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ABSTRACT

This article describes the conception and implementation of a web platform which uses special charts and maps for climate monitoring and analysis. At first it gives an overview of related web applications and their advantages and limitations. This is followed by a basic introduction of current technologies and methods for working with climate data, geospatial web services and visualization techniques. Finally, the implementation based on prior defined requirements is presented and its strengths and limitations are discussed. The application provides several basic charts for climate analysis, as well as a more complex one which uses a standardized visualization concept which is suitable for comparing different local climates (Walter-Lieth-Standard). The charts are based on different interpolated datasets with global coverage as well as data from the Global Historical Climate Network (GHCN). Overall, the application enables users to generate individual historical climate charts from the beginning of the twentieth century until present day.

1. Introduction

The process of collecting, storing, generalizing and visualizing long-term environmental parameters is known as environmental monitoring (Artiola, Pepper, and Brusseau 2004). The goal of the more specific climate monitoring is to transfer these principles to climate relevant parameters.

Due to the large amounts of data generated, gaining insight and sharing knowledge has become more and more complex (Nocke et al. 2008; Ladstädter et al. 2010). Especially in climate sciences, which not only interest those with scientific backgrounds but also students and teachers, finding an efficient way of communicating knowledge is important. This results in a growing need for Information Visualization (InfoVis, Johansson, Neset, and Linnér. 2010). It helps users understand and explore abstract data more easily as it provides a graphical representation. Therefore, it factors in the formation of mental images, which in turn plays a big part in decision making. Especially if there is no set goal for a task, InfoVis can aid in generating new hypotheses about the data (Keim 2002).

This form of communication should follow a consistent and standardized model (Ware 2012). Currently the fields of climate and atmospheric science are dominated by basic diagrams, e.g. bar charts, and unconnected plots, such as scatter plots, as well as map visualizations. Basic diagrams address the quantitative character of the underlying data, while map applications focus on the spatial components of it. There are advantages and disadvantages to both types of representation since each can only communicate parts of the overall information contained in the data. Therefore, representation is crucial in gaining insight and finding patterns in data. It is a powerful tool, that can

guide the user's view and may influence their interpretation (Rogowitz, Treinish, and Bryson 1996). The combination of these techniques can help to overcome some of these obstacles.

Additionally, the number of available web technologies has increased significantly in recent years. Thus, visualizations of climate data can be made available to a wide audience (Vitolo et al. 2015). Compared to common desktop applications there are several advantages.

Web services are highly specialized and designed for specific user needs. They extract only the amount of data desired by the users resulting in a much faster workflow since users do not have to investigate the datasets themselves. Instead they can focus on the visual end products, such as charts and maps. Furthermore, the target-oriented selection of data has an impact on the required storage space. Due to frameworks constantly evolving, websites gradually turn into complex applications with interactive maps, graphs, charts and user-friendly features (Papazoglou 2008).

A number of web-based applications that visualize different types of climate data already exist. The Earth Observation Monitor is one of them (Earth Observation Monitor 2020). It was developed at the Friedrich Schiller University Jena. The platform provides different climate parameters based on satellite data, such as land surface temperatures based on data of the Moderate-resolution Imaging Spectroradiometer (MODIS). Other data products such as vegetation indices like the Normalized Difference Vegetation Index (NDVI, Tucker and Sellers 1986) or the Enhanced Vegetation Index (EVI, Huete et al. 1997) are directly derived from MODIS (Huete et al. 1997). Additionally, the app obtains data from the Global Historical Climatology Network (GHCN), which contains a variety of other climate parameters (e.g. temperature, precipitation, snow) (Menne et al. 2012).

The Earth Observation Monitor offers several different analysis functions for climate data, which make it a particularly useful tool. For instance, different methods of time series decomposition can be applied to the data. Moreover, all analyses and visualizations meet the scientific standards and are available for download. Nevertheless, the use of this tool is likely to be aimed at experts and scientists (Eberle et al. 2013).

Another web tool providing visualizations of worldwide climate data is the Global Climate Monitor (Global Climate Monitor 2020), which was developed by the Climate Research Group of the University of Seville (Camarillo-Naranjo et al. 2019). The monitor processes different global gridded datasets, containing information on temperature, precipitation and evapotranspiration. An interactive map displays the global visualization of these parameters on monthly and annual aggregation level. In addition, visualizations for trends and anomalies are available. The platform offers a range of charts, including climograph visualizations, which visualize temperature and precipitation together in one chart. However, they can only be displayed in predefined monthly or annual resolutions. The diagrams themselves only contain little information about the selected locations and time periods, therefore it is sometimes difficult to understand to which periods the climographs refer. This tool is aimed more at experts as well, and even though it is not always intuitive to use, it is easier to understand and handle for laymen than the Earth Observation Monitor.

Both tools focus on the use of gridded data. However, an essential part of climate monitoring is based on the analysis of station data. Station-based datasets are offered by a large number of providers. In particular, the meteorological services of the different states play a decisive role in providing high quality meteorological data.

The integration of this data into a common database is a complex process. One web application that uses station data is the OpenSensorWeb data platform (Müller 2019; OpenSensorWeb 2020). It aggregates a large amount of environmental data in a single application. Not only does the platform provide climate data, but it also offers a wide variety of other environmental data. Currently, data from more than 200,000 measuring stations with more than 500,000 sensors is available. Simple visualization tools allow easy and, above all, fast access to the sensor data, but specific functionalities for data analysis are not yet included. For the exploration of existing open data on a global scale, the OpenSensorWeb is a very useful tool.

All three of the presented web-based tools fulfill different requirements and expectations and are aimed at different target groups. However, one large target group for climate information, namely

citizens, gets disregarded often. They are interested in getting climate information in a simple way. Even today, climate charts play an important role in school and university education, so that almost everyone is familiar with reading and interpreting climate diagrams on a basic level. There are a few web applications that visualize climate data in a simple to understand and easy to obtain way. Many of these applications, however, only offer a fixed selection of static diagrams that visualize data for selected locations on earth for a given time period (see Global Climate Monitor 2020).

The goal of our application is to build an easy-to-use web application for citizens, who have a basic knowledge about interpreting climate charts. We want to provide global, area-wide and time-variable climate diagrams for gridded as well as station dataset. We chose students and teachers as our target audience and therefore used a visualization standard known from the school environment. This ensures that the web application can also be used in schools and universities.

This paper explains the different aspects of developing a platform for globally available climate diagrams, based on the visualization rules for climate diagrams introduced by Walter and Lieth (Walter and Lieth 1967), Köppen and Geiger (Chen and Chen 2013) as well as several more universal techniques from the area of InfoVis. Section 2 starts with the basics of visual representation and gives an overview of globally available climate data, Section 3 covers the implementation of the platform. This includes the description of the technical setup as well as the design of the user interface and a brief explanation of the selected visualizations. Afterwards, we discuss the results of a user analysis in Section 4. This provides insight into the way the ClimateCharts.net application has been used in the past and enables us to draw conclusions about benefits of our application as well as possible functions required in the future.

2. Background

2.1. Aspects of visual representations

Information Visualization (InfoVis) is a growing field that has become more important in recent years (Ravi et al. 2013). Even though climate visualizations are common use cases in InfoVis and Scientific Visualizations, the fields of climate and atmospheric science are still dominated by basic diagrams, e.g. bar charts, and unconnected plots, such as scatterplots. However, several technical diagrams exist, that are commonly used in climate sciences, such as geographical map visualizations or the Walter-Lieth climate chart (Walter and Lieth 1967; MacEachren et al. 2004; Murray 2013).

Maps are well suited for visualizing climate data depending on geographical coordinates so that the spatial distribution of climate phenomena can easily be distinguished and understood by the user. However, when displaying more than one characteristic in one visualization, problems occur, since both characteristics have to be visualized simultaneously without overshadowing each other (McNabb and Laramee 2019).

One of many visual variables is color. It is commonly used in information visualization and depending on the goal it can be used for qualitative and quantitative data (Tominski and Schumann 2008). There are, however, better ways to encode quantitative data, e.g. position and length (Mackinlay 1986). Overall, color as a visual variable is supposed to catch a user's eye and help them see information quickly (Stauffer et al. 2015). It is important not to take any color scheme, but to adjust it according to user tasks and visualization goals, as well as prior knowledge and cultural background of the target group (Stauffer et al. 2015). While finding specifically colored items in a group is easier than finding a specific shape (Hoffman et al. 1993), it is important not to overload the human mind. A color palette should not consist of more than seven to ten different colors (Krebs and Wolf 1979).

Even then it is difficult to determine exact values from a color alone (Tominski and Schumann 2008). When mapping ordinal data to color it is important to choose a scale that preserves said order of elements and creates no ambiguities in interpretation. A prominent example for this is

the commonly used rainbow color map, which does not retain perceptual order (Stauffer et al. 2015). Colors are defined by a color space, such as RGB (red green blue), HSV (hue saturation value), and HSL (hue saturation luminance). They all have been developed based on different aspects. The RGB color space for example mimics the requirements of digital screens (Stauffer et al. 2015).

Depending on the characteristics of data, different color maps can be created. Isoluminant maps are well suited for classification tasks, while sequential maps support continuous data mapping (e.g. temperature and precipitation) (Kaye, Hartley, and Hemming 2011; Stauffer et al. 2015).

Different tools have been developed to help support the decision process, such as the HCL Wizard (2020) and ColorBrewer (Harrower and Brewer 2003; Stauffer et al. 2015).

Using multi-hue value color maps enables users to determine correlations between different characteristics better but is also makes the visualization more complex. A well known example for a specific climate visualization in combination with a map and a chosen color palette is the Köppen-Geiger climate classification scheme in Figure 1 (Kottek et al. 2006; Chen and Chen 2013).

It distinguishes between 31 classes to describe local climates based on long term mean air temperature and precipitation values. Hence, this type of classification offers a lot of information on a single map but it also requires the user to be aware about the meaning of the different classes and it disregards the rule of using only seven to ten different colors.

Charts and diagrams are another way of visualizing climate data over time, e.g. trends over multiple years or mean values. A prominent example is the Walter-Lieth climate chart (Walter and Lieth 1967). It offers a generalized representation of temperature and precipitation values during their annual period. The scales for temperature and precipitation are fixed for every chart in the ratio 1:2, which makes it easy to compare different geographical locations. Another advantage of the Walter-Lieth climate chart is that it graphically emphasizes humid and arid conditions. For this purpose the areas between the temperature and precipitation curves are mapped to specific colors or pattern accordingly. This is a simple but very distinguishable classification method and useful for estimating conditions for vegetation growth at first glance.

In conclusion, representation is crucial in gaining insight and finding patterns in data. It is a powerful tool, that can guide the user's view and may influence their interpretation (Rogowitz, Treinish, and Bryson 1996). Finding the right combination of different data visualizations is
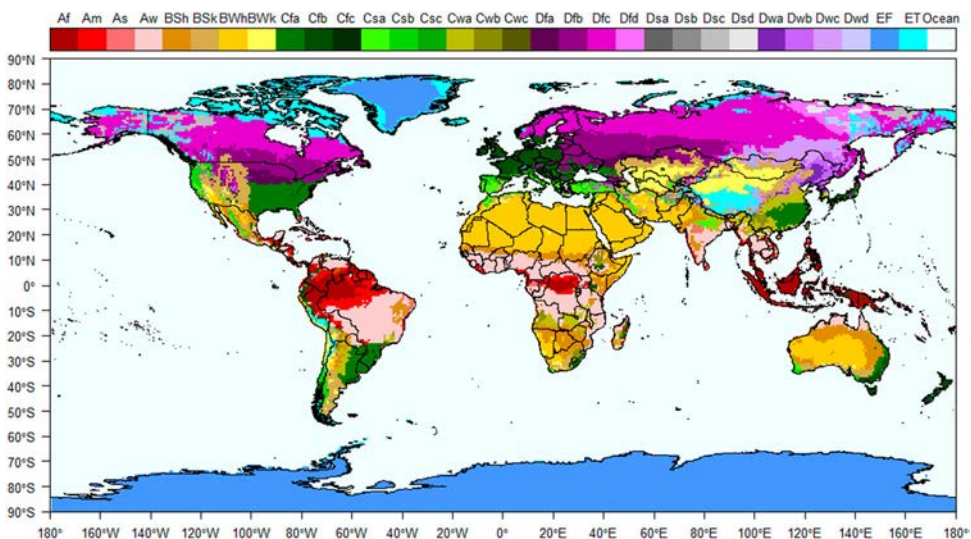

Figure 1. Köppen-Geiger classification scheme (Kottek et al. 2006; Rubel et al. 2017).

therefore an important step in the process. For a more in-depth overview on the topic of current InfoVis we recommend the works by Rees and Laramee (2019) and McNabb and Laramee (2017).

2.2. Climate data

The acquisition of climate data is mainly done by the Global Observing System (GOS) maintained by the World Meteorological Organization (WMO) as well as national meteorological agencies. Since this paper focuses on land observation, we distinguish between two basic types of data: in-situ measurements from terrestrial weather stations and gridded datasets. Within the GOS there are currently about 11,000 operating stations measuring variables like air temperature, precipitation and pressure (World Meteorological Organization 2020). Depending on continents and countries the earliest data available goes back to the 18th century which is beneficial for climate monitoring. In contrast, earth observation products from space satellites have only been publicly available since the 1970s. This type of observation has the advantage of covering areas worldwide including remote regions without local weather stations. However, compared to terrestrial stations remote sensing data suffers from other problems such as cloud coverage. According to the WMO the appropriate time interval for climate monitoring spans 30 years. Therefore the available data collected by space satellites is barely adequate in order to gain climate relevant information.

Datasets generated from these sensor networks are often available for free through web portals maintained by the University Corporation for Atmospheric Research (UCAR, UNIDATA 2020a) or the Centre for Environmental Data Archival (CEDA Archive 2020). These platforms enable researchers to explore and download datasets from large catalogs.

In general, two types of datasets can be found on these web portals: interpolated grid and non-interpolated point observation products. Both types of data have their advantages and drawbacks. Global, gridded datasets are more numerous since there have been various attempts of production in the last decades (Peterson and Vose 1997; Willmott and Matsuura 2001; Adler et al. 2018; Harris and Jones 2020). They are often created by merging the data from multiple sources, which increases the complexity for homogenization, since time series with large gaps or duplicate stations have to be removed. The gridding process includes common spatial interpolation methods such as climatology aided interpolation (New, Hulme, and Jones 2000; Harris and Jones 2020), splines (Hutchinson 1998; Tveito et al. 2006; Sluiter 2009), distance weighting (Hofstra et al. 2008) and kriging (Tabios and Salas 1985; Phillips, Dolph, and Marks 1992; Dirks et al. 1998), and can have a significant influence on deviations of the final dataset. Since any interpolation process is likely to produce errors, using gridded products is always a compromise between the advantages of global coverage and quality requirements (Berndt and Haberlandt 2018).

An alternative to gridded data are non-interpolated datasets from providers such as the Global Historical Climatology Network (GHCN 2020). They contain observations from multiple station networks compiled into time-series data (Lawrimore et al. 2011). These kinds of datasets include direct measurements without bias except measuring errors, which makes them more suitable for high precision tasks. However, while only containing spatially discrete objects they cannot be described as coverages, meaning that it is not possible to query them for data at every geographic location.

2.3. Web services

An alternative to downloading complete datasets are web services that provide subsets of data based on a client's needs. The NOAA for example offers a web API which can be queried for subsets of raster datasets or station based time series via HTTP requests. These services can be used free of charge but users have to register to get an access key. However, apart from the risk of server down-times these services are limited to a specific number of queries per day which can be an obstacle for large applications (NOAA 2020).

As described in an earlier section, environmental data in general can be modeled as gridded coverages as well as point vector data. Binding both types to a web environment would require a combination of multiple services since no current service standard represents an overall solution. Common web service standards by the Open Geospatial Consortium (OGC) are for example the Web Map Service (WMS, Open Geospatial Consortium Inc 2006), Web Feature Service (WFS, Open Geospatial Consortium Inc 2010) and Web Coverage Service (WCS, Open Geospatial Consortium Inc 2012). These are implemented by common open source server software like Geoserver or Mapserver. NetCDF is a current standard for working with scientific data. It is, however, not well supported by the previously mentioned implementations. The Geoserver WCS, for instance, cannot return subsets of data in NetCDF while the Mapserver WCS documentation in general recommends to convert NetCDF data to GeoTiff before providing it.

More suitable service types exist, but they are single implementations and not OGC conform. A good example is the THREDDS Data Server (TDS). It is completely build on top of the NetCDF (UNIDATA 2020b) interface and therefore supports data formats included by the CDM. It is designed for providing environmental and scientific data and implements unique service types like the NetCDF Markup Language (NcML UNIDATA 2020c) and the NetCDF Subset Service (NCSS, UNIDATA 2020d). NcML is a service that generates a standard metadata description for a CDM dataset via XML. NCSS is an alternative to the WCS standard and can provide spatiotemporal subsets of raw data from a NetCDF dataset. Instead of delivering data in the form of gridded images like a WCS it returns it encoded as NetCDF, XML or CSV.

In conclusion, a lot of functionality for providing and displaying geodata is offered by existing services, but there still is no straight-forward solutions for providing spatiotemporal raster- and vector datasets simultaneously. However, since the NetCDF standard is widespread for many datasets, the TDS fits well into a web application for climate analysis.

3. System components and user interface

3.1. Technical setup

3.1.1. Frameworks
ClimateCharts.net is a web application using several front-end libraries, frameworks, servers and web services.

Back-end. The back-end is implemented using Java and its *Servlet Specification 3.1.0*. Servlets are Java classes used to dynamically or statically generate a web-application's content. They support the request/response workflow within a web-application's environment and are part of the *Java SE Development Kit* (Oracle 2020).

In addition to Java Servlets the application is using the *Java NetCDF API 4.5.4* which is used to convert different data file formats into a *Common Data Model*. On top of this three server-side applications are being used.

- The **THREDDS Data Server** is a *Thematic Real-time Environmental Distributed Data Services*. It bridges the gap between an application and the data it needs to process. Through THREDDS, a developer has access to a wide variety of scientific data, such as temperature and precipitation, as well as meta data. The requested data can be taken in real-time or archived data (UNIDATA 2020e).
- **GeoNames** provides a Web Feature Service-Gazetteer. It is a service that returns a location name for given GPS coordinates (GeoNames 2020).
- **GeoServer** is a java-based server that is used to access the data of weather stations (GeoServer 2020).

Front-end. The client side is built on top of various libraries which are simplifying and enhancing the workflow, such as Bootstrap (Bootstrap 2020), a framework supporting HTML, CSS, and JavaScript development. It offers styling and container classes for HTML elements as well as a grid system.

For visualizing the data the JavaScript framework Data Driven Documents (D3) is added (D3 2020). D3 offers a solution for document manipulation and enables developers to create interactive charts and visualizations based on datasets. Instead of delivering prepared types of graphs it offers flexible functions and objects to construct complex, interactive graphs using the Scalable Vector Graphics (SVG) web standard.

Furthermore jQuery (2020) and jQuery UI (2020), JavaScript frameworks commonly used for manipulating the Document Object Model (DOM) and creating an intuitive user interface, are being used for the selection and manipulation of elements, event handling, animation, and visual effects. For interactively displaying map tiles Leaflet is applied (Leaflet 2020). This is an open source web mapping library which can be extended with many additional plugins. It handles everything concerning maps, which includes eventhandling, displaying of information, and popups, as well as the option to draw on the map.

Among these main libraries various smaller plugins are used for example to convert XML code into a JSON structure.

3.1.2. Datasets

The datasets used by ClimateCharts.net can be categorized into two classes. The application uses station weather data or interpolated data in-between weather stations. Figure 2 shows a section of the map used in the application. The red-brown dots represent weather stations, and when clicked, they display graphs based on these station data. The area in-between stations, marked as the blue rectangle, creates charts based on simulated raster cell data.

There are three different climate datasets a user can choose, that create the basis for raster cell calculations.

The gridded Climatic Research Unit (CRU) Time-series 4.01 offers month-by-month data ranging from January 1901 to December 2019 and the provided data grid has a resolution of 0.5×0.5 degrees (Harris and Jones 2020). They use a weighted interpolation based on angular distances. The following variables are offered: cloud cover, diurnal temperature range, frost day frequency, potential evapotranspiration, precipitation, daily mean temperature, monthly average daily maximum, and minimum temperature, and vapor pressure.

The University of Delaware's Terrestrial Air Temperature and Precipitation v4.01 dataset provides monthly and annual mean air temperature and total precipitation values. The offered data ranges from 1950 to 2014 and just as the CRU series, the datasets resolution is 0.5×0.5 degree. They used the spherical version of Shepard's distance-weighting method for interpolation (Willmott and Matsuura 2001).
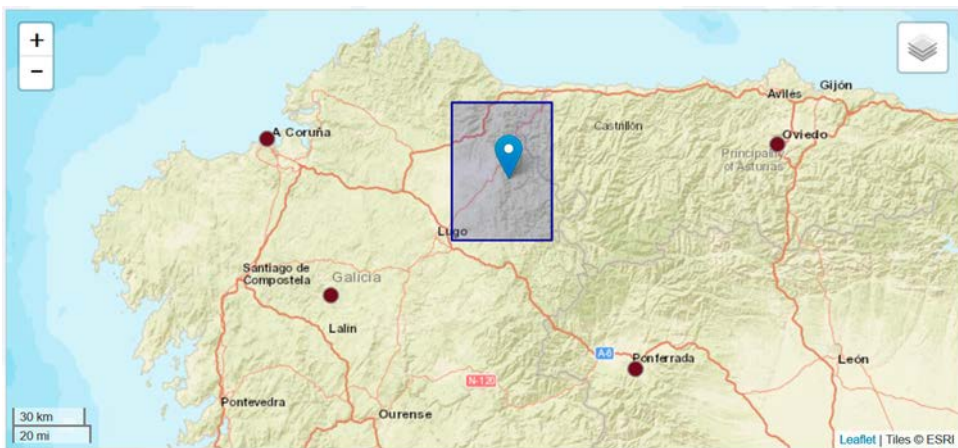

Figure 2. Weather Stations and raster cells in ClimateCharts.net.

The Global Historical Climatology Network V2 and Climate Anomaly Monitoring System (GHCN CAMS and CPCC v7) offers monthly values of mean surface air temperature with a grid resolution of 0.5 × 0.5 degrees. The evaluated time frame ranges from 1948 to the present. They combine two different datasets in their simulation and use various interpolation techniques such as an anomaly interpolation approach (Fan and van den Dool 2008).

In contrast the *Global Historical Climatology Network Monthly (GHCN-M)* provides data for 7280 weather stations. It offers values for monthly mean maximum temperature, minimum temperature, mean temperature, and monthly total precipitation. The network started collecting data in the early 1990s, but the data itself clearly depends on the selected station and can go back further (Menne et al. 2018).

Even though the taken and simulated measurements range across a variety of variables, ClimateCharts.net itself currently focuses only on temperature and precipitation. It uses minimum and maximum precipitation and temperature values as well as temperature means to generate several different charts.

3.2. The user interface

3.2.1. Overview

The concept for the user interface (UI) is rooted in the *Multiple Coordinated Views (MCV)* technique and can be seen in Figure 3. The main aspect of the technique is the display of multiple, coordinated views, that each show different representations of the data. This allows the user to interact with the data on multiple levels, enabling them to see patterns and relationships more easily (Roberts 2007).

With regards to ClimateCharts.net that means, that the UI centers around the global map (A) and the set of filters (B). A user can manually add tabbed chart containers (C) below this main setup by directly choosing a location on the map. Figure 4 shows the interaction. A popup opens, offering information about the location, and a *Create Charts* button. Each click on *Create Charts* generates a new chart container. A chart container displays visualizations for one location only.

The containers are arranged in a grid view and can be placed either full width or side-by-side. It is, however, restricted to two chart containers in one row. This way, the display does not get too crowded and the charts still retain a size big enough to display all the information (see Figure 5).

It enables the user to manipulate the interface without overwhelming them with options. In addition, it makes the tradeoff between screen real estate and task efficiency. A user's cognitive overload can be reduced by providing options to display data at the same time. Thus, a user does not have to remember individual aspects but can compare values at one glance. Offering too many options can be detrimental to the efficiency of the task, which is why a horizontal restriction is set (Wang Baldonado, Woodruff, and Kuchinsky 2000).

The Filter Menu. The filter menu is placed next the map (see B in Figure 3). This, in addition to the map, is part of the features that cannot be turned off. Both are visible at all times unless scrolled out of view. The system offers options to filter data based on location and time, as well as setting an individual title for a chart container.

The filter menu is part of the global settings. It influences the interaction with the global map. Once a chart container has been created, the global filter settings do not apply to this chart container anymore. That means, it is independent of the filter menu.

The Chart Container. Figure 6 shows the overall structure of a chart container. On the left side it has a band of tabs (A) that switch between visualizations. This includes the classic Walter-Lieth climograph, boxplots of monthly distributions of temperature and precipitation values as well as a data availability matrix (see Section 3.2.2). In the top left corner are visualization specific buttons
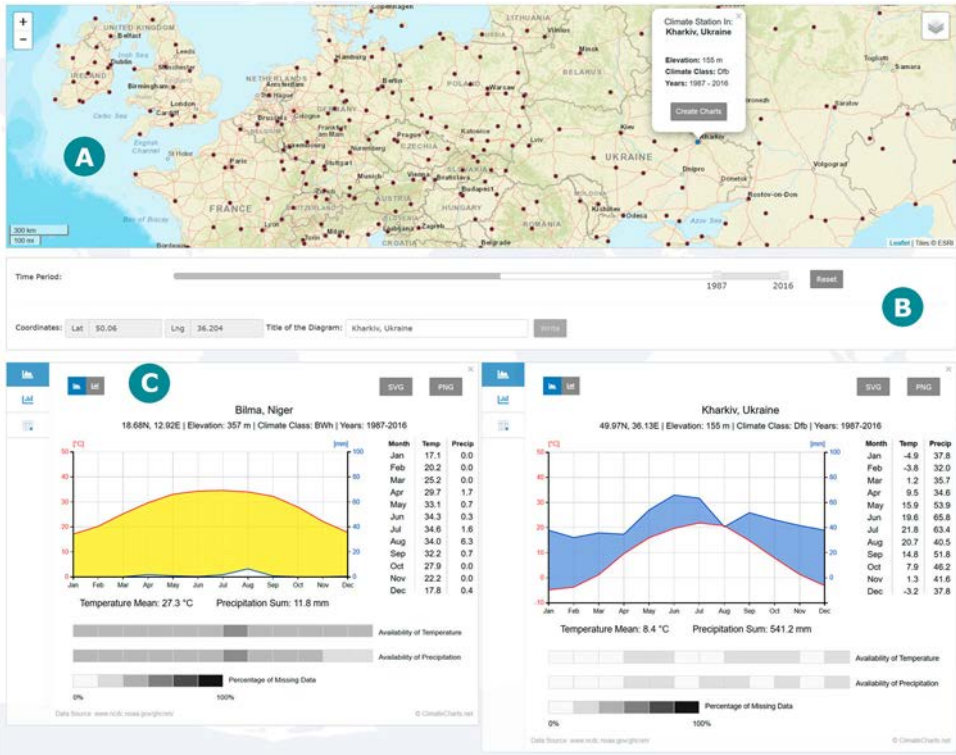
Figure 3. The overall interface concept is a combination of a global map (a), a set of filter (b) and multiple chart containers (c).

(B) right next to detailed information about the visualization's data. Besides the geographic location (Latitude/Longitude) the name of the location and its elevation are provided by the GeoNames database (GeoNames 2020). Furthermore, it displays the dataset's Geiger-Köppen classification, which is calculated individually for the selected period (C). In the top right corner a close button and two local download buttons can be found (D). The chart is completed by a visualization (E) and the Availability Bar (F) which shows information about the completeness of the dataset.

The tabbed chart container can be added to the display for any location and time and a user can open as many containers as they want. The containers get stacked on top of each other or set side-

Figure 4. The interface is showing a popup after the user has clicked on a specific location. It offers information about the location and its data and allows drawing a chart.

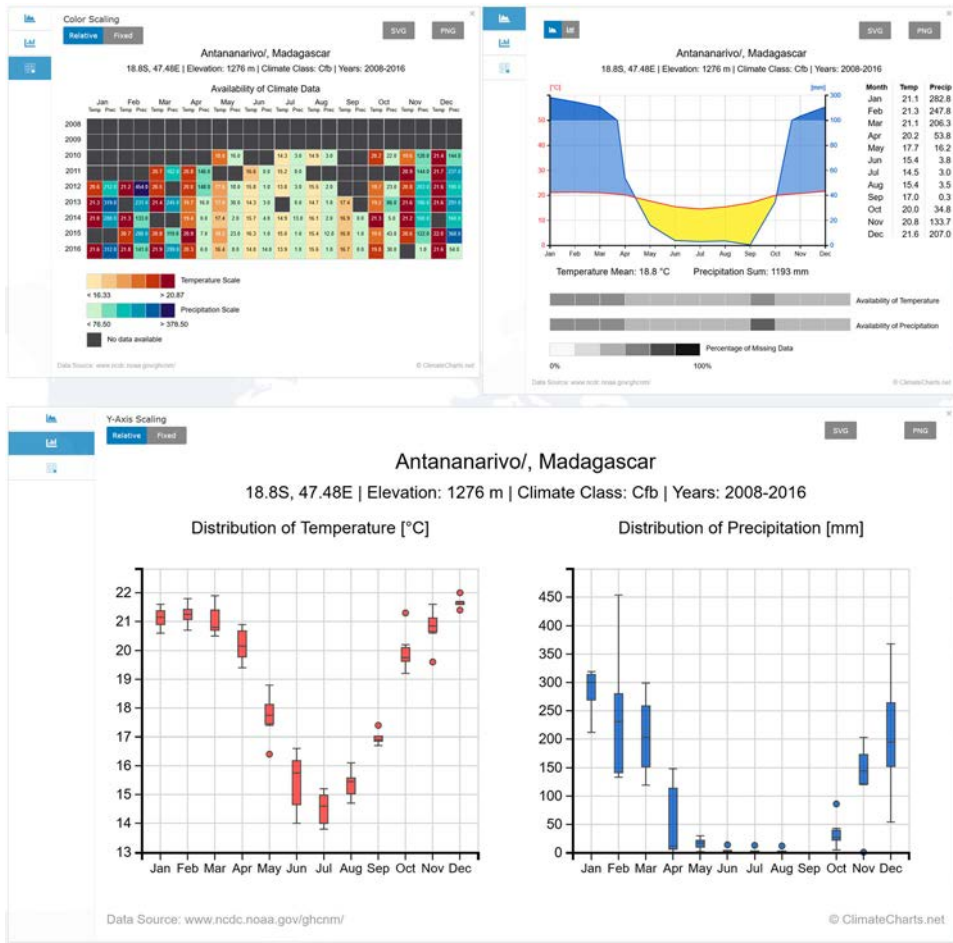**Figure 5.** A full overview of the MCV grid. It shows three gridded chart containers. They show different visualizations and the tab on the left indicates what part of the individual container a user is looking at.

by-side. After two containers have been opened in one row, the third will be placed in another row. Figure 5 shows a potential setup of several chart containers with individual visualizations.

One container consists of several tabs, each encompassing one particular visualization for the same dataset. This means that a user has to add the same amount of chart containers to the view as there are visualizations in order to see every chart for the chosen dataset simultaneously.

A set of icons on the left side of each container gives an overview for available options. Each chart has its own, unique icon and a user can switch between visualizations by clicking on the icons. This shifts to the chosen visualization of the same dataset in the same container. The icon of the active chart is highlighted by a dark background color.

3.2.2. Visualizations

Walter-Lieth Climate Chart. The Walter-Lieth climate chart is used to classify local climate. It is based on air temperature and precipitation and highlights humid, perhumid and arid conditions (see Figure 6). The local conditions are color coded. Humid is mapped to light blue, arid is mapped to yellow and per-humid (average monthly precipitation > 100 mm) is mapped to a darker blue as can be seen in Figure 6(e). We based our choice of color coding on the standard representation of
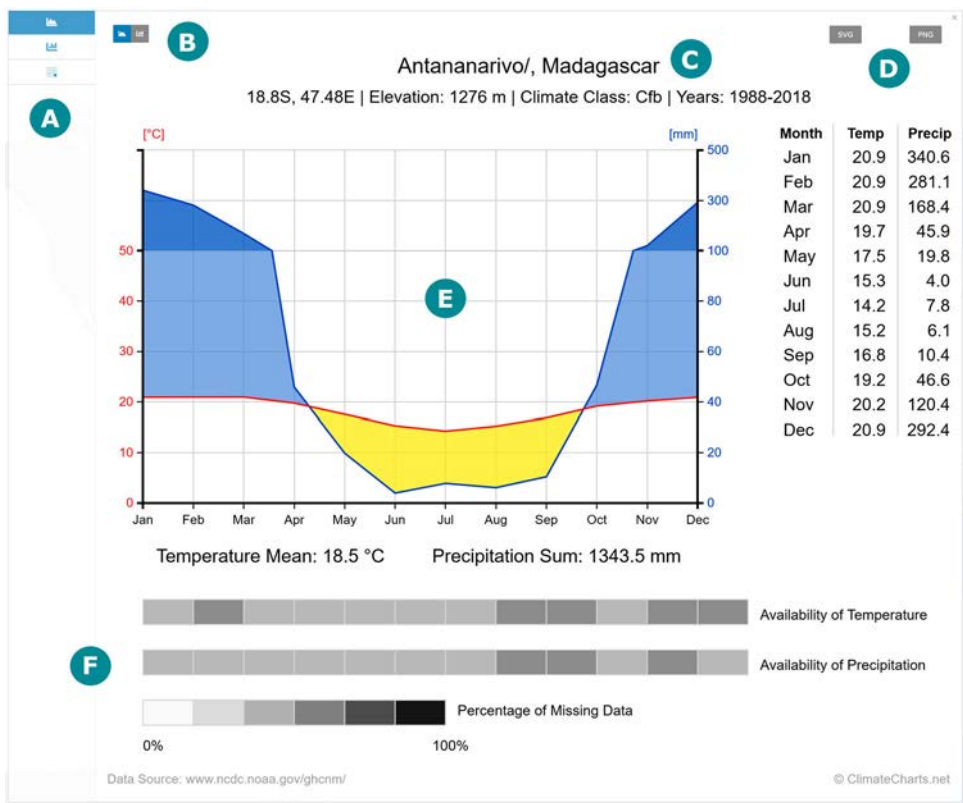
Figure 6. The overall structure of a chart container: (a) Tabs to switch between visualizations, (b) visualization specific buttons, (c) Detailed Information about the dataset, (d) Close Button and local download buttons, (e) area for visualization (yellow -- arid conditions; light blue -- humid conditions; dark blue -- per-humid conditions with > 100 mm average monthly precipitation), (f) availability bar.

Walter-Lieth climate charts as they can be found in schoolbooks, for example. This way we guarantee a recognition effect for user who worked with these diagrams before.

Furthermore, it is possible to switch to a classic bar chart depicting precipitation values. However, this means that the information on humid and arid conditions will not be shown in this visualization.

Additionally, a grey-scale bar (Availability Bar) is placed underneath the Walter-Lieth climate chart. Since this chart is one of the more important climate charts, additional information about the availability of data is advantageous to the user's understanding.

The *Availability Bar* maps the calculated mean values of availability for the selected time interval for each month onto a grey value, resulting in a bar containing several gradients. It shows the percentage of missing data measurements (see Figure 7(a,b)) from the dataset. The legend (see Figure 7 (c)) helps interpret the values. If no data is missing, the equivalent cell is shown in the lightest color of the grey scale.

The colors are chosen for each dataset based on an individually calculated five-step interval. The interval size was selected due to a human's ability to differentiate colors. A color palette should not consist of more than seven to ten colors, therefore we decided on a six color map after testing multiple possible setups.

The *Availability Bar* enables the user to understand how complete the data is without having to visually compare it with the availability chart. However, for a more detailed view opening the table is always an option. Figure 5 shows both visualizations of the same dataset side by side.

Figure 7. The Availability Bar added to the Walter-Lieth Chart is located below the chart. It gives an overview as to how much percent of the time interval is based on missing data.

Distribution Chart. The distribution chart seen in Figure 8 shows monthly box plots of temperature and precipitation values based on the selected time interval. It can display an automatic *y*-axis scale, calculating values based on a relative interval depending on the selected location and time. This means that the minimum and maximum values of the chosen temporal subset are set as lower and upper boundaries for the displayed interval. In contrast to this a user can select a global scale, which shows a fixed scale independent of the min/max values of the dataset. This ensures that different datasets can be compared to each other.

Additionally the chart offers two thematic visualization; one chart for temperature and one chart for precipitation.

Availability Chart. The availability chart shows temperature and precipitation values for a given location and time. The table is color coded to the variables and each cell contains the measured or calculated value. This can be seen in Figure 9. The table's color distinguishes between temperature values, precipitation values, and values for months where no measurements were taken. Temperature and precipitation values are shown alternating. Each row represents a year and each column represents a month and an attribute, such as temperature or precipitation. That means that the table consists of 24 columns, 12 for each attribute. Additionally, each cell contains the precise value of the attribute as text.

Figure 9 shows an overall view of the visualization. Based on the default colors for temperature and precipitation in weather visualizations, each attribute is mapped to a multi-hue-color scale. The values for temperature range from a light yellow to a dark red and the values for precipitation range from light to dark blue. Data points where no measurements were taken stay dark grey, making
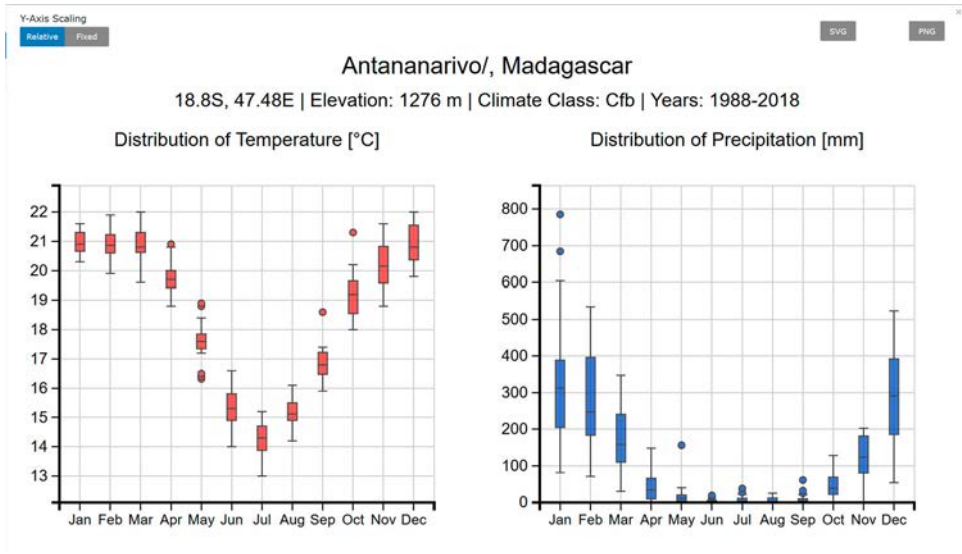

Figure 8. The distribution-chart created with ClimateCharts.net.

them visible between both color maps. This way, a user can find areas of high, low or missing values at first glance and can then investigate the areas of interest in more detail by reading the actual values written into each cell.

Furthermore, it is possible to switch between a relative and a fixed color scale, analogue to the distribution chart. The relative scale ensures that values can be found quickly and at one glance as it is calculated based on local values. This means that the discrete steps are evenly distributed between the actual values. The fixed scale enables users to compare several different availability charts with each other. But depending on local values, it is possible that a wide range of values fall within the same fixed interval. This results in colors missing from the chart and cells being less easy to distinguish.

Due to the fact that both color maps range from light to dark colors, finding a middle value that can be easily read on all backgrounds is difficult. Hence, text values switch from black to white depending on the background color of each cell. On the one hand, this adds to the colorful character of the chart, visually cluttering the display, but on the other hand, it makes reading the values easier once the user focuses on the details of a cell.

3.2.3. Interaction techniques

The previous sections introduced the visual aspect of ClimateCharts.net. But since user interactions are an integral part of any interface, many interaction techniques have already been introduced. The section covered all indirect manipulation techniques, such as the filter menu, as well as popup options and chart specific buttons (e.g. switch buttons, download buttons).
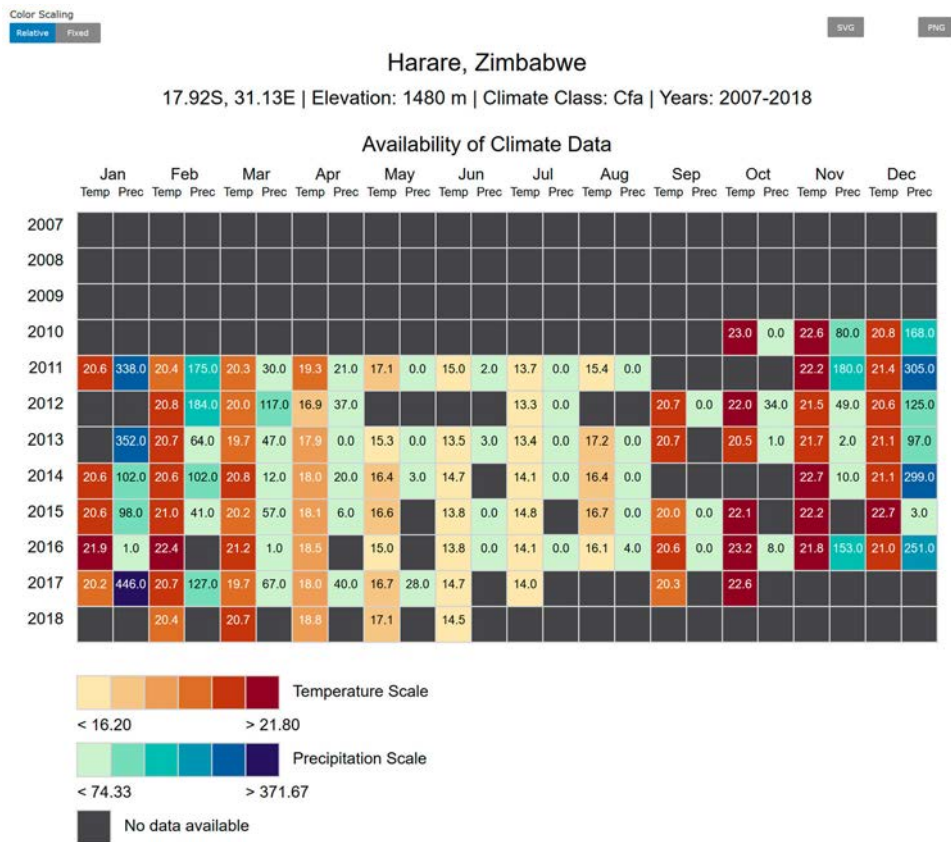
Color Scaling Relative Fixed   SVG   PNG

Harare, Zimbabwe
17.92S, 31.13E | Elevation: 1480 m | Climate Class: Cfa | Years: 2007-2018

Availability of Climate Data

Year	Jan Temp	Jan Prec	Feb Temp	Feb Prec	Mar Temp	Mar Prec	Apr Temp	Apr Prec	May Temp	May Prec	Jun Temp	Jun Prec	Jul Temp	Jul Prec	Aug Temp	Aug Prec	Sep Temp	Sep Prec	Oct Temp	Oct Prec	Nov Temp	Nov Prec	Dec Temp	Dec Prec
2007																								
2008																								
2009																								
2010																			23.0	0.0	22.6	80.0	20.8	168.0
2011	20.6	338.0	20.4	175.0	20.3	30.0	19.3	21.0	17.1	0.0	15.0	2.0	13.7	0.0	15.4	0.0					22.2	180.0	21.4	305.0
2012			20.8	184.0	20.0	117.0	16.9	37.0					13.3	0.0			20.7	0.0	22.0	34.0	21.5	49.0	20.6	125.0
2013		352.0	20.7	64.0	19.7	47.0	17.9	0.0	15.3	0.0	13.5	3.0	13.4	0.0	17.2	0.0	20.7		20.5	1.0	21.7	2.0	21.1	97.0
2014	20.6	102.0	20.6	102.0	20.8	12.0	18.0	20.0	16.4	3.0	14.7		14.1	0.0	16.4	0.0					22.7	10.0	21.1	299.0
2015	20.6	98.0	21.0	41.0	20.2	57.0	18.1	6.0	16.6		13.8	0.0	14.8		16.7	0.0	20.0	0.0	22.1		22.2		22.7	3.0
2016	21.9	1.0	22.4		21.2	1.0	18.5		15.0		13.8	0.0	14.1	0.0	16.1	4.0	20.6	0.0	23.2	8.0	21.8	153.0	21.0	251.0
2017	20.2	446.0	20.7	127.0	19.7	67.0	18.0	40.0	16.7	28.0	14.7		14.0				20.3		22.6					
2018			20.4		20.7		18.8		17.1		14.5													

Temperature Scale
< 16.20   > 21.80

Precipitation Scale
< 74.33   > 371.67

No data available

Figure 9. The availability-chart created with ClimateCharts.net.

In addition, a few direct manipulation techniques are part of the application. A user can directly interact with the global map to choose a location and they can manipulate the global maps with the usual map specific user interactions.

Furthermore, a user can hover over the Walter-Lieth climate chart and the corresponding entries in the adjacent data table and the *Availability Bar* are highlighted using thematic colors. This supports better readability of the chart and is part of the *Brushing & Linking* techniques.

4. User analysis and conclusion

The main parts of the present paper deal with the development of a web application for the generation of climate diagrams. The main aspects of visual representation and the technologies used are discussed. Therefore, two aspects can be considered as a conclusion of such an article. On the one hand a user-centered view, which gives information about the way the offered web tool is used and for which purpose. For this, user data are available for a more detailed user analysis. The second is a more developer centered view on ClimateCharts.net.

The goal of the chosen selection of climate diagrams was to find a representation that is easy to understand and handle for citizens and can also be used in school and university education. Due to available information about the user's behavior, we gained insight into the actual use of the tool.

The following results are based on a user analysis for the year 2019. 35,313 unique visitors used the web tool in this period and generated 217,619 climate charts. Approximately 50% of users are divided between several European countries, while approximately 22% come from the USA alone.

The user's behavior shows a clear weekly rhythm. The phase of intensive use of the tool begins around 8 am and is then mostly evenly distributed throughout the day (cf. Figure 10). A peak can be seen in the interval of core working hours between 8 am and 4 pm, where users overlap in both school and professional sectors. The analyses show, that there is no significant decrease of visitors in the evening hours. That indicates that the intensity of using ClimateCharts.net for private purposes is comparable with the educational and professional sectors.

In particular, the usage in the area of school and university education becomes clear by three analysis results. Firstly, a large number of user access ClimateCharts.net from collaborative learning platforms such as google class room or moodle, or from specific learning resources at schools, colleges or universities. In addition, it can be seen, that groups of users coming from the same region or city work simultaneously with the web tool for a period of 60–90 minutes. And furthermore an analysis of the long-term time series of visitors show a frequency that could correlate with the summer holidays in schools and universities. All these results are strong indicators, that the offers made by ClimateCharts.net are of great interest to curricula of schools and other educational institutions.

From a technological perspective, 79% of visitors use a desktop PC to work with the tool and 19% use mobile phones and tablets. The average time spent with the tool is about six minutes, in which
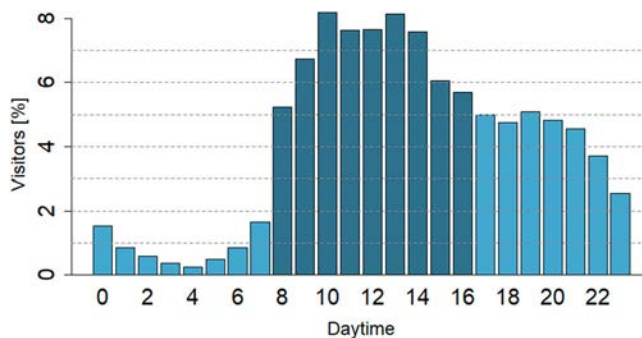

Figure 10. Relative hourly distribution of visitors on ClimateCharts.net (reference year: 2019).

an average of six climate diagrams is generated. However, it can also be seen that individual users create dozens of charts.

In addition to the analysis of our users' origin, it is interesting to analyze how people use ClimateCharts.net. These analyses can provide valuable insight into the way the provided data and features are being used.

ClimateCharts.net offers the user a choice between raster data and station data. The results of the user analysis show that two thirds of the users generate climate charts by using one of the three offered raster datasets. The remaining third uses the station data of the GHCN. This behavior shows that every available dataset on ClimateCharts.net is used. Another feature of our webapp is to change the time interval for which a climate diagram is generated. The default setting uses the period from 1987 to 2016. The analysis shows that only 49 % of users retain this default setting. A little more than half of the users adapt it to their own needs. Figure 11 shows the variability of the upper and lower limit of the generated climate diagrams as a boxplot. It becomes evident that the entire temporal spectrum of the data is used.

Furthermore, we can analyze the users' behavior regarding the selected location of generated climate diagrams. Figure 12 shows a hotspot analysis of the worldwide distribution of generated climate diagrams. It becomes apparent that a substantial part of the climate diagrams is located in Europe and in the coastal regions of the United States. The clusters correspond to what we have seen in our users' whereabouts.

Nevertheless, individual artifacts can be identified which suggest that climate diagrams are very often generated for specific, sometimes very sparsely populated, areas. These include, for example, single hotspots in northern Africa or the Himalaya region. An in-depth analysis has shown that these places and regions are sparsely populated but are of great interest from a tourism perspective (oases, national parks in North Africa, Lake Victoria, Mount Everest base camp). At this point, we assume that in addition to users in the school and university sector, citizens also use the ClimateCharts.net Webtool in a private capacity, for instance to prepare their own holidays.

Furthermore, the analysis of the generated climate diagrams shows that there is a need for additional features. In different regions of the world, climate diagrams are repeatedly generated along lines. This indicates that for some of the users a function to automatically generate several climate diagrams along a profile would be helpful.

The conducted user analysis allows us to draw a number of conclusions on how ClimateCharts.net is currently being used. The constantly growing number of users shows that the provided visualizations are needed and used frequently. Climate diagrams generated with ClimateCharts.net complete the range of information of many websites, primarily in the field of education. This also shows that the provision of appropriate teaching materials can be an aspect for future developments of the platform.

Due to the corona pandemic in 2020, in a majority of countries, classical school education is currently replaced with home and online schooling. This fact reflects in the use of ClimateCharts.net and we expect approximate 70,000 visitors for the year 2020.
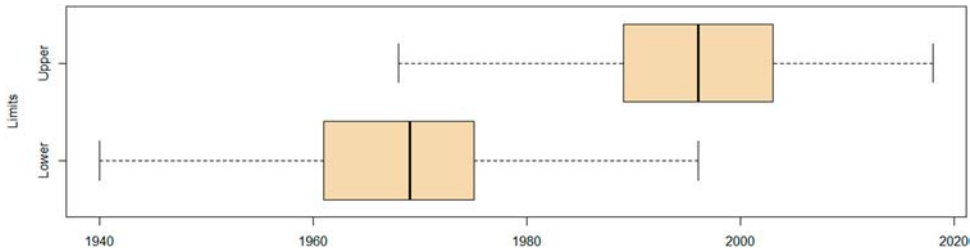

Figure 11. Distribution of individual chosen upper an lower limit (reference year: 2019; default settings unconsidered).
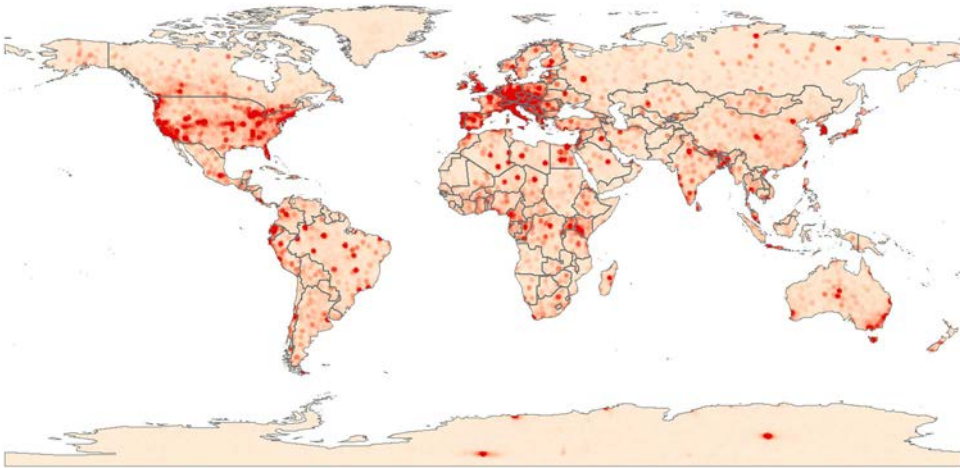
Figure 12. Hotspot analysis of generated climographs (reference year: 2019).

In addition to the in-depth user analysis we conducted an evaluation of an earlier prototype of the system. The group of participants were domain experts in various fields, such as Earth Science as well as Information Visualization. It consisted of three different phases:

Understanding the System: The first phase was designed for users to familiarize themselves with the system in an *Informal Evaluation*. They were given free access to the system and were asked to *Think Aloud* while exploring. This created opportunities for the observer to see how users handle the system and what features encourage them to engage. An additional goal was to assess how intuitive and self-explanatory the system is.

Solving User Tasks: The second phase consisted of an early usability study, where users were tasked with specific problems. Explanations were kept vague since the goal of this phase was to evaluate how users interact with the system if faced with specific tasks without guidance.

Rating the Experience: The evaluation was concluded by a questionnaire. The questions ranged from basic demographics to an evaluation of the usability, user experience and overall assessment of individual features.

During the evaluation, the aspect that stood out the most was the *Multiple (Coordinated) Views* system. It proved to be an effective and satisfying addition to the system, since it allows users to view several different chart containers (i.e. several different subsets of data) at once. This way, users could compare data more efficiently and easily, which was pointed out often.

Another aspect of the prototype that got a lot of attention was the color coded availability chart. Especially with real tasks, participants said it was intuitive, easy, and fun to use. Moreover, *Brushing & Linking* in the Availability Bar of the Walter-Lieth climate chart was mentioned in a positive context frequently. In general, participants seemed to like the workflow and clear interface of the prototype and enjoyed interacting with the system.

The feature that was missing from the prototype the most was system feedback. Participants had trouble to predict the system's behavior and therefore got lost several times before they learned and understood what action caused what reaction. Due to this an often requested feature was more help, i.e. offering a short introduction layer when opening the website, tooltips, or information popups.

Overall, some features, such as the Availability Bar, were not as intuitive as hoped. Other features that were missed entailed more interaction techniques (e.g. Brushing & Linking for all charts, Drag & Drop, mouseover effects for the table) and providing a button to close all chart containers at once.

This evaluation and further analysis of the system provided a lot of feedback for improvements and suggestions for essential features that were missing and have since been partly implemented (e.g. User Guide, optimization of workflows and robustness, link to further information, automatic

scaling of individual charts, etc.). Future improvements include a much more elaborate user feedback (help, information), as well as a more in-depth interaction design (e.g. Brushing & Linking between charts, Drag & Drop of charts).

Altogether, the system creates a solid basis for further iterations and supports our goals. In conclusion, we achieved our goal of an easy-to-use application for creating climate related diagrams. The conducted user analysis shows the tool's benefits and strengths for education in schools and universities and in private use. While there is still further potential for future development, the tools provided by ClimateCharts.net contribute a valuable and innovative addition to communicating climate data and information.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix

The actual release of the web application is available under the following weblink: https://climatecharts.net.

Both the client and server applications are available on GitHub: https://github.com/GeoinformationSystems/.