1. Introduction

The land-sea breeze cycle (LSBC) is an integral part of the atmospheric and ocean dynamics of coastal regions worldwide. Through its modification of the atmospheric boundary layer, it plays a central role in regional climates via surface air quality (Arya, 1999, Miller et al., 2003, Simpson, 1994, Stull, 1988), chemical and dust transport (Kitada, 1987; Miller et al., 2003, Dacre et al., 2007), as well as mesoscale convective activity (Hill et al., 2010; Pielke, 1974). It further influences the coastal ocean via effects on coastal upwelling and mixing which are essential to biological productivity (Clancy et al., 1979; Woodson et al., 2007). LSBCs and their impacts are most prominent in tropical latitudes where they manifest year-round. Here, we focus on new observations in the Red Sea, a region where one of the strongest LSBCs in the world is found.

In general terms, LSBCs occur in response to the differential heating between land and ocean surfaces which results in the development of mesoscale (2–2,000 km) horizontal pressure gradients driving cross-shore flow (e.g., Miller et al., 2003; Stull, 1988). A full description of the elements comprising the LSBC, as well as a thorough review of previous studies on the subject is presented by Miller et al. (2003). Advances in satellite wind measurements have enabled the evaluation of LSBC amplitudes globally (Gille et al., 2003; Gille et al., 2005). In particular, it has been seen that regions with large amplitude diurnal cycles are principally concentrated in the Tropics (Gille et al., 2005), with the Red Sea having one of the largest diurnal oscillations in the Northern Hemisphere.

Yet, beyond remote sensing studies, sparse information has been advanced in the characterization of the diurnal cycle above the Red Sea and its regional LSBC in particular. Among these, Pedgley’s (1974) survey of weather and climate over the Red Sea found that along the coasts, “daytime sea breezes and night-time land breezes occur almost daily year round with some evidence that the leading edges of both sea and land breezes form meso-scale fronts separating the diurnal circulations from the broad-scale flow.” Pedgley further assessed that the sea breeze around the Red Sea reaches far inland, to distances ranging from 50 to 100 km. Ensuing work by Steedman and Ashour (1976) presented further evidence that the Red Sea sea breeze is one of the largest reported in contemporary literature, penetrating as far as 225 km inland across
the northwestern Arabian Peninsula and overrunning mountainous terrain lining the coastline in the process.

The Red Sea is emerging as a region of interest in the study of climate processes and extreme weather, thus a solid understanding of its strong LSBC is important. The East African coastline of the basin has been characterized as a leading region for the production of atmospheric dust in the Northern Hemisphere (Hickey & Goudie, 2007) with extreme storms frequently lofting dust from the coastal Sudan and Egyptian coastal regions and severely impacting the Arabian Peninsula and other locations downwind (Prakash et al., 2015). The Red Sea basin serves as a leading pathway of atmospheric water vapor transport to the African highlands, a crucial center of regional rainfall (Viste & Sørteberg, 2011). There are extreme orographic jets blowing across the Red Sea in both winter and summer from within the gaps of fringing mountains (Jiang et al., 2009). The interplay of the Indian Ocean monsoons and the coastal topography (e.g., the Tokar Gap Jet) channels significant volumes of water vapor into the basin during the summer season, enhancing mesoscale convective activity around the basin in the process (Davis et al., 2015). These vapor transports have direct bearing on regional precipitation patterns, and perhaps more far-field precipitation through connections with cyclogenesis over the Atlantic and Indian Oceans (Hill & Lin, 2003).

Recent efforts have provided a preliminary understanding of the characteristics and dynamic role of the Red Sea LSBC in regional and global atmospheric processes. Jiang et al. (2009) concluded that the topography encircling the basin contributes to the intensities of the (seaward) land breezes in the Red Sea. More specifically, winds in the lower troposphere (LT) may be reinforced through interaction with mountain gaps and with synoptic and large-scale atmospheric circulations, leading to strong cross-axis surface winds based on mesoscale model simulations. Davis et al. (2015) detailed the role of these orographic flows in water vapor transport and further interactions between LSBC, East African topography, and the surface front associated with the Intertropical Convergence Zone (also referred to as the intertropical front or ITF) during the boreal summer. In particular, it was shown that the diurnal motion of the ITF facilitated the incursion of the Indian Ocean monsoons on the western side of the East African topography, forcing the nocturnal Tokar Jet and secondary gap flows with quasi-diurnal frequency. The LSBC was found to be a regulating influence in this, with the sea breeze opposing the outflow from East African coastal mountain gaps in the daytime and enhancing the gap flows in nighttime. Along the Saudi coast, Churchill et al. (2014) found the influences of the regional LSBC on the coastal ocean circulation to be significant year round, showing that the variance of the wind stress in the 11.5–34.1 hr period or sea breeze band comprised between 21% and 26% of the overall wind stress variance observed in 2 years of observations in the coastal waters of the central Red Sea (using the same data used here).

The goal of this study is to build on these recent efforts and to more fully characterize the Red Sea LSBC and its impact on regional climate with in situ meteorological measurements forming the basis for the analysis presented. We examine the magnitude of the LSBC over the Red Sea and its transformation throughout the seasonal cycle. An extension of the observational analysis is made using Weather Research and Forecasting (WRF) climate downscaling simulations and satellite measurements. In particular, the vertical structure of the LSBC, the basin-wide LSBC characteristics, as well as the LSBC ties to geography, topography, and other synoptic to mesoscale atmospheric patterns are explored. Details of the study region, measurements, and model simulations are presented in section 2. Results and discussion are presented in section 3, including an evaluation of the gravity-current nature of the LSBC, and impacts of the LSBC on regional moisture processes. Concluding remarks are presented in section 4.

2. Data, Model, and Methodology

2.1. Meteorological Tower and Air-Sea Mooring

The principal in situ measurements were taken between October 2008 and November 2011 via a Woods Hole Oceanographic Institution (WHOI) meteorological buoy deployed at 22.10°N, 38.29°E and a coastal meteorological tower constructed near Jeddah, Saudi Arabia at 22.17°N, 39.05°E (Farrar et al., 2009). The location of these platforms is indicated on the regional map presented in Figure 1a along with snapshots taken during their construction/deployment shown in Figures 1b and 1c. Two Improved Meteorological (IMET) sensor suites were installed on a surface buoy deployed in the Red Sea basin at a water depth of roughly 700 m. The IMET measurements included relative humidity, air temperature, barometric pressure, precipitation,
wind speed and direction, shortwave radiation, longwave radiation, near-surface ocean temperature, and conductivity (Colbo & Weller, 2009; Hosom et al., 1995; Payne & Anderson, 1999). The meteorological data were used to calculate surface wind stress and heat flux using the bulk formulae of Fairall et al.

Figure 1. A map of the Red Sea and surrounding region of interest is shown in (a) with red markers indicating locations of the air-sea buoy and coastal meteorological tower and blue dashed lines establishing the domain of the WRF simulations used. Photos of the buoy and tower are seen in (b) and (c), respectively.
Near-surface temperature and conductivity are measured with two SeaBird SBE-37 MicroCat instruments attached to the bottom of the buoy.

A modified VOS (Voluntary Observing Ship) IMET package was installed at a height of 10 m on the coastal meteorological tower. This instrument package measured shortwave and longwave radiation, vector winds, precipitation, humidity, barometric pressure, and air temperature. The basic sampling rates of both buoy and tower IMET sensors were 1-min averages.

2.2. WRF Model Simulations

The WRF climate downscaling simulations used in this study were initially conducted to examine atmospheric circulation patterns and air-sea dynamics in the Red Sea region (Jiang et al., 2009). Ensuing works have demonstrated that these simulations are capable of studying the four dimensional structure of the LT in the Red Sea region at seasonal to hourly timescales and resolving mesoscale processes (Davis et al., 2015; Ralston et al., 2013). The particular work of Davis et al. (2015) details how well the diurnal cycle is resolved in these simulations, including both phases of the LSBC.

The configuration of the model and the climate forcing fields have been previously described (Jiang et al., 2009), but pertinent details are restated here. For these simulations, a nested model configuration was used to dynamically downscale the 1° NCEP Global Final Analysis (FNL) to a regional subdomain as described by Jiang et al. (2009). The simulations used the WRF model with Advanced Research WRF (ARW) dynamic core version 3.0.1.1 (Skamarock et al., 2008). The subdomain consisted of a 10-km fine-resolution domain nested within a coarser 30-km-resolution grid (Figure 1), and the boundary conditions and re-initialization fields were from the 1° NCEP FNL. The time period of the simulations was 1 December 2007 and 31 January 2009. The model had 35 terrain-following vertical (eta) levels, and the first grid point was ~100–150 m above the surface. The SST boundary condition was from the NCEP daily data of 0.083° global SST analysis (RTG_SST_HR) (Thiébaux et al., 2003). The Yonsei University scheme was chosen for boundary layer parameterization.

The near-surface variability of the WRF downscaled winds and fluxes have been validated using buoy-model comparisons (Jiang et al., 2009), and additional verification in upper atmospheric layers has been done using vertical soundings taken across East Africa and the Arabian Peninsula in the 2008/2009 time frame (Davis et al., 2015).

2.3. Reanalysis and Satellite Data

In conjunction with the WRF simulations, the scope of our analysis was extended using climatic data sets and reanalyses. Surface temperatures from the Global Land Data Assimilation System (GLDAS) were utilized in the analysis of the LSBC forcing. These data are available and described at http://ldas.gsfc.nasa.gov/ldas/. Publically available output from the NASA Modern Era-Retrospective Analysis for Research and Applications (MERRA) and the National Center for Environmental Prediction (NCEP) was also used in the analysis and is described at http://gmao.gsfc.nasa.gov/merra/ and http://www.ncep.noaa.gov/ respectively. Subsets of remotely sensed data from the MODIS-AQUA satellite and the Tropical Rainfall Measuring Mission (TRMM) were obtained via the National Aeronautics and Space Administration (NASA) data portal: http://giovanni.gsfc.nasa.gov/giovanni/.

3. Results and Discussion

3.1. General Circulation Around the Red Sea

Atmospheric conditions over the Red Sea and coastal region were observed over a 26-month period. As seen in the time series of hourly averaged 1-min data presented in Figure 2, the zonal wind velocity (Figure 2a), atmospheric pressure (Figure 2b), atmospheric temperature (Figure 2c), and relative humidity (Figure 2d) measured at the buoy (blue lines) and tower (thinner red lines) exhibited similar variability. The LSBC dominated the daily variability in the observations and occurred in all four seasons. The LSBC is a three-dimensional, mesoscale circulation with distinct components (Miller et al., 2003). Of these, the near-surface, shoreward sea breeze (daytime) and the near-surface, offshore land breeze (nocturnal) were the prominent LSBC components in the Red Sea observational data with the sea breeze gravity current and on/offshore internal boundary layer formation being further resolved in the WRF simulations. Zonal wind velocity...
components were nearly cross shore, and speeds generally varied from ~2 to 6 m/s during the peak intensities of sea- and land-breeze elements. Periodic extreme values of ~10 to ~12 m/s were also recorded in the observation period during mountain gap wind jet events (see Jiang et al., 2009). Land and sea breezes were further distinguishable through their influences upon air temperature and relative humidity. Representative summer and winter cases of the LSBC, from 3–8 July 2009 and 2–7 December 2009, are shown in Figure 3. The intensity of the sea breeze in terms of positive cross-shore velocities was highest during the spring through fall seasons in the Red Sea, reaching velocities from 3–6 m/s as compared to a reduced range of 1–4 m/s during winter. Detection of the sea breeze at the buoy most frequently occurred between 4 and 6 UTC (7–9 a.m. local time) in summer and 8 to 12 UTC (11 a.m.–3 p.m. local time) in winter as shown in Figures 3a and 3e, respectively. Its arrival at the coastal tower was typically observed 1–2 hr later. Peak sea breeze intensities throughout the record occurred between 12 and 16 UTC (3–6 p.m. local time), and dissipated by late evening (17–18 UTC) prior to the onset of the offshore land breeze. Land breezes were observed in all seasons, yet fall and winter witnessed a greater number of extreme cases or land breezes with wind speeds exceeding 6 m/s. A high to low horizontal pressure gradient between the buoy/sea and tower/land remained throughout the year (Figure 2b) despite the wintertime reversal of the corresponding gradient of temperature (Figure 2c). This reversal in the sea-land temperature gradient also contributed to the warm/moist sea breeze events observed along the coast in winter (Figure 3g) versus the more typical cool/moist events in summer (Figure 3d).

At a separation distance of 79 km, the observations at the buoy and tower indicated the sea breeze front moved inland at rates ranging from 8 to 12 m/s (as shown in the case studies, Figure 3). This is comparable to an estimated range of 11–16 m/s for a 1.5-layer gravity current (GC) with speed $c = \alpha g H / g'$. Here $g'$ is the reduced gravity of approximately 0.16 m/s$^2$, $1 < \alpha < 1.3$, and 800 m $< H < 1,000$ m is the height of the intrusion along the leading edge of the front. Further details of the observed GC behavior are discussed later in section 3.8.

### 3.2. Seasonality

A more detailed evaluation of the seasonal modulation of the daily cycle, including the local LSBC, is presented through the composites of the hourly data (averages of each hour for a 3-month seasonal period for 2009 and 2010) shown in Figure 4. Stability in the marine LT influenced observations at both sites,
with relatively small variations of atmospheric temperature (Figures 4a and 4d) throughout the diurnal cycle. Seasonal land–sea temperature differences reversed sign for fall and winter, while a land–sea surface pressure gradient favorable for onshore flow was maintained year round (not shown). Fall and winter patterns have been shown in related studies by Khan et al. (2018), Qian et al. (2009), and Rotunno (1983) to be quasi-antitriptic, that is atmospheric flow based only on frictional forces and a local pressure gradient developing from uneven heating (prone to occur at latitudes less than 30°).

Largest amplitude increases in the onshore flow were seen in the sea breezes of the summer and fall seasons (Figures 4b). This onshore maximum coincides with the enhanced northwesterly mean flow along the Red Sea axis (discussed further in section 3.3) and the extreme nature of the sensible heat fluxes observed in those time frames (discussed in section 3.4) In summer and fall, there was a strong LSBC at the meteorological tower (~4 m/s, peak to peak), but there was only a very weak cycle at the buoy. Winter and spring measurements at the buoy showed stronger influences of the LSBC offshore, with sea breeze increases of 3–4 m/s.

Water vapor advected inshore via the LSBC is crucial to the convergence in the moisture flux and reduction in atmospheric stability necessary for convection and precipitation in the coastal region (Hsu, 1988). In the seasonal composites, this landward influx of atmospheric water vapor was largest during the LSBC's of

Figure 3. Representative cases of the Red Sea LSBC observed in July 2009 and December 2008. Buoy (blue lines) and tower (red lines) minute observations of (a) u-wind velocity (m/s), (b) relative humidity (%), (c) air temperature (°C), and (d) atmospheric pressure (hPa) are shown from 1–8 July 2009. Corresponding measurements during 1–8 December 2008 are shown in (e) through (h).
springs and summers, with relative humidity at the tower reaching 70% and 75%, respectively, with corresponding means at the buoy measuring ~75% in both cases.

### 3.3. Mean Lower Tropospheric Flow and Influences Upon the LSBC

The radial histograms of wind speed and direction presented in Figure 5 reveal a strong northwesterly LT flow prevailing throughout the study, significantly enhancing the onshore flow at both the buoy and tower locations. Data from both locations indicate that this mean LT circulation also exhibited seasonal variability and modulation of the LSBC throughout observation record.

The mean LT flow in the Red Sea is controlled by seasonal wind regimes (i.e., the Mediterranean northwesterly Etesians and the southerly Indian Ocean monsoons) and the variation of these winds in response to the topography around the basin. As the Red Sea stretches southward from ~30°N to 10°N, the Sarawat and Asir mountain ranges line its eastern coast, while the Red Sea Hills and East African Highlands line the opposing west coast. Mountain chains lining both eastern and western coasts constrain the mean, LT winds to flow along the basin axis (Bower & Farrar, 2015). Resulting meridional gradients of many atmospheric properties are found, such as sea surface temperature, evaporation rates, and atmospheric water vapor concentrations within the Red Sea LT (Davis et al., 2015; Sofianos & Johns, 2003; Tomasi, 1984). Seasonality marks this LT mean flow as well. However, seasonal changes manifest quite differently over the north half of the basin versus the south (Bower & Farrar, 2015; Davis et al., 2015; Jiang et al., 2009).

The air-sea buoy and meteorological tower are located along the southern limit of the northern Red Sea region (~20°N). LT flow in this region is largely an extension of northwesterly winds from the eastern Mediterranean (e.g., the spring through fall Etesians). To the south, the LT circulation is driven by the summer and winter phases of the Indian Ocean monsoon cycle which accompanies the seasonal migration of the Intertropical Convergence Zone, whose summer maximum latitude occurs midway up the Red Sea’s axis (~20–22°N) as seen in Figure 6a. Seasonal differences in southern Red Sea LT include a reversal of the mean wind direction, from northwesterly in summer to southeasterly in winter (as shown in Figure 6b). The region where the wintertime southern and northern Red Sea LT winds (~20°N) converge has been designated the Red Sea Convergence Zone in previous studies (Pedgley, 1974).
On the local scale, significant narrow spectral peaks at the diurnal frequency were seen in the rotary spectra computed from both buoy (Figure 7a) and tower (Figure 7b) wind speed observations, indicating an energetic LSBC present at both locations year-round. The presence of both positive and negative (clockwise and counterclockwise, respectively) components at the 24-hr spectral peak suggested an elliptical rotation of the horizontal surface wind vectors (a characteristic explored further in section 3.5). A smaller secondary peak at the 12-hr frequency was also present in both tower and buoy rotary spectra. This is likely indicative of the asymmetrical nature of the LSBC, with the sea breeze phase dominant, as discussed by Pearson et al. (1983), Orlic et al. (1989), and Prtenjak et al. (2008).

Interactions with the mean flow may enhance or reduce LSBC wind speeds and inland fetches, as well as dictate the timing and location of any frontogenesis (Arritt, 1987; Arritt, 1989; Segal & Pielke, 1985). Some aspects of mean flow-LSBC interactions initially indicated by the buoy and tower observations were further discernable in the WRF simulated conditions above the Red Sea basin. Chief among these were the differences between the LSBC on the East African coast versus that on the Arabian Peninsula side, as well as the persistence of the circulation throughout the year across both coasts.

Throughout the summertime (and throughout the year north of 20°N), the mean northwesterly mean flow is obliquely onshore or parallel to the Arabian Peninsula coastline. Backing of the winds (counter clockwise rotation of winds with height) developed with the onset of the sea breeze, rendering a circulation consistent with the “corkscrew” sea breeze type described in Miller et al. (2003) and Steele et al. (2013). Corkscrew sea breezes may initiate in the presence of smaller thermal contrasts than other LSBC types. This facilitation of LSBC initiation is consistent with the climatological study of sea breezes over the Saudi Peninsula conducted by Khan et al. (2018), who also found that the frequency of sea breeze occurrences increased from north to south.

Figure 5. Seasonal radial histograms derived from 2009 through 2011 observations. Charts for summertime averaged (JJA) buoy and tower winds are presented in (a) and (b), respectively. Corresponding wintertime (DJF) charts are shown for the buoy in (c) and tower in (d).
Differences in the mean-flow/coastline orientation over the East African side of the Red Sea resulted in gradient winds flowing roughly parallel to the coast and to the right of this flow. This configuration has been described as a “backdoor” sea breeze type (which may require greater thermal contrasts than in other types; Miller et al., 2003; Steele et al., 2013). This scenario persisted over the East African coastline of the Red Sea throughout the summer season. In winter however, the seasonal reversal of the monsoon winds induced a corkscrew LSBC configuration south of 20°N.

### 3.4. Forcing of the LSBC

Within the larger scale LT flow, LSBCs occur in response to the differential heating between land and ocean surfaces and the resulting development of mesoscale (2–2,000 km) horizontal pressure gradients that drive cross-shore flow (e.g., Miller et al., 2003; Stull, 1988). The nature of the thermal-pressure surface gradients forcing LSBC’s varies significantly from region to region (Atkinson, 1981) and may occur (under calm...
conditions) with land-sea horizontal gradients as low as 1 K/2 km (Hsu, 1988). A frequent measure of the thermal forcing is the sensible heat flux, \( Q_{\text{sensible}} \), which in a simple form may be expressed as

\[
Q_{\text{sensible}} = -\rho C_p \left( T_a - T_s \right) r_H,
\]

(1)

where \( T_s \) and \( T_a \) are the surface and air temperatures, \( \rho \) is the density of air (a function of temperature and humidity), and \( C_p \) is the heat capacity of air (approximately 1,010 J/kg °C). The transfer resistance, \( r_H \), is determined by wind speed and surface characteristics.

Sensible heat fluxes over both the African and Arabian coasts influence the Red Sea LSBC. As discussed in later sections, the presence of topography along both coastlines further enhances the LSBC, in part through contributions to the already extreme heat fluxes generated by the Saharan and Arabian deserts encompassing it. In Figure 8, land surface temperatures from the GLDAS data vary significantly around the basin depending on terrain type, latitude, and proximity to the Red Sea. In comparison, the sea surface temperature of the Red Sea (from 8-day averages of MODIS AQUA data) remains relatively constant, both spatially and temporally. MERRA/GLDAS sensible heat fluxes in the vicinity of the coastal tower reached 460 W/m² (Figure 8f) during the peak heating of July, and while the largest fluxes occurred over the arid regions surrounding the northern portion of the basin (the elevated regions such as the Sarawat Mountains on the Arabian Peninsula and the Red Sea Hills of Sudan and Egypt). Resulting land-sea temperature contrasts (T) at this time were on the order of 30–40 K (Figure 8b) coinciding with the strongest sea breezes of the year. Seasonality of the LSBC parallels that of the sensible heat flux. Aforementioned weaker sea breezes were
found in winter months like December, with a corresponding temperature difference of ~8 to 19 K and sensible heat fluxes peaking at ~300 W/m² (Figure 8e).

3.5. Rotation and Intensity

Hodographs of the surface wind vectors may serve as a means of gauging the amplitude of diurnal processes like the LSBC and slope winds. Haurwitz (1947) described the LSBC as a rotation of the local wind vector under the influences of friction and the Coriolis effect, resulting in a hodograph that cyclonically traces out an ellipse in the Northern Hemisphere. The length of the elliptical hodograph’s major axis reflects the wind speed intensity of the LSBC. Neuman’s and Mahrer (1971) study in conjunction with many subsequent others has shown that these hodographs also provide indications of potential influences including topography, ties to larger scale LT circulation, coastal geometry, as well as nonlinear heating (e.g., surface...

Figure 8. GLDAS 3-hourly land surface temperatures combined with AQUA 8-day composite sea surface temperatures for (a) 12 UTC, 1 July 2009, (b) 0 UTC, 1 July 2009, (c) 12 UTC, 1 December 2009, and (d) 0 UTC, 1 December 2009. Black circles and triangles designate the buoy and tower locations, respectively. The evolution of MERRA model surface heat fluxes at (e) the buoy location and (f) the tower location is shown over an 8-day period following 0 UTC 1 July (red lines) and 0 UTC 1 December (blue lines) is also shown.
inhomogeneities). Hodographs derived from the hourly averages (averages of each hour of day for the length of the record) of the buoy and tower wind measurements are presented in Figure 9a. Immediately discernible in the Red Sea hodographs are the differences in mean amplitudes of the LSBC, with that recorded at the buoy being 3.4 m/s and that at the tower nearly 7 m/s. A more eccentric elliptical path was also generated from the tower data as compared to the buoy, consistent with higher friction over land (Alpert et al., 1982). Friction and nonlinear heating in the terrestrial atmosphere may also contribute to an irregular rotation rate of the wind vectors measured at the tower (Neumann & Mahrer, 1971).

An extension of this hodograph analysis was made using a 1-year record of the WRF 10-m winds. Following the method of Gille et al. (2005), wind observations can be fitted to an elliptical hodograph with the semimajor axis of the ellipse being oriented in the direction of maximum diurnal variation. This method was done here using 3-month (seasonal) composites of the WRF simulated winds across the basin. Long axis magnitudes indicative of the diurnal oscillations determined for summer and winter seasons are presented in Figures 9b and 9c. From the figure, it is seen that the largest amplitudes were concentrated along the Saudi mountain ranges lining the eastern side of the basin during both seasons, where magnitudes reach ~10 m/s (red and orange contours).

We hypothesize that the regions of large amplitude diurnal oscillations result from a coupling between slope winds generated on the Sarawat Mountains and the Red Sea LSBC. With this, the topographical features lining the Red Sea basin play a crucial role in the intensity of the LSBC along both coasts of the Red Sea. As Mahrer and Pielke (1977) advanced, the combination of sea breeze and slope winds produces a more intense circulation during both day and night compared to the ones developed independently. This occurs as the upslope winds become integrated with the inland-advancing sea breeze, thus enhancing the LSBC inland reach and the strength of the upslope winds in the process. The converse occurs at night. Nocturnal cooling of the mountain slopes facilitates the development of land breezes with added katabatic influences, significantly enhancing the land breeze winds that flow across the coastal boundary and over the sea basin. This would also be consistent with the findings of Gille et al. (2003), where trade winds and LSBC oscillations were enhanced in tropical locations in the vicinity of coastal mountain ranges as well as Jury and Spencer-Smith (1988) who observed intensification of South African sea breeze winds downstream of topography.
The continuous cyan contours on either side of the basin in Figure 9 can be interpreted as the horizontal extent of the topographically enhanced LSBC. Specifically, it can be seen that the LSBC along the African side of the basin forms over the immediate coastal waters, while the LSBC along the Arabian Peninsula exists in the vicinity of the buoy location, about 25 km further out to sea. On both sides, the influence of the LSBC reaches extensively inland, on the order of 50–150 km on the western side of the basin with gaps between topographic elements facilitating large fetches of penetration. Along the eastern side, the amplitudes of the combined LSBC-slope winds are distinctly greater and seen at greater inland fetches (on the order of 300–400 km). However, the hodograph analysis does not show if this is a result of the combined LSBC-slope winds or the LSBC and slope winds acting separately but in phase.

3.6. Vertical Structure of the LSBC

The WRF simulations allow insight into the vertical evolution of this LSBC. A typical case study from the summer season (1–3 July 2009) is presented in Figure 10. Altitude-time plots of the model simulated potential temperature, cross-shore velocity, and water vapor mixing ratio illustrate the development of the LSBC starting with the well-defined onshore flow of marine air within a shallow layer above the buoy and tower locations. At the offshore buoy location, onset of the onshore flow was well-defined between the surface and 2,000 m and occurred between 12 and 19 UTC (Figure 10a). At the onshore tower location, the sea breeze component of the LSBC was shorter, prevailing between 13 and 16 UTC (Figure 10b), but was followed by a more pronounced land breeze between 17 and 22 UTC. Evidence of a return flow aloft was clearest 1,200–2,000 m above the buoy and was sustained from 2 to 9 UTC.

The altitude-time plots of the simulated u-wind velocity indicated that there was a 1,000–3,000-m height of the LSBC circulation, while a 700–1,000-m thickness of the marine air mass within this circulation was determined from the potential temperature-altitude-time plots (Figures 10c and 10d) at both tower and buoy locations. In these, it was also seen that the sea-breeze cycle enhanced variability near the tower more significantly than at the buoy at this time of year. There was strong evidence of coastal internal boundary layer (IBL) in the altitude-time plots of the water vapor mixing ratio (Figures 10e and 10f), which revealed that moisture during these events was confined to very shallow atmospheric layers (100–2,000 m) in the lower marine troposphere above the buoy, while at the coastal tower, it manifested as large surges reaching 1,000–2,000-m high. The role of the IBL in the stratification associated with the LSBC of the Red Sea is discussed further in section 3.7, while the likely role of convergence experienced by the sea-breeze front as well as with the topography adjacent to the tower location in these figures is explored in relation to the gravity-current behavior of the LSBC in section 3.8.

3.7. Coastal Internal Boundary Layers

Based on the altitude-time sections, it was seen that the LSBC plays a significant role in transforming the stratification of the atmospheric boundary layer in the coastal Red Sea LT. One prominent feature observed in this transformation is the creation of an IBL over the continental surface during the landward incursion of the sea breeze and, similarly, over the ocean during the seaward incursion of the land breeze. The tower and buoy were well-positioned to observe the surface impacts of IBL development onshore and offshore, while the evolution of the IBLs in the coastal LT above was seen throughout the WRF simulations as well.

Formation of an IBL is driven by the adjustment of an overlying air mass to contrasting surface characteristics as it passes above one surface to another. Coastal IBLs inherently form during the LSBC in response to airflow across the sharp discontinuities in land-sea surface properties (see Garratt, 1990; Hsu, 1988; Miller et al., 2003). They also may develop onshore and offshore, with the IBL height often depending on wind speed (Garratt, 1990). In the Red Sea, year-round land-sea contrasts in surface roughness and heat fluxes couple with the persistence of the LSBC to generate offshore and onshore IBLs regularly.

Figures 11a through 11c present typical wintertime conditions, with a well-developed, IBL generated in the wake of the land breeze’s offshore advancement (past the buoy location) at 19 UTC on 2 December. The offshore IBL is distinguishable by the sharp gradient of potential temperature (Figure 11a) seen along a boundary extending from the surface at the coastline seaward (white dashed lines in the figure), and increasing in altitude with fetch, x, as it passes over the buoy. The IBL caps a concentration of water vapor mixing ratio shown in Figure 11b with the height of the IBL developing with ~ 1/√x characteristic curvature (Stull, 1988) beginning at the surface near the coastline and reaching between 500 m and 800 m in height at the
end of the transect, 80 km from the shore. Vertical shear in the horizontal winds, as seen in Figure 11c is indicative of the IBL. This appeared to enhance summertime offshore IBL heights in the Red Sea, which typically exhibited greater heights at the same fetch than offshore IBLs formed during the ensuing land breeze. This is seen in the cross sections shown in Figures 11d through 11f, where an offshore IBL developed on 2 July at 18 UTC achieves a height between 800 and 1,000 m over the same 80 km fetch of its winter counterpart.

The development of offshore IBLs during the land breeze appeared to have significant bearing upon confinement moisture to the lower atmospheric layers. They may also affect dust and chemical transport above the Red Sea based on the findings of extensive IBL research in the past. The prevailing stability of the stratification within offshore IBLs further provides for detachment from the surface once a continental air mass

**Figure 10.** Vertical structure of the LSBC as simulated by the WRF model. Shown are time height figures of u-wind velocity at (a) the buoy and (b) tower locations between 1 July and 3 July 2009. Time height figures of potential temperature for the same times at (c) the buoy and (d) tower are also presented as well as corresponding figures of the water vapor mixing ratio for the respective locations in (e) and (f).
passes into the marine LT. This enables an efficient means for LT transport of trace gases and aerosols/dust over regional to intercontinental distances (Angevine et al., 2006; Dacre et al., 2007; Davis et al., 2004; Davis et al., 2012).

Formation of a wintertime, onshore IBL is seen during the incursion of the sea breeze at ~15 UTC, 2 December in the conditions shown in Figures 11g–11i. Like its offshore relative, the onshore IBL forms amidst the increase in cross-shore wind (the sea breeze) and is distinguishable by the sharp gradients in potential temperature (Figure 11g) above a moist air mass near the surface (Figure 11h). Larger cross-shore wind speeds (Figure 11i) resulting from the sea breeze and background LT winds combine with the larger surface heat fluxes on land to generate significantly elevated IBL heights of ~800–1,000 m at the base of the mountains, 70-km inland. Inland IBL heights increase significantly in summer, reaching ~1,200–1,400 m at the same fetch as seen in Figures 11j–11l. While the offshore IBLs are linked to strong, stable stratification, the development of onshore IBLs in the presence of the sea breeze is more frequently associated with instability in the LT caused by the heating of the moist marine air over land. The inland IBL forms within the marine air mass of the sea breeze, becoming thicker as it moves inland (e.g., Miller et al., 2003). The IBL can be important to air quality, either by trapping pollution in the shallow IBL in coastal cities or, farther inland where the IBL is thicker, by mixing down pollutants that were emitted above the IBL near the coast. Added buoyancy, convergence in the horizontal flow, and significant influx of moisture within the inland IBL further contribute to the potential for convective initiation (Pielke, 1985). Similar links to convection and precipitation occur in the offshore IBLs in the presence of converging land breezes (Hill et al., 2010). At smaller spatial and temporal scales, impacts of the IBL formation were seen as high frequency fluctuations in the 1-min observations of pressure, humidity, temperature, and wind speed. This is consistent with earlier IBL studies (Novitsky et al., 1992; Rogers et al., 1995) who found surface and near surface observations were influenced by shear instability near the top of the IBL as incoming air masses adjust to their new surrounding as well as from nonlinear interactions with heterogeneities in the surface.

Figure 11. Development of IBLs as seen in cross sections in the wintertime marine LT from the central Red Sea through the buoy and tower/coastline. Shown are simulated (a) potential temperature, (b) water vapor mixing ratio, and (c) zonal wind speed at 19 UTC on 2 December. Corresponding cross sections in the summertime LT, 18 UTC on 2 July, are shown in (d), (e), and (f). Cross sections at 15 UTC on 2 December reflect conditions the wintertime continental LT tower/coastline to the base of the Sarawat Mountains with the same respective simulated parameters in (g), (h), and (i). Corresponding conditions along this same cross section in summer, 15 UTC on 2 July are shown in (j), (k), and (l).
3.8. The LSBC as a Gravity Current

The WRF simulated coastal IBL development coincides with the aforementioned observed gravity current behavior of the sea-breeze propagation from the buoy to the tower. Indeed, numerous previous studies have advanced (e.g., Simpson, 1994) that the landward incursion of the cool marine air mass into the continental LT (the sea breeze component of the LSBC) may be described as a GC flow. The sea breeze, like other GCs, is driven by very small density differences (usually only a few percent). As the GC flows, sharp gradients appear along the leading edges. This leading edge frequently develops a raised head driven by lower level convergence and resulting upward vertical motion. This has been referred to as the sea breeze head (Miller et al., 2003) and is frequently associated with cumulus cloud formation and strong wind shear, which contributes to the development of Kelvin-Helmholtz billows (KHBs).

This distinct GC behavior was evident in the WRF model simulations of the Red Sea LSBC. The cross section of WRF simulated potential temperature during the summer 2009 LSBC case study shown in Figure 12 shows this GC evolution. Along a transect connecting the buoy and the tower positions, the 12 UTC cross section of $\theta$ (Figure 12a) reveals the sharp vertical gradients of temperature along the horizontal and vertical edges of the well-defined, ~800-m thick cool marine air mass moving towards the coast. At 16 UTC (Figure 10b), the head of the current began to form as the sea breeze progressed inland past the tower. The initial impact of rising motion along the edge of the front appeared to be slightly diminished due to the effects of the prevailing onshore flow, as Simpson’s (1994) laboratory experiments suggested. Within the WRF model, the propagation speed of the sea breeze front was generally ~11 m/s, comparing closely with the observations and GC speed calculation discussed earlier.

The limitations on the sea-breeze’s inland fetch rendered by the Sarawat and Asir mountain ranges is of some interest. This can be seen in the GC case study presented in Figure 12, where the sequential cross sections of simulated potential temperature and water vapor mixing ratio cross sections capture the evolution of a typical summertime GC/sea breeze between 1 July and 2 July 2009. Initial incursion of the sea breeze GC is seen...
between 0 and 6 UTC on 1 July as the cool marine air mass progresses past the buoy and the tower (Figures 12a and 12b), while the corresponding water vapor mixing ratios become more concentrated at the base of the coastal mountains (Figures 12f and 12g). The GC ascends the mountains between 6 and 12 UTC (Figures 12c and 12h), continuing until it reaches its maximum inland incursion around 14 UTC. Between 14 and 18 UTC the GC stalls then recedes back down the coastal mountains (Figures 12d and 12i), and it is evident that the marine air mass ascends the basin side of the mountain ranges but remains within the topographical confines of the basin. This contrasts with early studies by Pedgley (1974), and Steedman and Ashour (1976), where it was asserted that the sea breeze could travel more than 200–400 km inland, overrunning these steep topographical elements. Results throughout the period of study here suggest that is not likely the case and perhaps those earlier studies were in fact observing slope winds instead.

The reversed GC flow can be seen in the 18 UTC snapshots (Figures 12d and 12i) as it recedes downslope towards the coastal Red Sea. The GC diminished in thickness yet still discernable as it reaches the base of the mountains and returns past the tower and buoy observation points between 17 and 0 UTC. It was determined that this downslope return of the GC was responsible for the pulses in cool potential temperature, relative humidity/water vapor mixing ratio, and easterly zonal wind presented earlier in the tower observation summertime composites (Figures 4a–4c). It can further be seen in the time height diagrams from the WRF simulations at the tower location (Figures 10b, 10d, and 10f).

3.9. Basin-Wide Characteristics and Impacts

The characteristics of the Red Sea LSBC, including its GC nature, have important implications for its impacts on regional climate and weather. While contemporary efforts have focused upon the LSBC role in dust transport around the region (Prakash et al., 2015) we extend our analysis to explore its role in cloud formation and mesoscale precipitation. Specifically, we advance how the LSBC provides sources of moisture, LT instability, moisture, convergence, and uplift necessary for local moist convection. We examine two scenarios: the case of the sea breeze over the Saudi Peninsula and the case of the land breeze over the Red Sea waters.

The sea breeze air mass is characterized by high water vapor mixing ratio. The incursion of this air mass over the Arabian Peninsula not only delivers that moisture inland but reduces static stability in the atmospheric column in the process. This reduced stability in the coastal-continental LT (e.g., at locations similar to the tower) may be gauged by the buoyancy or Brunt-Vaisala frequency, \( N \), defined as

\[
N^2 = \frac{g}{\beta} \frac{\partial \theta}{\partial z}
\]

with \( g \) being the gravitational constant, \( \theta \) the potential temperature in K, and \( z \) the altitude in meters. As seen in Figure 13, the simulated profiles at the tower location on 1 July 2009, the LT’s were stable, with positive \( N^2 \) values prevailing from 15 (6:00 p.m. LST) to 3 UTC (6:00 a.m. LST) on the following day. Instability resulting from the displacement of denser dry air by moist marine air however is indicated by the negative \( N^2 \) values occurring in the lowest 1 km between 6 (9:00 a.m. LST) and 12 UTC (3:00 p.m. LST). This coincides with the arrival of the sea breeze front as seen in Figures 10a and 10c. A crucial step following the development of this instability is the increased convergence in the horizontal winds and by extension, the moisture convergence (the advection of moisture into a fixed region) along the sea breeze frontal zone. This horizontal convergence occurs basin wide along the land and sea breeze frontal boundaries, frequently facilitating vertical motion and moist convection.

The basin-scale patterns of LSBC-driven moisture convergence vary throughout the year in response to the seasonal shifts in the regional winds and the modulation of the cycle described previously. Based upon the
WRF simulations, the daytime maximum moisture convergence is achieved over the coastal plain as the leading edge of the SBF encounters the steeper topographic elements, while at nighttime, peak convergence manifests offshore in response to land breeze interactions with the regional southeasterly flow or the collision of land breezes from the opposing coasts. Summertime sea-breeze induced moisture convergence patterns (14 UTC) appeared along the coastal mountains/hills in a symmetric pattern around the basin as seen in the July case study (Figure 14a). This sea breeze generated moisture convergence along the Saudi Peninsula remains high throughout winter, while the reversal of the Southern Red Sea winds and seasonal shifts in surrounding continental wind regimes results in a concurrent reduction in convergence along the opposing East African side. Summertime nocturnal moisture convergence patterns are dominated by the collision of the land breezes from the opposing East African and Arabian coastlines. A typical summer convergence pattern concentrated along the central axis of the basin at 22 UTC during the July 2009 case study is shown in Figure 14c. The corresponding winter patterns differed noticeably, with sea breeze convergence weakened along the East African coastline (Figure 14b) and land breeze induced convergence resulting primarily from interactions with the regional offshore winds. A typical pattern of this is evident during the December 2009 case study seen in Figure 14d.

Vertical motion or uplift is achieved as a result of the convergence along the frontal boundaries as well as orographically as seen in Figure 12. This uplift of a moist air mass up the side of the mountain results in adiabatic cooling, and eventually condensation and precipitation. This aspect of the LSBC overcomes the limitation advanced by Chakraborty et al. (2006) that precipitation events throughout the Red Sea are limited by the absence of moisture flux convergence despite high concentration of atmospheric water vapor. The majority of the Red Sea coastline, both east and west, receives less than 250 mm of rainfall annually and is therefore classified as desert. While extreme events do occur, precipitation more frequently develops in small quantities. The LSBC is very much tied to precipitation of this variety, as seen in a case study of the LSBC-uplift along the Saudi coastline (just north of the tower and buoy location) for 2 July 2009. As seen in the Meteosat-7 infrared images at 6 UTC, 15 UTC shown in Figures 15a–15c, respectively, the sea breeze’s inland incursion (as shown earlier) coincides with cloud formation developing along the Sarawat mountain range (as highlighted by a yellow box). Scattered rainfall is observed by the TRMM satellite within the box (infrared images of the Red Sea at 6, 15, and 18 UTC), following the sea-breeze front’s ascent of the

Figure 14. WRF simulated moisture flux convergence in the lower 1,000 m. Shown are sea-breeze conditions (14 UTC) for the case studies on (a) 1 July 2009 and (b) 1 December 2009. Also shown are corresponding conditions during the land breeze phase (22 UTC) on those dates in (c) and (d).
mountain, a mesoscale convective system is observed in the southeast corner of the box (Figure 15c). In the TRMM satellite record of precipitation in that box for the month of July 2009, the 2 July event is the largest, with a 3-hourly averaged precipitation rate of 0.09 mm/hr as seen in Figure 15e.

Figure 15. Sea breeze influences upon coastal clouds and precipitation. Shown are Meteosat-7 infrared images of the Saudi Peninsula coastline north of the tower and buoy during a precipitation event on 2 July 2009 at (a) 6, (b) 15, and (c) 18 UTC. TRMM satellite precipitation rates within the sea breeze zone (yellow box) are shown in (d) with the corresponding July 2009 record of rainfall recorded in the box by the instrument in (e).
While the sea breeze within the LSBC contributes to mesoscale convection and precipitation along the coast, the land breeze figures more prominently in precipitation occurring over the Red Sea itself. A record of precipitation rates measured at the buoy is shown in Figure 16a. Year-to-year variability is evident in the buoy...
seasonal to daily variability of atmospheric conditions of the region. The most prominent observed feature, the Red Sea LSBC, is one of the strongest LSBCs in the world and exerts measurable influence upon regional climate via its influence upon LT wind speeds, temperature, humidity, and precipitation throughout all four seasons of the year. Seasonal changes in the nature of the LSBC were distinct. While “extreme” sea breeze and land breeze events were recorded in all seasons, higher sea breeze winds were observed at the coastal tower in late spring through early fall. Conversely, intensified land breezes were observed at the surface mooring in late fall through early spring. A seasonal reversal of the underlying land-sea horizontal temperature gradient occurred, contributing to warm-moist sea-breeze events observed at the coastline in winter and cool-moist sea-breezes in the warmer seasons.

Cyclonic rotation of the wind vector over the course of the daily LSBC was observed at both the onshore and offshore locations. Eccentricity in the elliptical path traced out in this rotation suggested that complicating influences such as friction and/or topography further affect the observed winds. An analysis of WRF model simulated conditions for this time frame supports this conclusion and further indicates that the largest amplitude diurnal variations in wind above the Red Sea occur in the vicinity of the high topographic elements along its coast. We hypothesize that the Red Sea LSBC is coupled closely with slope wind regimes intrinsic to the desert mountain chains encircling the basin. We suspect that earlier studies of the Red Sea LSBC claiming to observe the sea breeze over the interior of the Saudi Peninsula more likely have observed the katabatic slope winds generated independently on the lee side of the coastal mountains.

The observational platforms were well-positioned for observing the transit of the land and sea-breeze phases of the LSBC. The sea breeze was observed moving shoreward at 8–12 m/s, a propagation speed comparable to that of a gravity current in a 1.5-layer reduced gravity framework (10–16 m/s). This gravity current behavior was further captured in the WRF model simulations, with the sea breeze advancing onto the Arabian Peninsula but being limited in terms of inland fetch by the coastal mountains on either side of the basin. Examination of the vertical structure in the simulations suggested that while the LSBC ranged from 1–3 km in thickness, the marine air mass within was confined to 800–1,000 m above the surface.

Development of IBLs was observed onshore and offshore during both phases of the LSBC. IBL heights were significantly larger in summer over both the buoy and tower locations, with large onshore IBL heights showing likely influences of the enhanced heat fluxes and background flow amidst the sea breeze advance inland. High concentrations of water vapor confined within the IBL were seen offshore in the presence of land breeze activity and onshore amidst the sea breeze, adding considerable buoyancy to the lower layers of the LT. Indications of turbulent interactions manifesting as high frequency fluctuations in temperature, pressure, wind speed, and relative humidity were also observed in the high resolution (1-min) observations.

Horizontal convergence of winds and moisture during the incursion of the sea breeze on land appeared to combine with the diurnal anabatic upslope winds and contribute to cumulus cloud formation and mesoscale convection during LSBC events. Meteosat-7 infrared observations analyzed in conjunction with TRMM precipitation measurements, and the WRF simulations support this hypothesis. Further observations of
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