Visualization, Analysis and Collaborative Discussion of Severe Weather Events

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Abstract. Designing effective collaboration, visualization, and analysis of severe weather events (e.g., excessive rainfall accumulation, floods, severe thunderstorms, tornadoes, and droughts) for meteorologists on the web is challenging because it requires processing huge amounts of data from different sources, diverse technologies, as well as using appropriate visualization techniques. This paper presents an innovative web toolset for visualization, collaborative discussion, and analysis of severe weather events. It is composed of the tool Viewing events on Maps (VIMAPS), which allows users to visualize and analyze severe weather events using maps enriched with multivariate data glyphs to observe spatial relations from any desired angle; and the tool called Collaborative system for Meteorological Data Analysis (COMETA) that allows the collaborative analysis of severe weather events between remote users synchronously or asynchronously. These tools were tested using real data and showed that they fulfill the usability requirements of this class of application.

Keywords: severe weather · visualization · analysis · collaboration · maps

1 Introduction

The World Meteorological Organization (WMO) provides many guidelines on information systems that provide early warning to severe weather conditions [6]. Weather events (e.g., tornados, wind, rain, temperature inversions, and lightning) bring several consequences to the city population, either on economic or health aspects. The primary purpose of such guidelines is to help the construction of tools and rules for preparing the National Weather Services worldwide to

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deal with severe weather events. That is the case of storms followed by floods, especially in urban areas, causing mortality due to drowning, landslides, and buildings' collapse. Most of the time, such situations are followed by death and without an appropriate weather warning.

Severe weather is either becoming more frequent or reported more often. The latter has been possible mainly due to better information technology and the increasing number of observations. Nonetheless, it is necessary to have appropriate computational tools to help specialists visualize and analyze such events to prevent death and loss of property. Computational tools are necessary to define resources for prevention, and the anticipation of weather events, minimizing damage caused by the severe events [7,10]. Although technological advances have made it possible to tackle complex problems in diverse areas, such as those related to weather [2,8,12,14,20,23–25], it is still a challenging task to design and develops systems to assist in the visualization, analysis, and collaborative discussion of severe weather events. This paper presents a web toolset for the visualization, collaborative understanding, and analysis of severe weather events. The Visualizing Events compose it on Maps tool called VIMAPS (VIewing events on MAPS), which provides a user-friendly environment, allowing users to interact with weather data and analyze severe weather information. The toolset also includes the Collaborative System for Meteorological data Analysis Tool (COMETA) that allows collaborative analysis and discussion between remote users in a synchronous way [4], where everyone interacts in real-time, or an asynchronous way, where the interaction can be distributed over time. Usability tests were applied to the developed tools through an evaluation guided by five experts.

This paper's remainder is organized as follows: Sect. 2 presents related works on this subject; Sect. 3 presents the VIMAPS tool, including its architecture, details about the maps enriched with glyph icons, and the 3D charts. It also describes the usability tests that were performed; Sect. 4 shows the COMETA tool. It also shows the usability test performed and the obtained results; and finally, the implications of this work are discussed in Sect. 5.

2 Related Work

Related work has been found in data analysis and mitigation of natural hazards due to excessive rainfall accumulations, for instance, and all sorts of extreme weather events. These studies describe the intrinsic characteristics of the associated weather phenomena concerning the evidence of natural disasters. Thus, we investigated studies that bring alternative or innovative ways of using technology for weather data analysis or the prediction of severe weather events. The technology described in such studies included all types of sensors, such as radar, satellites and meteorological stations, lightning sensors, or numerical weather prediction model data.

Ohneiser et al. [19] present a prototype that highlights the meteorological conditions and routes of affected aircraft. Their approach gives concrete advice based on the 4D trajectory for redirection, taking into account the complete arrival flow. The authors assume that this ongoing support can help flight controllers optimize highly dynamic air traffic flow, even if they do not fully follow the automatically generated plan. However, all approach operations to severe weather conditions remain supported by controller assistance systems.

Li et al. [11] developed a weather data visualization system capable of performing preprocessing, transformation, and rendering. The study's primary purpose was to optimize the use of a graphics processing unit (GPU) and a central processing unit (CPU) to speed up a general geo-visualization process. They used sandstorms as case studies. To compare the two approaches (GPU and CPU), visualization components based on each architecture were developed and analyzed. According to the experiments, both multi and many-core architectures can improve mathematical calculations and rendering using multi-threaded techniques.

The mentioned studies have common characteristics when historical data on maps, images, or geometric shapes enhance a given region. The proposed visualizations are based on a 2D plan; the drawback of such an approach is the lack of detailed insight of the selected area, hampering analysis and an understanding of valuable information for accurate decision making. Those approaches do not use graphical and interactive techniques for manipulating 3D charts, which can be applied in different areas and situations, such as natural disasters.

Kern et al. [9] proposed a visualization approach to analyze three-dimensional atmospheric fronts' structures and their physical and dynamic processes. Their approach aimed to build three-dimensional models from traditional 2D models. This transformation is possible by using the temperature change's magnitude along the gradient of a potential wet temperature field as the primary identification factor.

Theuss et al. [22] presented a 3D environment to visualize the cyclonic storm Chapala. Their research aimed to predict the cyclone's movement and characteristics, which was the second most robust tropical cyclone on record in the Arabian Sea. Therefore, they customized the solution for a specific problem. Feng and Fan [3] simulated snow, rain, and fog conditions in ZuiYi city, GuiZhou province, China. However, the solution is not integrated with a natural resource.

Many studies use virtual reality to visualize weather-related content, such as [22], which presents a 3D immersive environment in which users can better visualize the thick ice layer of a cyclone to better understand the relationship between distinct aspects of the data. Murata et al. [15] presented a real-time 3D visualization system for observing data of an X-band phased array weather radar (PAWR) in conjunction with ecosystems provided by a cloud service. Although this research works with real data and creates 2D and 3D visualization, it does not promote collaboration between users.

Stäli, Rudi, and Raubal [21] presented a 3D user-centered approach (the usual method is 2D). They focused on the visualization of weather-related graphics

used during flight preparation. The authors conducted a study with 64 pilots. In their results, it was evident that using a 3D approach, there was a decrease in cognitive load, but an increase in spatial awareness and usability.

Afzal et al. [1] present a review on the state of the art of ocean and atmospheric data set visual analysis approaches. They interviewed researchers, experts, and professionals working with datasets related to the study objects. The authors discuss techniques, systems, and tools, categorizing them using the following taxonomy: task requirements, interaction methods, visualization techniques, machine learning and statistical methods, evaluation methods, data types, data dimensions and size, spatial scale, and application areas. Based on the professionals' answers, the authors present trends, challenges, and opportunities for future research in the area, making clear that there are several questions to be addressed regarding the taxonomy defined by them.

A common gap in the reviewed works is the lack of collaboration between remote users. The value of the collaborative analysis of severe weather events proposed here lies in the exchange of information to improve the understanding of underlying features in the multi-source data. The research is focused on building a collaborative solution to be used in practice. So far, in the literature, very few attempts have been made in this direction.

3 VIMAPS

VIMAPS aims to allow users to visualize and analyze severe weather events through easy interaction with meteorological data, helping them in their decision-making. It processes and adds weather events (e.g., wind, rain, temperature inversions, and lightning) represented by glyph icons on maps in which the users navigate and interact, and analyze the events. These functionalities allow, for example, visualization when lightnings occur in the air or when it strikes the ground, and also its incidence (low, medium, or high) and the position on the map; and weather data (e.g., temperature, wind direction, wind speed, and pressure). Details are presented when the mouse pointer is over the glyph icons. The more the view is closer to the ground, the more details are presented.

3.1 Essential Features of VIMAPS

The essential features of VIMAPS are:

a) Process and position data from Atmospheric Electrical Discharge (AED) and Weather Events under maps, allowing the user to visualize, navigate, interact and analyze data represented by two-dimensional and three-dimensional interactive objects (3D symbols on the map). Through this functionality, the visualization of the information of atmospheric electrical discharges (AED) from the cloud to the ground or vice versa, latitude, longitude and current, date and time) Furthermore, meteorological data (station code, date, time, instantaneous temperature, maximum temperature, minimum temperature, instantaneous humidity,

maximum humidity, minimum humidity, dew point, maximum dew point, minimum dew point, pressure, maximum pressure, minimum pressure, wind direction, wind speed, wind gust, radiation, and precipitation) run through layers or levels (zoom), where the user can view the groupings of this data represented by 3D objects (symbols) on online maps. By positioning the mouse on these objects, detailed information (represented by two-dimensional data) regarding the meteorological events in question is displayed, and the closer to the ground, the greater the number of objects the user will visualize. For processing and positioning, VIMAPS uses the concept of GIS (Geographic Information Systems) to convert geographic coordinates into geometries, making it easier to manipulate spatial data and calculate a region's area, the distance between points, data exports for use in GISs, among others. This functionality is detailed in Sect. 2.

b) From a depth on the map and selected data sets, allow navigation, exploration, and interaction with a 3D representation, resulting from a combination of visualization techniques, which relate electrical discharge data, data from surface weather stations and their locations.

Through this functionality, the process of understanding a vast amount of data is simplified since the interactive 3D representations are organized in a tree structure that represents the data grouped by geographical regions and indexed by the types of electrical discharge data: cloud and soil. The division of a geographic region represents each graph into four parts (quadtree). Each part groups the sum of the sets of electrical discharges in that area. The data captured by the meteorological stations, referring to the area in question, are integrated into the graphic, creating the relationship between them in the visualization. This functionality is detailed in Sect. 2.

3.2 Vimaps Architecture

- Visualization module, which provides two types of interaction: global and specific. "Global" refers to manipulating the angles of the map, facilitating the visualization of the terrestrial globe and its objects. Specific interaction occurs when the user hovers over a particular map area. Users can visualize and analyze the data using maps enriched with multimedia elements (e.g., glyph icons, text, and images). Users can view and analyze data using 2D maps or an environment composed of 3D representations;
- Engine module, which consists of algorithms used to manipulate the data:
  - Mapping of multimedia elements that are superimposed on the environment; and
  - Data mining allows users to manipulate the database (by applying filters - e.g., levels of rain accumulation, humidity, and lightning).
- Database module, VIMAPS uses PostGIS [30] stores the severe events data from different sources; and
- Web technologies, which are the back-end solution implemented. It follows the web technologies described by [30–32], developed using HTML5 and Javascript as they can be used to develop complex web applications compatible with all major browsers, whether on PCs or mobile devices. These

browsers can also render 3D charts, as they support the Web-based Graphics Library (WebGL) [33], which brings hardware-accelerated 3D graphics to the browser without the use of plug-ins:

- Three.js Javascript library was used to abstract WebGL through virtual objects and environments;
- Cesium.js Javascript library was used to create 3D globes and 2D maps in web browsers without using plugins; and
- Node.js, a runtime system used for creating server-side applications, is built on Google Chrome's JavaScript Engine (V8 Engine).

3.3 Visualization Using 2D Maps

VIMAPS can use maps from any provider, such as Microsoft, Google, and the OpenStreet community. Usually, these maps also offer an application programming interface (API) with a set of functions, classes, methods, and standards to be used in an application without understanding the details of their implementation. Using the APIs, one can have access, in real-time and constant updating, to satellite images and their coordinates, computational methods for requesting data (for example, latitude and longitude of a given place), and different types of satellite images, among others. Client applications can use these providers via HTTP requests or by using their Software Development Kit (SDK); in both cases, service access keys are required. When communication between the application and the library is performed, an environment for manipulating the map is loaded, making requests through the Internet for images and/or information. The providers distribute the resources, which use data structures, hardware, and software mechanisms to organize and disseminate this information.

The hierarchical navigation was based on quadtree [34], and it allows the user to select pieces of data (subsets) according to specific interests. This feature was implemented using the CesiumJS framework. This framework, which was developed using JavaScript, allows 3D globes and 2D maps to be created in web browsers without using plug-ins. It uses WebGL for hardware-accelerated graphics. The implementation of hierarchical navigation in VIMAPS was based on the camera distance concept in the globe. Therefore, the smaller the distance, the greater the level of detail, and when there is an inclination of the camera on the map, different tiles levels are presented. The slope is a user interactivity function, with the map allowing the user to view the glyphs in depth, facilitating the analysis process.

The operation of VIMAPS can be demonstrated using real data on lightning flashes. On January 1st, 2014, a mesoscale convective system quickly developed over South of Brazil, being associated with a cold front active in the region. This weather system propagated from Paraguay to the Brazilian east coast in Santa Catarina in about two hours. It brought many severe weather activities, including strong thunderstorms and lightning, as depicted in Fig. 1. The civil defense authorities had to warn the population about floods and landslides in 13 cities in the eastern portion of Santa Catarina state, as reported by local newspapers.

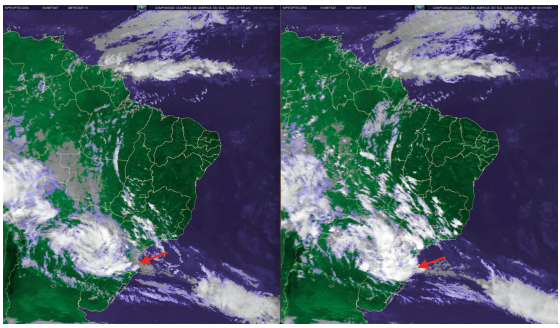

Fig. 1. Eumetsat satellite images on January 1st, 2014, at 16:00 local time (right) and 18:30 local time (left). The red arrow indicates the city of Florianopolis, Santa Catarina, Brazil (Color figure online)

Glyph icons are associated with lightning data (electrical discharge weather events) in a cloud format, inserted over the map in its corresponding position. Glyphic discharge icons can be recognized by the number of events in a region of the quadtree. An example is when an event is registered over a region presented by two types: cloud or cloud-ground. The cloud type is only when an electrical discharge is in the sky (there is no contact with the ground), while the cloud-ground is when there is contact with the ground (presented as a green region below the cloud).

The lightning and meteorological data related to Fig. 1 were introduced in VIMAPS and 1706 flashes were counted in the period of thunderstorm activity. This hierarchical visualization figure depicts the bounding boxes (cross-cross yellow lines painted) covering the map on VIMAPS. Each box represents some part of the map that is being indexed, with the root node covering the entire area. Each box is divided such that it contains a maximum of four children (quadtree). Each child is either a point or a smaller box. The map on the left highlights a box with a blue cloud in the center; it received 1706 electric discharges during the thunderstorm activity. The map on the right shows details of this area, divided into four smaller areas, which still sum 1706 flashes. This area corresponds to the beginning of lightning activity, and successive updates of the maps (not shown) suggested that the activity would follow the east, i.e., in the Great Florianopolis metropolitan region. The COMETA tool (Sect. 3), a collaborative environment, allows users to interact with the system and draw conclusions regarding the weather system's real-time development.

VIMAPS uses PostGIS [34], a spatial database extension, for the PostgreSQL database. It allows location queries to be run in Structured Query Language (SQL) for geographic objects. This tool was used mainly to convert geographic coordinates into geometries. Hence, it is easier to manipulate spatial data (such as data conversions using only a single SQL line) and to perform functions, such as calculations of the area of a region or a distance between points, and exports of data for use in a geographic information system (GIS). PostGIS supports

geometries such as points, line sequences, polygons, multiple points, multiple polygons, a collection of geometries, and multiple line sequences. We received text files from the meteorological institutes that had to be preprocessed before uploading them into our database.

In the VIMAPS graphical user interface (Fig. 2), the user can view the globe using different maps. Icons are available to allow searches by address or specific references. It is also possible to return to the starting point of the visualization, change the map image provider or the visualization parameters (weather events/electrical discharges and date ranges for viewing the events), and view the map's quadtree divisions as well as information. Figure 2 depicts data related to meteorological events captured by automatic ground weather stations in Brazil's southern part. By clicking on a weather station (antenna icons), users are presented with a window (left side) showing data captured by the station (e.g., wind direction, atmospheric pressure, rainfall accumulation, air humidity, and air temperature). In the option box (right), the user can select the details in which he/she is interested.

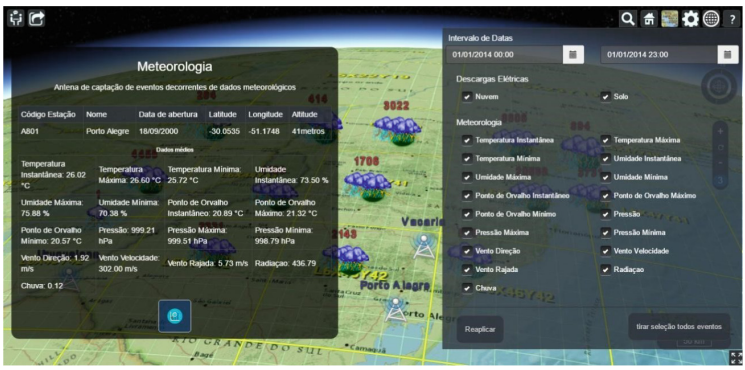

Fig. 2. VIMAPS graphical user interface

3.4 Interactive Three-Dimensional Environment

VIMAPS collects large amounts of different and isolated data, making it difficult to understand and relate to them. As presented in Sect. 2, data on electrical discharges and weather events are presented under maps with no relationship between them to allow faster and more punctual navigation, exploration, and analysis.

We created different epistemic actions to increase the user's attention to the different views. We also intended to facilitate the interaction between the views of details and context, seeking to decrease the cognitive load and increase the rate of capture of information. To achieve this goal, we created an interactive three-dimensional juxtaposed context environment to present the relationship between various data related to meteorological events. We used information regarding latitude, longitude, date, time, the radius of coverage, and

position/distance of weather event capture stations. This information can help create three-dimensional representations that can support analyzing complex sets of information for quick, accurate, and safe decision-making.

Also, we organized the 3D representations in a tree structure, following the quadtree groupings, where the leaf nodes have no other subdivisions. This form of organization allows different depth levels and contents so that the lower the depth level, the more detailed the region observed will be. It is worth noting that the representations show the viewer's direction and angle, connected by lines that visually link each secondary representation to its source, creating an easy hierarchical structure.

Another critical point is related to the user's distinction from multiple windows to view and manipulate data in both VIMAPS and COMETA. This way, it is possible to use each system separately without confusing the user. Each window presents details and allows data manipulation uniquely and autonomously, with defined policies, functionalities, and hierarchies. Using VIMAPS, large data spaces can coexist in one or more windows, aiming to demonstrate a more extensive and detailed part of the data space, improving the presentation and readability of text and information. It proves an alternative visual representation (3D context) for the data, locations, and directions, allowing navigation, manipulation, and work on these representations.

After uploading the events in VIMAPS, the user can navigate/interact with the map and can also perform these activities in the 3D context environment, being able to switch between the environment and the map at any time. A representation is formed by five rows and six columns, with row one consisting of the groupings by divisions; row two by the groupings by types of discharge; and rows three, four, and five by weather events. In addition, the current geographic position and the range of the data presented in the representation are indicated. All the data displayed are related to each other by means of latitude, longitude, date, time, the radius of coverage, and position/distance of the weather event capture stations.

In Fig. 3, we present a Level 3 grouping on the VIMAPS. In the line of the grouping by divisions, we can see the green color bar that represents the grouped amount of electric discharges of current Level 3 in the quadtree hierarchy. Level 3 is indicated by the icon at the top and represents the current level of the scene on the map, based on the camera's position relative to the Z-axis. On the line, the white color bar represents the Level 2 grouping, referring to the number of electrical discharges of its parent in the quadtree hierarchy. The orange bars show the Atmospheric Electrical Discharge groupings of the quadtree subregions (Level 4) of the current one (Level 3) represented in the form of clusters (Cluster A, Cluster B, Cluster C, and Cluster D). The sum of the quantities of the Level 4 clusters (sum of the divided regions) total the value of Level 3. In Depth 2, we have the grouping by discharge types: cloud or cloud-ground and their corresponding quantities. Lines 3, 4, and 5 present weather events captured by automatic surface weather stations, such as temperature, humidity, dew point, pressure, wind direction, wind gust, radiation, wind speed, and rain.

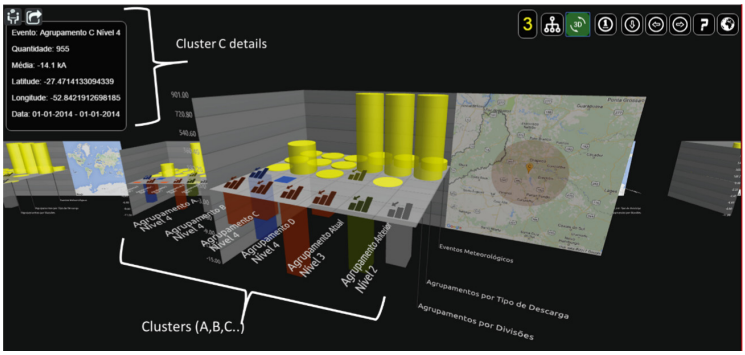

Fig. 3. Accurate view of the region selected (electrical discharges)

In this visualization environment, a set of icons is available for navigation, for example, icons to allow navigating and manipulating individual elements of a chart. Some bars in the chart have navigation functions. For example, it allows the user to navigate directly to another chart in the hierarchical order. The user can navigate freely using the mouse by clicking on a particular chart or navigating between the charts by moving the mouse left/right or forward/backward by clicking the corresponding left and right mouse buttons.

3.5 Usability Tests of VIMAPS

The usability evaluation verifies the relation established between users, tasks, hardware, applications, and other aspects in which users use the software. Problems can occur whenever users find it challenging to perform a task or access the documentation. Several methods can be attempted to evaluate applications, such as usability inspection, involving just expert users, while end-users can perform usability tests. One way to verify the users' opinion is by using questionnaires.

As part of this research, we prepared a questionnaire for usability inspecting of our application, based on heuristic evaluation [18]. This evaluation method is one of the most well-known ways to inspect usability, and it is a low-cost inspection method since it does not involve the final users. A few expert users can carry it out, and it can be applied when the software is already implemented. According to Nielsen [17], the best results from usability tests come from small tests with no more than five users. Nielsen [16] proposed heuristics, and some of them had to be adapted. The questionnaire evaluated aspects such as the objective, design, level of difficulty, documentation, help, and user satisfaction. All these aspects are important because they influence the system's acceptance.

A group of five experts that are specialist in visualization, and analysis of severe weather events performed the following steps in the usability test:

1. The experts were accommodated in the computer laboratory (each user was visually isolated from each other);

2. The experts filled out a pre-test questionnaire, which aimed to identify their profile (age, sex, education attainment and technological literacy). Each one had 5 min to fill the questionnaire;
3. VIMAPS was explained by an instructor for 30 min;
4. Each expert had 30 min to use VIMAPS; and
5. The experts filled out the usability questionnaire - each one had 15 min to complete the questionnaire.

We determined the users' profiles by analyzing the pre-test questionnaire results: five expert users between 30 and 45. A Likert scale [13] has been adopted (1 - Strongly disagree, 2 - Disagree, 3 - Neither agree nor disagree, 4 - Agree, 5 - Strongly agree) in the questionnaire. The heuristics adapted by the authors were assigned to a template to organize the information. Our questionnaire is an informal inspection tool, which is intended to be practical and answered by specialists. We aimed to identify usability problems and to classify and quantify the problems encountered. We also selected and prioritized the problems that needed to be corrected. We chose some Nielsen heuristics, whose initial focus was on desktop applications in the 1990 s and extended it, and we included satisfaction, according to ISO 9241-11:

- Ease of use: it refers to how comfortable and secure a user feels in using the application, both on the 2D map and the 3D objects: Question 1 It is easy to understand how to use the application and what purpose it serves.
- Accuracy: it deals with how precisely the symbols (rays) are positioned on the maps: Question 6 The objects (electrical discharges, clouds) are merged correctly with the maps (position, texture, scale).
- Satisfaction: this is how well the user's expectations are met: Question 13 The application is pleasant to use. Question 14 I would like to use the application again.

Table 1 depicts the consolidated report with evaluation results from the experts. VIMAPS was very well accepted by experts, indicating a perceived benefit in mixing 2D maps and 3D charts as part of one visualization solution. It is necessary to consider improvements in some functionality for novice users who have a low learning curve (question 12 had the lower grade). Even though VIMAPS is a complex application, involving a large amount of data, as well as unconventional interface and interaction, the answers to the usability questionnaire showed a high acceptance rate of the system, obtaining an average of 4.3 between all the questions.

4 COMETA

COMETA is a collaborative web application that allows multiple users to discuss weather information. During a collaboration session, users can add multimedia elements (video, images, and text) and also drawn objects (arrows, lines, circles) over 2D images captured from VIMAPS canvas (screenshot). In this way,

Table 1. VIMAPS usability results

Questions	**Heuristics**	Average	Standard deviation
1) It is easy to understand how to use the application and what purpose it serves.	Flexibility and efficiency of use	4.8	0.4
2) Error messages are clear and easy to understand (i.e., video, text, audio).	Error prevention	4.4	0.8
3) The interaction and navigation follow real-world conventions, thereby making the actions appear in a natural and logical order.	Match between system and the real world	4.2	0.4
4) I never get lost when using the application, not knowing what to do.	Visibility of system status	4.0	1.2
5)The application has a 2D interface for visualizing maps and 3D charts. I was not confused by the use of both.	Flexibility and efficiency of use	4.0	1.0
6) The glyph icons (i.e., electrical discharges, clouds) are merged correctly with the maps (i.e., position, texture, scale).	Match between system and the real world	4.6	0.5
7) The actions/feedback are standardized (i.e., same actions to trigger the same functionality).	Consistency and standards	4.0	1.2
8) The interface has an appropriate design (i.e., icons, messages).	Aesthetic and minimalist design	4.8	0.4
9) The system provides help and documentation (i.e., video, audio, text).	Help and documentation	4.2	1.0
10) The help and documentation are easy to understand.	Help and documentation	4.4	0.8
11) I felt I had freedom to interact and navigate with the visual elements (i.e., users can have different perspectives).	Flexibility and efficiency of use	4.2	0.8
12) I believe novice users can easily use the application.	Flexibility and efficiency of use	3.8	1.6
13) The application is pleasant to use.	Satisfaction	3.8	0.4
14) I would like to use the application again.	Satisfaction	4.6	0.5
15) It is easy to understand how to use the application and what purpose it serves.	Satisfaction	4.6	0.5
	Overall average	4.3	

COMETA creates a shared workspace where participants can annotate, draw, brainstorm, and convey ideas during a synchronous or asynchronous discussion between participants in the collaborative session.

The rest of this Section is organized as follows: Sect. 3.1 presents the key motivating features of COMETA, Sect. 3.2 details COMETA architecture, as well as the usability tests performed.

4.1 Essential Features of COMETA

The essential features of COMETA are:

– It provides a set of tools that allows the creation of collaborative sessions for meteorological data analysis between remote users in a way that all interact in real-time, synchronously or asynchronously, and the interaction can be distributed over time. Through this feature, the user can capture an image (screenshot of the canvas) of the current VIMAPS scene view and its parameterized URL, and send it to COMETA to be added to a collaborative session. A collaborative session is formed by one or more images (called session object(s)) and between two or more participants. Collaborative discussions can occur synchronously or asynchronously. In synchronous form, two or more

participants are collaborating in a session and on a session object and talking through an audio conference and using the interactive multimedia elements (any modification is updated, in real-time, for all participants, in its web interface). Asynchronously, the user enters a collaborative session, individually, opens a session object, and adds interactive multimedia elements, which will be available to the other participants at the time of opening the session. Therefore, a collaborative session can be viewed and analyzed later, allowing for its continuity, as well as being built synchronously among its participants.
- A collaborative session consists of session objects made up of an image (screenshot of the canvas) created with VIMAPS referring to the desired meteorological data, and interactive multimedia elements made available by COMETA. Through these elements, participants can add audio, video, images, texts, markers, graphics, geometric shapes positioned and organized chronologically, when the same element has more than one input. It is worth mentioning that the multimedia element will have a name and a color that indicates the user who owns the element. Moreover, the use of screenshots (2D images) simplifies and minimizes the computational cost in collaboration, if compared with the real-time processing and positioning of meteorological data (VIMAPS).

4.2 COMETA Architecture and Usability Test

- The Visualization Module, which allows users to create collaborative sessions. Images exported from VIMAPS, including multimedia elements and drawn objects, are shared during a collaboration session. It follows the paradigm What You See Is What I See (WYSIWIS) [5]:
  - Map Canvas is an area where VIMAPS 2D images are rendered;
  - Multimedia elements, through which users make a voice or video call with any participant. It also allows video, sound, and texts to be added; and
  - Drawn objects, which allows users to drawn over an image from VIMAPS. A tool palette allows the user to pick various drawing tools, such as a paintbrush or an eraser.
- The Engine Module, which manages and manipulates data from VIMAPS: it captures and exports images from VIMAPS to COMETA. VIMAPS allows capturing a 2D image and its URL parameterized to be visualized in COMETA. It is possible to visualize the meteorological data presented in VIMAPS. Through the URL, it is possible to load the data into VIMAPS precisely where the image was captured. The URL has the actual positions (coordinate systems, level, weather data used, slope, depth, and filters) obtained when the session object was created. While the user is visualizing the image in a collaborative session, when questions arise, they can click on the image and request its opening on VIMAPS. Through the URL, VIMAPS is loaded with the information (weather data) that generated this image, so the user can interact and analyze it in real-time. The user can restart the process if they want to capture a new image for the session;

- Real-time session sharing allows users to keep track of changes as they occur, without refreshing the browser. All elements added over the images are updated automatically. They can be recovered from the database;
- Drawn on canvas, which draws objects over the images. The objects can be recovered from the database;
- Voice chat allows communications between users via a voice channel;
- Audio/Video sharing, which manages voice and video calls;
- The Relational Database module manages and stores the session data (e.g., maps, drawings, texts, videos) that are retrieved during asynchronous sessions. It was implemented using the NHibernate framework and the SQL Server database; and
- Web technologies, which are the back-end solution implemented. ASP.NET is a framework designed for web development that allowed dynamic web pages and services to be produced. SignalR is a library for ASP.NET developers that facilitated the addition of real-time web functionality to the applications. WebRTC is a web framework that enabled real-time communication over peer-to-peer connections in the browser.

Computers and modern networks enable users to work together toward a common goal in real-time. COMETA users can overlap elements over a map; thus, it is necessary to preserve consistency across instances of the tool opened in different browser windows/tabs, which means that the state of objects and the history of operations must be the same for all users. In order to prevent inconsistencies and conflicts, objects were locked. Each object has a color that identifiers the user responsible for it. The architecture adopted was centralized that the server controls the distributed work of all users. The server collects and decides what to do with all users' events and where to display the output. This architecture's advantage is that the synchronization is easy, as state information always remains consistent since it is all located on the same computer [42].

COMETA works in an integrated way with VIMAPS, so it was necessary to consider using both tools to evaluate the collaboration. The questionnaire and the help of the usability experts described in Sect. 2 were used to evaluate the collaborative environment provided by COMETA and VIMAPS. The five experts who had already completed the pre-test questionnaire during the VIMAP test and performed the following tasks:

a) Use VIMAPS to visualize weather events about the city of Florianopolis, Brazil, and export the resulting map to COMETA. This task required users to navigate the map hierarchy in VIMAPS to the eighth level of depth (Fig. 4). Glyph icons represent weather events, and the user can click on them to see the details about them. The user is directed to the three-dimensional context environment when a user clicks on the glyph.

b) Use the 3D chart environment of VIMAPS to find the same meteorological events found in item a); navigate it, and export an image to COMETA.

c) Each expert must discuss the meteorological events of Florianópolis found on the item a) and b) with two other participants. Users were free to use collaborative tools (i.e., voice chat, video, lines, circles).



Fig. 4. 2D map of the city of Florianópolis on VIMAPS with overlapping 3D and 2D elements

The following steps were performed for the COMETA usability test:

1. The experts were accommodated in the computer laboratory (each user was visually isolated from the others);
2. COMETA integration with VIMAPS was explained by an instructor for 15 min;
3. Each expert had 30 min to use the tools however they wanted;
4. The tasks were explained;
5. Each expert had 10 min to solve each task; and
6. Each expert had 30 min to answer the questionnaire.

Table 2 depicts the results of the collaborative usability test. We chose some Nielsen heuristics, whose initial focus was on desktop applications in the 1990 s and extended it, and we included satisfaction, according to ISO 9241-11. Satisfaction aims to evaluate how much COMETA surpasses user expectations. We consider that reviews were consistent across experts and questions since the variations were not significant. Even though the results are preliminary, they proved useful in the validation of the applications. However, during the COMETA usability test, the collaborative test had the lowest score for question 12. This was expected since this class of application involves a large amount of data and requires diverse functionalities. This feedback review is important for improving applications.

The experiment successfully demonstrated the usability and usefulness of both VIMAPS and COMETA as tools for synchronous and asynchronous discussion. It appears that the users' engagement, motivation, participation, and awareness during the task led them to become unaware of the distance between them and cooperated naturally.

Table 2. Collaborative session using VIMAPS and COMETA - usability results

Questions	Heuristics	Average	Standard deviation
1) It is easy to understand how to use the application and what purpose it serves.	Flexibility and efficiency of use	4.8	0.4
2) Error messages presented are clear and easy to understand (i.e., video, text, audio).	Error prevention	4.4	0.5
3) The interaction and navigation follow real-world conventions, thereby making the actions appear in a natural and logical order.	Match between system and the real world	4.6	0.5
4) I never get lost when using the application, not knowing what to do.	Visibility of system status	4.4	0.5
5) The application has a 2D interface to map visualization and a 3D interface to chart visualization. This mixture does not cause confusion.	Flexibility and efficiency of use	4.2	0.8
6) The interactive multimedia elements (text, video, audio, for example) are positioned correctly in the environment.	Match between system and the real world	4.8	0.4
7) The actions/feedback are standardized (i.e., same actions to trigger the same functionality).	Consistency and standards	4.6	0.5
8) The interface has an appropriate design (i.e., icons, messages).	Aesthetic and minimalist design	4.6	0.5
9) The system provides help and documentation (i.e., video, audio, text).	Help and documentation	4.4	0.8
10) The help and documentation are easy to understand.	Help and documentation	4.4	0.8
11) User have freedom to interact and navigate (i.e., users can rotate the 3D charts easily).	Flexibility and efficiency of use	4.8	0.4
12) Novice users can use the application easily.	Flexibility and efficiency of use	4.6	0.5
13) The application is pleasant.	Satisfaction	4.0	0.7
14) I would like to use the application again.	Satisfaction	4.8	0.4
15) It is easy to understand how to use the application and what purpose it serves.	Satisfaction	5.0	0.0
	Overall average	4.3	

5 Conclusions

This paper presented a web toolset to easily and flexibly facilitate the visualization, analysis, and discussion of severe weather events. It is composed of VIMAPS, which allows users to visualize and analyze severe weather events using 2D maps and a 3D chart environment to visualize spatial relations from any desired angle. Moreover, COMETA allows the collaborative analysis of severe weather events between remote users synchronously or asynchronously. The collaborative approach presented here lies in the broad exchange of information to better understand the underlined features hidden in the multi-source data. This tool set's main scientific benefits include understanding weather systems' characteristics and studies related to trajectories of thunderstorms.

VIMAPS and COMETA were tested using real data and showed that they fulfill their class of application's performance and usability requirements. VIMAPS, naturally a complex application, was very well accepted by experts, indicating that it is possible to perform detailed observations of a region over time, using 2D maps and a 3D chart environment. This approach allows users to visualize objects of interest in detail and, at the same time, get an overview. However, the VIMAPS usability test indicates that some of its aspects must be improved;

for example, novice users should be enabled to learn how to use the application as fast as possible.

Tools such as VIMAPS are necessary to study and discuss severe weather events and define resources for prevention and the anticipation of services, minimizing the damage caused by extreme climatic events. Images have always been used to improve how people visualize information, primarily using charts and figures. However, 3D environments can amplify the user's ability to process data in more dimensions. It also supports multimodal interactions, allowing for more intuitive use of the applications.

Decision-makers need appropriate tools to prepare for future severe weather events and engage in appropriate actions. A collaborative tool such as COMETA is necessary to facilitate information exchange among experts to assist decision-makers in taking action efficiently. COMETA works in an integrated way with VIMAPS, and then both tools were considered to evaluate collaboration. The experiment was very successful, although some improvements are also necessary, for example, a mechanism to ensure the user never gets lost when using the application.

From the observed results, we can conclude that our tool has achieved its purpose. For future work, we intend to adapt VIMAPS and COMETA to support the visualization, analysis, and discussion of other data, such as epidemic information (for such things as the Zika virus, dengue fever, chikungunya, and H1N1), electoral data, information on deforestation, fire data, the latest global data on drug production, trafficking and consumption, and crime data, among others.

We believe that future advances will be made by better promoting collaborative work between scientists interested in climate forecasts. Decision-makers will thus be able to take proactive actions to avoid or minimize damages. Also, the use of immersive visualization of interactive three-dimensional representations can allow easy attention between detail and context views to improve the process of data analysis.

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