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USING XR FOR IMPROVING SCIENTIFIC DISCOVERY WITH NUMERICAL WEATHER MODELS

Thomas Grubb¹, Kaur Kullman⁴, Thomas Clune¹, Leslie Lait², Matthias Zwicker³,
Stephen Guimond^{4,1}, Ruth West⁵, Roger Eastman³, Ian Afflerbach⁵, Don Engel⁴

¹ NASA ² Science Systems and Applications, Inc ³ University of Maryland, College Park

⁴ University of Maryland, Baltimore County ⁵ University of North Texas

ABSTRACT

Our work explores the use of extended reality (XR) to improve scientific discovery with numerical weather/climate models that inform Earth science digital twins, specifically the NASA Goddard Earth Observing System (GEOS) global atmospheric model. The overall project is named the Visualization And Lagrangian dynamics Immersive eXtended Reality Toolkit (VALIXR), which has two main areas of focus: (1) enhancing the understanding of and interaction with model output data through advanced visualizations in the XR environment, and (2) the integration of Lagrangian dynamics into the GEOS model, which allows a natural, feature-specific analysis of Earth science phenomena as opposed to traditional, fixed-point Eulerian dynamics. Here, we report initial work on these focus areas.

Index Terms— numerical weather prediction, virtual reality, extended reality, Lagrangian models

1. INTRODUCTION

An Earth science (ES) digital twin is a digital replica of the Earth system that combines numerical models, observations and analysis/visualization tools to support applications and decision making for human hazards. These digital twins help us understand the complex interactions and interrelationships that make up our Earth system and how to provide optimal information for making actionable predictions. Our work addresses two areas of ES digital twin research: (1) improving the understanding and interaction with ES model output by using Virtual and Mixed Reality (XR) visualization tools and (2) improving the interpretation of natural phenomena simulated with ES models by incorporating Lagrangian dynamics, which follows features of interest, into the model and visualization package.

Traditionally, scientists working on ES view and analyze the results of calculated or measured observables with static

1-dimensional (1D), 2D or 3D plots displayed on flat computer screens or paper. Using such mediums, it can be very difficult to identify, track, and understand the evolution of key features due to poor viewing angles and the nature of flat computer screens. In addition, numerical models, such as the NASA Goddard Earth Observing System (GEOS) ES model, are almost exclusively formulated, visualized, and analyzed in an Eulerian reference frame [1] with fixed grid points in space and time. However, ES phenomena such as convective clouds [2], hurricanes [3], and wildfire smoke plumes [4, 5, 6] are often visualized and analyzed best in a Lagrangian reference frame [1]. Therefore, it is often difficult and unnatural to understand such Lagrangian phenomena in relation to the Eulerian fields output by models such as GEOS.

As XR has been shown to enable domain scientists in other fields to develop a better understanding of their data [7], we seek to use XR to support GEOS users. Our implementation is in NASA's open source toolkit for XR, the Mixed Reality Exploration Toolkit (MRET) [8], because MRET has a track record in supporting the modular development of tailored visualizations for other application domains [9].

2. VISUALIZATIONS FOR VALIXR

In 3D visualizations, data generally takes one of three forms: gridded data [10, 11], where space is divided into regions sometimes represented as voxels (i.e., as a grid of rectangular prisms); point clouds [12, 13], where data is represented as a set of points; and meshes, where objects are rendered as surfaces composed of small polygons (usually triangles). A gridded, Eulerian reference frame has been the default representation for the 2D and 3D visual analysis of atmospheric data in part because most numerical methods used to solve the governing equations use a structured grid approach. Another reason why Eulerian, gridded representations tend to be used for visualizing data from such models is because Lagrangian trajectories [14] are often difficult to interpret from representations on 2D surfaces, due to line-of-sight ambiguity - immersive visualization could help with that.

In our work, we are particularly interested in data from

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GEOS. Instead of attempting to visualize a fixed grid of voxels calculated by GEOS, we embed a trajectory model in GEOS to simulate particle movement throughout the timesteps calculated as the Eulerian model runs. Examples of the resulting trajectories are depicted in Figure 1. We then combine these particle trajectories as animated point clouds with GEOS gridded data and other ES phenomena data to form a combined visualization that the user can intuitively interact with using MRET.

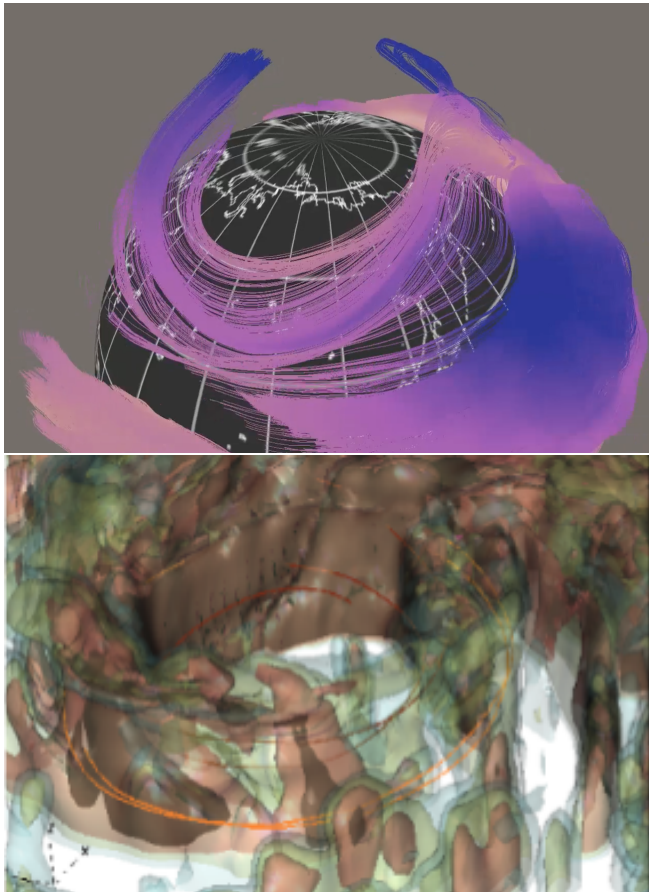


Fig. 1. Preliminary sketches of our visualization idiom, (top) Altitude represents pressure coordinates; color represents warm-cool gradient. (bottom) Isosurfaces are combined with Lagrangian paths.

While the technical implementation of our visualization is non-trivial, the considerations regarding human factors are at least as important. In order to provide domain scientists with useful visualizations, we needed to first determine the mental models [15] they use to understand their own datasets. This is accomplished through observational studies and interviews. While our visualizations may be interesting to non-experts, our primary goal is accelerating scientific work by specialist users. Therefore, our design choices reflect their mental models, even if the resulting visualizations turn out to be less

intuitive for the general public.

2.1. Point clouds for VALIXR

Efficient rendering of arbitrarily large point clouds is an ongoing challenge that is being addressed by the computer science community [16], with GPU-based optimizations and efficient GPU memory utilization a common theme of recent advances [17]. These factors are particularly important for rendering point clouds in XR, where sustained high frame rate is mandatory.

As MRET is built using Unity 3D game engine, we must implement appropriate point cloud optimization methods within Unity or make the resulting optimized point cloud accessible from MRET. Unlike recent versions of Unreal Engine, where Nanite could be used for visualizing large point clouds, Unity lacks such capabilities. Our initial tests established that Unity's native point cloud rendering component can handle a cloud consisting of around 30,000,000 static points with sufficient frames-per-second for a tethered Virtual Reality headset (RTX3080Ti with HTC Vive Pro Eye). However, this is less than what is needed for the VALIXR datasets. We must also be able to visualize point clouds in a manner where some or all of those points may need to be in motion relative to each other and to the observer.

To achieve that goal, we are investigating multiple options in parallel: a) adapting the idea published by Schütz et al [17] for Unity, despite Unity High-Level Shader Language (HLSL) limitations in comparison to OpenGL Shading Language (GLSL) and Microsoft HLSL; b) optimize point clouds outside of Unity but on the same machine, to optimize the point clouds based on the MRET user's current position and orientation; c) employ composite rendering where an external system calculates and renders the optimized point cloud based on MRET user's current direction and rotation, to then merge the resulting view into Unity's framebuffer. We anticipate that this point cloud visualization component will be beneficial for visualizations across a wide range of scientific and technical disciplines. In the meantime, we are using Potree v2 [18] for our initial experiments and user interaction development. While Potree cannot handle point clouds in motion, some of our initial user interaction studies can be conducted with Potree.

2.2. User interaction in VALIXR

While tracking the XR headset enables a user's immersion within a 3D scene of a data visualization, tracking of XR handheld controllers or user's hands enables us to implement intuitive user interactions with the visualized datasets. Conventional 2D tools require a user working with an ES visualization to conduct a series of complex interactions in order to accomplish relatively straightforward tasks, such as selecting or manipulating a set of points in 3D space. In a flat screen

interface, this has traditionally required specifying a set of points in three distinct 2D coordinate system projections (XY, XZ, and YZ). In other scientific domains, it has been shown that specifying or selecting a location or volume in XR using handheld controllers or tracked hands allows for greater speed and accuracy [19].

We anticipate the same will hold true for atmospheric data, and we will be sharing the results of measuring the utility of such an interface in our future publications about the VALIXR project. Notably, as the data being visualized is generated by GEOS as a prediction based on initial conditions, an intended application of our tool is to serve as part of an iterative feedback loop. Through XR, a scientist will review and manipulate the time series produced by a GEOS model run, modifying initial conditions as needed to do subsequent runs of GEOS. Thereby, XR-based improvements to speed and accuracy of tagging of points-of-interest using immersive data visualizations minimizes the effort required, enabling scientists to save valuable time and shared supercomputing resources to have more cycles available for other important projects.

2.3. Lagrangian dynamics in GEOS

A Lagrangian trajectory model, GigaTraj, has been developed at NASA's Goddard Space Flight Center for use in atmospheric research. It traces particle motions as they are carried by the wind fields obtained from any of several meteorological sources (selectable at run-time). It can trace particles in any of several coordinate systems, reflecting different physical approximations. For example, particles may be traced kinematically (i.e., using vertical wind fields), isentropically (along surfaces of potential temperature), or diabatically (approximately along isentropic surfaces, while using diabatic heating fields to move the particles vertically). This provides maximum flexibility for researchers.

The GEOS architecture is an integrated hierarchy of independent components based upon the Earth System Modeling Framework (ESMF). Lagrangian dynamics have been incorporated by wrapping GigaTraj as a new ESMF component that sits as a sibling component to the AGCM (atmospheric general circulation model). GEOS provides all prognostic and diagnostic fields as imports to the GigaTraj component. GigaTraj uses the selected AGCM meteorological fields to integrate the trajectories of a set of atmospheric particles. The end user can select a set of diagnostic quantities which will be interpolated by GigaTraj at the parcel locations. This makes the GEOS-embedded GigaTraj of immediate use to a wide range of scientists who use GEOS for a variety of simulations.

Whether a scientist is studying wave disturbances over the Atlantic ocean that develop into a hurricane or the eddies associated with the polar vortex, this module can be of tremendous value for advancing scientific understanding or diagnosing the internal model calculations, providing access to such

things as budget terms and dynamical feedback mechanisms that would otherwise be inaccessible. Additionally, the trajectory model can continue to be used in its original offline mode, using data from regularly-generated GEOS products to trace large numbers of trajectories passively for an even wider range of investigations.

2.4. Visualization Science Use Cases

2.4.1. Use Case #1: Wildfire Smoke Plumes

Global climate change has led to an increase in large and intense wildfires with recent events in the western United States producing devastating effects on the ground. Plumes of smoke from these fires can rise deep into the stratosphere where they can potentially lead to measurable climate forcing. VALIXR will be used to understand the transport and fate of these smoke plumes, as well as their interaction with surrounding features, through the Lagrangian dynamics tool and immersive visualization experience. Scientists would like to know what physical processes are responsible for the evolution of the smoke plumes, such as their vertical transport. The vertical transport of smoke is governed largely by convective cells pushing the smoke upwards and radiation-induced lofting effects. VALIXR will calculate trajectories and dynamical tendencies within smoke plumes and they will be displayed in the virtual environment to gain a deeper understanding of the vertical transport processes. Trajectories colored by radiative heating tendencies will allow a user to decipher the contribution of radiation-induced lofting to the total vertical acceleration. Dry and wet deposition terms viewed along the trajectories will help establish the mechanisms behind the decay of the smoke plumes. These trajectories and associated tendencies will be viewed alongside model output data to place the smoke plumes in context with surrounding atmospheric features.

2.4.2. Use Case #2: Convective Plumes

VALIXR will be used to examine the fate of overshooting thunderstorm tops, where polluted near-surface air is injected into the lower stratosphere. (See for example [11] and [2].) An important component of this problem is to identify and track the air that has reached the stratosphere, which allows the post-injection chemical history of the air to be modeled. Not only may the consequences of individual injection events be determined, but on the global scale the effects of deep, moist convection worldwide can be estimated, an important part of gauging the effects of climate change.

VALIXR will be used both for initialization and analysis. In the former, the user interactively creates clouds of particles above the GEOS tropopause over sites of strong convection systems (forecast or observed). These particles are then fed into the standalone GigaTraj model, and the output is communicated back to into VALIXR visualization system. A

similar process can be used to initialize particles at the locations of interesting measurements and then run the Gigatraj model backwards in time to examine the history that made those measurements interesting. Either way, the researcher can prune distracting and irrelevant trajectories and add new particles to under-sampled regions of interest, as the process repeats iteratively.

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