Modulation of Winter Precipitation Dynamics Over the Arabian Gulf by ENSO

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Abstract The Arabian Gulf (Gulf) and the surrounding regions are centers of intense economic activity. The precipitating weather systems that form over the Gulf are important for this predominantly arid region. It is suggested that El Niño–Southern Oscillation (ENSO) influences the Middle East precipitation variability through an equatorward shift of the subtropical jet. Here we present compelling evidence to illustrate the role of ENSO in modulating the local dynamics and moisture transport in initiating precipitation during different ENSO phases using satellite and reanalysis data. It is found that the moisture transport from the Red and Arabian Seas toward the Gulf is stronger during El Niño years. The pattern and strength of moisture transport toward the Gulf is weakened during La Niña and neutral years, with most of the transport directed toward the northern Gulf. Using a 120 h back trajectory analysis, it is found that while the air parcels coming toward the Gulf from the Arabian and Red Seas side originate at lower tropospheric levels, the air parcels from the Mediterranean originate at middle and upper tropospheric levels during El Niño years. In contrast, upper tropospheric air parcels originating over the southern Arabian Sea plays a dominant role on Gulf precipitation during La Niña and neutral years. The seasonal mean transients of zonal winds show a robust ENSO signature over the Gulf, indicating a favorable (less favorable) condition for the penetration of midlatitude eddies over the region during El Niño (La Niña) winters.

Plain Language Summary The Arabian Gulf and the surrounding regions are centers of intense economic activity. The precipitating weather systems that form over the Arabian Gulf are important for this predominantly arid region. A major portion of the Middle East precipitation variability is known to be associated with the El Niño–Southern Oscillation (ENSO) phenomenon. The sources of moisture for the heavy precipitation events over the Arabian Gulf are the Arabian and Red Seas. In this study, it is found that the local dynamics that favor precipitation differs during El Niño, La Niña, and neutral years. The moisture transport from the Red and Arabian Seas toward the Arabian Gulf is stronger and covers the entire Gulf during El Niño years. The pattern and strength of moisture transport toward the Gulf is similar during La Niña and neutral years, with most of the transport directed toward the northern Gulf. The air parcels that come from the Mediterranean side originate at middle and upper tropospheric levels during El Niño years. However, during La Niña and neutral years, air parcels primarily originate at the upper tropospheric levels over the southern Arabian Sea.

1. Introduction

The Arabian Peninsula is mostly arid, with a few intermittent precipitation events in the winter months. Due to its rich natural resources and high level of economic activity, the region supports a large population. A major center of economic activity is the Arabian Gulf (Gulf) and the surrounding regions. The Arabian Gulf is a shallow sea between the Arabian Peninsula and Iran. The region is already water stressed, and the desalinated water from the Arabian Gulf is extensively used to support the population in the surrounding cities that causes further environmental stress on the water body (Sheppard et al., 2010). Despite its importance, the mechanisms of precipitation over the Arabian Gulf are not explored in detail, primarily due to scarcity of observations (Xue & Eltahir, 2015). It is essential to understand the mechanisms of precipitation and its variability over this region to make robust assessments of water stress that the Gulf undergoes in a warming climate, especially in the wake of projections of a decreased storm track activity and changes in spatial pattern of simulated precipitation over the region (Evans, 2009a, 2009b). Also, it is suggested that some of the recent socioeconomic issues affecting the Middle East region are in part related to prolonged droughts in the recent decades (Gleick, 2014; Kelley et al., 2015).
In the literature, studies on the precipitation variability over the Middle East and Arabian Peninsula have got some attention, whereas the Arabian Gulf has not been given much emphasis (Abdullah & Al-Mazroui, 1998; Almazroui et al., 2012; Alpert et al., 1990; Athar et al., 2013; Chakraborty et al., 2006; Mandoos, 2005; Nazemosadat & Ghasemi, 2004; Niranjan Kumar & Ouarda, 2014; Niranjan Kumar et al., 2016; Pourasghar et al., 2012; Ouarda et al., 2014). While part of the precipitation variability over the Gulf may be linked to that of the rest of the region, the orographic convection over the Zagros mountain that lies on the eastern side of the Arabian Gulf gives a distinct character to the Arabian Gulf precipitation (Barth & Steinkohl, 2004; Zaitchik et al., 2007). Hence, a regional focus to the Arabian Gulf precipitation is necessary to unravel the underlying mechanisms of its variability.

The winter rainfall over the Middle East region has similar characteristics of midlatitude precipitation as the rainfall primarily comes from baroclinic storms (Alpert et al., 1990). The El Niño–Southern Oscillation (ENSO) phenomenon has been found to be responsible for large-scale interannual changes in global weather patterns (Ropelewski & Halpert, 1989). A large fraction of precipitation variability over the Middle East is argued to be linked to ENSO (Athar et al., 2013; Hoell et al., 2015; Krichak et al., 2014; Niranjan Kumar & Ouarda, 2014; Niranjan Kumar et al., 2016; Roghani et al., 2016). Besides, the North Atlantic Oscillation (NAO) is also found to influence the climate extremes of the western part of the Arabian Peninsula (Donat et al., 2014). It is thought that the remote influence of ENSO on the Middle East precipitation is through the Rossby wave activity (Niranjan Kumar & Ouarda, 2014; Niranjan Kumar et al., 2016). The equatorward shift in Northern Hemisphere storm tracks during ENSO is found to cause enhanced rainfall over southern Mediterranean (Alpert et al., 1990; Chang et al., 2002). While the northern Middle East precipitation is primarily associated with storms, the southern region encompassing the Arabian Peninsula may not have the same impact from storms.

Although the development of most of the Arabian Gulf precipitating weather systems is triggered by large-scale atmospheric waves, the source of moisture is not unique. The western parts of the Arabian Peninsula often get precipitation due to moisture coming from the Red Sea in the presence of active Red Sea trough (de Vries et al., 2013). The central parts of the Arabian Peninsula receive extreme precipitation when a favorable synoptic condition is accompanied by moisture transport from the Mediterranean and Arabian Seas (Kumar et al., 2015). The enhanced moisture flux from the Arabian Sea is responsible for precipitation over southwest central Asia during El Niño years (Mariotti, 2007).

The variability of precipitation over different parts of Middle East in relation to ENSO has got attention in the past, as mentioned above. However, the precipitation process and variability over the Arabian Gulf are least studied, despite its importance. One unique feature of the Arabian Gulf compared to the rest of the Arabian Peninsula is the local availability of moisture. In this paper, our focus is on understanding the underlying mechanisms of the genesis and variability of precipitation over the Arabian Gulf during different phases of ENSO. One major hurdle in carrying out such an investigation is the lack of in situ observations. To overcome this problem, we use daily satellite precipitation observations in conjunction with high-resolution reanalysis data. Our investigation focuses on the modulation of the Arabian Gulf precipitation during various facets of ENSO (warm, cold, and neutral phases) and their mechanisms.

2. Data and Methods

One main issue in investigating Arabian Gulf precipitation is the lack of publicly available observations. Here we utilized daily precipitation data from Tropical Rainfall Measuring Mission (TRMM version 3B42; Huffman et al., 2007) and specific humidity, wind, geopotential, and temperature fields from ERA-Interim reanalysis (ERA; Dee et al., 2011). We have also used the daily sea surface temperature (SST) data from the Advanced Very High Resolution Radiometer (AVHRR; Reynolds et al., 2007). The period of analysis spans from 1998 to 2014. All calculations are done for the boreal winter season (November–February). In order to avoid the sampling errors that are associated with the detection of low- and moderate-intensity precipitation events by the TRMM (Bell et al., 2001; Indu & Nagesh Kumar, 2014), here we consider rainfall events with at least 5 mm d\(^{-1}\) intensity. When the area-averaged daily precipitation over the Arabian Gulf (only oceanic precipitation) exceeds 5 mm d\(^{-1}\), then it is considered as a heavy precipitation day. When two or more consecutive days meet the threshold criteria, then only the first day is considered for the back trajectory and composite analyses. A particular year is considered El Niño (La Niña) year if the 3 month running mean of SST anomaly for the Niño 3.4 region (5°S–5°N, 120°W–170°W) is +0.5°C (−0.5°C) (Trenberth, 1997). In this study, El Niño years are identified as 2002, 2004, 2006, and 2009. La Niña years are 1998, 1999, 2000, 2005, and 2007. We did not consider
the La Niña years of 2010 and 2011 so that both El Niño and La Niña years have the same number (20) of heavy precipitation events. It may be noted that the results do not alter by adding these two La Niña years. Neutral years are 2001, 2003, 2008, 2012, and 2013. These neutral years have a total of 15 heavy precipitation events over the Arabian Gulf.

The back trajectories are calculated for all heavy precipitation events during El Niño, La Niña, and neutral years. The calculation of back trajectories is carried out for 120 h from the day of heavy precipitation over the Arabian Gulf. For these calculations, the events are identified based on the area averaged precipitation over the oceanic region of Arabian Gulf (24°–30°N; 48°–56°E). As the characteristics of back trajectory changes with height at which the air mass is arrived, we have chosen three representative heights (500 m, 1,500 m, and 5,000 m) over a location (27.05°N and 51.55°E) that is centered over the Gulf. In order to address the uncertainty in the back trajectory calculations, 27 ensembles of trajectories are computed by offsetting the meteorological field by a fixed grid factor (one grid cell in the horizontal and 0.01 sigma in vertical). The back trajectories are computed using National Oceanographic and Atmospheric Administration (NOAA) Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT; Stein et al., 2015) model.

The Q-vector is calculated following Holton and Hakim (2012)

\[
Q = -\frac{g}{N^2} \left( \frac{\partial V}{\partial x} \nabla \theta + \frac{\partial V}{\partial y} \nabla \theta \right)
\]  

(1)

where \(N^2\) is the Brunt-Vaisala frequency, \(\theta\) the potential temperature, and \(V_G\) the geostrophic wind. The Q-vector can provide a reliable measure of vertical motion in the midlatitude atmosphere that is often associated with the development of a frontal weather system.

3. Results

3.1. Teleconnection of Arabian Gulf Weather With ENSO

The teleconnection between ENSO and global weather patterns is well known (e.g., Ropelewski & Halpert, 1989, and references therein). The El Niño winters are found to have more frequent precipitation events over the Middle East region (Niranjan Kumar & Ouarda, 2014). The subtropical jet strengthens on equatorward side in both hemispheres during El Niño events, in line with Gill-type response to tropical forcing (Gill, 1980; Seager et al., 2005). This change in jet was shown to influence transient eddy momentum fluxes (Seager et al., 2005). It was argued that this shift in subtropical jet, associated with El Niño, is responsible for the enhanced precipitation over the Arabian Peninsula (Niranjan Kumar et al., 2016). The equatorward shift in the jet during warm phase of ENSO is evident from Figure 1a. Further, the jet is anomalously stronger by as much as 10 m s⁻¹ over the Middle East region, and the shift in jet during El Niño years is visible throughout the troposphere (Figure 1b). Although the changes in the location of jet illustrates the large-scale dynamical pattern during El Niño winters, it does not explain the associated local dynamics and moisture transport happening during the precipitation events over this region. In this paper, we aim to fill these gaps in understanding the precipitation variability over the Arabian Gulf in various ENSO phases. Such improved understanding of the local precipitation processes in relation to the large-scale variability can aid in advancing the seasonal predictability on a regional scale.

The North Atlantic Oscillation (NAO) and Mediterranean oscillation are two of the large-scale atmospheric variabilities that are important for the larger Middle East and Mediterranean climate. The NAO can affect the midlatitude storm tracks, with an equatorward (poleward) shift in the storm tracks in negative (positive) phase of the oscillation (Hurrell, 1995). Such shifts in storm tracks will be reflected in the precipitation pattern over the affected regions. It was argued that a significant correlation exists between the NAO and Eastern Mediterranean precipitation (Eshel & Farrell, 2000). However, later studies have shown that the NAO influence on the precipitation over the regions that are located east of eastern Mediterranean, such as the Levant, is insignificant (Ziv et al., 2006). Further, it was found that the observed rainfall record for Kuwait, which is located on the rim of the Arabian Gulf, is not correlated with the NAO (Marcella & Eltahir, 2008). Similarly, it was found that the spatial extent of the influence of Mediterranean Oscillation is confined between the western and eastern Mediterranean, and the Middle East rainfall is not affected by this variability (Martin-Vide & Lopez-Bustins, 2006). For these reasons, we limit our study to understand the changes in the local atmospheric dynamics over the Arabian Gulf precipitation during different phases of ENSO. Nevertheless, we have done the composite analysis by removing two strong negative NAO years (2002–2003 and 2009-2010) and found that there are no significant changes in the results when these years are included in the analysis (not shown).
3.2. Precipitation Pattern During Different ENSO Phases

A 17 year winter (November–February) composite pattern of all heavy rainfall events that occurred over the Arabian Gulf shows maximum rainfall over the northern Gulf and the land region east of it (Figure 2). The cities that lie on the rim of the Gulf seems to receive rainfall from the precipitation systems that form over the Gulf. The precipitation pattern has a strong westward extent indicating that most of the eastern Saudi Arabia benefit from the Gulf rainfall events. The southward extent of the precipitation pattern is limited up to northern United Arab Emirates (UAE). This suggests that the southern Arabian Peninsula receives precipitation that originates elsewhere. The precipitation systems that form over the Arabian Gulf very rarely travel as far south as Oman (Membrey, 2007).

The enhanced southward extent of rainfall during El Niño years is evident in the spatial pattern of the number of heavy precipitation events (Figure 3a). During La Niña years, the heavy rainfall events are mostly confined to the northern Gulf and adjacent land region (Figure 3b). The spatial pattern of heavy rainfall events in neutral years are similar to that of La Niña years, although the precipitation extends farther southward (Figure 3c). The difference between the pattern of heavy precipitation events during El Niño and La Niña years clearly shows more frequent rainfall over the entire Gulf during the warm phase of ENSO (Figure 3d). In general, heavy precipitation events over the southern parts of the Arabian Gulf are less frequent during La Niña years compared to El Niño and neutral years.
3.3. Dynamics of the Gulf Precipitation

Identifying the sources of moisture and the mechanism of the development of atmospheric instability is vital in understanding the dynamics of the precipitating weather systems. The model-based estimates of the Arabian Gulf water budget suggest that the Gulf receives more precipitation than the local evaporation, indicating the importance of moisture transport from elsewhere (Xue & Eltahir, 2015). The lagged composites of moisture transport vectors in Figure 4 illustrate that the moisture transport is from the Arabian and Red Seas during heavy precipitation events. During heavy precipitation events in El Niño years, a strong buildup of moisture that peaks on lag 0 (day of heavy rainfall) can be seen over the Gulf (Figures 4a–4d). The buildup of moisture during El Niño years starts at lag −3 (Figure 4a) and progresses steadily leading to a heavy rainfall event. In contrast, the moisture transport toward the Gulf is weak during La Niña years (Figures 4e–4h). The strength of moisture transport toward the Arabian Gulf during winter precipitation events in neutral years is moderate compared to El Niño and La Niña years (Figures 4i–4l). Further, the moisture transport vectors are directed more toward the northern Gulf during neutral and La Niña years as against El Niño years when a substantial moisture transport occurs all over the Gulf.

A clearer picture of atmospheric mass transport during the precipitation events over the Gulf can be obtained through a back trajectory analysis from the location of the rainfall. The back trajectory analysis has been successfully applied to identify the source location of moist air (Fleming et al., 2012). As the characteristics of the trajectory can vary with the height at which the air parcel is arrived, we computed the back trajectories of the air parcels arriving at three different representative heights, viz., 500 m, 1,500 m, and 5,000 m above a location over the Arabian Gulf (27.05°N and 51.55°E) for a total of 55 heavy precipitation events. Further, 27 ensembles of back trajectories are computed for each identified heavy rainfall case. The ensembles are computed by slightly offsetting the meteorological data by a fixed grid factor in horizontal and vertical directions. These measures ensure the robustness of the back trajectory analysis. Consistent with the lagged composite of moisture transport, the 5 day back trajectories arrived at 500 m above Arabian Gulf during El Niño years show that low-level atmospheric air transport, which often carries the moisture, originates over the Arabian and Red Seas (Figure 5a). The trajectories corresponding to low-level air transport during La Niña years originate from locations closer to the Arabian Gulf (Figure 5b). This suggests a weak moisture transport toward the Gulf during La Niña winter precipitation events. On the contrary, a strong low-level mass transport from the Arabian Sea toward the Gulf is visible during neutral years (Figure 5c). In fact, the mass transport from
the Arabian Sea toward the Gulf during the neutral years is stronger than El Niño years. These results are consistent with the composite pattern of moisture transport during intense rainfall events over the Gulf during neutral years (Figure 4l). The composites of $\theta_e$ anomalies clearly shows the presence of warm moist air prior to precipitation events during El Niño years, where the $\theta_e$ anomalies show values of 8 K, while those for La Niña composite show 4 K and neutral composite 6 K. In the El Niño and neutral composites, the presence of negative $\theta_e$ anomalies west of the Red Sea shows the presence of a cold air mass which suggests possibility of strong occlusion of warm and cold air masses in these years as compared to La Niña years. This could lead to baroclinic development and heavy precipitation events over the region during El Niño and neutral years.

The air parcel that arrived at 1,500 m level also shows back trajectories that transport air from the lower 1 km of the atmosphere over the Arabian and Red Seas during all phases of ENSO (Figures 5d–5f). The westerly trajectories that originate over the Mediterranean are mostly from above 4,000 m levels of the atmosphere. A clear descent in these trajectories is seen over the northern and western parts of the Gulf. The air parcel that arrived at 5,000 m over the Arabian Gulf traces the origin of air mass mostly in a westward direction (Figures 5g–5i). These air masses originate over north Africa and the Mediterranean. During El Niño and neutral years upper level mass transport from the Arabian Sea is limited (Figure 5g). In contrast, upper level mass transport from the atmosphere over the Arabian Sea can be seen during La Niña (Figure 5h). A close examination of these
Figure 4. Lagged composites of vertically integrated moisture transport (arrows, kg kg\(^{-1}\) ms\(^{-1}\)) for (a) 3 day lag, (b) 2 day lag, (c) 1 day lag, and (d) lag 0 for all heavy precipitation events that occurred during El Niño winters of years 1998–2014; (e–h) same as Figures 4a–4d except for La Niña years; and (i–l) same as Figures 4a–4d except for neutral years. The shading shows the magnitude of moisture transport. The stippling shows the grids where the composite is statistically significant (\(p < 0.05\)) as revealed by a two-tailed \(t\) test. Statistically significant (\(p < 0.05\)) vectors are shown in brown color.

Trajectories also reveal an ascending motion of the air mass, especially those originating over the southwest. Such ascending motion could result in an adiabatic cooling of the air parcel. From this analysis, it appears like the upper level cooling coupled with low-level influx of warm moist air creates unstable atmospheric conditions favorable for the development of precipitation. The composites of SST anomalies clearly shows a warmer Arabian Sea during El Niño and neutral years (Figures 5g and 5i). During La Niña years, a large fraction of the Arabian Sea is anomalously cooler (Figure 5h). These SST anomalies clearly suggest that the large positive \(\theta_v\) anomalies during El Niño and neutral years are supported by the enhanced evaporation from warmer Arabian Sea and the cooler SSTs must be contributing to weaker \(\theta_v\) anomalies during La Niña years. The cold SST anomalies over the Arabian Gulf during El Niño suggest that local evaporation is also contributing to the heavy precipitation events in the warm phase of ENSO.

ENSO is suggested to influence Middle East precipitation through teleconnections (Niranjan Kumar et al., 2016). However, the local dynamics that support the development of weather systems are not properly
Figure 5. The 120 h back trajectories calculated for all heavy precipitation events over the Arabian Gulf during winter season for (a) El Niño, (b) La Niña, and (c) neutral years during 1998–2014 period, with the air parcel that arrived at a height of 500 m over a representative Arabian Gulf (27.05°N, 51.55°E) location (indicated by the marking). The contours superimposed on Figures 5a–5c show the composite of equivalent potential temperature (θ_e) anomalies (averaged over 975–700 hPa, units: K) 1 day prior to the precipitation events; (d–f) same as Figures 5a–5c except for air parcel that arrived at a height of 1,500 m; (g–i) same as Figures 5a–5c except for air parcel arrived at 5,000 m. The semitransparent shading over water bodies shows the composite of SSTs (K) 1 day prior to the precipitation events. Twenty-seven ensembles of back trajectories are calculated for each event, where each ensemble is computed by offsetting the meteorological data by a fixed grid factor (one grid point in horizontal and 0.01 sigma in vertical) in the X, Y, and Z directions.

understood. The midlatitude weather systems usually develop due to baroclinic instability (Simmons & Hoskins, 1978). Q-vector is a parameter that is useful in explaining the upward motion and thereby precipitation process in a midlatitude baroclinic system (Holton & Hakim, 2012; Pierrehumbert & Swanson, 1995). Here we computed the lagged composites of Q-vector at 500 hPa level for heavy precipitation events during El Niño, La Niña, and neutral years (Figure 6). The lagged composite of Q-vector shows the existence of a vertical motion field north of the Red Sea 2 days before the heavy precipitation event over the Arabian Gulf which then moves southeastward and locates over the northern Arabian Peninsula and Gulf on the day of heavy rainfall (Figure 6). The pattern of movement of this baroclinic wave is somewhat similar during all phases of ENSO, with considerable variability in intensity. The magnitude and spatial extent of vertical motion field during El Niño years (Figures 6a–6c) is stronger than that during La Niña (Figures 6e–6g) and neutral
years (Figures 6i–6k). The weaker vertical motion suggest the presence of a weak instability in La Niña composites. The zonal mean lead lag structure of Q-vector magnitude clearly shows the strength and southward movement of the vertical motion field prior to the precipitation event which is followed by a northeastward transition after the heavy precipitation event over the Gulf, during El Niño years (Figure 6d). The zonal mean lead lag composite shows a weak upward mass flux during La Niña years, with a short life cycle (Figure 6h). A stronger vertical mass transport exists during the precipitation events in neutral winters as compared to La Niña winters (Figure 6l). Also, the peak intensity of the Q-vector is achieved 1 day before the Gulf precipitation event in the La Niña and neutral composites, while the Q-vector magnitude peaks 1 day after the Gulf precipitation event in El Niño years. This suggests that the baroclinic wave is already in the dying phase by the time it reaches over the Gulf in La Niña and neutral winters, while it strengthens over the Gulf in El Niño years. As mentioned in previous sections, the equatorward shift of subtropical jet during El Niño years is a notable feature (Seager et al., 2003; Niranjan Kumar et al., 2016). Such a southward shift in the jet can induce a larger baroclinicity over the Gulf region during El Niño years compared to cold and neutral phases of ENSO.

Apart from the local dynamics, the remote forcing of ENSO also aids in the occurrence of precipitation over the Gulf. It would be interesting to look at the signature of remote forcing of the ENSO on the seasonal mean anomalies. The local changes in the mean location of the subtropical jet over the Arabian Peninsula during warm and cold phases of ENSO is already illustrated in Figure 1. Often, strengthening of the jet on the equatorward flanks would result in stronger eddy activity and shift of storm tracks toward equator (Seager et al., 2003). Such changes in the eddy fluxes and stormtracks are found to affect the precipitation pattern over the west coast of the United States (Seager et al., 2003). The changes in location and strength of the subtropical jet over the Arabian Gulf influence the transient eddy activity over this region, which is illustrated here.
The anomalous position of the subtropical jet over Arabian Gulf during various ENSO phases and its association with ENSO is shown in Figure 7. The composite structure of seasonal mean zonal wind anomalies shows a stronger jet over the Arabian Gulf during El Niño winters (Figure 7a). However, a similar composite structure during La Niña years indicates a poleward shift of the jet, as evidenced by easterly (westerly) anomalies in the zonal winds equatorward (poleward) of about 25°N (Figure 7b). The composite of seasonal mean zonal wind anomalies during neutral years shows a weak equatorward strengthening of the jet over the Arabian Gulf (Figure 7c) compared to the El Niño composite (Figure 7a). The weakening of the jet on the equatorward flanks is much larger than the strengthening on the poleward side, suggesting a poleward shift and weakening of the jet during La Niña years. The weakening of the jet on the equatorward side during La Niña years (Figure 7b) is consistent with the low frequency of occurrence of precipitation events over the Arabian Gulf (Figure 3b). To further illustrate the connection between the remote forcing of Pacific SST anomalies on Gulf weather, Niño 3.4 SST time series is regressed on to an all-year composite of seasonal mean zonal anomalies (Figure 7d). The linear regression of Niño 3.4 SSTS on the transients of zonal wind reveals a pattern that is very similar to the El Niño composite (Figures 7a and 7d), linking local changes in seasonal mean transients to the remote Pacific SST anomalies. This further implies the role of remote signature of ENSO on seasonal mean anomalies over the Arabian Gulf.

4. Discussion and Conclusions

Many of the major cities of the Arabian Peninsula are located around the rim of the Arabian Gulf. These are some of the most important cities of the region, in terms of economic activity and the population that inhabits
the region. The Arabian Peninsula in general is arid, and the growing population in these cities is partially supported by desalinated water from the Gulf. The few winter precipitation events received over this region are important for the society and ecology of the region. Also, the Gulf is a shallow sea with an average depth of about 37 m (Xue & Eltahir, 2015) and the precipitation received is important to maintain the heat and salinity budgets and thereby the ecology of the Gulf itself. Despite its importance, there were not many studies that focus on the dynamics of the Arabian Gulf rainfall. Many of the studies dealing with this region considered either the larger Middle East or the Arabian Peninsula as a whole. Here we have shown that the precipitation over the Arabian Gulf is modulated by ENSO.

For a long time, it was known that the El Niño favors precipitation over the Middle East, while La Niña is accompanied by less frequent precipitation (e.g., Niranjan Kumar et al., 2016). However, the local mechanisms that support the large-scale dynamics of the enhanced (decreased) precipitation during El Niño (La Niña) years were not studied in detail. Our analyses shows that there are precipitation occurrences over the northern Gulf, irrespective of the ENSO state. The frequency of the northern Gulf rain events is low during La Niña years. It is noteworthy that some of the most intense precipitation events occurred during neutral years. The major difference between El Niño and neutral years is that the southward extension of the precipitation pattern is stronger during El Niño years. The southward movement of baroclinic waves triggers more frequent rainfall over the southern Gulf in El Niño years. Further, stronger vertical motion supports more precipitation events all over the Gulf during El Niño years. The enhanced baroclinicity over the Arabian Gulf during El Niño years is aided by the equatorward shift in the subtropical jet. The air mass few days prior to heavy precipitation events also shows distinct characteristics during ENSO and non-ENSO years. In general, the air mass transported by westerly winds from the Mediterranean and northern Africa dominates the upper atmosphere, while the easterly winds aid the transport of low-level air mass from the Arabian Sea toward the Gulf during heavy rain events. The Red Sea is also found to be a major contributor of moisture to the Arabian Gulf precipitation events. The noticeable feature seen from back trajectory analysis is the influx of warm moist lower level air from the Arabian and Red Seas during El Niño years which results in heavy rainfall events over the northern Gulf. The ENSO signature seen on the seasonal mean transients over the Arabian Gulf indicates the prevalence of favorable conditions for the penetration of extratropical systems over the region during warm ENSO events. The Gulf region gets rain events when the extratropical systems move over the region, together with the local moisture supply. When we juxtapose together the spatial patterns of evolution of baroclinicity and moisture transport, this study highlights the relative role of local dynamics in modulating the heavy rainfall events over the Arabian Gulf in different facets of ENSO. The future precipitation variability in a warming environment over the Gulf region is an important issue which must be investigated by taking into account both remote effects of ENSO variability and potential changes in local atmospheric dynamics.

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