Workshop on Visualisation in Environmental Sciences (EnvirVis) (2023)
S. Dutta, K. Feige, K. Rink, and D. Zeckzer (Editors)

Visualization Environment for Analyzing Extreme Rainfall Events: A Case Study

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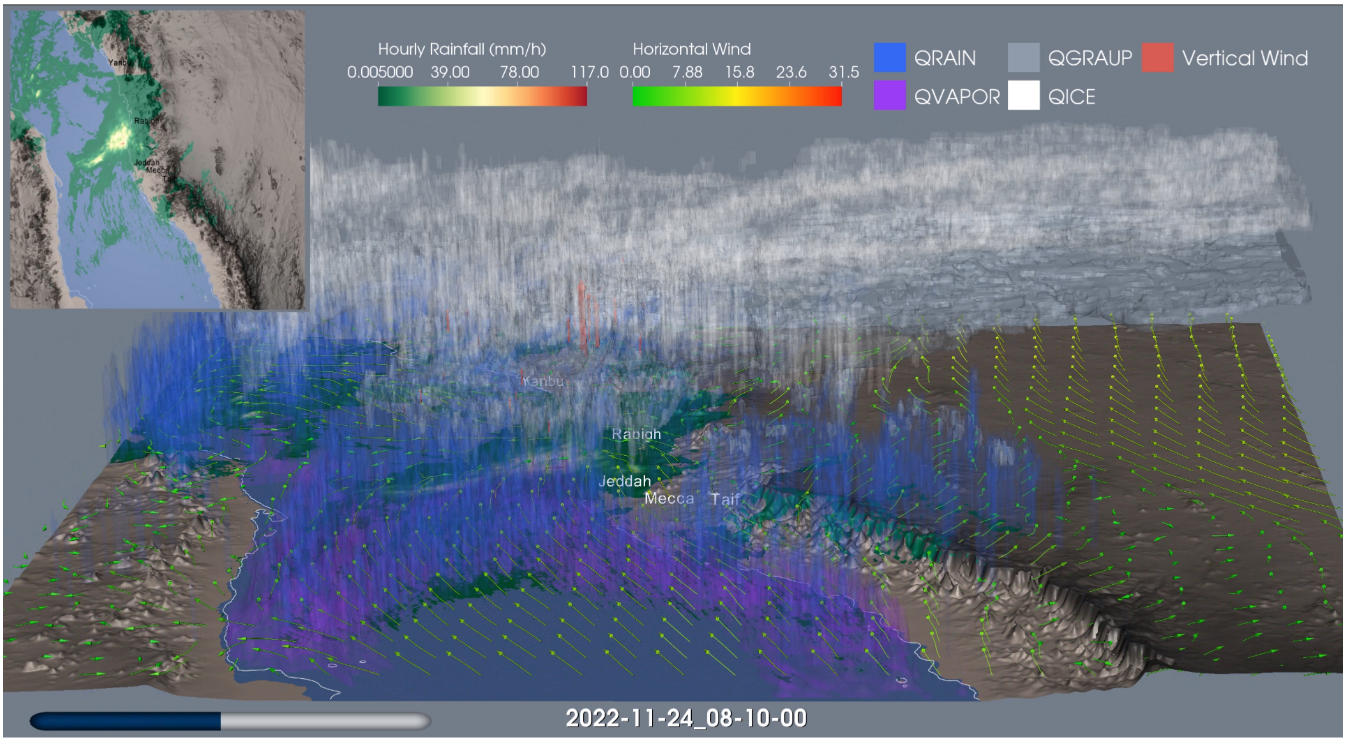


Figure 1: *Visualization environment for analyzing extreme rainfall events showing the details of Jeddah extreme rainfall (Nov. 24, 2022)*

Abstract

Extreme rainfall events can devastate infrastructure and public life and potentially induce substantial financial and life losses. Although weather alert systems generate early rainfall warnings, predicting the impact areas, duration, magnitude, occurrence, and characterization as an extreme event is challenging. Scientists analyze previous extreme rainfall events to examine the factors such as meteorological conditions, large-scale features, relationships and interactions between large-scale features and mesoscale features, and the success of simulation models in capturing these conditions at different resolutions and their parameterizations. In addition, they may also be interested in understanding the sources of anomalous amounts of moisture that may fuel such events. Many factors play a role in the development of these events, which vary depending on the locations. In this work, we implement a visualization environment that supports domain scientists in analyzing simulation model outputs configured to predict and analyze extreme precipitation events. This environment enables visualization of important local features and facilitates understanding the mechanisms contributing to such events. We present a case study of the Jeddah extreme precipitation event on November 24, 2022, which caused great flooding and infrastructure damage. We also present a detailed discussion about the study's results, feedback from the domain experts, and future extensions.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Meteorological Visualization—

DOI: 10.2312/envirvis.20231103

1. Introduction

Extreme weather events such as extreme rainfalls can cause severe impact and damage, such as loss of life, infrastructure, agricultural crops, and economic costs. Predicting the occurrence, severity, duration, and impact areas is challenging. Although weather alert systems generate rainfall warnings, the timely classification of these events as extreme rainfall events is also critical to generate early alerts. Scientists examine previous rainfall events to understand better such extreme events and the physical processes involved. They look into multiple factors while analyzing these extreme events, such as understanding the role of large-scale processes, characteristics of mesoscale features, resolution of available observational datasets, relationships and interactions between such features, domain resolution, physical characteristics of the region, and overall meteorological conditions. They also need to analyze the capabilities of high-resolution regional atmospheric simulation models adapted for detecting and predicting such events.

Domain scientists need such an environment where they can analyze the outputs of these simulation models, overlay different observational datasets, examine the behavior and interactions of large-scale and mesoscale features, incorporate terrain and regional characteristics, analyze meteorological conditions, etc. To this end, we have implemented a visualization environment that supports domain scientists in their analysis workflows focused on the diagnostic analysis of extreme rainfall events. This environment can support scientists in testing different hypotheses and gaining a better understanding of underlying physical processes and factors in the evolution of extreme precipitation events.

In this work, we present in detail the design and development of such a visualization environment and the challenges involved in its design, considering the unique requirements of relevant simulation models and observational datasets. The design and implementation was conducted in close collaboration with domain scientists working on the prediction and modeling of such extreme weather events.

We also include a case study related to Jeddah (a coastal city in the Kingdom of Saudi Arabia) extreme rainfall event that occurred on November 24, 2022. During this extreme precipitation event, the city received more than 200 mm of rainfall in one day, which is four times the climatological mean for that city in the month of November. Utilizing this visualization environment, we analyze the results of a very high grid resolution simulation model to understand and analyze the evolution and behavior of this mesoscale convective storm. We also provide key takeaways and findings based on the results of this case study.

2. Related Work

Various works have been presented in interactively analyzing meteorology and oceanography data using visualization and analytics tools [AHG*19, RBS21]. Some toolkits [KWA*11, RBW*12] have also been designed for extreme climate analysis. Researchers have focused on both 2D and 3D visualization techniques to study weather and atmospheric data. In general, 2D visualizations dominate this area; however, 3D techniques are also effectively used, especially for forecasting [RBS*17].

2D Visualization Techniques: 2D techniques are common for visualizing meteorological data [RBS*17]. In this domain, observation and numerical data are often displayed on the 2D maps [Mon00]. On the maps, various 2D glyphs and pathlines are often used to depict the 3D movement of the wind data [SW15, WP13]. Multiple charts and analytics are also used to depict the variation of other meteorological variables [Sau55]. Afzal et al. [AGT*19] designed an interactive tool with different 2D charts and glyphs on the maps to visualize atmospheric data. Joshi et al. [JCS20] used 2D visualization techniques to analyze rainfall predictions. Lundblad et al. [LLEJ11] designed a multi-view visualization tool consisting of various 2D visualization techniques and a 2D map to assist weather forecasting. Jänicke and Scheuermann [JS14] showed how a web-based tool GeoTemCo, could be used to visualize geospatial environmental data.

3D Visualization Techniques and Tools: Various 3D visualization techniques and tools have been designed recently to analyze meteorological data [RBS*17]. National Center for Atmospheric Research (NCAR) Graphics package [PSJ88] is one of the earliest visualization tools proposed for weather data analysis. Wilhelmson et al. [WJS*90] used 3D animation movies style visualization to depict severe storm movement. Kern et al. [KHS*18] proposed an interactive 3D visualization technique to visualize atmospheric fronts. They presented a case study of cyclone Vladiana to show how their 3D visualization technique of atmospheric fronts can help analyze the cyclone. Hibbard et al. [Hib05] developed the Vis5D tool to analyze weather data using multi-dimension visualizations. Weather 3D eXplorer (W3DX) [KDV*14, KN18] is another 3D visualization framework for interactive metrological data analysis. There are various other tools available as well for meteorological data visualization, such as Vapor [LJP*19], IDV [MMWE03], Met.3D [RKSW15], Avizo [AVI23], and Paraview [AYA15]. In this work, we used a similar open-source tool called VisIt [CBW*12].

Meteorological data is often complex and big in nature and is often visualized using 3D techniques such as volume rendering, streamlines, and isosurface [LGY15b]. However, volume rendering is one of the popularly used techniques [LCY*17, YW10, LJY*13, LGLI14, LGY15a]. Guo et al. [GXY12] used volume rendering with interactive transfer function design to visualize multivariate volume data. Kniss et al. [KHGR02] showed that volume rendering could be effectively used to analyze multivariate meteorological data. Song et al. [SYS*06] used volume rendering along with other 2D techniques to visualize weather simulation data. Zhang et al. [ZYCH19] presented a volume rendering method to visualize large-scale meteorological data. In this work, we also used a volume-rendering technique and 2D visualizations to analyze extreme rainfall events.

3. Problem Definition and Domain Requirements

Interactive visualization tools are required to support the analysis workflows of domain scientists working with extreme rainfall events datasets. They deal with extremely big datasets, and they often need to examine the overlay of multiple datasets to understand better the relevant physical processes at different scales and their interactions. Interactive filtering, supporting animations that provide an overview of the datasets, visualizing multiple variables at once, and showing topographical features and other regional characteristics are also desired features. This work aims to provide a visualization environment that can facilitate understanding of the physical and dynamical features of extreme precipitation events. Further, this work will be useful in disseminating information about extreme rainfall events to alert the public.

4. Visualization Environment for Analyzing Rain Events

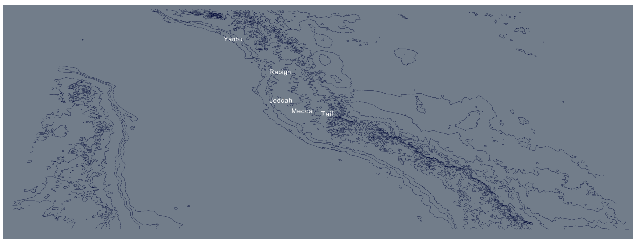
The visualization environment is iteratively designed in close collaboration with domain experts. At each step, feedback from the experts is incorporated to improve the design of the environment. The domain experts include scientists from academia and industry. Below we explain the weather research and forecasting (WRF) model used to generate the rainfall data, the design of the visualization environment, and the implementation details.

4.1. Simulation Models and Datasets

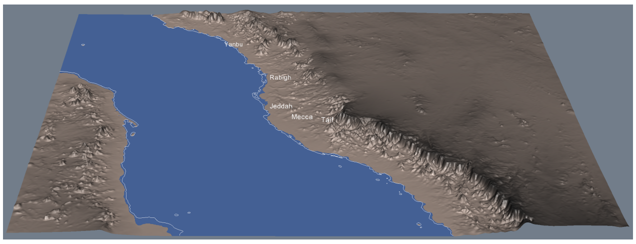
This study used the WRF model [SKD*08] (WRF 4.4) to predict the extreme rainfall event at a very high grid resolution of 1 km. It is a non-hydrostatic model based on primitive equations approximating atmospheric flow, which is widely used to understand meso-scale convective storms, including tropical cyclones or hurricanes, thunderstorms, extreme heavy rainfall events, urban heat islands, etc. We have configured the WRF model for the Jeddah region with three two-way interactive nested domains with horizontal resolutions of 9, 3, and 1 km. The grid point in X and Y directions are 443x360, 613x685, and 742x670 for 9, 3, and 1 km domains, respectively. Along with the ultra-high-grid resolutions, we have also configured the WRF model with 57 vertical levels, which allows the model to exchange the convective processes in the vertical direction. We used the National Centers for Environmental Prediction (NCEP) operational Global Forecast System (GFS) forecasts, available at 0.25° x 0.25° horizontal resolution and at multiple vertical levels, to initiate high-resolution prediction experiments utilizing the WRF model. We did not assimilate any datasets to improve the initial or boundary conditions. The simulation models were run using a high-performance computing platform (SHAHEEN supercomputer [HKF*15]). The model computed a forecast for 36 hours starting from 1200UTC on 23 November 2022; the outputs were saved every 10 minutes. These 10 minutes data sets are stored in NetCDF format, which amounts to 1.2 TB with each file size of 2.6 GB. We have developed a pipeline with visualization capabilities to visualize the important localized features and associated mechanisms that contributed to the extreme rainfall over Jeddah.

4.2. Visualization Design

The visualizations created for this visualization environment were designed to be modular so that different levels of detail could be shown to the user depending on their needs and the specific phenomena of interest. Therein though, lies the main design challenge with this visualization environment. There are a multitude of variables of interest, and complex interactions that take place between each and every one of them. This complex interaction means that many variables will need to be displayed simultaneously across the entire simulated domain. Therefore, there is potential for a great deal of occlusion of events due to the many overlapping variables, making modularity a necessity. With modularity, we can add or remove different variables as needed to create tailored environments for asking specific questions about our data.



(a) *Basic contour plot of the regions terrain, outlining the Red Sea, mountains, and plains.*



(b) *Enhanced elevation plot of the region with a custom color map with basic terrain shading to enhance details and emphasize the Red Sea and mountainous regions.*

Figure 2: *Base Map Layer*

The first step in the design was to create a base layer that would orient the user geographically. Without any geographic markers, the data is difficult to understand visually, as the data interactions are based on the physical features of the terrain. In creating this base layer, we initially started with the simplest representation we could think of, contour lines (see Figure 2a. These contours defined the Red Sea, mountain ranges, and the plains. Initially, this representation was chosen because it would impart the least amount of noise and occlusion to the actual data of interest. However, that came at a trade-off of the region still not being completely defined, taking the user more time to orient themselves and understand the data. After consultation with domain experts, they were willing to incur the penalty of more occlusion and color saturation in order to have a more detailed base map. We then created the elevation plot based on model orography seen in Figure 2b with a custom color map to show water and a minimal amount of terrain shading, allowing the details of the terrain to easily be seen, with as little occlusion as possible to the variables of interest. In addition to this representation and color change, we added a number of major city names to make the region more recognizable when additional variables were overlaid.

The next step was to visualize each of the variables of interest defined by the domain scientists. Nine initial variables were of interest, ranging from vector fields to volumes to 2D surfaces. We began our design with the volumes: QICE, QRAIN, QGRAUP, QVAPOR, and QCLOUD (hydrometeors) [SKD*08]. We have presented different cloud micro-physical parameters which contribute to the surface rainfall. The first step for each of these variables was to filter out extremely low values; otherwise, the entire region was occluded with near 0 values. These values could be safely removed as they were contributing very little to the understanding of the phenomena of interest. With these low values filtered out, each of the variables was individually plotted and assigned a different color table. At this point, we asked the domain scientists for feedback on the visualization to better understand what they wanted to learn and to see their process for understanding their data, as this can vary widely from researcher to researcher. Based on their feedback, we did two main things. First, we removed QCLOUD completely, as it was not a major contributor to what they wanted to understand from the simulation. Second, we switched all of these variables to a single color with varying opacity based on the data value; low values were more transparent than higher values. This change was done as the researchers were more interested in the variables as a macro phenomenon, and not necessarily the varying values within each variable set.

With all of the color maps changed, we again spoke to the researchers who had further design changes. First, they wanted to better show the formation and movement of QICE and QGRAUP, so we translated the QICE variable vertically in the renderings by a small amount so that it could easily and clearly be shown as being on top of QGRAUP. Finally, the opacity of the variable was further changed after seeing how the simulation progressed over time. During the heavy rain event, there was heavy occlusion of variables across most of the domain due to the extent of each variable, so we further reduced the opacity of the variables to help compensate.

The next step was to visualize the 2D surface rain. The domain scientists were interested in seeing the hourly rainfall accumulation on the ground. As this information is not directly available, we calculated it by subtracting the cumulative rainfall at a given time from the cumulative rainfall from 1-hour prior. With this information in hand, we then needed to apply the same elevation field to the data as was applied to the terrain maps for the data to display properly on our elevated terrain. Finally, the color map was chosen to show a natural color scale from light (green) to heavy (red), and the minimum and maximum hourly accumulation values were pinned to a minimum of 0.005 and a maximum of 117 mm/h so that accumulations could be visually compared across time. The minimum value was chosen to remove the noisy data where rain accumulation was very near 0, and was occluding the interesting rainfall as well as other variables. The maximum value was obtained by getting the maximum 1-hour accumulation across all time steps.

The final step was to introduce the vector fields into the visualization. There are two types of vectors of interest, horizontal wind and vertical wind. The horizontal wind represents wind as we would traditionally think of it, blowing across the landscape. Vertical wind represents either upward or downward wind forces, which affect the formation of different cloud types. To visualize the horizontal wind (wind at 10m height), we used traditional streamlines, densely seeding a uniform grid covering the entire surface of the region of interest. Given that streamlines show instantaneous paths, and it does not make much sense to visualize them over time, we only advected them for a very short duration. This short advection gives the effect of a vector plot but better denotes the changes in the vector field using fewer seeds. This was important to avoid overcomplicating and occluding the visualization further. For the vertical wind, we opted for vector plots. On the advice of the domain scientists, we removed all vectors that had a magnitude of less than 1.5, opting to only show high-magnitude vectors. Initially, we showed both upward and downward vectors using the same color bar, but it was difficult to see the differences. We then split the vectors into two classes, one for upward wind vectors and one for downward wind vectors. After the domain scientists reviewed this, they opted to remove the downward vertical wind, as it was not important for their current research. They also opted to have a single color for the upward vectors versus a color var, so we instead used glyph size as the representation of vector magnitude.

Finally, we put all of these individual elements together to form different sets of animations, each one showing different combinations of variables, that enabled the domain experts to scroll through time and see the interactions of each of the variables of interest. The first movie used all of the final variables of interest combined with a 2D overview map showing the hourly rainfall. This 2D map was added due to the levels of occlusion on the surface due to all of the variables being present. It lets the user easily see the amount of rain accumulating on the surface and where that accumulation is taking place. The second movie focused on the vector fields and the hourly rain, removing everything else. The final movie contained the vector fields, hourly rain, and the QRAIN variable.

4.3. Implementation Details

This visualization pipeline was primarily based on VisIt [CBW*12] using Python scripts as the drivers. There were essentially three main steps in our pipeline: file conversion and reduction, visualization, and movie making.

In the first step, the data was filtered and converted using VisIt via a Python script. The filtering was done to remove unnecessary variables from the WRF output, which drastically reduced the file size. This file size reduction made later visualization faster, especially during the iterative design process. The file conversion was done to split the file into a multi-block file which allowed VisIt to run the visualizations in parallel, speeding up the pipeline. In our case, we exported the data as Silo [Lab23] files.

The second step was visualization using VisIt. We did all of the design using VisIt's GUI, and then the images for each time step were generated and saved by loading the saved VisIt state in a Python script. There were four main visualization components in our pipeline: base map creation, volume data visualization, 2D data visualization, and vector field visualization. The base map was created by applying an elevation filter to a pseudocolor plot of the *HGT* variable (topographic height in meters) from WRF, which provides a 2D slice of the topography, and the elevation is determined by the pixel intensity value. The volume data was visualized by also creating pseudocolor plots. The data was scaled slightly in the z-direction to enable to viewer to easily see the variables of interest. The main 2D value of interest was hourly rainfall. This value was visualized also using a pseudocolor plot with an elevate filter applied to match the base map elevation. Finally, the vector data was visualized in two different ways. The horizontal wind vectors were

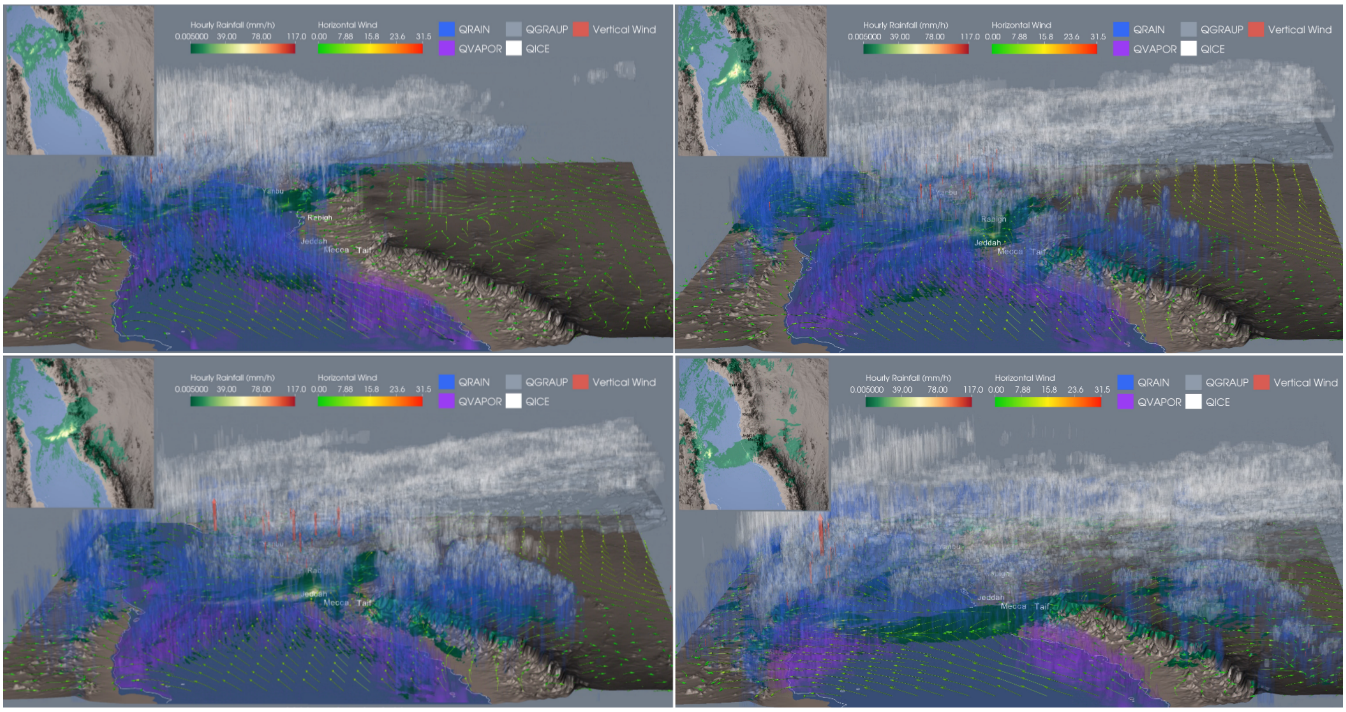


Figure 3: *Jeddah extreme rainfall event (occurred on November 24, 2022) visualization. The figure shows the evolution of cloud systems over time. Four cloud variables, along with vertical wind, horizontal wind, and hourly rainfall, are shown in the visualization. (Top left) 2:10 UTC, (top right) 8:30 UTC, (bottom left) 10:10 UTC, (bottom right) 15:50 UTC. The event intensified at 8:30 and 10:10 UTC.*

visualized using the streamline plot. The streamlines were only advected for a very short duration in order to better show the instantaneous wind directions. The vertical wind values were shown using vector plots.

The final step in the pipeline was to create the movies. These were generated by loading the saved VisIt state (generated in the GUI using feedback from the domain scientists). This script then runs over every time step from the simulation, saves an image, and at the end, composites them all into a movie. In this instance, VisIt was launching with 6-cores for each invocation of the script. To speed up the movie making multiple instances of the script were launched simultaneously, each one generating a subrange of the simulation time steps.

For the main overview video, one final step remained. The scientists wanted a 2D overview map composited over the video, showing a top-down view of the hourly rain. This was accomplished by rendering a separate video of just the hourly rain with the topographic base map, and compositing both movies together using ffmpeg.

5. Case Study: Jeddah Extreme Rainfall Event

Jeddah, a coastal city in the Kingdom of Saudi Arabia, received unprecedented rainfall on November 24, 2022. During this extreme precipitation event, 220 mm of rainfall was recorded in one day, and almost 180 mm was recorded in the span of almost six hours. This rainfall event was almost four times the climatological mean for the month of November, and it caused significant damage and flooding in the city resulting in human deaths and significant financial loss.

We examined this event using our visualization environment (Figure 1) to gain an understanding of the large-scale features associated with this extreme rainfall event, analysis of the mesoscale features and their interactions with the large-scale processes, meteorological conditions surrounding this event, how the normal rainfall event evolved into an extreme event, and other physical processes.

A high-resolution (1-km) WRF simulation model, as explained in section 4.1, is used to reproduce this extreme rainfall event using a suitable parametrization and domain. Domain scientists examined the results in a collaborative session to analyze the evolution of this extreme event and discussed the insights gained from this analysis.

According to domain scientists, this rainfall event was initiated in the beginning, probably due to the incursion of cold air from mid-latitudes. This is shown in Figure 3 (top left). This figure shows the evolution of this extreme rainfall event in four snapshots and also the extent of this event. This visualization is showing four species of the cloud system (QRAIN, QGRAUP, QVAPOR, and QICE), horizontal wind, vertical upward wind, and hourly rainfall. The cold air from mid-latitudes and the warm winds from the southeast form a frontal system that causes usual rainfall events in November in this region, but these rains do not evolve into extreme rainfalls. Looking at the horizontal wind patterns and knowledge about large-scale dynamics and features, and analyzing the con-

Proceedings published by Eurographics - The European Association for Computer Graphics.

vective features near the northwestern part, domain scientists mentioned that in usual circumstances, if the southeastern winds are not too strong, the convective system moves on, but in this case, it was blocked by the strong southeastern winds that caused this system to stay there for an extended duration that was around 6 hours. Figure 3 (top right and bottom left) shows the snapshot of the cloud system and rainfall during this duration. Thumbnails in each figure show the intensity of the rain during each time step. The convective system finally escapes, and the rainfall intensity drops, as shown in Figure 3 (bottom right).

Another important question the domain scientists were interested in looking into was the water intake by this cloud system. Figure 5a shows the strong vertical upward wind vectors in the beginning phases of this rainfall event. Domain scientists think that one contributing factor to extreme rainfall is the strong continuous water intake by the cloud system. Other prevailing meteorological conditions, along with these strong vectors, contributed heavily to the sustained water intake from the Red Sea. One interesting phenomenon that the scientists noticed was that, once the extreme rainfall event slowed down in intensity and magnitude, the convective system moved onto the western part of the Red Sea, as shown in Figure 4. This eventually resulted in another extreme rainfall event. Figure 5b shows the vertical upward wind vectors that may have contributed towards fueling water and sustaining this second extreme rainfall event.

The domain scientists also discussed the importance of showing topography and the domain of the physical area. It plays an important role in understanding and explaining the behavior of the physical processes associated with these extreme events.

6. Feedback from Domain Experts

We collected feedback from two domain scientists (not co-authors) who are experts in the area of meteorological data analysis. We explained the environment to them and showed them the example of the Jeddah rainfall event. They then interacted with the system and filtered various variables to understand various phenomena. They also analyzed the animation of the whole rainfall event with all the variables.

In their feedback, they mentioned that overall the environment enables them to understand the mesoscale-level details of the evolution of the storm. Without the environment, they were analyzing different variables individually. The environment enables them to not only better understand the evolution of the event but also lead to various unexpected results. One of the experts mentioned that the ability to interactively filter the variables to see how they interact over time is very helpful.

They pointed out a few occlusion issues with multiple variables enabled. However, they like the overview window of the rainfall as it helps them understand the rainfall over time in the occluded view. They also mentioned that in the future, they would like to add various analytics charts to see the variation of various variables.

7. Future Work

In future extensions of the system, we want to support more overlay of observational datasets (such as in-situ and satellite). We also want to support including large-scale features in the system and the capability to study multiple scenarios generated by varying simulation parameters. We will also analyze the model results and compare different observations to understand the accuracy of the model-predicted fields.

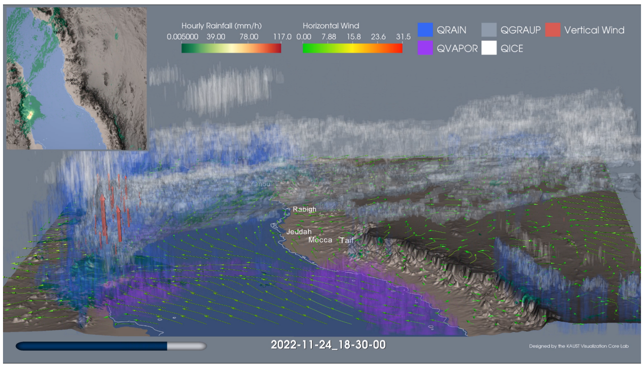


Figure 4: *Another extreme rainfall event originated from the Jeddah extreme rainfall event and touched the west coast at around 18:30 UTC.*

8. Conclusions

In this work, we presented a visualization environment to analyze extreme rainfall events. We iteratively designed the environment in close collaboration with domain experts. The rainfall data was generated using the WRF model at a high resolution of 1 km. The visualization enables domain experts to interactively analyze multiple variables of the generated simulation data. We also presented a case study of an extreme rainfall event that happened in Jeddah on November 24, 2022. The domain experts were able to better understand the evolution of the storm through the visualization. The environment also enables them to analyze the interaction of various variables present in the data, which leads them to more details about the behavior of the mesoscale convective storm.

9. Acknowledgments

This work was supported by the Climate Change Center at King Abdullah University of Science and Technology (KAUST) under the National Center for Meteorology (NCM), Saudi Arabia. We also like to thank KAUST Visualization Core Lab for their help and support.

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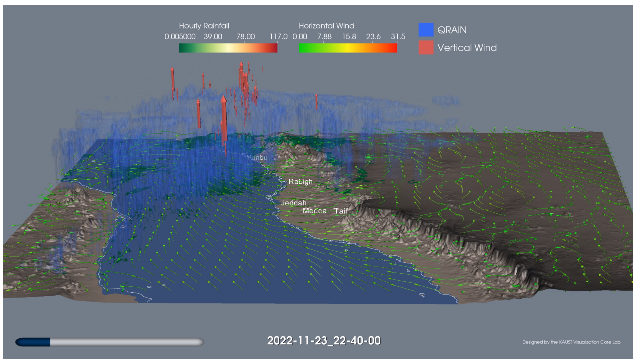
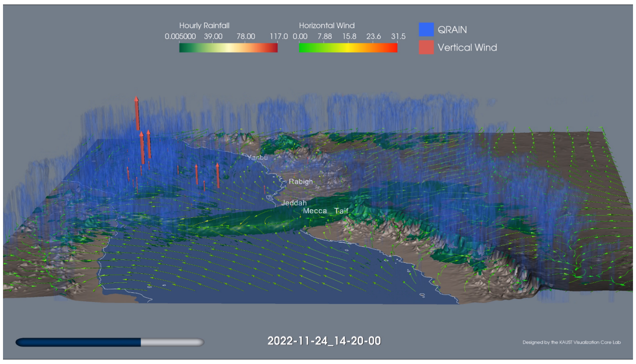


(a) *Vertical upward wind vectors associated with Jeddah extreme rainfall event (November 23, 2022, 22:40 UTC.*



(b) *Vertical upward wind vectors associated with Secondary extreme rainfall event emerged after Jeddah event(November 24, 2022, 14:20 UTC)*

Figure 5: *Vertical Upward Wind Vectors shown along with QRAIN variable*

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