MeteoVis: Visualizing Meteorological Events in Virtual Reality

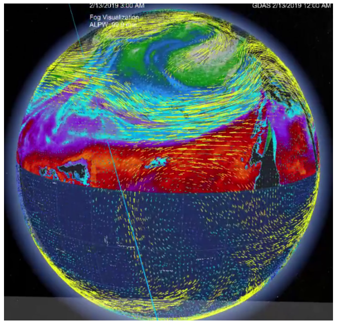

Figure 1: A global overview from MeteoVis: By visualizing wind vector fields overlaying water moisture data, meteorologists can quickly identify the speed and direction of moisture flux in the atmosphere in virtual reality.

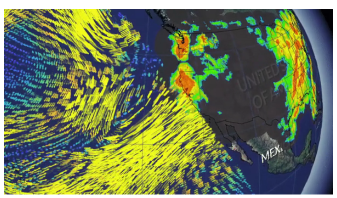

Figure 2: A zoom-in view from MeteoVis: As wind (leftwards vector fields) from the Pacific Ocean pushes moisture in the atmosphere towards the west coast of North America, record-breaking rainfall (depicted as heat map in the right) rapidly accumulates throughout California near San Francisco in February 2019.

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Abstract

Modern meteorologists in the National Oceanic and Atmospheric Administration (NOAA) use the Advanced Weather Interactive Processing System (AWIPS) to visualize weather data. However, AWIPS presents critical challenges when comparing data from multiple satellites for weather analysis. To address its limitations, we iteratively design with Earth Science experts and developed MeteoVis, an interactive system to visualize spatio-temporal atmospheric weather data from multiple sources simultaneously in an immersive 3D environment. In a preliminary case study, MeteoVis enables forecasters to easily identify the Atmospheric River event that caused intense flooding and snow storms along the western coast of North America during February 2019. We envision that MeteoVis will inspire future development of atmospheric visualization and analysis of the causative factors behind atmospheric processes improving weather forecast accuracy. A demo video of MeteoVis is available at https://youtu.be/pdkXhkTtimY.

Author Keywords

scientific visualization; virtual reality; meteorological data; immersion; interactive visualization; vector field

CCS Concepts

•**Human-centered computing** → **Geographic visualization;** *Virtual reality;* Scientific visualization;

Figure 3: Meteorologist Oklahoma Norman tracks super cell tornado outbreak using AWIPS, May 5, 2013. NOAA©. AWIPS visualizes regional meteorological data across multiple panel window displays.

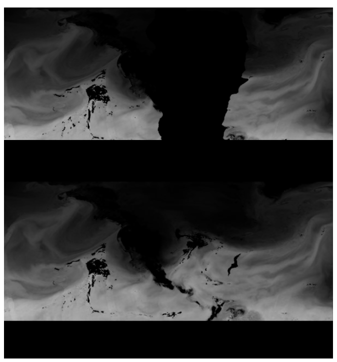


Figure 4: MeteoVis can assist meteorological analysis by inpainting missing regions. (a) shows a frame of the original ALPW data with a large region of missing data over the Atlantic Ocean. (b) shows the inpainted data where missing regions have been filled by interpolating data from the neighboring time intervals.

Introduction

Improvement in weather and climate prediction can have a significant impact on environment, natural resources, infrastructure, economy, and public health [2]. Nowadays, meteorologists at the National Oceanic and Atmospheric Administration (NOAA) use the state-of-the-art Advanced Weather Interactive Processing System (AWIPS)[1] [12] to visualize spatio-temporal meteorological data. As shown in Figure 3, AWIPS presents meteorological data in 2D displays, with different data sources spread across multiple windows. However, mentally fusing data from multiple sources with varying spatial domains comes with a high cognitive burden [16, 4]. To address the limitations of AWIPS, we started with the following research questions: How can we leverage virtual reality to efficiently fuse spatio-temporal meteorological data? Will 3D visualization of meteorological data assist in weather prediction and collecting insights? How can we design a user interface to be approachable and useful for domain experts inexperienced with virtual reality systems?

To answer these questions, we engaged in a 6-month iterative design process with a group of 3 Earth Science experts to develop MeteoVis, an interactive application to visualize the spatio-temporal atmospheric data from multiple sources simultaneously in an Oculus VR environment. We contribute to the scientific visualization and HCI community by presenting the challenges and initial solutions for fusing spatio-temporal meteorological data in immersive environments. We use real-world data and demonstrate the capability of MeteoVis through a pilot case study with meteorologists [15, 14].

[1] AWIPS: https://www.esrl.noaa.gov/gsd/eds/awips

Data Sources and Related Work

MeteoVis enables users to visualize meteorological data from several different sources and advances over prior meteorological visualization systems.

NOAA Microwave Integrated Retrieval System

Our primary dataset is the Advected Layered Precipitable Water (ALPW) product [7]. The ALPW product displays liquid water content in the atmosphere using data from NOAA's Microwave Integrated Retrieval System (MIRS) [1]. Data is estimated in four atmospheric pressure layers: surface-850 hPa, 850-750 hPa, 700-500 hPa, and 500-300 hPa. Each layer corresponds to an altitude of roughly 1 KM, 2.5 KM, 4.5 KM, and 8KM respectively. Estimated water content is advected across a 3-hour time interval. Traditionally, time-varying features are displayed with an slideshow-animation with images from each 3-hour time interval. The spatially-varying moisture is displayed using a colormap which highlights higher-moisture areas in more salient colors and lower-moisture areas in less salient colors.

NOAA and NWS students are trained to identify weather events by analyzing the ALPW product through Virtual Institute for Satellite Integration Training (VISIT)[2] at Colorado State University.

NOAA GOES Geostationary Satellite Server

Our second dataset is from NOAA's GOES-16 and GOES-16 Geostationary Satellite Server. We focus on visualizing three products from the GOES-16 and GOES-17 satellites: Radiance [3], Cloud Top Height [4], and Derived Motion Winds

[2] VISIT: http://rammb.cira.colostate.edu/training/visit

[3] Radiance datasets: https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C01501

[4] Cloud Top Height dataset: https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C01505

Figure 6: MeteoVis renders volumetric clouds from the GOES Cloud Top Height Data. We shade the clouds based on the relative heights: lower clouds are shaded in a darker color.

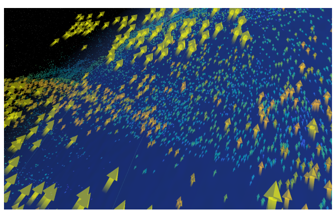


Figure 7: MeteoVis aggregates and renders wind data as "wind arrows". "Wind arrows" are animated with their movement speed based on the spatio-temporal data from GOES Derived Motion Winds. Their altitude is estimated from their pressure. Wind arrows are shaded based on either their speed or their estimated altitude.

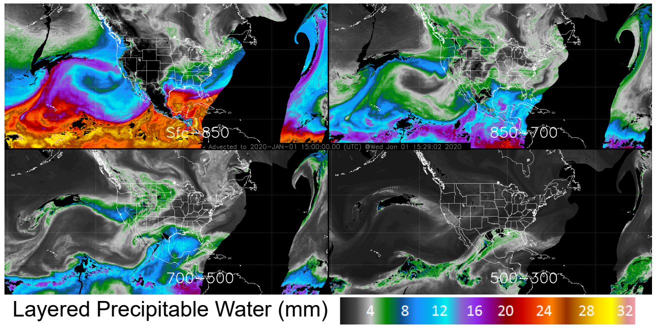


Figure 5: The Advected Layered Precipitable Water Product (ALPW) visualizes water moisture in the atmosphere at four different levels. Water moisture is measured in millimeters (mm) of precipitable water and ranges from 0 mm to 32 mm. Traditionally, each layer is shown separately in different windows.

[5]. Data for all three products is available for the full Earth disk every 15 minutes. The radiance and cloud top height data are encoded as images in a geostationary projection. The derived motion winds data is encoded as a list of 5-dimensional vectors consisting of latitude, longitude, angle, speed, and pressure. Although all 3 products are available in 15-minute intervals, they are not reported simultaneously.

Global Data Assimilation System

Our third dataset is wind data from NOAA's Global Data Assimilation System (GDAS)[6]. We visualize wind data provided as an (x, y) vector field of size 360×180 across the entire globe. Data is provided in 6-hour intervals along several pressure levels from 20 millibars to 1000 millibars.

[5]Derived Motion Winds dataset: https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C01518

[6]Wind data: https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-data-assimilation-system-gdas

Visualization of Meteorological Data

In past decades, computer graphics and scientific visualization researchers have investigated visualization of meteorological data. The seminal work by Hibbard [8] in 1986 combines perspective, shading, depth precedence, transparency, brightness, shadows, and motion parallax to visualize the cloud, wind, and radar data. Papathomas *et al.* [17] summarize a line of algorithms and applications of 3D visualization of meteorological data [21, 22, 25]. A recent survey by Marc *et al.* [20] covers visualization displays [9], techniques [13], rendering [11], and visual analysis [24] by 2017. However, few addressed virtual reality visualization.

MetVR [26], is the closest system to our MeteoVis. MetVR uses volume rendering, particle fields, and isosurfaces to visualize temperature, precipitation, and cloud density in a virtual environment. However, MetVR focuses on weather at a local scale whereas our development focuses on visualizing meteorological events on a global scale along with their impacts on local weather.

Visualization Techniques

MeteoVis integrates several visualization approaches to fuse and display each product in virtual reality and supports showing multiple products simultaneously. We use Unity 2019 and Oculus Rift for development and case studies.

Atmospheric Moisture Sphere

In early iterations, we focus on visualizing the ALPW product. For this product, we develop a dense 3D volume visualization shown in Figure 8 using a custom fragment shader which performs cubic across the 4 layers. By interpolating the 4 discrete layers into a volume, MeteoVis allows meteorologists to visualize the data as a single continuous moisture volume. We use the same colormap to represent different values of moisture levels from 0 mm to 32 mm which is familiar to meteorologists already using the ALPW product.

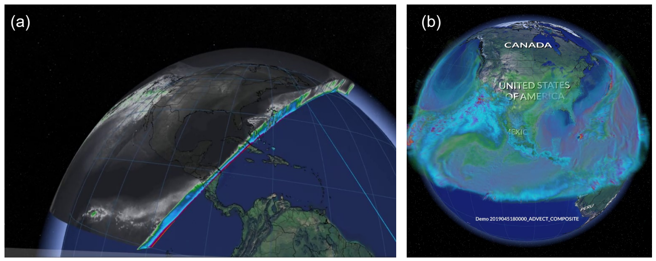
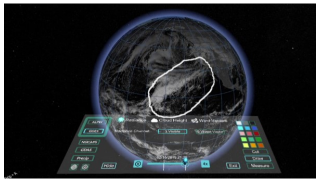


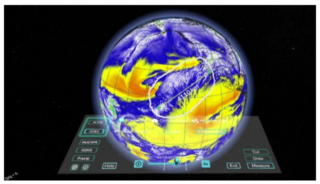
Figure 8: MeteoVis renders a dense 3D volume of the ALPW product for better understanding of the moisture level. (a) shows our dense 3D volume ALPW visualization. (b) shows our ALPW visualization with transparency applied to low-moisture areas with the same colormap as shown in Figure 5.

To visualize multiple altitudes simultaneously, MeteoVis can change the visibility of low-moisture areas, as shown in (b) for Figure 8. When this mode is enabled, areas with less than 5 mm of moisture are made transparent, allowing users to only observe high-moisture areas. We also allow users to cull the visualization based on the moisture level.

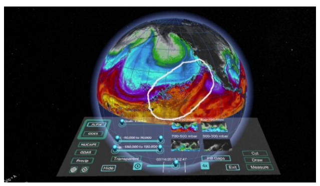
The ALPW product is sampled at 3-hour intervals, each with distinct areas of missing data as shown in Figure 5. Due to the temporal sparseness and missing data, animation of the ALPW product over time appears choppy and discontinuous. To address these issues, we developed a scheme to interpolate the ALPW data using SuperSloMo [10] which interpolates between video frames using a neural network. By preprocessing the data using SuperSloMo, MeteoVis enables a smooth playback of ALPW data without large missing regions distracting users.



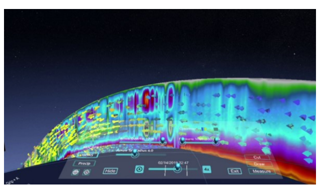
(a) Visible Radiance



(b) IR Radiance



(c) ALPW Moisture



(d) Close-up with Wind

Figure 9: The Atmospheric River event which struck California on Feb. 13–15, 2019 can be quickly identified in MeteoVis by fusing several different data sources and from multiple perspectives.

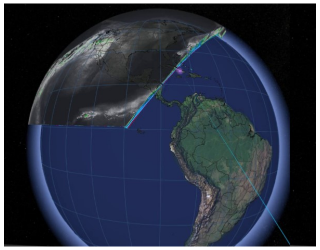
Clouds
Next, we focus on visualizing the cloud top height data from the GOES-16 satellite. We use volume rendering to depict spatio-temporal characteristics of clouds. Our visualization, shown in Figure 6, employs animated Perlin noise [18] and real-time ray marching in a fragment shader inspired by Inigo Quilez's "Clouds" [7]. We colorize the clouds based on height, with lower-altitude clouds shown in a darker color.

Winds
Furthermore, we depict wind data from the GOES dataset as animated 3D arrows as shown in Figure 7. Our animated 3D arrows at placed in 3D space allowing users to see wind data across several altitudes simultaneously. We allow the user to shade the wind arrows either based on their speed or their altitude.

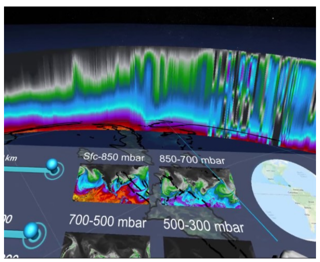
Overlays
Finally, we focus on visualizing GOES radiance and precipitation data. MeteoVis renders the 2D data with projective texture mapping [3] onto the globe surface, as shown in Figure 2. By presenting 2D data in VR visualization, users are able to see how 2D datasets, such as radiance images, relate to 3D datasets such as atmospheric water moisture and cloud top height.

User Interaction
Following Shneiderman's mantra: "Overview first, zoom and filter, then details-on-demand" [23], MeteoVis offers several ways to manipulate and present meteorological data suitable for data exploration and teaching applications. Through our iterative design process, we develop a user interface which is both approachable by novice users and useful for domain experts.

[7] Clouds: https://www.shadertoy.com/view/XslGRr



(a) Global View



(b) Surface View

Figure 10: MeteoVis provides both a global overview (a) and a close-up surface view (b) for analyzing ALPW data from two different perspectives. When the user zooms in, filters and enables the surface view, the annotation tools are replaced with a mini-map in virtual environments to help orient the user.

Perspectives in levels of detail
MeteoVis allows users to view data from two perspectives in VR: global view with a high altitude, and surface view with a low altitude. The global view allows users to see structures at a synoptic-scale (macro) while the surface view allows users to see meso-scale (local) level details.

In the global view, we position the globe in front of the user. The user rotates the globe along two-axes using the joystick on the Oculus touch controller. Moving the right joystick up and down tiles the globe along the x-axis while moving the right joystick left and right rotates the globe along the y-axis (the rotational axis). We lock the tilt of the globe so that it is never inverted, *i.e.,* so that the north pole never faces down. Moving the joystick on the left Oculus touch controller moves the user closer and further from the globe. In our pilot case study, we found that offering a full 3 degrees-of-freedom rotation for the globe disorients novice users, oftentimes preventing users from achieving their desired orientation.

In the surface view, we position the globe below the user so that they are hovering over the data. We allow users to enter the surface view by selecting a position on the globe. When in the surface view, the left joystick allows users to "move" on the globe by rotating the globe beneath them. The right joystick controls their rotation on the globe.

Control Panel
To minimize the learning curve of MeteoVis, we allow users to manipulate the system through natural interactions with a 3D control panel in the virtual environment, taking advantage of the hand gesture and motion tracking afforded by the Oculus Touch motion controllers. In developing the controls for our visualization, we incorporated feedback from both first-time visitors and experienced meteorologists in

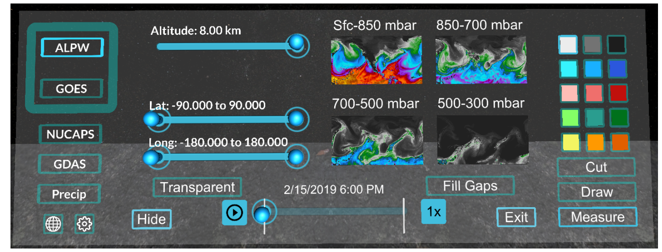
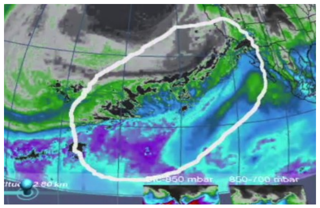


Figure 11: The control panel of MeteoVis. Users manipulate the visualizations using a combination of buttons and sliders. The control panel layout changes depending on the dataset selected.

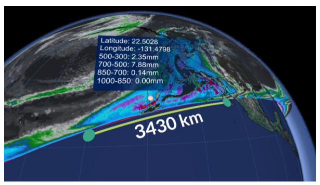
our iterative design process. Their suggestions led to the current design for our control panel shown in Figure 11.

The sliders on our control panel affect features of our data which are continuous in nature. For instance, the altitude slider allows users to control the height of the ALPW visualization shown in Figure 8 from 1 km to 8 km. For ranges of continuous values, we develop a two-handle slider. To control the sliders, users hover their virtual hand, over the knob of the slider. While grabbing the knob using the hand trigger on the Oculus Rift controller, users physically move their hand to adjust the position of the knob. We found that for sliders, the physical motion allows more precise control of sliders than using joysticks.

The control panel is also used to toggle visualizations. While different visualizations can be simultaneously enabled, only one layout on the control panel is shown at any given time to reduce the visual clutter and allow users to find desired controls faster. When a user clicks on one of the visualization buttons, such as GOES, the corresponding sub-menu controls are presented on the control panel and its visualization is enabled. A second click disables both the visualization and its controls.



(a) Drawing Tool



(b) Measuring Tool

Figure 12: Two annotations created by meteorologists with the drawing and measuring tools in MeteoVis during our pilot case study. The purple indicator shows the exact location on the globe where the user is pointing. Annotations provide a reference when switching between data sources and changing perspectives.

Culling and Annotations

We incorporate three spatial tools to facilitate data exploration and presentation: cut, draw, and measure. The cut tool culls portions of the data as shown in part (a) of Figure 8. This allows users to see vertical cross-sections of the data or focus on specific areas of the data. The draw tool allows users to annotate the data which facilitates discussion and teaching. Finally, the measure tool allows users measure the length atmospheric weather events. The length is presented in kilometers along the great-circle distance on the surface of the globe.

Flythrough Recording

We develop a flythrough recording feature to assist meteorological training in VR. MeteoVis allows senior users to create a "flythrough" using keyframes as they operate the system. After recording keyframes, a flythrough is automatically generated with spline interpolation between keyframes and can be played back in the future. The flythrough feature is particularly useful for illustrating how weather events appear across different data products and progress over time to first-time users.

Case Study

In a pilot case study, meteorologists use MeteoVis to visualize the atmospheric river (AR) event impacting the western coast of North America during Feb. 13-15 2019 as shown in Figure 9. This AR event [8] caused flash flooding and mudslides throughout California with some regions observing over 12 inches of rainfall. A video of our case study is available at https://youtu.be/pdkXhkTtimY.

We demonstrate MeteoVis to dozens of visitors at the Maryland Blended Reality Center (MBRC) as well as domain experts at COMET[9], a training center for environmental sciences. We also demonstrate MeteoVis to meteorologists at the 2020 annual meeting of the American Meteorological Society [15, 14] and VR experts at MAVRIC 2019 [19]. In our initial case study, outside meteorologists have praised MeteoVis as "the most advanced VR software for meteorological data [they have ever seen]."

Conclusion and Future Work

In this paper, we present MeteoVis, a virtual reality visualization system that fuses and depicts meteorological data from multiple sources simultaneously in an immersive environment. We present a brief overview of the state-of-the-art visualizations used by meteorologists and how MeteoVis improves upon it by offering various controls and tools to manipulate, explore, and present the data. In a preliminary case study, we demonstrate MeteoVis being used by Earth Science experts to explore and present the atmospheric river (AR) event of Feb. 13-15, 2019.

In the future, we hope to improve MeteoVis by offering richer visualizations and more interactivity. Future work will focus on creating realistic weather simulations and incorporating live interaction similar to Geollery [5, 6] for real-time collaboration and education in VR. Incorporating real-time weather models may allow us to simulate future weather conditions and improve weather forecast accuracy.

[8] Feb. 2019 AR Event: https://www.climate.gov/news-features/event-tracker/wild-weather-west-coast-february-2019

[9] COMET: http://www.comet.ucar.edu/

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