Visualization of Climate and Climate Change Data: An Overview

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Abstract

Visualization is a key technology for analyzing and presenting climate simulations and observations as well as related social and ecological data. Furthermore, mediating research results to decision makers and to the general public in an easily-understandable way is of growing importance. This paper provides the results of a questionnaire with climate impact researchers using visualization and a overview of the state-of-the-art in climate visualization, incorporating standard visualization techniques, tools and systems as well as alternative approaches from visualization literature. Furthermore, specific aspects such as the simplified usage of complex visualization systems, climate model and data quality and the integration of statistics and visualization will be briefly discussed.

1 Introduction

With increasing computing power, climate modellers generate increasingly large simulation data sets. Enhanced observation techniques such as satellite operations contribute to the growth of climate related data. When trying to identify the underlying properties in the data – such as patterns and statistical relations between the variables – analysis increasingly becomes the bottleneck. Furthermore, there is a rising demand for methods which support the evaluation of the reliability of conclusions based on simulation data.

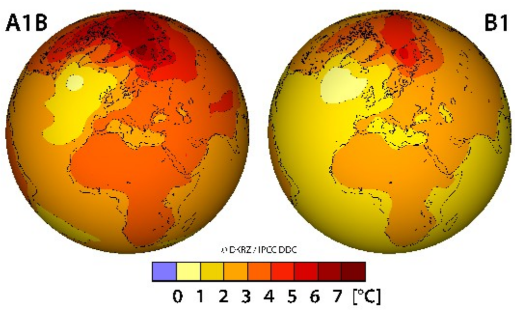

Figure 1: Temperature change for 2080-2099 in comparison to 1980-1999 (IPCC AR4)

Designing intuitive and meaningful visual representations in climate context faces a variety of challenges. First, the heterogeneity of climate related data (spatial, temporal, multi-variate; gridded, region-based, station-based; ...) requires a variety of standard visualizations (e.g. 2d-maps, 3D-globes (see fig. 1), time charts and scatterplots). Furthermore, alternative yet intuitive visualization techniques are required for analyzing large time-dependent 3D or long time series data multi-variately and interactively. Second, climate data visualization faces heterogeneous user groups, including users with different skills, qualification grades, interests, and from different disciplines, who are confronted with numerous tasks. Third, applying visualization to scientific data is not straightforward. This is due to a variety of available tools, techniques and parameters. Sophisticated technologies (graphical user interfaces, visualization design, ...) are essential for bridging the gap between such systems and users. At best, they reduce the obstacles for applying the full functionality of advanced, interactive data visualization systems.

2 Results from a user questionnaire

To gain an overview on the requirements in the heterogeneous field of climate and climate impact research, we performed a questionnaire (oral interviews with 76 researchers at Potsdam Institute for Climate Impact Research: 24 meteorologists, climatologists, oceanographers & hydrologists, 30 economists & sociologists, 27 ecologists & biologists, 14 physicists, 14 geo-statisticians & geographers, and others (multiple disciplines were possible)). 5 scientists interviewed do not use visualization at all. Important results normed to the researchers performing visualization (71) are the following:

- standard 2D presentation techniques are most frequently used (90% time charts, 77% bar charts, 66% 2D maps, 56% scatterplots) and 2.5D and 3D visualization techniques are of minor importance only (18% height fields, 37% 3D visualization techniques)
- major tasks visualization is used for: 93% present results in a scientific context, 76% use visualization for model evaluation and 70% to verify hypotheses, 69% explore unknown patterns and structures and 58% make scientific results comprehensible to decision makers, stakeholders & media
- visualization technique features related to the (spatial) reference of the data are of importance or of high importance (81% axis labelling, 56% support of geographic projections), and interactivity is of minor importance only (14%)
- systems & tools used for visualization (from time to time and/or frequently): 75% use office software (Excel, Powerpoint), 44% script-based systems (R, Ferret, Grads and GMT), 44% commercial mathematical packages (Matlab, Mathematica), 38% GIS (ArcGis) and 20% use special purpose systems (Ferret, Grads, GMT, ODV, Vis5D); sophisticated scientific visualization systems (OpenDX, AVS/Express, IDL, Spotfire, InfoVis TK) are only marginally used (7%) or even unknown.

3 Visualization techniques

Visualization is the process of generating images by filtering, mapping and rendering of data. Visualization techniques exist for different data classes, e.g. flow, volume and multivariate visualizations (for overviews see Brodlie & Wood (2001), Laramee et al. (2004), Bürger & Hauser (2007)). In the recent two decades, new advances have been made in establishing visualization as a flexible, easy-to-use data exploration tool (e.g. Shneiderman, 1996), interacting directly with the image and linking several views to the data. Visual Analytics is a new approach to couple human perception abilities with automatic computational methods, allowing new insights into huge amounts of data sets (e.g. Thomas (2007)).

On the other hand, visualization has a long tradition for meteorology and climatology (e.g. Galton (1863)). Recent computer based climate visualizations can be subdivided into two major approaches: climate and climate impact researchers applying standard visualization tools and visualization researchers applying techniques / tools under development for visualizing weather and climate data. Treinish (1999) classifies visualization techniques representing meteorological data in 4 classes due to their dimensionality and interactivity. Furthermore, there is a variety of implicit conventions and guidelines for the visualization of meteorological and climate data, including colour mapping, iconic wind vector mapping, axes labelling and geographic projections (American Meteorological Society (1993), Treinish (1994), Baker & Bushell (1995), Treinish (1999), Kottek & Rubel (2003)).

Most frequently, climate data is visualized in their temporal reference to identify temporal trends directly using time charts. For the representation of aggregated data values, interpolated stacked bar charts are frequently used for multi-variate trend analysis (e.g. Nocke et al. 2004). An alternative approach is 2-tone colour mapping (Saito et al., 2003) which compactly represents longer climate time series. Other temporal visualization techniques such as pixel-oriented visualizations are rarely used.

Being of similar importance, meteorological and climate data are represented in their spatial reference, with animation to display the time axis. Table 1 summarizes work done in spatial visualization due to the spatial data dimensionality, the data grid and the data type.

	2D data		3D data
	scattered data	regular grid	
scalar	**triangle-mesh-based:** Treinish (1994) **uni- and multi-variate icons:** Scanlon (1994), Nocke et al. (2007), Stier et al. (2005) **iconic time diagrams:** Saito u. a. (2005)	**standard color & isoline images:** Kottek & Rubel (2003), Stier et al. (2005) **height representation:** Treinish (1999) **globe representation:** Chen (1993), Fig. 1	**isosurfaces**: Treinish (1994), Baker & Bushell (1995) **decomposition methods**: Treinish (1999) **direct volume rendering**: Riley et al. (2003), Ribarsky et al. (2002) **realistic rendering**: Baker & Bushell (1995), Marchesin et al. (2004)
vector (& scalar)	-	**arrows or wind barbs**: Treinish (1999), Kottek & Rubel (2003) **topology based methods**: Wong at al. (2000), Doleisch et al. (2004)	**icons**: Chen (1993) **field lines**: Chen (1993), Treinish (1994), Griebel et al. (2004) **decomposition methods**: Doleisch et al. (2004) **texture based / direct volume rendering**: Griebel et al. (2004)

Table 1: Summery of literature for spatial climate visualization

In many cases, the multi-variate properties of climate data are of interest, typically in combination with spatial and/or temporal reference of the data. Beside static representations of scatterplots (Stier et al., 2005), scatterplots are used to interactively select certain features and analyse their spatial and temporal behaviour (Macedo et al. (2000), Doleisch et al. (2004)). Other techniques representing high dimensional climate data, such as scatterplot matrices, parallel coordinates, graphical tables or using multi-dimensional scaling are less frequently used (e.g. Nocke et al. (2007), Jänicke et al. (2008a)).

4 Systems and Tools

A variety of tools & systems, ranging from general purpose solutions to special purpose solutions for climate data, providing different levels of interactivity have been developed.

Typically, they provide only a small subset of the techniques discussed in section 3. Table 2 lists an excerpt of systems / tools applied in climate research.

type	name	location	properties
Special purpose systems	Ferret GrADs Vis5D+ GMT ODV IDV NCAR Graphics	http://ferret.wrc.noaa.gov/Ferret http://www.iges.org/grads http://vis5d.sourceforge.net http://gmt.soest.hawaii.edu http://odv.awi-bremerhaven.de https://www.unidata.ucar.edu/software/idv http://ngwww.ucar.edu/	2D script-based 2D script-based 3D interactive 2D script-based 2D script-based 3D interactive 2D script-based
General purpose vis. systems	Avizo OpenDX AVS/Express IDL	http://www.tgs.com/products/avizo.asp http://www.opendx.org http://www.avs.com http://rsinc.com/idl	climate features open source climate features 2D/3D Script

Table 2: Selected visualization tools / systems applied for climate data visualization

Very important practical aspects for the visual analysis of climate model results are the file formats and the file sizes of the data. A quasi standard used in the climate community is NetCDF (in the CF-1.0 (“Climate Forecast”) convention), a self describing file format suitable for georeferenced scientific data which is supported by most special purpose systems. While these special purpose systems are mostly developed by domain researchers with specific requirements, general purpose tools have to face data from a variety of scientific disciplines and were developed by computer scientists who are not familiar with the special requirements of climate researchers. In consequence, general purpose systems may lack support for some of the typical domain specific requirements such as support for native file fomats, and metadata, different grid types and mapping.

Furthermore, geographic information systems (GIS) visualizing are frequently regularly applied for storing, processing, and visualizing climate data. Moreover, in the last few years, a variety of web-based-services and platforms have been developed and spread - used for climate data representation - particularly facilitated by major advancements in cartography through web-based, ubiquitous technologies (e.g. Google Maps & Earth).

5 Discussion

Bridging the gap between complex visualization systems on the one hand and climate scientists and decision makers on the other hand, methods from human-computer interaction and visualization design have been applied to climate data visualization, providing easy-to-use graphical user interfaces even for complex data sets and a multitude of possible visual representations (Nocke (2007), Wrobel et al. (2008), Nocke et al. (2008)).

In this context, the visual representation of the model and data quality becomes of increasing importance for the communication of climate knowledge to decision makers, visualizing uncertainties in one image (e.g. using textures IPCC (2007), pp. 76), representing differences between selected models, scenarios and impacts in an interactive tool (Nocke et al. (2008)) or representing and visually analyzing large ensembles simulations (Nocke et al. (2007)).

Most frequently, considering for instance climate (impact) model ensemble simulations, climate data is processed using statistical methods, and visualization is used in the manner of a final "post-processing". However, this does not exploit the possibilities using visualization for selection and parameterization of statistical filters and the evaluation / comparison of statistics results. First steps towards such an in-depth climate data analysis – tightly coupling statistics and visualization – has been done for cluster and principal component analysis (Nocke et al. (2004), Nocke (2007)).

Furthermore, going beyond the generation of static images, looking from a technical point of view, the interactive visual analysis of the very large climate data sets requires tailored solutions including optimisations in regard to both hard- and software such as parallelisation and out-of-core-techniques (see e.g. Böttinger, 2007).

6 Conclusion

Visualization as a tool has been established in climate and climate impact research, communicating results between climate scientists and conveying results beyond the scientific community (e.g. providing web-based services and portals). The visualization techniques, tools and systems used range from general purpose office systems, mathematical packages and GIS to special purpose climate visualization tools.

However, recent developments in interactive visualization using alternative visual metaphors are not wide-spread in the climate community. Thus, a major task for future developments is to further bridge the gap between climate and visualization expertise, exploiting the chances arising from sophisticated visualization approaches, smoothly supporting and integrating the alternative visualization techniques into the users' ongoing research processes. An example of a promising technology are feature extraction methods, semi-automatically extracting unknown but interesting (e.g. multi-variate) patterns from climate data (e.g. Doleisch et al. (2004), Jänicke et al. (2008b)).

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