

Spatial and temporal variability of the evaporation duct in the Gulf of Aden

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ABSTRACT

An evaporation duct climatology is constructed for the Gulf of Aden using a 31-year high-resolution data set from the climate reanalysis product National Centers for Environmental Prediction Climate Forecast System Reanalysis. The climatology reveals spatio-temporal heterogeneity in the evaporation duct height (EDH) regulated by the strong interplay between the seasonal monsoon reversals and the related atmospheric and oceanic responses. It also reveals that the Gulf of Aden exhibits a special EDH distribution that is distinct from the adjacent Arabian Sea when the south-west monsoon dominates the gulf. Under these conditions, the EDH of the entire gulf is significantly higher than that of the adjoining Arabian Sea. A cliff-style EDH drop (referred to as the EDH cliff) forms at the mouth of the Gulf of Aden. Furthermore, the influence of the EDH cliff on marine radar was investigated using a ray-optics method. Based on the analysis, it was found that the local EDH significantly affects the radar detection ability beneath the evaporation duct for ships sailing in the Gulf of Aden.

Keywords: marine atmospheric boundary layer, climatology, somali low-level jet, evaporation duct height cliff, marine radar

1. Introduction

The Gulf of Aden is a narrow strip of water between Somalia and Yemen, connected to the Arabian Sea through a wide opening (Fig. 1). As part of the Suez Canal shipping lane, it is an important seafaring route for international trade between the West and the East. Its importance also rises from the local abundant marine fishery resources. Despite its importance, little information on the marine environment in the Gulf of Aden is available for the sailing, fishing and navigation. Most studies of the oceanographic features of the Gulf of Aden have focused on water masses (Al Saafani and Shenoi, 2007), sea-surface temperature (SST) and salinity profile variability (Nandkeolyar et al., 2013), and the local marine ecosystem (El-Mashjary and Ali, 2010; Yao and Hoteit, 2015). However, there is little research on the features of the marine atmospheric boundary layer in the Gulf of Aden.

When the moisture content of the marine atmospheric boundary layer decreases rapidly with increasing altitude, a

leaky atmospheric waveguide forms. In this region, radio waves are refracted towards the ocean surface and behave as though they are trapped in the waveguide. This atmospheric duct, a result of evaporation from the ocean, is known as an evaporation duct. Evaporation ducts are nearly permanent features around the globe (Barclay, 2012). They can have dramatic effects on microwave instruments, especially those operating in the C- and X-bands. They can also lead to a decreased path loss and affect both low-altitude radar detection and maximum communication ranges (Anderson, 1995; Woods et al., 2009; Dinc and Akan, 2014).

As a crucial parameter, the evaporation duct height (EDH) is used to define the strength of the ducting mechanism. Ideally, the EDH would be determined by using *in situ* measurements (Levy and Craig, 1989; Wash and Davidson, 1994; Pons et al., 2003). However, it is not feasible to routinely measure refractivity close to the ocean surface. Hence, it is common to determine the EDH from evaporation duct models using bulk measurements. Numerous evaporation duct models are widely used such as the Paulus-Jeske (PJ) model (Paulus, 1985), the Musson-Gauthier-Bruth (MGB) model (Musson-Genon et al., 1992), the Babin-Young-Carton (BYC) model (Babin et al., 1997;

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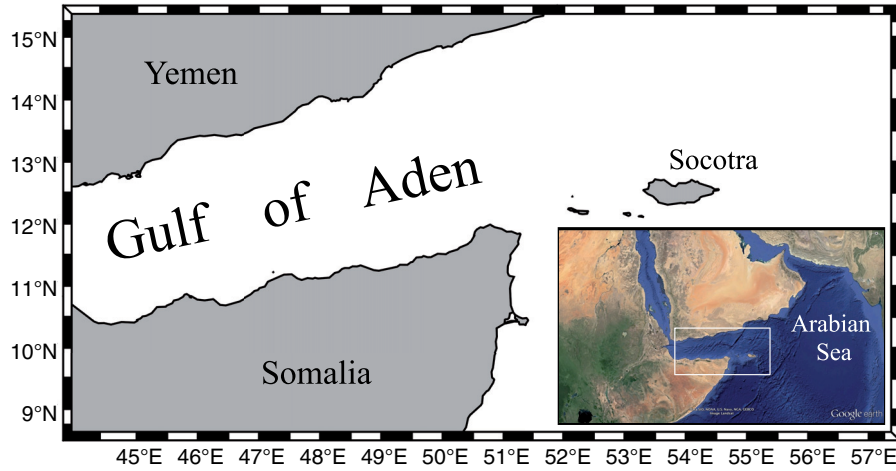


Fig. 1. The location of the Gulf of Aden.

Pasricha et al., 2002) and the Naval Postgraduate School (NPS) model (Frederickson et al., 2000). Much work has been carried out to compare the NPS model with the PJ, MGB and BYC models using ocean buoy data (Babin et al., 1997; Babin and Dockery, 2002). It has been found that the NPS model is the optimal model for calculating the EDH and estimating the modified refractivity profile. Recently, Shi et al. used the NPS model and National Centers for Environmental Prediction Climate Forecast System Reanalysis (NCEP CFSR) climate reanalysis product to study the spatiotemporal characteristics of EDH in South China Sea (Shi et al., 2015). However, this work mainly focused on the statistical features of the EDH distribution and no detailed analysis of the regional climate variations and its effects on the EDH distribution was given.

Marine radar is an essential shipborne navigation tool that relies on the centimetric frequency band, as lower frequencies give a poor picture of the sea surface and higher frequencies suffer excessive precipitation clutter. According to the International Safety of Life at Sea Convention (SOLAS), all large fishing vessels and merchant ships have to carry a marine radar working at 9 GHz (Briggs, 2004). This means that when the merchant ships or fishing vessels sail across the Gulf of Aden, shipborne marine radar may be badly affected due to the presence of an evaporation duct in the region. This can result in ships being unable to detect and locate the hazards. Therefore, timely and accurate assessments of the evaporation duct and its impact on marine radar are very important for the safety of life when sailing across the Gulf of Aden.

To this end, this study provides comprehensive climate analyses of the spatial and temporal variations in EDH in the Gulf of Aden. Moreover, the influence of EDH on the marine radar is also discussed in details. The paper is organised as follows. Section 2 describes the reanalysis data

used in this study and the methodology used to calculate the EDH and assess the trapping effect. In Section 3, the spatiotemporal variability of the evaporation duct in the Gulf of Aden is described in detail and the influence of the evaporation duct on the shipborne marine radar is investigated. Finally, Section 4 presents the summary and conclusions.

2. Data and methodology

2.1. Data

The climate reanalysis product NCEP CFSR (Saha et al., 2010) was used to investigate the spatiotemporal variation of the evaporation duct in the Gulf of Aden. The NCEP CFSR runs data from a number of sources, including, but not limited to, ship reports, land stations, radiosondes, aircraft, buoys and satellites, through a global circulation model in hindsight and produces an analysis of this model every 6 hours (NCAR, 2014). It can provide forecasts from these 6-hourly analyses at an hourly resolution. The NCEP CFSR extrapolates the data over a spatial coverage from 0°E to 359.687°E and 89.761°N to 89.761°S with 1152×576 grid points to achieve high spatial resolution ($0.313^\circ \times 0.312^\circ$). The NCEP CFSR data set covers a temporal scope of 31 yr, from 1979 to 2009. Hence, this data set is suitable for long-term high-resolution analyses of EDH. Recently, McKeon (2013) and Shi et al. (2015) applied the NCEP CFSR data set in the climatological analysis of the evaporation duct in the South China Sea. The results showed great potential for the NCEP CFSR data set to be utilised for in-depth studies of the relationships between EDH distribution and climate variations.

To model the EDH in the Gulf of Aden, some reanalysis variables were directly obtained from this data set. The other

Table 1. Reanalysis variables and variables calculated from reanalysis variables that were used in this paper

		Height	Units
Reanalysis variables	Air temperature (TA)	2 m	°C
	Sea-surface temperature (SST)	Sea surface	°C
	Specific humidity (SH)	2 m	g/kg
	u component of wind	10 m	m/s
	v component of wind	10 m	m/s
	Sea level pressure (SLP)	Sea surface	hPa
Calculated variables	Wind speed (WS)	10 m	m/s
	Air-sea temperature difference (ASTD)	2 m	°C
	Relative humidity (RH)	2 m	%

variables necessary for the modelling were derived from the reanalysis variables. Table 1 lists the reanalysis variables obtained from NCEP CFSR data set and the calculated variables derived from the reanalysis variables.

2.2. Improved NPS model

The NPS model uses the Monin–Obukhov similarity (MOS) and Liu–Katsaros–Businger (LKB; Liu et al., 1979) theories to derive profiles of temperature and specific humidity (Babin and Dockery, 2002). These profiles are then used to calculate modified refractivity profiles and EDH.

In the NPS model, the temperature and specific humidity profiles are represented by the following equations (Babin and Dockery, 2002).

$$T(z) = T(z_{0\theta}) + \frac{\theta_*}{\kappa} \left[\ln \left(\frac{z}{z_{0\theta}} \right) - \psi_h \left(\frac{z}{L} \right) \right] - \Gamma_d z \quad (1)$$

$$q(z) = q(z_{0q}) + \frac{q_*}{\kappa} \left[\ln \left(\frac{z}{z_{0q}} \right) - \psi_h \left(\frac{z}{L} \right) \right] \quad (2)$$

where T is the ensemble average temperature, q is the ensemble average specific humidity, θ_* is the Monin–Obukhov temperature scale, q_* is the Monin–Obukhov specific humidity scale, $Z_{0\theta}$ and Z_{0q} are integration constants for called the temperature and specific humidity roughness length, respectively. κ is von Kármán’s constant, Γ_d is adiabatic lapse rate, Z is the height above sea surface and L is the Obukhov length. The value of Z/L is usually used to indicate the atmospheric conditions. Stable, neutral and unstable conditions are defined as $Z/L > 0$, $Z/L = 0$ and $Z/L < 0$, respectively.

Ψ denotes the stability functions, which accounts for deviations from neutral stability in the atmosphere and is an integrated form of the dimensionless gradient functions. The NPS model assumes that the stability functions are the same for temperature and specific humidity but different for wind speed. The wind function is commonly notated as Ψ_m and the temperature (specific humidity) function notated as Ψ_h .

The NPS model tends to have difficulty resolving evaporation ducts under stable conditions. Stable conditions, along with light winds and/or low relative humidity, can result in a very high EDH to the point of being above the surface layer in which MOS theory is valid (Frederickson et al., 2000).

The surface-layer stability conditions can be classified by the values of the air–sea temperature difference (ASTD): $ASTD > 0$, $ASTD = 0$ and $ASTD < 0$ roughly correspond to stable, neutral and unstable thermodynamic atmospheric conditions, respectively (Karimian et al., 2013). The stable and unstable conditions can be further divided into four regimes: $ASTD > 1^\circ\text{C}$ (strongly stable), $0^\circ\text{C} < ASTD \leq 1^\circ\text{C}$ (weakly stable), $-1^\circ\text{C} \leq ASTD < 0^\circ\text{C}$ (weakly unstable) and $ASTD < -1^\circ\text{C}$ (strongly unstable) (Gunasekar et al., 2010).

Figure 2 shows the monthly means of the ASTD distribution in the Gulf of Aden. In winter, conditions are generally strongly unstable. From March to May, while much of the area is unstable, the coastal area begins to change and occasionally becomes neutral or weakly stable. After spring, the whole area begins to turn red and stable conditions dominate until October. In July and August in particular, the area is mainly in a strongly stable condition and the ASTD is larger than 2°C . As a result, new stability functions need to be imported to improve the NPS model’s performance when the Gulf of Aden is in a stable condition.

The NPS model uses the Beljaar and Holtslag’s stability function for stable conditions (Babin and Dockery, 2002). This function has been proven to be suitable only for weakly stable conditions and causes a very high EDH for some stable conditions. The Cheng’s stability function (Cheng and Brutsaert, 2005) and the Grachev’s stability function (Grachev et al., 2007) were obtained from the recent boundary layer experiments. These functions have better performance for stable conditions. For simplicity, the abbreviations of the NPS-BH, NPS-CB and NPS-GA models are used to denote the models employing Beljaar and Holtslag’s stability function, Cheng’s stability function

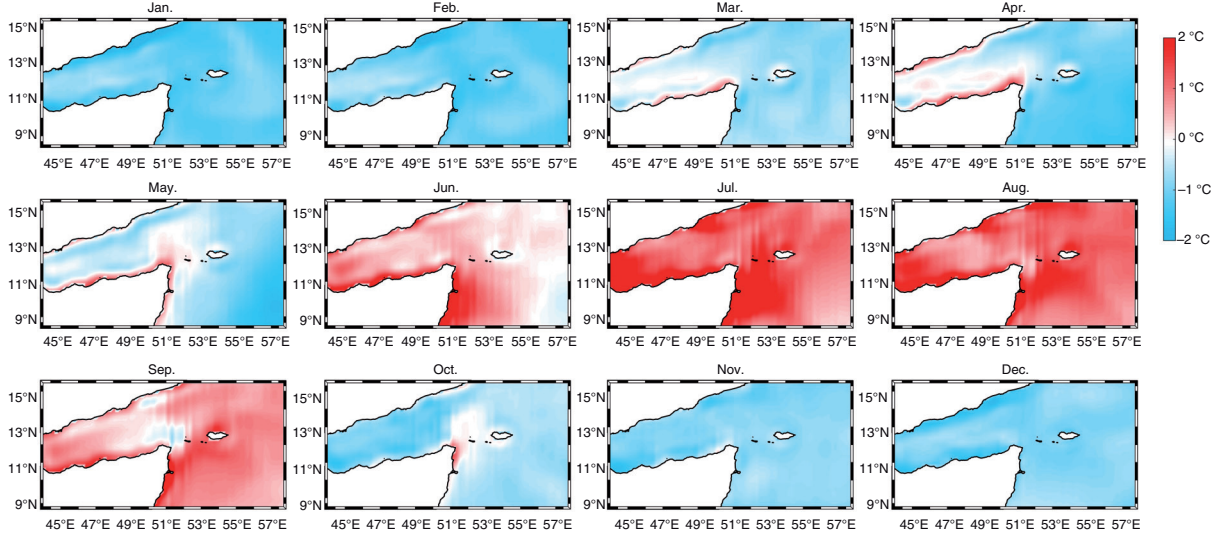


Fig. 2. Monthly means of air-sea temperature difference in the Gulf of Aden (units: °C).

and Grachev's stability function, respectively. For unstable or neutral conditions, the stability functions of the three models are the same as the NPS model. See Babin and Dockery (2002) for further details. In the equations that follow, ζ represents z/L which is the stability parameter.

a. NPS-BH model

For stable conditions, the Ψ_h and Ψ_m functions are from Beljaars and Holtslag (1991):

$$\psi_h = 1 - \left(1 + \left(\frac{2\zeta}{3}\right)\right)^{1/2} - \frac{2}{3} \left(\zeta - \frac{5}{0.035}\right) \exp(-0.35\zeta) - \frac{1}{1.05} \quad (3)$$

$$\psi_m = -\zeta - \frac{2}{3} \left(\zeta - \frac{5}{0.035}\right) \exp(-0.35\zeta) - \frac{1}{1.05} \quad (4)$$

b. NPS-CB model

For stable conditions, the Ψ_h and Ψ_m functions are from Cheng and Brutsaert (2005):

$$\psi_h = -a \ln \left[\zeta + \left(1 + (\zeta)^b\right)^{1/b} \right] \quad (5)$$

$$\psi_m = -c \ln \left[\zeta + \left(1 + (\zeta)^d\right)^{1/d} \right] \quad (6)$$

where $a = 53$, $b = 1.1$, $c = 6.1$ and $d = 2.5$.

c. NPS-GA model

For stable conditions, the Ψ_h and Ψ_m functions are from Grachev et al. (2007):

$$\psi_h = -\frac{b_h}{2} \ln(1 + c_h \zeta + \zeta^2) + \left(\frac{a_h}{B_h} + \frac{b_h c_h}{2B_h}\right) \times \left(\ln \frac{2\zeta}{c_h} + \frac{c_h - B_h}{c_h + B_h} - \ln \frac{c_h - B_h}{c_h + B_h}\right) \quad (7)$$

$$\psi_m = -\frac{a_m}{b_m} (x - 1) + \frac{a_m b_m}{2b_m} \left[2 \ln \frac{x + B_m}{1 + B_m} - \ln \frac{x^2 - x B_m + B_m^2}{1 - B_m + B_m^2} \right] + 2\sqrt{3} \left(\arctan \frac{2x - B_m}{\sqrt{3} B_m} - \arctan \frac{2 - B_m}{\sqrt{3} B_m} \right) \quad (8)$$

where $a_h = 5$, $b_h = 5$, $c_h = 3$, $B_h = \sqrt{5}$, $a_m = 5$, $b_m = 5$, $B_m = -0.8^{1/3}$ and $x = (1 + \zeta)^{1/3}$.

A comparison of Ψ_h and Ψ_m versus z/L for the three models in stable conditions is shown in Figs. 3 and 4, respectively.

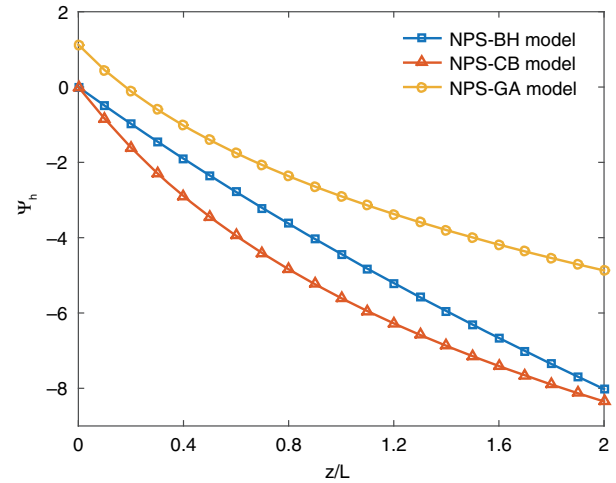


Fig. 3. Comparison of the temperature stability function, Ψ_h , versus the atmospheric conditions, functions versus z/Z , for the three different NPS models.

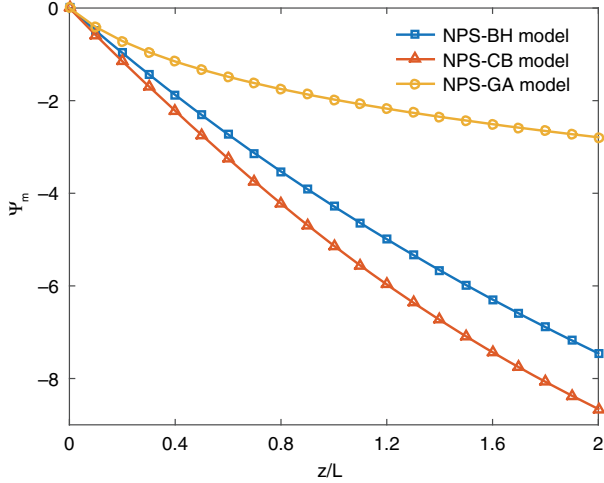


Fig. 4. Comparison of the wind stability function, Ψ_m , versus the atmospheric conditions, z/L , for the three different NPS models.

These figures only show the results when $z/L > 0$. Both the Ψ_h and Ψ_m functions of the NPS-GA model decreased slower than the other two models when z/L increased. Note also that the magnitude of the Ψ_h and Ψ_m functions of the NPS-GA model was the smallest among the three models.

A test was conducted to evaluate the effectiveness of the three different NPS models in calculating the EDH in our research area. The parameters were chosen as follows to represent the typical atmospheric conditions in the Gulf of Aden in July when strongly stable conditions are prevalent: SST 29 °C, ASTD 1.5 °C, relative humidity 78 %, wind speed 6 ms⁻¹ and sea-level pressure 1002 hPa. In Fig. 5, the lines represent the modified refractivity profiles computed by the NPS-BH (red), NPS-CB (green) and NPS-GA (blue) models. The results showed that the NPS-BH model could

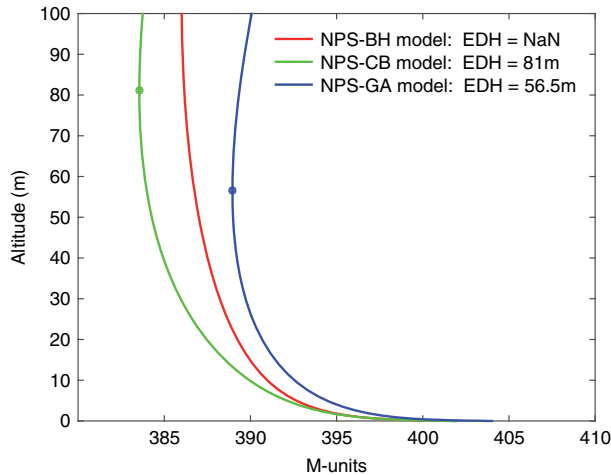


Fig. 5. Modified refractivity profiles computed by the different NPS models. The dot in each line indicates the location of the EDH.

not define EDH in this strongly stable condition. This meant that the NPS-BH model was not suitable to study the EDH in the Gulf of Aden. Frederickson also validated the NPS-GA model and concluded that the NPS-GA model produced better agreement with the measurements (Frederickson, 2012). Another test was also done to compare the computed EDH based on NPS-GA model with the evaluated results in a recent statistical study of EDH over the Arabian Sea (Pasricha et al., 2002). The model configurations were set as follows: SST = 2.2 °C, air temperature = 1.6 °C, relative humidity = 73.3 %, wind speed = 4.6 ms⁻¹, atmospheric pressure = 1024.15 mbar. The calculated EDH is 4.7 m, and according to the Table 1 in Pasricha's paper, the evaluated EDH is 4.5 m. The slight difference confirms the credibility of our model. Therefore, the NPS-GA model was chosen to compute EDH in our study.

2.3. Validation of reanalysis data

To confirm the reliability of the NCEP CFSR data set, independent observations were required for comparison. Buoy data are considered the best benchmark data because the buoys are often located in open ocean and only slightly affected by land and research vessels (Newton, 2003).

At present, there are no *in situ* buoy observation data from the Gulf of Aden available to assess the NCEP CFSR data set. Therefore, buoy data from the Arabian Sea experiment were used for the comparison. A buoy, moored at 15.5°N, 61.5°E, collected data including air temperature, relative humidity, sea temperature, barometric pressure and wind speed every 7.5 min from 16 October 1994 00:00 to 20 October 1995 00:00 (Weller et al., 2002). The monthly means were obtained by averaging the daily values. The data from the NCEP CFSR reanalysis grid point nearest to the buoy location were used in the comparison.

Figure 6a shows the atmospheric parameters and SST obtained from the buoy data and the NCEP CFSR data set from 16 October 1994 00:00 to 20 October 1995 00:00. In general, the NCEP CFSR data set agreed well with the buoy measuring data; however, there were some slight deviations at some points. These deviations could be due to data assimilation techniques or the insufficient observations (Shi et al., 2015).

As shown in Fig. 6b, the monthly averages and standard deviations from NCEP CFSR data set were compared with the buoy data. The monthly averages of the parameters were consistent with each other. The monthly averages for EDH are displayed in Fig. 6c, which shows good agreement between the NCEP CFSR data set and the buoy data, with the maximum difference about 1.5 m. From October 1994 to April 1995, the EDH calculated from the buoy data was higher than that obtained from the NCEP CFSR data set, because the air temperature was higher and the relative humidity was lower

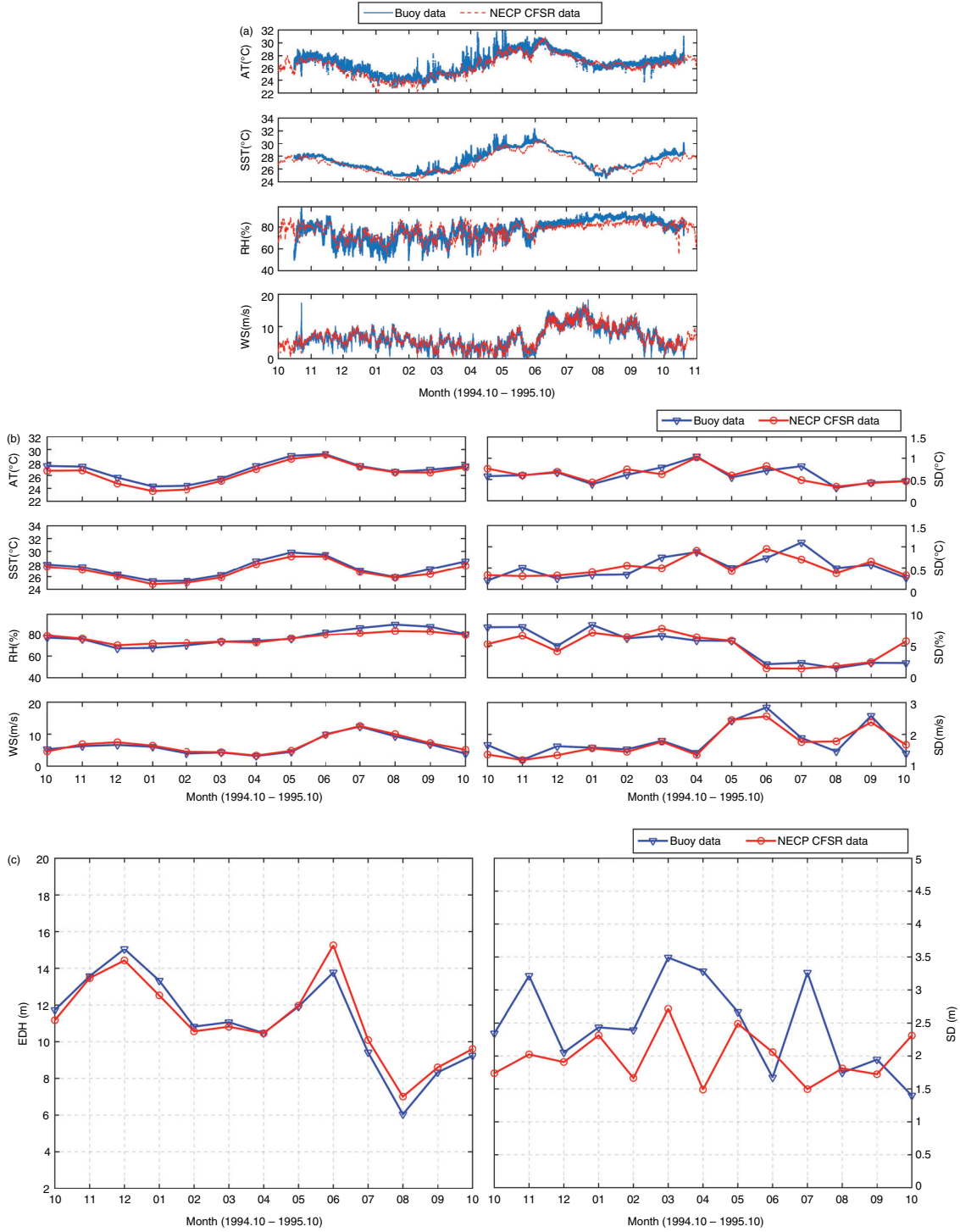


Fig. 6. Comparisons of the Arabian Sea experiment and NCEP CFSR data set. (a) Air temperature (AT), sea-surface temperature (SST), relative humidity (RH) and wind speed (WS) data from 16 October 1994 to 20 October 1995. (b) Monthly mean and standard deviations (SD) of AT, SST, RH and WS. (c) Monthly mean and SD of the evaporation duct height (EDH) calculated from the buoy data and NCEP CFSR data.

for the buoy data. The situation was opposite from May to October in 1995. As also shown in Fig. 6c, the difference in EDH standard deviation was within an acceptable range.

These comparisons suggest that the accuracy of applying the NCEP CFSR data set to calculate EDH is comparable with that using *in situ* buoy data. As the atmospheric and oceanic

conditions are similar between the Arabian Sea and the Gulf of Aden, it is reasonable to assume that the NCEP CFSR data for the Gulf of Aden are as accurate as in the Arabian Sea.

2.4. Ray-optics method

The effects of evaporation ducts on radar performance are manifold. One of the most severe problems is that a radar may lose contact with low targets and cannot detect the targets in such conditions (Pasricha et al., 2002). In order to evaluate the ducting effects, ray-optics method is applied. The ray-optics method has gained much special attention in the last decade (Barrios, 2003; Akbarpour and Webster, 2005; Zhao et al., 2010; Dinc and Akan, 2015). Based on the Snell's equation, the ray-optics method simulates the ray trajectories in the evaporation duct to estimate the ducting effects on the radar waves. The electromagnetic field is locally considered as a plane wave represented by rays. The field energy propagates along the trajectories orthogonal to the wave front at each point. The ray traces outwards from the transmitter can be described by the differential equations derived from repeated application of Snell's law. For more technical details of the ray-optics method, see Akbarpour and Webster (2005), Barclay (2012) and Dinc and Akan (2015).

3. Results and discussion

3.1. Long-term mean EDH seasonal cycle

We began our analyses by giving a basic understanding of the principles of how the EDH in the Gulf of Aden changes throughout the year. Among the analyses, an anomalous distribution of the EDH in Gulf of Aden was specified.

The understanding of seasonal variation of the EDH also provides a context to examine the impact of climate varying on the duct conditions and to specific months on which to focus our study in the next section.

A monthly climatology of EDH distributions in the Gulf of Aden is depicted in Fig. 7. From January to May, the EDH distributions were homogeneous for most of the area. The average EDH was about 10–12 m, and the variation was slight. When summer approached, the EDH increased rapidly and the monthly mean reached a maximum in July (> 30 m). However, during this period, an inhomogeneous distribution started to appear, particularly in the Gulf of Aden. The rapid increase in EDH first occurred in the western gulf (June) and then spread further to the east (July). Furthermore, the increase in EDH stopped at the mouth of the gulf, with a cliff-style drop in EDH (an EDH cliff) forming at the border between the Gulf of Aden and the western Arabian Sea. The EDH cliff has a drop of more than 15 m. This prominent feature tends to persist into September. This abrupt change in EDH could influence the navigation and communication of the ships crossing the Gulf of Aden, which is discussed in Section 3.3. After September, the EDH quickly reduces to winter values.

The Gulf of Aden and the adjoining Arabian Sea are mainly dominated by the Indian monsoon. Hence the surface winds in the Gulf of Aden are subject to semi-annual wind reversals that are associated with the monsoon cycle, which results in two periods of monsoon activity: the south-west monsoon (SWM, June–September) in boreal summer and the north-east monsoon (NEM, December–March) in boreal winter. These two periods are separated by the spring intermonsoon (SIM, April–May) and the fall intermonsoon (FIM, October–November), during which surface wind becomes relatively quiescent (Krishnaswami and Nair,

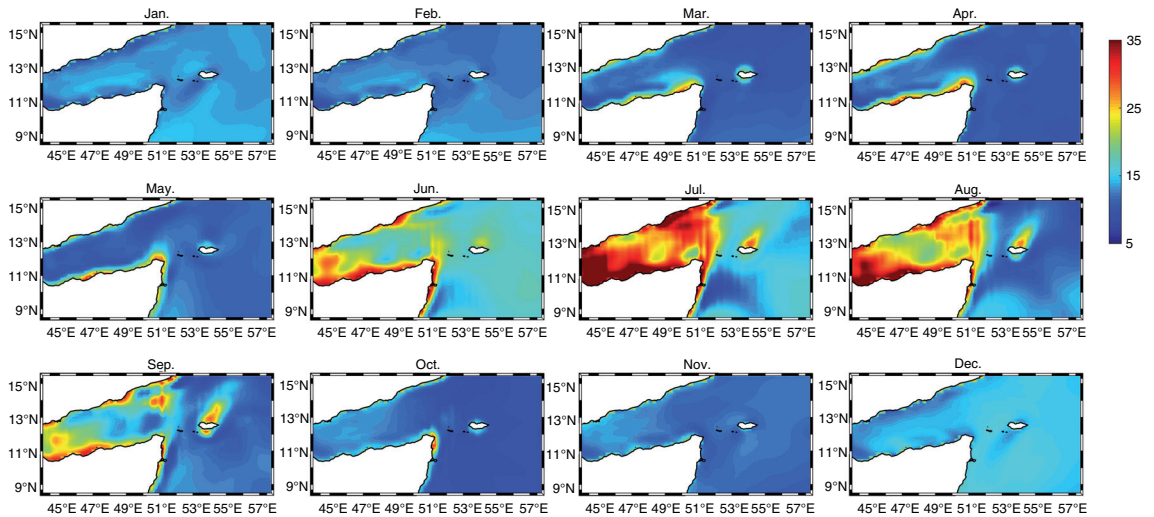


Fig. 7. Spatial and temporal variation of evaporation duct height in the Gulf of Aden (units: m).

1996; Wiggert et al., 2005). We chose January, April, July and October as the focus months of each climatological season to illustrate how environmental factors influenced the distribution of the EDH in the following discussion. The labels (a), (b), (c) and (d) in the following charts represented NEM, SIM, SWM and FIM, respectively. Analyses of these four months can be further used to better analyse and understand the other eight months of the year.

It is worth noting that the high EDH period shown in Fig. 7 overlaps with the SWM (June–September). This suggests that the SWM is the main physical mechanism driving the extremely large EDH difference between the Gulf of Aden and the western Arabian Sea during June to September, which will be confirmed in the following discussion.

3.2. Physical mechanisms for the EDH distributions

The evaporation duct is mainly affected by four factors: air temperature, SST, wind speed and relative humidity (Babin and Dockery, 2002). Therefore, a brief overview of the monthly and spatial variations of the atmospheric and sea-surface factors that influence the EDH will be helpful to develop a basic understanding of the likely physical mechanisms of the spatiotemporal characteristics of the EDH discussed above. Furthermore, a sensitivity analysis of the EDH to meteorological parameters is also needed to specify the relationships between EDH and these factors in the Gulf of Aden. Our analyses in the rest of this section are focused on these two aspects.

Figure 8 shows the seasonal variation of the surface wind. As already mentioned, surface winds are sustained at a high level in July and January and reduce to a low level during October and April. The surface winds in the gulf during the NEM are similar to those in the Arabian Sea (Fig. 8a). During summer, the Gulf of Aden experiences much weaker surface winds than the Arabian Sea (Fig. 8c) because it is located off the axis of the Somali low-level jet and is shielded from the mountains along the Somali coast (Yao and Hoteit, 2015).

Seasonal variation in surface wind also impacts the air temperature and relative humidity, as shown in Figs. 9 and 10. When the wind speed is homogenous, the air temperature is also homogenous. For example, the NEM flows from the west over Asian land and brings dry, cool air to the Gulf of Aden. The air temperature of the Gulf of Aden drops to 23 °C, the lowest air temperature of the year. The same holds true for the SIM and FIM, when the wind influences the whole of the Gulf of Aden. During the SWM, the situation is reversed. Owing to the geographical isolation of the Gulf of Aden the Somali low-level jet has little influence on the gulf. The Somali low-level jet brings cool air from the Southern Hemisphere winter across the Equator. Within the reach of the jet, the air becomes cooler. However, the winds crossing the Gulf of Aden are from neighbouring desert land (Fig. 8c), and they advect hot, dry air to the Gulf of Aden. From Fig. 9, it can be clearly seen that the air temperature around the Socotra Island is about 26–27 °C, while the air temperature in the Gulf of Aden is higher than 32 °C.

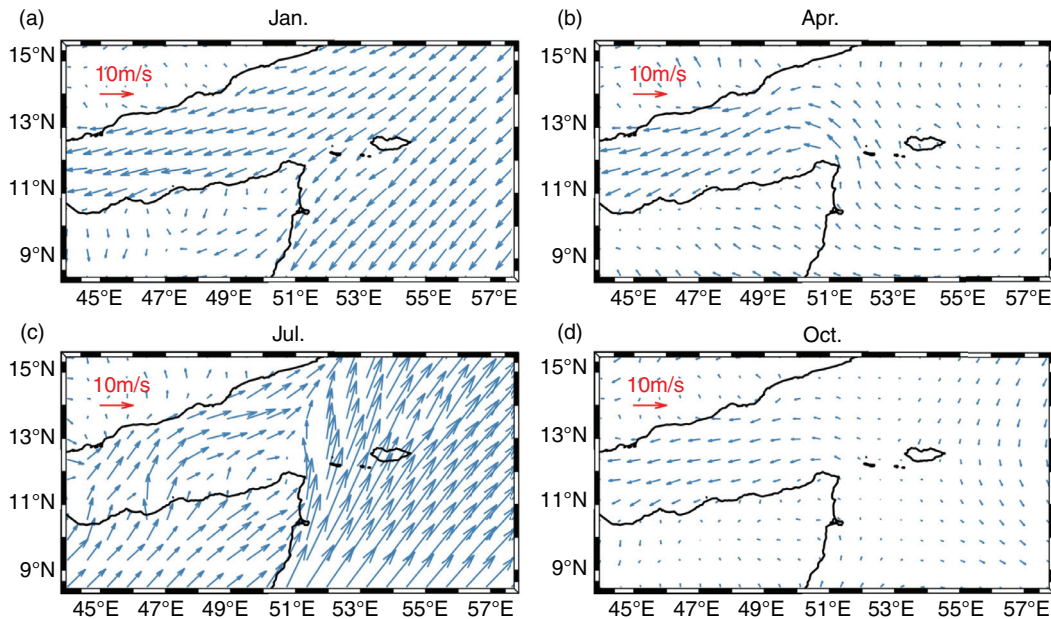


Fig. 8. Seasonal variation in surface wind. Arrows represent the wind direction. (a) North-east monsoon. (b) Spring intermonsoon. (c) South-west monsoon. (d) Fall intermonsoon.

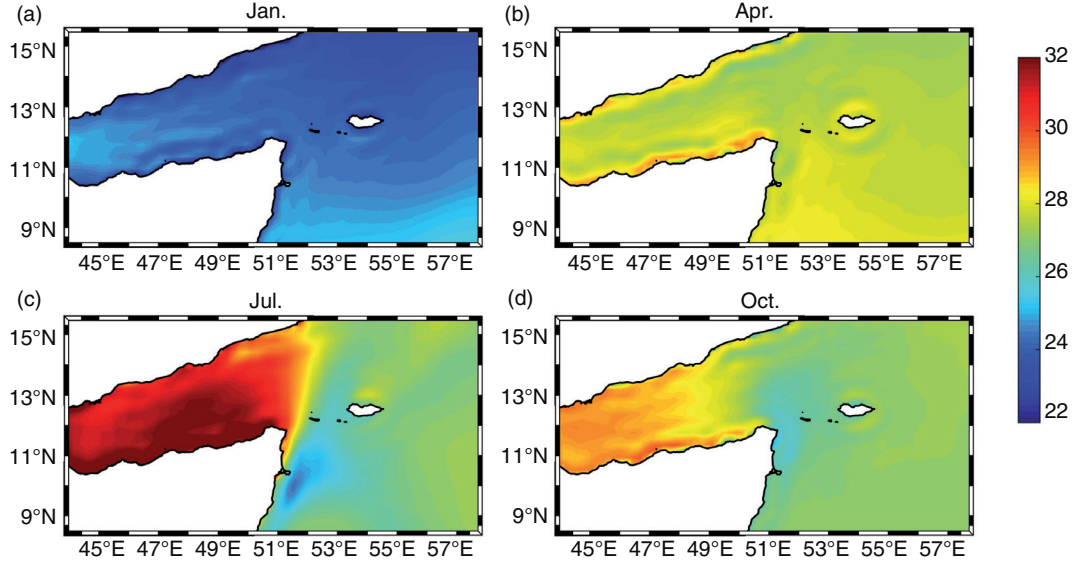


Fig. 9. Seasonal variation in air temperature (units: $^{\circ}\text{C}$). (a) North-east monsoon. (b) Spring intermonsoon. (c) South-west monsoon. (d) Fall intermonsoon.

There is an obvious temperature difference between the two sides of the mouth of the Gulf of Aden.

When it comes to relative humidity, the situation is almost the same as for air temperature. The largest relative humidity difference occurs in the SWM (Fig. 10c) when the Somali low-level jet brings humid air from the Equator. Beyond the reach of the jet, the Gulf of Aden remains at low relative humidity. The difference was as much as 15 %.

Owing to the coupled nature of the atmosphere–ocean boundary, the surface current within this region is also affected by the monsoon regimes. This resulted in a

temperature difference between different parts of the Gulf of Aden (Fig. 11). During the NEM, the SST of the whole region is between 25 and 26 $^{\circ}\text{C}$, less than 1 $^{\circ}\text{C}$. After entering the SWM, when the Somali low-level jet is onset, the temperature difference between the western and eastern parts of the Gulf of Aden becomes greater than 10 $^{\circ}\text{C}$.

To illustrate the impact of the monsoon on the SST variations explicitly, Fig. 12 shows the change in SST during the SWM (June–September). The SST of the western part remains at a high temperature, about 30–31 $^{\circ}\text{C}$, from June

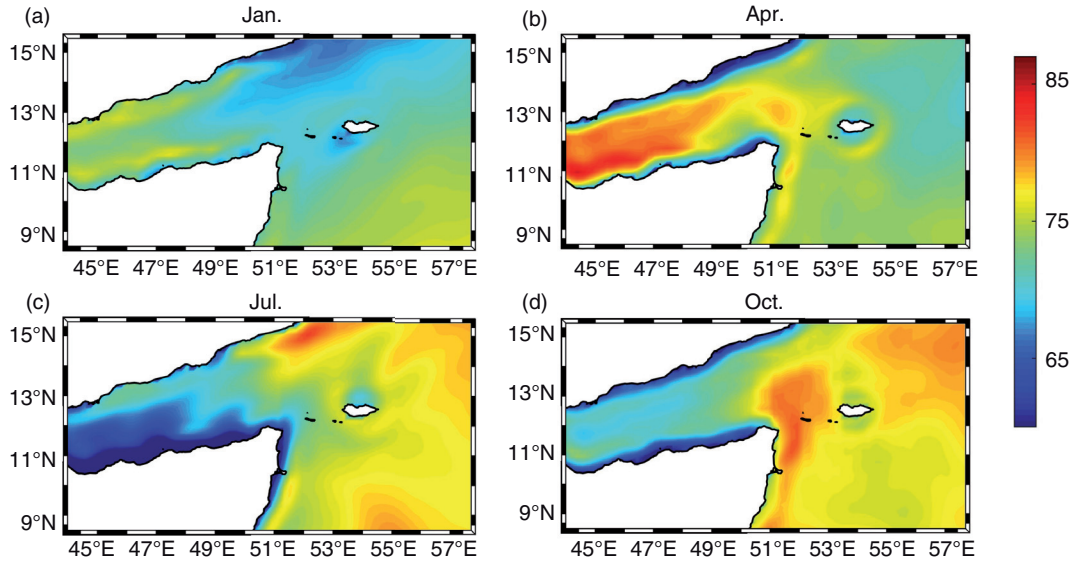


Fig. 10. Seasonal variation in relative humidity (units: %). (a) North-east monsoon. (b) Spring intermonsoon. (c) South-west monsoon. (d) Fall intermonsoon.

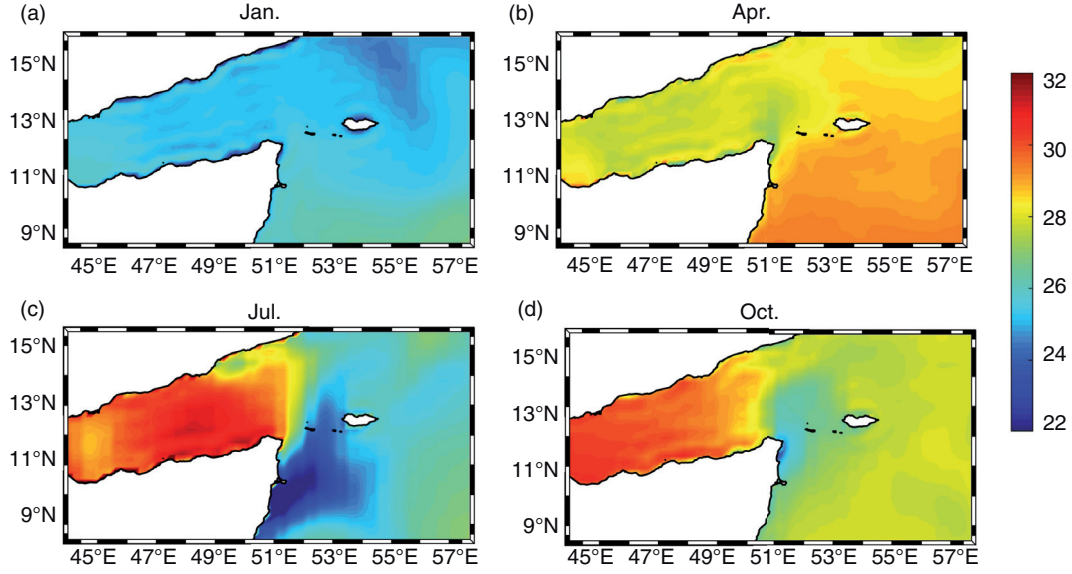


Fig. 11. Seasonal variation of the sea-surface temperature (SST) (units: $^{\circ}\text{C}$). (a) North-east monsoon. (b) Spring intermonsoon. (c) South-west monsoon. (d) Fall intermonsoon.

to September. A cooler current derived from the Somalia south-eastern coastal region invades into the eastern part between Socotra Island and the mouth of the Gulf of Aden from June to the end of September. Combining Figs. 8 and 11, it can be concluded that when the SWM is onset, the western boundary current forced by the Somali low-level jet advects the cooler upwelling water from the Somali coast into the sea area around Socotra Island. Furthermore, owing to the wind direction of the SWM, this cool current has little influence in the Gulf of Aden. Meanwhile, surveys conducted by Bower and Furey (2012) show that large-scale

upwelling also takes place in the Gulf of Aden during the SWM. However, due to the strong heating effect of the nearby dessert, the SST of the Gulf of Aden remains high. Hence, the SST in the Gulf of Aden is on average approximately 10°C warmer than that nearby the Socotra Island.

The main factors that determine EDH are air temperature, SST, wind speed and relative humidity. The differences in these factors between the two sides of the Gulf of Aden result in the foundation of the EDH cliff. In the following part, the sensitivity of the EDH to meteorological parameters is analysed based on the real data for each of

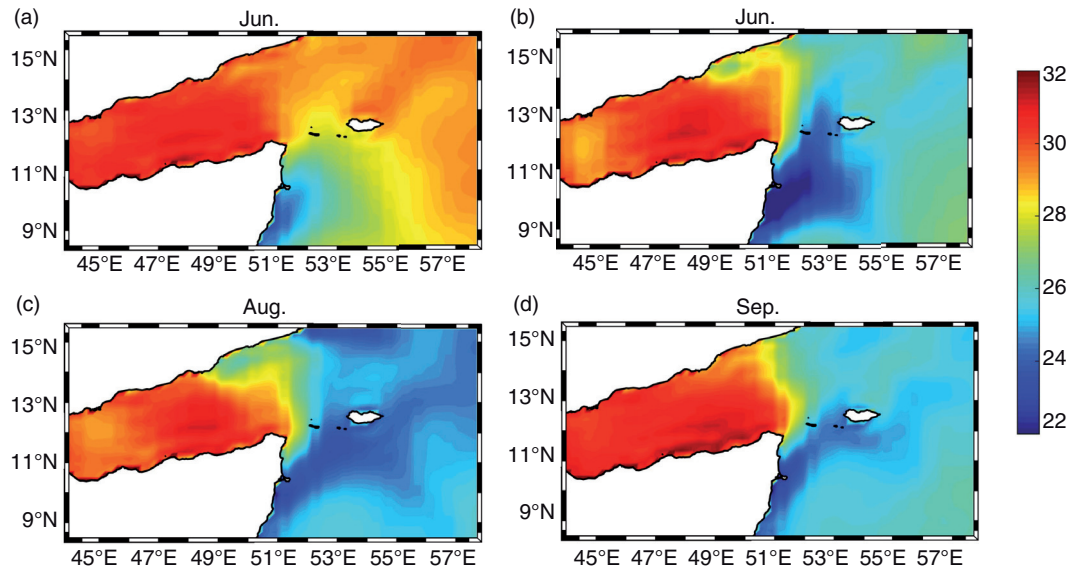


Fig. 12. The change in sea-surface temperature (SST) during the south-west monsoon (units: $^{\circ}\text{C}$).

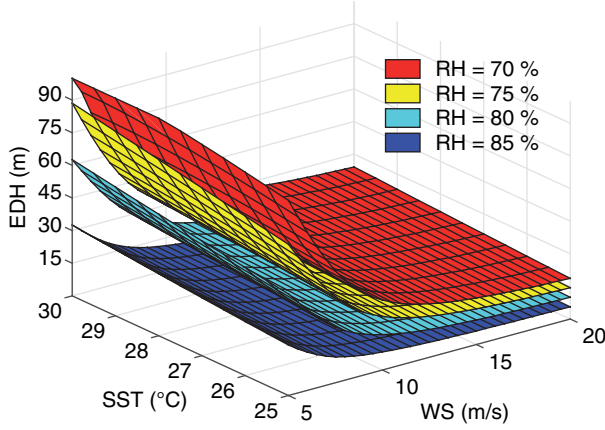


Fig. 13. Sensitivity of evaporation duct height to meteorological parameters.

the factors in July, as this is the month when the EDH cliff is the most obvious.

Figure 13 shows different EDH curves as a function of SST and wind speed. Generally, the NPS models are insensitive to the sea-level pressure (Fairall et al., 2003), and a constant sea-level pressure of 1020 hPa was used here. It was assumed that the ASTD was 1.5 °C (strongly stable condition), which is the average value in July, obtained from Fig. 2. It is evident that when the relative humidity is constant, EDH generally increases with increasing SST (equal to an increase in air temperature) or decreasing wind speed. When the relative humidity is changing, the decrease in relative humidity leads to a dramatic increase in EDH.

For the Gulf of Aden and the adjacent Arabian Sea, the ASTD is around 1.5 °C and the strongly stable conditions are almost the same. However, the wind speed in the Gulf of Aden is much weaker than in the Arabian Sea and, due

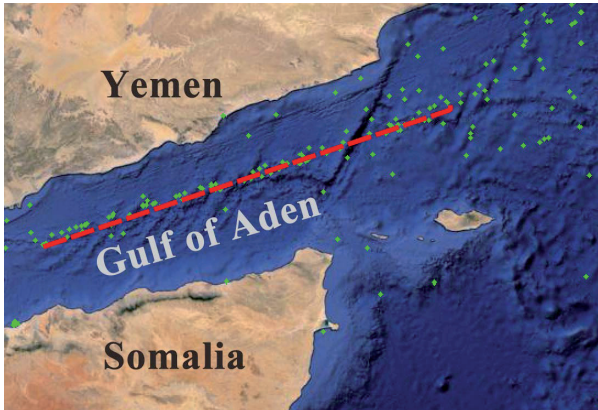


Fig. 14. Real-time AIS map of ships in the Gulf of Aden. The green points represent the real-time positions of the ships. The red line represents the approximate marine route for ships crossing the Gulf of Aden.

to the influence of the wind, the relative humidity in the Gulf of Aden is also lower than in the Arabian Sea. All of these contribute to the higher EDH in the Gulf of Aden than that in the Arabian Sea. This could also explain why a small-scale area at the lee of Socotra Island exhibits much higher EDH than the surroundings.

3.3. Ducting effects on marine radar

Based on the spatio-temporal distributions of EDH obtained in the previous section, we will focus on how evaporation duct affects the work conditions of marine radar for the ships in the Gulf of Aden in this section.

The marine route of ships in the Gulf of Aden was identified from the real-time AIS (Automatic Identification System) maps and is shown in Fig. 14. Figure 15a shows the evaporation duct distribution along the obtained marine route in July when the EDH cliff is the most obvious. Figure 15b shows how the EDH varies as the route crosses the EDH cliff. Points A and B were chosen to represent the two different parts: left side of the EDH cliff (high EDH side) and right side of the EDH cliff (low EDH side). From Fig. 15b, it can be seen that the EDH at points A and B was 30 and 16 m, respectively.

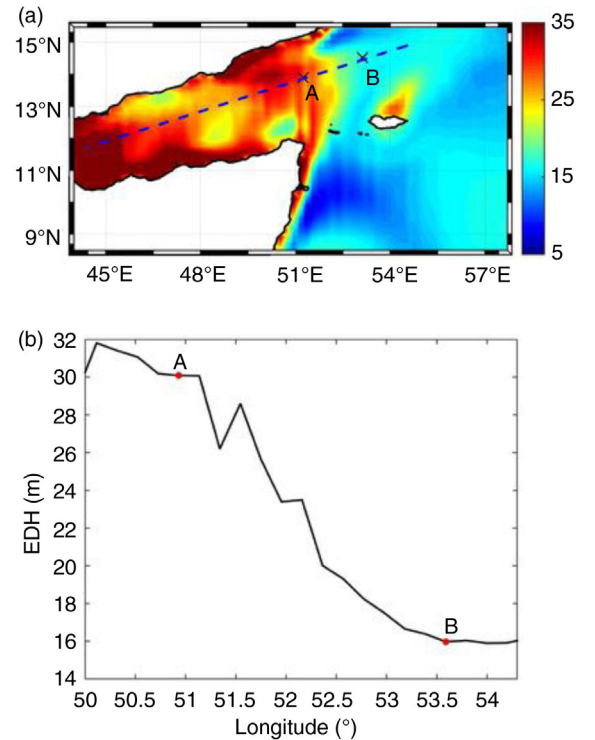


Fig. 15. (a) Evaporation duct height (EDH) distribution along the marine route in July in the Gulf of Aden. (b) The EDH cliff on the marine route.

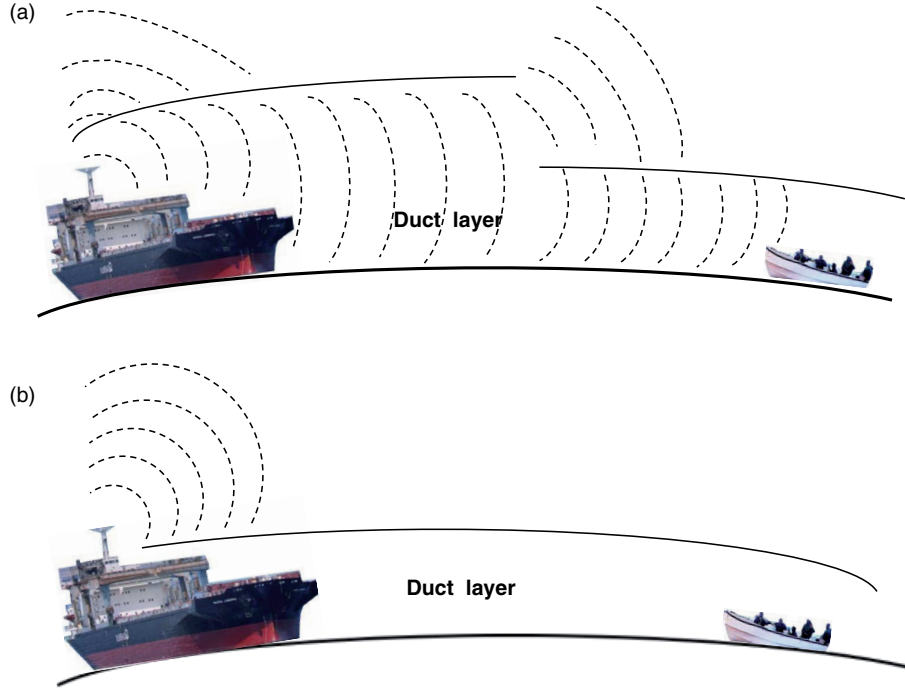


Fig. 16. Ducting effects on the detection ability of marine radar. (a) Marine radar is located in the duct layer. (b) Marine radar is located out of the duct layer.

The existence of the EDH cliff could affect the detection ability of the marine radar. For instance, as shown in Fig. 16, when a ship sailing along the marine route from the Gulf of Aden to the Arabian Sea approaches the EDH cliff, the difference in EDH could result in a serious leak of the radar energy, damaging the radar detection ability (Fig. 16a). When the ship enters the low EDH region, if the marine radar is located out of the duct layer, there would be little or no energy trapped in the evaporation duct (Fig. 16b). This means that the marine radar could not detect and locate the hazards, such as pirate speedboats, which are common in the Gulf of Aden.

Furthermore, we utilised a ray-optics method to study the ducting effects. Two different sailing directions across the EDH cliff, namely entering the Gulf of Aden from the Arabian Sea (east to west, EW) and leaving the Gulf of Aden to the Arabian Sea (west to east, WE), were considered.

The radar height was set to 20 m, located between the high ducting layer (EDH = 30 m) and the low ducting layer (EDH = 16 m). The EDH cliff was located at a range of 100 km. First, it was assumed that the ships sailed in the WE direction from the high EDH region to the low EDH region. Most of the trapped rays leaked from the evaporation duct, which means that the detection ability is weakened as the

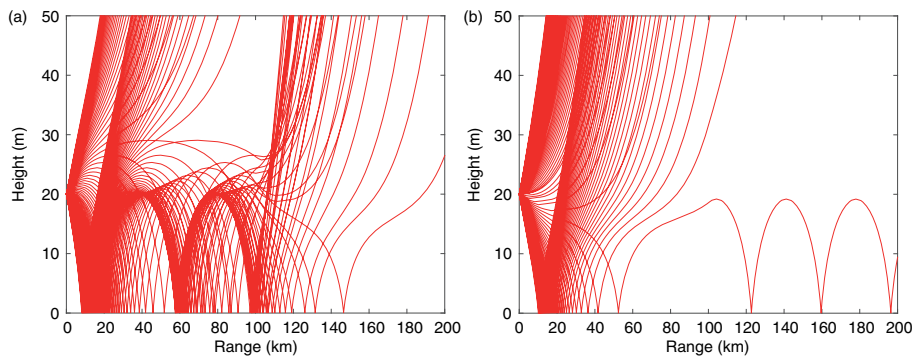


Fig. 17. Ray trace of the radar waves in the evaporation duct when ships sail in different directions to cross the evaporation duct height (EDH) cliff: (a) from high EDH region to low EDH region, and (b) from low EDH region to high EDH region.

EDH decreased from 30 to 16 m (Fig. 17a). This is the same situation as shown in Fig. 16.

Second, it was assumed that the ships sailed in the EW direction from the low EDH region to high EDH region (Fig. 17b). Owing to the fact that the marine radar was located out of the ducting layer, few rays were trapped in the evaporation duct within the range of 50 km. Beyond 50 km, almost all of the trapped rays escaped the evaporation duct, which means the radar could not detect any objects near the sea surface.

According to this analysis, we can conclude that it is of great importance to pay much attention to the different evaporation duct environments when sailing in the Gulf of Aden.

4. Summary and conclusions

Climate analyses of the spatial and temporal variations in EDH in the Gulf of Aden were conducted in this study. It was shown that the EDH in the Gulf of Aden is strongly influenced by the seasonally reversing monsoonal winds.

Furthermore, the Gulf of Aden is a separate meteorological and oceanographical province from the adjacent north-western Arabian Sea. It exhibits a distinctive spatio-temporal variability in the evaporation duct distributions.

The climatological evolution of the EDH revealed that the Gulf of Aden experiences a summer EDH increase larger than the neighbouring Arabian Sea. At the mouth of the Gulf of Aden, an EDH cliff forms during the SWM. The analysis revealed the basic physical processes responsible for the EDH distribution in the Gulf of Aden: the monsoon reversals induce variations in the atmospheric and oceanic factors, and the fluctuation of these factors regulates the seasonal fluctuation of the evaporation duct. The EDH cliff has a large effect on marine radar. Therefore, the monsoon variations and the EDH changes should be closely monitored when sailing in the Gulf of Aden.

In situ measurements that cover the Gulf of Aden at a suitable resolution to resolve the highly variable spatial patterns are required to provide field validations of the results presented in this study.

References

- Akbarpour, R. and Webster, A. R. 2005. Ray-tracing and parabolic equation methods in the modeling of a tropospheric microwave link. *IEEE Trans. Antennas Propag.* **53**, 3785–3791.
- Al Saafani, M. A. and Sheno, S. S. C. 2007. Water masses in the Gulf of Aden. *J. Oceanogr.* **63**, 1–14.
- Anderson, K. D. 1995. Radar detection of low-altitude targets in a maritime environment. *IEEE Trans. Antennas Propag.* **43**, 609–613.
- Babin, S. M. and Dockery, G. D. 2002. LKB-based evaporation duct model comparison with buoy data. *J. Appl. Meteorol.* **41**, 434–446.
- Babin, S. M., Young, G. S. and Carton, J. A. 1997. A new model of the oceanic evaporation duct. *J. Appl. Meteorol.* **36**, 193–204.
- Barclay, L. 2012. *Propagation of Radiowaves*. 3rd ed. IET, London, pp. 91–92, 95–96.
- Barrios, A. E. 2003. Considerations in the development of the advanced propagation model (APM) for US Navy applications. In: *Proceedings of the International Radar Conference, 2003*. Adelaide, Australia.
- Beljaars, A. and Holtslag, A. 1991. Flux parameterization over land surfaces for atmospheric models. *J. Appl. Meteorol.* **30**, 327–341.
- Bower, A. S. and Furey, H. H. 2012. Mesoscale eddies in the Gulf of Aden and their impact on the spreading of Red Sea Outflow Water. *Prog. Oceanogr.* **96**, 14–39.
- Briggs, J. N. 2004. *Target Detection by Marine Radar*. IET, London, pp. 59–60.
- Cheng, Y. and Brutsaert, W. 2005. Flux-profile relationships for wind speed and temperature in the stable atmospheric boundary layer. *Boundary-Layer Meteorol.* **114**, 519–538.
- Dinc, E. and Akan, O. 2014. Beyond-line-of-sight communications with ducting layer. *IEEE Commun. Mag.* **52**, 37–43.
- Dinc, E. and Akan, O. 2015. Channel model for the surface ducts: Large-scale path-loss, delay spread, and AOA. *IEEE Trans. Antennas Propag.* **63**, 2728–2738.
- El-Mashjary, M. S. and Ali, A. M. 2010. The effect of environmental conditions on coral reef habitat in Balhaf Bay, Gulf of Aden, Yemen. *J. Adv. Res.* **1**, 221–225.
- Fairall, C., Bradley, E. F., Hare, J., Grachev, A. and Edson, J. 2003. Bulk parameterization of air-sea fluxes: Updates and verification for the COARE algorithm. *J. Clim.* **16**, 571–591.
- Frederickson, P. A. 2012. Improving the characterization of the environment for AREPS electromagnetic performance predictions. *Weather Impacts Decision Aids (WIDA) Workshop*, Reno, NV.
- Frederickson, P., Davidson, K. and Goroch, A. 2000. *Operational Bulk Evaporation Duct Model for MORIAH. Version 1* **2**, 93943–95114, Naval Postgraduate School.
- Grachev, A. A., Andreas, E. L., Fairall, C. W., Guest, P. S. and Persson, P. O. G. 2007. SHEBA flux–profile relationships in the stable atmospheric boundary layer. *Boundary-layer Meteorol.* **124**, 315–333.
- Gunashekar, S., Warrington, E. M. and Siddle, D. R. 2010. Longterm statistics related to evaporation duct propagation of 2 GHz radio waves in the English Channel. *Radio Sci.* **45**, RS6010.
- Karimian, A., Yardim, C., Haack, T., Gerstoft, P., Hodgkiss, W. S. and co-authors. 2013. Toward the assimilation of the atmospheric surface layer using numerical weather prediction and radar clutter observations. *J. Appl. Meteorol. Climatol.* **52**, 2345–2355.
- Krishnaswami, S. and Nair, R. 1996. JGOFS (India)-Introduction. *Curr. Sci.* **71**, 831–833.
- Levy, M. and Craig, K. 1989. Case studies of transhorizon propagation: Reliability of predictions using radiosonde data.

- In: *Proceedings of Sixth International Conference on the Antennas and Propagation, 1989*. ICAP 89, (Conf. Publ. No. 301), Coventry, England.
- Liu, W. T., Katsaros, K. B. and Businger, J. A. 1979. Bulk parameterization of air-sea exchanges of heat and water vapor including the molecular constraints at the interface. *J. Atmos. Sci.* **36**, 1722–1735.
- McKeon, B. D. 2013. *Climate Analysis of Evaporation Ducts in the South China Sea*. Naval Postgraduate School, Monterey, CA.
- Musson-Genon, L., Gauthier, S. and Bruth, E. 1992. A simple method to determine evaporation duct height in the sea surface boundary layer. *Radio Sci.* **27**, 635–644.
- Nandkeolyar, N., Raman, M. and Kiran, G. S. 2013. Comparative analysis of sea surface temperature pattern in the eastern and western gulfs of Arabian Sea and the Red Sea in recent past using satellite data. *Int. J. Oceanogr.* **2013**, 1–16.
- NCAR. 2014. *Climate Data Guide*. NCAR, Boulder, USA.
- Newton, D. A. 2003. *COAMPS Modeled Surface Layer Refractivity in the Roughness and Evaporation Duct Experiment 2001*. Naval Postgraduate School, Monterey, CA.
- Pasricha, P. K., Prasad, M. and Sarkar, S. K. 2002. Comparison of evaporation duct models to compute duct height over Arabian Sea and Bay of Bengal. *Indian J. Radio Space Physics* **31**, 155–158.
- Paulus, R. 1985. Practical application of an evaporation duct model. *Radio Sci.* **20**, 887–896.
- Pons, J., Reising, S. C., Padmanabhan, S., Camps, A. and Duffo, N. 2003. Passive polarimetric remote sensing of the ocean surface during the Rough Evaporation Duct experiment (RED 2001). In: *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium, 2003. IGARSS'03*, Toulouse, France.
- Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J. and co-authors. 2010. The NCEP climate forecast system reanalysis. *Bull. Am. Meteorol. Soc.* **91**, 1015–1057.
- Shi, Y., Yang, K. D., Yang, Y. X. and Ma, Y. L. 2015. A new evaporation duct climatology in the South China Sea. *J. Meteorol. Res.* **29**, 764–778.
- Wash, C. and Davidson, K. 1994. Remote measurements and coastal atmospheric refraction. In: *Proceedings of the Geoscience and Remote Sensing Symposium, 1994. IGARSS'94*. Surface and Atmospheric Remote Sensing: Technologies, Data Analysis and Interpretation, International, 1994. Pasadena, USA.
- Weller, R., Fischer, A., Rudnick, D., Eriksen, C., Dickey, T. and co-authors. 2002. Moored observations of upper-ocean response to the monsoons in the Arabian Sea during 1994–1995. *Deep Sea Res. Part II Top. Stud. Oceanogr.* **49**, 2195–2230.
- Wiggert, J., Hood, R., Banse, K. and Kindle, J. 2005. Monsoon-driven biogeochemical processes in the Arabian Sea. *Prog. Oceanogr.* **65**, 176–213.
- Woods, G. S., Ruxton, A., Huddleston-Holmes, C. and Gigan, G. 2009. High-capacity, long-range, over ocean microwave link using the evaporation duct. *IEEE J. Ocean. Eng.* **34**, 323–330.
- Yao, F. and Hoteit, I. 2015. Thermocline regulated seasonal evolution of surface chlorophyll in the Gulf of Aden. *PLoS One* **10**, e0119951.
- Zhao, X. F., Huang, S. X. and Sheng, Z. 2010. Ray tracing/correlation approach to estimation of surface-based duct parameters from radar clutter. *Chin. Phys. B* **19**, 049201.