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Abstract

We apply a Lagrangian-based moisture back trajectory method on two reanalysis datasets to determine the moisture sources for wet season precipitation over the Arabian Peninsula, defined as land on the Asian Continent to the south of the Turkish border and west of Iran. For this purpose, we make use of evaporative source region between 65°W–120°E and 30°S–60°N which is divided into twelve sub-regions. Our results indicate a north to south spatiotemporal heterogeneity in the characteristics of dominant moisture sources. In the north, moisture for precipitation is mostly sourced from European land and major water bodies, such as Mediterranean and Caspian Seas. Areas further south dependent on moisture transport from the Western Indian Ocean and parts of the African continent. El Nino Southern Oscillation cycle (ENSO) oscillation exhibits an overall positive but sub-seasonally varying influence on the precipitation variability over the region with mostly positive moisture anomalies from all major source regions. A significant drying trend exists over parts of the Peninsula, which is partly attributed to anomalies in the moisture advection from the Congo Basin and South Atlantic Ocean. However, precipitation trends over the terrestrial part of evaporative source region vary across observations and reanalysis datasets, which warrants the need for additional modeling studies to further our understanding in the identification of key processes contributing to the negative trends.

1. Introduction

The Arabian Peninsula (AP) exhibits arid climate characteristics (Abdullah and Almazroui, 1998; Almazroui, 2011; Almazroui et al. 2012; Edgell, 2006) with limited freshwater resources, a fragile ecosystem, and fossil fuels driven economies. More than 75% of the annual precipitation over the region is received between November and April (Abdullah and Almazroui, 1998; Almazroui, 2012; Almazroui et al 2012), which is also known as the wet season. Recent decades have witnessed statistically significant warming and reduced precipitation trends across the AP (Almazroui et al., 2012), which are precursors of water cycle intensification. These changes in the regional climate characteristics are causing an increase in desertification that has the potential to effect biodiversity and socioeconomic stability in the region. While the anthropogenic footprint is the likely cause of recent trends in regional hydrological cycle, slow varying climate forcing, such as sea surface temperatures, are also known to have an influence in the precipitation variability over the region. More specifically, studies show that both wet and dry extremes over the AP can be related to sea surface temperatures variability in the central-eastern equatorial Pacific region (Kang et al..2015). Similarly, wetter (drier) than normal wet season is experienced over AP during the El Nino or positive (La Nina or negative) phase of the El Nino Southern Oscillation (ENSO) (Abid et al. 2016; Atif et al. 2020). Previous studies also indicate a moderate and statistically insignificant influence of the North Atlantic Oscillation where the region may experience a drier (wetter) than normal wet season over northern and western portions of the AP during the positive (negative) phase of the North Atlantic Oscillation (NAO;Atif et al. 2020; Donat et al. 2014; Ehsan et al, 2017; Saeed and Almazroui, 2019

Even though a general understanding of climate characteristics of the AP exists, there remains several gaps in our understanding of factors impacting wet season precipitation variability. For instance, it is relatively unknown which terrestrial and oceanic evaporative sources provide moisture to the region during the wet season. Few studies suggest that much of the rainfall over the northern AP can be attributed to extratropical cyclones from the Mediterranean (Almazroui et al. 2016), and that moisture flux from the Mediterranean over eastern Africa provides rainfall over the Ethiopian highlands (Viste and Sorteberg, 2013). However, an explicit identification of moisture sources for the wet season precipitation over the AP is yet to be established. Similarly, thermodynamic pathways through which natural modes of climate variability, such as ENSO, exert their influence on precipitation distribution over the AP have not been clearly understood. Likewise, no mechanistic understanding exists regarding the thermodynamic factors influencing prevailing precipitation trends over the region. Therefore, this study aims to improve our understanding of AP climate by addressing knowledge gaps in the above three aspects.

Three physical sources including moisture already present in the atmospheric column, moisture advected into the region, and moisture sourced through local evapotranspiration, facilitate precipitation over a region (Batibeniz et al. 2020; Brubaker et al. 1993; Burde and Zangvil 2001; Ciric et al. 2018; Dominguez et al. 2006; Dominguez and Kumar 2008; Drumond et al. 2011; Eltahir and Bras 1996; Gómez-Hernández et al. 2013; Schicker et al. 2010; Trenberth 1999). Most commonly, the moisture flow over or from a region is either studied by observing the spatiotemporal trajectories of moist air parcels, also known as Lagrangian approach, or by observing the moisture in-and outfluxes at fixed positions, also known as Eulerian approach. The Lagrangian-based moisture back trajectory analyses is the most used approach due to its

relatively better accuracy in determining moisture sources and sinks (Gimeno et al. 2012; Gimeno et al. 2020; Nieto et al. 2006; Sodemann et al. 2008).

As previously noted, in this study, we aim to investigate the thermodynamic drivers of spatiotemporal distribution of precipitation and its variability during the wet season over the AP. For this purpose, we employ a Lagrangian moisture tracking algorithm to identify major evaporative sources at climatological scale, variation of their moisture contribution at inter-annual and intra-seasonal timescales, and during positive and negative phases of ENSO and NAO. The details of data and moisture tracking analyses is provided in Section 2. Section 3 describes main results and discussion of these analysis. Section 4 summarizes key findings and proposes future research directions.

2. Data and Methods

2.1. Data

We use two reanalysis datasets, the Modern-Era Retrospective Analysis for Research and Application Version 2 (MERRA-2, Gelaro et al. 2017), available at $0.5^\circ \times 0.625^\circ$ horizontal grid spacing, and the European Reanalysis version 5 (ERA5; Herschbach et al. 2020), available at $0.25^\circ \times 0.25^\circ$ horizontal grid spacing. The use of multiple datasets is to ensure robust understanding of moisture sources over the study region. The ERA5 dataset is remapped to the MERRA-2 horizontal grid before its use. From these datasets, we obtained four variables: daily evapotranspiration, daily precipitation, six-hourly vertically integrated eastward moisture flux, and six-hourly vertically integrated northward moisture flux.

Given that reanalyzed and observed precipitation are often not in high correspondence at daily timescale, we make use of reanalyzed precipitation in our analyses for it to be consistent with the reanalyzed moisture fluxes and evapotranspiration used in the determination of moisture

pathways. While this methodological choice is necessary for accuracy in the calculation of moisture trajectories, it may lead to inaccuracies in the identification of moisture sources if spatial distribution of precipitation substantially varies between reanalyzed and observed. Therefore, precipitation from the two reanalysis is compared with several gridded observations to understand the degree of uncertainty associated with our methodological choice. The observations include data from the University of East Anglia Climatic Research Unit (CRU; Harris et al. 2013), NOAA's Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN; Sorooshian et al. 2014; Ashouri et al. 2015), the Global Precipitation Climatology Centre monthly precipitation dataset (GPCC; Schneider et al. 2016), and the Climate Hazards Group InfraRed Precipitation with Station dataset (CHIRPS; Funk et al. 2015). All observational datasets are also remapped to match the MERRA-2 grid spacing. Note that not all observations fully span our analyses period that covers 1980 to 2019, as PERSIANN (GPCC) is not available for 1980–1982 (2017–2019).

2.2. Moisture back-trajectory analyses

We make use of evaporative source region between 65°W–120°E along the longitudes and 30°S–60°N along the latitudes for moisture back trajectory analyses over the AP. The source region is divided into 12 sub-regions, as depicted in Figure 1. The sub-division broadly separates known oceanic basins and large water bodies to ensure relatively accurate attribution of precipitation over the study region to remote sources. Most subdivision of terrestrial regions are based on the homogeneity of precipitation seasonality within a sub-region during the November to April season, such as Central/Western Asia, Europe, Northern Africa, Eastern Africa. Regions such as East Asia are separated from the rest as little contribution is expected from there due to its downstream location. These sub-regions include the AP as target region (1; Asian Continent

west of Iran and South of Turkey), Northern Africa (2; African continent north of 20°N), Europe land (3; all European countries including portions of Turkey and Russia in Asia), North Atlantic Ocean (4; areas west of Europe/Africa North of 20°N), the Mediterranean and Caspian Seas (5; all water bodies between 5°W to 65°E and 29°N to 50°N), South Atlantic Ocean (6; Atlantic ocean west of African continent and south of 20°N), East Asian land (7; Asian land outside Russia and Turkey that is not in regions 1 or 10), Western Indian Ocean (8; Indian Ocean between 30°E to 80°E and south of 31°N), Eastern Indian Ocean (9, Indian Ocean east of 80°E), western and central Asia land (10; Asian continent between 40°E to 80°E and 25°N to 45°N not part of regions 1 or 3), western Africa land (11; African continent south of 20°N and west of 22.5°E), and eastern Africa land (12; African continent south of 20°N and east of 22.5°E). Note that the study region defined in our analyses as the AP includes northern parts of Iraq and Syria that are formally not considered a part of the Peninsula.

For this study, we employ a Lagrangian-based Dynamic Recycling Model (DRM), like that implemented over the Mediterranean by Batibeniz et al (2020), and over South Asia by Ashfaq et al. (2017) and Mei et al. (2015). This model was originally developed by Dominguez et al (2006), which was modified to not include the reliance on parameterization (Dominguez et al. 2006; Gimeno et al. 2012; Stohl 2005) and has been detailed in Mei et al (2015). Note that it assumes a well-mixed atmosphere and therefore makes use of vertically integrated moisture flux, which may be an issue over regions with strong vertical wind shear. However, this assumption should not be a concern in this study, as the atmosphere above the AP does not exhibit strong shear environment during the wet season. Also, note that the use of data assimilation in reanalysis may lead to a violation of moisture conservation assumption, however, Dominguez et al (2006) note that any correction for this assumption not being followed has little impact on the

results. We implement our analysis from 15 October through 30 April continuously. The first 15-days are discarded as those account for the residence time of moisture vapor in the atmosphere. Our analyses span over 39 seasons, starting with the wet season from 1 November 1980 to 30 April 1981 and ending with the wet season from 1 November 2018 to 30 April 2019.

2.3. ENSO and NAO influences

We investigate changes in precipitation variability caused by ENSO and NAO along with the changes in moisture sources associated with these teleconnections. ENSO is defined based on the standardized Nino 3.4 index, which is the area averaged detrended sea surface temperature anomaly over the equatorial Pacific Ocean (5°S to 5°N, 170°W to 120°W). NAO is defined as the standardized principal component of the first EOF of the detrended sea level pressure over the North Atlantic (20°N to 80°N, 90°W to 40°E). These standardized indices are regressed onto the anomalies of sourced moisture from individual and aggregated source regions over the AP, as well as with the anomalies of 850mb winds over the evaporative source region.

3. Results and Discussion

3.1. Reanalyzed versus observed precipitation

First, we address the question that how comparable precipitation distribution is between the reanalysis and the observations (Fig. 2). At the annual time-scale, relatively high magnitudes of precipitation exist along the Zagros Mountains in the north, and over Asir and Sarat mountains in the southwest. These precipitation hot spots are present in all datasets, however, their strength over the southwestern AP is relatively weak in CHIRPS. All maxima are relatively stronger in ERA5 while CRU and PERSIANN tend to be wetter over Yemen and Oman. The precipitation distribution over central Saudi Arabia is comparable across all datasets with CRU being the

driest among all. Overall, there are no distinct or systematic differences between reanalyzed and observed precipitation datasets. We further compare the percentage of annual precipitation that falls during the wet season across datasets (Fig. S1). The purpose of this comparison is twofold. First, we would like to ensure that there are no noticeable systematic differences in the intra-annual distribution of precipitation between the reanalyzed and observed datasets. Second, we want to highlight the fact that November to April season, used in this study, covers most of the annual precipitation that falls over the region. Both observational and reanalyzed datasets show that over 75%, and in most cases over 90% of the precipitation, is received during the wet season. The Red Sea Coast and Asir mountains receive considerable precipitation through warm season convection (Almazroui, 2011), which is reflected in relatively lower (30-60%) fractions during the wet season. There is discrepancy among the datasets pertaining to the wet season contribution over parts of Yemen and Oman. This location however is in the Empty Quarter where seasonal precipitation is very low and small differences can lead to higher fractional changes. Overall, these comparisons suggest that there are no distinguishable systematic differences in reanalyzed and observed precipitation distributions. Therefore, possibility of unreliable determination of moisture sources based on the use of reanalyzed precipitation in our analyses is quite remote.

3.2.Characteristics of major moisture sources

The fraction of moisture falling as precipitation in a specific grid cell that originated as evapotranspiration from the entire evaporative source region (Fig. 1), also known as recycling ratio, is shown in Figure 3a as an average of two datasets (ERA5 and MERRA2). At a grid point, the highest recycling ratio is obtained when all the precipitation is sourced back to its origin. In our case, recycling ratio varies between 90 to 96% (expressed in % of the total) over most of the AP, reflecting that the evaporative source domain used in this study is sufficiently large to

account for the origin of almost all precipitation falling over the AP during the wet season. The contribution from most prominent (all) source regions is shown in Figure 3 (Fig. S2) as an average of recycling ratio based on two reanalysis datasets, while Figures S3 and S4 show individual contributions from all regions separately for ERA5 and MERRA2, respectively. In the north, most of the moisture comes from the Mediterranean/Caspian Seas (up to 50%), North Atlantic, and Europe (up to 40%). The influence of these moisture sources progressively diminishes towards the central to southern AP. In the central parts of AP, moisture advection from the African continent and south Atlantic has sizeable contribution (up to 30% when aggregated), while moisture transport from the western Indian Ocean dominates the southern half of the AP (30 to 65%). It is important to note that the geographical footprint of moisture from the western Indian Ocean, which also includes Arabian and Red Seas, is the largest with maxima over the southwestern tip of Yemen (~65%) and minima over the Zagros Mountains along the border of Turkey in the north (~5%). Interestingly, local recycling of moisture does not have a major role in the precipitation distribution over the AP, as its maximum contribution remains less than ~10–15%. The relative contribution of individual evaporative sources is quite comparable between ERA5 and MERRA2, reflecting little sensitivity to the choice of reanalysis in the determination of moisture source regions. Due to this close correspondence between the two datasets, we present rest of the analyzed results based on their average.

There is considerable intra-seasonal variability in moisture contribution from individual source regions (Fig. 4). The contribution from Mediterranean/Caspian Seas is the highest until the start of March when it gradually starts diminishing. Note that the northern part of the AP, where Mediterranean/Caspian Seas have the most significant contribution, receives relatively less rainfall towards the end of the rainy season (Fig. S5). On the other hand, the moisture

contribution from the western Indian Ocean gradually strengthens and reaches its maxima towards the end of the rainy season, which is consistent with relatively large amounts of rainfall in March and April over the southern half of the AP (Fig. S5). The intra-seasonal variability in the contribution from eastern Africa is quite in sync with that from western Indian Ocean. Note that, over this period, monsoon gradually moves southward and back over eastern Africa (Ashfaq et al., 2021), which is substantially influenced by the Indian Ocean variability (Spinks and Lin, 2014). Some syncing is also noticed between moisture from Mediterranean/Caspian Seas and North Atlantic, which is understandable as same atmospheric dynamics influences the movements of storm tracks and moisture from Mediterranean and beyond (Batibeniz et al., 2020). However, it is interesting to note that moisture contribution from Europe gradually increases over the wet season and reaches its maxima at a time when moisture supply from North Atlantic, Mediterranean/Caspian Seas depletes.

3.3. Thermodynamic pathways of ENSO/NAO influence over the AP

ENSO exhibits positive association with precipitation variability over the AP, meaning that more rains are expected during the wet season when warm phase of ENSO is active and vice versa (Abid et al. 2016; Atif et al. 2020). While earlier studies suggest above normal moisture advection from the Indian Ocean during El Nino (Abid et al. 2020; Abid et al. 2018; De Vries et al. 2016), more specific understanding of anomalies in moisture from oceanic and terrestrial moisture source regions is yet to be determined. Our analyses suggests that ENSO enhances the moisture influx over the AP from almost every source region during the positive phase of ENSO (Figs. 5, S6). In particular, a statistically significant increase in moisture advection from the Indian Ocean and African continent occurs. Note that Walker circulation disruption during El Nino causes anomalous convection (subsidence) in the western (eastern) Indian Ocean (Abid et

al. 2020). As a results, an anomalous westward flow emerges over the Indian Ocean in the lower atmosphere, which is reflected in the regressed 850mb winds map (Fig. 5a). These conditions favor enhanced moisture advection from the Indian Ocean, and northern parts of eastern Africa. Moreover, wetter than normal conditions are well known over equatorial and eastern Africa during the warm phase of ENSO (Mbigi and Xiao, 2021) and more moisture is available to be transported to the AP. An excessive moisture transport is also witnessed from Europe and Mediterranean/Caspian Seas, however, most of these increases are not statistically significant. Local recycling also exhibits a significant increase over Iraq and Saudi Arabian region along the Arabian Gulf (Fig. S6).

Substantial intra-seasonal variability in moisture anomalies from individual source regions exists during ENSO (Figs. S8-S10). Overall, ENSO teleconnection becomes insignificant and reverses over Iraq and adjacent Saudi Arabia region in Jan–Feb creating a reversal in moisture anomalies from major source regions (Europe, North Atlantic and Mediterranean/Caspian Seas). The circulation anomalies in the lower atmosphere (850mb) exhibit an anomalous dry air entrainment from northern Africa during Jan–Feb in contrast to the rest of season where moisture advection from abovementioned source regions is favored (Figs. S8-S10). At individual level, the increase in contribution from eastern Africa and western Indian Ocean is statistically more robust during Nov–Feb while that from South Atlantic only becomes significant during Mar–Apr. Note that near the equatorial belt over east Africa ENSO teleconnections lead to onshore wind anomalies from Indian Ocean and winds over land changing direction in Mar–Apr, which limits the moisture advection from these regions to the AP (Figure S10).

As previously noted, NAO influence on the AP climate is not as robust as it is in the case of ENSO. A positive phase of NAO causes the westerlies over the Mediterranean and Northern Africa to weaken, decreasing the amount of moisture that advects from Europe and the North Atlantic into the target region. Spatially, the moisture change from the NAO teleconnection exhibits a dipolar pattern over the AP, with negative association in the northern two thirds and positive association in the southern one third. However, most of the negative influence over that region is statistically insignificant (Fig. 6a) due to a lack of robustness in moisture anomalies from the major source regions (Fig. 6b-6d). More specifically, the negative association in the northern two thirds is associated with reduced moisture advection from Europe and North Atlantic. While the moisture advection from Mediterranean/Caspian Seas also decreases significantly over parts of central Saudi Arabia, its reduction is insignificant over Syria whereas it shows a mixed response over Iraq. The positive association over the parts of southern AP is due to an enhanced moist advection from western African, Indian Ocean and eastern Africa, and more local recycling (Fig. S6). The effects of NAO teleconnection over the AP also exhibits intra-seasonal variability (Figs. S11-S13). For instance, the statistically significant negative NAO association over the central AP only exists during Nov–Dec where moisture supply from most of the prominent sources shows a decrease. Similarly, increase in moisture advection from Indian Ocean and parts of Africa over the southern AP is only significant in Mar–Apr.

3.4. Wet season precipitation trends

We use Mann-Kendall test for the calculation of trends in total precipitation and moisture contribution from individual evaporative sources and test their significance at 95% confidence level. Generally, the wet season precipitation over the AP exhibits negative trends (Fig. S14). However, substantial agreement does not exist across datasets (observations/reanalysis) in the

316 spatiotemporal distribution as well as the significance of these trends. Areas with most
317 agreement are Zagros Mountains in northern Iraq and Syria, Asir and Sarat mountains ranges in
318 southwestern Saudi Arabia and Yemen, and Najd in central Saudi Arabia, where precipitation
319 exhibits negative trends (Fig. S14). In reanalysis datasets, these trends are consistent and
320 significant over the southwestern and central parts of the AP, while agreement is low over
321 Zagros Mountains where negative (but insignificant) trends are only present in ERA5. Based on
322 the trends in moisture advection from individual source regions (Fig. 7), it is apparent that the
323 negative trends over the central and southwestern AP (Fig. S14) are mostly driven by reduced
324 moisture advection from western Africa, south Atlantic, western Indian Ocean, and eastern
325 Africa (ordered from most to least important). When trends are analyzed over the terrestrial parts
326 of the evaporative source region, both ERA5 and MERRA2 display significant strong negative
327 trends over the Congo basin and parts of central Africa (Fig. S15) – the region which is
328 partitioned as western Africa in our subdivision of moisture sources (Fig. 1). This region
329 experiences dry season between Nov to March (Ashfaq et al., 2021), which is why moisture
330 contribution from western Africa gradually increases during the wet season over the AP (Fig. 4;
331 mustard line). Studies have shown that dry season length has increased over this region in the
332 recent times (Froidurot and Diedhiou, 2017), which would limit moisture contribution from this
333 region to the AP. However, it is important to note that drying pattern seen in both reanalysis is
334 only replicated in CHIRPS and to some extent in PERSIANN, while CRU exhibits mostly
335 positive and GPCC exhibits strong positive trends. As previously noted, the moisture
336 contribution from the eastern African region also exhibits a decline over the southwestern AP,
337 which is present in both reanalyses (Figs. S16, S17). This reduction in moisture supply from
338 eastern African is most likely due to drying trend over the Ethiopian highlands, which is present

in both datasets. The negative trend over the Ethiopian highlands is also present in most of the gridded observations (Fig. S14). Despite the noticeable differences between the reanalysis and observations is the spatial distribution of precipitation trends over the evaporative source region, the dependence of AP precipitation on the terrestrial evaporative sources demonstrates that how precipitation trends over one source region can impact its distribution over a distant sink region and highlight the complexity and intricacy of thermodynamic drivers impacting the precipitation variability over a region.

4. Summary and Conclusions

An arid region like the AP primarily receives moisture through advection from other sources. Except for the northern parts of the AP where Mediterranean storms bring moisture from the Mediterranean Sea, North Atlantic and Europe over the region, the rest of the AP receives most of the moisture from the western Indian Ocean with some contribution from the African continent. The influence of the western Indian Ocean over the AP shows a gradient in the contribution from west-southwest to north (Figs 3, S2-S4). Precipitation distribution varies spatially during the wet season over the AP, which is driven by the presence of an intra-seasonal variability in moisture sources. Perhaps, it is this intra-seasonal variation in moisture advection from various sources that is the cause of lack of persistence in the ENSO and NAO teleconnections during the wet season, which may result into the limited precipitation prediction skill over the region (Abid et al. 2016; Ehsan et al. 2017). Therefore, it is worthwhile to revisit the precipitation predictability over the region by considering the models ability in representing the moisture sources and by identifying its relationship with seasonal prediction skill. Moisture source anomalies may also act as predictors for the regional precipitation on sub-seasonal to seasonal time scale during the wet season.

Lack of consistency among the datasets regarding long-term trends is an issue that requires some attention. There is more consistency between the two reanalysis datasets than that among the observations or between the observations and reanalysis. The accuracy of datasets is imperative for precise attribution of prevailing precipitation trends. If precipitation trends over the AP and the central/west Africa are indeed accurate in the two reanalysis, it implies that the processes at play in the variability of AP climate are complex. Note that Congo basin and adjacent areas are heavily influenced by moisture transport from the tropical South Atlantic (Sori et al., 2017), and both regions exhibit a negative trend in moisture contribution to the AP. Therefore, it is not unrealistic to assume that South Atlantic is one of the main players in the negative precipitation trends over the parts of southwestern and central AP through its direct and indirect (via Congo basin) influences on the AP climate. We also note that the collective maximum moisture contribution from these two regions (western Africa and South Atlantic) over any part of the AP is not more than 15–20% of the total, however, substantial reduction in moisture supply from these areas can still have a significant impact on the AP climate.

Overall, this study furthers our knowledge of the thermodynamic processes leading to wet season precipitation over the AP. More specifically, it provides new insights regarding the thermodynamic structure of climate over the AP, its intra-seasonal and interannual variability, and pathways taken by important modes of climate variability (ENSO, NAO) impacting this region. A significant fraction of moisture over the AP is transported from the terrestrial source regions (African and European continent), which suggests that climate variability in those regions has the potential to impact the precipitation distribution over the AP. Nonetheless, there are still several gaps in our understanding towards such interdependencies of terrestrial climates which warrant further studies in this area. The inconsistency in trends between multiple

observational datasets leaves some uncertainties in our conclusions, which should also spark further studies to test the validity of thermodynamic pathways, identified in our analyses, through numerical model experiments. Note that we only analyzed the direct pathways through which ENSO and NAO exert their influence on the AP precipitation variability. However, teleconnections of natural modes of variability, particularly ENSO, are often a result of multiple pathways such as those through inter-basin interactions (Abid et al., 2020). Therefore, further investigations are needed to fully unravel the physical mechanisms responsible for these teleconnections. Despite these caveats, this study has enhanced knowledge towards precipitation variability in the region and the thermodynamic processes leading to it.

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Statements and Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose

Author Contributions

M.A. supervised the research. M.F.H collected data and performed analyses. All authors were involved in discussions of the results. M.F.H prepared the manuscript with contributions from all co-authors.

Data Availability

ERA5 data are available online (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>)

MERRA2 data are available online (<https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>)

CRU data are available online

(<https://catalogue.ceda.ac.uk/uuid/edf8febfdaad48abb2cbaf7d7e846a86>)

GPCC data are available online (<https://psl.noaa.gov/data/gridded/data.gpcc.html>)

PERSIANN data are available online (<https://www.ncei.noaa.gov/products/climate-data-records/precipitation-persiann>)

CHIRPS data are available online (<https://www.chc.ucsb.edu/data/chirps>)

Figure Captions

Fig. 1 Evaporative source region and its sub-divisions. Region 1 represents the study area.

Fig. 2 Mean annual precipitation (mm) during 1980-2019 in a) CRU, b) PERSIANN, c) GPCC, d) CHIRPS gridded observations and e) MERRA2, f) ERA5 reanalysis. Note that PERSIANN data was unavailable for 2017 through 2019 and GPCC data was unavailable for 1980 through 1982.

Fig. 3 Average recycling ratio (expressed in % of the total) during the wet season (Nov-April). a) Sum of all regions, b) Western Indian Ocean, c) Mediterranean and Caspian Sea, d) East Africa, e) sum of North Atlantic and Europe, f) sum of North Africa and South Atlantic, g) sum of the other regions. Results are based on the average of recycling ratio from ERA5 and MERRA2.

Fig. 4 Climatological intra-seasonal variability in regional contributions, shown as 10-day running mean area averaged over the Arabian Peninsula. Only those regions have been shown that reach a seasonal maximum of more than 5%. Note that symmetric averaging has been used at the end points. Line colors match the ones used to define regions in Figure 1. Results are based on the average of recycling ratio from ERA5 and MERRA2.

Fig. 5 (a) Regression of seasonal average winds and accumulated total sourced precipitation anomalies onto the standardized ENSO index during the wet season. (b-e) same as in (a) but for the seasonal accumulated sourced precipitation from individual source regions. The stippling represents statistical significance at 90% confidence level. The two reanalysis are averaged before regression.

Fig. 6 Same as in Figure 5 but for NAO.

Fig. 7 Trends (mm/year) in seasonal accumulated contribution from each source region over 1980-2019. Stippling indicates significance at 95% confidence level. Trends are based on the average of ERA5 and MERRA2.

Fig. S1 Climatological percent of annual precipitation received during the wet season (1980-2019) in a) CRU, b) PERSIANN, c) GPCC, d) CHIRPS gridded observations and e) MERRA2, f) ERA5 reanalysis. Note that PERSIANN data was unavailable for 2017 through 2019 and GPCC data was unavailable for 1980 through 1982.

Fig. S2 Average recycling ratio (expressed in % of the total) during the wet season (Nov-April) from individual source regions. Results are based on the average of recycling ratios from ERA5 and MERRA2.

Fig. S3 Average recycling ratio (expressed in % of the total) during the wet season (Nov-April) from individual source regions in ERA5.

Fig. S4 Average recycling ratio (expressed in % of the total) during the wet season (Nov-April) from individual source regions in MERRA2.

Fig. S5 Mean monthly precipitation (mm) during 1980-2019 in a) CRU, b) PERSIANN, c) GPCC, d) CHIRPS gridded observations and e) MERRA2, f) ERA5 reanalysis. Note that PERSIANN data was unavailable for 2017 through 2019 and GPCC data was unavailable for 1980 through 1982.

Fig. S6 Regression of anomalies in seasonal accumulated sourced precipitation from individual regions onto the standardized ENSO index during the wet season. The stippling represents statistical significance at 90% confidence level. Results are based on the average of ERA5 and MERRA2.

Fig. S7 Regression of anomalies in seasonal accumulated sourced precipitation from individual regions onto the standardized NAO index during the wet season. The stippling represents statistical significance at 90% confidence level. Results are based on the average of ERA5 and MERRA2.

Fig. S8 (a) Regression of Nov-Dec average winds and accumulated total sourced precipitation anomalies onto the standardized ENSO index. (b-e) same as in (a) but for the seasonal accumulated sourced precipitation from individual source regions. The stippling represents statistical significance at 90% confidence level. Results are based on the average of ERA5 and MERRA2.

Fig. S9 Same as in Figure S8 but for Jan-Feb.

Fig. S10 Same as in Figure S8 but for Mar-Apr.

Fig. S11 (a) Regression of Nov-Dec average winds and accumulated total sourced precipitation anomalies onto the standardized NAO index. (b-e) same as in (a) but for the seasonal accumulated sourced precipitation from individual source regions. The stippling represents statistical significance at 90% confidence level. Results are based on the average of ERA5 and MERRA2.

Fig. S12 Same as in Figure S11 but for Jan-Feb.

Fig. S13 Same as in Figure S11 but for Mar-Apr.

Fig. S14 Seasonal accumulated precipitation trends (mm/year) during 1980-2019 in a) CRU, b) PERSIANN, c) GPCC, d) CHIRPS gridded observations and e) MERRA2, f) ERA5 reanalysis. Note that PERSIANN data was unavailable for 2017 through 2019 and GPCC data was unavailable for 1980 through 1982. The stippling represents statistical significance at 95% confidence level.

643 **Fig. S15** Same as in Figure S14 but for the whole evaporative source region.

644 **Fig. S16** Trends (mm/year) in seasonal accumulated contribution from each source region over

645 1980-2019 in ERA5. Stippling indicates significance at 95% confidence level.

646 **Fig. S17** Trends (mm/year) in seasonal accumulated contribution from each source region over

647 1980-2019 in MERRA2. Stippling indicates significance at 95% confidence level.

Figure 1. Evaporative source region and its sub-divisions. Region 1 represents the study area.

[Annual Precipitation]

Figure 2. Accumulated mean annual precipitation (mm) during 1980-2019 in a) CRU, b) PERSIANN, c) GPCC, d) CHIRPS gridded observations and e) MERRA2, f) ERA5 reanalysis. Note that PERSIANN data was unavailable for 2017 through 2019 and GPCC data was unavailable for 1980 through 1982.

[Recycling Ratio]

Figure 3. Average recycling ratio (expressed in % of the total) during the wet season (Nov-April). a) Sum of all regions, b) Western Indian Ocean, c) Mediterranean and Caspian Sea, d) East Africa, e) sum of North Atlantic and Europe, f) sum of North Africa and South Atlantic, g) sum of the other regions. Results are based on the average of recycling ratio from ERA5 and MERRA2.

Figure 4. Climatological intra-seasonal variability in regional contributions, shown as 10-day running mean area averaged over the Arabian Peninsula. Only those regions have been shown that reach a seasonal maximum of more than 5%. Note that symmetric averaging has been used at the end points. Line colors match the ones used to define regions in Figure 1. Results are based on the average of recycling ratio from ERA5 and MERRA2.

Figure 5. (a) Regression of seasonal average winds and accumulated total sourced precipitation anomalies onto the standardized ENSO index during the wet season. (b-e) same as in (a) but for the seasonal accumulated sourced precipitation from individual source regions. The stippling represents statistical significance at 90% confidence level. The two reanalysis are averaged before regression.

Figure 6. Same as in Figure 5 but for the NAO index.

[Trends in Seasonal Contribution]

Figure 7. Trends (mm/year) in seasonal contribution from each source region over 1980-2019. Stippling indicates significance at 95% confidence level. Trends are based on the average of ERA5 and MERRA2.

[Wet Season Precipitation]

Figure S1. Climatological percent of annual precipitation received during the wet season (1980-2019) in a) CRU, b) PERSIANN, c) GPCC, d) CHIRPS gridded observations and e) MERRA2, f) ERA5 reanalysis. Note that PERSIANN data was unavailable for 2017 through 2019 and GPCC data was unavailable for 1980 through 1982.

[Recycling Ratio]

Figure S2. Average recycling ratio (expressed in % of the total) during the wet season (Nov-April) from individual source regions. Results are based on the average of recycling ratios from ERA5 and MERRA2.

[Recycling Ratio]

Figure S3. Average recycling ratio (expressed in % of the total) during the wet season (Nov-April) from individual source regions in ERA5.

[Recycling Ratio]

Figure S4. Average recycling ratio (expressed in % of the total) during the wet season (Nov-April) from individual source regions in MERRA2.

Figure 5. Accumulated mean monthly precipitation (mm) during 1980-2019 in (1st row) CRU, (2nd row) PERSIANN, (3rd row) GPCC, (4th row) CHIRPS gridded observations and (5th row) MERRA2, (6th row) ERA5 reanalysis. Note that PERSIANN data was unavailable for 2017 through 2019 and GPCC data was unavailable for 1980 through

[Regression (ENSO, P)]

Figure S6. Regression of anomalies in seasonal accumulated sourced precipitation from individual regions onto the standardized ENSO index during the wet season. The stippling represents statistical significance at 90% confidence level. The two reanalysis are averaged before regression.

[Regression (NAO, P)]

Figure S7. Regression of anomalies in seasonal accumulated sourced precipitation from individual regions onto the standardized NAO index during the wet season. The stippling represents statistical significance at 90% confidence level. The two reanalysis are averaged before regression.

Figure S8. (a) Regression of Nov-Dec average winds and accumulated total sourced precipitation anomalies onto the standardized ENSO index. (b-e) same as in (a) but for the seasonal accumulated sourced precipitation from individual source regions. The stippling represents statistical significance at 90% confidence level. The two reanalysis are averaged before regression.

Figure S9. Same as in Figure S8 but for Jan-Feb.

Figure S10. Same as in Figure S8 but for Mar-Apr.

Figure S11. (a) Regression of Nov-Dec average winds and accumulated total sourced precipitation anomalies onto the standardized NAO index. (b-e) same as in (a) but for the seasonal accumulated sourced precipitation from individual source regions. The stippling represents statistical significance at 90% confidence level. The two reanalysis are averaged before regression.

Figure S12. Same as in Figure S11 but for Jan-Feb.

Figure S13. Same as in Figure S11 but for Mar-Apr.

[Wet Season Precipitation Trends]

Figure S14. Seasonal accumulated precipitation trends (mm/year) during 1980-2019 in a) CRU, b) PERSIANN, c) GPCC, d) CHIRPS gridded observations and e) MERRA2, f) ERA5 reanalysis. Note that PERSIANN data was unavailable for 2017 through 2019 and GPCC data was unavailable for 1980 through 1982. Stippling indicates significance at 95% confidence level.

[Wet Season Precipitation Trends]

Figure S15. Same as in Figure S14 but for the whole evaporative source region.

[Trends in Seasonal Contribution]

Figure S16. Trends (mm/year) in seasonal accumulated contribution from each source region over 1980-2019 in ERA5. Stippling indicates significance at 95% confidence level.

[Trends in Seasonal Contribution]

Figure S17. Trends (mm/year) in seasonal accumulated contribution from each source region over 1980-2019 in MERRA2. Stippling indicates significance at 95% confidence level.