Visual Analysis of the Propagation and Cyclic Regulation of Salinity Levels in the Bay of Bengal

A PROJECT REPORT
SUBMITTED IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

Master of Technology

IN

Faculty of Engineering

BY

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July, 2020

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Visual Analysis of the Propagation and Cyclic Regulation of Salinity Levels in the Bay of Bengal

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Acknowledgements

First, I would like to thank Prof. Vijay Natarajan of the Visualization and Graphics Lab (VGL), under the Department of Computer Science and Automation, IISc Bangalore, for his involvement in this journey from the beginning and providing the necessary support and direction throughout. He was gracious and enthusiastic to accept to mentor and guide me. Regular discussions with him, and his inquisitive questioning at every detail of my work, has propelled me to be a good researcher.

This thesis would have been impossible without the support of the renowned Oceanographer and recipient of the prestigious Shanti Swarup Bhatnagar Award, Prof. PN Vinayachandran of the Centre for Atmospheric and Ocean Studies (CAOS), IISc Bangalore. I consider myself fortunate in collaborating with him to study the various oceanographic challenges involved in understanding the ocean salinity dynamics of the Bay of Bengal, from a visual analysis perspective.

I am very appreciative of the great support I received from my friend Upkar Singh, of the VGL Lab. The progress of my work picked up great pace thanks in parts to the countless discussions and knowledge-sharing sessions I had with him.

I would finally like to express my gratitude to my dear wife, my friends in the VGL Lab and all the loved ones who were always willing to provide a patient ear when I needed it, and constant encouragement to bring this work to the finish line.

Abstract

The Bay of Bengal plays a crucial role in controlling the weather systems that make up the South Asian summer monsoon. Freshwater inputs from both − rivers and a large amount of rainfall, make the Bay of Bengal a rather unique place. How does the freshwater make a difference to the ocean in that region - is an important climatological aspect that is being studied by leading oceanographers. The influx of freshwater into the northern part of the Bay dilutes the salinity of the sea water: while the mean salinity of the ocean is 35 PSU, in the northern part of the Bay, this number can be as low as 20 PSU, whereas in the rest of the ocean, changes in salinity are only in decimal places. The aim of this project is to leverage the advances in the visual analysis domain, to aid the oceanographers achieve an enhanced perspective regarding the phenomenon under study.

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Chapter 1

Introduction

This chapter introduces the various challenges faced by oceanographers, followed by the motivation for the project, and the targeted goal.

1.1 Motivation

Oceanographic scientists often generate simulation data using different models with varying initial conditions and parameter configurations. In their analytical tasks, they may also utilize observational datasets. These models simulate different phenomenon related to the ocean, and may have different scale, resolutions, data uncertainity, memory and computational requirements, depending on the requirements of their analysis tasks and the target application area. Analyzing the output of these models, overlaying different model outputs, making comparisons across multiple simulation runs, encoding uncertainty etc., are challenging time-consuming tasks, especially in the absence of a suitable interactive analysis environment. As discussed in Lipsa et al[9], two of the major challenges that are faced in this domain are -

- *Multi-field visualization* - Often the ocean data contains multiple attributes for the same point in space. The major challenge here is the ability to effectively visualize several fields simultaneously to facilitate the study of the relations and correlations between those fields.
- *Feature detection* - Modern sensors and simulations generate gigabytes to terabytes of data. The major challenge here is locating the features of interest in these vast amounts of data, representing them and tracking their evolution in time and space.

The authors in Vinayachandran et al[15] theorize about the existence of a salinity pump, that facilitates the mixing of saltier waters from the Arabian Sea with the freshwaters of Bay of Bengal (BoB), which helps maintain the salinity of the BoB. Salinity increases from the

BoB(North) to Arabian Sea(North). This salinity gradient is maintained by the active role of ocean dynamics. At the surface of the Bay of Bengal, climatological salinity decreases from ∼35 PSU at the mouth to ∼28 PSU at the head. Therefore, in order to maintain the salt balance of the bay, an export of freshwater is required. This is achieved by the inward movement of saltier water via the Southwest Monsoon Current (SMC). The SMC flows eastward from the saltier Arabian Sea into the southern Bay of Bengal during the summer monsoon, theorized as the Railroad Switch effect in Sanchez et al[12]. This SMC carries a high-salinity core, which brings the saltier waters from the Arabian Sea into the BoB.

1.2 Project Goal

Tracking the high-salinity core (HSC) that enters the BoB from the Arabian Sea, is one of the key challenges faced by the oceanographers. This is due to the very nature of the salinity core - it does not possess a clearly defined feature. It is a continuously evolving mass of salinity that undergoes irregular and unpredictable shape transformations, as it moves across successive timesteps. A mixture of several ocean dynamics factors like temperature, oceanic currents, salinity diffusion etc. makes it a difficult problem to track this HSC in the parameter space.

The goal of this project is to develop a visual analysis framework to explore the propagation dynamics of the high-salinity core entering into the Bay of Bengal from the Arabian sea, using relevant geometric and topological techniques, so as to aid our oceanographer collaborators achieve an enhanced perspective regarding the salinity propagation phenomenon in the BoB.

Chapter 2

Related Work

This chapter discusses about the existing frameworks, visualization techniques and relevant literature from the oceanography domain regarding tracking of watermasses.

2.1 Existing Frameworks

As discussed in Grochow et al[5], the typical tasks of an oceanographer can be described as -

- Inspect temperature and surface salinity values and compare the locations.
- Explore cross-sections of temperature and salinity ocean model.
- Compare the recently collected salinity data with model salinity data.
- Determine the current vorticities and circulation based on flow vectors.
- Analysis of extreme events.

Analysing the dynamically-varying attributes such as temperature and salinity in the large-sized simulated data from ocean models is a particularly challenging task. Iso-surfaces can present the boundary of a certain value in a volume, but looking at more than one scalar value requires more sophisticated techniques such as cutting planes, cutaways, transparency, or exploded views to show occluded layers (Li et al[8]). Viola et al's[17] work on importance-driven volume sampling provided a way to determine how to effectively remove layers for the user, automatically. Li et al[8]. described a conceptual basis for visualizing layered models and showed how user interaction can be helped by rigging for intelligent cutaways.

Collaborative Ocean Visualization Environment (COVE - Grochow et al[5]) is designed based on guidelines established through a conceptual design study, and collaboration with ocean scientists. Using COVE (Figure 2.1), analysts can interactively analyze ocean models data and other diverse datasets through a web-based repository of data and visualizations.

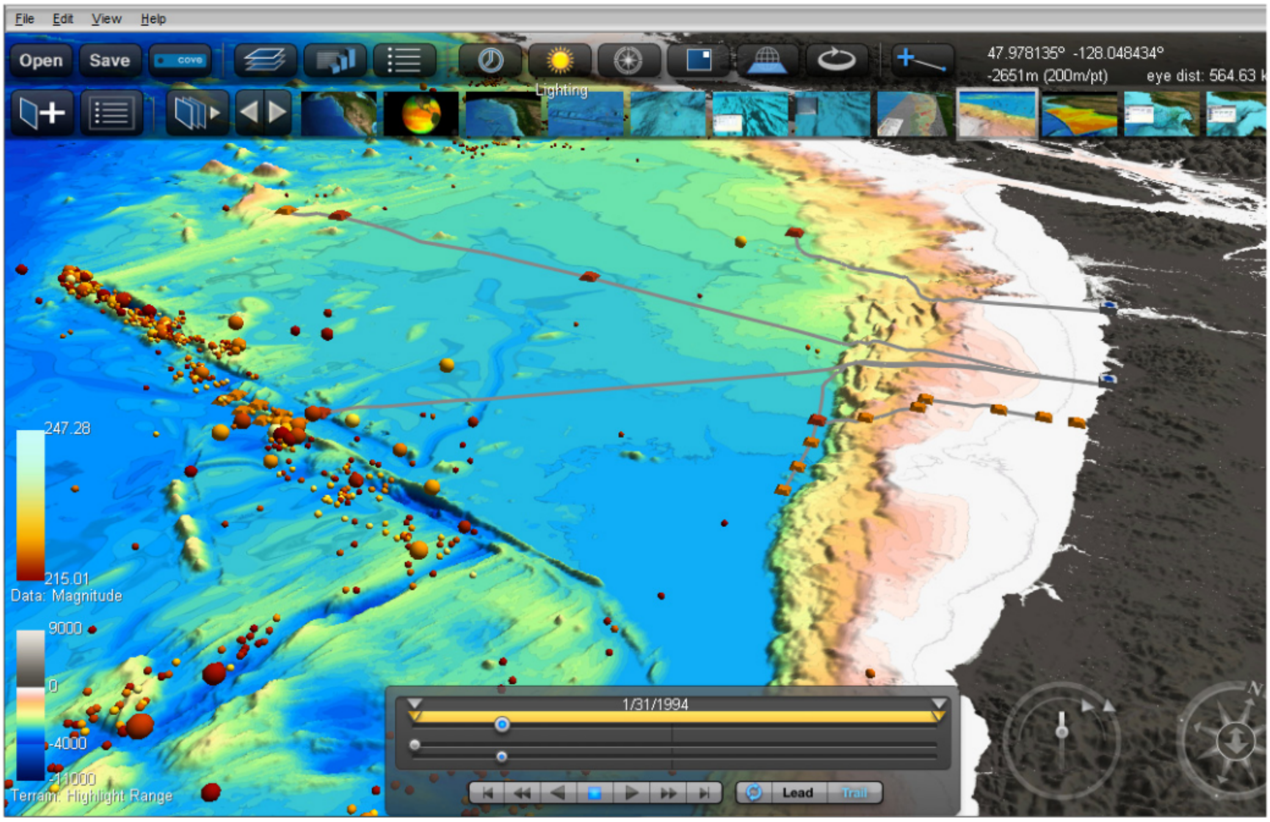


Figure 2.1: COVE (Lazowska et al[5]) displays geolocated scientific data, seafloor terrain, terrain specific color gradients, and instrument layout.

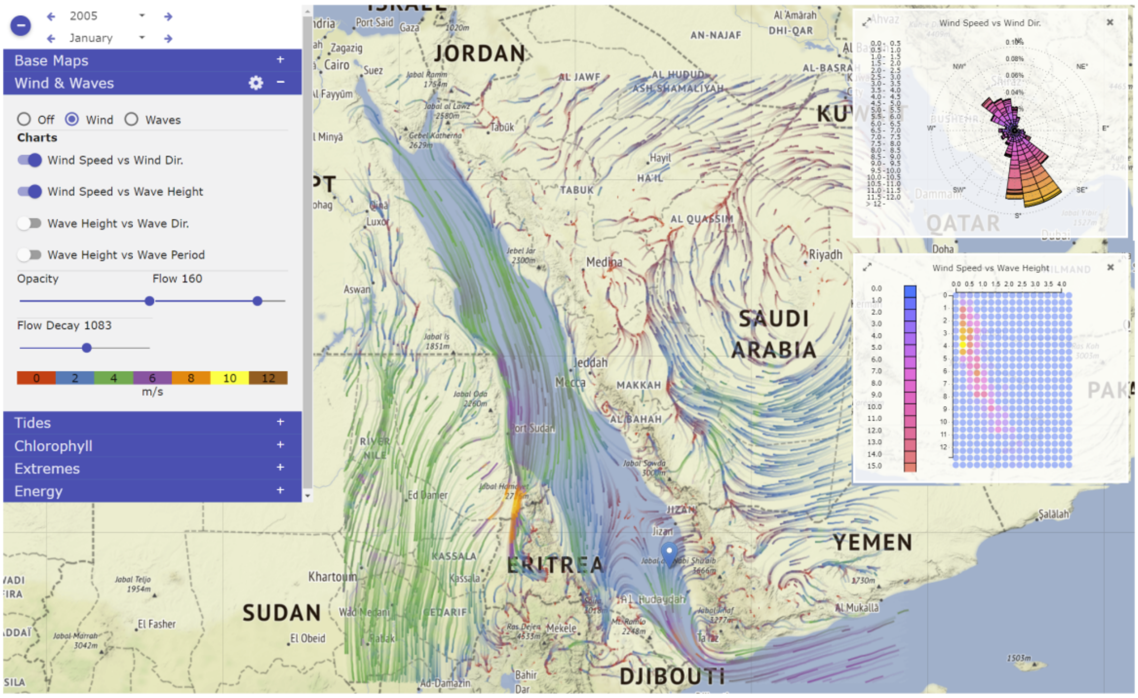


Figure 2.2: The RedSeaAtlas system (Afzal et al[1]) showing the wind dataset and associated attributes. Users can select any region on the map to see detailed information of the interactive visual charts.

The RedSeaAtlas system (Afzal et al[1]) as shown in Figure 2.2 shows the wind dataset and associated attributes, and allows the users to select any region on the map to see detailed information of the interactive visual charts. OceanPaths(Nobre et al[10]) supports interactive visual analysis of multivariate oceanography datasets by defining pathways along the currents and enabling spatio-temporal analysis of variations in water properties. Similarly, Vimtex (Dasgupta et al[3]) is a visual analytics system of coordinated linked views to study multivariate geology datasets to understand temporal patterns and behavior of different chemical species, while Vismate (Li et al[7]) is another visual analytics tool for analyzing station-based observation data using three linked visualizations:

- *Global Radial Maps* - using a customized radial layout with a map embedded in the center to study spatio-temporal patterns.
- *Time Series Discs* - using triangular heatmaps to study temporal trends.
- *Scatterplots* - to study abnormalities or unusual cases.

In the domain of Ensemble Visualization, Wang et al[18] discusses aggregation before volume-rendering. Direct volume rendering is the most popular traditional volume visualization technique, which visualizes a 3D deterministic scalar field as a 2D image through the ray-casting algorithm. An ensemble dataset usually has a multi-valued volume (it can also be considered as a collection of single-valued volumes), which makes traditional volume visualization techniques not directly applicable. Figure 2.3 shows aggregation before visualization. The first group of volume-oriented ensemble visualization techniques work by aggregating the multiple instances at each grid point to a single-volume instance.

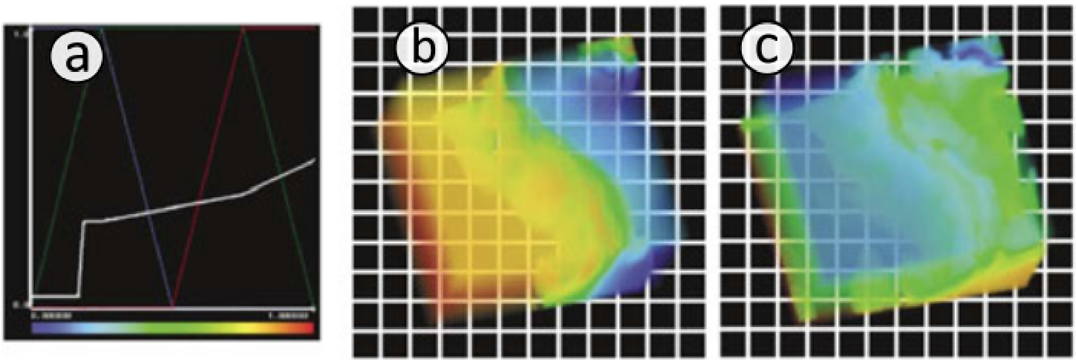


Figure 2.3: Aggregation of Volume Rendering of Salinity (Wang et al[18]). A 1D transfer function that maps mean values to color and uncertainty values to transparency.

Glyph based visualizations are often used in visualizations of different atmospheric and ocean data attributes. Glyphs on the map of Figure 2.2 show overall wind patterns in the Red Sea region, color-coded to demonstrate the strength of winds. Wang et al[18] discusses about Glyph Visualization in the context of ensemble data, as shown in Figure 2.4.

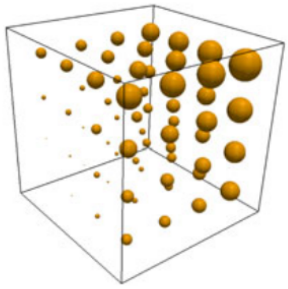


Figure 2.4: 3D Glyph Visualization (Wang et al[18]). The size of spheres is used to encode the scalar value at each grid point.

2.2 Tracking of Watermass

In the domain of Oceanography, tracking water masses using the T-S diagrams, is a well-studied problem. T-S diagrams are temparature-salinity diagrams, that are used to identify water masses. Temperature and salinity combine to determine the potential density of seawater. Contours of constant potential density are often shown in T-S diagrams. By identifying an original water mass in the T-S diagram, tracking a general water mass when multiple original water masses mix can be achieved in the T-S space. The most common water masses found in the Atlantic Ocean are marked with their abbreviations in Figure 2.5 at their TS-space characteristics (Talley et al[6])) - SACW, NACW = South and North Atlantic central waters, MW = Mediterranean water, AAIW = Antarctic intermediate water, NADW = North Atlantic deep water and AABW = Antarctic bottom water. The authors in Sara et al[2] discuss about tracking of water masses in the temparature-salinity space, using a thermohaline stream function.

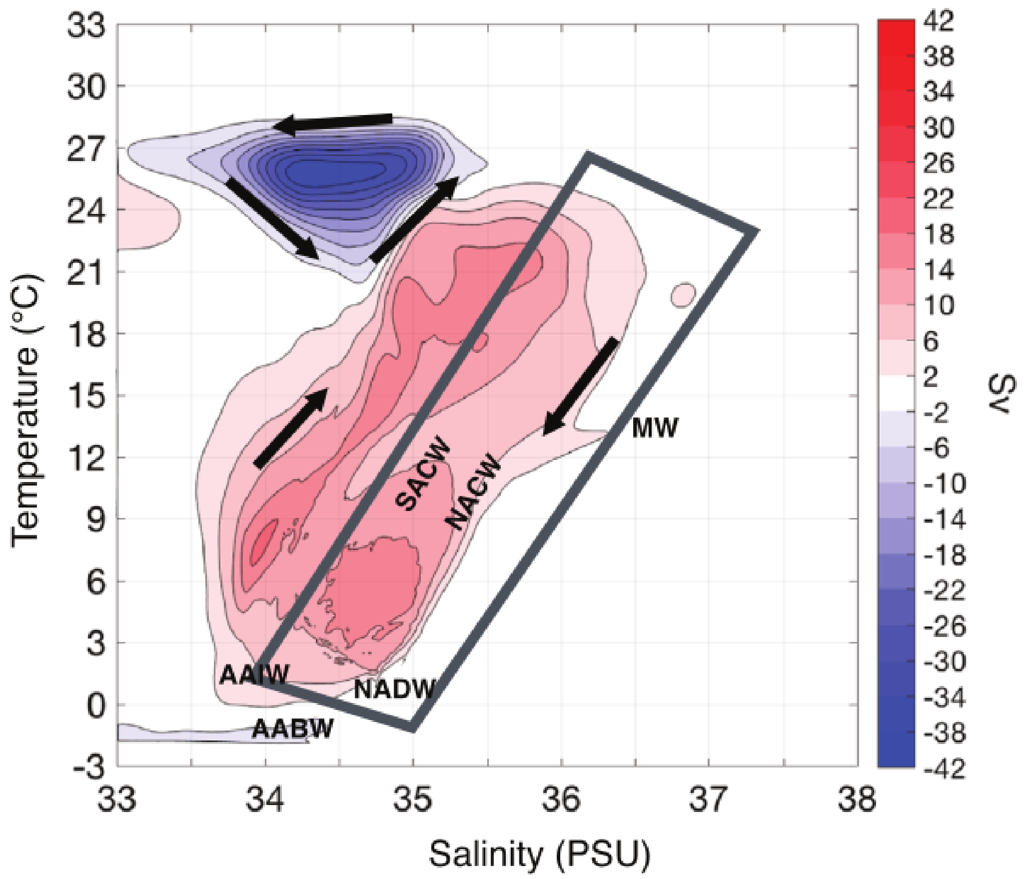


Figure 2.5: Watermasses in the Atlantic Ocean (Sara et al[2]). The marked area is suggested to represent the circulation of the Atlantic Ocean in the thermohaline stream function.

All of the above analysis frameworks and visualization techniques have been designed to cater for particular dataset requirements, and focus majorly on user interaction aspects. The requirements of our oceanographer collaborators differ from the typical use-cases of the above frameworks, in that the salinity core in the ocean needs to be clearly defined using suitable structures and these structures need to be subsequently tracked across successive timesteps. Although similar problems have been well-studied under the field of scalar field visualization and tracking, for various applications like cyclone tracking (Akash et al[14]) and wind datasets (Afzal et al.[1]), no framwework exists for the problem of salinity core tracking. On the other hand, tracking water masses in the T-S space involves computing complex thermohaline stream functions, that are not scalable for data with high-resolution. Additionally, the T-S diagram methods work only when both the dependant data - temparature and salinity, are available for a particular geographical area. The collection of the temperature-salinity data from the all the involved original water masses (BoB, Arabian Sea and the Indian Ocean in this case) in itself is a tedious process as it requires sophisticated measuring devices and supportive weather conditions.

Chapter 3

Problem Description

This chapter states the problem definition and an overview regarding ways to solve the problem. It also presents a summary of the major contributions.

3.1 Problem Stament

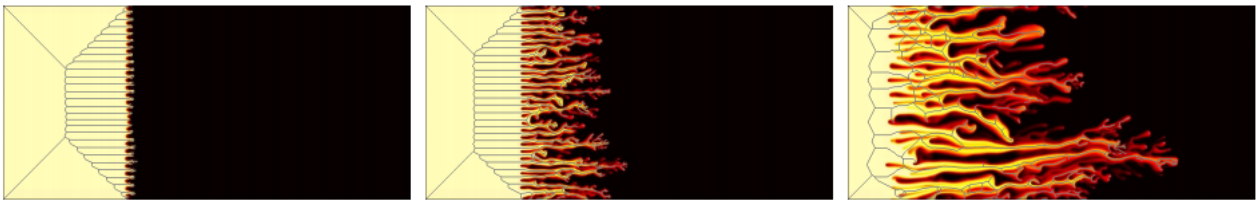
To define, characterize and track the high-salinity core and its propagation using relevant geometric and topological techniques, so as to aid the oceanographers in their study of salinity levels in the Bay of Bengal.

The key challenge in tracking the high-salinity core is that it is not well-defined. Due to the various ocean dynamics factors like diffusion, ocean currents etc, the core is a continuously evolving mass of salinity that undergoes irregular and unpredictable shape transformations, as it moves across successive timesteps. The constant change in the shape also necessitates a new visual representation to depict the propagation of salinity through the BoB.

3.2 Solution Overview

In the domain of scientific visualization techniques, isosurfaces are useful data visualization methods that can be used to represent the boundary of a certain value in a volume. Isosurface represents points of a constant value (e.g. pressure, temperature, velocity, salinity) within a volume of space. Mathematically, it is a level-set of a continuous function whose domain is 3D-space. A collection of such isosurfaces over a range of scalar values defines an isovolume. After discussions with our oceanographer collaborators, it emerged that the representation of the high-salinity core under study as a 35 PSU isovolume is the best possible representation, as compared to other representations such as point clouds and meshes. This is particularly true in a time-varying setting. Our study is aimed at extracting and tracking the temporal evolution of this 35 PSU isovolume.

While the movement of the isovolume front can be tracked through various front-tracking methods, those methods will give the general direction of movement of the boundary of the isovolume. We were interested in tracking the core of the isovolume. Several topological structures exist for tracking the core of the isovolume. The popular methods majorly follow one of the two paradigms - discrete morse theory based approaches, and skeleton based approaches. While the dicrete morse theory based approaches, like Contour trees and Reeb graphs, are powerful in a more general setting, their applicability is dependant on the noise in the data(Rieck et al[11]). Hence we focus on the conceptually simpler skeleton-based approach for tracking the 35PSU isovolume. Volumetric skeletons are derived from 2D and 3D volumes for measurement of length and to determine branching and winding structures. In the paper by Sato et al[13], the authors introduce an efficient volumetric skeletonization algorithm to study CT and MRI scans. The authors in Rieck et al[11] extend this skeletonization idea in a 2D setting to understand the evolution of viscous fingers, as shown in Figure 3.2. They implement an analysis pipeline to study the evolution of a whole series of evolving time-varying skeletons. We extend these ideas into the 3D domain, for tracking the 35PSU isovolume.



(a) $t = 8$ (b) $t = 30$ (c) $t = 70$

Figure 3.1: Evolution of 2D viscous fingering simulation (Rieck et al[13]).

3.3 Major Contributions

Thus, the novel contributions of our study can be summarized as –

- Coarser and finer analysis of the ocean salinity data of the Bay of Bengal region, and their subsequent verification with our oceanographer collaborators.

- Defining the constantly evolving high-salinity core as a 35PSU isovolume and its extraction, for individual timesteps of the data.
- Tracking the 35PSU isovolume over time across the complete timesteps in the data.
- Interactive methods to allow the oceanographers to select representative tracks for further analysis.

Chapter 4

Dataset Description

> This chapter discusses the various datasets that have been used for the visual analysis tasks.

In consultation with the oceanographer collaborators, the analysis of the BoB salinity involved 2 stages -

4.1 Stage-I (NOAA Data)

For coarser analysis, we studied the decadal averaged National Oceanic and Atmospheric Administration (NOAA) salinity data, with monthly resolution, all the decades between 1955-2012. The data is available as a decadal averaged statistical mean of salinity data per month, on 1° grid, 5° grid and $(1/4)^\circ$ grid.

4.2 Stage-II (NEMO Data)

For finer analysis, we studied the Nucleus for European Modelling of the Ocean (NEMO) data with daily resolution, for the months June-September 2016 (122 timesteps). The data, available in $(1/12)^\circ$ grids, faithfully represented the variability of the Southwest Monsoon Current (SMC) and associated water masses. This data contained salinity values for 50 vertical levels ranging in thickness from 1 m at the surface to 450m at the bottom and comprising 22 levels in the upper 100m.

4.3 Data Format

Both the dataset are available in structured NetCDF format - a self-describing, grid-oriented binary format common in earth science. The dataset was pre-processed to focus on the BoB region.

Chapter 5

Methodology

This chapter discusses the complete methodology involved in the visual analysis of salinity propagation in the Bay of Bengal, achieved over 2 stages - Stage-I and Stage-II.

5.1 Stage-I (Coarse Analysis)

We started with the objective of extracting and visualizing the salinity pump as theorized in Vinayachandran et al[15]. We used VAPOR tool to extract the isosurface and isovolume visualizations corresponding to the salinity layer of 35 PSU. We then proceeded to characterize this 35 PSU layer corresponding to their depths (Figure 5.1). Blue represents 0m depth (Sea Surface), while Red represents 1500m depth (depth bound as per the data). The rest of the depths are interpolated colormap between blue-red. We could see the salinity variations on a monthly basis. In particular, we could infer that while the south of BoB remains less saline in the month of April at the surface due to the influx of freshwaters from the rivers, the 35 PSU salinity water is pumped to the surface, as theorized by Vinayachandran et al[15]. This is represented as the 'Salinity Pump' in Figure 5.1 . This was also verified with the author of Vinayachandran et al[15].

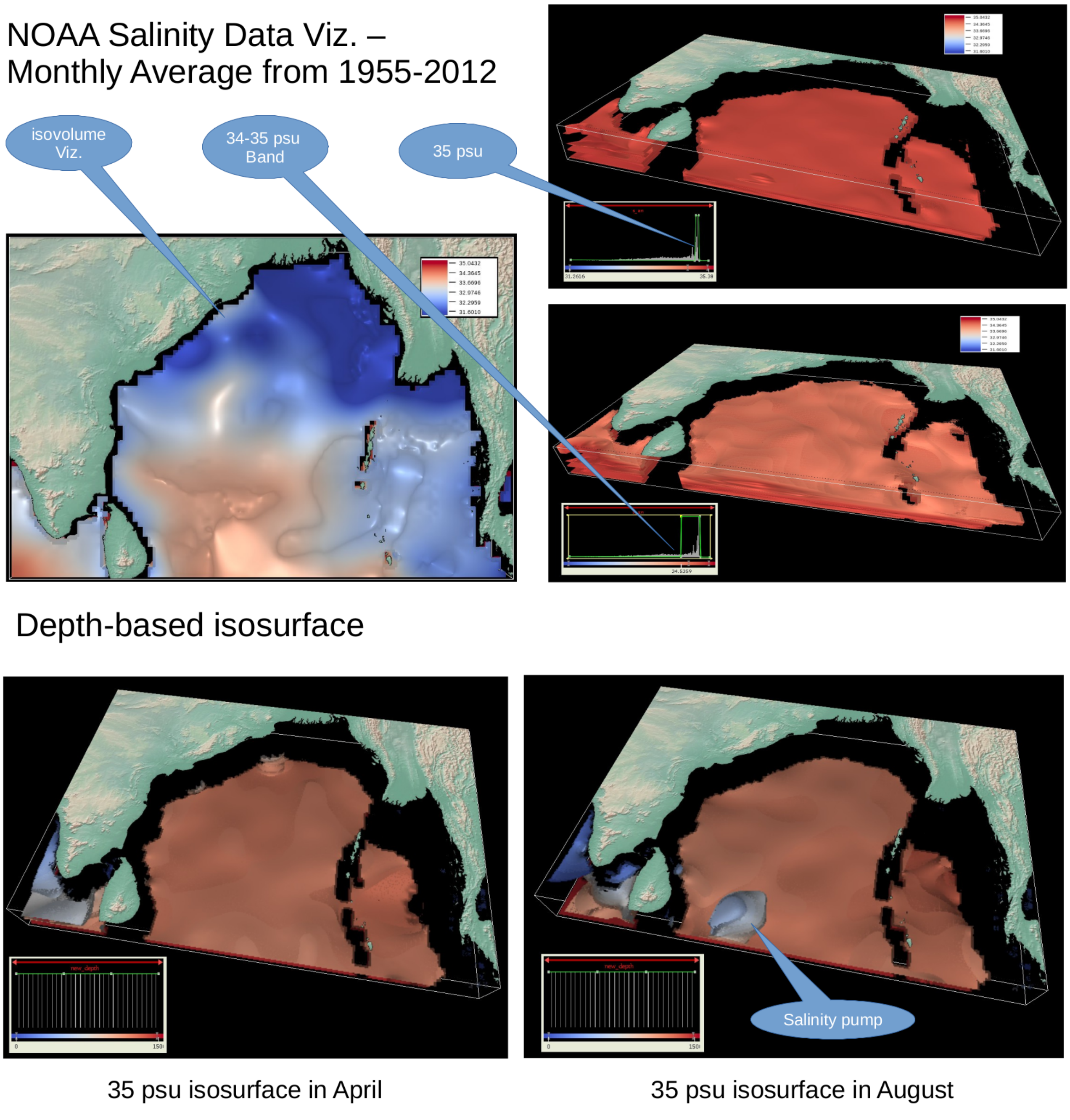


Figure 5.1: Characterization of 35 PSU Isohaline Surface in the Bay of Bengal, extracted using VAPOR tool. Blue represents 0m depth (Sea Surface), while Red represents 1500m depth (depth bound as per the data). The 'Salinity Pump' detected in the month of August is clearly marked visible from the analysis (marked using callout). Also, the south of BoB remains less saline closer to the sea surface in the month of April.

Although the VAPOR tool supports necessary visual analysis workflows, the support for programmatically controlling the workflows were found to be rigid and limited. The VAPOR Data Collection (VDC) data model allows users progressively access the fidelity of their data, allowing for the visualization of terascale data sets on commodity hardware. But the shortcoming with VAPOR is that the programming flexibility powers of the tool could be harnessed better only when the data is converted into the VDC data format.

5.2 Stage-II (Fine Analysis)

The success of Stage-I necessitated a finer analysis of the salinity propagation - Stage-II. For this, we started studying the finer resolution NEMO data. The availability of this data in NetCDF format and the associated shortcoming of the VAPOR tool resulted in using another popular analysis tool - PARAVIEW. It has a robust programmable framework which enables the users to develop other applications using the framework, as well as the capability of embedding the same in other applications and frameworks. Using PARAVIEW as the tool for extracting the 35PSU isovolume, we evolved the following analysis pipeline for the Stage-II -

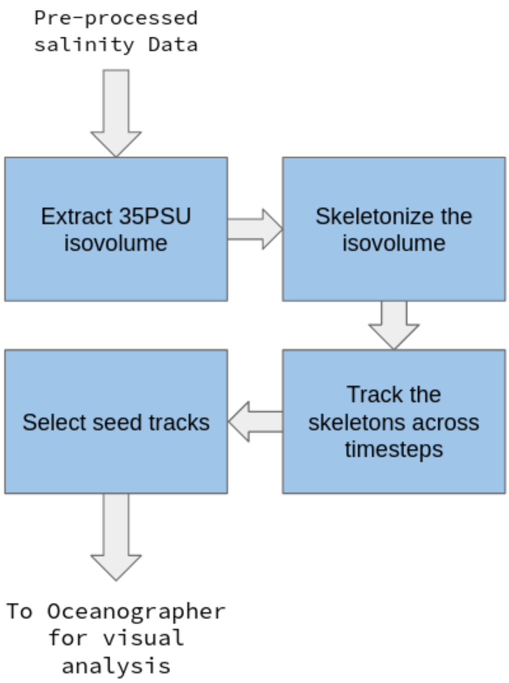


Figure 5.2: Visual analysis pipeline evolved and implemented for Stage-II (finer analysis) of the salinity data.

The NEMO salinity data contains salinity values sampled in the *(latitude,longitude,depth)* grid. In the pre-processing step, a subset of the salinity data corresponding to the Bay of Bengal region with a geographical bounding box of *longitude* 50°E to 95°E, *latitude* -10° to 27° and *depth* upto 450m, is extracted. The pre-processed data is passed through the visual analysis pipeline, wherein the 35PSU isovolume is extracted first. This isovolume is then converted into a binary format. From the binary format of isovolumes corresponding to each of the timesteps, skeleltons are computed inorder to represent the evolving shape of the salinity core. These skeletons are then tracked through time which then results in a collection of tracks over the complete timesteps of the data. These collection of tracks, which represent the propagation direction of the salinity core, is then presented to the oceanographer. The oceanographer can then interactively choose his point of interest, corresponding to a region of his choice. This salinity route of the selected point of interest is then traced back through the collection of tracks and presented as the representative tracks, using glyph-based visualization methods, for depicting the the representative tracks for the salinity core with clarity.

5.2.1 Isovolume Extraction

The first step in the pipeline is to extract the 35PSU isovolume from the pre-processed salinity data. Isovolume extraction is done using the *Isovolume* filter in the PARAVIEW tool. PARAVIEW extracts the isovolume efficiently by utilising the computing power of GPU's in the host machine.

Taking into consideration the allowable tolerances[4] inherently present in the measurements, the 34.8-35.2 PSU range of salinity was found to be adequate for the describing the 35PSU isovolume. Also, as described in Vinayachandran et al[15], the pumping and mixing phenomenon is observed at the depths of about 200m from the sea surface. Hence, the isovolume extraction algorithm considers the salinity values only upto the 200m depth. Isovolume is extracted for each of the 122 timesteps present in the data. The extracted isovolume is shown in Figure 5.3. This extracted isovolume is then converted into a regular grid and then binarized for processing in the subsequent pipeline step.

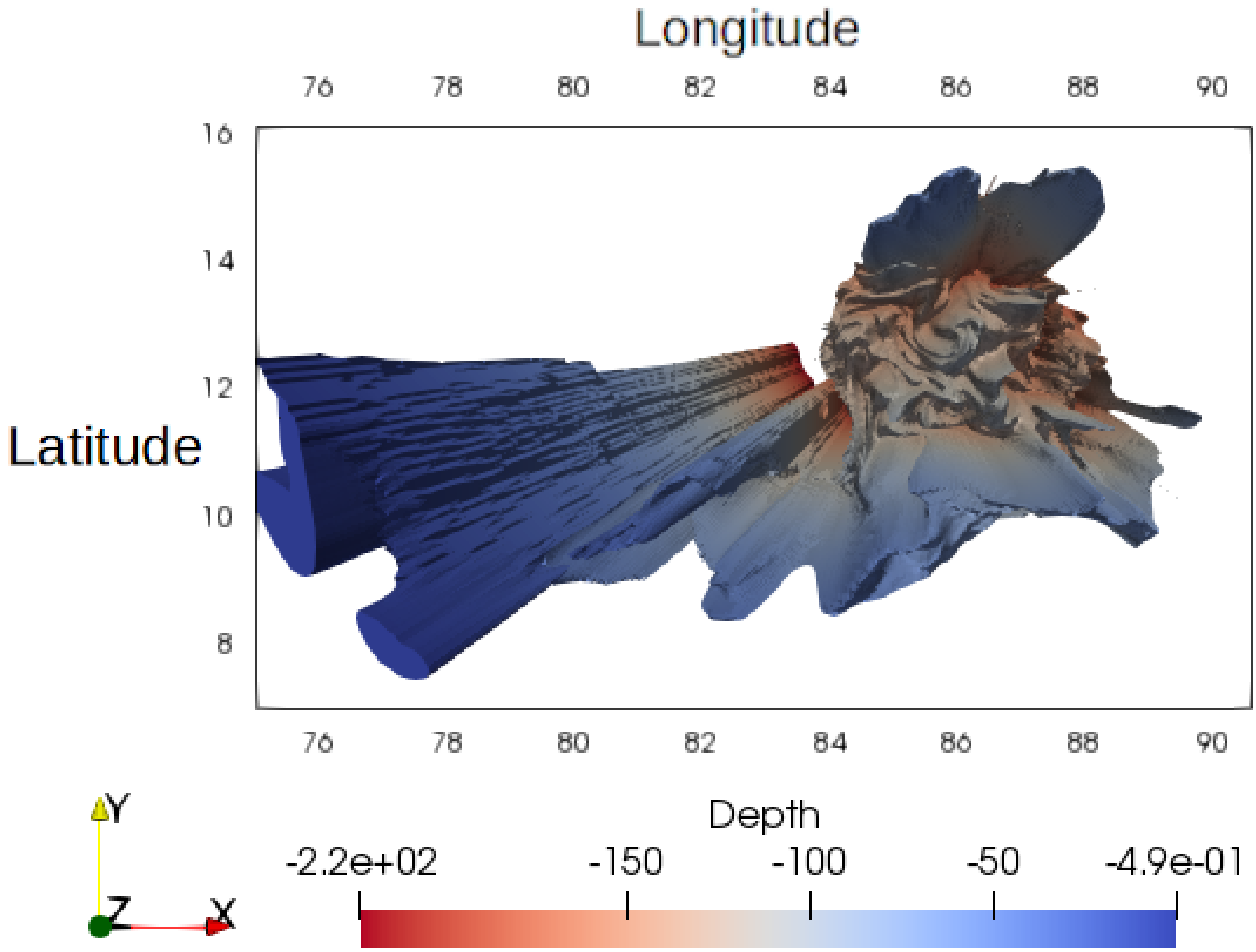


Figure 5.3: Extracted isovolume corresponding to 34.8-35.2 PSU. Coloring is based on depth where Blue corresponds to 5m depth and Red corresponds to 220m depth.

5.2.2 Skeletonization of Isovolume

The second step in the pipeline is to construct the skeletal structure of each of the isovolumes extracted in the previous step. The main motivation for this step is to construct a collection of paths, that together describes the skeletal structure of the isovolume. The TEASAR[13] algorithm is a conceptually simpler technique for skeletonizing the isovolume. We use this algorithm to extract the skeleton of the isovolumes corresponding to each timestep.

This algorithm works by finding a root point on a 3D object and then serially tracing paths via

Dijksta's shortest path algorithm through a penalty field to the most distant unvisited point. After each pass through an isovolume, iterative thinning is performed using a sphere. The sphere is expanded around each vertex in the current path and part of the object are marked as visited. This results in a set of connected components. The important parameters of the algorithm are –

- *scale* and *const* – they control the radius of this invalidation sphere according to the equation –

  $$r(x, y, z) = scale * DBF(x, y, z) + const$$

  DBF(x,y,z) is the physical distance from the shape boundary at that point.

- *dust_threshold* – This threshold culls the connected components. Connected components with less than 100 nodes are considered as *dust pieces* and are discarded.

After the skeletonization step, a sequence of skeletons $S_0, S_1, ..., S_{122}$, each corresponding to a time step $t_0, t_1, ..., t_{122}$, are generated.

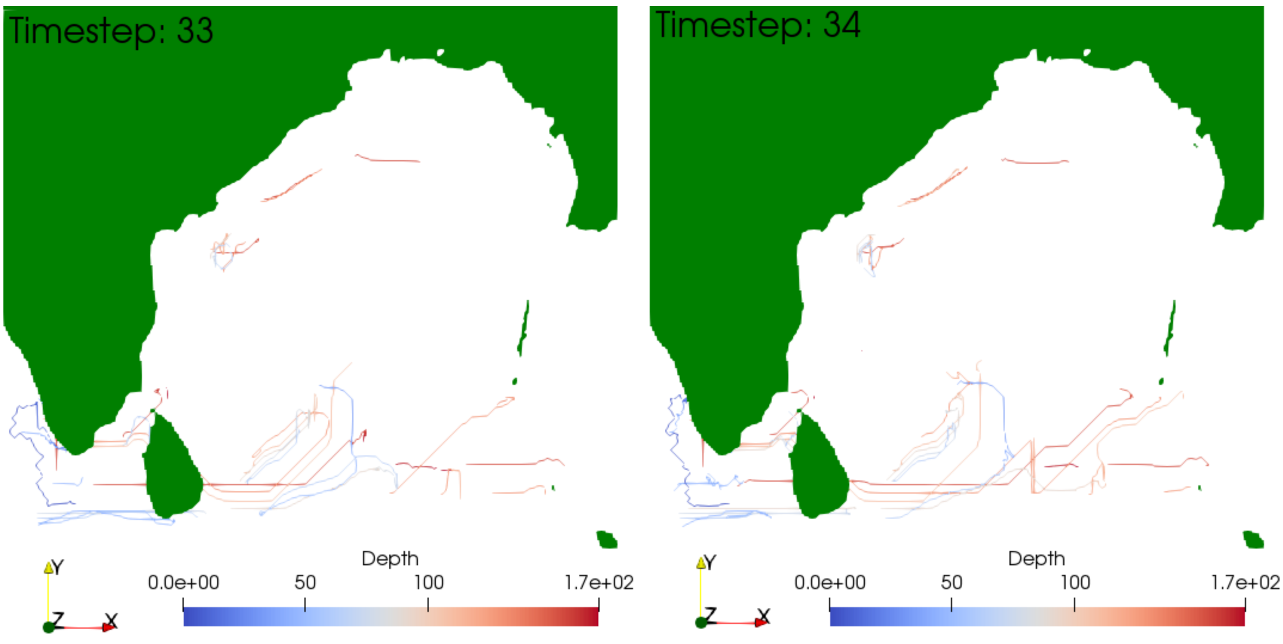


Figure 5.4: Skeleton of isovolumes corresponding to timesteps 33 and 34.

5.2.3 Temporal Tracking of Skeletons

The third step in the pipeline is to track the sequence of skeletons generated in the previous step, across successive timesteps, by dividing them into small intervals. The authors in Rieck et al[11] discuss about a tracking algorithm for tracking skeletons of viscous fingers in 2D space. We extend this to track the salinity core skeletons in 3D space.

The algorithm begins by segmenting the connected components of each of the skeletons into small intervals. To speed up the computation within acceptable tolerances, instead of looking up *point-to-point* correspondences, we look at *interval-to-interval* correspondences among connected components. This ensures acceptable correspondences between 2 connected components between 2 successive timesteps. For uniformity, we take the start point in an interval as the salinity interval point. Given 2 time steps t_i, t_{i+1}, we assign every salinity interval point $s \in S_i$ the salinity interval point $s' \in S_{i+1}$ that satisfies -

$$s' = \operatorname*{argmin}_{t \in S_{i+1}} dist(s, t)$$

where $dist()$ is the Euclidean distance. Likewise, we assign every salinity interval point in S_{i+1} its nearest neighbour in S_i, which represents a match from S_{i+1} to S_i. This results in a set of directed matches between S_i and S_{i+1}. Each salinity interval is guaranteed to occur at least once in the set. We refer to matches from S_i and S_{i+1} as *forward matches*, while we refer to matches in the other direction as *backward matches*. The combined set of *forward matches* and *backward matches* across all the 122 timesteps represents the complete tracks of the skeletons across time.

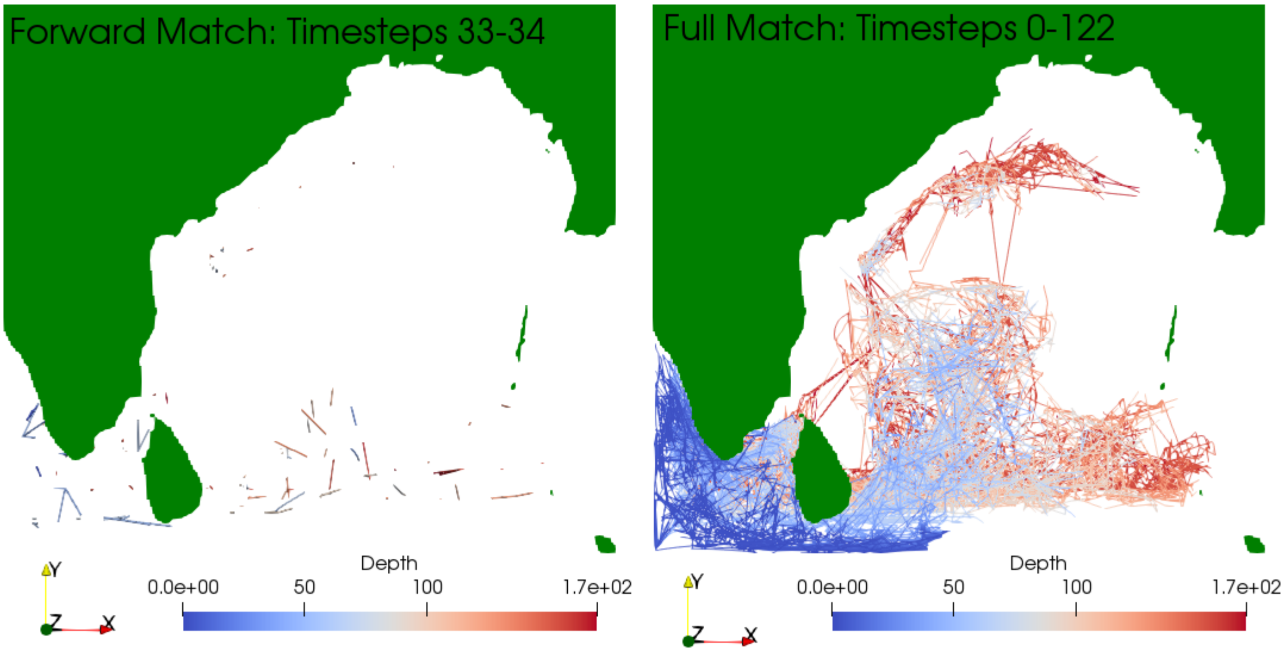


Figure 5.5: The left figure represents the forwards matches between the skeletons of timesteps 33 and 34. The right figure represents the complete set of tracks obtained through forward matching of skeletons from timesteps 0-122.

5.2.4 Selection of Seed Tracks

The final step in the visual analysis pieline is user interaction. The main motivation behind this step is to generate representative seed tracks that clearly describes the overall movement of the salinity core, as per the selection of points of interest by the oceanographer.

The oceanographer interactively chooses a set of points of interest in the Bay of Bengal region, after observing the temporal tracks. These selected points of interest are then traced backwards in time to arrive at a set of likely propagation routes of the salinity mass. These points are also traced forward in time, to understand the likely propagation paths in the successive timesteps.

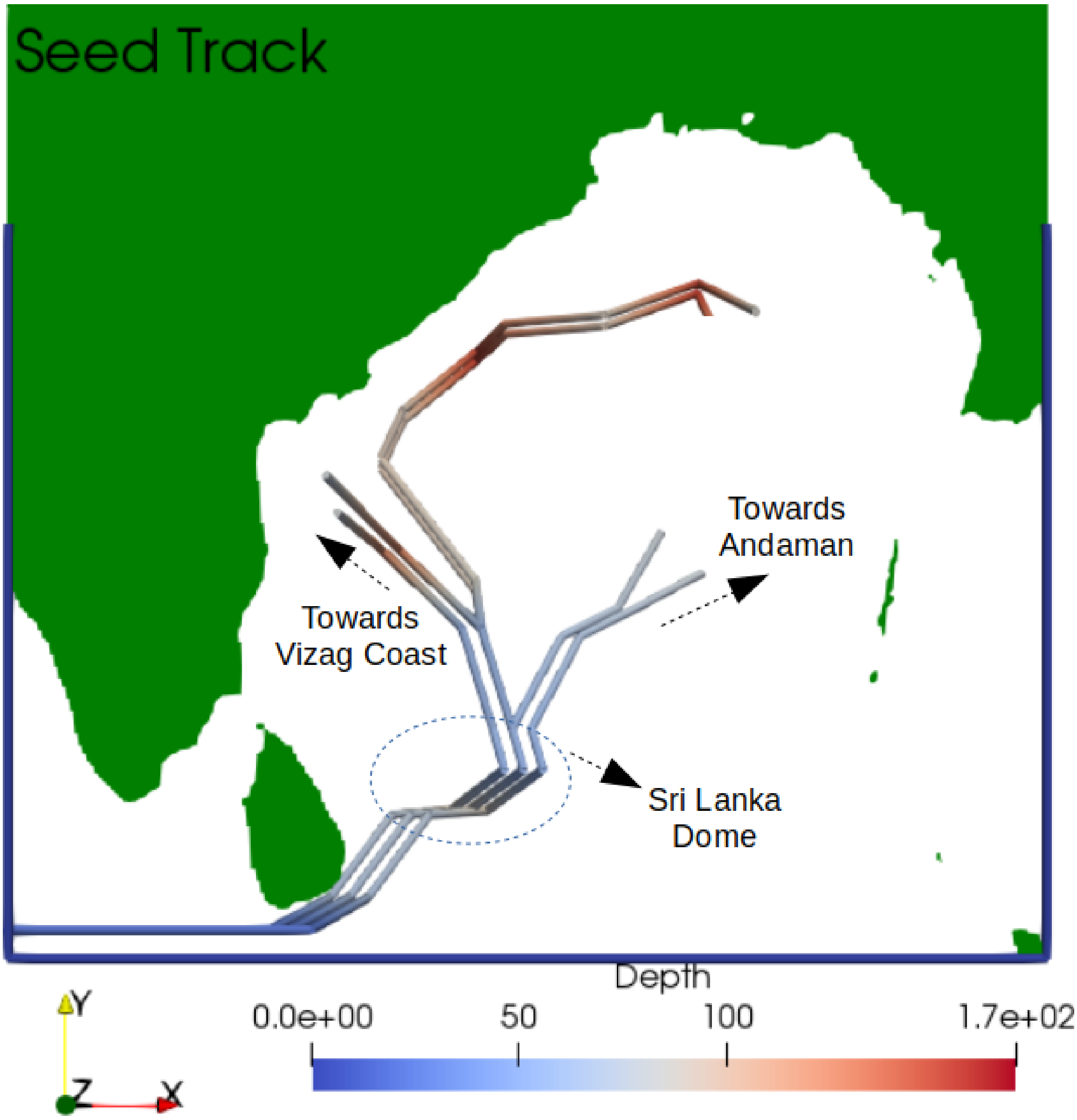


Figure 5.6: Representative seed tracks traced corresponding to the points of interest selected by the oceanographer.

The interaction for the oceanographer is facilitated through the PARAVIEW tool, as shown in Figure 5.7. It supports several built-in as well as programmable visualization filters. The various steps in the visual analysis pipeline are programmatically incorporated into PARAVIEW through external scripts. It also supports various display representations in 2D and 3D, as well as color and opacity controls as per users choice.

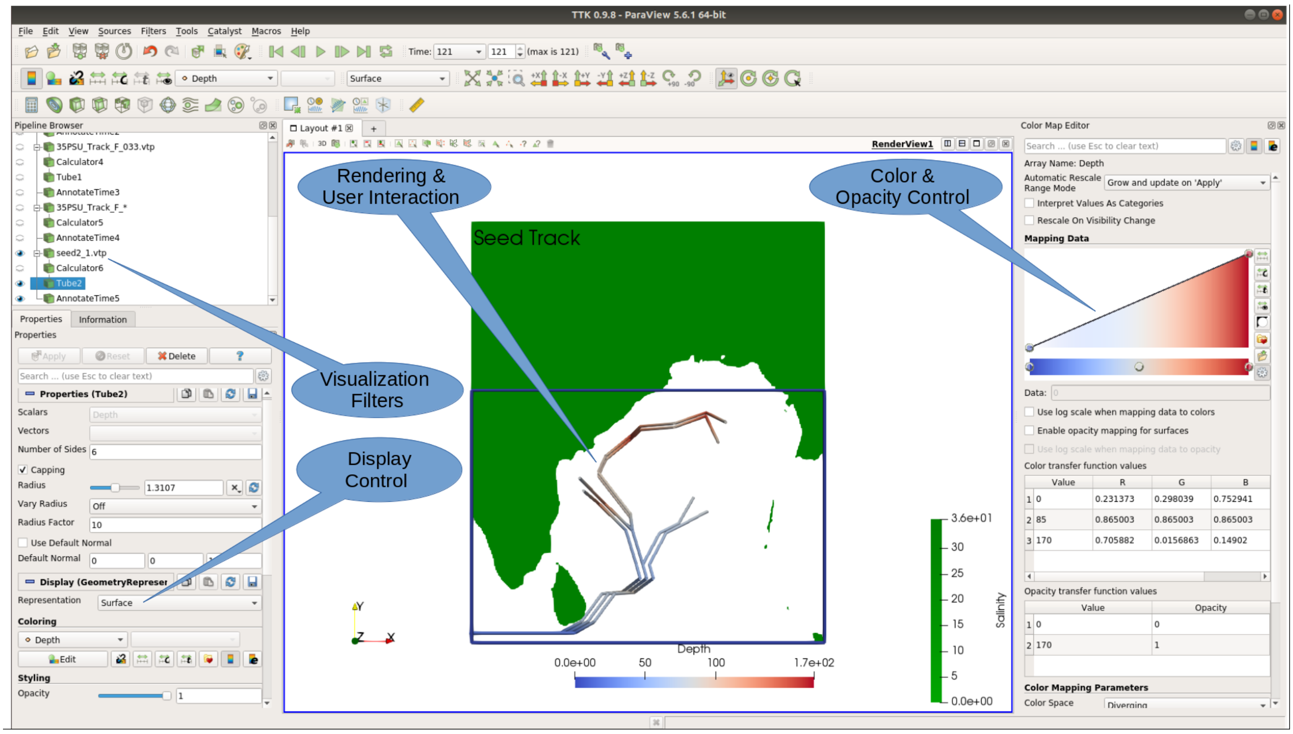


Figure 5.7: PARAVIEW tool through which the oceanographer interacts. The various steps in the visual analysis pipeline are programmatically incorporated into PARAVIEW through external scripts.

Chapter 6

Design & Implementation

This chapter discusses the design implementation details of the visual analysis pipeline.

6.1 Modes of Operation

The visual analysis pipeline has been designed in a semi-automatic mode comprising of an automatic mode followed by an interactive mode.

6.1.1 Automatic Mode

This mode involves utilising 2 major capabilities of the PARAVIEW tool - (i) ability to programmatically invoke the various filters through python-scripts using the *pvpython* utility, and (ii) ability to run external scripts alongwith the *pvpython* utility. The external scripts have been organized into the following 4 python scripts −

- *preprocess.py*− The preprocessing of the NEMO data to focus on the Bay of Bengal region is achieved through the *Climate Data Operators (CDO)* command line tools, available for manipulating the NetCDF files.

- *isovolume.py*− Isovolume is extracted by invoking the 'Iso volume' filter programmatically. The extracted isovolume is then binarized and converted into a regular grid.

- *skeletonize.py*− TEASAR algorithm has been implemented to skeletonize each of the extracted isovolumes. Euclidean distance graph computations and array manipulations have been carried out using the functionalities of the *scipy* and *numpy* libraries. *Dijkstra's* algorithm has been used to compute the shortest path. Each skeleton is then converted into a *networkx* graph.

- *tracking.py*− Forward matching and Backward matching is then traced using euclidean distance between the seed points of intervals, across successive timesteps, by traversing through the *networkx* graph. The final set of tracking graphs is the converted into corresponding *VTKGraph* and subsequently visualized in PARAVIEW using the *VTKPolydata(VTP)* format.

6.1.2 Interactive Mode

The automatic mode is followed by the interactive mode. The various interaction capabilities of PARAVIEW make it an ideal tool for user interaction. PARAVIEW supports several built-in as well as programmable visualization filters. It also supports various display representations in 2D and 3D like *glyph*, *tube*, $wireframe$, $surface$ and *volume* as well as color and opacity controls as per users choice. The oceanographer interacts with the set of temporal tracks obtained in the previous mode, in PARAVIEW, to select a set of seed points. These selected points of interest are then traced backwards through the *networkx* graph, in time, to arrive at a set of likely propagation routes of the salinity mass. These points are also traced forward in time, to understand the likely propagation paths in the successive timesteps.

6.2 Algorithm Details

6.2.1 Skeletonization Algorithm

The TEASAR(Sato et al[13]) algorithm is a conceptually simpler skeletonization algorithm comprising, briefly, of the following steps −

1. Start from a root point.
2. Use Dijkstra's shortest path algorithm to draw a path from the root(s) to the the most distant point(t).
3. Perform iterative thinning using a sphere of appropriate radius.
4. Draw a path to the next surviving max distance point and invalidate.

6.2.2 Tracking Algorithm

The tracking algorithm is an extension of Rieck et al[11], comprising of −

1. Segment each connected component in a skeleton into intervals.
2. Select a seed point per interval.

3. Given 2 time steps t_i, t_{i+1}, we assign every seed point $s \in S_i$, the seed point $s \in S_{i+1}$ that are closer to each other in euclidean distance.

4. This results in a set of *forward matches* and *backward matches*.

The novelty of this algorithm is that instead of looking up point-to-point correspondences, we look at interval-to-interval correspondences among connected components. In this way, careful choice of interval speeds up the computation without causing structural mismatches.

Chapter 7

Analysis and Results

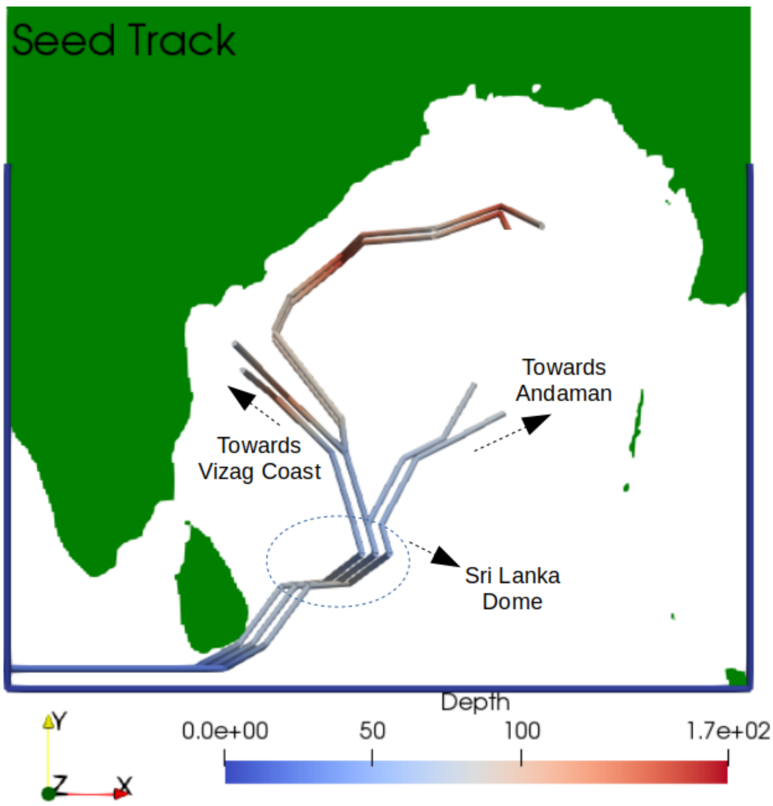


Figure 7.1: The important results from the analysis are marked as - 1) The verification of the presence of Sri Lankan dome, and 2) The bifurcation of the salinity core's - towards the Vizag coast and subsequently into the Bay of Bengal, and towards the Andaman islands.

7.1 Sri Lanka Dome

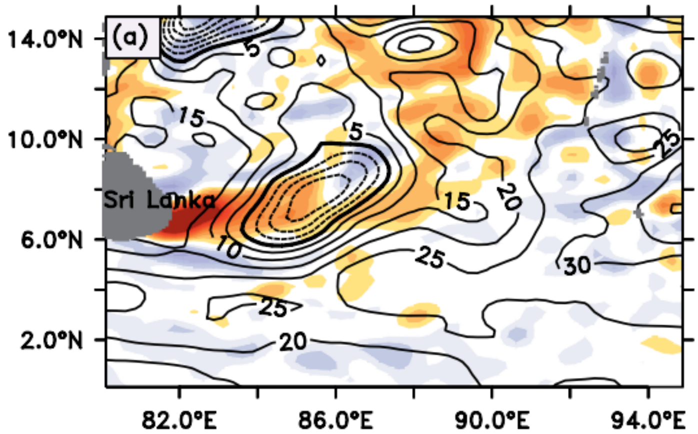


Figure 7.2: Sri Lankan Dome depicted in Weber et al[19], as reported in Vinayachandran et al[16].

The authors in Vinayachandran et al[16] report about the Sri Lankan Dome (SLD), as shown in Figure 7.2, caused by cyclonic curl in the local wind field. The SLD was evident in our results (Figure 7.1), as there was a considerable reduction in the number of matches going through this region. This way, we could validate our analysis in consultation with the oceanographer collaborators.

7.2 Salinity mixing off the Vizag Coast

This is the most significant result that we were able to achieve. The authors in Vinayachandran[16] clearly identify the region in the South side of BoB where the high-salinity core is enters from the Arabian Sea, after surrounding the Sri Lankan Dome (Weber et al[19]). After entering the South region of BoB, the general mixing direction of propagation of the high-salinity core with the freshwaters in the BoB remained unknown.

From our results, we could identify this general direction as North-West towards Vishakhapatnam coast, from where it turns North-East into the North side of BoB, as shown in Figure 7.1. This can be inferred from the fact that the majority of the tracks pass through the Vizag coast towards the Bay of Bengal region. This could mean either of the 2 following observations –

- The oceanic currents in play take a westerly turn towards the Vizag coast thereby pushing the salinity core along.
- The volume of mixing is more towards east of the Bay of Bengal region, than towards the vizag coast.

This is a new result, which has hitherto been unreported. This result has been shared with our oceanographer collaborators, who found it to be an interesting phenonmenon that needed to be validated with measured data.

7.3 Salinity propagation towards Andaman Islands

This was another original result that we could infer from our analysis. The salinity core, after going around the Sri Lankan dome, bifurcates into 2 major pathways. One of the pathways, as reported above, is towards the Vizag coast. The second pathway is towards the Andaman islands, as shown in Figure 7.1. This result has also been shared with the oceanographer collaborators, which needs to be verified through actual measurements.

Chapter 8

Conclusions & Future Work

8.1 Conclusions

The problem of tracking the propagation of the high-salinity core from the Arabian Sea into the Bay of Bengal was studied in 2 stages - coarse and fine, using appropriate geometric and topological methods.

- Stage-I (Coarse analysis) - Successfully reproduced the 'Salinity Pump' phenomenon as reported by Vinayachandran et al[15].
- Stage-II - (Fine analysis) - Successfully evolved and implemented a novel visual analysis pipeline.

. The visual analysis pipeline implemented in the Stage-II involved −

- Isovolume extraction corresponding to the 35PSU salinity layer.
- Skeletonization of the extracted isovolume.
- Tracking of the computed skeletons throughout the entire timesteps in the data.
- Allowing the oceanographer to select a set of points of interset which are then traced through the matches to derive a set of representative seed tracks.

The subsequent visual analysis yielded 3 important results pertaining to the study of salinity propagation by the oceanographers.

- Verification of the Sri Lankan Dome(SLD) phenomenon.

- Propagation of the salinity core towards the Vizag coast and subsequently into the Bay of Bengal.
- Propagation of the salinity core towards the Andaman islands

All the 3 results have been shared with our oceanographer collaborators. The results pertaining to the bifurcation of the salinity core towards Vizag coast and Andaman islands, are of great interest to our oceanographer collaborators. This needs to be verified through epxerimental evaluation of measured or modeled data.

8.2 Future Work

In future, advanced topological *Persistence* concepts like *Age Persistence* and *Branch Inconsistency* could be incorporated to further refine and automate the seed track selection process. Also, the variability of salinity with temperature could be an interesting problem to study using the *Ensemble Visualization* methods.

Bibliography

[1] Shehzad Afzal, Sohaib Ghani, Garth Tissington, Sabique Langodan, Hari Prasad Dasari, Dionysios Raitsos, John Gittings, Tahira Jamil, Madhusudhanan Srinivasan, and Ibrahim Hoteit. RedSeaAtlas: A Visual Analytics Tool for Spatio-temporal Multivariate Data of the Red Sea. In Roxana Bujack, Kathrin Feige, Karsten Rink, and Dirk Zeckzer, editors, *Workshop on Visualisation in Environmental Sciences (EnvirVis)*. The Eurographics Association, 2019. ISBN 978-3-03868-086-4. doi: 10.2312/envirvis.20191101. v, 5, 8

[2] Sara Berglund, Kristofer Ds, and Jonas Nycander. Lagrangian tracing of the watermass transformations in the atlantic ocean. *Tellus A: Dynamic Meteorology and Oceanography*, 69(1):1306311, 2017. v, 7, 8

[3] A. Dasgupta, R. Kosara, and L. Gosink. Vimtex: A visualization interface for multivariate, time-varying, geological data exploration. *Comput. Graph. Forum*, 34(3):341350, June 2015. ISSN 0167-7055. 5

[4] Paul J. Durack and Susan E. Wijffels. Fifty-Year Trends in Global Ocean Salinities and Their Relationship to Broad-Scale Warming. *Journal of Climate*, 23(16):4342–4362, 08 2010. ISSN 0894-8755. doi: 10.1175/2010JCLI3377.1. 17

[5] K. Grochow, M. Stoermer, J. Fogarty, C. Lee, B. Howe, and E. Lazowska. Cove: A visual environment for multidisciplinary ocean science collaboration. In *2010 IEEE Sixth International Conference on e-Science*, pages 269–276, 2010. v, 3, 4

[6] Talley L.D., Pickard G.L., Emery W.J., and Swift J.H. *Descriptive Physical Oceanography: An Introduction (Sixth Edition)*. Elsevier, 2011. 7

[7] J. Li, K. Zhang, and Z. Meng. Vismate: Interactive visual analysis of station-based observation data on climate changes. In *2014 IEEE Conference on Visual Analytics Science and Technology (VAST)*, pages 133–142, 2014. 5

[8] Wilmot Li, Lincoln Ritter, Maneesh Agrawala, Brian Curless, and David Salesin. Interactive cutaway illustrations of complex 3d models. *ACM Trans. Graph.*, 26(3):31es, July 2007. ISSN 0730-0301. 3

[9] Dan R. Lipsa, Robert S. Laramee, Simon J. Cox, Jonathan C. Roberts, Rick Walker, Michelle A. Borkin, and Hanspeter Pfister. Visualization for the physical sciences. *Computer Graphics Forum*, 31:2317–2347, 12/2012 2012. 1

[10] Carolina Nobre and Alexander Lex. Oceanpaths: Visualizing multivariate oceanography data. In *Proceedings of the Eurographics Conference on Visualization (EuroVis 15) - Short Papers*. The Eurographics Association, 2015. doi: 10.2312/eurovisshort.20151124. 5

[11] Bastian Alexander Rieck, Filip Sadlo, and Heike Leitte. Persistence concepts for 2d skeleton evolution analysis. *arXiv: Algebraic Topology*, 2019. 11, 20, 25

[12] Alejandra Sanchez-Franks, BGM Webber, BA King, PN Vinayachandran, AJ Matthews, Peter MF Sheehan, A Behara, and CP Neema. The railroad switch effect of seasonally reversing currents on the bay of bengal high-salinity core. *Geophysical Research Letters*, 46(11):6005–6014, 2019. 2

[13] Mie Sato, Ingmar Bitter, Michael A. Bender, Arie E. Kaufman, and Masayuki Nakajima. Teasar: tree-structure extraction algorithm for accurate and robust skeletons. *Proceedings the Eighth Pacific Conference on Computer Graphics and Applications*, pages 281–449, 2000. v, 11, 18, 25

[14] A. A. Valsangkar, J. M. Monteiro, V. Narayanan, I. Hotz, and V. Natarajan. An exploratory framework for cyclone identification and tracking. *IEEE Transactions on Visualization and Computer Graphics*, 25(3):1460–1473, 2019. 8

[15] P. N. Vinayachandran, D. Shankar, Siddharth Vernekar, K. K. Sandeep, P. Amol, C. P. Neema, and Abhisek Chatterjee. A summer monsoon pump to keep the bay of bengal salty. *Geophysical Research Letters*, 40(9):1777–1782. 1, 14, 17, 30

[16] P. N. Vinayachandran, Adrian J. Matthews, K. Vijay Kumar, Alejandra Sanchez-Franks, V. Thushara, Jenson George, V. Vijith, Benjamin G. M. Webber, Bastien Y. Queste, Rajdeep Roy, Amit Sarkar, Dariusz B. Baranowski, G. S. Bhat, Nicholas P. Klingaman, Simon C. Peatman, C. Parida, Karen J. Heywood, Robert Hall, Brian King, Elizabeth C. Kent, Anoop A. Nayak, C. P. Neema, P. Amol, A. Lotliker, A. Kankonkar, D. G. Gracias,

S. Vernekar, A. C. DSouza, G. Valluvan, Shrikant M. Pargaonkar, K. Dinesh, Jack Giddings, and Manoj Joshi. BoBBLE: OceanAtmosphere Interaction and Its Impact on the South Asian Monsoon. *Bulletin of the American Meteorological Society*, 99(8):1569–1587, 09 2018. ISSN 0003-0007. vi, 28

[17] Ivan Viola, Armin Kanitsar, and Meister Eduard Groller. Importance-driven volume rendering. In *Proceedings of the Conference on Visualization 04*, VIS 04, page 139146. IEEE Computer Society, 2004. ISBN 0780387880. 3

[18] J. Wang, S. Hazarika, C. Li, and H. Shen. Visualization and visual analysis of ensemble data: A survey. *IEEE Transactions on Visualization and Computer Graphics*, 25(9):2853–2872, 2019. v, 6, 7

[19] Benjamin G. M. Webber, Adrian J. Matthews, P. N. Vinayachandran, C. P. Neema, Alejandra Sanchez-Franks, V. Vijith, P. Amol, and Dariusz B. Baranowski. The Dynamics of the Southwest Monsoon Current in 2016 from High-Resolution In Situ Observations and Models. *Journal of Physical Oceanography*, 48(10):2259–2282, 09 2018. ISSN 0022-3670. vi, 28