Flowmaps and Coherent Sets for Characterizing Residence Times and Connectivity in Lagoons and Coral Reefs: The Case of the Red Sea

M.M. Doshi¹, C.S. Kulkarni¹, W. Hajj Ali¹, A. Gupta¹, P.F.J. Lermusiaux¹, P. Zhan², I. Hoteit² and O.M. Knio²
¹ MIT, ²Kaust

1. Introduction

Predicting the residence times and biophysical connectivity of ocean regions is extremely important to characterize the behaviors, dynamics, and health of marine ecosystems as well as to predict the effects of human activities in localized areas on the ecosystems connected to these areas. This is especially critical for the health and resiliency of marine lagoons and coral reefs. Considering the case of the Red Sea, its lagoons and coral reefs constitute an amazing undersea world home to 300 hard coral species and about 1,200 fish, of which 10 percent are local to the region. Its large number of lagoons along the coast (75 on the coast of Saudi Arabia) have large residence times that help coral growth due to the absence of erosion. However, the restricted exchange of water between these lagoons and the Red Sea is also responsible for pollution in the lagoons (Rasul, 2015). Characterizing the different connectivities in the region is thus very important. For example, Raitsos et al. (2017) have showed that connectivity patterns can explain the gene diversity of the coral reefs found in the Red Sea.

To address these challenges in lagoons and coral reefs, our first motivation is to utilize a wealth of our recent advances in efficient four-dimensional (time and space) Lagrangian theory and methods (Feppon and Lermusiaux, 2018a,b) for characterizing in a principled fashion the residence times and connectivity, showcasing the results for the Red Sea. Specifically, we study the connectivity patterns between the Eastern and Western coasts of the Red Sea Basin and the isolation of the southern part of the sea. By looking at how the structures of the flow evolve in presence of seasonal streams, we better understand the effects of these streams on connectivity patterns. Our approach is rooted in the fundamental Eulerian partial differential equations (PDEs) for the Lagrangian flowmap. With our novel numerical method of composition, we can solve these PDEs accurately and efficiently (Kulkarni and Lermusiaux, 2019) and provide rigorous characterization of the Red Sea coherent water masses, residence time, and connectivity dynamic features. As a result, we showcase quantitative 4D Lagrangian predictions, analyses, and characterizations of multiscale ocean transports, coherent structures, material sets, residence times, connectivity, and stirring and mixing processes in the Red Sea region.

A second motivation is to apply and expand the capabilities of two ocean research groups in multi-resolution submesoscale-to-regional-scale ocean modeling, 2-way nesting and tiling, and uncertainty and predictability predictions (Haley and Lermusiaux, 2010; El Mohtar et al., 2018), to allow innovative studies of the dynamics in the Red Sea region. The third motivation is to illustrate how we can collaborate with observational scientists to help design field campaigns and plan principled optimal sampling strategies for characterizing the 3D residence times and connectivity in lagoons and coral reefs. The campaigns can be optimized to provide the most information on: dynamic 3D pathways, residence times, connectivity, 4D coherent structures; and/or quantities most useful to learn accurate biogeochemical parametrizations.

The objectives of the present paper are to: (i) Utilize our new Lagrangian transport theory and methods to forecast, characterize and quantify ocean processes involved in the three-dimensional transports and transformation of water masses, residence times, and connectivity dynamics in the Red Sea; (ii) Apply and expand our multi-resolution submesoscale-to-regional-scale ocean modeling, 2-way nesting, and uncertainty predictions, for real-time forecasting and process studies in the region; (iii) Help design field
experiments and predict sampling strategies that maximize information on residence times, 4D pathways and dynamics in the region.

2. Results

We show the residence times and connectivity fields in 4D (3D+time), as computed based on our MSEAS forward flowmap forecast in the Red Sea region. They illustrate in 3D+time where these waters start, how they move, where they end up, and what are the connections among regions over several time scales. The residence times are the times needed for specific volumes of water that start in our Red Sea modeling domain and leave the domain after a certain time. The connectivity fields represent the connections among waters in different regions, over certain periods of time.

These times and fields are computed using a flowmap-based and composition-based advection scheme, using our estimates of the 3D ocean currents (u, v and w). We separate the different water volumes as a function of their residence times and connectivity dynamics. Since our method predicts the time varying flow maps, we can easily and efficiently compute the patches in a domain as a function of the residence times (the time after which the forward flow map value at a point is outside the domain). As also shown in the forecasts, the ridges of the forward Finite-Time Lyapunov Exponents (FTLEs) are the repelling FTLE structures: they tend to 'repel' water parcels. Two parcels that are close to each other at initial time but on different sides of the forward FTLE ridge will advect further away from each other than other parcels. The forward FTLEs thus act as material barriers to connectivity. The forward FTLE ridges can thus be thought of as a skeleton to the connectivity pattern. On the other hand, the ridges of the backward FTLEs are the attracting FTLE structures: they tend to 'attract' water parcels. They thus increase the chances of connectivity among different water regions, ultimately by sub-mesoscale or turbulent mixing along the ridges in the backward FTLEs. Using the available flow fields, we thus provide the dominant water pathways, residence times, and connectivity fields over several periods in the Red Sea.

3. References


