Regional Hydrological Cycle over the Red Sea in ERA-Interim

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ABSTRACT

The major sources of atmospheric moisture over the Red Sea are analyzed using ERA-Interim for the 1979–2013 period. The vertical structure of moisture transports across the coastlines has been computed separately for the western and eastern coasts of the Red Sea. The vertical structure of the moisture transport from the Red Sea to the continents is dominated by a breeze-like circulation in the near-surface layer and the Arabian high above 850 hPa. The lower-layer, breeze-like circulation is acting to export the moisture to the northwest of Africa and to the Arabian Peninsula and contributes about 80% of the moisture exports from the Red Sea, dominating over the transport in the upper layer, where the moisture is advected to the Arabian Peninsula in the northern part of the sea and to the African continent in the southern part. Integrated moisture divergence over the Red Sea decreased from the early 1980s to 1997 and then increased until the 2010s. Associated changes in the moisture export were provided primarily by the increasing intensity of the breeze-associated transports. The transports above the boundary layer, while being strong across the western and the eastern coasts, have a smaller effect on the net moisture export. The interannual variability of the moisture export in the near-surface layer was found to be closely correlated with the variability in sea surface temperature, especially in summer. Implications of the observed changes in the moisture advection for the hydrological cycle of the Middle East are discussed.

1. Introduction

The Red Sea is a unique basin characterized by extremely high evaporation, which amounts to 1.6–1.9 m yr$^{-1}$ for the whole sea (Tragou et al. 1999) and may increase to more than 3 m yr$^{-1}$ in the northern part (e.g., Papadopoulos et al. 2013). Upon rising into the atmosphere, this moisture participates in the regional hydrological cycle, influencing water content and precipitation over the adjacent continents. Over the Arabian Peninsula, precipitation, while very rare, has undergone downward changes during the last decade, as reported by station data (AlSarmi and Washington 2011, 2014) and the Tropical Rainfall Measuring Mission (TRMM; Almazroui 2011). Nevertheless, moisture transports from the Red Sea and the Arabian Sea result in heavy precipitation events even over the hyperarid Arabian Peninsula (Kumar et al. 2015). While Viste et al. (2013) reported an intensification of drying conditions over northeastern Africa, Mekasha et al. (2014) demonstrated that heavy precipitation events intensified over the last three decades, particularly in the East African Rift Valley.
The impact of the Red Sea on the climate of the adjacent continents is influenced not only by the evaporation from the Red Sea but also by moisture transports that are closely related to the regional and larger-scale circulation patterns, including the North African jets, intertropical convergence zone (ITCZ), ENSO, Indian monsoon, and Mediterranean circulation modes linked to the Atlantic circulation patterns, such as the NAO (see, e.g., Kar and Rana 2014). Most of these factors have strong seasonal manifestations (e.g., Athar and Ammar 2016). Thus, seasonally dependent moisture export from the tropics to the Mediterranean region (Krichak et al. 2014) implies seasonality in the northeastern Africa–Arabian moisture advection. Spinks and Lin (2015) and Spinks et al. (2015) demonstrated that, in summer, the Arabian high may contribute to the intensification of the local winds and to the westward propagation of the easterly waves and that this effect has intensified over recent decades. Large-scale circulation modes (the NAO and Indian monsoon) can influence air–sea exchanges over the Red Sea (Papadopoulos et al. 2013; Abualnaja et al. 2015). As a diabatic source of heat and moisture, the Red Sea contributes to the generation of local circulation patterns, such as the Red Sea Trough (Krichak et al. 2012), that are associated with abundant precipitation in northeastern Africa. Viste and Sorteberg (2013) identified the southern Red Sea as one of the major sources of moisture transport to the Ethiopian highlands.

An important factor affecting surface fluxes and contributing to moisture transports is the variability of the Red Sea SST. In addition to the interplay with surface turbulent fluxes, SST steers to a large extent the sea–land temperature contrasts and associated breeze-like circulation in the lower atmosphere. Raitos et al. (2011) recently reported an abrupt warming signal in the Red Sea SST in 1994–95, which has important implications for coral growth (Cantin et al. 2010) but should also have a signature in the dynamics of the atmospheric moisture transports.

In this study, we analyze the mechanisms forming atmospheric moisture exports from the Red Sea during the last decades. We use ERA-Interim data (Dee et al. 2011) over the Red Sea and adjacent continents. We will place our analysis in the context of ocean-to-land moisture transports (Trenberth et al. 2011; Trenberth and Fasullo 2013a,b; Zahn and Allan 2013b). Originally proposed for the global and continental scales, this concept can also be used for regional studies. The paper is organized as follows. Section 2 briefly describes the data and the methods used to compute moisture transports. Section 3 is focused on the climatological characteristics of the moisture budget components over the Red Sea, and section 4 analyses the interannual variability in the regional moisture sources in association with atmospheric dynamics. Section 5 concludes the paper by discussing the potential role of local and nonlocal mechanisms in forming the interannual variability of the moisture export from the Red Sea.

2. Data and methods

a. ERA-Interim

We used atmospheric variables and derived parameters from ERA-Interim (Simmons et al. 2007; Dee et al. 2011) produced using the T255L60 ECMWF operational model with 60 levels in the vertical and the four-dimensional variational data assimilation (4DVAR). SST in ERA-Interim was combined from different operational products (Dee et al. 2011). We used the 6-hourly latent heat flux and derived the evaporation, precipitation, components of the wind speed, specific humidity, and vertically integrated divergence of the moisture flux for the period 1979–2013. We used ERA-Interim output available on a 0.125° grid. Of course, the output at this resolution does not refine the atmospheric state variables originally computed either at T255 spectral resolution or on the reduced N128 grid. However, this grid allows a better matching of the reanalysis variables to the coastline and more accurate analysis of sea-to-land transports over the Red Sea. We also performed the analysis using the 0.75° output (approximately equivalent to the original spectral resolution of ERA-Interim), and the results were very close to the ones obtained using the 0.125° output. The performance of ERA-Interim over the Middle East has been analyzed by Almazroui et al. (2015), who demonstrated a reliable representation of the major circulation types, and also by de Vries et al. (2013), who associated regional circulation patterns (the Red Sea Trough) with extreme precipitation events. Viste and Sorteberg (2013) used ERA-Interim in conjunction with the Flexible Particle Dispersion Model (FLEXPART) code (Stohl et al. 2005) to identify moisture sources for the Ethiopian highlands.

b. Methods

We considered the vertically integrated moisture budget equation (e.g., Trenberth and Guillemot 1995; Cullather and Bosilovich 2011; Trenberth et al. 2011; Trenberth and Fasullo 2013b)

\[
\frac{\partial W}{\partial t} + \text{VIDMF} = E - P, \tag{1}
\]

where \( W \) is the vertically integrated atmospheric moisture content, \( E \) is evaporation, \( P \) is precipitation, \( t \) is time, and VIDMF is the vertically integrated divergence of the moisture flux:
VIDMF = \nabla \cdot VIMF = \nabla \frac{1}{g} \int P_{\text{sat}} v dq dp, \quad (2)

where VIMF is the vertically integrated moisture flux (vq), with v being the wind velocity vector and q the specific humidity, g is gravity, and the integration is performed with pressure p from the top of the atmosphere \( P_{\text{sat}} (\approx 0) \) to surface \( P_{\text{sat}} \). For the atmospheric column over the Red Sea, considered as a finite area A bounded by the contour L associated with the sea coastline,

\[
\int_A \frac{\partial W}{\partial t} \, da + \int_A \text{VIDMF} \, da = \int_A (E - P) \, da, \quad (3)
\]

which, according to the Ostrogradsky–Gauss divergence theorem, is equivalent to

\[
\int_A \frac{\partial W}{\partial t} \, da + \int_L \text{VIMF} \cdot n \, dl = \int_A (E - P) \, da, \quad (4)
\]

where VIMF \cdot n is the moisture flux normal to the domain boundary. Note that diagnostic evaluation of the moisture budget in the reanalysis associated with the computation of finite divergences results in the mismatch between \( \int_A \text{VIDMF} \, da \) and \( \int_L \text{VIMF} \cdot n \, dl \) highlighted by Seager and Henderson (2013). For the sufficiently long times (e.g., annual average), however, \( \partial W/\partial t \) in (1)–(4) is near zero and can be neglected.

We analyzed 6-hourly estimates of \( E, P \), computed components of the moisture transports at different levels as well as moisture content, and the divergence of the moisture flux over the Red Sea area, as defined by the ERA-Interim land mask (Figs. 1a,b). The importance of applying this procedure to the instantaneous state variables was justified by Zahn and Allan (2011, 2013a). For vertical integrations, we used all 60 model levels. Then, for the analysis of the vertical structure of the transports, we derived vertical profiles of the zonal and meridional transport components for each grid point at 23 pressure levels from the surface to 200 hPa. To analyze the mechanisms associated with the Red Sea modulation of the moisture transports, we vertically integrated the transports across the western coast (WC) and the eastern coast (EC) of the Red Sea (Fig. 1b) separately. Together, these two transports account for \( \approx 97\% \) of the VIMF over the Red Sea, implying a relatively minor role of the transports through the northern and the southern boundaries.

3. Climatology of the moisture budget components over the Red Sea

a. Climatological structure of the vertically integrated moisture transport

Figures 1c–f demonstrate the major components of the moisture budget over the region \( 10^\circ–35^\circ N, 26^\circ–60^\circ E \). The orography of the region is shown in Fig. 1a. The climatological evaporation in ERA-Interim shows that the major sources of moisture are associated with the adjacent ocean areas. Over the Red Sea, the maximum annual evaporation of approximately \( 5 \text{ mm day}^{-1} \) (equivalent to \( \approx 150 \text{ W m}^{-2} \)) is observed in the northern region, where it varies from \( 4.6 \text{ mm day}^{-1} \) in July to \( 6.3 \text{ mm day}^{-1} \) in January. This finding is consistent with OAFlux (Yu and Weller 2007) estimates (Papadopoulos et al. 2013; Abualnaja et al. 2015) as well as with other modern-era reanalyses, such as MERRA (Abualnaja et al. 2015).

The climatological maximum of annual precipitation (Fig. 1d) is associated with the elevated southwestern Arabian Peninsula and northeastern Africa, where local precipitation may amount to \( 9 \text{ mm day}^{-1} \). This finding is consistent with station-based analyses by AlSarmi and Washington (2011) and Almazroui et al. (2012). While ERA-Interim generally realistically represents regional precipitation, some uncertainties may exist and are difficult to quantify because there are very few rain gauge observations in this area (AlSarmi and Washington 2011, 2014). The precipitation data from TRMM should be used with care in this area because of the impact of dust storms on TRMM retrievals. The dust storms (on average 20 annually) over the Arabian Peninsula are especially intense in summer. Over the Red Sea, dust optical depth in summer exceeds 1 in the southern region (Brindley et al. 2015), with an average value of 0.4–0.5 (Jish Prakash et al. 2015). Almazroui (2011) found an overestimation of precipitation in TRMM by approximately 10% compared to station data over the Arabian Peninsula.

The climatological net evaporation \( E - P \) (Fig. 1e) clearly demonstrates the major role of marine areas in net evaporation. Over the Red Sea, \( E - P \) is very close to \( E \) and varies from \( 3–4 \text{ mm day}^{-1} \) in the south to more than \( 5.5 \text{ mm day}^{-1} \) in the north. The seasonal variations in \( E - P \) (not shown) are most pronounced in the northern region, where net evaporation increases from \( 4.5 \text{ mm day}^{-1} \) in summer to \( 6.5 \text{ mm day}^{-1} \) in winter. These changes are almost completely driven by evaporation. A strong impact of precipitation on \( E - P \) is observed only in the southern elevated part of the Arabian Peninsula and over the East African Rift Valley, where precipitation ranges from \( 2.7 \text{ mm day}^{-1} \) in winter to \( 10.9 \text{ mm day}^{-1} \) in summer (no figure shown).

Figure 1f shows that the Red Sea represents an area of strong moisture divergence with the maximum transport between \( 20^\circ \) and \( 26^\circ N \), where the annual mean divergences amount to \( 75 \times 10^{-6} \text{ kg m}^{-2} \text{ s}^{-1} \) (up to \( 85 \times 10^{-6} \text{ kg m}^{-2} \text{ s}^{-1} \) in winter and from \( 60 \times 10^{-6} \) to \( 70 \times 10^{-6} \text{ kg m}^{-2} \text{ s}^{-1} \) in summer). The large-scale pattern of
Vertically integrated moisture advection is controlled by the Arabian high, driving the eastward moisture transport over the northern part of the Red Sea and primarily westward advection in the southern part. The annual mean divergences also reveal a pattern associated with the Asir mountain ridge. In summer, locally strong moisture convergence over land is associated with the southern coast of the Arabian Peninsula and the Ethiopian highlands (no figure shown). January–July intensification (30%–50%) of the westward moisture transports in the southern region results from the 2°–2.5° latitude shift of the Arabian high because of interseasonal
changes in the Hadley circulation and the associated migration of the ITCZ.

Table 1 summarizes the area-integrated climatological moisture budget over the Red Sea. Throughout the year, $E - P$ is dominated by evaporation, which exceeds precipitation by approximately 15–17 times. This ratio may even be slightly underestimated given the somewhat positively biased precipitation in ERA-Interim (Simmons et al. 2007). The net evaporation is balanced by the moisture divergence from the Red Sea to the adjacent continents. The mismatch between $E - P$ and integrated divergence is approximately 3%–5% for the annual and winter values and amounts to 12% in summer.

The transport components across the shorelines of the WC and EC (Fig. 2a) were integrated within 1° bands (Fig. 1b). The distance between the WC and EC ranges from 200 km in the northern region to approximately 400 km at 16°–18°N. In the northern part of the Red Sea, the eastward transports through the EC are from $0.5 \times 10^6$ to $2 \times 10^6$ kg s$^{-1}$ (°)$^{-1}$ [i.e., the mass per unit time transport through 1° latitude (111.2 km) base; see caption of Fig. 2a for a detailed explanation of the units] higher than through the WC. In the southern region, the westward transport through the WC is somewhat stronger than through the EC by $0.2 \times 10^6$ to $1.5 \times 10^6$ kg s$^{-1}$ (°)$^{-1}$. The total transport across the WC and EC (approximated as in Fig. 2a) closely matches the moisture transports precisely integrated along the coastline (Table 1). Thus, we can reasonably assume that the moisture is exported primarily across the WC and EC, forming the moisture convergences over the Arabian Peninsula (eastward transport from the Red Sea in the north) and over northwestern Africa (westward transport in the south).

The seasonal variations of the vertically integrated moisture transports through the WC and EC (Figs. 2b, c) are small to the north of 21°N, where they are from $0.1 \times 10^6$ to $0.5 \times 10^6$ kg s$^{-1}$ (°)$^{-1}$ (approximately 1%–6% of the annual transports). At the same time, in the southern region, the moisture transports undergo significant seasonal changes associated with the migrations of the ITCZ. South of 16°N, westward July transports across both the WC and EC become 1.2–2 times stronger than in January. Note that the southernmost westward transport values may be affected by the moisture transport

<table>
<thead>
<tr>
<th>Source term</th>
<th>Annual</th>
<th>January</th>
<th>July</th>
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<tr>
<td>$E - P$</td>
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<td>4.59</td>
<td>3.69</td>
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<tr>
<td>$E$</td>
<td>4.45</td>
<td>4.82</td>
<td>3.80</td>
</tr>
<tr>
<td>$P$</td>
<td>0.24</td>
<td>0.31</td>
<td>0.17</td>
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<tr>
<td>Moisture divergence</td>
<td>4.13</td>
<td>4.88</td>
<td>4.23</td>
</tr>
<tr>
<td>Divergence diagnosed from the transport across the EC and WC</td>
<td>4.11</td>
<td>4.52</td>
<td>4.35</td>
</tr>
</tbody>
</table>

Table 1. Atmospheric moisture budget components integrated over the Red Sea (mm day$^{-1}$; equivalent to $5.249 \times 10^3$ kg s$^{-1}$ or $1.1574 \times 10^{-8}$ kg m$^{-2}$ s$^{-1}$ for the Red Sea mirror being $4.535 \times 10^3$ m$^2$). Positive signs correspond to the divergence of moisture from the atmospheric column over the Red Sea.

Fig. 2. (a) Spatial latitudinal structure of the climatological mean (1979–2013) vertically integrated moisture transport through the WC (green) and EC (yellow) shown in inset, as well as January (cyan) and July (orange) vertically integrated moisture transport (1979–2013) through the (b) WC and (c) EC of the Red Sea. Transports are given in units of $10^6$ kg s$^{-1}$ per degree latitude (111.2 km) base [$10^6$ kg s$^{-1}$ (°)$^{-1} = 9$ kg s$^{-1}$ m$^{-1}$].
from the Gulf of Aden, rather than from the Red Sea, which becomes very narrow in the west–east direction at these latitudes.

b. Climatology of the vertical structure of the moisture transport

Figure 3 demonstrates the virtual alongshore sections of the annual mean moisture transport across the WC and EC, which were constructed by integrating transports at every level over 1° latitudinal bands. The integrated transports result from two major advective mechanisms. In the boundary layer, the strong divergence of moisture out of the Red Sea is associated with the westward moisture flux to Africa through the WC and the eastward flux to the Arabian Peninsula across the EC. This behavior is the effect of the sea-to-land transports driven by temperature gradients between the African and Arabian deserts and the sea. The extent to which this pattern can be directly attributed to the Red Sea breezes (Miller et al. 2003; Eshel and Heavens 2007; Peleg and Morin 2012; Gille and Llewellyn Smith 2014), however, is questionable. ERA-Interim with its ~75-km resolution is unlikely to resolve the real breeze circulation, which has shallow cells that can only be captured by much finer resolution configurations. However, without resolving the local breezes, ERA-Interim captures the larger-scale, breeze-like flows associated with diurnal variations of the pressure gradient in the coastal regions, and the integrated effect of breezes can thus be observed in ERA-Interim. It is possible that data assimilation may trigger breeze-like effects in ERA-Interim. The capability of ERA-Interim to capture this effect was also reported by Muppa et al. (2012) for the Bay of Bengal.

Analysis of the cell structure of breezes in ERA-Interim (not shown) shows that in most cases, the reanalysis is capable of reproducing the diurnal change in the wind direction and associated moisture transports. However, the cell structure of breezes could be captured in only 30%–40% of cases. Zahn and Allan (2013b), in their continental-scale computations of ocean-to-land moisture fluxes, also demonstrated two-layer structure of the moisture transport for the EC and WC of the Red Sea. In some regions, the influence of breezes over the EC and WC may expand to the whole sea (Khan et al. 2015) and also affect surface conditions over the sea (Blythe et al. 2011; Churchill et al. 2014).

The integrated effect of breeze-like circulation consists of moisture exports from the sea because the small desert-to-sea transports during the nighttime cannot compensate for the much stronger advection from the sea to the land during the daytime. Figure 4a demonstrates the structure of the moisture transports across the WC and EC at 975 hPa (maximum intensities of the boundary layer transports; Fig. 3). The strongest export of moisture is observed at 18°–23°N across the WC and southward of 20°N across the EC. The spatial structure of the moisture fluxes at 975 hPa (Fig. 4a) clearly shows
that the breeze-like circulation results in a strong divergence of moisture over the Red Sea because of the moisture export across both coasts. Note that the export through the EC in the southern part also provides the conditions for the local moisture divergence over the 3-km-high Asir mountain ridge, which shows a clear signature in the vertically integrated convergence (Fig. 2) as well as in precipitation (Fig. 1d).

Above the boundary layer, the moisture transport is primarily steered by the Arabian high (Fig. 4b). Eastward moisture advection over the northern part of the sea has the maxima of $14.2 \text{ g kg}^{-1} \text{ m s}^{-1}$ through the EC and $15.9 \text{ g kg}^{-1} \text{ m s}^{-1}$ through the WC at 700 hPa. A westward moisture flux at 700 hPa with magnitudes of approximately $20 \text{ g kg}^{-1} \text{ m s}^{-1}$ at both coasts is observed south of $18^\circ \text{N}$. This structure implies that the pattern of the moisture transport at 700 hPa is qualitatively similar to the pattern shown in Fig. 4b, reflecting the signature of the Arabian high in the regional moisture advection. This structure also holds for the upper troposphere, with the magnitudes strongly decreasing (by 4–5 times at 400 hPa and by more than 20 times at 200 hPa) as the amount of moisture becomes very small (Fig. 3). Note that in summer, the breeze-associated transports in the southern part of the sea are particularly dumped (no figure shown), resulting in an annual mean seaward transport of approximately $17.5 \text{ g kg}^{-1} \text{ m s}^{-1}$ even at the 975-hPa level. This finding might be associated with the summer shift of ITCZ as well as with the active phase of the Somali jet, blowing to the east.

4. Interannual changes in the moisture budget over the Red Sea

a. Changes in the net evaporation and total moisture divergence

Figure 5a shows the annual time series of evaporation, precipitation, and net evaporation from the Red Sea, as implied by ERA-Interim. In the late 1990s, the hydrological cycle over the Red Sea underwent considerable change. Before 1997, the annual area-integrated precipitation varied from 0.18 to 0.36 mm day$^{-1}$, and
Evaporation declined slightly from 4.5 to 4.3 mm day$^{-1}$. A strong precipitation anomaly in 1997 (exceeding by 3 times the long-term average) was recorded by several rain gauges (AlSarmi and Washington 2011, 2014; Almazroui et al. 2012) and was also detected in other Middle East regions (Dayan et al. 2001). After 1996, there was a sharp increase in evaporation by 0.4–0.5 mm day$^{-1}$ over a few years and a simultaneous decrease in precipitation by 0.1 mm day$^{-1}$, which resulted in an increase in the net evaporation from the Red Sea by approximately 0.6 mm day$^{-1}$ compared to the period prior to the mid-1990s. This increase in evaporation (and latent heat flux) is confirmed by alternative datasets (not shown). Thus, OAFlux (Yu and Weller 2007) implies an increase of 0.6 mm day$^{-1}$ from 1996 to 2002, and National Oceanography Centre, version 2.0 (NOC-2.0), climatology (Berry and Kent 2009) suggests an increase of approximately 0.7 mm day$^{-1}$ for the same period. These estimates are generally consistent with the increase reported by ERA-Interim (Fig. 5a).

During the 1980s and 1990s, changes in the moisture divergence from the Red Sea due to lateral moisture transport (Fig. 5b) were generally consistent on a long-term scale, with the changes in $E - P$ showing a moderate decrease in the period until 1997, followed by sharp growth from $17 \times 10^6$ to $18 \times 10^6$ kg s$^{-1}$ to more than $26 \times 10^6$ kg s$^{-1}$, implying a drastic (more than 50%) increase in the moisture export from the Red Sea to the adjacent land. As we noted above, a simultaneous increase in $E - P$ was observed only until 2000 and became quite stable afterward.

Figure 5c shows that the interannual variabilities in the transports across the two coasts are at first glance very similar to each other, and neither is correlated with the total moisture divergence shown in Fig. 5b. The strongest transports integrated over both the WC and EC (from $60 \times 10^6$ to $70 \times 10^6$ kg s$^{-1}$ and from $40 \times 10^6$ to $55 \times 10^6$ kg s$^{-1}$, respectively) were observed in the mid-1990s. The moisture transports then considerably declined, ranging from values near zero to approximately $20 \times 10^6$ kg s$^{-1}$ across the African coast and from $20 \times 10^6$ to $45 \times 10^6$ kg s$^{-1}$ across the coast of the Arabian Peninsula. Thus, the strong increase in the moisture export from the Red Sea after 2000 (Fig. 5b) is implied by the difference between the transports across the WC and EC.

The increase in moisture divergence after the late 1990s was qualitatively consistent in sign throughout the year for
all seasons (not shown), with approximately 50% stronger changes in spring and in autumn. Similarly, the time evolutions of the moisture transports across the WC and EC are consistent with each other and are highly persistent throughout the year. Seasonality in the magnitude of the transports at both coasts appears after the early 2000s, when positive anomalies during the winter/spring season are associated with negative anomalies in summer.

b. Changes in the spatial structure of moisture transport

We compared the vertically integrated moisture transports through the WC and EC for the pentads 1995–99 and 2008–12, when the moisture divergences were, respectively, the smallest [(19.0 ± 0.79) × 10^6 kg s^-1] and the largest [(24.9 ± 0.74) × 10^6 kg s^-1], along with E − P [20.7 ± 1.08] × 10^6 kg s^-1 and (22.9 ± 0.58) × 10^6 kg s^-1]. The corresponding downward change in precipitable water content between the two periods was equivalent to 3.93 × 10^6 kg s^-1, roughly compensating for the changes in moisture divergence and E − P and implying drier conditions for 2008–12 than 1995–99. The increase in the annual mean moisture divergence between the two periods has been provided primarily by moisture export through the southern part of the WC, which increased by 12%–17% in 2008–12 compared to 1995–99 (Figs. 6a,b). Note also a change in sign of the transport between the two periods at latitudes 18°–21°N. At latitudes north of 18°N, the transports through the EC to the Arabian Peninsula were stronger during 1995–99 than in 2008–12 by 15%–45%.

The annual pattern was primarily produced by the northward shift of the point of change of the transport sign, which is especially evident in July (Figs. 6c,d). During 2008–12, strong advection of moisture from the Red Sea to Africa is observed south of 21°N, while during 1995–99, westward transport is detected only south of 17°N and is 15%–20% weaker than in 2008–12. Thus, the integrated westward moisture transport through the WC in July during 2008–12 was 2.2 times larger than in the period 1995–99. A similar change in the moisture advection to Africa across the WC is observed in January (no figure shown), when it is likely associated with the change in the Red Sea convergence zone (RSCZ; Pedgley 1966). For all seasons, estimates for the southernmost band should be considered with some caution because of considerable advection of moisture in this region from the Gulf of Aden rather than from the Red Sea, which is diminished sharply south of 14°N. Nevertheless, even excluding this southernmost part, we obtain 93.5 × 10^6 kg s^-1 in July for 2008–12, which is 2.8 times higher than in 1995–99.

Figure 7 shows the changes in the vertically integrated moisture transport between 1995–99 and 2008–12. Between these two periods, a distinct northward shift of the Arabian high by 200–300 km resulted in a weakening of the annual mean moisture transport in the northern part and a turn of the transport vectors over the Red Sea clockwise, implying a significant transport component along the sea axis. This change likely demonstrates the shift in the RSCZ noted for the winter period by, for example, Tucker and Pedgley (1977). As a result, a considerable amount of air transported across the northern part of the WC during 2008–12 was further advected to the south, gaining moisture over the sea. This moisture then returned to the African continent at latitudes 15°–22°N, moistening southern Egypt and northern Ethiopia. Thus, the eastward transport across the northern part of the EC decreased considerably between 1995–99 and 2008–12 (Fig. 7c).

c. Interannual variability of the vertical structure of moisture transport

The vertical structure of the moisture transport (Figs. 3, 4) suggests different impacts of the boundary layer and the layer above 850 hPa in the observed changes in the vertically integrated moisture advection. Figure 8 shows that in the boundary layer, transport across the EC due to the breeze-like sea–land advection has been increasing since the mid-1980s, implying an intensified advection of moisture to the Arabian Peninsula. The overall trend at the 975-hPa level was nearly 9% decade^-1, with the change from 1989 to 2013 being over 20% decade^-1. At the same time, after a sharp drop in magnitude in the mid-1990s, the moisture transport across the WC (the negative sign in Figs. 5 and 8 corresponds to westward transport) intensified in the late 1990s by approximately 20%–25%. Thus, the breeze-like circulation intensified the moisture exports from the Red Sea during the 1980s because of the increasing advection through the WC, which weakened from the late 1980s to the early 1990s. After the mid-1990s, sea-to-land transport acted to increase moisture divergence due to both growing advection to the Arabian Peninsula across the EC and intensified moisture export to Africa. Above 850 hPa the transports at the individual coasts show qualitatively similar patterns above the boundary layer (Fig. 8). They were the strongest in the early and mid-1990s, peaked in 1997 at approximately 800 × 10^-2 g kg^-1 m^-1 s^-1, and then decreased considerably during the late 1990s by approximately 2.5 times to values of 200 × 10^-2 to 300 × 10^-2 g kg^-1 m^-1 s^-1. However, the net effect of moisture export above 850 hPa is ~8 times weaker than the contribution from the boundary layer (Fig. 8). Thus, during the last 20 years, the sharp increase in moisture export from the Red Sea (Fig. 5) was provided primarily by the changing structure and intensity of the low-level, breeze-like sea-to-land advection over the EC and
WC. The downward changes in the upper-layer moisture export (Fig. 8) compensated for less than 15% of the low-level signal.

The seasonal variability in the moisture transport for the 975-hPa level (Figs. 9a,b) shows an important role of the summer season in the annual mean changes due to breeze-like circulation. At the WC, the negative anomalies before 1993 (stronger moisture advection to the African continent) and the positive anomalies during the mid- and late 1990s (weaker moisture export to Africa)
FIG. 7. Vertically integrated atmospheric moisture transports (kg m$^{-1}$ s$^{-1}$) for the periods (a) 1995–99 and (b) 2008–12 as well as the differences in the moisture transports (c) between 2008–12 and 1995–99.
during June–August (JJA) are 5–16 times larger than in the other seasons. The strongest negative anomalies of the moisture transport across the EC during the 1980s and early 1990s (weaker moisture advection to the Arabian Peninsula) as well as the positive anomalies after the mid-1990s (stronger moisture export to the Arabian Peninsula) are also observed in summer. The stronger effect of the breeze-like circulation on the moisture export during summer can be explained by the extremely dry air over the adjacent continents, which results in negligible land-to-sea moisture transport during the nighttime breeze. Thus, the net effect of moisture transport in the lower layer is almost wholly due to the daytime advection acting to export moisture from the Red Sea to the land. Above the boundary layer, changes in the moisture transport across the WC and EC are well coordinated with each other in all seasons (no figure shown) and demonstrate strong positive anomalies during the 1990s followed by negative anomalies in the 2000s, with somewhat stronger magnitudes in winter.

Figure 10 shows the vertical profiles of the moisture transport for the annual mean and July for the latitudinal band 22°–25°N during the periods of low (1995–99) and high (2008–12) moisture exports from the Red Sea. The increasing landward moisture advection in July in the boundary layer across both coasts contributes to the divergence of moisture to both the Arabian Peninsula and northeastern Africa (Fig. 10b). This effect, which is largest in summer, is also evident in the annual average (Fig. 10a). Above the boundary layer, the changes are much smaller, and the integrated effect is small compared to the boundary layer. Thus, while the moisture transports above the boundary layer may experience strong interannual variability, they are highly correlated with each other at both coasts, and their net effect on the moisture divergence over the Red Sea is quite small.

The variability of the transports across the both coasts above the boundary layer is largely controlled by the large-scale circulation patterns. Figure 11 shows the first empirical orthogonal functions (EOFs) at the 700-hPa level for January–March (JFM) and July–September (JAS) and the normalized principal components (PCs) along with the normalized anomalies of the moisture transports at 700 hPa. The leading EOFs (44% of explained variance for JFM and 32% for JAS) imply intensification/deintensification of the transports associated with the Arabian high and its south-to-north shifts. Papadopoulos et al. (2013) and Abualnaja et al. (2015) argued that these changes are likely dominated by the North Atlantic–European circulation pattern. The corresponding normalized PCs (Figs. 11b,c) are negatively correlated with the anomalies of the moisture transport at 700 hPa at both coasts, with correlation coefficients from −0.77 to −0.79 for winter (JFM) and −0.56 to −0.63 for summer (JAS). However, this variability does not imply a similar variability in the moisture divergence because the net effect of the transports across both coasts is quite small.

The strong variability of the intensity of the breeze-associated moisture transports across both coasts suggests a careful look at the mechanisms of intensification of sea-to-land circulation in the late 1990s and 2000s. Raitos et al. (2011) reported an abrupt change in the Red Sea SST in the mid-1990s characterized by a change of approximately 1.5°C during 1993–95, which resulted in a 0.7°C difference in the average SST between the periods before and after 1994. Air temperatures followed this signal, but with a smaller magnitude. Assuming sea-to-land advection to be controlled by sea–land temperature differences, an increasing SST could potentially result in the intensification of moisture divergence. Figure 12 shows the correlations of the moisture divergence below 850 hPa with the Red Sea SST from the Hadley Centre Sea Ice and Sea Surface Temperature dataset, version 1 (HadISST1; Rayner et al. 2003). Remarkably, in summer (JAS), when the effect of
breezes is likely the strongest, the correlation amounts to more than 0.78 (Fig. 12a). In winter, the correlation is somewhat lower (no figure shown) but exceeds 0.55 in most locations. The correlation for annual anomalies (Fig. 12b) is higher than 0.6 in many locations. Thus, the SST strongly influences the intensity of the moisture export from the Red Sea throughout the year, implying a modulating role of the Red Sea in the hydrological cycle of the adjacent continents.

5. Summary

We analyzed the moisture sources over the Red Sea and its role in modulating the regional hydrological cycle during the last 35 years in ERA-Interim. Our study performs a regional zoom on the global assessments of the ocean-to-land moisture transports (Trenberth et al. 2011; Trenberth and Fasullo 2013a,b; Zahn and Allan 2013b). The moisture export from the Red Sea is associated with two major mechanisms: breeze-like circulation, providing moisture divergence across the WC (westward) and EC (eastward) in the layer below 850 hPa, and moisture advection in the layer above 850 hPa (with a maximum at 650–700 hPa), providing moisture export to the Arabian Peninsula in the northern part and in the opposite direction to Africa in the central and southern parts of the sea. The moisture export in the boundary layer dominates over the transport above 850 hPa, contributing more than 80% of the total moisture export from the Red Sea to the adjacent continents. The atmospheric moisture divergence from the Red Sea demonstrated a minimum in 1997 and then sharply increased from the late 1990s to the early 2010s by approximately 40%, implying strong vertically integrated moisture export from the Red Sea. This strong increase was primarily driven by the changes in the moisture flux due to breeze-like circulation in the boundary layer. During the 1980s, breezes contributed greatly to the moisture export to the Arabian Peninsula, whereas starting in the mid-1990s, they transported moisture equally to northeastern Africa and to the Arabian Peninsula. The moisture transports above 850 hPa are closely correlated with the time behavior of the Arabian high. These changes result in quite strong anomalies of the moisture transports across both coasts; however, the net effect on the moisture export is minor. The interannual variability in the moisture export from the sea by breezes is closely correlated with the

Fig. 9. Interannual evolution of the monthly transport anomalies (smoothed with 5-yr running mean) at the 975-hPa level for the (a) WC and (b) EC of the Red Sea.
interannual variations in the SST, driving the intensity of the sea-to-land advection.

6. Discussion and perspectives

Our work opens several interesting lines of further development. The first question is how robust the identified climatological structure and variability patterns are. Thus, an intercomparison of the results revealed by ERA-Interim and other reanalyses will be desirable. Abualnaja et al. (2015) used MERRA (Rienecker et al. 2011) to link the Red Sea heat flux anomalies with atmospheric circulation patterns. Differences in the reanalysis resolutions, model vintage, and data assimilation systems may result in differences in the estimates of the atmospheric hydrological cycle components. Intercomparison will help to identify the components and variability patterns that are most consistent across different products. In the extratropics reanalyses demonstrate a strong spread of $E - P$, but they are quite consistent in terms of the moisture transport and its interannual variability (Dufour et al. 2016). It will be interesting to determine whether this case holds for the Middle East tropics.

Next, a validation of the evaporation changes in ERA-Interim against alternative products such as OAFlux (Yu and Weller 2007) and ICOADS-based flux (Josey et al. 1999; Grist and Josey 2003; Berry and Kent 2009) would be highly desirable. It is interesting how changing surface winds (Papadopoulos et al. 2013; Abualnaja et al. 2015) can affect surface evaporation, which in turn modulates local moisture transports. A sharp increase in evaporation in the 1990s that is somewhat delayed with respect to the change in SST (Raitsos et al. 2011) can be also analyzed in a view of long-term changes in surface fluxes (both synchronic and lagged) modulated by the Red Sea SST and associated with longer-term intrinsic modes of the Red Sea variability. This analysis, however, requires much longer time series than those available from the modern reanalyses. Given that the Red Sea is characterized by very good sampling of surface meteorological observations starting from 1900 (Woodruff et al. 2011), a challenging possibility is the analysis of interdecadal changes in evaporation, which can be derived using the approach of Gulev and Belyaev (2012), along with the moisture transports revealed by centennial reanalyses (Compo et al. 2011; Poli et al. 2013).

FIG. 10. Vertical profiles of the moisture flux across the WC (solid lines) and EC (dotted lines) for the periods 1995–99 (black) and 2008–12 (red) for (a) annual average and (b) July.
Further analysis of the major driving mechanisms can involve high-resolution regional mesoscale models with a nonhydrostatic setting (e.g., WRF). We demonstrated strong differences in the moisture transports in the near-surface layer, where the transports are dominated by breezes driven by SST, and above the boundary layer, where the advection is controlled by the regional circulation patterns. The interplay between these two factors is not trivial and may also involve strong vertical motions. Locally, the transports above and within the boundary layer may show a significant correlation, higher than 0.5. In this respect, a detailed analysis of the regional moisture trajectories, which can be derived from numerical tools such as FLEXPART (Stohl et al. 2005; Brioude et al. 2013; Viste and Sorteberg 2013) embedded into reanalyses and nonhydrostatic models, would be of interest. Furthermore, high-resolution modeling of the breezes will allow an understanding of their mesoscale variability, which is not likely to be controlled by SST but rather by orographically driven jets (Jiang et al. 2009). Such modeling efforts can also help to quantify the extent to which reanalyses are capturing the effect of breezes on the moisture transports in the lower layer.

This approach may also allow analysis of the role of remote moisture sources, first of all the Mediterranean Sea and the Arabian Sea. Analyses of the moisture transports over the eastern Mediterranean using high-resolution models (Jin et al. 2011), reanalyses (Krichak et al. 2012; Zveryaev and Hannachi 2012; Sahin et al. 2015), and satellite data (Krichak et al. 2016) hint at strong linkages between the moisture budgets over the Mediterranean and the Red Sea, also involving eastern Mediterranean cyclones (Almazroui and Awad 2016). Also of interest is the role of the moisture sources associated with the Indian Ocean and controlled by the monsoon systems and the Somali jet. Although Viste and Sorteberg (2013) demonstrated that most backward trajectories do not pass through the southern part of the Red Sea, quite a few of them do so.

It is also desirable to quantify the effect of interannual variability on the positioning of the ITCZ. There is evidence that the ITCZ has shifted considerably northward over the last decade (Laderach and Raible 2013), in line with the shift of the position of the Arabian high demonstrated above. The extent to which this shift affected changes in the moisture transport can be quantified using the long-term climatology of the ITCZ position, developed from ERA-Interim using lower-tropospheric humidity (Laderach and Raible 2013).
The strong interannual changes identified in the moisture export from the Red Sea should have a profound impact on precipitation over the Arabian Peninsula and northeastern Africa. In this respect, further analysis of the precipitation variability using all available data will be desirable. We noted above that Mekasha et al. (2014) and Kumar et al. (2015) reported the growing intensity of heavy precipitation over the East African Rift Valley and the Arabian Peninsula. The mechanisms through which increased moisture export can affect precipitation over the adjacent continents are quite complicated, given that the moisture recycling in this region is modulated by various atmospheric processes in a heavily undersaturated atmosphere. Thus, it is useful to perform process studies with high-resolution model settings to illuminate these mechanisms. In this respect, the analysis of the statistical structure of moisture transports would be of particular importance, including high percentiles of the instantaneous transports. A simplified version of such an analysis was implemented by Zahn and Allan (2013a) for climate model simulations. This approach may help to identify tendencies in the occurrence of extreme moisture export episodes, which might be responsible for extreme precipitation events over land. For the Ethiopian highlands, this analysis can be complemented by Lagrangian analysis (e.g., Viste and Sorteberg 2013), allowing the identification of moisture source regions and the transport regimes associated with along-sea advection, as illustrated in Fig. 7.

Another point of interest would be the analysis of the Red Sea’s role in forming the regional hydrological cycle in climate model simulations. A realistic representation of the processes associated with the Red Sea signals is possible in very few models, given the spatial resolution of approximately 0.5°–2° of most configurations in CMIP5 (Flato et al. 2013). However, regional climate models with resolutions of, for example, 10 km (Jish Prakash et al. 2015; Kalenderski et al. 2013) may be capable of capturing the mechanisms involved. Another challenging line of investigation is the analysis of the ocean freshwater (and potentially heat) budget in the Red Sea. Given that the exchanges through the Bab el Mandeb Strait are well controlled (Murray and Johns 1997; Beal et al. 2000; Smeed 2004; Johns and Sofianos 2012), the analysis of the dynamics of the freshwater budget of the quasi-enclosed Red Sea might provide constraints for the estimation of $E - P$. Earlier works by Tragou et al. (1999), Sofianos and Johns (2002), and Sofianos et al. (2002) demonstrated that such an analysis could be accurately performed. Then, the $E - P$ estimates implied by the ocean analyses can be considered along with the ones derived from integration over an atmospheric column, thus providing a comprehensive assessment of the regional hydrological cycle.

![Fig. 12. Correlation of the moisture transport below the 850-hPa level with HadISST1 for 1° boxes of the Red Sea for (a) summer (JAS) and (b) annual average. Only statistically significant correlations at the 95% level (exceeding ±0.35) are shown.](image-url)
REFERENCES


