (INM) | 100             |
| IPSL-CM6A-LR   | Institute Pierre-Simon Laplace (IPSL)               | 250             |
| KACE-1-0-G     | National Institute of Meteorological Sciences,Korea Meteorological Administration (NIMS-KMA) | 250             |
| MIROC6         | Model for Interdisciplinary Research on Climate (MIROC)                             | 250             |
| MPI-ESM1-2-LR  | The Max Planck Institute for Meteorology (MPI-M)                                    | 250             |
| MPI-ESM1-2-HR  | The Max Planck Institute for Meteorology (MPI-M)                                    | 100             |
| MRI-ESM2-0     | Meteorological Research Institute (MRI)                                           | 100             |
| NEM3           | Nanjing University of Information Science and Technology (NUIST)                  | 250             |
| NorESM2-LM     | Norwegian Climate Centre (NCC)                                                            | 250             |
| NorESM2-MM     | Norwegian Climate Centre (NCC)                                                            | 100             |
Hadley Centre (HadISST; Rayner et al. 2003) and the grid-
dded high resolution (0.25°×0.25°) precipitation datasets
are from the India Meteorological Department (IMD; Pai
et al. 2014).

2.2 AZM indices

We define the AZM index as the average seasonal mean
(June through August) SST anomalies over the eastern equa-
torial Atlantic Ocean (5°S-3°N, 20°W-10°E). A cold (warm)
phase of AZM is the year when the normalized AZM index
exceeds one negative (positive) standard deviation. Prior to
the analysis, we remove the ENSO influence from all the
variables following the methodology described in previous
studies (Pottapinjara et al. 2016; Sabeerali et al. 2018). For
instance, the ENSO free component of boreal summer mon-
soon rainfall anomalies \(R_{\text{res}}(t)\) is defined as follows

\[
R_{\text{res}}(t) = R(t) - a\text{NINO34}(t)(\text{pres}) - b\text{NINO34}_{\text{res}}(t)(\text{prev})
\]

(1)

Where the \(R(t)\) represents the raw total rainfall anomalies,
which include all the variabilities arising from ENSO, IOD,
and AZM, etc. The constant \(a\) is defined as the slope of
regression fit between rainfall and NINO3.4 index in the pre-
sent monsoon season. The constant \(b\) is defined as the least
square regression fit between the rainfall and residual of
NINO3.4 index in the previous monsoon season. This resid-
ual component of NINO3.4 index in the previous monsoon
season is uncorrelated with the NINO3.4 index in the present
monsoon season. The last term in the equation represents
the influence of ENSO of the previous monsoon season on
rainfall which is not related to ENSO of the present season.

Here, the term \(\text{NINO34}_{\text{res}}(t)(\text{prev})\) is defined as follows.

\[
\text{NINO34}_{\text{res}}(t)(\text{prev}) = \text{NINO34}(t)(\text{prev}) - c\text{NINO34}(t)(\text{pres}).
\]

(2)

The constant \(c\) is defined as the slope of the least square
regression fit between NINO3.4 indexes in the present and
previous monsoon seasons.

2.3 Sign-dependent area average

This study follows a sign dependent area-average of regres-
sion and correlation coefficient following Jia et al. (2019).
This method considers only the statistically significant
regression or correlation coefficient grid points and discards
the coefficients at other grid points. To check whether the
retained values are positive or negative, we first take an area
average of all significant values in the domain of interest. If
this area-average value is positive (negative), we repeat the
area-averaging by considering only significant positive (neg-
avative) coefficients over the region of interest. If there is no
statistically significant correlation/regression coefficient in
an area of interest, we set zero as the average of that region.

3 AZM-monsoon teleconnection in CMIP6
historical simulations

The AZM–ISMR relationship from the present day simula-
tions (historical) of the 23 CMIP6 models is analyzed to
identify models that realistically simulate observed telecon-
nexion. To assess the performance of models in simulating
the AZM-monsoon relationship, a correlation analysis is
conducted between the boreal summer central Indian rainfall
anomalies and the tropical Atlantic SST anomalies (Fig. 1).
Observations show an inverse relationship between central
Indian rainfall and SST anomalies over the eastern equatorial
Atlantic (Figs. 1 and 2a) consistent with the previous studies
(Kucharski et al. 2008; Pottapinjara et al. 2016; Sabeerali
et al. 2018, 2019). Out of 23 CMIP6 models analyzed, a
total of 12 models simulate the observed inverse relation-
ship, although the magnitude of correlation values is weak
(Fig. 1). We term these 12 models as ‘good’ models and use
these model outputs for further analysis and projections
in this study. One caveat, of course, is that we choose the
“good models” based on the ability of those models to cap-
ture the observed features in the historical period. This is
the common practice in assessing the model (Sharmila et al.
2015). The general concise is that if the model captures the
observed phase relationship in a historical time slice, future
changes in the phase of the AZM–ISMR relationship should
occur according to observed changes. However, the results
from this kind of time-slice experiment should be interpreted
carefully on a system with considerable decadal variabil-
ity. Six models show a positive correlation, whereas five
models show no significant relationship between ISMR and
AZM (Fig. 1). For comparison, we term these six models as
‘weak’ models (weak in the sense that the models simulate
opposite teleconnection between AZM and ISMR compared
to observations). A spatial correlation analysis shows that
12 ‘good’ models mimic the observed inverse relationship
between AZM and ISMR, although the magnitude of the
simulated correlation is less (Fig. 2a, b). The 6 ‘weak’ mod-
els simulate a positive correlation which means that these
models simulate an in-phase relationship between AZM and
ISMR (Fig. 2c).

To visualize how the pattern of rainfall anomalies over
the Indian continent correlate with AZM, a spatial correla-
tion analysis between the AZM index and seasonal mean
rainfall is carried out. The multimodel mean of 12 ‘good’
models shows negative correlation values over central
India and western Ghats as in observations (Fig. 2d, e). As
expected, the ‘weak’ models show positive correlation val-
ues over central India (Fig. 2f). In summary, we find that few
models in the CMIP6 archive simulates an opposite phase relationship between AZM and ISMR when compared to observations. The dynamics behind the odd behaviour of these few models will be evaluated in a separate study.

The spatial correlation pattern of AZM index and SST anomalies simulated by the selected CMIP6 models is shown in Fig. 3. Observations show a peak correlation near the eastern equatorial Atlantic (Fig. 3a). While the models show a similar pattern, SST anomalies are weak and more confined to the equator in the simulations compared to observations (Fig. 3). There is no significant difference between 'good' and 'weak' models with regard to SST anomalies.

4 Weakening of AZM–ISMR relationship in future global warming scenario

In this section, we investigate the changes in the AZM–ISMR teleconnection between the present and future climate. A regression analysis is conducted between the AZM indices with the boreal summer (JJAS) rainfall anomalies (after removing ENSO influence) at every grid point over the Indian subcontinent for each period. An average (sign dependent area averaging discussed in Sect. 2) regression value over central India represents the response of ISMR to the AZM. All the 12 'good' models show a weakening of the AZM–ISMR relationship in the future warming scenario (Fig. 4a). The sign of the relationship has changed from negative to positive in the future climate in 7 models (Fig. 4a). The spatial pattern of the AZM–ISMR relationship shows an inverse relationship between AZM and rainfall over central India and the Western Ghats in the present climate (Fig. 4b). However, the pattern changes significantly towards the end of the 21st century with patches of positive and negative correlation coefficients (Fig. 4c). In particular, northwest India shows an increase (decrease) in ISMR in response to warm (cold) phases of AZM in the future scenario in sharp contrast to the present climate. Besides, some parts of south-east central India and western Ghats show a decrease (increase) in seasonal rainfall in response to warm (cold) phases of AZM in a warming scenario (Fig. 4c). This implies that in the future climate, the seasonal prediction of ISMR will be more challenging as the memory from the eastern equatorial Atlantic forcing weakens.

As mentioned earlier, observational studies indicate a robust AZM-ISMR relationship in recent decades due to the increase in the tropical Atlantic SST variability (e.g. Sabeerali et al. 2019). The interesting aspect coming out from the CMIP6 simulations is that the AZM-ISMR teleconnection in the future climate is not in line with the present climate and observations (Fig. 4). However, the AZM variability in the future period (2050-2099) when compared with the present (1965–2014), as assessed from the 12 'good' models do not show a marked difference (Fig. 5a, b). The
intermodel relationship between AZM amplitude change and the changes in rainfall response over central India displays a near-zero correlation (Fig. 5c). Hence, there is no evidence to attribute the changes in AZM-ISMR teleconnection to the eastern equatorial Atlantic SST variability in the SSP5-8.5 simulations. In the following sections, we explore the factors responsible for the weakening of AZM-monsoon teleconnection in the future climate.

4.1 Role of model biases to the weakening of AZM–ISMR relationship in future climate

The CMIP6 models also display biases like the CMIP5 models (e.g. Kucharski and Joshi 2017; Richter et al. 2014) in simulating the tropical Atlantic mean SST variability and AZM-ISMR teleconnection. Most models show a warm SST bias over the eastern tropical Atlantic (figure not shown). The warm bias in the mean state SST can have a strong impact on the interannual variability in the eastern equatorial Atlantic Ocean (Richter and Xie 2008; Wahl et al. 2011; Wang et al. 2014). Ding et al. (2015a) have shown that the warm SST bias over the eastern equatorial Atlantic Ocean in a coupled model severely inhibits the ability of that model to reproduce both the observed SST variability in the equatorial Atlantic Ocean and dynamics governing that variability. Models also show a weak AZM-ISMR teleconnection compared to observations (Fig. 1). Although the 12 selected models capture the sign of the relationship between AZM and ISMR, the magnitude of the correlation varies from model to model indicating a bias. The question

**Fig. 2** The multimodel mean of AZM–ISMR teleconnection in the historical simulations (1965–2014) of CMIP6 coupled models. Spatial correlation between the boreal summer central India rainfall anomalies (average of rainfall anomalies over the core monsoon domain) and the SST anomalies (after removing ENSO influence) over the tropical Atlantic. a Observations, b multi-model mean of 12 ‘good’ models, c multi-model mean of six ‘weak’ models. d–f is the same as a–c, but represents the spatial map of correlation between the AZM index and the rainfall anomalies. In observations (a and d) correlation values greater than 95% confidence levels are stippled. Stippling in panels b, c, e, and f denotes that the multimodel mean exceeds 1 standard deviation.

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is whether these biases have any impact/role on the future projection of the AZM-ISMR relationship. To answer this question in Fig. 6 we plotted the intermodel relation of the eastern equatorial Atlantic mean SST bias and the bias in the AZM-ISMR teleconnection over the present day climate with changes in AZM rainfall response over central India. The eastern equatorial Atlantic mean SST bias is measured by the difference of climatological mean SST over the eastern equatorial Atlantic during the historical period between model and observations. The AZM-ISMR teleconnection bias is measured by the difference of AZM rainfall response (a residual component of rainfall after removing ENSO effect) over central India during the historical period between model and observations. The changes (HIST vs SSP5-8.5 simulations) in central India rainfall response and the biases in the eastern equatorial Atlantic mean SST do not show any significant relation ($r = 0.17$; Fig. 6a). Similarly, the changes in central India rainfall response and biases in the AZM-ISMR teleconnection also do not show any significant relationship ($r = 0.08$; Fig. 6b). This implies that there is no clear evidence to suggest either the SST bias over the tropical Atlantic or the bias of the AZM–ISMR teleconnection itself plays a dominant role in the future weakening of AZM-ISMR teleconnection.

4.2 Underlying mechanism driving the weak AZM-monsoon teleconnection in future climate

Previous studies discuss the detailed physical mechanism through which the AZM influences the Indian summer monsoon (Kucharski et al. 2008; Pottapinjara et al. 2014; Sabeerali et al. 2018, 2019). The Gill-Matsuno type response of the atmosphere (Gill 1980) to the eastern equatorial Atlantic SST anomalies leads to eastward propagating atmospheric Kelvin waves to the Indian Ocean and westward propagating Rossby waves to North America and East Pacific. The atmospheric Kelvin waves reduce (enhance) the meridional gradient in upper tropospheric temperature over the monsoon domain during warm (cold) AZM phases. This is the basic theory through which the AZM impact ISMR. Yadav et al. (2018) showed an additional pathway through which the AZM influences the ISMR. According to their theory, the AZM modulates the Asian jet through the wave train in mid-latitudes and extra-tropics and finally, alters the ISMR. A detailed study is required to understand the relative contribution of these two teleconnection bridge and its is beyond the scope of this study. As a result of changes in the meridional upper tropospheric temperature gradient over the monsoon domain, the large-scale winds and moisture transport to the Indian subcontinent weakens (enhances). This leads to the weakening (strengthening) of the monsoon rainfall during warm (cold) AZM phases. The warm (cold) SST anomalies associated with AZM induce an enhanced (decreased) convection over the eastern tropical Atlantic region. As a response of this, an upper-level divergence (convergence) over the tropical Atlantic region and a compensating upper-level convergence (divergence) in the tropical west-central Pacific region is evident during the warm (cold) phase of AZM (Sabeerali et al. 2019). The strength of the AZM–ISMR teleconnection depends on the strength of the tropical Atlantic convection response to the underlying SST anomalies, manifested in a maximum rising motion at around 600 hPa (see Jia et al. 2019).

The response of tropical Atlantic convection to the underlying SST anomalies can be shown by regressing the AZM index onto atmospheric vertical velocity and flow vectors (Fig. 7b, c). In both the present and future climate, the response of equatorial Atlantic convection to the underlying
SST anomalies shows ascending motion in the eastern tropical Atlantic and descending motion in the central/western Pacific during the positive/warm phase of AZM (Fig. 7b, c). The multimodel mean of 12 ‘good’ models shows a reduction of eastern equatorial Atlantic vertical velocity response in the future climate (Fig. 7c). However, in the future climate, there is a stronger sinking motion over the central/western Pacific compensating for the rising motion over the eastern tropical Pacific. It should be kept in mind that this sinking motion over the central/western Pacific is still not significant. Further, for the sake of clarity, we regressed the 600 hPa vertical velocity (maximum vertical velocity occurs at around 600 hPa) onto the AZM index, and the resultant regression coefficient averaged over the eastern equatorial Atlantic Ocean is shown in Fig. 7a. The 600 hPa vertical velocity response to AZM over the eastern equatorial Atlantic Ocean displays a weaker response in future climate in all 12 ‘good’ models (Fig. 7a).

The thermal structure of the atmosphere is of utmost importance in determining convection over a region. In
the atmosphere, thermal stability refers to the ability to resist vertical motion/convection. The mean vertical thermal profile of the troposphere shows a decrease in atmospheric temperature with height. In the warming scenario, the mid-troposphere warms faster than the near-surface levels due to the diabatic heating anomalies (Fig. 8a) consistent with previous studies (Allen and Sherwood 2008; Jia et al. 2019). This means that the thermal contrast between the upper and lower troposphere decreases in future climate. The negative vertical temperature gradient over the eastern tropical Atlantic reduces in the SSP5-8.5 simulations (Fig. 8b). Here, a negative vertical gradient is defined as the difference between the atmospheric temperature at 600 and 925 hPa. The term ‘negative’ vertical gradient is used
to compensate for the decrease in atmospheric temperature with altitude. The reduction of negative vertical temperature gradient implies an increase in the atmospheric stability and its ability to resist vertical motion/convection in a warming scenario. All the 12 'good' models show a weakening of the negative vertical temperature gradient (positive values in the X-axis of Fig. 8b) in SSP5-8.5 simulations. The damping effect of increasing atmospheric stability dominates the SST changes in the eastern equatorial Atlantic in the future. As a result, the atmospheric convection over the eastern equatorial Atlantic reduces in the future climate.

The weakening of equatorial Atlantic convection influences the circulation pattern over the Indian subcontinent during boreal summer. The present climate shows an upper-level convergence over the equatorial Atlantic and an upper-level divergence over the Indian subcontinent in response to the cold phase of AZM (Fig. 9a). Note that the pattern reverses in a warm AZM phase. This result is consistent with previous observational results (Kucharski et al. 2008; Sabeerali et al. 2018, 2019). The strengthening of atmospheric thermal stability over the tropical Atlantic and the associated changes in convection leads to the weakening of velocity potential response over the Indian subcontinent in a warming scenario (Fig. 9b).

During boreal summer, the low-level winds are westerlies, and the upper-level winds are easterlies over the Indian subcontinent, indicating a baroclinic vertical structure (e.g. Goswami and Ajayamohan 2001a). The warm (cold) phases of AZM shows an anticyclonic (cycloic) low-level wind response over central India in HIST simulations. This anticyclonic (cycloic) wind response weakens in a warming scenario. In the historical run, a well defined anticyclonic (cycloic) circulation anomalies are evident over the Indian subcontinent in response to the warm (cold) phase of AZM, whereas it is very weak in the future scenario. However, the strength of low-level monsoon winds is almost the same between present and future climate. The weakening of this low-level wind response over the Indian subcontinent in the SSP5-8.5 simulations (Fig. 10b), entailing the weakening of AZM-ISMNR teleconnection in the future climate. The changes in ISMR response and changes in the negative vertical temperature gradient over the equatorial Atlantic correlate very well (Fig. 8b). Jia et al. (2019) also find a weakening of vertical velocity response caused by the enhanced atmospheric stability in the future climate over the eastern equatorial Atlantic in CMIP5 simulations. These results give an inkling that the recent strengthening of AZM-ISMNR teleconnection in the observational data is not an after-effect of greenhouse warming, but instead, it is induced by the increase in Atlantic SST variability, as shown in Sabeerali et al. (2019). In other words, the changes in eastern equatorial SST variability dominates the atmospheric thermal stability change in determining...
1839 Atlantic zonal mode-monsoon teleconnection in a warming scenario

Conclusion

The AZM is a dominant mode of interannual climate variability in the tropical Atlantic Ocean that emerges from the air-sea coupled interaction similar to ENSO in the Pacific. The AZM peaks during the boreal summer season, and it impacts the global weather pattern in different ways. An inverse relationship between the ISMR and the eastern equatorial Atlantic SST variability is evident. Observational
studies indicate a strengthening relationship between ISMR and AZM in recent decades due to an increased interannual SST variability in the tropical Atlantic. The enhanced AZM–ISMR relationship provides an additional parameter for predicting seasonal mean monsoon in advance. In that respect, the impact of AZM–ISMR response in a warming scenario assumes significance. Here, we study the AZM–ISMR relationship in the future climate using a suite of CMIP6 coupled model simulations.

In this study, first, we analyze the simulation of AZM–ISMR teleconnection in a suite of 23 CMIP6 coupled models. Most CMIP6 models show systematic bias in simulating the AZM–ISMR teleconnection compared to observations. Out of 23 models analyzed, only 12 models capture
the correct sign of AZM−ISMR teleconnection. The rest of the models either capture an opposite teleconnection or no significant relationship. Here, these 12 models are used to study the AZM−ISMR teleconnection in the future climate. All these 12 models show a weakening of AZM−ISMR teleconnection in the SSP5-8.5 (the highest emission scenario) simulations.

Most CMIP6 models show a warm SST bias over the eastern tropical Atlantic. Although the selected 12 models capture the correct sign of the relationship between ISMR and AZM, biases in simulating the teleconnection’s strength vary from model to model. Almost all models underestimate the strength of this relationship. The study finds no clear evidence to suggest either the tropical Atlantic SST bias or the bias of the AZM−ISMR teleconnection itself is responsible for the future weakening of AZM−ISMR teleconnection.

The atmospheric thermal structure has a crucial role in determining the convective responses over the eastern equatorial Atlantic. The mid-troposphere warms faster than the near-surface levels in the future climate in the selected models. It indicates an increase in the thermal stability of the atmosphere in the warming scenario. The increase in atmospheric thermal stability over the tropical Atlantic weakens the convective responses over the eastern equatorial Atlantic in response to warm phases of AZM. This lead to a reduction in the upper-level velocity potential and low-level wind response over the Indian subcontinent resulting in weak AZM-ISMIR teleconnection. The changes (HIST vs. SSP5-8.5) in ISMR response and atmospheric thermal stability changes over the eastern equatorial Atlantic show a strong correlation. However, there is no clear evidence to connect the changes in tropical Atlantic SST variability to the weakening of AZM−ISMR teleconnection in the SSP5-8.5 scenario.

This analysis demonstrates that the damping effect of increasing atmospheric thermal stability dominates over the SST variability changes over the tropical Atlantic in a warming scenario. However, the recent strengthening of AZM−ISMR teleconnection seen in the observational data is caused by increased tropical Atlantic SST variability; not by greenhouse warming. The take-home point from this study is that if greenhouse warming continuously increases at the current rate, the future prediction of ISMR will be more challenging as the memory from the tropical Atlantic Ocean weakens.

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