ENSO Influence on the Interannual Variability of the Red Sea Convergence Zone and Associated Rainfall

Journal:	<i>International Journal of Climatology</i>
Manuscript ID	JOC-16-0652.R1
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Dasari, Hari Prasad; King Abdullah University of Science and Technology, Physical Sciences and Engineering Division Langodan, Sabique; King Abdullah University of Science and Technology, Physical Sciences and Engineering Division Viswanadhapalli, Yesubabu; King Abdullah University of Science and Technology, Physical Sciences and Engineering Division; National Atmospheric Research Laboratory, Weather and Climate Research Group Rao, V.; Instituto Nacional de Pesquisas Espaciais, Centro de Previsão de Tempo e Estudos Climáticos Papadopoulos, Vassilis; Hellenic Centre for Marine Research, Marine Research Center Hoteit, Ibrahim ; King Abdullah University of Science and Technology, Physical Sciences and Engineering Division
Keywords:	Red Sea Convergence Zone, Red Sea Trough, ENSO, Rainfall, Moisture Convergence

SCHOLARONE™
Manuscripts

ENSO Influence on the Interannual Variability of the Red Sea Convergence Zone and Associated Rainfall

Hari Prasad Dasari¹, Sabique Langodan¹, Yesubabu Viswanadhapalli², Brahmananda Rao Vadlamudi³, Vassilis P. Papadopoulos⁴, and Ibrahim Hoteit^{1,*}

1. King Abdullah University of Science and Technology (KAUST), Physical Sciences and Engineering Division, Thuwal, Saudi Arabia
2. National Atmospheric Research Laboratory, Gadanki, Andhra Pradesh, India
3. Centro de Previsão de Tempo e Estudos Climáticos (CPTECH), INPE, Brazil
4. Hellenic Centre for Marine Research, Anavissos, Greece

***Corresponding author: Ibrahim.hoteit@kaust.edu.sa**

Abstract

The Red Sea Convergence Zone (RSCZ) is formed by opposite surface winds blowing from northwest and southeast directions at around 18°–19°N between October and January. A reverse-oriented, low-level monsoon trough at 850 hPa, known as the Red Sea Trough (RST), transfers moisture from the southern Red Sea to RSCZ. The positions of the RSCZ and RST and the intensity of the RST have been identified as important factors in modulating weather and climatic conditions across the Middle East. Here, we investigate the influence of the El Niño southern oscillation (ENSO) on the interannual variability of RSCZ, RST, and regional rainfall during winter months. Our results indicate that El Niño (warm ENSO phase) favors a shift of the RSCZ to the north and a strengthening of the RST in the same direction. Conversely, during November and December of La Niña periods (cold ENSO phase), the RSCZ shift to the south and the RST strengthens in the same direction. During El Niño periods, southeasterly wind speeds increase (20-30%) over the southern Red Sea and northwesterly wind speeds decrease (10-15%) over the northern Red Sea. Noticeable increases in the number of rainy days and the intensity of rain events are observed during El Niño phases. These increases are associated with colder than normal air intrusion at lower levels from the north combined with warm air intrusion from the south over the RSCZ. Our analysis suggests that during El Niño winters, warmer sea surface temperatures and higher convective instability over the Red Sea favor local storms conditions and increase rainfall over the Red Sea and adjoining regions.

Keywords: Red Sea Convergence Zone, Red Sea Trough, ENSO, Rainfall, Moisture Convergence

1. Introduction

The elongated Red Sea acts as a channel that transports moisture between the Mediterranean and Arabian Seas (Pedgley, 1966; Tsvieli and Zangvil, 2005), influencing the weather and climate of the Middle East. During winter, between October and March, the northern Red Sea experiences northwest winds blowing from the Mediterranean region, while the southern Red Sea experiences southeasterly winds blowing from the Gulf of Aden. These opposing wind streams meet at the center of the Red Sea (Fig. 1) to form the Red Sea Convergence Zone (RSCZ, Pedgley, 1966, 1972, Abualnaja *et al.*, 2015; Langodan *et al.*, 2015). This area is characterized by cloudy skies and drizzle in contrast with the typically clear weather in the region. Converging winds in RSCZ funnel out to the west through a valley called the Tokar Gap, an area spanning ~50 km in width between the Sudanese coast and its northeastern mountains (Pedgley, 1966, 1971, 1974; Jiang *et al.*, 2009; Langodan *et al.*, 2014, Yesubabu *et al.*, 2016).

A trough of low pressure, known as the Red Sea Trough (RST), controls the occurrence of heavy rainfall over the area (Krichak *et al.*, 1997a, b; De Vries *et al.*, 2013). At around 850 hPa, RST is a low-level trough that originates from the equatorial Eastern Africa. It extends northward from the southern Red Sea toward the eastern Mediterranean, influencing regional weather and climatic conditions (Krichak *et al.*, 2012; De Vries *et al.*, 2013). The positions of the RST and two high-pressure systems, one over northeast Africa and another over the Arabian Peninsula, modulate both the location of RSCZ and the intensification of convective activity and

70 associated rainfall (De Vries *et al.*, 2013). Several studies have attributed the formation of RST
71 to thermal and orographic effects, suggesting that it occurs more frequently in autumn than in
72 winter or spring (Alpert *et al.*, 2004a, b; Tsvieli and Zangvil, 2005, 2007; Krichak *et al.*, 1997a,
73 1997b, 2012).

74 Occasionally, the RST is accompanied by a mid-latitude upper trough, which leads to
75 unstable conditions capable of triggering convective storms and heavy rainfall over the Red Sea
76 and adjoining regions (Kahana *et al.*, 2002; Ziv *et al.*, 2005; Krichak *et al.*, 2012). The dynamics
77 of this type of RST, known as an active RST (ARST), have been well described (Krichak *et al.*,
78 2012; Dayan *et al.*, 2001; Kahana *et al.*, 2002; Ziv *et al.*, 2005; Dayan and Morin, 2006; Tsvieli
79 and Zangvil, 2005, 2007). Recently, De Vries *et al.* (2013) studied the dynamic features
80 associated with RST and ARST based on an analysis of 13 heavy rainfall events over the Red
81 Sea.

82 The moisture transport over the Red Sea and the adjacent continents are closely related to
83 the regional and larger-scale circulation patterns, including the North African jets, subtropical
84 westerly jet, inter tropical convergence zone (ITCZ), ENSO, Indian monsoon, and Mediterranean
85 circulation modes linked to the Atlantic circulation patterns, such as the NAO (Bronnimann,
86 2007; De Vries *et al.*, 2013; Kar and Rana, 2014; Kang *et al.*, 2015; Babu *et al.*, 2016). The
87 climatological characteristics of the moisture budget components over the Red Sea suggest that
88 nearly 80% of the moisture from the Red Sea is transferred over the Arabian Peninsula through

the upper layer transportation (above 850 hPa), which is closely correlated with the Arabian high (Zolina *et al.*, 2017).

Previous studies of the RSCZ and RST have primarily focused on their formations and associated characteristics, such as moisture transfer and the generation of cyclonic/anticyclonic pressure systems over the Middle East. A few studies also focused on the relationship between the El Niño southern oscillation (ENSO) and rainfall over the Middle East. From the analysis of multi decadal rainfall data over the Arabian Peninsula, Kang *et al.* (2015) concluded that the wet seasons in the Arabian Peninsula during the recent decades (1980 onwards) show a stronger correlation with ENSO than the early periods (1950-1979). Niranjana Kumar and Ouarda (2014) suggested that the precipitation variability over the United Arab Emirates is mostly influenced by ENSO. Babu *et al.* (2016) also reported the influence of El Niño and La Niña on the summer and winter precipitation patterns over the Arabian Peninsula. However, the interannual variability of the RSCZ and RST, particularly the role of El Niño and La Niña in modulating the climate of the Middle East and the weather over the Red Sea, has not yet been investigated.

In this study, we analyze the wind field, rainfall, sea surface temperature, convective available potential energy (CAPE), and moisture budget to investigate the potential link of the interannual variability of the RSCZ and RST and the associated rainfall over the Red Sea and adjoining regions to the warm and cold phases of the ENSO during the 37-year period from 1979 through 2016 of available ERA-interim data. Our results suggest that El Niño (the warm ENSO phase) is associated with (i) intensification of RSCZ and RST and modification of the rainfall

over the Red Sea and eastern Middle East; (ii) colder than normal air intrusion from the north over the northern half of the Red Sea; (iii) a significant increase of moisture and total column precipitable water vapor; and (iv) an increase in rainfall events over the Middle East. During La Niña, the RSCZ shifts southward, which in turn brings more rainfall over the southern parts of the Red Sea. The remainder of this paper is organized as follows: Section 2 describes the data and methodology; Section 3 presents our analysis and results; and finally Section 4 offers a summary and discussion of our main findings.

2. Data and Methodology

To investigate the dynamics of the RSCZ and RST, we examined several variables from the ERA-Interim reanalysis for the 37-year period 1979–2016 (Dee *et al.*, 2011, T255 and 60 model levels) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). We analyzed monthly mean values of surface and 850 hPa winds, 850 hPa geopotential, CAPE, total column precipitable water (TCPW), and vertically integrated moisture convergence. We also used the Advanced Very High Resolution Radiometer (AVHRR) infrared satellite sea surface temperature (SST) data (Reynolds *et al.*, 2007) available at $0.25^\circ \times 0.25^\circ$, daily APHRODITE precipitation data sets (version V1101, Yatagai *et al.*, 2012) between 1979 and 1997 and Tropical Rainfall Measuring Mission (TRMM) 3B42 version 7 data (Huffman *et al.*, 2007, Huffman and Bolvin, 2012) between 1998 and 2016 (TRMM data for 1979 to 1997 were not available).

Both the APHRODITE and TRMM data sets are available at $0.25^{\circ} \times 0.25^{\circ}$ resolution. The TRMM estimated precipitation overestimates station rainfall over the Arabian Peninsula by approximately 10% on average (Almazroui, 2011 and Almazroui *et al.*, 2012). The mean observed and TRMM data (in brackets) in millimeters are 25.81 (25.27), 29.76 (35.74), 9.21 (12.85), and 14.10 (14.33) during winter, spring, summer and autumn respectively. The correlation coefficient between the TRMM and the rain-gauge rainfall data is about 0.90, with a 99% level of significance on the monthly scale. TRMM has been described as the best precipitation dataset for the Middle East (Almazroui, 2011; Almazroui *et al.*, 2012). APHRODITE's (Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation) daily gridded precipitation is the only long-term (1951 onward) continental scale daily product that uses a dense network of daily rain-gauge data for Asia. Tabarhte *et al.* (2012) inter-compared different gridded global (CRU, CPC, DEL, GPCC, ERA40) and regional (APHRODITE and E-OBS) precipitation datasets over the Mediterranean and the Middle East for the period 1961–2000. The study concluded that APHRODITE is a unique source of precipitation data for the Middle East region with minimal errors and highest correlations among the different examined datasets. The quality of the latest version of APHRODITE (version V1101) was further improved due to the additional rainfall observations that were included in the APHRODITE data from the southward extension of the APHRODITE domain.

In addition, we used precipitation data from more than 110 rain gauges placed across the region. The precipitation data are available for the entire period of study (Kenawy and McCabe, 2016; Almazroui, 2011). The El Niño (1994/1995, 2002/2003, 2004/2005, 2006/2007,

2009/2010, 2015/2016) and La Niña (1983/1984, 1988/1989, 1998/1999, 2000/2001, 2007/2008, 201/2012) years were selected based on the central Pacific ENSO Index (Zhiyu *et al.*, 2015).

3. Results

We investigate the influence of El Niño and La Niña on the RSCZ, RST, and their associated rainfall by analyzing winds, geopotential, temperature, SST, CAPE, TCPW, evaporation and moisture convergence. The rainfall is retrieved from APHRODITE and TRMM, from October to January, a period representative of the most pronounced RSCZ and RST (Krichak *et al.*, 2012; De Vries *et al.*, 2013).

3.1 The wind regime

The 37-year ECMWF climatology of 10 m winds from October to January (Fig. 1a) shows a well-organized convergence zone (RSCZ) at about 18°N across the Red Sea formed by the convergence of southeastern and northwestern winds. This is a salient winter feature throughout the investigated period, with some variability in its position and intensity. Composite means computed exclusively for El Niño and La Niña years are shown in Figures 1b and 1c, respectively. El Niño years are characterized by about 15-20% lower wind speeds in the northern Red Sea and 10-20% higher wind speeds in the southern Red Sea and Gulf of Aden compared with the climatological mean (Figs. 1b and 1d), resulting in a broader RSCZ (17°-21°N). Alternatively, La Niña years are characterized by ~15% stronger northwest winds in the northern Red Sea and slightly weaker southeasterly winds in the southern Red Sea (5-10%) compared with the climatological mean (Fig. 1c), causing a southward shift of the convergence zone.

Figure 1d confirms the differences in wind flow between the composite means of El Niño and La Niña years, suggesting a significant increase (about 20-30%) in the narrow flow branch of southeasterly winds in the southeastern part of the Red Sea (12°N to 20°N) and East Arabian Peninsula. This observation is consistent with the findings of Raitso *et al.* (2015), who attributed the increased chlorophyll concentration in the Red Sea to stronger southeasterlies during El Niño winters. Ha *et al.*, (2012) also showed that the interannual variability in the East Asian winter monsoon is highly related to ENSO and Arctic Oscillation. During El Niño, the Siberian High (SH) strengthens significantly and shifts southward. As a result, stronger southerlies over the southern Red Sea during El Niño years may increase evaporation and feed more moisture to RSCZ.

Along with the differences in wind speeds, we also observed changes in wind direction between El Niño and La Niña years over the Middle East. In particular, the northwesterly winds over the northwestern domain of the study area during El Niño years shifted to northerlies during La Niña years.

3.2 Winds, geopotential and temperature at 850 hPa

To understand the influence of El Niño and La Niña on RSCZ and RST and their associated dynamics, we analyzed the winds and the geopotential fields at 850 hPa. The composite means of El Niño and La Niña years are presented in Figure 2. The mean circulation at 850 hPa (Fig. 2a) clearly exhibits two high-pressure domains around 25°N on the eastern and western sides of the Red Sea; the western high-pressure system over the Sahara is stronger than

the eastern system over the Arabian Peninsula. Between these two high-pressure systems is a squeezed low-pressure trough, named RST (Krichak *et al.*, 1997a, b; De Vries *et al.*, 2013). At $\sim 30^\circ\text{N}$, a weaker trough, known as the subtropical jet, is apparent between the two high-pressure systems. De Vries *et al.* (2013) studied the relationship between the moisture transport over the region and the pressure systems and concluded that the intensities and positions of the high-pressure systems strongly influence RST, which ultimately modulates moisture transport and associated rainfall patterns over the Middle East. The positions and intensities of these semi-permanent systems influence the north-to-south movement of RSCZ. The difference (El Niño - mean, Fig. 2b) shows a distinct northward movement of the Saharan high-pressure system, with a decrease in intensity ranging from 5 to 10 gpm. As shown in Figure 2, at 850 hPa, a cold air mass originating from the Mediterranean region enters from the lower troposphere towards RSCZ. Similarly, we also considered mean temperatures at different levels (Fig. 3). At lower levels (Fig. 3b and 3c), colder temperatures over the northwestern parts of the Red Sea are observed during El Niño than during normal and La Niña years. In addition, during El Niño years air temperatures are warmer on both sides of the Red Sea, and the temperature difference is more pronounced when compared to air temperatures during La Niña years (Fig. 3c). The stronger winds in the region of the RST (south of the Red Sea) transfer moisture from the south towards the RSCZ. When these moist and warm air masses meet the cold masses transferred by the trough over the northern Red Sea, a thermal gradient occurs and leads to stronger than normal convection. Furthermore, the cyclonic circulation associated with RSCZ and the channeling by the Ethiopian Mountains steers orographic lifting, which results in increased air

uplift that favors stronger convection and higher rainfall (Krichak *et al.*, 2012; De Vries *et al.*, 2013). During La Niña years (Fig. 2c), the trough over the northern Red Sea is weaker and is associated with dry northwest winds that extend along the Red Sea. Figure 2d (El Niño - La Niña) shows a pronounced signal during La Niña years compared to the El Niño years (Fig. 2b); northwestward movement of the Saharan high-pressure system that has decreased in intensity with eastward movement of the Arabian high-pressure system that has increased in intensity. The position of these high-pressure systems directs the warm air from south of RSCZ to meet the relatively cold extra-tropical air masses from north of RSCZ, plausibly resulting in higher rainfall during El Niño periods (see Section 3.3). Although moisture seems to be preferably transported toward the western Red Sea, the intensities of the two anticyclones over the northwest and eastern sectors are crucial to the movement of moisture towards Saudi Arabia. The two high-pressure systems are stronger during El Niño than La Niña years, and favor increased rainfall over the eastern Red Sea during El Niño periods (i.e., the northern side of RSCZ, mostly over northern Saudi Arabia). We have also analyzed the winds and geopotential at 850 hPa level from the long-term 21st century reanalysis datasets from ECMWF covering (32) El Niño and (28) La Niña events (not shown). The results clearly show that the composite anomalies of El Niño and La Niña and the difference between El Niño and La Niña also exhibit the same patterns as those presented in Figure 2 (b, c and d). Since, observed daily rainfall and Sea Surface Temperature data were not available for this long-term period, we limit our further analysis to a period when the observations are available.

3.3 Mean daily rainfall

The mean amount of rainfall and the number of rainy days are relatively low across the study area (Benestad *et al.*, 2012). Nonetheless, we analyzed the interannual variability of rainfall over the Red Sea in relation to El Niño and La Niña years. The rainfall climatology estimated from APHRODITE and TRMM between October and January and the difference between El Niño and La Niña years are presented in Figure 4. The mean rainfall is higher below 15°N and north of the Red Sea (Fig. 4a). The RSCZ generates a rainfall zone over the Red Sea between 16°N and 21°N, and as such the amount of rainfall and its spatial variability are highly dependent on the movement and intensity of the RSCZ. A comparison of the mean rainfall during El Niño and La Niña years (Fig. 4b), especially along RSCZ and over the north and northeast regions of Saudi Arabia, shows that the amount of rainfall is higher during El Niño than La Niña years. The stronger RSCZ with its northward movement during El Niño years favors stronger convection and higher-than-normal amounts of rainfall over the northern parts of Saudi Arabian region, and decreases the amount of rainfall over the south-central Red Sea.

Figure 5 presents a Hovmöller diagram (time-longitude) of the mean rainfall averaged between 18°–24°N over the Red Sea for all (Fig. 5a), normal (Fig. 5b), El Niño (Fig. 5c), and La Niña (Fig. 5d) years during winter (October–January). Isolated rainfall events occur in all four cases, mainly at longitudes between 37° and 50°E. El Niño winters experience the highest mean rainfall from October to January with more isolated rainfall events over a wider region (Fig. 5c), whereas the highest rainfall during La Niña is confined to October and November. The results also suggest that during El Niño years, rainfall moves towards the north of RSCZ whereas during La Niña it is confined to the south of RSCZ. Rainfall is never continuous over several days and

there is no indication of any atmospheric wave propagation. During La Niña years, there is a distinct reduction in both the amount of rainfall and the number of rainy days (Fig. 5d). Figure 6 presents a time-latitude diagram of the mean total rainfall averaged over 37.5°-41°E for normal (Fig. 6a), El Niño (Fig. 6b) and La Niña (Fig. 6c) winters. Whereas rainfall is concentrated over the southern parts of the Red Sea and adjoining regions during normal and La Niña years, a northward shift of rainfall over time is evident during El Niño years. These findings suggest that the northward shift of RSCZ increases the amount of rainfall over the northern parts of the Red Sea during El Niño, whereas a southward shift of RSCZ increases the amount of rainfall in the southern parts of the Red Sea.

To substantiate these results, we analyzed daily rainfall data from the east and west coasts of the Red Sea along the RSCZ. Between October and January, fewer rainy days are observed on average in the area between 18°-24°N and 34°-36°E (western side of the Red Sea, Fig. 7a) than in the area between 18°-24°N and 40°-42°E (eastern side, Fig. 7b). Heavy rainfall events are rare over both sides in October. The number of rainfall events is considerably higher (Fig. 7c) during El Niño years. In general, the relatively high amount of rainfall in October on both the western and eastern sides of the Red Sea is associated with a more active, stronger RSCZ. Similarly, the eastern coast of the Red Sea (18°-24°N and 40°-42°E) experiences more rainfall than the western coast and also more rainy days (Fig. 7d) with higher rainfall during October, December, and January. With the exception of a few days in January, more rainfall and rainy days occurred during El Niño years compared with the long-term mean, normal years, and La Niña periods. At the same time, the amount of rainfall is higher in the east, north, and

northeastern parts of the Red Sea during El Niño years. The intrusion of cool air into the Middle East (Section 3.2) that is likely associated with strong and prolonged winters over the Mediterranean Sea during El Niño years (Moron and Plaut, 2003; Mariotti *et al.*, 2002; Lopez *et al.*, 2012, 2015; Wang *et al.*, 2014) plays a significant role. This intrusion results in a higher amount of rainfall over the Middle East and more rainy days over the Red Sea and adjoining regions during El Niño winters. Kang *et al.* (2015) reported that during recent years, the intensified upper-level zonal wind enhances the frequent passages of transients over this region and enhances the rainfall amount.

The analysis of historical precipitation data available from more than 110 rain gauges over the region (Kenawy and McCabe, 2016; Almazroui, 2011) helps in understanding the variability of rainfall during El Niño and La Niña years. Based on the total amount of rainfall at each station, we categorized stations into two groups. The first group includes stations with higher amounts of rainfall recorded during El Niño years and the second group includes stations with higher amounts of rainfall during La Niña years. Figure 8a and 8b respectively present histograms of the mean seasonal accumulated rainfall during El Niño and La Niña years. Figure 8c shows the distribution of the rain gauges over the study area. The stations in the group with a higher amount of rainfall during El Niño years are marked in red; those with a higher amount of rainfall during La Niña years are marked in blue. In general, the gauges located in the northern parts of RSCZ recorded more rainfall during El Niño years (red), whereas the gauges located in the southern parts of RSCZ and in the western parts of Saudi Arabia recorded more rainfall during La Niña years (blue). The distribution of rainfall accumulation at different stations

suggests that El Niño brings a higher amount of rainfall windward of the southern mountains near the Red Sea coastline. In contrast, a higher amount of rainfall is observed on the lee side of the mountains during La Niña years. The higher amount of rainfall windward of the mountains during El Niño years could be attributed to orographic-driven convection along with moisture from the Arabian Sea entering through Yemen and adjoining regions (Krichak *et al.*, 2012; De Vries *et al.*, 2013).

3.4 Convective available potential energy and sea surface temperature

In arid and semi-arid regions, rainfall events can be characterized as discontinuous, highly variable rainfall pulses with unpredictable frequency and intensity (Pedgley, 1971, 1974; Kenawy and McCabe, 2016). Most rainfall events are associated with storms triggered by strong convection. CAPE is an indicator of the instability of the atmospheric column; an increase of CAPE indicates higher probability of convective storms. Figure 9a shows CAPE from October to January as computed from ERA Interim data, and Figure 9b plots the difference in CAPE between El Niño and La Niña years. The mean CAPE values during El Niño years are higher than during La Niña and normal years, an indication that the El Niño years favor convective storm conditions (Cotton *et al.*, 2011).

An oceanic parameter that can affect the instability of the atmospheric column is the sea surface temperature (SST). Warmer than normal water may trigger convective storms over the sea (Deb *et al.*, 2008). The anomalies in SST for El Niño and La Niña years during the 35-year period from 1979 through 2014 are plotted in Figures 10a and 10b. These figures clearly show

that during El Niño years, warmer surface temperatures occur during October, November and December in the southern parts of the Red Sea. Similar features are also observed in the surface air temperatures (Figure 3a) along the Red Sea. The observed SST indicates a northward propagation of warmer water from October to January during El Niño years. This may be related with the strong southeasterly winds in the Gulf of Aden, which push the warm water from the Arabian Sea into the Red Sea during El Niño years. In contrast, during La Niña years, slightly negative SST anomalies seem to propagate from south to north along the southern Red Sea between November and January. These colder surface waters are less favorable to the development of convection events over the Red Sea.

3.5 Moisture balance

In general, over the tropics, the intensity of rainfall is associated with the convergence or divergence of water vapor flux (Rao *et al.*, 2002, Li *et al.*, 2013, Wei *et al.*, 2015, Ramakrishna *et al.*, 2016; Zolina *et al.*, 2017). Therefore, examining the amount of moisture over a broader area around the Red Sea and its probable origin is also of interest. We aim to clarify whether the increase in rain during El Niño years is associated with higher moisture over the studied area or if it is simply a result of stronger than normal convection in RSCZ. To measure atmospheric moisture, we use TCPW and moisture convergence that is vertically integrated from the surface to 300 hPa.

The moisture budget equation can be written as:

$$\frac{\partial w}{\partial t} = -\nabla Q + E - P \quad \text{with } Q = \frac{1}{g} \int_{p_0}^{p_t} \mathbf{q} \cdot \nabla p, \quad (1)$$

333

334 where $p_t = 300$ hPa, p_0 is the surface pressure, g is the acceleration of gravity, and $\mathbf{v}$ is
 335 horizontal wind vector. Equation (1) states that the rate of change in total precipitable water (w)
 336 in the column is equal to the difference between evaporation (E) and the sum of precipitation and
 337 the vertically integrated moisture convergence (∇Q).

338 Figure 11 plots the total precipitable water for the mean (Fig. 11a), El Niño (Fig. 11b), La
 339 Niña (Fig. 11c), and the difference between El Niño and La Niña (Fig. 11d) years. The latter
 340 shows positive values over the northern Red Sea and negative values over the southern Red Sea.
 341 However, the differences are on the order of 5 g/kg, which are non-significant. Figure 12 shows
 342 the mean vertically integrated moisture convergence ($\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) for all (Fig. 12a), El Niño (Fig.
 343 12b), La Niña (Fig. 12c) and the difference between El Niño and La Niña (Fig. 12d) years.
 344 During El Niño years (Fig. 12b), a greater amount of moisture (about 10-25%) is available along
 345 the Red Sea and in Saudi Arabia than during mean and La Niña years. Figure 12d clearly
 346 outlines an increased south-to-north transport of moisture ($\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$) over the Red Sea during El
 347 Niño years; this moisture turns toward northwestern Saudi Arabia after crossing RSCZ,
 348 suggesting that rain is more likely to occur in the north of RSCZ than in the south of RSCZ
 349 during El Niño years. The correlation of monthly mean ($\sim 36 \times 4$ data points at every grid) of
 350 TCPW and moisture convergence with their corresponding multivariate ENSO index (MEI,
 351 <http://www.esrl.noaa.gov/psd/enso/mei/table.html>) are computed and presented in Figure 13. The

correlations are highly significant (>95%) over RSCZ and eastern Saudi Arabia. A negative correlation between moisture convergence and MEI indicates higher moisture convergence (Fig. 13b) in the central Saudi Arabia and coastal regions of the northern Red Sea. Another interesting characteristic is the evaporation variability during El Niño and La Niña years (Fig. 14). The mean values of evaporation for all (Fig. 14a) and the anomalies of El Niño (Fig. 14b) and La Niña (Fig. 14c) years indicate that during El Niño periods, evaporation is lower over the northern parts and higher over the southern parts of the Red Sea. In contrast, during La Niña years, evaporation is higher over the northern parts of the Red Sea.

The difference in evaporation between El Niño and La Niña (Fig. 14d) years suggests that evaporation is 10-15% lower in El Niño years, with positive values over the Red Sea and Saudi Arabia. The lower evaporation over the northern Red Sea is related to the lower SST (Fig. 10a) and weaker northwesterly winds. The mean vertically integrated TCPW and moisture values suggest that the Red Sea receives the majority of its moisture from the Indian Ocean during the winter monsoon, and both values are highest over RSCZ during El Niño years. This confirms that stronger RSCZ conditions are the dominant factor associated with the increased rainfall during El Niño winters. The rate of change in precipitable water vapor difference ($\frac{\partial w}{\partial t}$) is small between El Niño and La Niña years (5 g/kg) compared with the mean values of 60 g/kg. Generally, stronger moisture convergence is related to higher amounts of rainfall. Although stronger moisture convergence occurred during El Niño years, the excess rainfall was only 0.5 mm/day compared to La Niña periods. This observation is explained by Equation (1), where we expect equilibrium between E, P and $-\nabla Q$.

The individual components of the moisture budget are computed using ERA-interm data for winter seasons and presented in supplementary Figure S1. The climatological mean evaporation shows nearly 50-75% higher magnitude over the northern Red Sea (around 24N) than the southern Red Sea. The analysis also confirms that the Red Sea and adjacent oceans are the major sources of moisture over the region. It is important to note that evaporation is high/low over the southern/northern Red Sea during El Niño and it is exactly opposite during La Niña. The mean climatological winter precipitation is higher over the north and northeastern parts of the Saudi Arabia during El Niño and is minimum during La Niña. The mean net evaporation (E-P) patterns of climatology, El Niño, and La Niña over the Red Sea exhibit similar from evaporation (E) (minimal precipitation). The mean vertically integrated moisture convergence (Fig S1d) suggests that the moisture from the Arabian Sea is transported to the northeastern parts of the Saudi Arabian peninsula through the Red Sea. During El Niño, the vertically integrated moisture convergence is about 15-20% higher than normal and La Niña over the northern parts of the Red Sea, indicating higher probability of precipitation. The eastward advection of the vertically integrated moisture is mainly controlled by the position of RST and high pressure systems on both sides of Red Sea. Since the difference in precipitation is very small, we anticipate that the total evaporation difference (1 mm/day) is counter balanced by the divergence of the water vapor. A similar water balance argument for arid regions is demonstrated in previous studies, e.g., Star and Peixoto (1958).

A schematic description of the synoptic scale features and related dynamical processes over RSCZ during normal, El Niño and La Niña years is illustrated in Figure 15. While El Niño

394 favors the northeastern Red Sea and adjoin region with an increased number of rainy days, La
395 Niña brings more rainfall to the southern parts of the Red Sea. During El Niño periods (Fig.15b),
396 the significant warming over the tropical regions in summer produces increased temperature
397 gradients from pole to equator and amplifies (Bronnimann, 2007) the polar jet, which in turn
398 triggers a shift of the subtropical westerly jet (STJ) towards the equator in the following winter.
399 These changes accompanied with a northward moisture transport from the Arabian Sea to the
400 Red Sea set favorable conditions for rainfall over the northeastern parts of the Red Sea. During
401 La Niña (Fig. 15c), stronger northeast surface winds blowing from north pushes the RSCZ and
402 RST southward, the presence of the Arabian Anti cyclone over the southern Arabian Peninsula
403 transports the moisture through the Gulf of Aden towards the southern Saudi Arabia and favors
404 rainfall in the region.

405 **4. Summary**

406 The distribution of rainfall over the Red Sea and adjacent regions depends on the strength and
407 location of RSCZ and RST. In this study, we analyzed the interannual variability of RSCZ and
408 associated rainfall. We investigated the differences in the wind flow patterns around RSCZ
409 during El Niño, La Niña and normal years. Weaker northwest winds over the northern Red Sea
410 and stronger southeast winds over the southern Red Sea during El Niño years are observed
411 compared with stronger northwest winds over the northern Red Sea and weaker southeast winds
412 over the southern Red Sea during La Niña years. These varying wind conditions shift the
413 position of RSCZ toward the north during El Niño years and toward the south during La Nina

years. During El Niño years, the stronger southeast winds over the Gulf of Aden pump warmer water from the Arabian Sea into the Red Sea, causing increased SST, evaporation, and transport of more moisture toward RSCZ. Stronger convection and higher moisture in the air increase the number of rainy days and the total amount of rainfall over the Red Sea and the Middle East during El Niño years. The prolonged and relatively cold winters over the Mediterranean Sea is associated with El Niño propels cold air at 850 hPa towards RSCZ. This intrusion of cold air is integral to the formation of a stronger than normal RST. At surface, RSCZ and RST trigger convection over the region, subsequently increasing rainfall over the Red Sea and adjoining areas. The position of RST at 850 hPa and the subtropical jet associated with stronger anticyclonic systems along the eastern and western Red Sea are prominent features that transport moisture between the Arabian and Mediterranean Seas and across the Red Sea and its adjoining regions. Occasionally, anticyclonic systems on the eastern and western Red Sea intensify the low-pressure system that forms over the northern Red Sea, a pattern that can contribute considerably to the transport of moisture towards the Saudi Arabian peninsula, particularly to its northern regions. The correlations of MEI with TCPW and moisture convergence during winter suggest that the majority of moisture into the Red Sea is transported from the Indian Ocean and that an increase in TCPW is favored during El Niño years.

Our analysis shows that the strengthening of the conditions of RSCZ, the deepening of RST, and increases in SST and CAPE are the dominant factors regulating the associated stronger convection and stronger rainfall over the Red Sea and adjoining regions during El Niño years.

During El Niño, the upper tropospheric cyclonic circulation shifts the position of STJ to the Central Arabian Peninsula (Kang et al., 2015), which directly enhances the moisture convergence over the region and subsequently increases the precipitation from the frequent passage of transients. The northward migration of RST and RSCZ, southward shift of STJ and increased strength of circulation patterns enhance the moisture advection towards the northeastern parts of Saudi Arabia.

This study focused on the ENSO influence on the interannual variability of winter rainfall over the Red Sea region and its relation to the movement of the RSCZ. The dynamical links between the reported local processes and the large scale modes are still yet to be investigated and this will be addressed in future study.

Acknowledgments:

This research was funded by King Abdullah University of Science and Technology (KAUST) and the Saudi ARAMCO Marine Environmental Research Center at KAUST (SAMERCK). This research made use of the resources of the Supercomputing Laboratory and/or computer clusters at KAUST.

References:

Abualnaja, Y, Papadopoulos, VP, Josey, SA, Hoteit I, Kontoyiannis H, Raitos, DE. 2015. Impacts of Climate Modes on Air–Sea Heat Exchange in the Red Sea. J. Climate, 28, 2665-2681, doi: 10.1175/JCLI-D-14-00379.1.

- 453 Almazroui M, Islam MN, Jones PD, Athar H, Rahman MA. 2012. Recent climate change in the
454 Arabian Peninsula: Seasonal rainfall and temperature climatology of Saudi Arabia for 1979–
455 2009. *Atmos. Res.*, 111,29-45, doi:10.1016/j.atmosres.2012.02.013.
- 456 Almazroui M. 2011. Calibration of TRMM rainfall climatology over Saudi Arabia during 1998–
457 2009. *Atmos Res.*, 99, 400-414, doi:10.1016/j.atmosres.2010.11.006
- 458 Alpert P, Osetinsky I, Ziv B, Shafir H. 2004a. Semi-objective classification for daily synoptic
459 systems: Application to the Eastern Mediterranean climate change. *Int. J. Climatol.*, 24 (8),
460 1001–1011, doi:10.1002/joc.1036
- 461 Alpert P, Osetinsky I, Ziv B, Shafir H. 2004b. A new seasons definition based on classified daily
462 synoptic systems: An example for the Eastern Mediterranean. *Int. J. Climatol.*, 24(8), 1013–
463 1021, doi:10.1002/joc.1037.
- 464 Babu CA, Jayakrishnan PR, Varikoden H. 2016. Characteristics of precipitation pattern in the
465 Arabian Peninsula and its variability associated with ENSO. *Arab J Geosci*, 9: 186.
466 doi:10.1007/s12517-015-2265-x
- 467 Benestad R, Nychka D, Mearns L. 2012. Spatially and temporally consistent prediction of heavy
468 precipitation from mean values. *Nat. Clim. Change*, 2, doi:10.1038/NCLIMATE1497.
- 469 Brönnimann S, 2007. Impact of El Niño– Southern Oscillation on European climate, *Rev.*
470 *Geophys.*, 45, RG3003, doi:10.1029/2006RG000199.

- Cotton WR, Bryan GR, Van den Heever SC, 2011. Storm and cloud dynamics the dynamics of clouds and precipitating mesoscale systems. International Geophysics series. 99, 1–809. Academic press, ISBN: 978-0-12-088542-8.
- Dayan U, Morin E, 2006. Flash flood-producing rainstorms over the Dead Sea. New frontiers in Dead Sea Paleo environmental research: Geological Society of America Special Paper 401, 53–62, doi:10.1130/2006.2401(04).
- Dayan U, Ziv B, Margalit A, Morin E, Sharon D. 2001. A severe autumn storm over the Middle-East: Synoptic and mesoscale convection analysis. Theor. Appl. Climatol, 69(1-2), 103–122, doi:10.1007/s007040170038.
- De Vries AJ, Tyrllis E, Edry D, Krichak SO, Steil B, Lelieveld J. 2013. Extreme precipitation events in the Middle East: Dynamics of the Active Red Sea Trough. J. Geophys. Res. Atmos., 118, 7087–7108, doi:10.1002/jgrd.50569.
- Deb SK, Kishtawal CM, Pal PK, Joshi PC. 2008. Impact of TMI SST on the simulation of a heavy rainfall episode over Mumbai on 26 July 2005, Monthly Weather Review, 136 (10), 3714-3741
- Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Andrae U, BalmasedaMA, Balsamo G, Bauer P, Bechtold P, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Delsol C, Dragani R, Fuentes M, Geer AJ, Haimberger L, Healy SB, Hersbach H, Hólm EV, Isaksen L, Kållberg P, Köhler M, Matricardi M, McNally AP, Monge-Sanz BM, Morcrette J-J, Park B-K, Peubey C, de Rosnay P, Tavorato C, Thépaut J-N, Vitart F. 2011. The ERA-

- 491 Interim reanalysis: configuration and performance of the data assimilation system. Q. J. R.
492 Meteorol. Soc. 137(656): 553–597, doi: 10.1002/qj.828.
- 493 Ha KJ, Heo KY, Lee SS, Yuna KS, Jhunc JG. 2012. Variability in the East Asian
494 Monsoon: a review. Meteorol. Appl. 19: 200–215.
- 495 Huffman GJ, Adler RF, Bolvin DT, Gu G, Nelkin EJ, Bowman KP, Hong Y, Stocker EF, Wolff
496 DB. 2007. The TRMM multi-satellite precipitation analysis: Quasi-global, multi-year,
497 combined-sensor precipitation estimates at fine scale. J. Hydro meteorol., 8, 38–55, doi:
498 <http://dx.doi.org/10.1175/JHM560.1>.
- 499 Huffman GJ, Bolvin DT. 2012. TRMM and other data precipitation data set documentation
500 (ftp://meso-a.gsfc.nasa.gov/pub/trmmdocs/3B42_3B43_doc.pdf).
- 501 Jiang H, Farrar JT, Beardsley RC, Chen R, Chen C. 2009. Zonal surface wind jets across the Red
502 Sea due to mountain gap forcing along both sides of the Red Sea. Geoph. Res. Letters, 36,
503 L19605. doi:10.1029/2009GL040008.
- 504 Kahana R, Ziv B, Enzel Y, Dayan U. 2002. Synoptic climatology of major floods in the Negev
505 desert. Israel, Int. J. Climatol, 22 (7), 867–882, doi:10.1002/joc.766.
- 506 Kang, In-Sik, Irfan Ur Rashid, Fred Kucharski, Mansour Almazroui, Abdulrahman A. Al Khalaf,
507 2015. Multi-decadal changes in the relationship between ENSO and wet-season precipitation
508 in the Arabian Peninsula. Journal of Climate, 28, 12, 4743–4752.

- 509 Kenawy AM, McCabe MF. 2016. A multi-decadal assessment of the performance of gauge- and
510 model-based rainfall products over Saudi Arabia: climatology, anomalies and trends. *Int. J.*
511 *Climatol.*, 36: 656–674, doi: 10.1002/joc.4374
- 512 Krichak SO, Alpert P, Krishnamurti TN. 1997a. Interaction of topography and tropospheric flow
513 – A possible generator for the Red Sea Trough? *Meteorol. Atmos. Phys.*, 63(3-4), 149–158,
514 doi:10.1007/
- 515 Krichak SO, Alpert P, Krishnamurti TN. 1997b. Red Sea Trough/cyclone development -
516 numerical investigation. *Meteorol. Atmos. Phys.*, 63 (3-4), 159–169,
517 doi:10.1007/BF01027382.
- 518 Krichak SO, Alpert P. 1998. Role of large scale moist dynamics in November 1-5, 1994,
519 hazardous Mediterranean weather. *J. Geophys. Res.*, 103, 453–468, doi:10.1029/98JD01710.
- 520 Krichak SO, Breitgand JS, Feldstein SB. 2012. A conceptual model for the identification of the
521 Active Red Sea Trough Synoptic events over the southeastern Mediterranean. *J. App.*
522 *Meteorol. Climatol.*, 51(5), 962–971, doi:10.1175/JAMC-D-11-0223.1.
- 523 Langodan S, Cavaleri L, Yesubabu V, Hoteit I. 2014. The Red Sea: A Natural Laboratory for
524 Wind and Wave Modeling. *J. Phys. Oceanography*, 44, 3139–3159.
- 525 Langodan, S., L Cavaleri,, Yesubabu, V., Hoteit, I., 2015. Wind□wave source functions in opposing seas.
526 *J. Geophys. Res: Oceans* 120 (10), 6751-6768
- 527 Li L, Li W, Barros AP. 2013. Atmospheric moisture budget and its regulation of the summer
528 precipitation variability over the Southeastern United States. *Clim. Dyn.*, 41:613–631

- 529 López-Parages J, Rodríguez-Fonseca B, Laurent Terry. 2015. Mechanism for the multi decadal
530 modulation of ENSO teleconnection with Europe. *Clim. Dyn.*, 45, 867-880.
- 531 López-Parages J, Rodríguez-Fonseca B. 2012. Multi decadal modulation of El Niño influence on
532 the Euro-Mediterranean rainfall. *Geophys. Res. Lett.*, 39, L02704,
533 doi:10.1029/2011GL050049.
- 534 Mariotti A, Zeng N, Lau KM. 2002. Euro-Mediterranean rainfall and ENSO-a seasonally varying
535 relationship. *Geophys. Res. Lett.*, 29(12), doi:10.1029/2001GL014248
- 536 Moron V, Plaut G. 2003. The impact of El Niño–southern oscillation upon weather regimes over
537 Europe and the North Atlantic during boreal winter. *Int. J. Climatol*, 23, 363–379.
- 538 Niranjan Kumar K, Ouarda TBMJ. 2014. Precipitation variability over UAE and global SST
539 teleconnections. *J. Geophys. Res. Atmos.*, 119, doi:10.1002/2014JD021724.
- 540 Pedgley DE. 1966. The Red Sea Convergence Zone. *Weather*, 21, 350–358. doi: 10.1002/j.1477-
541 8696.1966.tb02776.
- 542 Pedgley DE. 1971. A Heavy Rainstorm over North-Western Arabia. *Proc. Syrup. Trop. Met*,
543 Honolulu, 1970, E VII 1-6.
- 544 Pedgley DE. 1972. Desert depressions over North-east Africa, *Meteorological Magazine*,
545 London, 101, 228-244.
- 546 Pedgley DE. 1974. The winter and spring weather at Riyadh, Saudi Arabia. *Meteorological*
547 *Magazine*, London, 103, 551.589.1 (53), 225-236.

- 548 Raitzos DE, Yi X, Platt T, Racault MF, Brewin RJW, Pradhan Y, Papadopoulos VP,
549 Sathyendranath S, Hoteit I. 2015. Monsoon oscillations regulate fertility of the Red Sea,
550 *Geophys. Res. Lett.*, 42, doi:10.1002/2014GL062882.
- 551 Ramkrishna SSVS, Rao VB, Srinivas BR, Hari Prasad D, Nanaji Rao N, Roshmitha P. 2016. A
552 study of 2014 record drought in India with CFSv2 model: role of water vapor transport.
553 *Clim. Dyn.*, DOI 10.1007/s00382-016-3343-9
- 554 Rao VB, Srinivasarao C, Fernandez JPR, Franchito SH. 2001. A Diagnosis of rainfall over South
555 America during the 1997/98 El Niño event. Part II: Role of water vapor transport and
556 stationary waves. *Journal of Climate*, 15, 512-521.
- 557 Reynolds WR, Smith TM, Liu C, Chelton DB, Casey KS, Schlax MG. 2007. Daily High-
558 Resolution-Blended Analyses for Sea Surface Temperature. *J. Climate* 20, 5473–5496, doi:
559 10.1175/2007JCLI1824.1
- 560 Star VP, Peixoto JP. 1956. On the Global Balance of Water Vapor and the Hydrology of Deserts.
561 *Tellus*, 10, 188-194.
- 562 Tanarhte, M., P. Hadjinicolaou., J. Lelieveld., 2012. Intercomparison of temperature and
563 precipitation data sets based on observations in the Mediterranean and the Middle East, *J.*
564 *Geophys. Res.*, 117, D12102, doi:10.1029/2011JD017293.
- 565 Tsvieli Y, Zangvil A. 2005. Synoptic climatological analysis of ‘wet’ and ‘dry’ Red Sea troughs
566 over Israel. *Int. J. Climatol*, 25(15), 1997–2015, doi:10.1002/joc.123.

- 567 Tsvieli Y, Zangvil A. 2007. Synoptic climatological analysis of Red Sea trough and non-Red Sea
568 trough rain situations over Israel. *Adv. Geosci.*, 12, 137–143.
- 569 Wang S, Huang J, He Y, Guan Y. 2014. Combined effects of the Pacific Decadal Oscillation and
570 El Niño- Southern Oscillation on Global Land Dry–Wet Changes. *Sci. Rep.*, 4, 6651;
571 DOI:10.1038/srep06651
- 572 Wei J, Su H, Yang ZL. 2015. Impact of moisture flux convergence and soil moisture on
573 precipitation: a case study for the southern United States with implications for the globe.
574 *Climate Dynamics*. DOI 10.1007/s00382-015-2593-2
- 575 Yatagai A, Kamiguchi K, Arakawa O, Hamada A, Yasutomi N, Kitoh A. 2012. Aphrodite
576 constructing a long-term daily gridded precipitation dataset for Asia based on a dense
577 network of rain gauges. *Bull. Am. Meteorol. Soc.*, 93(9), 1401–1415, doi:10.1175/BAMS-
578 D-11-00122.1.
- 579 Yatagai A., Xie P, Alpert P., 2008. Development of a daily gridded precipitation data set for the
580 Middle East. *Adv. Geosci.*, 12, 165–170. www.adv-geosci.net/12/165/2008/
- 581 Yesubabu V, Hari Prasad D, Sabique L, Srinivas CV, Hoteit I. 2016. Climatic features of the Red
582 Sea from a regional assimilative model. *Int. J. Climatol.*, DOI: 10.1002/joc.4865
- 583 Zhiyu L, Xu H, Zhang W. 2015. Asymmetric Features for Two Types of ENSO. *J. Meteor. Res.*,
584 29 (6): 896-916, doi: 10.1007/s13351-015-5044-4.

585 Ziv B, Dayan U, Sharon D. 2005. A mid-winter, tropical extreme flood-producing storm in
586 southern Israel: Synoptic scale analysis. Meteorol. Atmos. Phys., 88(1-2), 53–63,
587 doi:10.1007/s00703-003-0054-7.

588 Zolina, O., A. Dufour, S. Gulev, and G. Stenchikov. 2017. Regional hydrological cycle over the
589 Red Sea in ERA-Interim. J. Hydrometeor., 18, 65-83, doi:10.1175/JHM-D-16-0048.1

590

Peer Review Only

591 **Figure captions:**

592 Figure 1. Mean seasonal (October – January) winds (m/sec) at 10m a) 35 years, b) El Niño, c) La Niña,
593 and d) El Niño - La Niña years between 1979-2015.

594 Figure 2. Mean seasonal (October – January) winds (m/sec) and geopotential (shaded, gpm) at 850 hPa.
595 a) 35 years, b) El Niño – Mean, c) La Niña - Mean, and d) El Niño - La Niña years between 1979-2015.

596 Figure 3. Mean seasonal (October – January) temperatures ($^{\circ}\text{C}$) at different levels. Right column is for 35
597 years mean, middle column is for El Niño – Mean, and left column is for La Niña – Mean years between
598 1979-2015. Top panel is for 925 hPa, middle panel is for 850 hPa and bottom panel is for 700 hPa.

599 Figure 4. Mean seasonal (October – January) rainfall (mm/day) a) 35 years, and b) El Niño - La Niña
600 years between 1979-2015.

601 Figure 5. Mean daily rainfall (mm/day) averaged over 20°N - 24°N latitude during October to January. a)
602 35 years, b) neutral c) El Niño, and d) La Niña.

603 Figure 6. Mean daily rainfall (mm/day) averaged over 37.5°E – 39.5°E latitude during October to January.
604 a) 35 years, b) neutral c) El Niño, and d) La Niña.

605 Figure 7. Mean daily rainfall (mm/day) averaged over a) Eastern side (18°E - 24°E ; 34°E – 36°E), b)
606 Western side (18°E - 24°E ; 40°E – 42°E), c) El Niño - La Niña (west coast), and d) La Niña - El Niño (east
607 coast) of the Red Sea.

608 Figure 8. Mean seasonal accumulated rainfall (mm) in winter months. a) Stations with rainfall higher in
609 El Niño years, b) Stations with rainfall higher in La Niña years, and c) Spatial distribution of station
610 rainfall both in El Niño (Red color bar) and La Niña (Blue color bar) years along with the terrain height
611 (m).

612 Figure 9. Mean seasonal (October – January) convective available potential energy (CAPE, J/Kg) a) 35
613 years, and b) El Niño - La Niña years between 1979-2015.

614 Figure 10. Difference of mean monthly Sea Surface Temperatures ($^{\circ}\text{C}$) along the Red Sea longitude axis.
615 a) El Niño – Mean, b) La Niña – Mean.

616 Figure 11. Mean seasonal (October – January) total column precipitable water vapor (g/kg). a) 35 years,
617 b) El Niño, c) La Niña, and d) El Niño - La Niña years between 1979-2015.

Figure 12. Mean seasonal (October – January) vertically integrated moisture ($\times 10^{-6} \text{ kg.m}^{-2}.\text{sec}^{-1}$, shaded convergence). a) 35 years, b) El Niño, c) La Niña, and d) El Niño - La Niña years between 1979-2015. The arrows indicate the moisture transport vectors ($\text{kg.m}^{-1}.\text{sec}^{-1}$).

Figure 13. Correlation Coefficients of Multi Variant ENSO Index and to a) Total Column Precipitable Water, and b) Vertically integrated moisture. Significance with more than 95% are presented with + symbol.

Figure 14. Mean seasonal (October – January) evaporation (mm.day^{-1}). a) 35 years, b) El Niño - Mean, c) La Niña - Mean, and d) El Niño - La Niña years between 1979-2015.

Figure 15. Schematic presentation of the different synoptic scale features associated with RSCZ and rainfall during (a) Normal, (b) El Niño, and (c) La Niña years. The direction of white line indicates the moisture transport pathways. Surface winds over the Red Sea are presented by red and blue arrows (thicker indicates stronger magnitudes). As in De Veries et al., (2013); (H) refers to High pressure system; (A) to Arabian Anticyclone, (RST) to Red Sea Trough, (STJ) to Sub Tropical Jet, (3L) to Upper Level Trough, (RSCZ) to Red Sea Convergence Zone, and white color clouds to convective activity.

Figure S1. Mean seasonal (October – January) hydrological cycle of a) evaporation (mm.day^{-1}), b) precipitation (mm/day), c) evaporation – precipitation (mm/day), and d) vertically integrated moisture ($\times 10^{-6} \text{ kg.m}^{-2}.\text{sec}^{-1}$, shaded convergence) between 1979-2015. The arrows indicate the moisture transport vectors ($\text{kg.m}^{-1}.\text{sec}^{-1}$). The right panel is (35 year mean), middle panel is (El Niño – Mean) and left panel is (La Niña – Mean).

Figure 2s. Mean seasonal (October – January) winds (m/sec) and geopotential (shaded, gpm) at 850 hPa. a) 110 years, b) El Niño – Mean, c) La Niña - Mean, and d) El Niño - La Niña years between 1901-2010.

Figure 1. Mean seasonal (October – January) winds (m/sec) at 10m a) 35 years, b) El Niño, c) La Niña, and d) El Niño - La Niña years between 1979-2015.

Figure 2. Mean seasonal (October – January) winds (m/sec) and geopotential (shaded, gpm) at 850 hPa. a) 35 years, b) El Niño – Mean, c) La Niña - Mean, and d) El Niño - La Niña years between 1979-2015.

Figure 3. Mean seasonal (October – January) temperatures ($^{\circ}\text{C}$) at different levels. Right column is for 35 years mean, middle column is for El Niño – Mean, and left column is for La Niña – Mean years between 1979-2015. Top panel is for 925 hPa, middle panel is for 850 hPa and bottom panel is for 700 hPa.

Figure 4. Mean seasonal (October – January) rainfall (mm/day) a) 35 years, and b) El Niño - La Niña years between 1979-2015.

Figure 5. Mean daily rainfall (mm/day) averaged over 20°N - 24°N latitude during October to January. a) 35 years, b) neutral c) El Niño, and d) La Niña.

705

706

707 Figure 6. Mean daily rainfall (mm/day) averaged over 37.5°E – 39.5°E latitude during October to January.

708 a) 35 years, b) neutral c) El Niño, and d) La Niña.

Figure 7. Mean daily rainfall (mm/day) averaged over a) Eastern side ($18^{\circ}\text{E} - 24^{\circ}\text{E}$; $34^{\circ}\text{E} - 36^{\circ}\text{E}$), b) Western side ($18^{\circ}\text{E} - 24^{\circ}\text{E}$; $40^{\circ}\text{E} - 42^{\circ}\text{E}$), c) El Niño - La Niña (west coast), and d) La Niña - El Niño (east coast) of the Red Sea.

Figure 8. Mean seasonal accumulated rainfall (mm) in winter months. a) Stations with rainfall higher in El Niño years, b) Stations with rainfall higher in La Niña years, and c) Spatial distribution of station rainfall both in El Niño (Red color bar) and La Niña (Blue color bar) years along with the terrain height (m).

Figure 9. Mean seasonal (October – January) convective available potential energy (CAPE, J/Kg) a) 35 years, and b) El Niño - La Niña years between 1979-2015.

Figure 10. Difference of mean monthly Sea Surface Temperatures ($^{\circ}\text{C}$) along the Red Sea longitude axis.
a) El Niño – Mean, b) La Niña – Mean.

Figure 11. Mean seasonal (October – January) total column precipitable water vapor (g/kg). a) 35 years, b) El Niño, c) La Niña, and d) El Niño - La Niña years between 1979-2015.

Figure 12. Mean seasonal (October – January) vertically integrated moisture ($\times 10^6 \text{ kg.m}^{-2}.\text{sec}^{-1}$, shaded convergence). a) 35 years, b) El Niño, c) La Niña, and d) El Niño - La Niña years between 1979-2015. The arrows indicate the moisture transport vectors ($\text{kg.m}^{-1}.\text{sec}^{-1}$).

793

794

795 Figure 13. Correlation Coefficients of Multi Variant ENSO Index and to a) Total Column Precipitable
796 Water, and b) Vertically integrated moisture. Significance with more than 95% are presented with +
797 symbol.

798

799

800

801 Figure 14. Mean seasonal (October – January) evaporation (mm.day⁻¹). a) 35 years, b) El Niño - Mean, c)
 802 La Niña - Mean, and d) El Niño - La Niña years between 1979-2015.

803

804

805

806

807

808

809

810

811

812 Figure 15. Schematic presentation of the different synoptic scale features associated with RSCZ and
813 rainfall during (a) Normal, (b) El Niño, and (c) La Niña years. The direction of white line indicates the
814 moisture transport pathways. Surface winds over the Red Sea are presented by red and blue arrows
815 (thicker indicates stronger magnitudes). As in De Veries et al., (2013); (H) refers to High pressure system;
816 (A) to Arabian Anticyclone, (RST) to Red Sea Trough, (STJ) to Sub Tropical Jet, (3L) to Upper Level
817 Trough, (RSCZ) to Red Sea Convergence Zone, and white color clouds to convective activity.

818

819

820 Figure S1. Mean seasonal (October – January) hydrological cycle of a) evaporation (mm.day^{-1}), b)
 821 precipitation (mm/day), c) evaporation – precipitation (mm/day), and d) vertically integrated moisture ($\times$
 822 $10^{-6} \text{ kg.m}^{-2}.\text{sec}^{-1}$, shaded convergence) between 1979-2015. The arrows indicate the moisture transport
 823 vectors ($\text{kg.m}^{-1}.\text{sec}^{-1}$). The right panel is (35 year mean), middle panel is (El Niño – Mean) and left panel is
 824 (La Niña – Mean).

825

826

827

828

829

830

Figure 2s. Mean seasonal (October – January) winds (m/sec) and geopotential (shaded, gpm) at 850 hPa. a) 110 years, b) El Niño – Mean, c) La Niña - Mean, and d) El Niño - La Niña years between 1901-2010.