





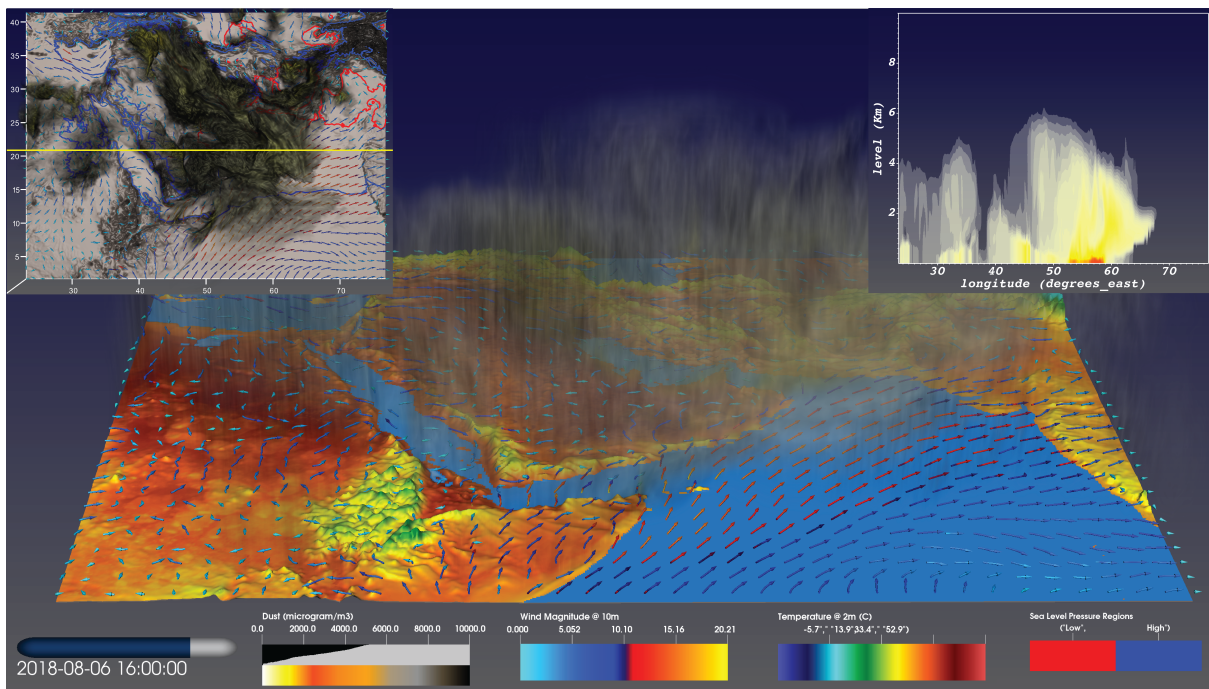


# Evolution of Extreme Dust Events in 3D Environment

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**Figure 1:** 3D visualization environment for visualizing the evolution of extreme dust events, showing a dust storm from August of 2018.

## Abstract

Dust is one of the main components of atmospheric particles in desert regions. The concentration, composition, and spatial distribution of these dust particles in the atmosphere vary over time and could significantly impact the weather, climatological conditions, radiative forcing and transfer, and ecosystem dynamics. Scientists and decision-makers are interested in analyzing the evolution of dust events (including their formation, dynamics, and interactions with the environment), understanding the main contributing factors and atmospheric conditions that intensify these events and lead to extreme dust events, examining the role of topographic features, and gaining insights into their relationship with global teleconnections. Scientists use high-resolution simulation models (such as WRF-Chem) to simulate the prevalent atmospheric conditions centered around extreme events and examine the model outputs to understand such events better. These simulation datasets are extremely large in scale, depending on the spatial domain, spatiotemporal resolutions, simulation duration, and number of atmospheric parameters. They need a specialized environment that facilitates analyzing such datasets. To this end, we provide a 3D visualization system that facilitates the analysis of dust simulation model outputs and provides information about dust loading, transport, evolution, deposition, and intensification into an extreme event. This system also aids in understanding the interactions between different atmospheric parameters, the impact of terrain surface characteristics, and more, providing a holistic view of the dust events. We present a case study demonstrating the system's capabilities in analyzing extreme dust events and also include feedback from the domain experts, along with a discussion on future extensions.

## CCS Concepts

• **Human-centered computing** → **Geographic visualization**;

## 1. Introduction

Dust storms are among the most significant atmospheric phenomena, influencing weather, climate, and environmental conditions. The Arabian Peninsula (AP) is a major global dust source, with frequent dust storms that impact air quality, visibility, and energy production. Understanding the evolution and dynamics of these extreme dust events requires analyzing large-scale simulation data that capture interactions between multiple atmospheric variables.

Domain scientists use high-resolution atmospheric models, such as WRF-Chem [GPS\*05], to simulate dust storm events. These models produce vast and complex datasets, often spanning multiple spatial and temporal dimensions. Effective visualization of these datasets is crucial for interpreting dust transport patterns, wind dynamics, and pressure systems influencing dust emissions and movement. However, traditional 2D visualization methods limit the ability to explore these interactions comprehensively. Dust storm evolution is influenced by atmospheric features and terrain, which are challenging to analyze in 2D due to occlusion, flat projections, and limited variable overlay.

To address these challenges, we propose a 3D visualization system specifically designed for exploring simulations of large-scale dust events. This system integrates multiple atmospheric variables, dust concentration, wind, temperature, and sea-level pressure, into a unified 3D environment and realistic terrain representation. By providing an interactive, multi-perspective view, the system enables domain scientists to analyze dust storm evolution, examine the spatial and temporal relationships between different variables, and identify key patterns in dust transport processes. This visualization system offers several key advantages:

- **Simultaneous Multi-Variable Visualization:** Displays dust concentration, wind, temperature, and sea-level pressure in a single 3D scene, allowing a holistic understanding of dust storm dynamics.
- **Flexible Perspective Views:** Enables users to rotate, zoom, and explore data from different angles, enhancing insights into vertical dust profiles and atmospheric interactions.
- **Realistic 3D Terrain Representation:** Incorporates topographic features, providing spatial context for analyzing dust movement and its interactions with surface characteristics.
- **Exploration of Large-Scale Events:** Facilitates the study of dust transport over extensive geographic regions, supporting analysis of large-scale atmospheric processes.

This work presents the design and implementation of this 3D visualization system, developed in collaboration with domain scientists. We demonstrate its capabilities through a case study of an extreme dust event in the AP region, highlighting how interactive 3D exploration aids in understanding the complex interactions driving dust events evolution.

## 2. Related Work

Interactive visualization and analytics tools have been widely explored for analyzing meteorological and atmospheric data [AHG\*19, RBS21]. Several toolkits [KWA\*11, RBW\*12] have been developed to facilitate climate analysis, employing both 2D

and 3D visualization techniques. While 2D visualizations remain predominant, 3D methods are increasingly utilized for forecasting and analyzing complex atmospheric interactions [RBS\*17].

### 2D Visualization Techniques:

2D visualization methods are extensively used in meteorology for visualizing observational and numerical datasets [RBS\*17]. Geospatial maps, often augmented with glyphs and pathlines, depict atmospheric flows such as wind patterns [SW15, WP13]. Additionally, time-series plots and comparative charts help analyze variations in meteorological variables [Sau55]. Afzal et al. [AGT\*19] developed an interactive tool integrating 2D charts and glyphs for atmospheric data exploration. Lundblad et al. [LLEJ11] designed a multi-view visualization system, which combines various 2D visualizations for analyzing weather forecasts. GeoTemCo, introduced by Jänicke and Scheuermann [JS14], provides web-based geospatial visualization for environmental datasets.

### 3D Visualization Techniques and Tools:

With the increasing complexity and volume of atmospheric datasets, 3D visualization techniques have been developed to enhance meteorological data analysis [RBS\*17]. Early tools, such as the NCAR Graphics package [PSJ88], facilitated weather data analysis. Wilhelmson et al. [WJS\*90] employed 3D animations to visualize severe storm dynamics, while Kern et al. [KHS\*18] introduced an interactive 3D approach for analyzing atmospheric fronts, demonstrated through a case study on cyclone Vladiana. Kress et al. [KAD\*23] implemented a 3D visualization environment to support in-depth analysis of extreme rainfall events. Weather 3D eXplorer (W3DX) [KdHD\*14, KN18] offers interactive 3D meteorological data analysis. Additionally, widely used tools such as Vapor [LJP\*19], IDV [MMWE03], Met.3D [RKS15], and ParaView [Aya15] provide advanced visualization capabilities.

To address the challenges posed by large-scale, multivariate atmospheric datasets, techniques such as volume rendering, streamlines, and isosurfaces are frequently employed [LGY15]. Guo et al. [GXY12] leveraged interactive transfer function design for multivariate volume visualization, while Kniss et al. [KHGR02] demonstrated the effectiveness of volume rendering in meteorological analysis. Song et al. [SYS\*06] integrated volume rendering with 2D techniques for weather simulations, and Zhang et al. [ZYCH19] introduced a scalable volume rendering approach for large-scale meteorological datasets.

**Dust Data Visualization:** While numerous atmospheric visualization methods exist, few cater specifically to the visual analysis of dust storm data. Previous research has extensively explored dust emission models [EFFD14, PSUK19, SWC\*11, KSL\*14] and their datasets [PSU\*23, JPSK\*15, UAGS21]. Understanding dust storm dynamics requires specialized visualization tools capable of handling large-scale, spatiotemporal, and multivariate datasets. Li et al. [LJYH13] developed a geo-visualization application for 3D spatiotemporal dust storm simulation with parallel computing capabilities. However, this tool is limited to visualizing only dust data and does not support the simultaneous visualization of dust with other atmospheric variables, restricting the ability to explore their interactions and dynamics.

To address these challenges, we propose a 3D visualization sys-

tem integrating dust, wind, temperature, and sea-level pressure into a unified interactive environment. This system enables domain scientists to analyze large-scale dust events by exploring multivariate data simultaneously, leveraging volume rendering and 3D terrain representation to enhance spatiotemporal analysis.

### 3. Problem Definition and Motivation

There are multifaceted challenges associated with supporting analysis workflows related to dust events. Dust model simulation outputs are extremely large, depending on the extent of spatial domain, grid resolution, and temporal scale and resolution. Dust data analysis tools must be flexible enough to accommodate these variations. Additionally, understanding the spatial context of dust storms is crucial, requiring visualization of terrain, topographic features, and interactions of meteorological variables and dust-based aerosols with the terrain surface. In typical domain scientist workflows focused on dust event analysis, there is limited integrated support for 3D visualizations capable of facilitating the analysis of multiple meteorological variables alongside contextual static datasets.

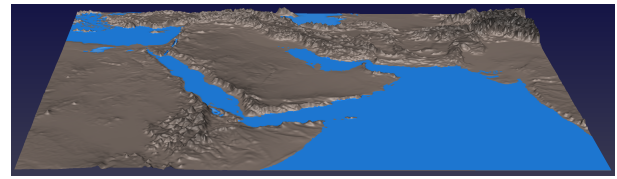
Dust-based aerosols undergo variations in size and composition, and their concentration varies over time during the evolution of dust storms. Understanding these variations is crucial for analyzing interactions between multiple meteorological parameters, the location of dust sources, topographical features, and more. Dust deposition also depends on multiple factors. To support such analysis, a holistic, unified visualization environment is needed to enhance the understanding of dust storm dynamics. Additionally, to better understand the effects of dust concentrations on radiative forcing and transfer, as well as their impact on weather and climate, tools are needed to analyze the vertical profile and cross-section of dust concentrations from the Earth's surface to the top of the atmosphere. In this work, we aim to address these requirements and provide visualization system with components that could facilitate developing a better understanding of dust storm evolution and dynamics.

## 4. Extreme Dust Events Visualization

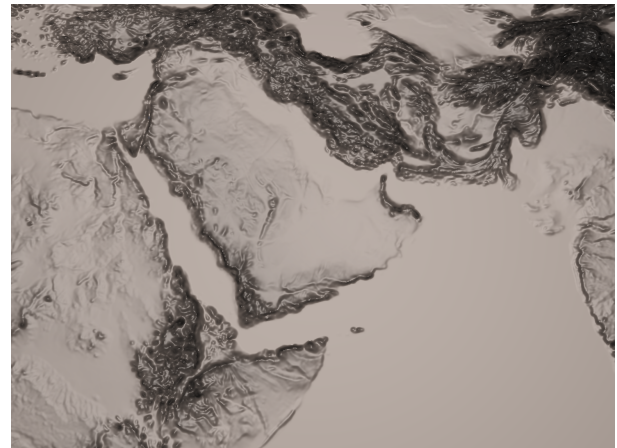
### 4.1. Dust Models and Datasets

To simulate the prevalent atmospheric conditions during the extreme dust events along with aerosol (suspended atmospheric particles such as dust) interactions, we coupled the Weather Research and Forecasting (WRF) model [SK08] with WRF-Chem (WRF with Chemistry) [GPS\*05]. In addition to simulating meteorological conditions, this coupling enables us to examine aerosol interactions with atmospheric parameters, including their formation, evolution, transport, and impact on radiative fluxes.

We configured the spatial domain of the model to the extent of the Arabian Peninsula (AP) with a 10 km x 10 km horizontal grid and 90 vertical levels. Spatial resolution, as well as temporal range and resolution, are configurable and can be further increased; however, this requires more computational resources on HPC infrastructure and results in larger simulation output files. In usual model runs, the temporal range is centered around the extreme dust events to examine the data around their lifecycle. The model configurations are based on the intended analysis requirements.



(a) 3D terrain used in our main visualization window.



(b) Monochrome version of the 3D terrain used in our 3D overlay view.

**Figure 2:** The two versions of the 3D terrain used in our visualization system.

We used the atmospheric initial and lateral boundary conditions from the National Centre for Environmental Prediction Final Reanalysis (NOAA/NCEP) to run this high-resolution model for the AP spatial domain at  $1^\circ \times 1^\circ$  spatial resolution. We ran this model with five nodes on an HPC infrastructure (Shaheen supercomputer [HKF\*15]), and it took approximately one hour to complete a one-day simulation, including all pre- and post-processing steps. The output files are in NetCDF format, and their size varies based on the selection of variables included in the output (such as dust concentrations, wind, temperature, and sea-level pressure). In our simulation setup, each 5-day simulation with hourly level resolution output file has a size of approximately 3.5 GB per variable.

### 4.2. Visualization Design

The 3D dust visualization system is designed with a focus on user flexibility and adaptability. Different users, particularly simulation and domain scientists, have varying requirements and variables of interest that they want to visualize; as such, the system was constructed with a modular architecture. This modularity allows for the easy addition, removal, or modification of specific visualizations, allowing users to tailor the system to their needs. The design process that we followed had regular feedback and input from domain scientists, ensuring that the visualizations were relevant and useful to their work. This iterative approach allowed us to explore numerous data representations and ideas, letting the scientists see their data in a way they had never done before with their existing tools.

The first step in creating the 3D visualization environment for

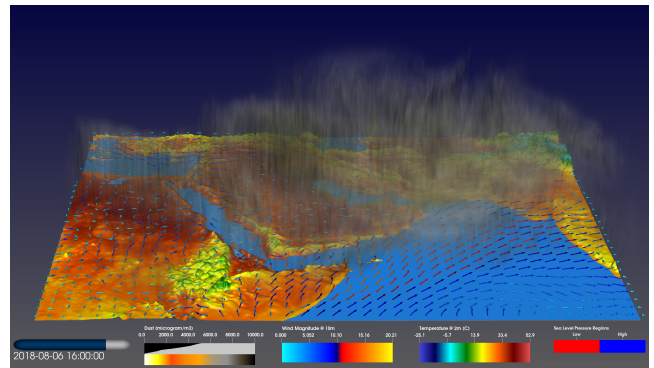
dust storms was to understand the geographical scale of the simulation. The simulation encompassed the entire Arabian Peninsula and slightly beyond, making the addition of geographic markers paramount for data understanding. To do this, we created a topographic surface using the ground and sea level height information contained in the simulation. We then took this data and applied two different color maps to it, one for the main 3D visualization (see Figure 2a) and one for a 3D overlay map used to display secondary variables and orient the user to what they are seeing in the main visualization (See Figure 2b). The main 3D view uses a custom color map to show blue for regions with water and a muted gray to black for land to show contrast across different altitudes. These colors allow the seas and mountains to stand out while causing as little occlusion as possible to the data being overlaid (Figure 1).

The second step was to visualize each quantity of interest shown below, including land *surface temperature* at two meters, *wind magnitude* at 10 meters, and *dust concentration*:

- *Surface temperature* was displayed in the main visualization window.
- *Wind magnitude* was displayed as traditional streamlines, densely seeding a uniform grid across the whole 3D terrain. We advected each streamline for a very short duration, ending up essentially a vector plot. However, unlike a vector plot, it does not have to create a seeding so dense that it occludes other values of interest in the visualization environment.
- *Dust concentration* was initially displayed using surface rendering with transparency applied to the surface. However, this did not show the concentrations of particle sizes well enough, so we had to switch to true volume rendering. With volume rendering we were able to make the smallest particles transparent, allowing the internal particles to be seen and the evolution of the dust storm tracked.

The choice of a color table for *dust concentration* was difficult due to the amount of other information that would simultaneously be displayed, e.g. wind magnitude and direction, surface temperature, sea level pressure regions, as well as the topographic map and associated colors. For this reason, we designed a color table that resembled the actual color of dust with a mix of colors ranging from white to black to red and orange. When combined with volume rendering, the effect looked dust-like. However, just like the rest of this visualization environment, the color tables can be changed at-will, so a scientist can easily choose a color table that they like better or one that highlights the specific range of information that they are interested in looking at.

The scientists were also very interested in seeing the high and low *sea level pressure* regions, and how they changed over time. In order to not occlude this data, it was added to the overlay view of the data we created (See Figure 4a). Initially, a surface plot representation was employed, which involved shading extensive areas of the overlay map. However, when this was combined with the existing wind and dust data, the resulting visualization suffered from significant occlusion. Additionally, the colors within the visualization did not accurately reflect the underlying data due to the compositing of multiple variables. To address this issue, we switched the representation of *sea level pressure* to contour lines. Using specific values provided by the scientists to define high and low-

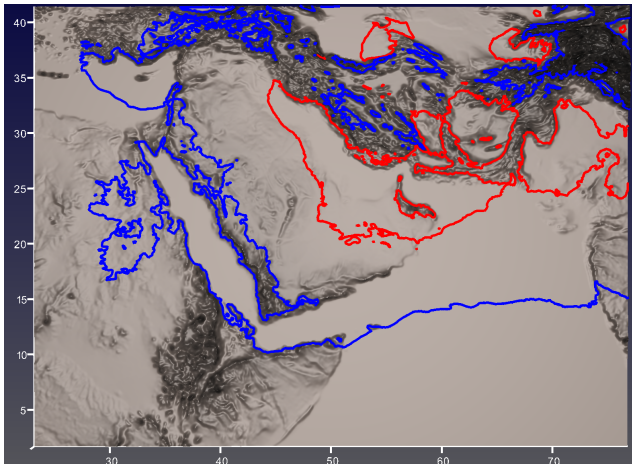


**Figure 3:** The main 3D view from our visualization system, showing dust concentration rendered as a volume with low values being transparent, wind magnitude being shown as arrow plots to show wind direction and colored to encode magnitude, as well as surface temperature being overlaid onto the 3D terrain.

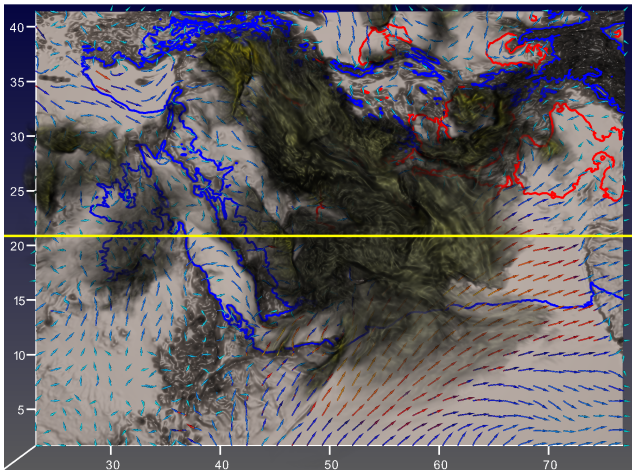
pressure areas, we plotted these two contours with static colors - blue for high pressure and red for low pressure. This approach allowed us to show the evolution of *sea level pressure* without overly obscuring the other variables displayed in the overlay window.

One problem we encountered when showing the 3D visualization to scientists (see Figure 3) was that they were unable to clearly see the height of the dust and its concentration. This led to the creation of a third visualization that tied into the main 3D and overlay views. This 2D view (see Figure 5) shows a Hovmöller plot of *dust concentration* at a user-specified latitude, giving the height in Km above sea-level for the *dust concentration* at every degree of longitude in the simulation. This view updates with every time step of the simulation, just like the main 3D visualization, making it very easy to instantly see how high different concentrations of dust are located and also to find the areas on the map where they are occurring. To complement this new 2D view, it was necessary to annotate exactly which latitude was being shown at any given time in the visualization. Therefore, we added a marker to our overlay view to show which latitude is being visualized on the Hovmöller plot, letting the user see where in the simulation dust concentrations are located (See Figure 4b).

Taking the three different visualization views we developed, we combined them to create our 3D environment for analyzing the evolution of extreme dust events (See Figure 1). The system's primary component is a 3D scene, which shows the topographic map overlaid with surface temperature, serving as the foundation for additional levels of information. Next, we display the wind direction and magnitude glyphs, while a volume-rendered view of dust concentration overlays everything. To enable quick interpretation of the data we added color bars to explain the color table for each of the variables, a time indicator showing how far in the simulation we have evolved, and the exact date and time. The final elements of our visualization environment are two overlay plots positioned at the top of the screen. One of these plots shows the Hovmöller diagram, which shows dust concentration by altitude for a given latitude. The other plot shows a bird's eye view of several key variables, includ-



(a) The 3D overlay map showing the high (colored blue), and low (colored red) sea level pressure regions for one step in the simulation.



(b) The 3D overlay map showing a birds-eye view of three variables: sea level pressure regions, wind magnitude and direction, and dust concentration, as well as a latitude marker for Hovmöller diagram.

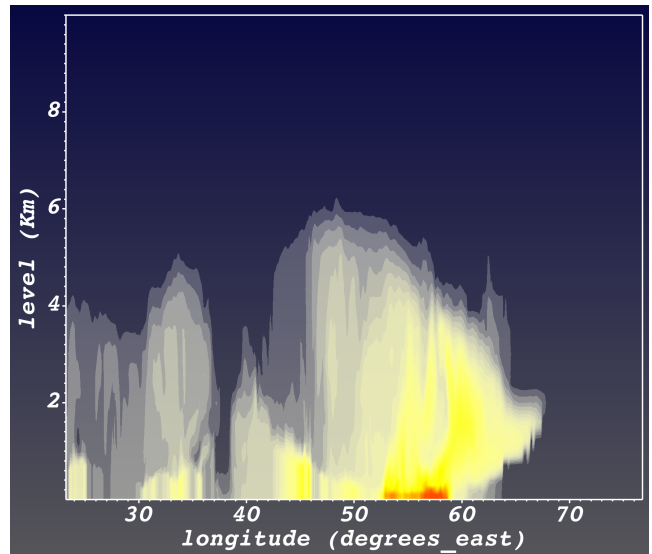
**Figure 4:** 3D topographic overview design

ing dust concentration, sea level pressure regions, wind direction and magnitude, and the latitude line for the Hovmöller diagram.

Combining these three diverse views into one visualization environment has provided domain scientists with an adaptable tool for analyzing and understanding the evolution of dust storm data. This environment further enables them to explore spatiotemporal patterns, identify relationships between variables, and gain deeper insights into the formation and evolution of extreme dust events.

### 4.3. The 3D Visualization Environment

This visualization environment was implemented with VisIt [CBW\*12], along with some Python scripting for data preprocessing and generating the video. Since all of the visualization is done in VisIt, users can interactively change and modify all aspects of the visualization, including colors, view orientations,



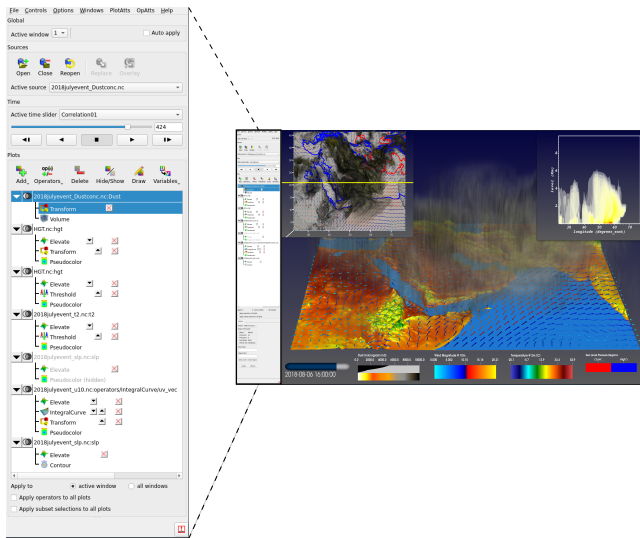
**Figure 5:** Dust concentration at a user-specified latitude.

and variables. New variables can be added, old ones removed, or derived functions put in place. This visualization system can be used as a "pipeline" because not only can pieces of the pipeline itself be modified, added, or removed, but the setup is such that as new simulations are run, data can be placed into the pipeline, and new results visualized with few or no changes necessary.

The first step involved two Python preprocessing scripts. One was used to create the Hovmöller data, generating a new file and variable for our visualization environment. The second script analyzed the simulation data, extracting each variable's minimum and maximum values over time. This information was then used to set the minimum and maximum ranges of the color bars in the visualization to maintain a consistent color range.

The second step involved using VisIt for visualization. The VisIt GUI was used for the entire design process, and four visualization types were employed in our visualization environment: 3D terrain map creation, volume data visualization, 2D data visualization, and vector field visualization. A view of the VisIt GUI in use during the design and exploration of the data can be seen in Figure 6. It contains a sources view for loading data, a time slider, and a operation view for selecting and configuring multiple climate variables.

The 3D terrain map was generated by applying an elevation filter to a pseudocolor plot of the *HGT* variable (topographic height in meters) from WRF. This provided a 2D slice of the topography, where the elevation was determined by the pixel intensity value. Volume rendering was used to visualize the volume data, *dust concentration*. A color map was applied to the data, and an opacity value was added to the color value at each point. This allowed less important data to be transparent or near-transparent while more important values were opaque. The user can easily modify the transfer function as their quantities of interest change; it is shown in Figure 1. In these visualizations, we chose to emphasize large dust particles over small particles. The data was also slightly scaled down in the z-direction to allow the viewer to easily see the variables of



**Figure 6:** User interface for 3D visualization system

interest; without scaling, the dust extended so far above the map surface that its actual location was difficult to discern.

The 2D values of interest were *sea level pressure* and *surface temperature*. A contour plot with two contour values was used to visualize *sea level pressure*, resulting in a plot with two sets of colored lines: one denoting high sea level pressure regions and the other showing low sea level pressure regions. *Surface temperature* was visualized using a pseudocolor plot with an elevated filter applied to match the 3D terrain map elevation.

Finally, the vector data was visualized. The *wind magnitude* vectors were visualized using a streamline plot. Seeds were created at regular intervals over the entire 3D terrain map, and each seed was advected for a very short duration to better show the instantaneous wind directions. These streamlines were then encoded with the wind magnitude along their length.

The last step involved adding support for generating rendering movies for each of the three visualization views and creating the final composited video. The domain scientist mentioned that this feature is important for later analysis and presentation of important events explored in the tool. To do this, we loaded the saved VisIt state (created in the GUI, allowing scientists to customize the view, visualized data, and representations) and ran the script over every time step from the simulation, saving an image at each step. The resulting three image sets were then composited into a final video, using the layout shown in Figure 1, with the 3D window as the centerpiece and the two overlays displayed in the top left and right corners.

## 5. Case Study: Evolution of Extreme Dust Events in Arabian Peninsula

In this case study, we demonstrate how the 3D visualization system facilitates the exploration of dust storm evolution by integrating key meteorological variables such as dust concentration, pressure, temperature, and wind. The system allows domain scientists to analyze

dust transport in a dynamic atmospheric environment, providing both an overview of spatial patterns and detailed insights into vertical dust distributions.

Figure 7 illustrates the spatiotemporal evolution of a dust event over three days, captured on Day 1 (00:00), Day 1 (12:00), Day 2 (06:00), and Day 3 (12:00). The dust storm is seen developing within a low-pressure area, with dust transport patterns closely following the prevailing wind currents.

The 3D view provides an immersive representation of dust transport, where users can observe how dust particles are carried through different atmospheric layers. The two linked sub-views further enhance analysis by offering a 2D overview of the dust distribution over the region and a vertical slicing view showing dust concentration at different altitudes along a selected latitude. These complementary views help domain scientists assess how dust behaves across spatial and vertical dimensions.

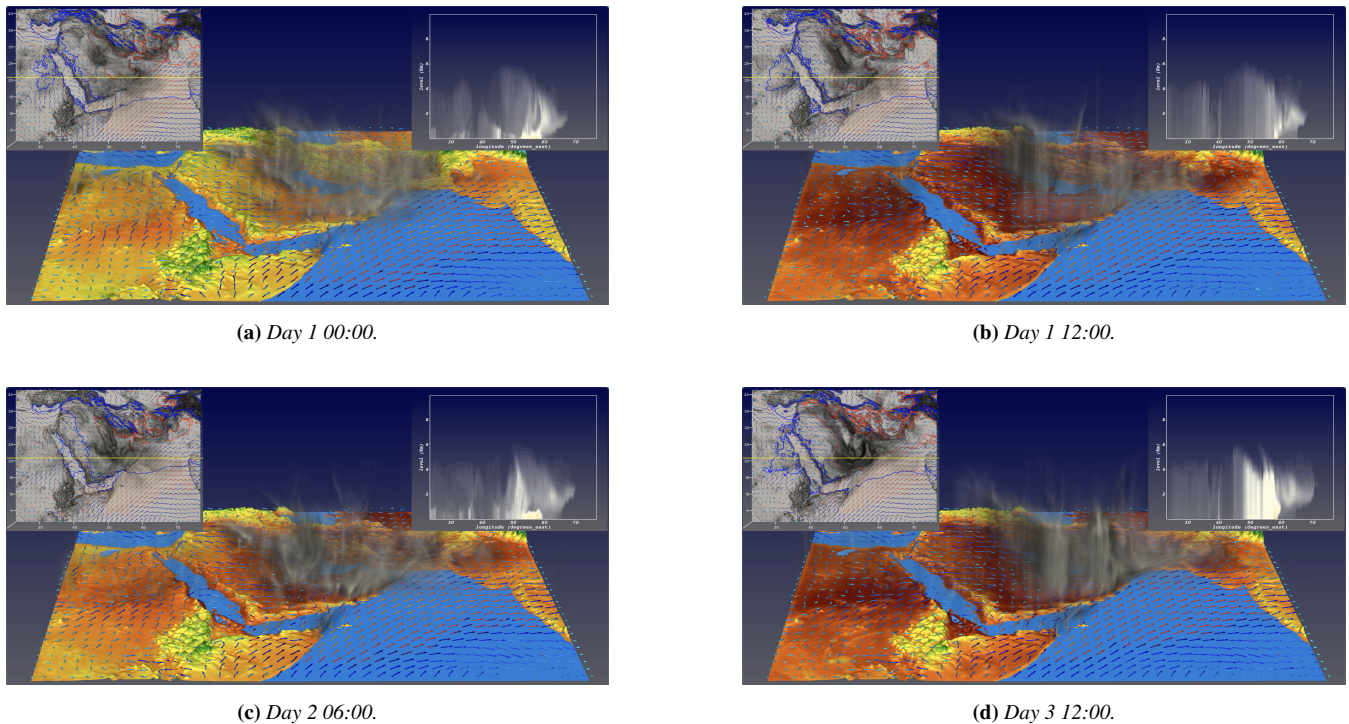
A key observation from Figure 7a is that dust emissions initiate near the low-pressure area, with wind-driven transport beginning to move the dust southeastward. By Figure 7b, a significant intensification of the dust event is observed. The increase in temperature causes the low-pressure area to expand, leading to stronger upward motion and enhanced dust lifting. The 3D view reveals that the dust becomes denser and visually darker, indicating a higher concentration of carried particles. In Figure 7c, a temperature decrease leads to a contraction of the low-pressure area, resulting in dust becoming more concentrated within a smaller region. The dust continues to move southeastward, guided by the prevailing wind flow. The slicing view further confirms this, showing that dust concentrations are highest between longitudes 50 and 60, reflecting the constrained movement of the dust storm. By Figure 7d, the dust storm has fully developed, with a significant volume of suspended dust circulating around the low-pressure area. The 3D visualization clearly illustrates the structured flow of dust along the atmospheric circulation pattern. A notable observation is that the dust does not extend over the sea, as a strong opposing wind from the ocean acts as a barrier, preventing further transport. This highlights the role of wind systems in confining dust movement to specific regions.

Overall, this case study highlights how our 3D visualization system enables an intuitive and detailed exploration of extreme dust events, allowing domain scientists to track dust emissions, analyze transport patterns, and assess interactions with meteorological variables in a 3D environment.

## 6. Feedback from Domain Experts

To assess the effectiveness of our 3D visualization framework, we gathered feedback from two domain scientists (both are not co-authors) specializing in dust event analysis and atmospheric processes. After explaining the framework to them, we guided them through the case study of an extreme dust event, demonstrating the interactive capabilities and multi-dimensional analysis. The domain scientists then independently interacted with the system, examining dust transport patterns, meteorological influences, and vertical dust distribution based on the visualization GUI shown in Section 4.3.

The experts highlighted that the 3D visualization significantly



**Figure 7:** The case study on visualization of the evolution of a dust storm over time.

enhances their ability to analyze dust evolution in relation to atmospheric variables. They noted that simultaneously visualizing pressure, temperature, wind, and dust concentration in a dynamic 3D environment provides a more comprehensive understanding than traditional 2D methods. The linked 2D overview and vertical slicing views were useful for allowing them to explore dust distribution across multiple dimensions efficiently. One expert emphasized that the ability to track dust movement within pressure and wind systems facilitates a more intuitive analysis of dust loading and deposition relationships. However, they pointed out occasional occlusion issues when multiple layers were visualized simultaneously. They suggested incorporating advanced filtering techniques or transparency controls to mitigate this challenge.

## 7. Conclusions and Future Work

In this work, we presented a 3D visualization framework for analyzing extreme dust events, designed and developed in collaboration with domain experts. The system enables exploration of dust transport and its associated meteorological variables by integrating a 3D spatial visualization, a 2D overview, and a vertical slicing view of dust concentration. The case study demonstrated how the visualization facilitates a deeper understanding of dust dynamics, including its interaction with pressure and wind. Feedback from domain scientists confirmed the framework's effectiveness in enhancing analysis workflows, enabling the exploration of large-scale simulation datasets in 3D space, and gaining insights into dust event evolution.

The future work will focus on expanding the framework's capa-

bilities by incorporating observational datasets from satellite and ground-based measurements, enabling direct comparisons between simulations and real-world data. We also plan to add components that will support understanding the impact of dust events on renewable energy generation through the analysis of radiative fluxes. These advancements will continue to refine the role of interactive 3D visualization in dust research, facilitating more comprehensive investigations of dust events and their broader environmental impacts.

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