Analysis of Climate Trends and Leading Modes of Climate Variability for MENA Region

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Abstract

The Middle East and North Africa (MENA), primarily the Arabian Peninsula (AP) is a region where the rate of mean surface temperature rise per decade is among the highest globally known during the recent past. Moreover, MENA regional climate is very sensitive to internal and external climate drivers. Therefore, it is of significant practical importance to analyze MENA sensitivity to climate trends as well as leading variability modes such as El Nino Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) and Indian summer monsoon (ISM). Using multiple regression technique on observations and the high-resolution atmospheric model (HiRAM) output, this study investigates the role of climate trends, and leading circulation modes such as NAO, ENSO, and ISM in inducing temperature and precipitation variability in MENA region for the period 1979-2008. Our results show substantial regional temperature and precipitation responses of ENSO, NAO, and ISM over MENA. Both the model and the observations indicate that positive phase of NAO and ENSO significantly cools central parts of MENA, in particular, the AP in winter. However, in boreal summer, the warm ENSO phase produces significant warming and drying over the tropical region. The strengthening (weakening) of ISM suggests cooling (warming) and wetting (drying) over MENA rain-belt region. Moreover, ISM induces a dipole precipitation structure over the tropics caused by ITCZ shift and associated cloud distribution. HiRAM slightly underestimates NAO and ENSO winter cooling over the AP, however; overall patterns are well reproduced. The conducted analysis sheds light on the internal mechanisms of MENA climate variability.

Key words: MENA, ENSO, NAO, Indian summer monsoon.

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1. Introduction

The Middle East and North Africa, primarily the Arabian Peninsula is a region where the rate of mean surface temperature rise per decade is among the highest globally known during the recent past (Hansen et al., 2010; Almazroui et al., 2012; Croitoru and Piticar, 2012; del Río et al., 2013; AlSarmi and Washington, 2011; 2013; Zhang et al., 2005). Earlier studies have shown that the MENA region is very sensitive to internal and external climate forcings (Osipov et al., 2016; Stenchikov and Dogar, 2012; Dogar et al., 2017a; 2017b; Haywood et al., 2013; Dogar, 2018; Bangalath and Stenchikov, 2015). Several past studies have discussed the importance of different leading modes of variabilities such as NAO (Hurrell, 1995; Abualnaja et al., 2015; Athar, 2015; Barlow et al., 2016), ENSO (Dogar et al., 2017a; Kumar et al., 2016) and Indian summer monsoon, however, there is barely any attempt conducted so far in which the sensitivity of MENA to these leading predictors is explored in detail. Using comprehensive statistical approaches, Zhang et al. (2005) examined in detail the trends in temperature and precipitation indices for Middle East region. Some recent studies have analyzed the response of Arabian Peninsula (AP) region to ENSO or NAO forcings (see e.g., Sandeep et al., 2018, Abid et al., 2018 AlSarmi and Washington, 2011; 2013; Kumar et al., 2016). Nevertheless, the impact of the leading climate factors on the MENA region is marginally explored and therefore further studies to improve our understanding are warranted. Hence, the aim of this study is to revisit and better understand the impact of leading modes of variabilities that influence MENA climate together with the assessment of climatic contribution of temperature and precipitation trends in winter (DJF) and summer (JJA) season. For this purpose we will make use of regression analysis, which is widely used to study the global and regional climatic impact of large-scale climate drivers (Yu and Zhou, 2004; Randel, 2010; Iles and Hegral, 2017; Dogar et al., 2017b). The regression analysis is employed on the output from high-resolution global climate model together with state of the art observational data to better analyze the leading variability modes and their regional impacts over MENA region. This study will surely help the policy makers to get prepared about the climatic impact of such leading predictors. To the best of our knowledge, this study is an antecedent and first of its kind in which a very fine resolution global climate model is used to uncover the regional climatic mechanisms of MENA and its sensitivity to leading modes of variabilities. The main questions that are discussed in this paper are as follows. 1). What is the role of temperature and precipitation trends over MENA region. 2). How the leading modes of variabilities (ENSO, NAO and ISM) affects MENA climatic regime?

The rest of the paper is organized as follows. In section 2 we have discussed the model, data and methodology used in the study. Subsection 2.1 describes model, experimental setup and the observational data used in the study. Subsection 2.2 explains the methodology that includes multiple linear regression technique and selection of leading climate modes of variability for MENA (subsection 2.2.2). In section 3, results and discussion are presented, in which we discuss climate
trends and the leading modes of variabilities along with their climatic impacts over MENA. In the last section, summary and conclusions of the study are presented.

2. Model, Data and Methodology

2.1. Model Description, Experimental setup and Data

For the study of temperature and precipitation trend in data and the impact of leading teleconnection modes in the MENA region, we employ the Geophysical Fluid Dynamics Laboratory (GFDL)’s global high-resolution atmospheric model, HiRAM. It is based on version 2 of the GFDL Atmospheric Model (AM2; Anderson et al., 2004), with improved horizontal and vertical resolutions. It has 32 vertical layers instead of 24 that reach up to 10 hPa, to better simulate the processes in the lower stratosphere and coupling with the troposphere. It has simplified parameterizations for moist convection and large-scale stratiform cloudiness. The relaxed Arakawa-Schubert convective closure scheme used in AM2 has been replaced by a shallow convective parameterization scheme (Moorthi and Suarez, 1992; Bretherton et al., 2004). HiRAM model uses a comparatively new cubed-sphere finite-volume dynamic core (Putman and Lin, 2007), and a prognostic cloud scheme with a sub-grid scale distribution of total water and multi-species tropospheric aerosol climatology that is based on the Model for OZone and Related chemical Tracers (MOZART) (Horowitz et al., 2003). HiRAM retains the surface flux, land surface, boundary layer, radiative transfer modules, gravity wave drag, and large-scale cloud microphysics of AM2 (Anderson et al., 2004; Zhao et al., 2009). The land model, LM3 used by HiRAM, includes soil sensible and latent heat storage, groundwater storage, and stomata resistance (Malyshev et al., 2015).

The shortwave (SW) radiation algorithm of HiRAM model follows Freidenreich and Ramaswamy (1999). The SW spectrum ranges from 0.17 to 4.0 µm and is divided into 25 bands: 10 bands in the near IR region, 4 bands in the visible region and 11 bands in the UV region. The SW radiation code includes absorption by H₂O, CO₂, O₃, O₂ and Rayleigh scattering. The longwave (LW) radiation code follows a modified form of the simplified exchange approximation (Schwarzkopf and Ramaswamy, 1999). It accounts for the absorption and emission by the principal gases present in the atmosphere, including H₂O, CO₂, N₂O, O₃ and CH₄, and the halocarbons, CFC-11, CFC-12, CFC-113 and HCFC-22. Aerosols and clouds are treated as absorbers in the longwave radiation code, with non-grey absorption coefficients specified in the eight spectral bands of the transfer scheme, following the methodology explained in Ramachandran et al. (2000). A detailed documentation of the HIRAM model and a list of recent publications can be found at http://www.gfdl.noaa.gov/hiram.

We conducted three HiRAM simulations at C360 grid resolution (approximately 25 km), typically a range that most regional climate models use in climate downscaling studies. This allows us to study regional climate changes using a global climate model that fully accounts for regional and global scale interactions, which are especially important in the tropics. A brief description of the methodology and
experimental setup is as follows.

We forced HiRAM model simulations with the observed monthly SST taken from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST1) data set (Rayner et al., 2003). The sea-ice part of the model assumes that each grid point is either ice-free or fully ice-covered, and also assumes a uniform ice thickness of 2 meters. The anthropogenic greenhouse gases (GHGs), ozone, natural forcings, tropospheric aerosol concentration and land use changes employed in the model follow the Atmospheric Model Inter-comparison Project (AMIP) simulation style, which is described in detail at http://cmip-pcmdi.llnl.gov/cmip5/forcing.html. The stratospheric volcanic aerosol spatial-time distribution and optical characteristics of volcanic eruptions falling in the simulation period of 1976-2008 (i.e. El Chichon and Pinatubo) are calculated following Stenchikov et al. (2006) based on (Sato et al., 1993). The indirect effect of aerosol particles through microphysical interaction with clouds and associated changes in cloud properties is not considered. Three different realizations were produced, each for a 33-year (1976-2008) simulation period, and each beginning with different atmospheric initial conditions, taken from the GFDL long AMIP run at January 1 of years 1976, 1977, and 1978. In all three realizations, the first three years of the integration are not used in the analysis, in order to avoid spin-up effects. To reduce the effect of internal natural variability in the model results, ensemble average over three HiRAM realizations is used in the analysis.

For validation of climate trends and the impact of leading circulation modes in the MENA region during the period 1979-2008, we used University of Delaware (UDEL) monthly global gridded temperature and precipitation data (0.5º x 0.5º horizontal grid resolution). The details of UDEL data set can be found at the University of Delaware website: http://climate.geog.udel.edu/~climate/. A two-tailed student t-test is applied to find the statistical significance of trends and regression coefficients at a 95% confidence level, both in the model and the observations (see e.g. Santer et al., 2000 for details).

2.2. Methodology

2.2.1 Multiple Linear Regression Analysis

In this study, we conduct multiple linear regression (MLR) analysis on surface air temperature and precipitation fields using simulated and observed anomalies for 30 years period (1979-2008) and compare the modeled and observed responses of trends and regression coefficients of ENSO, NAO and ISM over MENA region. We also conduct multiple regressions using a 109-year observation period (1900-2008). In the winter season, we perform the MLR analysis by employing a climate trend index (which references the calendar year of the studied season), the ENSO index (DJF sea surface temperature anomaly in the Niño 3.4 region) and the NAO index (Hurrell, 1995; Hurrell and Deser, 2010); whereas in the summer season we consider the climate trend index, the ENSO index, and the Indian summer monsoon rainfall index (total summer season rainfall computed over the
entire Indian region), introduced in Parthasarathy et al. (1994) and Parthasarathy (1995). We analyzed climate trend (linear for the 30-year interval and polynomial for the 109-year interval), ENSO and NAO in winter season. However, for summer, we considered climate trend, ENSO and ISM. The selection of input predictors for winter and summer season is discussed in detail in section 2.2.2. The multiple regression methodology employed in this study is explained as follows.

The MLR technique is an extension of the simple linear regression technique that is used when more than one independent factor (also termed as a predictor, regressor, input variable or controlled variable) affects a dependent variable (also referred as predictand, regressand, criterion variable, response variable, outcome or measured variable). Multiple linear regression analysis helps to detect change in dependent variable following the change in independent variables. As predictand or dependent variables we choose $T_W^i(\lambda, \phi)$ - winter temperature anomaly, $P_W^i(\lambda, \phi)$ - winter precipitation anomaly, $T_S^i(\lambda, \phi)$ - summer temperature anomaly and $P_S^i(\lambda, \phi)$ - summer precipitation anomaly, which are functions of longitude $\lambda$, latitude $\phi$ and the time index $i$, which reflects the year of a season and spans all years in the dataset. We choose the following indices as input predictors in the multiple regression analysis (see section 2.2.2 for details regarding selection of relevant predictor variables for MENA region):

Trend index $\alpha_{TR}^i$ - the standardized year of the season,

ENSO index $\alpha_{ENSO}^i$ - the standardized DJF NINO3.4 based ENSO index,

NAO index $\alpha_{NAO}^i$ - the standardized DJF NAO index of Hurrell (1995) and

ISM index $\alpha_{ISM}^i$ - the standardized JJA Indian summer monsoon (ISM) rainfall index, which depend only on the time index $i$. Since all the predictors are standardized, the regression relations take the following forms for winter season:

$$T_W^i(\lambda, \phi) = \alpha_{TR}^i \times T_{TR}^W(\lambda, \phi) + \alpha_{ENSO}^i \times T_{ENSO}^W(\lambda, \phi) + \alpha_{NAO}^i \times T_{NAO}^W(\lambda, \phi) \quad (1)$$

$$P_W^i(\lambda, \phi) = \alpha_{TR}^i \times P_{TR}^W(\lambda, \phi) + \alpha_{ENSO}^i \times P_{ENSO}^W(\lambda, \phi) + \alpha_{NAO}^i \times P_{NAO}^W(\lambda, \phi) \quad (2)$$

and for summer season:

$$T_S^i(\lambda, \phi) = \alpha_{TR}^i \times T_{TR}^S(\lambda, \phi) + \alpha_{ENSO}^i \times T_{ENSO}^S(\lambda, \phi) + \alpha_{ISMO}^i \times T_{ISMO}^S(\lambda, \phi) \quad (3)$$

$$P_S^i(\lambda, \phi) = \alpha_{TR}^i \times P_{TR}^S(\lambda, \phi) + \alpha_{ENSO}^i \times P_{ENSO}^S(\lambda, \phi) + \alpha_{ISMO}^i \times P_{ISMO}^S(\lambda, \phi) \quad (4)$$

where $T_{TR}^{WS}$, $P_{TR}^{WS}$, $T_{ENSO}^{WS}$, $P_{ENSO}^{WS}$, $T_{NAO}^{WS}$, $P_{NAO}^{WS}$, $T_{ISMO}^{WS}$, $P_{ISMO}^{WS}$ are the regression coefficients that for each $(\lambda, \phi)$ can be obtained from the following systems of linear equations for winter season:

$$\text{Cov}(\alpha_{TR}^i, T_W^i) = T_T^W + \text{cov}(\alpha_{TR}^i, \alpha_{ENSO}^i) \times T_{ENSO}^W + \text{cov}(\alpha_{TR}^i, \alpha_{NAO}^i) \times T_{NAO}^W$$

$$\text{Cov}(\alpha_{ENSO}^i, T_W^i) = \text{cov}(\alpha_{TR}^i, \alpha_{ENSO}^i) \times T_{TR}^W + \text{cov}(\alpha_{ENSO}^i, \alpha_{NAO}^i) \times T_{NAO}^W$$

$$\text{Cov}(\alpha_{NAO}^i, T_W^i) = \text{cov}(\alpha_{TR}^i, \alpha_{NAO}^i) \times T_{TR}^W + \text{cov}(\alpha_{NAO}^i, \alpha_{ENSO}^i) \times T_{ENSO}^W + T_{NAO}^W$$

$$\text{Cov}(\alpha_{TR}^i, P_W^i) = P_{TR}^W + \text{cov}(\alpha_{TR}^i, \alpha_{ENSO}^i) \times P_{ENSO}^W + \text{cov}(\alpha_{TR}^i, \alpha_{NAO}^i) \times P_{NAO}^W$$
\[
\text{Cov}(\alpha_{ENSO}^i, P_t^i) = \text{cov}(\alpha_{TR}^i, \alpha_{ENSO}^i) \times P_{TR}^w + P_{ENSO}^w + \text{cov}(\alpha_{NAO}^i, \alpha_{NAO}^i) \times P_{NAO}^w \\
\text{Cov}(\alpha_{ENSO}^i, P_t^i) = \text{cov}(\alpha_{TR}^i, \alpha_{ENSO}^i) \times P_{TR}^w + \text{cov}(\alpha_{NAO}^i, \alpha_{ENSO}^i) \times P_{ENSO}^w + P_{NAO}^w
\]

and for summer season we have:
\[
\text{Cov}(\alpha_{TR}^i, T_R^i) = T_{TR}^w + \text{cov}(\alpha_{TR}^i, \alpha_{ENSO}^i) \times T_{ENSO}^w + \text{cov}(\alpha_{TR}^i, \alpha_{ISM}^i) \times T_{ISM}^w \\
\text{Cov}(\alpha_{ENSO}^i, T_R^i) = \text{cov}(\alpha_{TR}^i, \alpha_{ENSO}^i) \times T_{TR}^w + T_{ENSO}^w + \text{cov}(\alpha_{ENSO}^i, \alpha_{ISM}^i) \times T_{ISM}^w \\
\text{Cov}(\alpha_{NAO}^i, T_R^i) = \text{cov}(\alpha_{TR}^i, \alpha_{NAO}^i) \times T_{TR}^w + \text{cov}(\alpha_{NAO}^i, \alpha_{ENSO}^i) \times T_{ENSO}^w + T_{ISM}^w \\
\text{Cov}(\alpha_{TR}^i, P_s^i) = P_{TR}^w + \text{cov}(\alpha_{TR}^i, \alpha_{ENSO}^i) \times P_{ENSO}^w + \text{cov}(\alpha_{TR}^i, \alpha_{ISM}^i) \times P_{ISM}^w \\
\text{Cov}(\alpha_{ENSO}^i, P_s^i) = \text{cov}(\alpha_{TR}^i, \alpha_{ENSO}^i) \times P_{TR}^w + P_{ENSO}^w + \text{cov}(\alpha_{ENSO}^i, \alpha_{ISM}^i) \times P_{ISM}^w \\
\text{Cov}(\alpha_{NAO}^i, P_s^i) = \text{cov}(\alpha_{TR}^i, \alpha_{NAO}^i) \times P_{TR}^w + \text{cov}(\alpha_{NAO}^i, \alpha_{ENSO}^i) \times P_{ENSO}^w + P_{ISM}^w
\]

Where Cov is the covariance operator. For further details see (Gujarati, 2009).

### 2.2.2. Selection of Leading Predictors used in MLR for MENA Region

It has been discussed in several studies that the North Atlantic Oscillation (NAO) is one of the primary modes of atmospheric variability in the North Atlantic sector that largely impacts the climate of Europe and MENA (Hurrell, 1995; Yu and Zhou, 2004; Abualnaja et al., 2015; Athar, 2015; Barlow et al., 2016). ENSO and Indian Summer Monsoon (or simply Indian Monsoon) have also been reported as important modes of variability that impact MENA climate (Wanner et al., 2001; Abualnaja et al., 2015; Athar, 2015; Athar and Ammar, 2016; Chakraborty et al., 2006). Wanner et al. (2001) and Athar (2015) have shown that both the NAO and ENSO are the prominent modes of variabilities that are essential to be considered while discussing Northern Hemisphere winter climate, especially, the climate of Arabian Peninsula region. There are other modes of variabilities with origin in the Atlantic sector such as East Atlantic (EA) and East Atlantic West Russia (EA/WR) patterns that presumably impact climate of Europe and the Middle East, however, Krichak et al. (2002) have discussed that the impact of EA/WR over Middle East is much less compared to NAO and ENSO impact. They further showed that the precipitation anomalies induced by EA/WR pattern over these regions are not significant. In recent studies, it has been discussed that the EA/WR’s pattern impacts Eastern North America and Eurasia including the Ural Mountains, Northeastern Africa and the Middle East region. However, these studies suggest that this variability pattern is modulated by NAO oscillation, as both are closely associated (Lim, 2015). Wanner et al. (2001) further suggest that the variability in the North Atlantic sector and associated global and regional impacts are largely explained by NAO pattern (which is closely related to Arctic Oscillation; AO) in the North Atlantic Ocean. We also tested the impact of the Indian Ocean Dipole (IOD) on the MENA region and found it small. However, the theory of the IOD itself as an independent mode of variability is still controversial and the ENSO-SST teleconnection pattern in the Indian Ocean resembles that of the IOD; therefore, the IOD’s independence may not be easy to demonstrate (Kucharski et al., 2010). The
Atlantic Multi-Decadal Oscillation (AMO) and Pacific Decadal Oscillation also seem important control on much longer time scales than those considered here. Some studies have focused on the impact of North Sea Caspian teleconnection Pattern (NCP; Kutiel and Benaroch, 2002) over east Mediterranean with focus over Turkey (Kutiel et al., 2002) and over Iran region (Ghasemi and Khalili, 2002). However, Kutiel et al. (2002) specified that its impact on precipitation is less pronounced compared to its impact on temperature as the former is influenced by local orography and associated climatic perturbations. The NCP impact in summer season is negligible compared to winter season (Kutiel et al., 2002). Moreover, the regional sensitivity and modulation of this regional scale NCP mode by large-scale ENSO and NAO circulation modes is not well established hitherto. Hence, to avoid multicolinearity issue in multiple regression analysis, we didn’t include NCP index in the present study.

Based on the above discussion, we anticipate that considering NAO and ENSO as leading patterns would be enough to account for most of the variability over MENA region in the winter season. Similarly ENSO and Indian summer monsoon (ISM) appear to have significant contribution in summer season over MENA (Almazroui et al., 2013; Athar, 2015; Abualnaja et al., 2015; Athar and Ammar, 2016). The ISM plays a significant role in strengthening of the coastal precipitation both in West Africa and over the Horn of Africa to the east by affecting the ITCZ (i.e. the upward branch of Hadley circulation) and the Somali jet. In the subsequent section we will analyze the NAO, ENSO and ISM regression coefficients and their climatic relevance for MENA domain.

3. Results and Discussion

3.1. Temperature and Precipitation Linear Trends

Figure 1 and Figure 2 show winter and summer decadal trend respectively of MENA temperature/precipitation (top/bottom) fields, which are calculated using MLR analysis using the period 1979-2008. The trend in simulated and observed data set shows a strong spatial and seasonal variability with an overall increase of both the temperature and precipitation, although important disagreements between the UDEL observations and model output are found. The spatial distribution of the winter decadal temperature trend over the entire MENA region (Figure 1) shows that the temperature has an overall growing trend that reaches to 0.5 K/decade both in the UDEL observation and HIRAM output. There exists some spatial inconsistency between observation and model results such that the UDEL observations show maximum warming over central Africa, especially over Sudan, Niger and Mauritania, whereas, the model shows a maximum warming trend over the northeastern part of the selected domain, especially, over Iran, Afghanistan and Turkmenistan. Moreover, observations show a decreasing trend that reaches up to -0.5 K decade^-1 over Turkey, Syria and Iraq whereas, the model does not capture this pattern; instead it displays an increasing trend distribution over these areas. The decadal trend in winter precipitation shows a mixed pattern with an
overall increasing trend over the tropical regions and a decreasing pattern over parts of Southern Europe, Arabian Peninsula and Iran both in the model and observations. The trend distribution of precipitation in winter is largely in agreement (both quantitatively and qualitatively) between the model and UDEL observations, except over Sudan and the Iberian Peninsula where they show a different spatial structure. The possible difference of the spatial structure and magnitude of the trend between the model and observation could be accounted for by the internal natural climate variability signal, as it needs not to be the same between the model and observation. Large discrepancies in observations and model trends (Figure 1) over the Taurus and Zagros Mountains in temperature, as well as the precipitation, could be partly attributed to the orographic effect that is not well simulated by the HiRAM model (El-Samra et al., 2018). However, further analysis is warranted to quantify the magnitude of the variation caused by the orographic effect and the internal climate variability signal. Alike its winter counterpart, the long-term trend of temperature in summer is also rising over the entire MENA region except in the tropical areas, where, we observe a decreasing tendency both in the model and the observations (Figure 2). That could be counted for by the increased water vapor and cloud distributions caused by the increased land-sea thermal gradient in summer season, which attenuates downward solar radiations resulting in surface cooling. Moreover, the decadal trend of temperature in summer over the northern half of the selected domain is larger which peaks at 1 K decade$^{-1}$ compared to the southern part of the domain that peaks at 0.5 K decade$^{-1}$, predominantly in the observations. The summer precipitation shows an overall increasing trend, especially over the tropical belt. Moreover, the precipitation shows a dipole structure, with a rising trend (which peaks at 0.5 mm/day/decade both in the model and observations) over the northern areas of the tropics and a decreasing trend southward of 10°N, especially in the UDEL observations. The trend pattern of temperature and precipitation in summer season is relatively more consistent between the model and observation compared to the winter counterpart, suggesting that model performs reasonably well in summer. The long-term trend in data could be associated with the internal noise and large-scale circulation changes such as NAO. It has been noticed in previous studies that the HiRAM model, like other up-to-date climate models underestimates the response of NAO in winter (Dogar et al., 2017b; Driscoll et al., 2011). The presented trend maps both for winter and summer seasons, show that the climate trends could add uncertainty in the forcings-induced climate signals, and therefore need to be filtered out while examining temperature and precipitation changes caused by internal and external climate forcing factors such as volcanism, NAO and ENSO. The presented long-term decadal trend results are consistent with earlier studies (e.g., Athar, 2014; Krishna, 2014), which also show an overall increasing temperature trend. We further find that the values of the decadal trend of temperature, especially in the northern part of the selected domain are relatively larger in summer than in winter. Moreover, the decadal trend of temperatures in both the seasons has statistically significant and relatively larger trend values, which are spatially more widespread compared to the precipitation decadal trend values.
Figure 1: The spatial distributions of the trends (per decade) of winter (DJF) temperature over the period of 1979-2008 using (a) UDEL, (b) HIRAM output and trend in Precipitation using (c) UDEL and (d) HIRAM output. Hatching indicates statistically significant decadal trends at 95% confidence level.
3.2. Temperature and Precipitation Polynomial Trends

To see the robustness of temperature and precipitation trends and to further understand the long term climatic changes over MENA region, we extended the trend analysis over a longer period 1900-2008 and computed trends in the temperature and precipitation fields using UDEL observed data set. For this purpose we computed polynomial trends, as the trends over longer period are not linear. Figure 3 shows polynomial trend curve computed by averaging over the entire MENA region for both the seasons. The polynomial trend over the longer period reveals that the MENA temperature has an overall increasing trend whereas precipitation has a decreasing trend. However, the long-term temporal evolution of temperature trend both in the winter and summer season shows an increasing trend curve for initial few decades and then it decreases for the period of 1920-1970. The decrease in temperature trend is more obvious in summer season than in winter. After year 1970 the temperature trend increases again. The polynomial trend of precipitation over MENA region has a downtrend for the entire period of analysis in both the seasons such that the decrease is slow in the initial decades.
and then it becomes relatively more pronounced especially after the year 1920. This analysis of trend using polynomial approach suggests that one has to consider removing polynomial trend from the data while considering analysis over longer period of time, which is 1900-2008 in our case. The temperature and precipitation anomaly for both the seasons before (red curve) and after (green curve) removing polynomial trend is also shown in Figure 3, indicating that the trends adds significant part in the anomaly signal and therefore need to be filtered out while considering climatic impact assessment for the MENA region.

**Figure 3:** The polynomial trend curve for temperature/precipitation (top/bottom) fields in winter/summer (left/right) computed over MENA region over a longer period of 1900-2008. The anomalies of temperature and precipitation before (red curve) and after removing polynomial trend (green curve) are also shown.

### 3.3. NAO, ENSO and ISM Regression Coefficients

Using multiple linear regression analysis (see section 2 for details), we computed regression coefficients of ENSO, NAO and Indian summer monsoon, which explain their long-term seasonal summer and winter climatic impact on MENA temperature and precipitation fields. The regression coefficient maps are helpful to summarize our understanding of consistent NAO, ENSO and Indian summer monsoon effects on MENA climate.
monsoon relations with MENA surface temperature and precipitation fields. As discussed above, the selection of the predictors used in multiple regression analysis are based on their strong correlation with MENA climate as well as their significant climatic impact discussed in the previous literature (see section 2.2.2 for details regarding the selection of independent input variables for MENA region in the winter and summer seasons). These regression coefficients represent the mean change in the dependent variable (temperature or precipitation) for one unit change in the corresponding predictor variable while holding the other predictors to be constant. In the following sections we will discuss each factor in detail.

3.3.1. NAO

The NAO plays a significant role to characterize the atmosphere of Europe and Middle East region (Hurrell, 1995; Wallace and Gutzler 1981; van Loon and Rogers, 1978; Cullen et al., 2002; Iqbal et al., 2013). Figure 4 displays NAO correlation coefficient with surface air temperature of Eurasia and MENA in winter and summer seasons computed using UDEL observation and HiRAM model over a period of 1979-2008. Both the model and observation depicts highly significant positive correlation in winter over northern part of Eurasia suggesting that the positive NAO phase significantly warms the northern part of Europe and Asia. Similarly we observed that NAO is negatively correlated with winter temperature of Southern Europe and MENA and its cooling impact further extends to South and East Asia. Spatial structure of NAO correlation with winter temperature of Europe and MENA region shows a dipole nature with positive correlation over Northern Europe and Siberia and negative correlation over mid latitude MENA domain. This suggests that the positive phase of NAO brings cooler and drier air into the Southern Europe and Middle East region, whereas negative phase brings warm and wet conditions over this region. The spatial patterns of temperature and precipitation fields clearly reveal that positive NAO will induce a cooling and drying pattern in winter. These results are consistent with earlier studies (Yu and Zhou, 2004, Dogar et al., 2017b), which also show strong cooling and drying over MENA following positive NAO phase. Temperature response to NAO circulation in winter is anticipated to be larger and more pronounced than in summer season because NAO correlation in winter with MENA temperature is much higher (Figure 4) than corresponding correlation in summer (Bladé et al., 2012, Hurrell et al., 2003; Iles and Hegral, 2017). The absolute magnitude of NAO correlation coefficient in winter peaks at 0.6 and 0.8 respectively in the model and observations (Figure 4). These values are statistically significant at 95% confidence level, suggesting that the NAO circulation plays a significant role to characterize climatic changes over MENA region in winter. HiRAM simulation slightly underestimates the magnitude of NAO correlation coefficient in winter season although overall spatial distribution is well captured by the model.
To further understand how the change in NAO influences the MENA region we looked at the NAO regression coefficient with MENA surface air temperature and precipitation. Figure 5 shows the map of regression coefficient of NAO respectively in winter season computed using multiple regression analysis, which explains the fractions of the variance of temperature and precipitation caused by NAO over MENA region. A detailed methodology dealing with the selection of these input explanatory variables, along with their importance for MENA region has been discussed in section 2.2.2.

The positive phase of NAO causes strong cooling (that peaks at 0.6 in UDEL and 0.4 in the model response) in winter especially over the Arabian Peninsula region (Figure 5), which is consistent with earlier studies that used simple linear regression (see e.g. Yu and Zhou, 2004; Iles and Hegral, 2017). Moreover, the positive NAO phase results in weakening of rainfall over the entire MENA region, mainly over Southern Europe extending to Iraq and Iran. The NAO induced patterns are largely consistent between the model and observation. The patterns of NAO regression coefficients, both for UDEL observation and HIRAM output represent statistically significant response over the entire MENA region. Moreover, it is observed that the NAO based temperature and precipitation changes in summer season over the MENA are weaker. These results are consistent with earlier studies (Bladé et al., 2012, Hurrell et al., 2003; Iles and Hegral, 2017). It is expected because the NAO correlation with MENA temperature in summer season is weaker (Figure 4, lower panel).

3.3.2. ENSO

The ENSO atmospheric teleconnections is considered as the leading mode of variability that causes profound effect on global and regional climate and weather events (Neelin et al. 1998; Trenberth et al., 1998; Timmermann et al. 1999; Trenberth and Caron, 2000; Kumar et al., 2016). It has been shown that the climate of Middle East in particular the Arabian Peninsula region is strongly impacted by ENSO (Barlow et al., 2016; Athar and Ammar, 2016; Dogar et al., 2017a; Dogar et al., 2017b; Sandeep et al., 2018; Abid et al., 2018). In this section we emphasized that both the El Niño and La Nina are important modes of variability that should be taken into account while discussing leading climate forcing factors and their climatic impacts in the Middle East and North Africa region. By modulating the near-equatorial zonal atmospheric overturning circulation i.e. the Walker circulation, ENSO atmospheric teleconnections induce changes in cloud cover and evaporation in remote ocean basins such as the Arabian Sea, Indian Ocean, and the tropical North Atlantic Ocean that in turn affects the land regions of Middle East and Asia (Klein et al., 1999; Wang, 2002; Barlow et al., 2016). For example, during a developing period of El Niño, the Walker circulation moves to the east, resulting in anomalous atmospheric subsidence over the Indian Ocean region and consequent suppression of convection there. This ENSO induced changes leads to warming in the Indian Ocean through intensified solar radiation as well as a weakening land-sea contrast in summer, resulting in
less Indian summer monsoon rainfall. Moreover, ENSO (El Niño/La Niña) are reported to produce increased/decreased precipitation activity over tropical MENA region by inducing thermal changes in the Indian and Atlantic Ocean in winter season and the reverse is observed for summer season. To see long-term ENSO effects over the MENA region we have analyzed their regression coefficients using multiple regression analysis.

Figure 6 show the map of regression coefficients of ENSO respectively in winter season computed using multiple regression analysis, which explains the fractions of the variance of temperature and precipitation caused by ENSO over MENA region. A detailed methodology dealing with the selection of these input explanatory variables, along with their importance for MENA region has been discussed in section 2.2.2.

The warming phase of ENSO i.e. El Niño results in cooling over Arabian Peninsula and warming over Northwestern as well as tropical parts of Africa (Figure 6). Moreover, the El Niño phase shows increased precipitation over the horn of Africa as well as over North Eastern part, in particular over Iraq and Iran domain. The model shows slightly weaker regression coefficient values than the observations and the spatial patterns are also somewhat shifted in the model compared to observation. The ENSO (El Niño/La Niña) regression coefficients show that the temperature change (cooling/warming) caused by ENSO reaches a maximum value of 0.6/0.2 in the observation and 0.1/0.2 in the model. However, these cooling/warming impacts are statistically significant especially in the observations, suggesting that ENSO produces substantial climatic signal over MENA region in the winter season.

The MENA region is also strongly influenced by ENSO in summer season as explained by the ENSO regression coefficients for temperature and precipitation (Figure 7). The ENSO (El Niño/La Niña) results in significant (at 95% confidence level) warming/cooling and decreased/increased precipitation over the tropical rain belt regions of MENA in summer both in the model and observations. The ENSO induced warming/cooling and drying/wetting over MENA ranges between 0.1 to 0.5 K for temperature and 0.1 to 0.6 mm/day for precipitation over the period of 1979-2008. From the spatial pattern of temperature and precipitation, we observed that the temperature and pressure based indices i.e. ENSO and NAO respectively have a higher value of statistically significant regression coefficients and are spatially more widespread as compared to the precipitation-based indices, i.e. ISM (section 3.3.3).

3.3.3. Indian summer monsoon

Several studies have emphasized that the global monsoon systems, especially the Indian and African monsoons are strongly affected by the internal and external climate forcing factors (Oman et al., 2006; Trenberth and Dai, 2007; Anchukaitis et al., 2010; Joseph and Zeng, 2011; Liu et al., 2016). It has also been observed that the temperature and rainfall distribution of the MENA tropical
region in summer is largely characterized by the strength of its monsoon system (Rodwell and Hoskins, 1996; Sultan and Janicot, 2000). External forcings such as explosive eruptions induce weakening to the monsoon system (Oman et al., 2006; Liu et al., 2016) and affect the position of ITCZ (Haywood et al., 2013). Earlier studies have shown that Indian and African monsoon systems are tightly linked to the rising branch of local Hadley Cell, also known as ITCZ (Joseph and Zeng, 2011; Wegman et al., 2014). Hence, the Indian and African monsoons are affected by climate forcings-induced seasonal changes in the ITCZ (Wegman et al., 2014). In summer season, ITCZ moves northward as a result of climate forcings-induced thermal gradient between land and ocean. This inter-hemispheric gradient drives Hadley circulation. A decreased land-sea thermal gradient following external or internal forcings suppresses the northward migration of ITCZ that result into a decreased amount of clouds and associated decrease in rainfall over the tropical ITCZ region. Moreover the tropical climate of the Arabian Peninsula and East Africa region is largely affected by the intensity of the Somali jets that are driven by the strength of the Indian monsoon system. A stronger Indian monsoon system drags immense moisture (through Somali jet) towards inland region of East Africa (Uganda, South Sudan, Kenya, Somalia, Ethiopia, Djibouti and Eritrea) and southern parts of Arabian Peninsula including Yemen and Oman. This moist wind system (Somali jet) then, following geostrophic wind relation, enters to northern and central India because of strong low pressure system over Indian landmass during summer period. Whereas, a weakened Indian monsoon will have weakened Somali current that will result in less transport of moisture laden air to Central and Eastern Africa (Aiki et al., 2006) and to the north and central India that consequently affects Hadley rising branch.

A strong teleconnection effect of Indian monsoon on African monsoon system, especially the influence of Indian monsoon on East and West African monsoon onset, is shown in previous studies (Camberlin et al., 2010; Flaounas et al., 2012). Based on regression analysis, we also observed that Indian and African monsoon systems are well correlated and therefore a weakened Indian and African monsoon will produce warming and drying anomaly over tropical MENA region.

As discussed above, the MENA region is strongly influenced by the Indian monsoon in summer season as explained by the ISM regression coefficient for temperature and precipitation (Figure 8). An increased ISM results in decreased/increased (temperature/precipitation) over the tropical parts of the MENA region in summer. The absolute value of ISM regression coefficients for temperature/precipitation fields peaks at 0.4/0.6 and these values are statistically significant, especially over the tropical areas, suggesting that ISM produces significant climatic impact over MENA tropical regions in summer. Both the model and observations show significant warming over Iran, Afghanistan, and northwestern African domain, especially over Morocco that extends to southern Europe, suggesting that ISM produces wide-ranging climatic impacts. The spatial pattern of ISM regression coefficient, especially for temperature case is relatively less smooth in the observations, compared to the model, probably because the observational data face scarcity in
observational measurements for this region. However, model shows much smoother response (both for temperature and precipitation) presumably because model results are averaged over three ensemble members that possibly minimize the effect of internal noise. The conducted multiple regression analysis emphasizes that the Indian monsoon modulates the strength of African monsoon and therefore a decreased Indian monsoon will produce a decreased precipitation over tropical MENA region. Indian monsoon-induced precipitation distribution shows a dipole structure at northern hemisphere tropical region (decreased precipitation northward of 10°N and subsequent increase southward of 10°N), which could be attributed to the southward shift of ITCZ (Haywood et al., 2013; Liu et al., 2016). This pattern suggests that a significant portion of the total precipitation over MENA tropical region is controlled by the strength of Indian monsoon as it could cause weakening to the rising branch of NH local Hadley circulation i.e. the ITCZ. A detailed discussion on possible mechanisms and teleconnection between Asian monsoon system and precipitation changes over MENA (through monsoon-desert mechanism) can be seen in Rodwell and Hoskins (1996). Our results are largely consistent with earlier studies that deal with ENSO and Indian Monsoon changes over African region using modeling and observational approaches (Preethi et al., 2015).

From the spatial pattern of temperature and precipitation, we observed that the temperature and pressure based indices i.e. ENSO and NAO respectively have a higher value of statistically significant regression coefficients and are spatially more widespread compared to the precipitation-based indices, i.e. ISM.
Figure 4: Winter (DJF) NAO correlation coefficient with surface air temperature calculated using a) UDEL 30-year winter period, b) Model 30-year winter period, c) UDEL 30-year summer period, d) model 30-year summer period. Hatching shows the statistically significant areas with at least 95% confidence level.
Figure 5: Winter (DJF) NAO regression coefficient with surface air-temperature (K) calculated using a) UDEL 30-year period, b) Model 30-year period, and with precipitation (mm/day) calculated using c) UDEL 30-year period, d) model 30-year period. Hatching shows the statistically significant areas with at least 95% confidence level.
Figure 6: Winter (DJF) ENSO regression coefficient with surface air-temperature (K) calculated using a) UDEL 30-year period, b) Model 30-year period, and with precipitation (mm/day) calculated using c) UDEL 30-year period, d) model 30-year period. Hatching shows the statistically significant areas with at least 95% confidence level.
Figure 7: Summer (JJA) ENSO regression coefficient with surface air-temperature (K) calculated using a) UDEL 30-year period, b) Model 30-year period, and with precipitation (mm/day) calculated using c) UDEL 30-year period, d) model 30-year period. Hatching shows the statistically significant areas with at least 95% confidence level.
4. Summary and Conclusions

Both the climate trends and the regression coefficients of leading climate variability modes are important parameters that are widely used to study the global and regional climatic changes induced by internal and external climate forcings. This paper focuses on the importance of trend in data and leading climate variability modes that play significant role in shaping MENA climate in winter and summer seasons. As MENA region is very sensitive to the changes induced by the internal and external climate forcings, thereby, understanding the processes that govern MENA climatic variability is of high priority, especially in the context of global and regional climate change. In order to better understand the climatic impact of leading modes of variabilities (i.e. their spatial structure, temporal evolution, mechanism and climate variability) over MENA region we used multiple regression analysis and looked at the impact of leading variability modes over the MENA temperature and precipitation fields. Regression analysis is widely used to identify the spatial patterns of climate change that are associated to internal and forced climate variability. The selection of leading
predictors used in multiple regression analysis for MENA region is based on their importance highlighted in the literature as well as our own assessment based on their strong correlation with MENA temperature and precipitation fields. For the analysis of trend in data we computed linear and polynomial trends over the period 1979-2008 and 1900-2008 respectively. We used polynomial trend for the longer 109-year period (1900-2008), as the trends over longer period are not linear. For better comparison of associated climatic impact, the trend and other leading predictors are standardized. The conducted MLR analysis emphasize that the trend in data could add significant contribution (it may add uncertainty or noise in climate signal) in climate variability pattern of a region and therefore trend-induced contribution need to be filtered out while analyzing the impact of different leading factors. Our results further emphasize that NAO, ENSO and Indian summer monsoon are the leading variability modes that significantly impacts the climate of MENA. The positive phase of NAO cause cold and dry climatic changes over the MENA in winter. The impact of NAO in summer is much weaker than its winter counterpart. It is expected because the NAO correlation with MENA temperature in summer is weaker and less significant than its winter counterpart. ENSO (El Niño/La Niña) also induce cold/warm anomalies over the Arabian Peninsula in winter season. Moreover, ENSO (El Niño/La Niña) brings warm/dry climatic changes especially over the MENA tropical region in summer season through ENSO-induced thermal changes in the Indian and Atlantic Ocean that in turn affect MENA tropical land areas. Indian monsoon also plays significant role to characterize the climate of MENA and South Asia in summer season. A weaker Indian monsoon will cause weakening to Hadley circulation as well as weakening to the Somali current that in turn affect the cloud distribution and moisture entrainment towards inland regions of south Asia and MENA. The analysis of trends and regression coefficients is necessary to better understand the climate variability of MENA. Both the observational and simulated results highlight the need to better understand the long-term trend in data and to better account for the circulation responses, such as that of the NAO, ENSO and Indian summer monsoon to better understand the MENA regional climate variability. In this research, we used a high-resolution global climate model, at a very high resolution, typically used by regional climate models in climate downscaling studies, which is especially important to better simulate the regional impacts of global teleconnection patterns. The main findings and results of this study can be summarized as follows.

MENA shows a significant upward temperature trend that reaches to 0.5 K/decade and 1 K/decade during the winter and summer period respectively both in the observations and model response. The precipitation shows a mixed trend pattern in winter; however, in summer, a decreased precipitation especially over the tropical belt, reaching to 0.5 mm/day/decade is observed. The Polynomial trend produced by averaging over entire MENA domain, considered for the longer period (1900-2008), depicts downward temperature trend line during 1900-1920, constant during 1920-1970 and strong upward temperature trend during the period 1970-2008, both in winter and summer
seasons, suggesting that one has to consider polynomial trend while discussing climatic impacts of
trends and leading teleconnections over longer period.

Both the ENSO and NAO positive phase significantly cools the central parts of MENA over the
period 1979-2008, especially the Arabian Peninsula region. The positive phase of NAO produces
strong cooling in winter over the entire MENA that reaches to 0.6 K and 0.4 K in the observation and
model respectively. The model underestimates the winter cooling response (both for ENSO and
NAO), however, the overall pattern is well reproduced by the model. The impact of NAO in summer
is small, as the correlation of NAO in summer is much weaker than its winter counterpart. The warm
ENSO phase in summer produces strong tropical warming and drying. Our results further reveal that
the Indian monsoon also produces strong impact over the MENA region, by impacting the MENA
ITCZ and associated cloud distribution. A strengthening (weakening) of ISM results in strengthening
(weakening) and associated increased (decreased) cloud distribution over MENA tropical rain belt
region, resulting in increased (decreased) precipitation. A decreased ISM suggests a southward shift
of ITCZ. The possible difference of the spatial structure and magnitude of the trend between the
model and observation could be accounted for by the internal natural climate variability signal, as it
needs not to be the same between the model and observation. The disagreements in observations and
model results over the Taurus and Zagros Mountains in temperature and precipitation trends over
MENA in winter season are attributed to the orographic effect that is not well simulated by the
HiRAM model. The conducted analysis sheds light on the internal mechanisms of MENA climate
variability and helps to selectively diagnose the impact of leading teleconnection modes.

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