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RedSeaAtlas: A Visual Analytics Tool for Spatio-temporal Multivariate Data of the Red Sea

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Abstract

Interactive visualizations play an essential role in supporting the analysis tasks of ocean and atmospheric scientists working on a variety of simulation models and observational datasets. Designing visual analytics systems intended for addressing problems in the ocean and atmospheric domain require careful task analysis of the requirements of domain experts and scientists, and understanding their analysis workflows. This paper explores the design of a visual analytics tool (RedSeaAtlas) based on meetings and interviews with domain experts working on diverse research problems that involve analyzing spatio-temporal multivariate datasets of the Red Sea region, to understand their task requirements. This kind of visual analytics tool has widespread applications in areas, such as navigational guidance of marine vessels, fisheries operations, environmental impact assessments, coastal development, renewable energy, risk management, policy making, etc. We provide expert evaluation of this tool based on different case studies targeting some of these application areas. We also discuss the challenges associated with the use of varying visualization tools in the ocean and atmospheric community, focusing on aspects related to visualization research.

CCS Concepts

• ***Human Centered Computing*** → *Visualization; Visual Analytics;* • ***Physical Sciences and Engineering*** → *Earth and atmospheric sciences;* • ***Information systems applications*** → *Spatial-temporal systems;*

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1. Introduction

Scientists working with ocean and atmospheric datasets deal with diverse data analysis tasks related to a variety of application areas such as identification of fishing zones, coastal developments, environmental planning, optimization of renewable energy generation, navigational guidance for marine vessels, tourism planning, risk management, and policy-making. They analyze data from heterogeneous sources, either generated by numerical simulation models or observational sensors. In their analysis tasks, they often have to combine data from disparate sources for simultaneous analysis, and have to overcome the differences in scale, granularity level, modality, spatial and temporal resolution, etc. They regularly have to experiment with varying simulation parameters, model resolutions, analyze ensembles, and uncertain data, etc. These diverse data and task requirements pose great visualization challenges that need to be addressed if weather and climate scientists are to adopt and use visualization tools. To this end, visualization researchers have to design custom tools [TDN11], bearing in mind these issues and tasks specific requirements.

The goal of this work is to design a custom visual analytics tool (*RedSeaAtlas*) intended for use by ocean and atmospheric scientists working on different analysis tasks, dealing with multivariate ocean and atmospheric datasets. To accomplish this goal, we collaborated with domain experts who routinely work with computer simulation models or observational datasets encompassing different phenomenon of the Red Sea. We conducted several meetings and interviews with domain experts to identify their task and system requirements that can not only advance the research in the area of ocean and atmospheric sciences but also provide operational support and facilitate decision making in relevant application areas.

The Red Sea is relatively less explored as compared to other seas and oceans of the world. Indeed, it is only recently that researchers have begun to gather, simulate and analyze data from the Red Sea in greater detail. Although this visual analytics tool was designed keeping in view the requirements of the scientists working on the Red Sea datasets, but the underlying framework itself is applicable to other ocean datasets as well.

In this paper, we present task and system requirements identified based on close collaboration with domain experts. We discuss details about the architectural and design decisions to satisfy the requirements laid out by the domain experts, and the rationale for these decisions. *RedSeaAtlas* provides interactive visualizations

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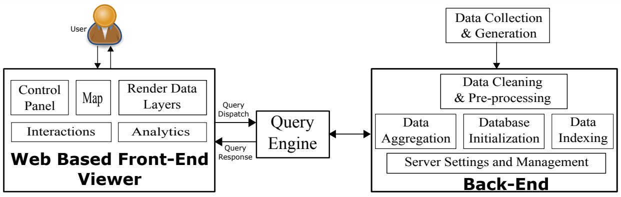


Figure 1: *The system architecture of 'RedSeaAtlas' visual analytics tool. The system is divided into two major components. Web-based front-end (left) contains all the interactive visualizations and can interactively load and visualize data in any standard web-browser. Back-end (right) is responsible for all data management tasks (cleaning & pre-processing, aggregation, etc.) and serves data to front-end by resolving interactive query requests.*

to study different oceanographical and meteorological elements through analyzing datasets such as winds, waves, Chlorophyll-a (Chl-a), sea surface temperature (SST), and wind energy. We conducted a qualitative evaluation of this system with domain experts based on multiple use case studies. These case studies highlight support for certain operational and research tasks provided by the system. Through these case studies, we discuss current capabilities of the *RedSeaAtlas* system and how adequately it addresses the task requirements of the ocean and atmospheric scientists. We also discuss current outstanding challenges and planned future extensions.

2. Related Work

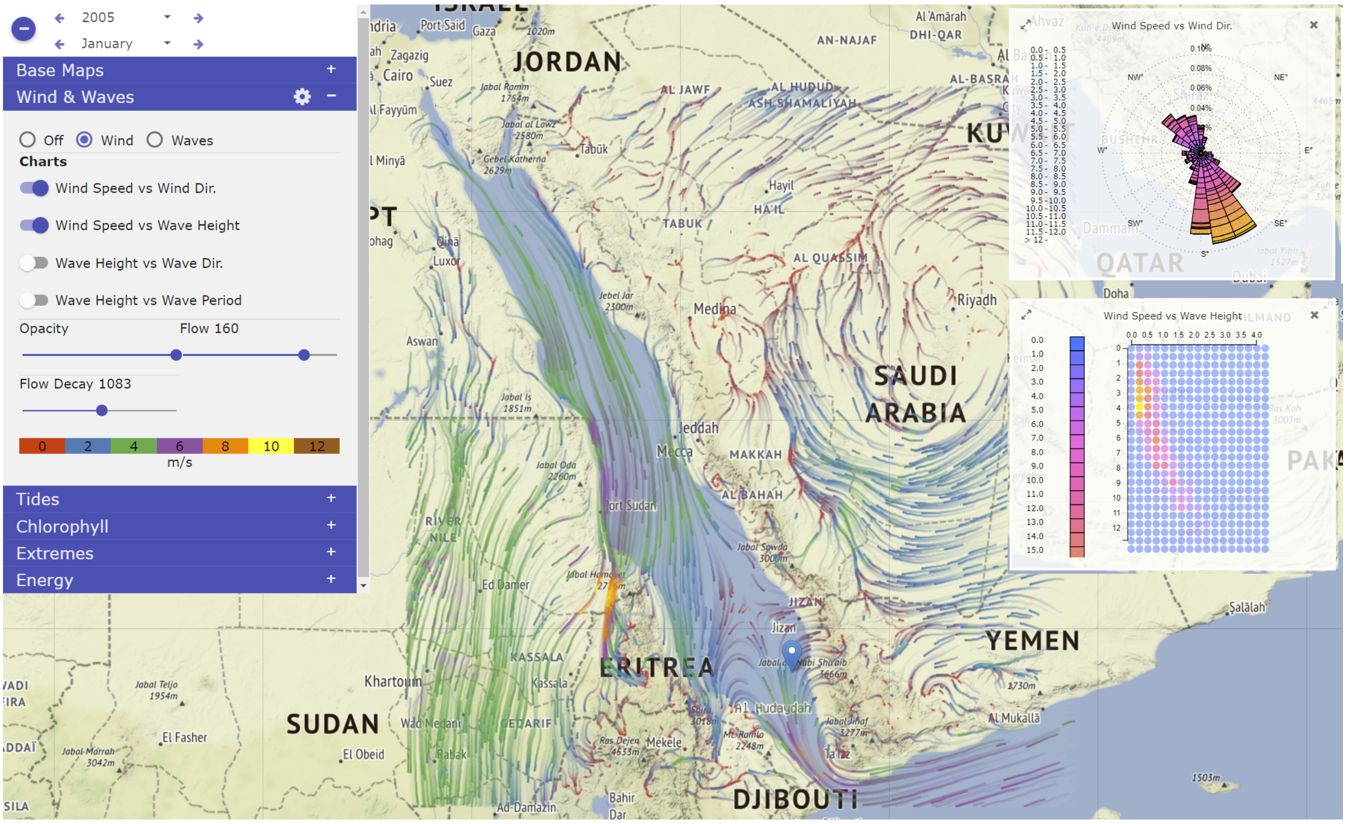
Considering task and design requirements of domain experts for a visual analytics tool, we discuss visualization research related to multivariate and high dimensional data, heterogeneous data integration and comparative analysis, multiple coordinated linked visualizations and web-based visualization environments for ocean and environmental datasets. Multivariate data visualization in the field of oceanography and meteorology has been explored by many researchers in the past. OceanPaths [NL15] supports interactive visual analysis of multivariate oceanography datasets by defining pathways along the currents and enabling spatio-temporal analysis of variations in water properties. Vimtex [DKG15] is a visual analytics system of coordinated linked views to study multivariate geology datasets to understand temporal patterns and behavior of different chemical species. Guo et al. [GXY12] provide interactive visualizations for multivariate volume data supporting interactive transfer function design supported by a coupled unified view based on parallel coordinate plots and multidimensional scaling based projection. Sukharev et al. [SWMW09] present a study focused on the correlative analysis of multivariate climate datasets by exploring temporal curves of the data variables and utilizing clustering and segmentation techniques.

Jänicke et al. [JBS08] transform high dimensional data into attribute space (2D) using multivariate density estimation and manifold learning techniques, and support operations like brushing points in attribute space and then highlight corresponding features in linked physical space. Lee and Shen [LS09] propose an algorithm focused on identifying temporal relationships in multivariate time-varying datasets. The extracted trend sequences are sequenced and then modeled using state machines and can be explored in space and time to identify correlations between different variables. Jin and Guo [JG09] present multivariate geovisualizations to analyze climate change patterns and anomalies from multivariate climate datasets across space and time, supporting different perspectives and resolutions, and utilizing clustering and aggregation approaches.

Visualizing multiple oceanographic data attributes is a challenging problem and such visualizations can be useful in analyzing the relationship between multiple data attributes [QCX*07]. Rocha et al. [RSAS17] present an integrated data visualization environment using layers of decals and colormaps encoding density, salinity, and ocean currents layered on top of temperature isosurfaces extracted from oceanographic models. Widanagamaachchi et al. [WJ*17] present an interactive visualization tool to study the evolution of pressure-perturbation events using tracking graphs. These graphs are built dynamically, and support extraction, filtering, and simplification operations. The system supports loading additional heterogeneous datasets for primary analysis. Elshehaly et al. [EGG*15] present an interactive GPU-based technique that can fuse the ground truth data with simulation model output to rebuild the missing data in real time.

Collaborative Ocean Visualization Environment (COVE) [Gro11] is designed based on guidelines established through a conceptual design study, and collaboration with ocean scientists. Using COVE, analysts can interactively analyze ocean models data and other diverse datasets through a web-based repository of data and visualizations. This is a generic ocean data analysis tool designed for catering to particular requirements. This, however, does not serve the needs of our domain experts, who want a custom tool with specific task and design requirements. Kehrer et al. [KLM*08] utilize interactive linked visualizations to generate hypothesis for climate change studies using multivariate time-varying climate datasets. This hypothesis generation is based on brushing data in linked views, and extract trends and patterns to identify regions that can act as climate change indicators. The SimilarityExplorer [PDW*14] visual analytics tool contains multiple coordinated linked views to analyze similarity in climate models across space, time, and output variables based on a classification scheme for domain-specific intents and data facets. Ladstädter et al. [LSL*10] evaluate the effectiveness of using undirected interactive visual exploration to analyze atmospheric and climate multivariate datasets, and found it to be complementary to statistical analysis especially for large scale geophysical multivariate datasets.

Glyph based visualizations are often used in visualizations of different ocean and atmospheric data attributes [WP13]. Insights based on human perception are useful in designing more effective visualizations. Ware et al. [WKP14] analyze human pattern perception principles for designing visualizations for simultaneously visualize winds, ocean currents, and waves. Vismate [LZM14] is a visual analytics tool for analyzing station-based observation data using three linked visualizations: *Global Radial Maps* to study spatio-temporal patterns through a customized radial layout with a



2005
January

○ Off ● Wind ○ Waves

Charts
Wind Speed vs Wind Dir. (on)
Wind Speed vs Wave Height (on)
Wave Height vs Wave Dir. (off)
Wave Height vs Wave Period (off)

Opacity
Flow 160
Flow Decay 1083

Figure 2: *The 'RedSeaAtlas' system showing the wind dataset and associated attributes. Glyphs on the map show overall wind patterns in the Red Sea region, color-coded to demonstrate the strength of winds. Users can select any region on the map to see detailed information of the interactive visual charts. The map shows a selected region by the user with blue marker and charts on the right visualize wind speed vs wind direction (top-right), and wind speed vs wave height (bottom-right) for that region. Users can make selections on the control panel on the left to select the combination of variables to visualize.*

map embedded in the center; *Time Series Discs* to study temporal trends using triangular heatmaps; and *Scatterplots* to study abnormalities or unusual cases. Bjuack and Middle [BM16] argue that the environment flow visualization is similar to flow visualization. However, there are differences, such as environment flow visualization prevalently uses basic techniques such as arrow glyphs, streamlines, and color coding, mainly due to issues like data scale and ease of integration with existing tools.

3. Motivation and Problem Definition

Scientists working on problems related to ocean and atmospheric sciences often generate simulation data using different models with varying configurations and initial conditions, and they may also utilize observational datasets in their analytical tasks. These models aim to simulate different phenomenon related to ocean or atmospheric circulations, and may have different resolutions, scale, computational and memory requirements, data certainty, accuracy, perturbations, depending on the requirement of analysis tasks and the target application area. Analyzing the output of these models, making comparisons across multiple simulation runs, overlaying different model outputs, encoding uncertainty, loading ancillary observational datasets, etc., are challenging time-consuming tasks, especially in the absence of any supporting interactive analysis environment. There are other desirable features like showing the context of these models (e.g., a background geographical map in models with spatial data), understanding time-varying data attributes (e.g., directional vectors), adjusting spatial and temporal resolutions, filtering and querying, details-on-demand, configurable visual encoding, ease of collaborative analysis, scalability and data management, ease of integration, etc. These issues are essential for understanding and addressing the visualization needs of researchers working in fields like oceanography and meteorology. Tominski et al. [TDN11] conducted a study with 76 participants working on problems in climate sciences and concluded that state-of-the-art visualization methods are rarely used in their work, and integration of existing visualization tools is not easy due to issues related to data integration. Considering these challenges, it is important for visualization researchers to collaborate with scientists and domain experts working in the areas of oceanography, meteorology, and climatology in interdisciplinary research efforts to understand their task and system requirements and identify different issues and deterrents in the use of visual analytics tools in their workflows.

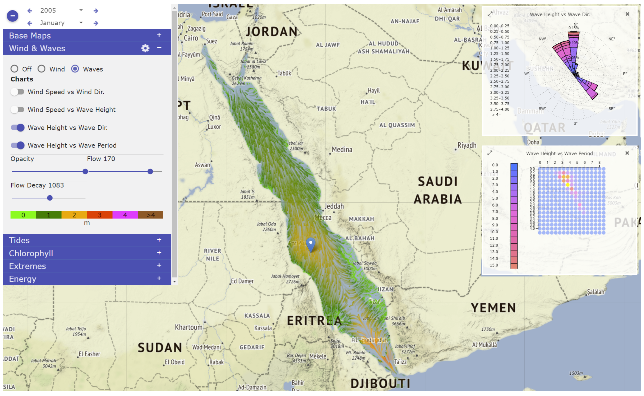


Figure 3: *Wave dataset along with different attributes are shown on the map view. Wave direction and height are encoded with color-coded glyphs shown on the map. The user has selected a particular region (shown by the place marker) on the map. Wave height vs wave direction (top-right) is shown through a polar chart, and wave height vs wave period is shown through a 2D histogram (bottom-right).*

In one such collaborative effort, a group of scientists and domain experts from both academia and industry working on ocean and atmospheric datasets related to the Red Sea approached us with their spatio-temporal multivariate data. They wanted to analyze and visualize their data interactively. After an extensive review of existing tools and literature, we decided to design a custom visual analytics tool that could satisfy their task and system requirements. Their datasets were generated either from simulation models related to wind, waves, tides, etc., or they were observational datasets such as SST and Chl-a.

These domain experts include people from academic research labs and industrial operational support, solving research problems related to coastal developments, marine ecology, identification of fishing zones, environmental impact assessments, tourism planning, navigational guidance for marine vessels, climate change, placement and optimization of renewable energy infrastructure, etc. We conducted several meetings, interviews, and observation sessions with these experts spanned over several months to understand their current research workflows, environment and work practices, tools and libraries usage, dataset handling (generation, management, conversion and loading process), data analysis tasks, computational and processing requirements, and visualization design requirements. Based on this collaborative effort, we identified the following design requirements of the domain experts for a custom visual analytics environment focused on their data analysis tasks:

D1 Interactive visual exploration, and analysis of ocean and atmospheric datasets. Feature selection, overview, and details on demand. Explore data across space, time, and other variables.
D2 Data pre-processing, cleaning, transformation, aggregation to support different spatial and temporal resolutions, and scale management.
D3 Heterogeneous data overlay. Visualize multiple layers of data (simulation or observational). Interactive data layer selection.

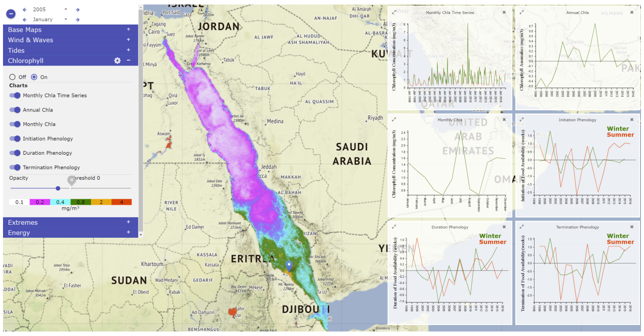


Figure 4: *The map view shows the overall Chlorophyll-a (Chl-a) concentration in the entire Red Sea. Chl-a concentration time series charts for different temporal resolutions along with Phenology summary charts (initiation, duration, and termination for summer and winter seasons) are shown for a specific location selected on the map.*

D4 Identify trends, patterns, and extreme events (anomalies) in the dataset.
D5 Interactive visualizations and controls to analyze and compare attributes of wind (speed, direction) and waves (height, direction, and period).
D6 Visual analysis of Chl-a at different temporal resolutions, and Phenology (initiation, duration, and termination) datasets.
D7 Visual exploration of SST and associated extreme events.
D8 Assessment of renewable energy potentials.

4. RedSeaAtlas: A Visual Analytics Tool

Bearing in mind the design requirements as detailed in Section 3, we have designed a web-based visual analytics tool (*RedSeaAtlas*) for spatio-temporal analysis of Red Sea datasets. Figure 1 shows the architectural diagram of this tool. As shown in this figure, we have sub-divided this system into two major components: the *web-based front end viewer* and the *back-end* (residing on a web-server). The datasets provided by the domain experts were either simulation model outputs or observational datasets. The datasets had different spatial and temporal resolutions, data representations, file and storage formats, scalar or vector-based representations, multi-dimensional, multivariate, and some of the data was sparse. The original raw datasets were very large in size (mostly Petabyte or Terabyte in scale). During our interviews and meetings with domain experts, we observed that data management issues are one of the biggest factors in utilizing interactive visualization tools in their workflows. To resolve these differences in datasets (representation, resolution, scale, format, etc.), we designed this server-based data management component that brings the data in a consistent uniform format suitable for on-demand querying by front-end visualizations (**D2**), and also decouples the visualization layer from the analytics and data management layer. This decoupling enables us to make changes to the back-end without affecting the front-end as long as the query interface stays the same and vice versa. This allows us to input heterogeneous datasets (**D3**) (after pre-processing and cleaning) into the same back-end and facilitates ease of extension in the

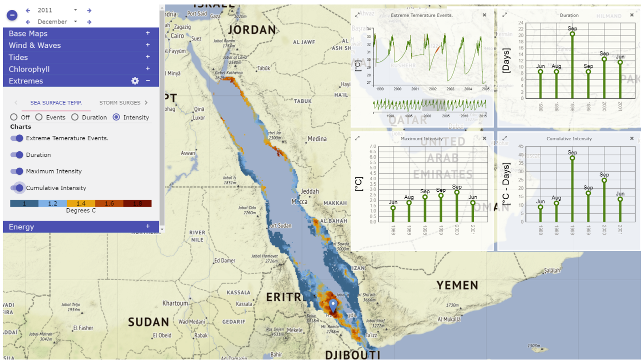


Figure 5: *Map view showing extreme temperature events based on sea surface temperature (SST) dataset. Charts on the right show total number of events, duration, maximum intensity, and cumulative intensity of these events for the selected region on the map (shown by blue marker).*

future. This also helps to represent both simulation and observational datasets. Another advantage of this multi-layer architecture is that we can manage the scale of the data by performing aggregation operations on the server side, and can also run any computationally expensive operations on the server side. We can also pre-render certain visualizations on the server side. These aggregation options are decided based on the domain experts feedback. Currently, we are aggregate by month, and the resultant data is stored on a server side database with various indexings.

The web-based front-end is interfaced with the back-end through a query engine interface. This query engine brings in aggregated data from the back-end based on interactions and user selections on front-end. Figure 2 shows the main screen of the *RedSeaAtlas* front-end. As shown in the figure, this front-end consists of a central map view for visualizing geospatial datasets, a control panel that enables users to scroll through time, select data layers and supporting analytics charts to show on top of the map view (**D1**). We use a layer-based architecture on the front-end and data layers corresponding to the user-selected data attributes are shown on top of the map view. We will now discuss in detail different visualizations supported on the front-end relevant to different types of data.

4.1. Wind

Figure 2 shows the *RedSeaAtlas* system loaded with the wind dataset. Overall, a vector field for wind direction is encoded through animated polylines color-coded to show the wind speed, and animation indicates the wind direction. Users can select any point or region on the map, and corresponding comparison charts are displayed on top of the map view for the chosen place. Wind speed vs wind direction is shown using a polar chart on top of a direction compass where each petal (or arc) provides the summary of overall wind speed in a particular direction at the user selected location on the map. Users can analyze wind speed and directions patterns using this type of chart (**D4**, **D5**). We also provide another bivariate statistical chart (a type of 2D histogram visualization) between wind speed and wave height at the user-selected point as shown in Figure 2. Y-axis represents wind speed whereas x-axis represents wave height. This chart is color-coded so users can quickly glance over this chart and identify regions of interest. These design choices were finalized taking into consideration the domain experts discussions and observing the diagrams or visualizations they routinely use to present their results.

4.2. Waves

Figure 3 shows the *RedSeaAtlas* map view visualizing the waves dataset. We use animations based on color-coded polylines capturing the wave heights and directions. As shown in the figure, the lower portion of the Red Sea has the largest waves for the selected time period. Bivariate statistical charts similar to the ones utilized in wind analyses are used to provide wave height vs wave direction, and wave height vs wave period comparisons (**D5**).

4.3. Chlorophyll-a and Phenology

Chl-a concentration (an index of phytoplankton biomass) is an important ecological indicator to determine the spatio-temporal variation of food availability for coral reefs [RBZ*17] and fisheries stocks [KRM*18], and could also be used to identify potential fishing zones. The analysis of the variability in Chl-a concentrations is also useful for studying the phenology (phytoplankton bloom timing metrics) and associated impacts of climate change on biology. Figure 4 shows the visualizations used to analyze Chl-a concentrations and the associated phenology metrics (bloom initiation, duration, and termination). To provide an overview of Chl-a concentrations in the Red Sea, a grid-like structure is induced in the entire spatial area of the Red Sea. Each grid cell is then coded based on the underlying Chl-a concentrations mapped to that cell. This type of visualization provides insights on the spatio-temporal distribution of phytoplankton biomass. Fisheries zones can also be linked to these concentrations (i.e., a more productive region can support more the local biodiversity). The analysis of the temporal variability and trends of Chl-a concentrations provides further insights into the changes of food availability, and those could be linked with environmental or climate change [RYP*15]. Selecting an area on the map provides more detailed charts about Chl-a concentrations and phenology metrics (**D6**). These Chl-a attributes and charts are selected and designed in close collaboration with domain scientists.

4.4. Sea Surface Temperature Extreme Events

Extreme temperature events defined by [HAP*16] are anomalously warm SST events that persist for a prolonged period. Extreme events can have notable impacts on marine ecosystems. According to domain experts, their occurrence and localization can be an indicator of probable locations of coral bleaching [HAC*18, OSZ*18]. Figure 5 shows the visualization of SST based extreme events detection and localization. These events are shown on the map as grid cells, and the number of events from 1985 to 2015 is used to color code these grid cells. Selecting an area on the map displays detailed charts providing a historical profile of extreme events annotated on top of the SST time series using red filled areas. The duration, intensity, and cumulative intensity of these events are also shown in the form of lollipop charts. The charts are designed in consultation

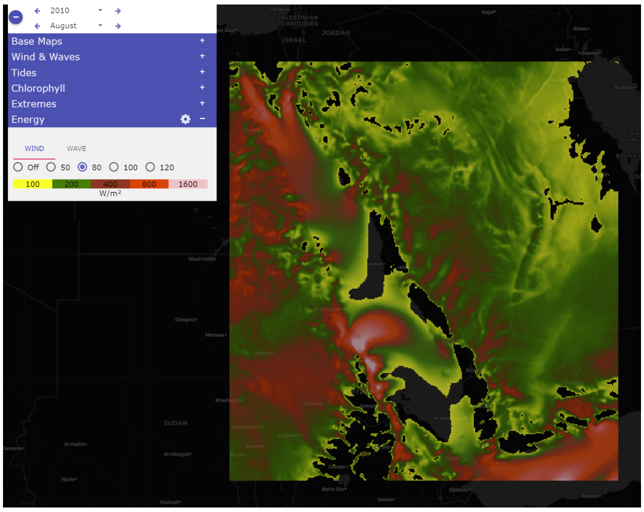


Figure 6: *Map view showing the overall wind energy distribution for the Red Sea, color-coded based on a legend.*

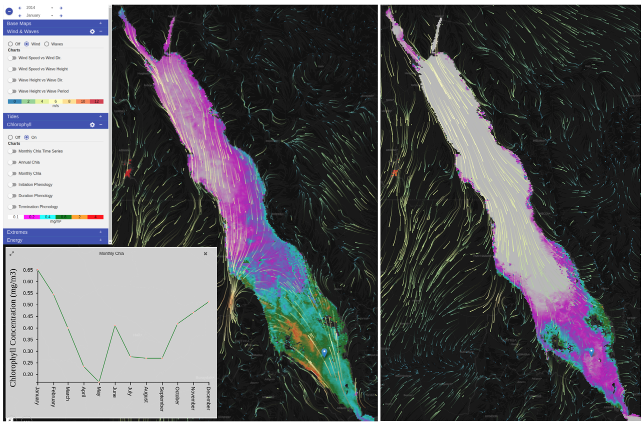


Figure 7: *Map view showing Chl-a concentrations for a location near the southern part of the Red Sea. (Left) Chl-a concentration in Jan 2014, and (Right) May 2014. Time series showing monthly concentration for the year 2014 for the selected location.*

with domain experts and are interactive such that users can zoom in or out in the long time-series. Also, the extremes are marked in red color in the time series chart (**D7**).

4.5. Wind Energy

Figure 6 shows visualization that encodes wind energy information using a color-coded spatial map. Assessment of wind energy potential is essential for locating suitable areas of energy harvesting and planning (**D8**). Analyzing the spatial variability of wind energy across time can provide useful information for decision makers.

5. Datasets

We use the output from multiple simulation models and observational datasets to input into the *RedSeaAtlas* tool. We use surface winds from the Weather and Research Forecasting (WRF) model configured at 5 km resolution for a time span of 38 years (1980-2017) at a one-hour interval [LVD*16]. Wind energy is also computed from the WRF model for different heights. To extract wave data, we use the Wavewatch III model configured at 5 km resolution for a time span of 38 years at a one-hour interval. We access the satellite data for SST from Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) [DMS*12], available at 1/20°resolution for 31 years at daily intervals. For Chl-a, we use satellite data for 20 years (1997 - 2016) at 4 km resolution.

6. Interactions

The *RedSeaAtlas* supports multiple types of interaction to enable data analysis tasks. A temporal slider allows users to scroll through time by selecting any combination of month and year, either through increments/decrements or direct selection. The user can choose any data layers to load, and these layers can be overlaid on top of each other facilitating simultaneous comparison of multiple datasets. Users can also interactively select different choices of variables to make cross-comparisons. Besides standard map pan/zoom options, the user can also make interactive selections in map view to see more details about data elements loaded in the map. These details are shown through interactive charts and visualizations that support subsequent analysis. Users can interactively build multidimensional queries through these interaction choices.

7. Implementation

We have implemented the front-end map view using the Leaflet API. We also use web-based visualization libraries based on JavaScript and SVG such as D3, Angular JS, and Windy-JS to implement front-end visualizations. In the back-end, we use ASP.NET web services, SQL databases, and Python scripts.

8. Evaluation with Domain Experts

We conducted a qualitative evaluation of the *RedSeaAtlas* visual analytics tool with domain experts (not the co-authors of this paper) working on different problems related to ocean and atmospheric sciences. We report the results of this evaluation based on three different use cases related to different application scenarios.

In the first use case, the domain expert was interested in tracking the Chl-a concentrations in the Red Sea, which is important for the marine ecosystem, including fish. These concentrations along with nutrient levels, temperature, and sunlight are important factors for phytoplankton growth. Analyzing spatio-temporal variation of these Chl-a concentrations can be useful in identifying potential fishing zones, and food availability for coral reefs. The southern part of the Red Sea has an inlet, and the water exchange with the Indian Ocean takes place through this inlet. This exchange also impacts the nutrient levels in the Red Sea, which is important along with Chl-a concentrations for marine ecosystem. Domain expert selected a location near the southern part of the Red Sea to analyze any patterns in the Chl-a concentrations as shown in Figure 7 in the year 2014. Using the Chl-a concentration chart and map view to visualize data from different years, analysts identified a pattern in the distribution of Chl-a concentrations. This is shown in Figure 7. The concentrations reach a maximum around January of each year and drop to a minimum around May for the selected location. The left map in this figure shows the spatial distribution of Chl-a concentrations in January 2014, and the right map shows the distribution for May 2014. The expert was also interested in the correlations of wind patterns with this nutrition transport. The expert also overlaid the wind data layer to study these patterns. As evident in the figure, there is a correlation between the overall wind direction and Chl-a concentrations that can be observed near the inlet as well. The left image shows that in January (2014) there was a high concentration of Chl-a near the inlet, which decreased in May (2014).

In the second use case, a domain expert was interested in analyzing the extreme events in the Red Sea. These events are derived from the SST as explained in section 4.4. This expert mentioned that these events are indicative of marine heat waves, and if these heat waves sustain for extended periods, they can cause coral bleaching. The expert analyzed these extreme events using the SST datasets loaded in *RedSeaAtlas*. Figure 8 shows a summary of the results of the expert analysis. The expert analyzed the overall spatio-temporal pattern of these extreme events and further analyzed three specific regions. These regions are shown in figure 8 using three different colored dash lines. These three regions are close to Yanbu, Thuwal, and Al-Lith (Saudi Arabia) located near one end of the blue, black, and white dashed lines respectively. The extremes are annotated as red areas on the SST time series plot. Associated lollipop plots provide an overall summary of the number of extreme events in different years and months for the selected location. The extreme events identified in these regions in year 2015 correlate with the reported coral bleaching events [HAC*18, OSZ*18].

In the third use case, a domain expert was interested in analyzing wind energy dataset to understand the spatio-temporal variability related to wind energy. These patterns are essential to optimize the locations for wind-based renewable energy infrastructure. These insights also help experts estimate the extractable energy from wind at different places and then optimize the grid systems for energy generation. This type of analysis is further applicable in other areas besides energy harvesting. For example, these spatio-temporal wind patterns are useful to define building codes for wind hazards for different structures and finding suitable locations for new infrastructure development. The domain expert analyzed the wind energy patterns for different months of the year 2013. Figure 9 shows the side by side comparisons of wind energy spatial distributions at 100m height for January, June, September, and November (2013). After analyzing this data, the domain expert pointed out that the area shown in the white rectangle has higher wind energy values throughout the year, whereas the area shown in the orange rectangle shows higher wind energy values throughout the year except in the beginning of the fourth quarter.

These are some of the interesting use cases that domain experts extracted from the tool. Overall, our collaborators and the domain scientists who evaluated the tool were excited about the tool. Indeed, they mentioned that "we normally use command line tools to analyze these datasets. With this tool, we can interactively explore large datasets with interactive graphics and charts". They are now using this tool in their routine analysis of Red Sea data.

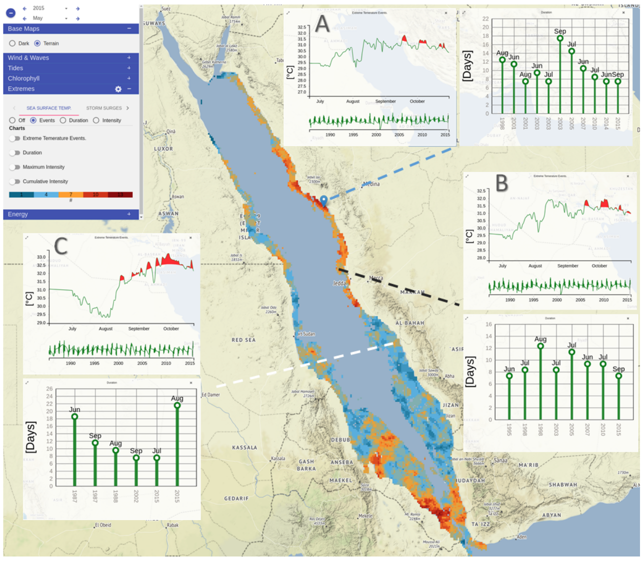


Figure 8: *Map view showing the distribution of extreme events over the Red Sea spanning from 1985-2015. Detailed charts for three different locations: Yanbu, Thuwal, and Al Lith (Saudi Arabia) are also shown. A, B, and C are the event lines showing the daily SST. The red filled areas are associated with extreme events. Lollipop charts are showing the duration of the events.*

9. Conclusions and Future Work

In this paper, we present a web-based visual analytics system (*RedSeaAtlas*) that contains a suite of interactive visualizations, designed with consideration for the task requirements of ocean and atmospheric scientists and domain experts. We conducted meetings, interviews, and observational sessions to understand their analysis workflows. Our system supports analyzing multiple types of Red Sea datasets such as wind, wave, SST and Chl-a. We provide a qualitative evaluation of *RedSeaAtlas* by domain experts based on several use-cases to demonstrate the usefulness of this system in different application scenarios.

In future extensions of this work, we plan to add visual analytics support for additional datasets such as solar energy, tidal data, rainfall, storm surge events, ocean currents, etc. We would also like to add support for collaborative data analysis using a setup like display walls, considering that they can provide more display space for simultaneous analysis and visualization of multiple types of data.

10. Acknowledgements

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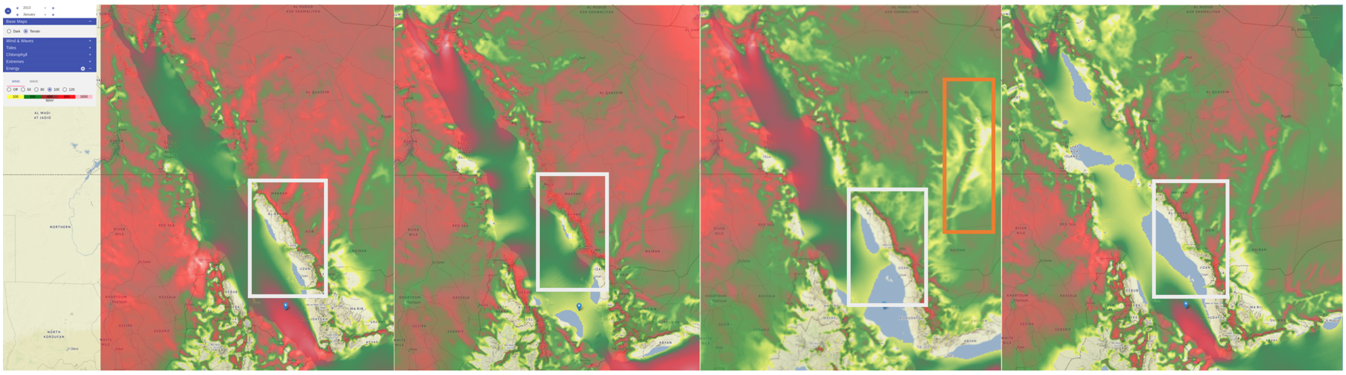

Figure 9: *Wind energy data for the Red Sea is shown for January, June, September, and November (2013) at the height of 100m.*

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