

VR Visualisation as an Interdisciplinary Collaborative Data Exploration Tool for Large Eddy Simulations of Biosphere-Atmosphere Interactions

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Abstract. Scientific research has become increasingly interdisciplinary, and clear communication is fundamental when bringing together specialists from different areas of knowledge. This work aims at discussing the role of fully immersive virtual reality experience to facilitate interdisciplinary communication by utilising the Duke Immersive Virtual Environment (DiVE), a CAVE-like system, to explore the complex and high-resolution results from the Regional Atmospheric Modelling System-based Forest Large-Eddy Simulation (RAFLES) model coupled with the Ecosystem Demography model (ED2). VR exploration provided an intuitive environment to simultaneously analyse canopy structure and atmospheric turbulence and fluxes, attracting and engaging specialists from various backgrounds during the early stages of the data analysis. The VR environment facilitated exploration of large multivariate data with complex and not fully understood non-linear interactions in an intuitive and interactive way. This proved fundamental to formulate hypotheses about tree-scale atmosphere-canopy-structure interactions and define the most meaningful ways to display the results.

1 Introduction

“Interdisciplinary research is a mantra of science policy” [1]. As our knowledge in each area advances, the need for information from other areas of knowledge becomes increasingly important. More and more of the critical research issues consist of problems that involve interactions between topics, which would have classically been affiliated in different disciplines. For example, global economic growth, climate change, and the recent food crisis cannot be fully understood by focusing only on economy, meteorology, or agronomy aspects: indeed, all these questions are inter-related, as they are linked to several other areas of knowledge. On the other hand, the interdisciplinary character of such questions poses the challenge of bringing together specialists from different areas of knowledge, and clear communication across disciplinary boundaries is fundamental in this case.

Virtual reality visualisation can be used as a powerful tool to facilitate communication. As pointed out by Riva [2], virtual reality constitutes an efficient communication tool because it is able to bring different inputs and data into a single experience, and more importantly, allows the users to explore and immerse themselves in virtual environments. The communicating efficacy of this full immersive experience can be confirmed by its use to foster scientific discussions [3] and the increased use as an educational tool [4, 5].

This work describes the development of a VR visualisation data viewer and explorer for the simulation output of the Regional-Atmospheric-Modelling-System-based Forest Large Eddy Simulation (RAFLES) [6, 7]. This model studies biosphere-atmosphere interactions, and in particular, the effects of sub-tree-scale (very high-resolution in meteorological terms) heterogeneity of the forest canopy on wind flow, turbulence and fluxes inside the canopy and above it at the atmospheric boundary layer. Intrinsically an interdisciplinary research tool, this high-power computing model resolves the interactions between forest canopy structure, ecosystem dynamics and the biological functioning of trees, atmospheric fluid dynamics, turbulence and dispersion.

Our project was the only study that simulated forest canopies as naturally realistic, 3-D heterogeneous structures that interact with atmospheric flow at high resolution (since we started our work two other research groups have used 3-D heterogeneous forest large eddy simulations [8-12]). Not much was known about the fine-scale effects of canopy structure, its interactions with turbulence, and with plant functions such as transpiration of water vapour. Atmospheric boundary layer flows, as any turbulent process, have chaotic structure in space and time with complex fractal-structured eddies that advect and evolve in space and time. A visualisation tool for data exploration was needed at the early stages of the study in order to detect and identify such effects because we had no *a priori* knowledge of what were the effects of canopy structure on the flow, where were they concentrated, and what were the resulting turbulence features that were most affected by particular canopy structures. This tool had to present both the dynamics atmospheric variables and the canopy structures in the same space, animate them in time, and do that in a way that would be intuitively interpreted by collaborating researchers from the atmosphere, ecology and remote sensing disciplines.

The main goal of this work is to present a system in which the modelled interactions between the heterogeneous structure of the canopy and the atmosphere can be visualised in an intuitive and interactive way. The data was explored inside the Duke Immersive Virtual Environment (DiVE), a 6-sided CAVE-like system [13]. We utilized the commercial scientific visualisation package AMIRA [14]. Although we used this system to analyse the interactions between canopy and atmosphere in a very fine resolution, it could easily be applied in other types of studies, such as regional and global scale simulations of biosphere-atmosphere interactions. This system is an effective tool to promote communication and facilitate collaboration at the early stages of data analysis between different scientific communities and to present the results of complex numerical models that study non-linear interactions between physical systems from different scientific disciplines.

In this paper we briefly describe the forest model and VR system design. We then present how the shared interdisciplinary communication using the DiVE with collaborating researchers resulted in scientific hypotheses that we were able to quantitatively verify using statistical methods.

2 Related Work

Virtual Reality in Atmospheric Sciences. Atmospheric science is amongst the most dependent on visual tools. In fact, most of the current knowledge of atmospheric dynamics became possible only after the development of the first meteorological charts during the 19th century [15]. By plotting observations collected at different places and integrating them into a two-dimensional chart, early meteorologists were able to identify weather patterns, giving rise to what is called synoptic meteorology, which, since then, has become the basis for most theories in atmospheric science and weather forecasting. As the knowledge of atmospheric dynamics evolved in time, the atmospheric scientists realized that atmospheric systems had complex three-dimensional structures. The traditional two-dimensional plots and meteorological charts were limited in their ability to visualise both horizontal and vertical structures.

Currently, meteorological model results, including RAMS, the parent model of the LES described here, are commonly visualised by specialized interfaces such as ViS5d. Virtual reality always had strong appeal among atmospheric scientists since it could simplify the visualisation of such complex structures. In fact, many three dimensional visual tools have been developed specifically for atmospheric analysis, for example, the VIS-5D software, developed at University of Wisconsin during the late 1980s [16, 17]. During the 1990s several virtual reality projects were developed from VIS-5D, including a CAVE- and ImmersaDesk-friendly version, called CAVE-5D [18]. Recently, the National Center for Atmospheric Research's Visualisation Laboratory (NCAR) contributed to the new VIS-5D generation, called Vis5D+ [19] by including an option for stereo/3D projection. The visualisation facility CAVCaM of the Desert Research Institute [20] included CAVE-5D capabilities in visualisation of wild fire, and atmospheric conditions including dispersion of dust, and other aerosols, including chemical and biological agents. These simulations are driven by atmospheric models (WRF and RAMS). VIS-5D has become extremely popular in the meteorological community and it is currently used for scientific purposes ranging from pollution dispersion [21] to transport of debris by tornadoes [22], as well as for educational purposes [23, 24]. It does not have built-in tools for visualizing forests.

Surprisingly, few works effectively used virtual reality to study atmospheric surface layer processes and their interaction with land surface heterogeneity and structure, other than topography. Some examples include: Loth et al. [25] developed a technique to study particle dispersion within the atmospheric boundary layer using immersive virtual reality; and Nichol and Wong [26], who used virtual reality combined with remote sensing data to depict temperature variations due to heterogeneous urban features in Hong Kong, which proved a useful tool identifying the effects of wall shading and vegetated pockets within the city.

Virtual Reality in Canopy Studies. Studies concerning canopy structure and forest landscapes are common and there are several different tools available, as reviewed by Sen and Day's [27] and Pretzsch et al. [28]. Most of these tools are focused on the representation of individual trees in a highly realistic way, and even include environment factors such as light competition, temperature and shading obstacles to drive the tree growth and shape [29]. However, as pointed out by Pretzsch et al. [28], fewer studies extended to more complex plant ecosystems [30], and even less have the

interactive character and portability to integrate model output [31]. To generate the realistic look of a tree or a forest stand, these models demand a large set of parameters describing the stand. These parameters for explicit, real forest stands are rarely available over large enough domains (several km^2) that are needed for even a small-scale atmospheric boundary layer simulation. While many of these parameters are essential for the realistic visualisation of trees, most of them are not effective in the interaction between the forest and the atmosphere and, thus, are not represented in atmosphere-biosphere simulations. Furthermore, no study has shown the interaction between the canopy structure and the surrounding atmosphere.

3 Method

Atmosphere-biosphere Large Eddy Simulation. Biosphere-atmosphere interactions couple vegetation function and structure with the atmosphere. This two-way coupling includes non-linear feed-back biophysical mechanisms primarily through the effects on the fluxes of water and heat emitted by vegetation and by modification to the soil moisture. The RAMS-based Forest Large Eddy Simulation (RAFLES) [6] explicitly resolves turbulence in realistic, observation-based, 3-D heterogeneous canopies. RAFLES' parent model, RAMS [32], is a regional atmospheric model with grid nesting capabilities that can run as an LES. It solves the Navier-Stokes equations, using a quasi-hydrostatic approach and the Boussinesq approximation, on a rectangular, vertically stretched grid mesh, with a staggered grid scheme, and uses a split-time leapfrog discretization scheme. It includes radiation and dispersion parameterizations. The sub-grid-scale turbulence kinetic energy (SGS-TKE) parameterization scheme is based on Deardorff [33] modified with additional turbulence backscatter terms [34].

RAFLES includes several developments from its parent model RAMS, specifically introduced to handle the effects of the canopy and to increase the numerical stability at the typically high spatial and temporal resolutions of the simulations. It includes a multi-layer, 3-D heterogeneous canopy. It allows for the effects of leaves on drag and fluxes to the atmospheric surface layer in the canopy air space. Tree stems are represented in the atmospheric model as restrictions to the free-air volume. Its typical grid-mesh spacing of the order of 1 m^3 , allows for the simulation of many of the features that are generated by tree-crown structures. Its simulation domain, typically on the order of 1 km^3 is large enough to simulate a fully dynamic boundary layer. The canopy structure in the model can be prescribed, based on remote sensing [35], or, as described here, constructed by the Virtual Canopy-Generator (V-CaGe [36]). V-CaGe generates a random canopy field, λ , using a 2-D Fourier transform with a specified correlation function and a random phase and observed allometric relationships of the simulated forest stand. Ecosystem dynamics and the biological functioning of trees in terms of leaf temperature, reflected and absorbed radiation and water vapour heat and CO_2 fluxes from leaf surfaces to the atmosphere are calculated by a dynamically coupled version of the Ecosystem Demography model (ED2RAMS [37]).

Visualisation in the DiVE facility. The DiVE is a $3\text{m} \times 3\text{m} \times 3\text{m}$ room with rigid ceiling and floor, flexible walls, a sliding door and using a 7 PC workstation Cluster running Windows XP with NVidia Quadro FX 3000G graphics cards as the graphics-rendering engine. Christie Digital Mirage S+2k DLP projectors connect with

Stereographics active stereo glasses. Head and wand tracking is supported by the Intersense IS-900 system. For virtual worlds designed for this system, it is a fully immersive room in which the individual literally walks into the world, is surrounded by the display and is capable of interacting with virtual objects in the world.

We have developed a post-processing package that reads the compressed RAFLES model output fields and converts a specified sub-domain (in space and time) into binary AMIRA data scripts. These scripts specify data objects according to data type. We used the native stacked slice coordinate to fit the model's coordinates which are horizontally regular and with a specified stretching in the vertical direction. Atmospheric scalars were written as density fields, wind as a vector field (the vertical component of the wind was also duplicated as a density field). Leaf density of the canopy was incorporated as a density field and surface patch. The tree stems are line/cylinder objects. Dispersing particles (simulating seeds) were viewed as line objects. Once the data is loaded into the program, a rich GUI provides many techniques and approaches for visualizing and exploring the data. AMIRA was selected as an interface because its VR interface was already developed in the DiVE system, and because it allows a flexible and rich GUI for visualization. AMIRA comes with many visualisation techniques which can be easily applied to the data. Of particular use for this data exploration, are: orthogonal and oblique slicing; volume and surface rendering; isolines and isosurfaces; vector fields; stream line rakes and illuminated stream lines.

Head tracking allows the user to move their head, and then see the proper view for the new position and orientation. This, coupled with the active stereo, allows the user to gain a better perception of the size and structure of 3D objects. A virtual wand is useful for multi user sessions, in that the tracked user can point out regions of interest to the other users. By pressing a button on the wand the user can move and slice planes, or stream line sources, rotate and reposition the domain anywhere in the space. This allows the user to see relevant aspects of the model from other angles and other positions. Finally, a tablet style display is mounted to a swing arm, which can be moved inside the DiVE. By using a stylus, the user is able to interact with the AMIRA GUI directly while in the DiVE. With the tablet, the user can toggle what is displayed, change visualisation settings, add new data files, or load new models. Both the wand and the stylus-tablet interfaces were routinely used throughout data exploration and increased the flexibility of data visualization and allowed the users freedom to immediately view new variables and angles and test ideas about the meaning of the data.

4 Results

Visualisation and VR Experience. The major advantage of VR data exploration initially was the ability to view and communicate data of different types, canopy wind and scalar fluxes, at the same space and time. The VR environment allowed walking through the data, tilt and move points of view, and observing the relationships between different variables from many angles. Conventional visualisation of LES results are performed using a 2-D vertical cross-sectional plane, with arrows for wind vectors and colour for scalars. As we were suspecting that one of the major effects of the canopy's leaf density structure on the wind flow will be a modification to the vertical wind, we have treated the vertical component of the wind as an additional scalar (fig. 1.A).

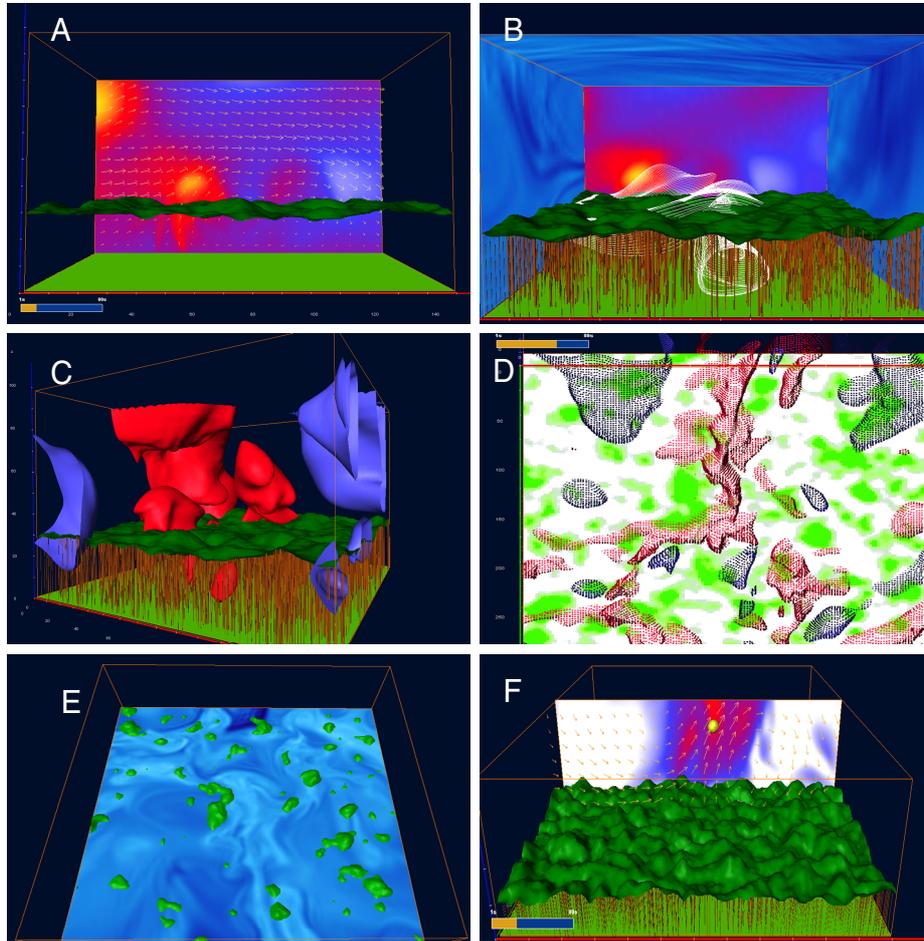


Fig. 1. A. “Conventional” visualization. Data presented on a vertical cross section through the centre of the domain. Arrows show wind vectors, colour indicates the vertical component of the wind (w). The canopy top is visualized as a green surface. B. Humidity (blue colormap, side and top walls), w (physics colormap, back wall) and streamlines through the canopy. Stems illustrated as brown lines. C. “Cloud” visualization of momentum ejections and sweeps. Red and blue “clouds” are isosurfaces where w is 0.8 and -0.8 m/s, respectively. The thin “legs” that connect the “cloud” to the canopy top tend to penetrate the canopy where it is relatively low. D. A view from under the canopy. Canopy leaf density is projected using a white (low)-green (high) colormap on a horizontal cross-section through the mean canopy height. Ejection and sweep isosurface “clouds” are semi-transparent point surfaces. In this snapshot, ejections aggregate in areas where the canopy is lower (leaf area = 0, white). E. Viewed from above, humidity shown using a white (moist)-blue (dry) colormap on a horizontal cross-section just below the highest trees in the forest (green “islands”). During ejection events humid air from inside the canopy rise and mix with the dryer air in the atmosphere above the canopy. F. Seed dispersal from an ejection hot-spot. A puff of seeds (yellow spheres) dispersing above the canopy. w is projected on a vertical cross-section (white – negative, red-positive).

The flexibility of AMIRA in specifying a frame and mesh for each variable meant that despite the staggered-grid setup of the model and the stretched vertical coordinates, variables could be correctly collocated in space without interpolation to a common grid. By using the meteorologically conventional visualisation (vector arrows, physics colormap for vertical velocity) with intuitive colormaps for additional scalars and canopy variables (blue-white for water vapour, green for leaf density and canopy, brown for stems) the data became intuitive for viewers that are accustomed to either the real forest (from the ecology discipline) or meteorologists. An unexpected but perhaps the largest advantage was the fact that VR is exciting and new and therefore it drew many viewers that would not have normally found the time to participate in preliminary stages of raw data analysis.

Initial excitement about the possibilities of volumetric visualisations, led to “loaded” visualisations, showing many variables, but giving little benefits in terms of additional insight into the canopy-atmosphere interactions. Of particular disappointment were streamlines and animated streamlines. These gave a very sparse sample of the volume and therefore, without initial knowledge about the preferred location for their initiation, provided very little additional information. Streamlines proved to be non intuitive for non meteorologist viewers, because they do not illustrate the actual path of a virtual object in the flow, but the potential path, assuming a frozen snapshot in time. The meaning of an animation of streamlines was therefore rather confusing for researchers, who do not regularly work with streamlines (fig 1.B).

One such “opportunistic” session with a cloud expert and an empirical forest micrometeorologist and a cloud meteorologist led to a breakthrough in the conceptual understanding of the effects of the canopy. Cloud visualisation often use wind iso-surfaces to visualise updraft and downdraft channels within a cloud system. Forest micrometeorologists often analyse time series taken from point observations in and above the forest canopy. Typical dynamic micrometeorological features of the flow are ejection and sweep events. These are rapid transitions toward a strong updraft and downdraft, correlated with a strong scalar flux and exchange of air between the canopy volume and the atmospheric surface layer above it. Using “cloud” visualisation (two isosurfaces at prescribed negative and positive thresholds for vertical velocity) to illustrate ejection and sweeps allowed locating these flow feature and focused our attention on the fact that they tend to concentrate at locations where the canopy is relatively low and surrounded by tall trees (fig. 1.C). Consequent sessions with remote sensing experts lead to more informative, yet more abstract views. These views emphasized the canopy-influenced bias in the distribution of ejection events (fig. 1.D-E).

Scientific Results from VR Experience. Thanks to comments from many collaborating researchers in several disciplines during joint data exploration sessions in the DiVE, a clear picture of the effects of canopy structure began to emerge. Given a good hypothesis, it was now possible to use statistical analysis and test these effects. The 30-minute time-averages (denoted by hat) of perturbations from the horizontal domain averages (denoted by pointed brackets) are calculated and used to evaluate the mean fluxes at each point along a horizontal cross-section through the domain, i.e. $w'\phi' = (\overline{w - \langle w \rangle})(\overline{\phi - \langle \phi \rangle})$ where w is the vertical component of the wind, ϕ is any scalar and a prime marks a perturbation quantity. The vertical fluxes of momentum, heat and water vapour were calculated at each height in the model. Fluxes were split using

conditional analysis to updraft ($w > 0$) and downdraft ($w < 0$) fluxes, indicating ejection and sweep events (respectively). A correlation coefficient for a second order polynomial correlation between the fluxes and the canopy height was calculated. The significance of these correlations was tested with a randomisation test, by generating 1000 canopies with the same parameters but a random phase. This made sure that spurious correlations due to mode-locking of wave patterns between turbulence and the canopy shape would be identified as not significant. Surprisingly, correlations were significant at relatively high altitudes (up to 5 times the canopy height), indicating a strong and persistent effect of canopy structure.

This effect is concentrated in “ejection-sweep” hot spots where low drag due to low leaf density and strong surface gradients of temperature lead to increased ejection and sweep occurrence and affects the triggering of new sweep events aloft. This realisation led to the design of a virtual experiment of the effects of canopy structure on seed dispersal. Seeds dispersing from these ejection hot-spots experience higher probabilities of ejecting above the canopy and dispersing for long distance, and thus affecting the population dynamics of some wind dispersed forest species that are typically growing in or near gaps in the canopy [7] (fig. 1.F).

5 Conclusions

The DiVE facility has proven an invaluable resource to bring the complex results from a dynamics, high resolution atmosphere-biosphere large eddy simulations of forest environments into a single framework that was both intuitive and interactive. Displaying the canopy and atmospheric data in conventional and intuitive ways, allowed forest ecologists and meteorologists to start the virtual tour at a “familiar” environment. While analysing the data using VR we learnt that some display schemes may prove non-intuitive and in the immersive experience. For example, streamlines were not helpful to identify patterns and were rather confusing for those not accustomed to their physical meaning.

Importantly, the fully immersive animated VR has a strong visual appeal, which attracted viewers whom otherwise would not have participated in data exploration at early stages. These interactions with specialists from related fields across disciplines brought interesting insights that allowed improving the display and eventually led to new understandings of the simulation results.

The ability to show multi-variable 3-D time dynamic data in an intuitive immersed environment allowed communication and exchange of ideas about effects that became apparent in the data and the mechanisms that led to these effects. The wand and stylus interfaces allowed changing the visualization and variables and focusing the viewers’ attention at different scales and sub-domains. This led to highly productive work sessions for collaborative data exploration that would have otherwise been very difficult on a non-VR computer screen, even with the same AMIRA visualization, and proved the major attraction of this application in the VR and the reason for repeated visits of the data in the DiVE that progressed to improved understanding of the data.

Finally, the intuitiveness, flexibility and possibilities to collaborate in the VR interface facilitated initial data exploration, where the size and complexity of the data made it hard to determine the effective patterns of interactions between canopy and

atmosphere without *a priori* knowledge of these effects. The joint cross-disciplinary data exploration in the VR facility was fundamental to establish hypotheses on the interaction between canopy and surrounding atmosphere, which we were able to statistically define and test. These led us to design several new experiments, ultimately showing the bi-directional interaction between the atmosphere and the biosphere in small scale, with important outcomes to ecology and meteorology, such as gap effect on seed dispersal.

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