Simulating Coral Reef Connectivity in the Southern Red Sea

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ABSTRACT

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Connectivity is an important component of coral reef studies for its role in the enhancement of ecosystem resilience. Previous genetic structure and physical circulation studies in the Red Sea reveal a homogeneity within the coral reef complexes in the central and northern parts of the basin. Yet, genetic isolation and relatively low connectivity has been observed in the southern Red Sea. Raitsos et al. (2017) recently hypothesized that coral reefs in the southern Red Sea are more connected with regions outside the basin, rather than with the central and northern Red Sea. Using a physical circulation approach based on a 3-D backward particle tracking simulation, we further investigate this hypothesis. A long-term (> 10 years), very high resolution (1km) MITgcm simulation is used to provide detailed information on velocity in the complex coastal regions of the Red Sea and the adjacent narrow Bab-El-Mandeb Strait.

The particle tracking simulation results support the initial hypothesis that the coastal regions in the southern Red Sea exhibit a consistently higher connectivity with the regions outside the Bab-El-Mandeb Strait, than with the central and northern Red Sea. Substantially high levels of connectivity, facilitated by the circulation and eddies, is observed with the coastal regions in the Gulf of Aden. A strong seasonality in connectivity, related to the monsoon-driven circulation, is also evident with the regions outside of the Red Sea. The winter surface intrusion plays a leading role in transporting the particles from the Gulf of Aden and the Indian Ocean into the Red Sea, while the summer subsurface intrusion also supports the transport of particles.
into the Red Sea in the intermediate layer. In addition, the connectivity with the central and northern Red Sea is more affected by the intensity of the eddies. Evidence also suggests that potential connectivity exists between the coastal southern Red Sea and the coasts of Oman, Socotra, Somalia, Kenya, Tanzania and the north coast of the Madagascar.
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# TABLE OF CONTENTS

- Examination Committee Page .................................................. 2
- Copyright ................................................................................. 3
- Abstract .................................................................................... 4
- Acknowledgements .................................................................... 6
- List of Figures ........................................................................... 9

## 1 Introduction ............................................................................. 14

## 2 General Circulation and Connectivity ....................................... 17
  2.1 General Circulation ............................................................... 17
  2.1.1 The Red Sea and Gulf of Aden ...................................... 17
  2.1.2 The Indian Ocean ......................................................... 20
  2.2 Connectivity Studies in the Red Sea .................................... 22

## 3 Datasets and Methods ............................................................. 25
  3.1 Datasets ............................................................................... 26
  3.1.1 Coarse Resolution Datasets in the Indian Ocean Domain ... 26
  3.1.2 High Resolution Datasets in the Red Sea Domain .......... 27
  3.2 CMS model ........................................................................... 28
  3.3 Experiment Design ............................................................... 29
  3.3.1 Particle release locations in the Southern Red Sea .......... 29
  3.3.2 Particle Receiving Locations ......................................... 32
  3.3.3 Other Experimental Settings ....................................... 33
  3.4 Quantifying Connectivity .................................................... 33
  3.4.1 Lagrangian PDF .............................................................. 33
  3.4.2 Source Strength and MCT ............................................ 34
  3.4.3 Resident Particle Fraction (RPF) ................................. 36
  3.5 Supercomputing Resources ................................................. 37
4 Results and Discussions

4.1 Particles Backward Dispersal Pattern ........................................ 38
  4.1.1 Backward Dispersal Pattern in Trajectories Diagram ............... 38
  4.1.2 Backward Dispersal Pattern in Lagrangian PDFs .................... 40

4.2 Source Strength and MCT Analysis ........................................... 41

4.3 RPF Analysis ........................................................................... 44
  4.3.1 Consistency of the RPFs ...................................................... 44
  4.3.2 Seasonality in the RPFs ...................................................... 46

5 Conclusions ............................................................................. 51

References .................................................................................. 53

Appendices .................................................................................. 62
LIST OF FIGURES


2.2 Schematic representation of identified current branches during the summer (southwesterly) monsoon cited from Schott et al., 2009. . . . . . . 21

2.3 Schematic representation of identified current branches during the winter (northeasterly) monsoon cited from Schott et al., 2009. . . . . . . 22

3.1 Selected 1 releasing polygon and 9 receiving polygons distinguished by color, together with 2 boundaries implying the regional division: 1. releasing polygon sRS: coastline of the southern Red Sea; 2. receiving polygon cnRS: coastline of the central and northern Red Sea; 3. receiving polygon SB: coastline of the Strait of Bab-El-Mandeb; 4. receiving polygon GA: coastline of the Gulf of Aden; 5. receiving polygon cS: coast of the island Socotra; 6. receiving polygon eS: east coast of Somalia; 7. receiving polygon eKT: east coast of Kenya and Tanzania; 8. receiving polygon nM: north coast of Madagascar and coast of islands north of Madagascar; 9. receiving polygon sO: south coast of Oman; 10. receiving polygon GO: coastline of Gulf of Oman; 11. Boundary 1: the demarcation line for the region Out-RS (region outside of the Red Sea, east of the line); 12. Boundary 2: the demarcation line for the region In-cnRS (region in the central and northern Red Sea basin, north of the line). The region In-sRS (region in the southern Red Sea basin) is located in between boundary line 1 and 2. . . . . . . . . . . 30
4.1 Backward-tracked Lagrangian trajectories of randomly selected 200 particles. The particles are released in polygon sRS (red band in Fig. 3.1) on the 15th of every month during 10 simulation years, and are backward tracked for 360 days. The red lines are simulated 360-day trajectories, the blue dots indicate the releasing points, the green crosses indicate the particles locations after the 360-day simulation and the pink lines are the demarcation (see Fig. 3.1). Selected trajectories can reach limited distances thus figures are trimmed in a smaller geographic area to better demonstrate the dispersal pattern.

4.2 The Lagrangian Probability Density Functions (PDFs) of particles released from the polygon sRS and backward-tracked for (a) 60 days, (b) 120 days, (c) 180 days, (d) 240 days, (e) 300 days and (f) 360 days. The Lagrangian PDFs are computed with equation(2) accounting of all particles regardless of the releasing month and year. The color indicates the probability density with a unit of km$^{-2}$. The colorbar is shading logarithmically due to the large span of the order of magnitude.

4.3 (a) Source Strength and (b) mean connectivity time (MCT) of the two studied receiving regions (Out-Rs and In-cnRS) and the 9 receiving polygons over the total backward simulating time of 360 days. All Lagrangian particles regardless of year and month are used.

4.4 The evolution in time of the Resident Particles Fractions (RPFs) for (a) the polygon sRS, the region In-sRS, In-cnRS and Out-RS, (b) the polygon cnRS, GA and SB, (c) the polygon eS, sO, cS, nM, eKT and GO. All Lagrangian particles are used here regardless of year and month.

4.5 Annual and seasonal RPFs of (a) the region In-cnRS, (b) the region Out-RS, (c) the polygon cnRS and (d) the polygon GA, with color denoting the seasons. The annual RPFs are calculated using all months simulation, the seasonal RPFs are calculated using only the corresponding months: spring (March, April and May), summer (June, July and August), autumn (September, October and November), winter (December, January and February).

4.6 Backward-tracked Lagrangian trajectories of 100 particles. The particles are released in polygon sRS on 15th of (a) March and (b) September during all simulation years and are backward tracked for 90 days. The color indicates the depth of the particle in different locations.
4.7 Backward-tracked Lagrangian trajectories of 1000 particles to demonstrate the relatively stronger connectivity to the central and northern Red Sea in winter than in summer. The particles are released in the polygon sRS on 15th of (a) May and (b) November during the 10 simulation years and are backward tracked for 180 days. The selection of particle number 1000 is to well present the difference of trajectories in the central and northern Red Sea.

A.1 High resolution map for releasing polygon sRS (colored in Red). The resolution is from GEBCO 1/60 degree bathymetry data. The small gap between the blue and red color is the step of 0.05° to avoid high particles mortality and being too close to the sea-land boundary, followed by the red band with a width of 0.2°.

B.1 Selected 1200 particles geographical distribution after a simulation time of 0 days (0 months). The color indicates the backward simulating time and the particle depth. Two red lines distinguish the region In-cnRS (north of the upper line) and region Out-RS (east of the lower line).

B.2 Selected 1200 particles geographical distribution after a simulation time of 30 days (1 months). The color and red lines are explained in Fig. B.1.

B.3 Selected 1200 particles geographical distribution after a simulation time of 60 days (2 months). The color and red lines are explained in Fig. B.1.

B.4 Selected 1200 particles geographical distribution after a simulation time of 90 days (3 months). The color and red lines are explained in Fig. B.1.

B.5 Selected 1200 particles geographical distribution after a simulation time of 120 days (4 months). The color and red lines are explained in Fig. B.1.

B.6 Selected 1200 particles geographical distribution after a simulation time of 150 days (5 months). The color and red lines are explained in Fig. B.1.

B.7 Selected 1200 particles geographical distribution after a simulation time of 180 days (6 months). The color and red lines are explained in Fig. B.1.
B.8 Selected 1200 particles geographical distribution after a simulation time of 210 days (7 months). The color and red lines are explained in Fig. B.1.

B.9 Selected 1200 particles geographical distribution after a simulation time of 240 days (8 months). The color and red lines are explained in Fig. B.1.

B.10 Selected 1200 particles geographical distribution after a simulation time of 270 days (9 months). The color and red lines are explained in Fig. B.1.

B.11 Selected 1200 particles geographical distribution after a simulation time of 300 days (10 months). The color and red lines are explained in Fig. B.1.

B.12 Selected 1200 particles geographical distribution after a simulation time of 330 days (11 months). The color and red lines are explained in Fig. B.1.

B.13 Selected 1200 particles geographical distribution after a simulation time of 360 days (12 months). The color and red lines are explained in Fig. B.1.

C.1 The (a) Source Strength and (b) MCT for the region Out-RS and In-cnRS, grouped according to the particle releasing month in the backward tracking experiment.

C.2 The (a) Source Strength and (b) MCT for the polygon cnRS, GA and SB, grouped according to the particle releasing month in the backward tracking experiment.

C.3 The (a) Source Strength and (b) MCT for the polygon eS, eKT, nM, cS, sO and GO, grouped according to the particle releasing month in the backward tracking experiment.

D.1 Annual and seasonal RPFs of the polygon sRS. The annual RPFs are calculated using all months simulation, the seasonal RPFs are calculated using only the corresponding months: spring (March, April and May), summer (June, July and August), autumn (September, October and November), winter (December, January and February).

D.2 Annual and seasonal RPFs of the polygon SB.

D.3 Annual and seasonal RPFs of the polygon eS.

D.4 Annual and seasonal RPFs of the polygon eKT.

D.5 Annual and seasonal RPFs of the polygon nM.
D.6 Annual and seasonal RPFs of the polygon cS.  

D.7 Annual and seasonal RPFs of the polygon sO.  

D.8 Annual and seasonal RPFs of the polygon GO.
Chapter 1

Introduction

Coral reefs, often known as the rainforests of the sea, inhabit just 0.09% of the oceans and yet are an essential habitat relied upon by more than one third of all marine species[1]. Coral reefs are also an important economic asset through the provision of commercial and artisanal fisheries, recreation and tourism[2]. However, as a result of anthropogenic activities (e.g., overfishing and pollution) and climate change[3], global coastal coral reef coverage has decreased by \(\sim 20\%\) over the past 40 years[4][5], and recurrent bleaching events (the loss of symbiotic zooxanthellae from coral tissue) have contributed to ecosystem degradation, as well as a reduction in overall coral health and resilience[6][4][7].

Connectivity usually refers to the demographic linking among marine populations across geographically separated regions, through the dispersal of individuals as larvae, juveniles or adults[8][9]. For most benthic marine species like corals, this exchange of individuals occurs primarily during the pelagic larval stage[8]. The recruitment of coral reefs that exhibit high levels of connectivity depends largely on larval exchange among populations[10], which is known to enhance the resilience of coral reef ecosystems to natural and human disturbance[10][11]. Accordingly, over the past decades, connectivity has become an important research topic for coral reef study[12], and an influential factor for designing no-take marine protected areas (MPAs)[13][10]. The spatial extent of connectivity may be strongly influenced by physical mechanisms such as tides and currents[14][10], thus, connectivity can be detected using a physical circulation approach, which predicts the larval dispersal using methods like particle
The Red Sea accommodates one of the longest coral reef ecosystems on Earth, with reef complexes being present almost along the entire Red Sea coastal region (>5000 km). Red Sea coral reefs also provide habitat for over 1,000 fish species. The Southern Red Sea in particular is generally regarded as a different marine ecoregion from the rest of the Red Sea, due to its unique oceanographic and ecological characteristics, including its shallow bathymetry, high turbidity, increased productivity and reduced coral reef development in comparison to the rest of the Red Sea basin. Previous studies of connectivity in the Red Sea related to the analysis of genetic structure and physical circulation have revealed that connectivity is higher within the central and northern Red Sea, in comparison to the southern Red Sea, which is more biologically isolated and exhibits relatively low levels of connectivity. Yet, the mechanism contributing to decreased instances of connectivity in the southern Red Sea remains unclear.

Being a relatively confined ocean, the only water exchange in the Red Sea is through the Gulf of Aden, via the Strait of Bab-El-Mandeb, a narrow, shallow strait that is 18 km in width and has a maximum depth of 137 m. In consideration of this, it has been hypothesized that the southern Red Sea coral reef complexes may connect more with the regions outside of the Red Sea, via the water exchange with the Gulf of Aden and Indian Ocean. However, research related to the exploration of this hypothesis has been restricted by the low resolution of flow field data, especially for the narrow Strait of Bab-El-Mandeb.

In this study, the hypothesis that coral reef complexes in the southern Red Sea connect more with regions outside of the Red Sea, compared to the central and northern Red Sea, is investigated using a backward particle tracking model applied to high resolution Red Sea velocity data over a time range over 10 years. The results of this simulation are then used to explore the connectivity characteristics of coral
reef complexes in the southern Red Sea.
Chapter 2

General Circulation and Connectivity

2.1 General Circulation

2.1.1 The Red Sea and Gulf of Aden

The Red Sea is located between the Arabian Peninsula and the African continent and is an elongated basin of about 2000km long and 280km wide, with an average depth of 490m deep, ranging from the shallow areas close to the coasts to more than 2500m in the deep trench spanning its axis[25][26]. The Red Sea is well-known for its extreme warm and saline hydrological environment with surface temperatures reaching up to 35°C in summer and surface salinity up to 40 psu in the northern basin[27]. It presents a typical seasonal overturning circulation and thermohaline features and is also strongly influenced by the monsoon seasonal reversals[28][29][30][31].

During winter, the Red Sea is characterized by typical inverse estuarine circulation, with a surface intrusion from Gulf of Aden bringing relatively fresh, cold and nutrient-rich water northward, crossing the central basin and sinking in the northern Red Sea[32][30]. A return flow of a subsurface highly saline (over 40 psu) water mass, known as Red Sea Outflow Water (RSOW), occupies the intermediate layer of the basin and finally outflows to the Gulf of Aden and into the Indian Ocean[33]. This highly saline RSOW can be even traced down to the equatorial and southern subtropical regions of the Indian Ocean[30][31]. The RSOW outflows at intermediate depths, has a maximum flow located at about 120m depth[30] and its interface with the surface inflow is located at a depth of around 90m. The northward surface intru-
Figure 2.1: Schematic representation of the main thermohaline cells in the Red Sea cited from Sofianos and Johns, 2015. RSOW: Red Sea Outflow Water; RSDW: Red Sea Deep Water; GAIW: Gulf of Aden Intermediate Water.

...
ized by outflows at the surface and deep layer, and an in-between inflow consisting of the fresh and nutrient-rich Gulf of Aden Intermediate Water (GAIW)\[10\]\[29\]. The summer GAIW intrusion, located between 50-100m depth with a maximum inflow velocity up to 0.5m/s\[29\], plays an essential role in the southern Red Sea productivity and regulates the southern Red Sea summer phytoplankton blooms\[35\]. The relatively saline surface outflow and the nutrient-rich subsurface GAIW inflow compose the upper layer summer overturning circulation. The deep outflow consists of Red Sea Deep Water (RSDW), which is also one of the most saline waters, similar to the RSOW, completing the summer three-layers circulation. Despite the seasonal circulation changes, the annual averaged circulation remains an inverse estuarine structure.

In the Gulf of Aden, the north-easterly monsoon blowing during winter change to a south-westerly monsoon in summer\[33\], which causes upwelling along the northern coastline of the gulf (Yemen) and leads to an increase in nutrient\[41\]. This upwelling enhances the phytoplankton growth in the western part of the Gulf\[42\]\[41\], also facilitates the GAIW intrusion to the southern Red Sea\[43\]\[29\].

Another important feature of the Red Sea circulation is the vigorous eddy field\[44\]. Eddies play an important role, especially in the central and northern Red Sea basin where kinetic energy of eddies (EKE) can be orders of magnitude higher than the general circulation and has a strong influence on the transport in the upper layers\[45\]. The EKE is distributed unequally, concentrating mainly in the upper layer (400m) of central and northern basin and intensifying during winter. The southern Red Sea exhibits a weak eddy field mainly driven by turbulent wind stress, while the central and northern Red Sea present a much stronger EKE influenced by the tilting of density isopycnals\[44\]\[45\].

The Gulf of Aden connects the Red Sea to the Indian Ocean. Its circulation is also characterized by strong mesoscale eddies field\[46\]\[42\]. Large and deep-reaching (up to 1000m) eddies have been observed in the Gulf of Aden, bringing the fresh and cold
Arabian Sea water to the Bab-El-Mandeb Strait\cite{47,48}. During winter monsoon, the eddies are a result of the westward propagating Rossby waves from the Arabian Sea and the west coast of India, and during other seasons, the eddies are generated due to the instability of the Somali Current and the large eddies like Great Whirl and Socotra Gyre\cite{49,50}. The eddies play an important role in transporting the Red Sea outflow water into the Indian Ocean\cite{47,51}. A cyclonic eddy in the western Gulf of Aden tends to reinforce the Red Sea outflow being transported and become a western boundary undercurrent along the east coast of Somalia, while an anticyclonic eddy tends to transport the Red Sea outflow water mass eastward. But both cyclonic and anticyclonic eddies will increase the mixing of the Red Sea outflow in the western Gulf of Aden\cite{51}.

### 2.1.2 The Indian Ocean

The Indian Ocean presents a complicated surface circulation driven by southwesterly monsoon during summer and northeasterly monsoon during winter\cite{52}. There are some permanent (e.g. South Equatorial Current) and seasonal (e.g. Somali Current) currents which are important for the particle transport from the Indian Ocean to the Gulf of Aden.
Schott et al. (2009) established that, during summer, the westward South Equatorial Current (SEC) splits into the Northeast Madagascar Current (NEMC) and the Southeast Madagascar Current (SEMC) at around 17°S. The NEMC meets the northward East Africa Coastal Current (EACC) and supplies the northward Somali Current. After crossing the equator, the Somali Current partially propagates eastward joining the eastward South Equatorial Countercurrent (SECC) and partially turns into the Southern Gyre forming a complicated circulation together with the Great Whirl and the Socotra Gyre. During winter, the SEC, the NEMC and the EACC remains the same, but the Somali Current flows southward and meets the northward EACC in a confluence zone from 2 to 4°S. They then flow eastward
Figure 2.3: Schematic representation of identified current branches during the winter (northeasterly) monsoon cited from Schott et al., 2009.

together as the South Equatorial Countercurrent (SECC). Besides, the South Monsoon Current (SMC) in summer will turn into the North Monsoon Current (NMC) in winter[52][53].

2.2 Connectivity Studies in the Red Sea

Compared to coral reef complexes in the Great Barrier Reef and the Caribbean, there are very limited studies on Red Sea connectivity, especially those based on genetic approaches[12]. Generally speaking, fish are one of the best-studied groups in coral reefs in terms of population connectivity[10][12]. Some genetically-based connectivity studies of fish in the Red Sea support the notion of dividing the basin
into two different ecoregions. A previous genetic study of anemonefish (*Amphiprion bicinctus*) indicated a homogeneous genetic pattern in the central and northern Red Sea, however, a distinct genetic break was observed in the southern Red Sea at around 19°N [22]. Another genetic analysis of 215 fish species and 90 benthic categories also revealed a homogeneity of the east coast of the central and northern Red Sea [23], in which Roberts *et al.* (2016) proved the existence of the within-Red-Sea ecological boundary described by Spalding *et al.* (2007), but also suggested that 17.5°N is a more reasonable division of the two ecoregions. Roberts *et al.* (2016) suggested further genetic studies should be conducted for the far southern Red Sea (below 18°N to the Strait of Bab-El-Mandeb). Beyond the fish taxa, there are also genetic population connectivity studies of coral [54] and sponge taxa [55], both supporting the homogeneity of the central and northern Red Sea.

In addition to genetic studies, connectivity can also be investigated using a physical circulation approach. Raitsos *et al.* (2017) integrated satellite-derived biophysical observations, particle dispersion model simulations, genetic population data and shipborne in situ profiles to investigate the coral reef connectivity in the Red Sea. In this study, the satellite-derived biophysical observations demonstrate that surface currents appear to connect fringing coral reefs across and along the Red Sea basin. The particle dispersion model simulations indicate that connectivity within the central and northern Red Sea is generally high, while the southern Red Sea seems to be isolated from the rest of the basin and exhibits relatively low connectivity. These results are consistent with previous genetic studies in the region. However, the particle dispersion model in this specific study was based on a 0.25° gridded geostrophic velocity data derived from the Absolute Dynamic Topography provided by satellite altimetry observations. Due to the coarse resolution of the physical circulation datasets available at that time, these results were limited to interactions only inside the Red Sea. A very high resolution dataset is necessary in order to accurately resolve the velocity
field, especially at the narrow strait of Bab-El-Mandeb.

Besides the connectivity studies conducted within the Red Sea, a previous study outside of the Red Sea, based on the genetic structure of *Amphiprion* spp. (anemonefish), suggests that there is a genetic similarity between the Farasan Islands (in the southern Red Sea) and Djibouti (near the Bab-El-Mandeb Strait in the Gulf of Aden), highlighting the existence of a connectivity pathway between the two regions[56].
Chapter 3

Datasets and Methods

To investigate the connectivity of coral reef complexes in the southern Red Sea, a particle tracking model Connectivity Modeling System (CMS) was implemented to conduct a backward Lagrangian particle tracking simulation (see section 3.2). Backward particle tracking will concentrate more on the origin of the particles that settle down in the southern Red Sea coral reef complexes, instead of the destiny of particles originating in the southern Red Sea. Commonly, in forward particle tracking simulations, the connectivity is defined and calculated according to the exchange of particles among different sites\cite{57}, and are presented with a two-way concept (influencing and being influenced). Here, to directly simulate the potential influence of different regions to the coastal regions in the southern Red Sea, only backward tracking is applied. Thus the connectivity in this scenario is a one-way concept instead of two-way. In this backward simulation, connectivity describes only the potential influence of other regions on the southern Red Sea.

The flow field within the Red Sea and the Gulf of Aden is supplied by a high resolution (1/100 degree) MITgcm simulation (see section 3.1.2). The research domain is then extended to the Indian Ocean by coupling with the coarser resolution (1/4 degree) Mercator Ocean (Toulouse, FR) GLORYS2V4 reanalysis data (see section 3.1.1). Consistency at the boundary between the two simulations was maintained by providing the high resolution Red Sea simulations with open boundary conditions from the coarser reanalysis product. The high resolution MITgcm is used to simulate the important and complex topographic details of the Red Sea and its connection to
the Gulf of Aden through the narrow strait of Bab-El-Mandeb.

In the simulations, particles are released in a chosen area of the Southern Red Sea defined as the polygon sRS (see section 3.3.1), and backward tracked for 360 days. In this study, the term polygon refers to the coastal area which particles may originate from or settle down on, and are usually shaped as a band that covers an area near the coastline (Fig. 3.1). A group of possible receiving polygons for backward-tracked particles are also chosen to detect their connectivity with the coastal southern Red Sea (see section 3.3.2).

The backward particle tracking simulation as well as the post-simulation results analysis (see section 3.4) are conducted in parallel on the KAUST Supercomputer Shaheen (https://www.hpc.kaust.edu.sa/; see section 3.5).

3.1 Datasets

3.1.1 Coarse Resolution Datasets in the Indian Ocean Domain

For the coarse-resolution model domain, we use the Mercator Ocean (Toulouse, FR) GLORYS2V4 reanalysis product. This reanalysis provides an eddy permitting (1/4 degree) global ocean simulation covering the recent period from 1993 to 2015. The daily mean velocity data from 2002 to 2012 are used here to create a 10-year climatology connectivity of the southern Red Sea.

GLORYS2V4 uses the ERA-interim atmospheric surface forcing, with assimilation of all available observations (e.g., along track satellite Sea Level Anomaly, Sea Ice Concentration, Sea Surface Temperature, and in situ profiles of temperature and salinity from CORA4 data base) in delayed time. It has a 0.25° horizontal resolution and unequally divided 75 layers vertical resolution from surface (0.5056m) to deep sea (5902.0583m), finer in surface and coarser in deep sea. The velocity data used
here have a spatial coverage between $20^\circ$E and $90^\circ$E/ $30^\circ$S and $35^\circ$N, ensuring the simulation won’t be limited by the geographical space. All 75 vertical levels are used to support a 3D flow field. However, GLORYS2V4 provides only 3D horizontal velocity, and the vertical velocity was calculated using simplified continuity equation under the assumption of incompressible fluid:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]

(3.1)

The GLORYS2V4 dataset was downloaded from Copernicus Marine Environment Monitoring Service (CMEMS) (http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_REANALYSIS_PHY_001_025).

### 3.1.2 High Resolution Datasets in the Red Sea Domain

The nested, high resolution simulations were performed with the MIT general circulation model (MITgcm)[58] configured for the Red Sea[29][30]. MITgcm is a dynamical model designed to solve both atmospheric and oceanic physical problems with a spatial scale ranging from 100m to 10,000m. MITgcm simulates the Red Sea circulation with a $0.01^\circ$ (around 1 km) horizontal resolution covering region between $30^\circ$E and $50^\circ$E and $10^\circ$S and $30^\circ$N, including the entire Red Sea basin, the Gulf of Suez, the Gulf of Aqaba and the Gulf of Aden. The model is implemented with 50 vertical levels, unequally distributed from 0m to 3028m with the vertical resolution varying between 4 m at the surface and 300 m near the bottom. The model has previously been used for various studies in the Red Sea, including the overturning circulation[29][30], eddies[44][45], connectivity[59][60], ecosystem[61], and so forth. The open boundary conditions with the Indian Ocean were provided on a monthly basis by the parent global reanalysis product GLORYS2V4. The atmospheric forcing used for the spe-
cific simulation is a downscaled version of the ERA-Interim reanalysis, provided by the European Center for Medium-Range Weather Forecasts (ECMWF)\[62\], with spatial resolution increased to about 5km\[37\]. The downscaling was performed with a two-way nested domains of horizontal resolutions of 15 and 5 km over the Red Sea and adjacent regions, using the Advanced Research version of Weather Research and Forecasting model\[63\]. The increased resolution of the new dataset provides a more detailed representation of the regional atmospheric features, which is essential for the analysis of the Red Sea thermohaline circulation, and account of the small size of the basin, the complex bottom relief and the complexity of the regional atmospheric dynamics\[64\].

The model was initialized from a state of no-motion using annual mean Temperature and Salinity from the World Ocean Atlas 2013. After a 5-year spin-up period using the 2001 atmospheric forcing, the model was integrated from January 2001 to December 2016 with a time step of 90 s. The simulation contains both daily average horizontal and vertical velocity and have a time span from 2001 to 2014 (2002∼2012 were used). To reduce the boundary effect, the area east of 49.90°E is trimmed to avoid the uncertainty in the boundary region. The MITgcm data is provided by George Krokos.

### 3.2 CMS model

The Lagrangian particle tracking model Connectivity Modeling System (CMS) developed by Paris et al. (2013) was used here to simulate the coastal southern Red Sea connectivity. CMS is a multi-scale biophysical modeling system\[16\], coupling a nested-grid technique to a stochastic Lagrangian framework, which allows CMS to track seamlessly a large number of particles over multiple, independent ocean model domains\[65\]. The direct output of CMS is the trajectories information consisting of latitude, longitude and depth for each particle\[65\]. Further indicators to quantify
connectivity are calculated based on these particles simulations.

The build-in biological package permits CMS to simulate the actively swimming biotic particles with consideration of different biological traits such as particle buoyancy, mortality rate and vertical migration\cite{65}. Yet in this study, only physical circulation will be considered and thus all particle behaviors functions are closed (more experiment setting seen in section 3.3.3). The build-in backward tracking function allows CMS to simulate the particle displacement by integrating the velocity field backward in time and track the particles origin\cite{65}, which in this study represents the potential influence of different regions to the Southern Red Sea coral reef complexes.

CMS is also capable of handling a multiple nests of velocity fields. Particles within MITgcm data domain will be simulated using 0.01° finer nest, while outside of this domain the trajectory will be calculated according to 1/4 degree GLORYS2V4 coarser nest.

3.3 Experiment Design

3.3.1 Particle release locations in the Southern Red Sea

The locations of the backward tracking particles released in the Southern Red Sea is designed based on a gridded coastline data derived from a bathymetry data extracted from the 1/60 degree global GEBCO product, which has a resolution high enough to investigate the area of interest. The 1/60 degree global GEBCO product is available at: https://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_one_minute_grid/.

The southern Red Sea has a shallower bathymetry than the central and northern Red Sea, with a slowly decreasing continental shelf off the coast. Meanwhile regions like the Gulf of Aden have extremely steep continental shelf\cite{27}. Thus, defining polygons using a unified bathymetry threshold can lead to unreasonable polygon
Figure 3.1: Selected 1 releasing polygon and 9 receiving polygons distinguished by color, together with 2 boundaries implying the regional division: 1. releasing polygon sRS: coastline of the southern Red Sea; 2. receiving polygon cnRS: coastline of the central and northern Red Sea; 3. receiving polygon SB: coastline of the Strait of Bab-El-Mandeb; 4. receiving polygon GA: coastline of the Gulf of Aden; 5. receiving polygon cS: coast of the island Socotra; 6. receiving polygon eS: east coast of Somalia; 7. receiving polygon eKT: east coast of Kenya and Tanzania; 8. receiving polygon nM: north coast of Madagascar and coast of islands north of Madagascar; 9. receiving polygon sO: south coast of Oman; 10. receiving polygon GO: coastline of Gulf of Oman; 11. Boundary 1: the demarcation line for the region Out-RS (region outside of the Red Sea, east of the line); 12. Boundary 2: the demarcation line for the region In-cnRS (region in the central and northern Red Sea basin, north of the line). The region In-sRS (region in the southern Red Sea basin) is located in between boundary line 1 and 2.
size between different regions (e.g. larger polygon in the southern Red Sea due to
the shallow bathymetry and smaller polygon in the Gulf of Aden due to the steep
continental shelf). To select a reasonable region in the Southern Red Sea for particles
to be released, a polygon defined by an off-coast distance between 0.05° to 0.25° with
in a latitude range of 14°N to 18°N (red band in Fig. 3.1 labeled as sRS) was chosen as
the southern Red Sea particles releasing polygon–sRS. The distance of 0.05° off coast
is selected in order to prevent reaching too close to the land and reduce the number
of stranded particles. The distance limit of 0.25° from the coast was selected since it
represents a reasonable area for the coral reef complexes regions, while avoids excessive
calculations when a large number of releasing locations is included. The boundaries
at 18°N and 14°N are chosen according to Roberts et al. (2016), which defined the
southern Red Sea region using genetic studies below 18°N up to the Strait of Bab-
El-Mandeb. The boundary at 18°N is also consistent with Nanningas 19°N genetic
break theory, however, it is selected shorter by 1° south to avoid potential influence
introduced by the adjacency to the 19°N genetic break. Similarly, the boundary of
14°N avoids the adjacency to the strait.

Here, the releasing location is defined by the latitude and longitude of the releasing
particles, while the releasing point consists of the longitude, latitude and depth. The
aggregation of all releasing locations from the southern Red Sea is termed as polygon,
which as mentioned above, refers to the patchy coastal area which particles may
originate from (releasing polygon) or settle down (receiving polygon). Particles were
released every 5 meters at depths between 2m (representing the surface) and 97m.
For locations where bathymetry is shallower than 97 m (bathymetry data provided
by 1/60 degree GEBCO product), the local maximum depth is used instead. The
maximum depth of 97m was chosen in order to account for the summer subsurface
intrusion of the Gulf of Aden Intermediate Water (GAIW) (located between 50-
100m)[29], which plays an important role in the southern Red Sea water transport.
There are overall 15,601 releasing locations and 143,880 releasing points in the polygon sRS.

### 3.3.2 Particle Receiving Locations

To investigate the potential connectivity between the polygon sRS and different possible regions, 9 potential polygons representing the backward-tracked particles receiving locations (colored bands in Fig. 3.1) were defined. The selection considered the results presented in the trajectories (Fig. 4.1) and Lagrangian PDF (Fig. 4.2) diagrams, using a similar method of selecting the releasing polygon sRS. These 9 potential receiving polygons are selected using the same distance (between 0.05° and 0.25°) off coast for consistency with the releasing polygon sRS. An integrated coastline data was used, consisting of an 1/60 degree resolution coastline data within the MITgcm domain, derived from the GEBCO bathymetry product, and a 1/4 degree resolution coastline data in the Indian Ocean, derived from the GLORYS2V4 product. An integrated coastline prevents the chosen polygons from residing in areas outside the model grid.

To reduce the potential impact introduced by adjacency to the southern Red Sea, a meridional gap of 1° was applied between the central and northern Red Sea polygon cnRS (dark green band in Fig. 3.1) and the polygon sRS, and a meridional gap of 0.5° was applied between the Strait of Bab-El-Mandeb polygon SB (brown band in Fig. 3.1) and the polygon sRS. Besides the 9 receiving polygons, three regions, divided by two boundary lines, are also defined, representing the grid points that reside in the central and northern Red Sea (In-cnRS), in the south Red Sea (In-sRS), and those that are located anywhere outside of the Red Sea (Out-RS) (Fig. 3.1).
3.3.3 Other Experimental Settings

Particles are released from a total of 143,880 points on the 15th of each month during the 10 years experiment (from 2003 to 2012). The particles are simulated backward in time for a 360-day period, which corresponds to the pelagic larval durations (PLDs) ranging from weeks to over one year\[66][67][68]\). The location of a particle was calculated every 4 hours and was recorded every day. Based on over 13 million of valid particle trajectories, further statistical analysis can be conducted illustrating the long-term southern Red Sea connectivity. Even though all biological functions is turned off, as a marine larvae capable of swimming, particles are not supposed to get stranded on the land, thus an avoid coast function was used in the CMS model simulations\[65]\.

3.4 Quantifying Connectivity

Based on the output of the particle trajectories, generated directly by CMS, connectivity can be assessed and quantified by a set of indicators: the Lagrangian Probability-Density-Function (PDF), the Source Strength, the Mean Connectivity Time (MCT) and the Resident Particle Fraction (RPF). These are briefly described in this section.

3.4.1 Lagrangian PDF

The Lagrangian PDF describes the Probability-Density-Function of particle displacement for a given simulation time $t$\[57]\). This approach, which computes the probability of particles being released from one location to reach another over a certain advection time, was initially introduced by Taylor (1921) and has since been widely used to predict an ensemble dispersal pattern\[69][70][71][72][57]\). Here, this method is adapted to a polygon that is characterized by several releasing locations. The simplified discrete
representation of the Lagrangian PDF can be calculated as:

\[ \text{LagrangianPDF}(\xi, t) = \frac{n_{\xi}(t)}{S_{\xi} \times N}, \quad (3.2) \]

where the \( \xi \) is the sample space variable (here, \( \xi \) is related to the resolution of the discrete Lagrangian PDF grid), \( S_{\xi} \) is the sample space area, \( N \) is the total number of Lagrangian particles and \( n_{\xi}(t) \) is the number of particles residing in sample space \( \xi \) over the simulation time \( t \) (\( t \leq \) total simulation time \( \tau \), here \( \tau = 360 \) days). In this experiment, the discrete Lagrangian PDF has a grid of 1/12°, which is merged from the 1/60° GEBCO data, for the purpose of smoothing the field. Thus, \( \xi \) represents each cell in the grid and has an area of \( (\frac{1}{12})^2 \) (around 85 km²). The value of the Lagrangian PDF represents the number of particles in sample space \( \xi \) and have a unit of km\(^{-2}\).

### 3.4.2 Source Strength and MCT

In previous studies of connectivity, Source Strength and MCT are widely used in forward particle tracking analysis, which are characterized by multiple experimental sites\[57\][17][15]. Those experimental sites are both releasing and receiving sites. The Source Strength is defined as the average frequency of particles released from the site (i) to visit all other sites within the total simulation time \( \tau \), it measures the relative success of particles from site (i) to encounter other sites; the MCT is defined as the average time for particles released from the site (i) to reach all other sites within the total simulation time \( \tau \), it measures the relative speed of particles released from site (i) to encounter other sites\[57\].

Here, based on the single releasing polygon sRS, the definition and calculation will changed accordingly. The Source Strength of the polygon (i) can be defined as the probability of the backward-tracked Lagrangian particles released from polygon...
sRS, to reach polygon (i) within the total simulation time \( \tau \). Source Strength can be calculated using the equation:

\[
SourceStrength(i) = \frac{N_i}{N},
\]

where \( N \) is the total number of backward-tracked Lagrangian particles released from the polygon sRS, and \( N_i \) is the overall number of particles that ever reach polygon (i) within the total simulation time \( \tau \). The Source Strength is a function of receiving polygon and is influenced by the total simulation time \( \tau \). Essentially, Source Strength can be interpreted as: for particles which settle down on the polygon sRS after a drifting time less than \( \tau \), how many percentage of them may originate from the polygon (i). A higher Source Strength indicates a higher level of connectivity with the polygon sRS.

One should notice that, a particle which has reached the polygon (i) at the simulation time \( t_1 \) may also reach the polygon (j) at the simulation time \( t_2 \), thus the Source Strength of different polygons may have a sum higher than 1.

Similarly, the MCT of polygon (i) is defined as the average time taken for backward-tracked Lagrangian particles released from the polygon sRS, to reach the polygon (i) within the total simulation time \( \tau \). The MCT can be calculated using:

\[
MCT(i) = \frac{\sum_{k=1}^{N_i} T_{k,i}}{N_i},
\]

where \( T_{k,i} (T_{k,i} \leq \tau) \) is the time a Lagrangian particle (k) needs to reach polygon (i) and \( N_i \) is described above. Similarly, the MCT is also a function of the receiving polygon and is influenced by the simulation time (\( \tau \)). Essentially, the MCT can be interpreted as: on average, how long does it take for a particle released from polygon (i) to reach polygon sRS within a drifting time \( \tau \). A higher MCT is indicative of a longer connection time and lower levels of connectivity with the releasing polygon.
3.4.3 Resident Particle Fraction (RPF)

The Source Strength and MCT are efficient indicators that can be used to quantify connectivity between the polygon sRS and the other polygons. However, they are both ultimately influenced by the total simulation time ($\tau$). One indicator that can be utilized to investigate connectivity without the influence of the total simulation time ($\tau$) is the Resident Particle Fraction (RPF). The RPF of polygon (i) can be defined as the probability of a backward-tracked Lagrangian particle released from the polygon sRS, to reach polygon (i) at the simulating time $t$. The RPF can be calculated using the formula:

$$RPF(i, t) = \frac{n_i(t)}{N},$$  \hspace{1cm} (3.5)

where $n_i(t)$ is the number of particles residing in polygon (i) at the simulation time of $t$. $RPF(i, t)$ is actually the probability function, converted from the $LagrangianPDF(\xi, t)$ by multiplying the area of polygon (i), where $\xi$ is the polygon (i). Essentially, $RPF(i, t)$ can be interpreted as: for particles who settle down on the polygon sRS after a drifting time $t$, what percentage of them originate exactly from the polygon (i). In particular, the $RPF(sRS, t)$ represents the self-recruitment ability of the polygon sRS. It is defined here as the fraction of particles that remain in the sRS polygon over a given simulation time $t$.

The equations (3.3) (3.4) and (3.5) can be all applied to the 9 receiving polygons, as well as the 3 regions shown in Fig. 3.1.
3.5 Supercomputing Resources

For the needs of the connectivity studies, a number of 13 millions particle trajectories were simulated in a 3-D velocity field on daily resolution for a period of 10 years. These calculations have been conducted on the KAUST supercomputing resources Shaheen II (https://www.hpc.kaust.edu.sa/content/shaheen-ii).

Shaheen II has 6,174 dual CPU sockets nodes with 128GB memory per node and each CPU has 16 processors cores. It has been ranked as the eighteenth fastest supercomputer in the world according to the TOP 500 list of June 2017.

Considering the calculation time, the simulations are conducted in 10 groups, each corresponding to one year. Each group of simulation occupied a number of 180 nodes (or the equivalent of 720 processors cores) and lasted for 24 hours. Due to the large size of the MITgcm and GLORYS2V4 data files, only 4 out of 32 processors per node could be used to avoid the collapse due to memory limits.

A large amount of computational resources was also required for the post processing of the simulation results and further calculation of various indicators such as Lagrangian PDFs, Source Strengths, MCT and RPF. These computations were implemented in MATLAB programming language (https://www.mathworks.com/products/matlab.html) with parallel computations that utilized an estimated 144,000 extra core hours (equivalent to 94 days using 64 cores).
Chapter 4

Results and Discussions

4.1 Particles Backward Dispersal Pattern

4.1.1 Backward Dispersal Pattern in Trajectories Diagram

Lagrangian trajectories for particles released from the sRS polygon show the backward dispersal patterns (Fig. 4.1). The trajectories clearly demonstrate the pathways followed by the released particles, whilst the density of the trajectories indicates the level of connectivity. Sharing a similar geographic distance to the polygon sRS, the Gulf of Aden presents a denser trajectories pattern in comparison to the central and northern Red Sea, implying a stronger degree of connectivity between the Gulf of Aden and the coastal regions in the southern Red Sea. Cyclonic structures can be observed in the Gulf of Aden and the central and northern Red Sea, corresponding to the regional circulation characterized by mesoscale eddies. The dense trajectories within the southern Red Sea basin highlight a potential strong local retention ability.

The green crosses in Fig. 4.1 are the final locations of the 200 particles after a 360-day simulation, and their distribution density indicates the level of connectivity with the polygon sRS after 360 drifting days. Similar diagrams from 0 days to 360 days with an interval of 30 days are presented in Appendix B. They exhibit the evolution of the backward dispersal patterns, which demonstrate a consistently larger number of particles in regions outside of the Red Sea and indicate a higher level of connectivity between the coastal regions in the southern Red Sea and the outside regions.
Figure 4.1: Backward-tracked Lagrangian trajectories of randomly selected 200 particles. The particles are released in polygon sRS (red band in Fig. 3.1) on the 15th of every month during 10 simulation years, and are backward tracked for 360 days. The red lines are simulated 360-day trajectories, the blue dots indicate the releasing points, the green crosses indicate the particles locations after the 360-day simulation and the pink lines are the demarcation (see Fig. 3.1). Selected trajectories can reach limited distances thus figures are trimmed in a smaller geographic area to better demonstrate the dispersal pattern.
4.1.2 Backward Dispersal Pattern in Lagrangian PDFs

Figure 4.2: The Lagrangian Probability Density Functions (PDFs) of particles released from the polygon sRS and backward-tracked for (a) 60 days, (b) 120 days, (c) 180 days, (d) 240 days, (e) 300 days and (f) 360 days. The Lagrangian PDFs are computed with equation(2) accounting of all particles regardless of the releasing month and year. The color indicates the probability density with a unit of $km^{-2}$. The colorbar is shading logarithmically due to the large span of the order of magnitude.

Compared to the dispersal pattern shown in Figure 4.1, the Lagrangian PDF (Fig. 4.2) depicts a more advanced illustration of the dispersal patterns and represents all particles (instead of just a subset of the 13 million particles). Here, six typical simulation time points are chosen to demonstrate the revolution in time of the Lagrangian PDF (Fig. 4.2). For example, at a simulation time of 60 days (Fig. 4.2a), the Lagrangian PDF shows that, particles can reach the central Red Sea, but do not travel to the northern Red Sea. Particles can pass through the Strait of Bab-El-Mandeb and reach regions outside of the Red Sea, but are mostly contained in the Strait and along the coast of the western Gulf of Aden. Generally, most of the particles remain in the
southern Red Sea region, indicating a high local retention ability. This Lagrangian PDF demonstrates a strong local retention capacity and a relatively high connectivity with the central Red Sea and the Gulf of Aden for particles with a drifting time of 60 days.

Lagrangian PDFs of simulation times of 120, 180, 240, 300 and 360 days highlight the gradual expansion of the backward dispersal patterns to the northern Red Sea (northwestward), the Gulf of Oman (northeastward), the central Arabian Sea (eastward), the Maldives (southeastward), the east African coast and the north coast of Madagascar (southward). The limited expansion of the dispersal patterns towards the east at the equatorial regions can potentially be explained by the eastward South Equatorial Countercurrent (SECC), which subsists throughout the year. Similarly, the expansion in the region east of Madagascar could be linked to the permanent South Equatorial Current (SEC) and Northeast Madagascar Current (NEMC). The expansion towards the Maldives is likely related to the Northeast Monsoon Current (NMC) during winter. Overall, the Lagrangian PDFs extend more to the south than to the north in the Indian Ocean regions, which indicates a higher level of connectivity with the regions south of the Gulf of Aden. This higher connectivity is likely to be facilitated by the permanent northward East African Coast Current (EACC) and the northward Somali Current during summer.

4.2 Source Strength and MCT Analysis

A histogram displaying the Source Strength and MCT for different regions or polygons is presented to elucidate the connectivity of different regions or polygons with the coastal regions in the southern Red Sea (Fig. 4.3). Sharing similar geographic distance to the polygon sRS, the region Out-RS has a MCT of 131 days and a Source Strength of 67%, yet the region In-cnRS has a MCT of 129 days and a Source Strength of 29%, indicating that the polygon sRS has a stronger connectivity with the region
outside of the Red Sea. Considering that coastal water plays a much more important role in coral reef complexes, a comparison between the polygon GA and the polygon cnRS is further needed. The polygon GA has a Source Strength of 63% and an MCT of 153 days, which means that 94% of the particles that entered the region Out-RS will also reach the polygon GA. In comparison, polygon cnRS has a Source Strength of 22% and an MCT of 167 days, which means only 73% of the particles that entered the region In-cnRS will also reach the polygon cnRS. This suggests that the particles in the Gulf of Aden are more easily and quickly transported to the coastal areas, in comparison to the central and northern Red Sea. This may be a result of the respective eddy fields. The eddies in the Gulf of Aden are generally more intense than those in the central and northern Red Sea, and can capture the particles and transport them more easily. Once a particle is trapped in the eddy, it has a higher probability of reaching coastal areas due to the rapid cyclonic flow, ultimately resulting in a lower MCT.

For polygons located further away than the Gulf of Aden, the Source Strength decreases substantially (Fig. 4.3). Although, the moderate Source Strength of the polygon eS, eS and sO (5-12%) indicates that there is still some level of connectivity with the polygon sRS, and highlights the existence of the potential connectivity pathways between the southern Red Sea and the east coast of Somalia, the coast of Socotra and the south coast of Oman. The markedly lower Source Strength for the polygon eKT, nM and GO implies an even weaker connectivity with these areas. The Source Strength is inversely correlated with the MCT except for the polygon GO, which may be a result of the very minimal connective particle number $N_i$ in this polygon.

Besides the annual averages, seasonal averages of the Source Strength and MCT are also computed to investigate how the circulation seasonality impacts connectivity (Figures in Appendix C). Seasonal histograms (Fig. C.1 - Fig. C.3) are grouped
Figure 4.3: (a) Source Strength and (b) mean connectivity time (MCT) of the two studied receiving regions (Out-Rs and In-cnRS) and the 9 receiving polygons over the total backward simulating time of 360 days. All Lagrangian particles regardless of year and month are used.

according to the month that particles were released from the polygon sRS. For most regions or polygons, a clear seasonality can be observed, which may come from the impact of the seasonal circulation or eddies. Yet, this is difficult to explain because, with a total simulation time of 360 days, the trajectories contain information of
circulation structures in all seasons and become hard to predict. For example, in Figure C.1, for the region Out-RS, the Source Strength peaks in September and reaches a minimum in May. Surprisingly the MCT peaks in October and also reaches a minimum in May, which is no longer inversely proportional to the Source Strength. Apparently, the Source Strength and MCT are not appropriate indicators to directly investigate the seasonality when the total simulation time \( \tau \) is long enough to cover the seasonal characteristics.

### 4.3 RPF Analysis

#### 4.3.1 Consistency of the RPFs

The RPF eliminates the influence introduced by the total simulation time \( \tau \) and demonstrates the evolution of connectivity in simulation time \( t \). In Figure 4.4, expect for the polygon SB and GA, all RPFs have a monotonic tendency of either increasing or declining, although some may exhibit small fluctuations.

The red line in Fig. 4.4a is the RPF for the polygon sRS, it represents the self-recruitment ability of the coastal regions in the southern Red Sea. As simulation time increases, the RPF for the polygon sRS decays exponentially but is higher than any other polygon over most of the simulation days (only after 340 days does the RPF for the polygon sRS become lower than the RPF for the polygon GA), indicating a relatively high self-recruitment ability for the coastal regions in the southern Red Sea.

The point of intersection in Fig 4.4a denoted at 180 days, occurs when the RPFs for the region In-sRS (the pink line) and the region Out-RS (the black line) become equal, indicating that for particles with a drifting time less (more) than 6 months, the southern Red Sea itself (the regions outside of the Red Sea) will be a better source of the polygon sRS. This also implies a relatively strong local retention for the southern Red Sea.
Figure 4.4: The evolution in time of the Resident Particles Fractions (RPFs) for (a) the polygon sRS, the region In-sRS, In-cnRS and Out-RS, (b) the polygon cnRS, GA and SB, (c) the polygon eS, sO, cS, nM, eKT and GO. All Lagrangian particles are used here regardless of year and month.
Figure 4.4a also demonstrates the consistent result of the RPF with the Strength Source and MCT. After 7.6 simulation days, the RPF for the region Out-RS (the black line) is always higher than the region In-cnRS (the gray line), and the difference increases steadily with the simulation time. Before 7.6 days, the RPFs for both regions are small enough to be ignored. By that simulation time, most of the particles still remain inside of the southern Red Sea. Thus, the RPF for the region Out-RS can be regarded as consistently larger than the RPF for the region In-RS, implying a consistently higher level of connectivity between the coastal regions in the southern Red Sea and the regions outside of the Red Sea.

Similarly, the RPFs for polygon cnRS and polygon GA (Fig. 4.4b) also correspond to their Source Strength and MCT, indicating a consistently higher connectivity between the coastal regions in the southern Red Sea and the coastal regions in the Gulf of Aden.

For polygons characterized by the RPFs continuously below 0.3% (eS, sO and cS, Fig. 4.4c), small fluctuations can be observed. This fluctuation may be related to the presence of eddies (e.g. the Great Whirl, the Socotra Gyre and the Southern Gyre) or the experiment releasing interval (one month). However, more information is needed to investigate this further. Expect for the fluctuations, their rising tendency indicates an increasing connectivity with the drifting time growing.

### 4.3.2 Seasonality in the RPFs

The RPF is not influenced by the total simulation time \( \tau \), and can be a suitable indicator to examine how the seasonal circulation structure will impact the connectivity. Figure 4.5 displays the annual and seasonal RPFs for 2 typical receiving polygons (cnRS and GA) and 2 regions (In-cnRS and Out-RS).
Figure 4.5: Annual and seasonal RPFs of (a) the region In-cnRS, (b) the region Out-RS, (c) the polygon cnRS and (d) the polygon GA, with color denoting the seasons. The annual RPFs are calculated using all months simulation, the seasonal RPFs are calculated using only the corresponding months: spring (March, April and May), summer (June, July and August), autumn (September, October and November), winter (December, January and February).

Figures 4.5 (b) and (d) display the RPF for the region Out-RS and the polygon GA, representing the basin-scale and coastal-scale connectivity for the regions outside of the Red Sea, respectively. The higher RPFs for spring and winter before 90 simulation days is a result of the Gulf of Aden and the Red Sea water exchange seasonality. Particles released from the polygon sRS in winter and spring are mostly influenced by the winter circulation, when the monsoon-driven surface inflow facilitates the intrusion of particles into the southern Red Sea[30]. During summer, the surface flow reverses, but the subsurface flow consisting of the Gulf of Aden Intermediate Water (GAIW) brings particles between 50-100m into the Red Sea[29][31]. Yet, this subsurface intrusion during summer has a limited ability to transport particles into the Red Sea in comparison to the surface intrusion during winter. Thus, the RPFs for summer
and autumn present a relatively lower value in the first 90 simulation days. Figure 4.6 confirms the seasonality using the trajectories of particles with a simulation time of 90 days. Particles released in September (March) will be influenced by the summer (winter) circulation. The density and depths of the trajectories in the Gulf of Aden indicate that the inflow, which transports particles into the Red Sea, is dominated by the subsurface intrusion during summer and the surface intrusion during winter (the latter playing a leading role).

Figure 4.6: Backward-tracked Lagrangian trajectories of 100 particles. The particles are released in polygon sRS on 15th of (a) March and (b) September during all simulation years and are backward tracked for 90 days. The color indicates the depth of the particle in different locations.

Figures 4.5 (a) and (c) display the RPFs for the polygon cnRS and the region In-cnRS, representing the basin-scale and coastal-scale connectivity of the central and northern Red Sea. Unlike Figures 4.5(b) and (d), these two subgraphs demonstrate consistently higher RPFs for spring and winter. However, during the two seasons, particles are supposed to be influenced by the winter northward surface flow within the Red Sea basin, and thus should present a lower value than the annual average. This
can potentially be explained by the fact that the particles in the central and northern Red Sea are more affected by the eddy field rather than the seasonal circulation\textsuperscript{[44]}. The backward-tracked particles released in winter and spring are more easily transported to the central and northern Red Sea due to the intensification of the eddy field during the winter season\textsuperscript{[45]}. Since the order of magnitude of eddies velocity is much higher than the general circulation in the central and northern Red Sea\textsuperscript{[44]}, the difference introduced by the seasonality of the general circulation may be easily masked by the difference introduced by the seasonality of the eddy field. To further investigate this, Figure 4.7 presents the trajectories of particles released in May (the month when eddy field in the Red Sea change from winter to summer) and November (the month when eddy field in the Red Sea change from summer to winter) and backward tracked for 180 days. The particles released in May extend further to the northern Red Sea and present denser trajectories in the central Red Sea, corresponding to the presence of a stronger eddy field during winter. The trajectories support the hypothesis that the connectivity between the coastal regions in the southern Red Sea with the central and northern Red Sea, is more influenced by the eddy field.
Figure 4.7: Backward-tracked Lagrangian trajectories of 1000 particles to demonstrate the relatively stronger connectivity to the central and northern Red Sea in winter than in summer. The particles are released in the polygon sRS on 15th of (a) May and (b) November during the 10 simulation years and are backward tracked for 180 days. The selection of particle number 1000 is to well present the difference of trajectories in the central and northern Red Sea.
Chapter 5

Conclusions

Based on a long-term (> 10 yrs.), large-scale (20°E-90°E; 30°S-35°N) analysis of over 13 million Lagrangian particles released from the coastal regions in the southern Red Sea, a consistently high level of the connectivity of this region is observed with the regions outside of the Bab-El-Mandeb Strait (including the Gulf of Aden, Arabian Sea and Indian Ocean). Significantly high levels of connectivity, facilitated by the regional circulation and the eddy field, is observed with the coastal regions in the Gulf of Aden. Both basin-scale and coastal-scale analyses indicate a stronger connectivity with the regions outside of the Red Sea, characterized by a high Source Strength, in comparison to the central and northern Red Sea. In addition, a relatively strong local retention ability is indicated by the presence of dense particle trajectories within the southern Red Sea, in conjunction with the high self-recruitment rate and the high value areas in the Lagrangian PDFs.

The monsoon-driven circulation has a significant impact on particle transportation through the Strait of Bab-El-Mandeb into the southern Red Sea, yet a negligible influence on particle transportation from the central and northern Red Sea. The winter surface inflow plays a major role in the particle transport from the Gulf of Aden into the Red Sea, and during summer, the subsurface intrusion consisting of the Gulf of Aden Intermediate Water (GAIW) is revealed to be able to carry particles below a depth of 50m through the Strait, into the Red Sea. For the central and northern Red Sea, the connectivity with the southern Red Sea appears to be affected more by the eddy field rather than the general circulation, and thus increases during
the winter due to the intensification of the eddies activities.

The dispersal patterns revealed by the Lagrangian PDFs demonstrate the time evolution of connectivity. A potential connectivity is seen with the coasts of Somalia, Kenya, Tanzania, the north coast of Madagascar, the east coast of Oman and the Maldives. The permanent surface eastward South Equatorial Counter-current (SECC) carries the particles off the African continent, leading to an absence of the dispersal patterns in the equatorial region. In addition, the permanent surface Northeast Madagascar Current (NEMC) and East African Coastal Current (EACC), together with the summer northward Somali current and the accompanying complex eddy structure around Socotra, all facilitate the transportation of particles from the Indian Ocean to the Gulf of Aden, and eventually to the Red Sea.

Overall, the backward particle simulation demonstrates that, the coastal regions in the southern Red Sea connect more with the regions outside of the Bab-El-Mandeb Strait (Gulf of Aden), than with the central and northern Red Sea. Connectivity was also found to exhibit aspects of seasonality, which is attributed to the monsoon-driven circulation and eddy dynamics. Future studies based on this work may include the incorporation of biological features into the model (e.g., spawning season, vertical migration characteristics), to better simulate the connectivity.
REFERENCES


More information of the selected releasing polygon sRS and the 9 receiving polygons is provided. Fig. A.1 and Fig. A.2 demonstrate a reasonable releasing polygon selection compared to the global coral reef distribution.

Figure A.1: High resolution map for releasing polygon sRS (colored in Red). The resolution is from GEBCO 1/60 degree bathymetry data. The small gap between the blue and red color is the step of 0.05° to avoid high particles mortality and being too close to the sea-land boundary, followed by the red band with a width of 0.2°.
Figure A.2: Screen shot of WCMC global distribution of coral reefs in the southern Red Sea (http://data.unep-wcmc.org/). Without the open access of the gridded data, only screen shot is provided.
B Appendix 1 Sampled Particles Distribution after Different Simulation Times

Unlike Lagrangian PDFs, the scatter plot of the particle locations after a given simulation time is an easy but effective way to detect the dispersal patterns, and can indicate the depth information as well (the Lagrangian PDF cannot indicate the depth unless calculated and plotted in 3D). The shallow bathymetry feature in the southern Red Sea and the Strait of Bab-El-Mandeb can be noticed.

Figure B.1: Selected 1200 particles geographical distribution after a simulation time of 0 days (0 months). The color indicates the backward simulating time and the particle depth. Two red lines distinguish the region In-cnRS (north of the upper line) and region Out-RS (east of the lower line).
Figure B.2: Selected 1200 particles geographical distribution after a simulation time of 30 days (1 months). The color and red lines are explained in Fig. B.1

Figure B.3: Selected 1200 particles geographical distribution after a simulation time of 60 days (2 months). The color and red lines are explained in Fig. B.1
Figure B.4: Selected 1200 particles geographical distribution after a simulation time of 90 days (3 months). The color and red lines are explained in Fig. B.1

Figure B.5: Selected 1200 particles geographical distribution after a simulation time of 120 days (4 months). The color and red lines are explained in Fig. B.1
Figure B.6: Selected 1200 particles geographical distribution after a simulation time of 150 days (5 months). The color and red lines are explained in Fig. B.1

Figure B.7: Selected 1200 particles geographical distribution after a simulation time of 180 days (6 months). The color and red lines are explained in Fig. B.1
Figure B.8: Selected 1200 particles geographical distribution after a simulation time of 210 days (7 months). The color and red lines are explained in Fig. B.1

Figure B.9: Selected 1200 particles geographical distribution after a simulation time of 240 days (8 months). The color and red lines are explained in Fig. B.1
Figure B.10: Selected 1200 particles geographical distribution after a simulation time of 270 days (9 months). The color and red lines are explained in Fig. B.1

Figure B.11: Selected 1200 particles geographical distribution after a simulation time of 300 days (10 months). The color and red lines are explained in Fig. B.1
Figure B.12: Selected 1200 particles geographical distribution after a simulation time of 330 days (11 months). The color and red lines are explained in Fig. B.1

Figure B.13: Selected 1200 particles geographical distribution after a simulation time of 360 days (12 months). The color and red lines are explained in Fig. B.1
Appendix C Histogram of Source Strength and MCT

Histograms of the Source Strength and MCT for the 9 receiving polygons and 2 receiving regions grouped according to the releasing month from the polygon sRS demonstrate the seasonality.

Figure C.1: The (a) Source Strength and (b) MCT for the region Out-RS and In-cnRS, grouped according to the particle releasing month in the backward tracking experiment.
Figure C.2: The (a) Source Strength and (b) MCT for the polygon cnRS, GA and SB, grouped according to the particle releasing month in the backward tracking experiment.
Figure C.3: The (a) Source Strength and (b) MCT for the polygon eS, eKT, nM, cS, sO and GO, grouped according to the particle releasing month in the backward tracking experiment.
Appendix D More Seasonal RPFs

Besides the evolution in time of the RPFs in section 4.3, more RPFs for the other receiving polygons demonstrating the seasonality are included in this appendix.

Figure D.1: Annual and seasonal RPFs of the polygon sRS. The annual RPFs are calculated using all months simulation, the seasonal RPFs are calculated using only the corresponding months: spring (March, April and May), summer (June, July and August), autumn (September, October and November), winter (December, January and February).
Figure D.2: Annual and seasonal RPFs of the polygon SB.

Figure D.3: Annual and seasonal RPFs of the polygon eS.
Figure D.4: Annual and seasonal RPFs of the polygon eKT.

Figure D.5: Annual and seasonal RPFs of the polygon nM.
Figure D.6: Annual and seasonal RPFs of the polygon cS.

Figure D.7: Annual and seasonal RPFs of the polygon sO.
Figure D.8: Annual and seasonal RPFs of the polygon GO.