Information Visualization in Climate Research

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***Abstract*—Much of the work conducted in climate research involves large and heterogeneous datasets with spatial and temporal references. This makes climate research an interesting application area for visualization. However, the application of interactive visual methods to assist in gaining insight into climate data is still hampered for climate research scientists, who are usually not visualization experts.**

In this paper, we report on a survey that we conducted to evaluate the application of interactive visualization methods and to identify the problems related to establishing such methods in scientific practice. The feedback from 76 participants shows clearly that state-of-the-art techniques are rarely applied and that integrating existing solutions smoothly into the scientists workflow is problematic. We have begun to change this and present first results that illustrate how interactive visualization tools can be successfully applied to accomplish climate research tasks. As a concrete example, we describe the visualization of climate networks and its benefits for climate impact research.

***Index Terms*—Information Visualization, Climate Research, Climate Networks, Graph Visualization, Geo-Visualization**

I. Introduction

Climate research involves many different scientific activities, among which data analysis and exploration play an important role. Interactive visualization methods aim to ease the interpretation of countless data tables filled with large quantities of numbers by providing an interactively steerable mapping process that transforms data into more easily interpretable visual representations.

When climate researchers visually analyze data, the typical procedure is to reduce or aggregate the data by analytical means and then to visualize them in a rather straightforward way as a static image. The consequence is that only little or no interaction is possible. For the purpose of presenting research results, the scientists use online portals such as the Climate Wizard (http://www.climatewizard.org), which provide access to a large number of climate-related maps, but these maps are also limited in terms of interaction and analysis facilities.

On the other hand, advances in the field of information visualization have yielded a number of innovative and promising solutions (see for example [1], [2], [3]). However, an interactive visual exploration of heterogenous climate data with multiple coordinated interactive visual representations has not yet become common practice in this field.

In order to better understand the current situation of application of visualization in climate research, we conducted a survey among 76 scientists at the Potsdam Institute for Climate Impact Research (PIK). Our major interest was in getting to know:

- Which visual, interactive, and analytical tools are applied by the scientists?
- Which tasks are accomplished with the help of these tools?
- What are the reasons for the low pervasion of state-of-the-art visualization tools?

In Section II, we summarize the feedback that we got with regard to these questions and discuss possible interpretations of the results. Based on the feedback from the questionnaires we launched an effort to convince the scientists of the advantages of interactive visual analysis and exploration. In this effort, PIK has begun to incorporate visual methods into the research workflow.

In this paper, we present a concrete application of information visualization to the exploration and analysis of climate networks. As we will see in Section III, analyzing climate networks is a recent movement that has already yielded promising results in climate research.

How this new branch of climate research can be supported with interactive visualization will be explained in Section IV. We describe the specific requirements of the application background and how interactive visualization was utilized to accomplish climate research tasks, including visual exploration for hypothesis generation and visual confirmation for hypothesis evaluation. We also include the scientists' feedback and indicate where they saw shortcomings and disadvantages. Section V will summarize our work and suggest possible directions for future work.

II. Scientist Interviews on Visualization in Climate Research Practice

To gain an overview of the requirements in the heterogeneous field of climate and climate impact research, we informally interviewed researchers at the Potsdam Institute for Climate Impact Research (PIK). We took notes of the interviews and collected answers to key questions in a questionnaire for later investigation. In total, we had 76 participants including senior researchers, researchers, post-docs, PhD students, and student assistants. The participants had a wide range of scientific backgrounds: 24 participants classified themselves as meteorologists, climatologists, oceanographers & hydrologists, 30 as economists & sociologists, 27 as ecologists & biologists,

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14 as physicists, 14 as geo-statisticians & geographers, and others (multiple disciplines were possible).

As our interest is mainly in scientists who have already applied visualization tools and in those who could potentially use such tools in the future, we filtered out 5 participants for whom this was not the case.

For the remaining 71 interviewees, we analyzed the questionnaire in more detail. We sought answers to the following questions: (1) Which visualization techniques are used? (2) For which tasks are visualization techniques applied? (3) Which systems and tools are utilized to generate visual representations? (4) Which are important features of visualization software?

In the following, we summarize the main results from the questionnaire:

Visualization techniques – The majority of participants apply classic visualization techniques. Time charts are applied most of the time (90%) followed by bar charts (77%), basic maps (66%), and scatter plots (56%). There is a clear preference for 2D techniques. Visualization techniques that generate 2.5D and 3D presentations are of minor relevance: Only 18% of the participants mentioned the use of height fields and 37% of them apply 3D techniques.

Tasks accomplished with visualization – 93% of the participants use visualization mainly for the purpose of presenting results in a scientific context (e.g., publications and conference talks). The evaluation of models and the verification of hypotheses are also quite relevant: 76% and 70% of the participants use visualization to accomplish these tasks. Even 69% of the participants said that they use visualization for data exploration in order to find unknown patterns and structures. The communication of scientific results in a comprehensible manner for decision makers, stakeholders & public media has been mentioned by 58% of the participants.

Applied systems & tools – Office suites (spreadsheets, diagramming, presentation) are the most frequently applied software for generating visual representations. Such tools are applied by 75% of the participants. In the shared second place follow script-based systems (e.g., R, Ferret, Grads and GMT) and commercial mathematical packages (e.g., Matlab, Mathematica), where each group of software is used by 44% of the participants. Unsurprisingly, 38% of the participants apply geographic information systems (GIS) (e.g., ArcGIS) to accomplish climate research tasks. Special purpose systems (Ocean Data View, Vis5D) were mentioned in only 20% of the questionnaires. Sophisticated visualization systems and toolkits (e.g., OpenDX, AVS/Express, IDL, Spotfire, InfoVis Toolkit, prefuse) are only marginally used (7%) or are even unknown.

Important features of visualization software – Appropriate labeling was mentioned as an important feature in 81% of the questionnaires. The ability to faithfully represent geo-spatial aspects of the data (e.g., different geographic projections) was mentioned as important by 56% of the participants. Surprisingly, a high degree of interactivity is important to a minority of only 14% of the participants.

With our survey, we found that there is a lack of utilization of visualization as an interactive analysis tool in the routine work of these scientists. The major task accomplished with the help of visualization is to transform data and analysis results into classic static visual representations for scientific publications (often called "plotting").

Possible reasons for this are manifold. First, the advantages of sophisticated visualization methods and tools are hardly known. Second, data heterogeneity due to different types of data, different scales, and different climate scenarios is not easily resolvable by scientists because there is no system that covers all of these aspects. Third, managing the volumes of data to be queried interactively requires elaborate data structures and caching mechanisms, so the scientists tend to believe that a large dataset can not be handled by an interactive analysis system at all.

Data size and heterogeneity are most challenging in this context, because they burden climate researchers with the task of making an appropriate choice for the methods or tools to be applied. In practice however, climate researchers are familiar with one visualization system and hardly know alternatives. Thus, the users' flexibility of using interactive visualization techniques is strongly restricted, and therefore they tend to resort to basic "plotting" solutions.

Furthermore, discussions with the scientists revealed that there is a kind of mistrust in interactivity in general. They fear the arbitrariness of visual representations that have been generated by interactive adjustments of thresholds or visualization parameters. In (natural) sciences, the comparability of visual representations is very important. Therefore, script-based visualization systems that generate reproducible representations are favored over interactive solutions where it is often unclear which parameter settings are required to generate a certain view on the data.

However, in recent years, new technologies such as "Google Maps", "Gapminder", and other web-based visualization services serve as a kind of starter. Many young scientists are very accustomed to utilizing the interactive features that such tools offer. So, nowadays, there is a rising acceptance of interactive visualization, however, mainly for the purpose of presentation.

Using this "new wave", we have started to go beyond presentation and to provide researchers with interactive visual tools for data exploration and analysis. Our goal is to incorporate such tools into the researchers' typical workflows. This also includes raising the awareness of well-accepted interactive visualization concepts such as multiple coordinated views, brushing and linking, or dynamic queries. Although not queried in the questionnaire, our experience was that climate researchers hardly use such concepts. After introductory lessons and demonstrations of tools that support these features, the feedbacks have been very encouraging and first successes were achieved with the help of such tools.

In the next sections, we describe this in more detail with the example of visual exploration and analysis of climate networks.

III. Climate Networks: Background & Data

Climate researchers are investigating the impact of natural phenomena and human society on the earth's climate and vice versa. These investigations involve a variety of data sources as well as complex models, which in turn produce an enormous amount of data. Linear statistical analysis is currently the main means to gain insight into such data.

In this context, the analysis of climate data from the point of view of complex network theory is a very recent and powerful approach for studying the rich data available to researchers today. In this novel approach, which has become known as climate network analysis, the idea is to construct a network or graph $G = (V, E)$ representing the structure of significant pairwise statistical relationships present within a spatiotemporally resolved data set [4]. Here V and E denote the sets of vertices and edges, respectively. This method is complementary to the by now classical and exclusively linear principle component analysis of climate data fields [5], which is commonly used in climate science [6]. Climate network analysis has been successfully applied to detect the signature of El-Niño Southern Oscillation (ENSO) variability in climate data [7] even if only data from the Arctic is considered [8], and a backbone structure carrying a considerable amount of matter, energy and dynamical information flow was uncovered in the global surface air temperature field [9], [10]. More recently, a well pronounced community structure was detected in climate networks constructed from various climate observables and exploited to improve statistical predictions of future climate variability [11]. Furthermore the method has been generalized to coupled climate network analysis allowing to study the cross-correlation structure between two or more distinct fields of climate variables which already provided some interesting insights into the Earth's atmosphere's general circulation structure [12].

The *vertices* $i \in V$ of a climate network represent measurement stations or grid points, where data like temperature or precipitation is available in the form of time series $x_i(t)$. An *edge* is introduced between pairs of vertices (i, j) iff the value of a particular measure of statistical association C_{ij} between time series $x_i(t), x_j(t)$ (e.g., linear Pearson correlation or nonlinear mutual information [10]) exceeds a threshold T_{ij}. Hence, the network's adjacency matrix A_{ij} [13] is given by

$$A_{ij} = \Theta\left(C_{ij} - T_{ij}\right) - \delta_{ij},$$

with $\Theta(\cdot)$ the Heaviside function and δ_{ij} Kronecker's delta introduced to avoid artificial self-loops. Usually a global threshold T is prescribed such that $T_{ij} = T$ for all (i, j) [9], [10], [12], [4], [7], [8], but the threshold may also be chosen adaptively for each pair based on suitable statistical significance tests of time series analysis [11].

The so obtained climate network is then subjected to a detailed statistical analysis using the tools of complex network theory [13], where the choice of particular methods and network theoretical measures depends on the questions to be asked about the data at hand.

The types of data studied by means of climate network analysis range from purely observational such as raw data collected by the Deutscher Wetterdienst (engl: German weather service), which are the basis for refinement by scientists at PIK, to processed reanalysis data sets relying on observations, e.g., the one provided by the NCEP/NCAR Reanalysis 1 project [14], to pure model output as generated by Atmospheric and Oceanic General Circulation Models (AOGCMs), e.g., the WCRP CMIP3 Multimodel Dataset [15].

The main aim of climate network analysis is to serve as an explorative technique for investigating the wealth of information contained in the data's spatial correlation structure. Its validity may be confirmed by showing that known statistical relationships and structures are picked up by the method in a way that is consistent with physical expectations and the network theoretical interpretation of specific network measures under study. Moreover, the above cited studies demonstrate that climate network analysis has the potential to uncover previously hidden or unexpected structures in the data which subsequently have to be put through a process of interpretation and careful analysis using complementary methods to answer relevant questions of interest and to generate new insights into the climate system's functioning.

IV. Visualization of Climate Networks

In the following, we describe first successful applications of interactive visualization to climate network analysis. As described in Section III climate networks are complex multivariate structures. They typically contain $|V| = \mathcal{O}(10^4)$ vertices and $|E| = \mathcal{O}(10^6)$ edges rendering any attempt to extract useful information from a direct and unprocessed visualization (plot) of the network structure unfeasible. Hence, researchers applying climate network analysis have so far relied on static visualizations of statistical results such as degree and edge length distributions [7], time series of the number of edges $|E(t)|$ for time-dependent climate networks [8], global maps and scatter plots of local network measures such as degree, closeness and betweenness centrality and local clustering coefficient [9], [10], or line plots showing the evolution of global network measures such as average path length or transitivity with height [12]. This static approach is not unique to climate network analysis, but appears to be common practice in the modern analysis of general complex networks which is guided by quantitative ideas from physics (most prominently statistical mechanics), mathematics and social science [16], [13], [17].

However, the plethora of different metrics provided by complex network theory complicates the process of gaining an overall picture and, hence, a deeper understanding of climate network structure when following the static approach. This is particularly true since the spatial embedding as well as a possible time dependence of climate networks add additional dimensions to the problem. Given this challenging situation, interactive visualization promises to provide an intuitive way of combining information from the actual network structure, the network's spatial embedding and several statistical network

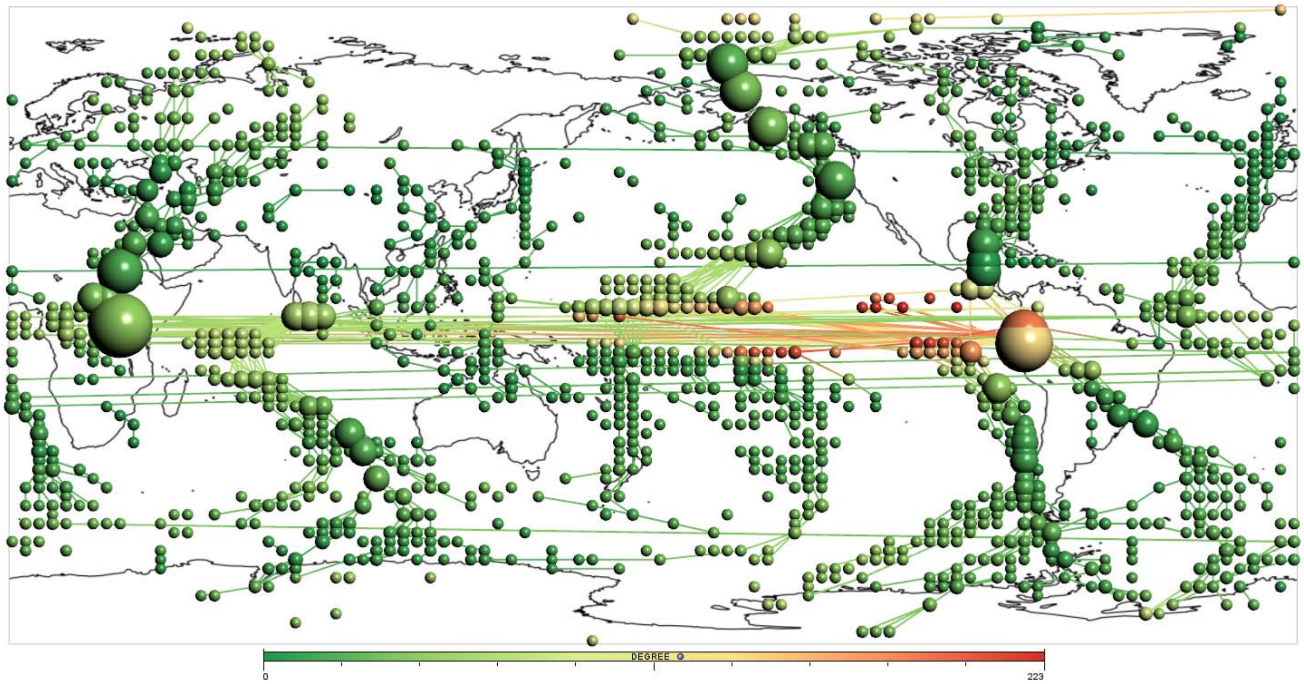


Fig. 1. The global SAT climate network visualized on a two-dimensional map, where vertex color and size encode degree and betweenness, respectively. The network has been filtered dynamically based on vertex and edge betweenness in order to reduce edge clutter. This revealed the backbone of the network.

quantifiers, e.g., degree and (edge-) betweenness centrality [13], to generate and test hypotheses ultimately based on the underlying climate data set.

Before going into detail with concrete visualization examples, let us first briefly summarize the requirements that have been derived from the interviews with the climate impact researchers:

- Climate networks with $|V| = \mathcal{O}(10^4)$ vertices and $|E| = \mathcal{O}(10^6)$ edges must be handled efficiently.
- Due to the size of the data, dynamic filtering mechanisms are mandatory. The filtering must be flexible in order to account for various data attributes and analysis tasks, and it must be reproducible (e.g., re-apply stored filters).
- The visual encoding of vertex and edge attributes should be interactively adjustable. However, this should be possible only within reasonable limits to tackle the arbitrariness of visual representations.
- The geographical frame of reference of the network is of utmost importance for the interpretation the data. Visualizing networks on two dimensional maps as well as on three dimensional globes is important, whereas graph layout algorithms are less relevant.
- To address the demand for comparability of visual representations, views must show data consistently. So, linking and coordination of views is required.
- Because network vertices have fixed geographical positions, the layout cannot be modified to reduce edge crossings. Therefore, other means are required to tackle edge congestion.

There are a number of graph visualization tools and systems, including Pajek [18], ASK-GraphView [19], GUESS [20], and Gephi [21]. However, only a few systems fulfill the requirements stated before: Tulip [22] and CGV [23]. While Tulip offers fully-fledged visual graph analysis functionality, CGV focuses on interactive exploration. Moreover, CGV is able to run in a web browser, a feature that matches with the scientists' common practice of making research results publicly available on web sites.

Next, we present two examples of applying the CGV system to interactive visualization of climate networks and discuss some first experiences as well as advantages and disadvantages with respect to this approach. The climate networks to be visualized are provided in the DOT or GraphML file format with precalculated vertex-based and edge-based network measures of interest included in the network as vertex and edge attributes, respectively.

A. Visualizing global climate networks

In this example, we study a climate network derived from the monthly averaged global surface air temperature (SAT) field taken from a 20th century reference run (20c3m, as defined in the IPCC AR4) by the Hadley Centre HadCM3 model [15] covering the time span January 1860 to December 1999. Consistently with [9], [10], we choose a global threshold T such that $0.5\,\%$ of all theoretically possible edges associated to the largest values of linear Pearson correlation between pairs of time series are included in the SAT climate network. The networks contains about 6k vertices and 115k edges.

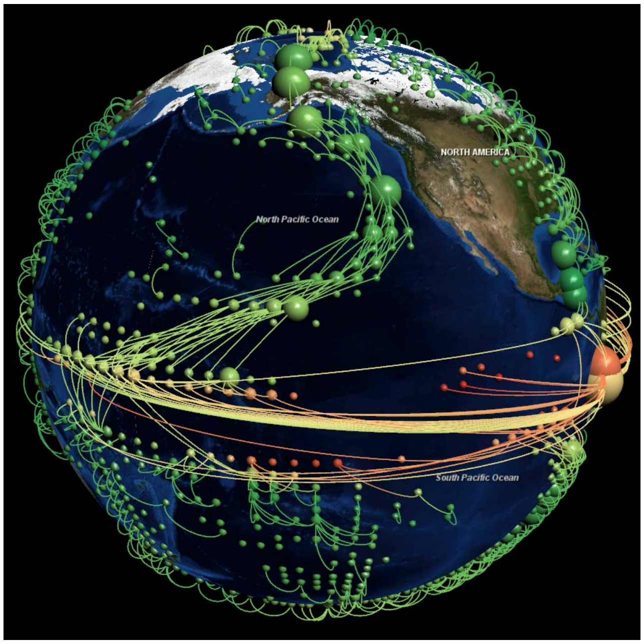


Fig. 2. Spherical three-dimensional globe representation of the SAT network. The visual encoding and filtering is the same as in Fig. 1.

The climate network of a selected time point is visualized as a node-link diagram, where the positions of vertices are fixed, and where vertex color and size encode the vertex attributes degree and betweenness, respectively. Using CGV's dynamic filtering facilities, we interactively filtered for vertices and edges with high vertex and edge betweenness, therefore highlighting structures with particular importance for hypothetical communication following shortest paths within the network.

A two dimensional lat-lon-projection of the filtered network (see Figure 1) reveals patterns consistent with the backbone of significantly increased vertex betweenness discussed in [9]. Moreover, this visualization contains additional information on edge betweenness, highlighting that high betweenness edges tend to fall into two categories: very short and very long edges. This fact becomes particularly clear in a spherical representation of the same filtered climate network (see Figure 2) which shows less visual clutter than the two dimensional projection, but on the downside restricts the view to one hemisphere only.

Based on both views we may formulate the hypothesis that certain short range as well as long range processes are particularly important for coupling the dynamics of the surface air temperature field. While the important short range edges may represent advection of heat by strong surface ocean currents, the long range connections appear to correspond to known teleconnection patterns, e.g., the long range edges in the tropical Pacific ocean seen in Figure 2 are consistent with teleconnections induced by ENSO. Interactively varying the filters one can easily evaluate the robustness of such patterns, which is particularly important when testing hypotheses.

One disadvantage with respect to this approach is that filter settings are not derived from quantitative criteria, thereby rendering the results arbitrary to some degree. However, it should be noted that visualizations such as the one presented in Figure 2 have already proven highly valuable and successful in intuitively conveying the basic ideas and results of climate network analysis to scientific audiences at international conferences (see [24]).

B. Visualizing regional climate networks

Our second example concerns a regional climate network constructed from daily mean surface air temperature time series covering the years 1951 to 2006 measured at climate stations scattered across Germany. While the raw data is provided by the Deutscher Wetterdienst, the scientists at the Potsdam Institute for Climate Impact Research have processed the data to improve its quality and consistency before compiling the climate network. A global threshold T was chosen to include $1\,\%$ of all maximally possible edges corresponding to the largest values of Pearson correlation. The resulting network contains 2k vertices and 27k edges.

A two-dimensional node-link visualization as provided by the CGV system at first glance highlights a pronounced community structure being particularly prevalent in the northeast of Germany (see Figure 3). Furthermore, one clearly sees that vertices of high degree tend to have a small betweenness, while those of high betweenness have a small degree. This behavior is typical for networks with an organized, non-random structure [13].

But what factors could be essential for organizing the network and, hence, the underlying temperature field's correlation structure in the observed way? We may hypothesize that geographic features, e.g., orographic structure such as hills or mountain ranges play a major role as one would expect from physical considerations.

This hypothesis could be tested interactively by adding information from a digital elevation model to the CGV system. If visual support were to be found, the next step would be to test the hypothesis in a statistically rigorous way. In this spirit, our second example illustrates how interactive visualization can aid in formulating and testing hypotheses on network structure and the underlying data, particularly if few a priori knowledge and expectations are present.

Although the visualization has been considered useful for exploring the climate network in general, the scientists also raised concern about the heavy clutter of edges in the node-link representation. One way to alleviate this problem is to dynamically filter out edges based on edge attributes. As an alternative, the edges can be routed into bundles. To this end, we adapted Boyandin's implementation [25] of the force-directed edge bundling approach of Holten and van Wijk [26].

The edge bundling was generally perceived as a suitable and aesthetically pleasing solution. However, as shown in Figure 4, there is a tradeoff between using straight edges and bundled edges. While bundled edges are quite useful for reducing edge clutter, individual edges can be best identified when using straight edges. This indicates that there is no visual representation that suits all of the different tasks that climate researchers

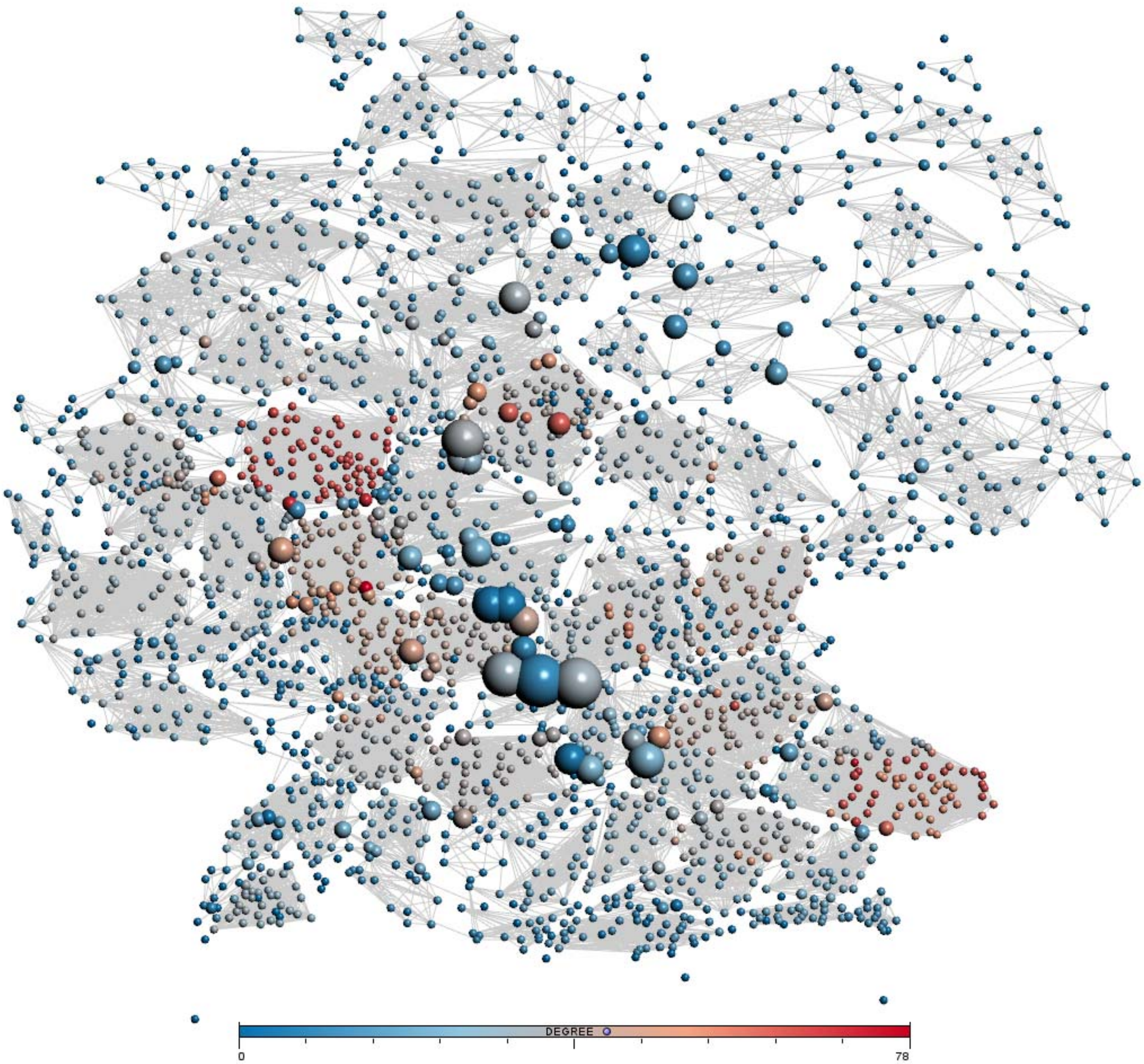


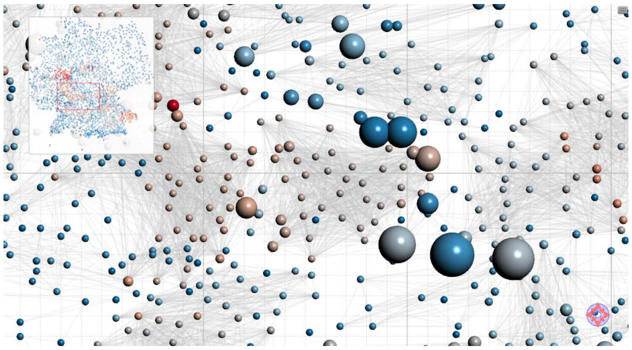
Fig. 3. Visualization of a climate network derived from daily mean temperature data collected at weather stations scattered across Germany. Vertex betweeness and degree are visualized with varying sizes and colors, respectively. The visual representation clearly reveals the network's strong community structure.

might have to accomplish. Therefore, interactive and task-dependent parametrization of the visualization is important in order to arrive at appropriate visual representations. So besides making climate scientists aware of new innovative information visualization approaches such as edge bundling, we also have to provide information about the approaches' usefulness for different data, tasks, and application scenarios.

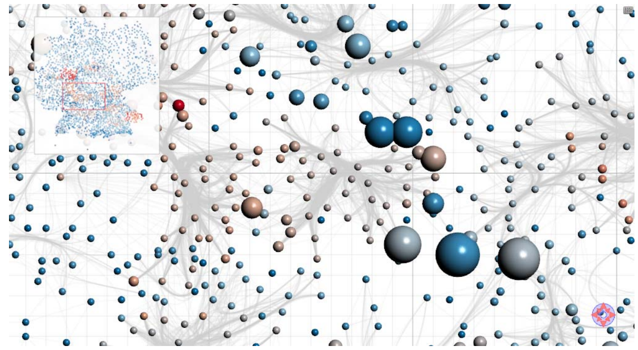
V. Discussion & Future Work

The examples presented in the previous paragraphs indicate that climate researchers have begun to recognize information visualization as a valuable tool. Based on a list of requirements, we were able to provide solutions that enable the scientists not only to present their research results, but also to evaluate hypotheses, and in particular to generate hypotheses through visual exploration. These first successes are very promising and motivate us to continue our work.

But still it is too early to claim that climate researchers would be *using* information visualization tools, and we feel that there is still more trust in statistics and analytical computations, rather than in visual representations, the interpretation of which may vary. In order to accomplish the ambitious goal



(a) Straight edges.



(b) Bundled edges.

Fig. 4. Rendering edges as straight lines better suits the task of identifying connections between vertices, but visual clutter is a problem. Bundling edges reduces clutter, however discerning individual edges becomes more difficult.

of really making information visualization common practice in climate research, further hurdles have to be taken.

As we learned from the questionnaire, the interactivity is not always appreciated because the options for different visual encodings and different perspectives on the data are sometimes experienced as indiscriminate. Additional methods are required to support the users in finding good views on the data and in determining appropriate parametrizations of visualization techniques. As researchers begin to integrate visualization systems in their daily work, there are a number of practical aspects to consider: Undo and redo mechanisms must be integrated, ongoing work must be storable on disk for later continuation, and derived findings must be annotatable, to name only a few (see [27], [28]).

Secondly, there is the pressing issue of time-dependency of climate networks. In general, time-dependency implies additional conceptual and technical challenges because the dimension of time can be structured in a number of different ways and because the data size is multiplied by the number of time steps [29]. Up to now, individual time steps have to be loaded separately, which hinders the exploration of temporal trends and patterns in the data. New visualization views have to be integrated to address this problem.

In future analysis scenarios, the climate networks' geographical frame of reference will not be restricted to latitude and longitude, but may also contain depth (oceanographic models) or height (atmospheric models). Additionally, uncertainty of model structure and hence of the generated data will play an increasingly important role. As a result, we have to consider the 3D visualization of uncertain graph structures with uncertain attributes, which we think is a formidable challenge.

In order to arrive at user-centered solutions for these issues, we will continue the close collaboration between our institutions, applying recent developments in the field of visualization to problems in climate impact research and non-linear analysis. We plan to extend existing solutions and to integrate additional tools (see Figure 5) into the researchers' workflows much like in the spirit of visual analytics [30].

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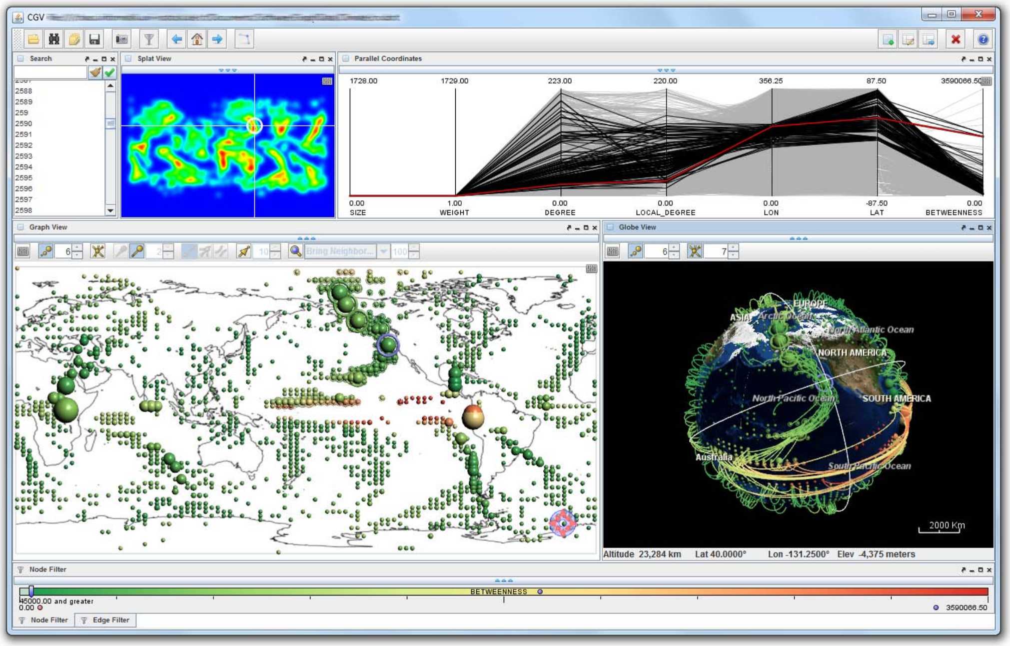

Fig. 5. Multiple coordinated views as provided by the system CGV to support the interactive visual exploration of climate networks.

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