A virtual thematic research environment for analysis of climate change and its consequences for Northern Eurasia: the current state of the art and perspectives

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Abstract. A virtual research environment aimed at analysis of climate change and its impact on Northern Eurasia based on climatic data archives and dedicated analytics embedded into a web-GIS called “Climate” is presented. An extended set of analytical procedures related to the analysis of climatic and meteorological extremes is described. An updated web portal structure is described to facilitate the system use by the general public, regional stakeholders, and decision makers and get the required information without using a tedious registration procedure.

1. Introduction

Now the major concern of climatic science is to meet the requests of the population and stakeholders on ways to diminish the negative consequences to the environment, human well-being, economy, and industry arising from the climate change impact. One of the important features of this impact is the increasing frequency and magnitude of extreme weather and climatic events [1] that lead to dramatic disasters and huge economical losses. As a response to these challenges, the Future Earth Program appears (http://www.futureearth.org/) and the former research program Northern Eurasia Scientific Partnership Initiative (NEESPI, http://neespi.org/) is transformed into the socio-economically oriented Northern Eurasia Future Initiative (NEFI). A detailed description of this program and its scientific plan were recently published [2]. In this paper, we present a thematic computational-information infrastructure under development aimed at supporting the declared NEFI objectives. The necessity of such dedicated infrastructure is caused by several factors. The on-going climate changes have stimulated the development of advanced climatic models and increase in the number of local and remote sensors measuring various climatic characteristics of the Earth system, which leads to a significant increase in the collected data volume. To process such data volumes and get an insight into the current and projected changes in the regular climatic characteristics and their impact on the environment, population, and social and economic processes determining the well-being of the humankind, special approaches based on distributed networks and use of modern information technologies should be developed. Significant efforts and resources of several large international programs are currently focused on creating a sustainable distributed information-computational infrastructure for open, permanent, reliable, and secure access to high-quality climatic modeling and
observational data and processing tools. These efforts can be described as the development of a Virtual Research Environment (VRE) for a climate domain [3]. A VRE consists of information resources located in the global network and computational tools. The very concept of a virtual research environment assumes that a working environment does not require a physical space to organize research activities. The interaction of researchers and/or their contacts with colleagues are performed through modern channels of communication using advances in information technology [4]. Thus, a VRE is a complex set of network tools, systems, and processes that contribute to strengthening the research process. It is flexible and adaptable to demands of researchers. A VRE has the following major features: (i) it is a web-based working environment; (ii) it is tailored to serve the needs of a targeted community; (iii) it is expected to provide a community with a set of scientific products needed to accomplish the community’s goal(s); and (iv) it promotes sharing of research results. The main idea of this approach is to develop an environment supported by a system/platform that comprises data, software tools for processing and visualization of results, computing resources to be used by researchers to perform selected data analysis providing Internet access to the system using a unified user-friendly interface [3]. The fact that climate science deals with georeferenced data requires using a combination of web and GIS techniques.

As a response to these challenges, the web GIS platform “Climate” (http://climate.scert.ru/) was developed [5-6]. It is a free, cross-platform, composite application with an open-source computational backend that complies with common data format conventions for climate data and provides the functionality of common desktop software in a window of a conventional Internet browser. Forming a thematic VRE the web GIS “Climate” provides interdisciplinary distributed research groups of non-experts in information technologies (climatologists, ecologists, biologists, and decision makers) with easy-accessible reliable online tools for rapid analysis and visualization of multidimensional heterogeneous climatological datasets obtained from various sources.

Occurring and expected negative consequences of climate change require from decision-makers responses based on reliable assessments of regional and local trends and impacts. This knowledge is required to develop adequate local and/or regional strategies for adapting and mitigating negative effects of climate change, for example, for sustainable agriculture and forestry, or planned infrastructure. To meet these challenges, several years ago the World Meteorological Organization initiated a large program for the development of a climate service system based on thematic web services (http://gfcs-climate.org/) [7]. However, reliable analysis of climate change impacts and choice of society’s responses to them requires skills in handling big datasets, abilities to interact with powerful computing resources and complex numerical models, knowledge of modern methods of statistical analysis, and skills in programming. The skills mentioned are not typical for specialists in the field of economic, political, and social sciences and, unfortunately, it is completely uncharacteristic for decision-makers. Therefore, an integration of relevant resources into an intuitively clear Internet-accessible research environment should be done to provide specialists and decision-makers with reliable and understandable tools for studying economic, political, and social consequences of climate change. The web-GIS platform “Climate” represents an example of such integration. The system also opens new possibilities for education. One of the modern educational instruments is a virtual learning laboratory (VLL) which is a specially designed virtual learning environment targeted at educational needs [8]. It allows one to simulate the behavior of real-world objects in a computer learning environment and helps learners to acquire new knowledge and skills in natural sciences. An important advantage is the ability to use a virtual laboratory in distance education where, in principle, it is impossible to work in university laboratories. It is typical to use simulation programs of studied objects, mathematical packages, optimization programs, and databases in a virtual laboratory. The use of a VLL based on a thematic VRE seems the most promising and perspective way to prepare specialists in environment science and applications domain where research is based on intensive use of observational and modeling data analysis. In such a VLL the number of executing tasks should be limited by those directly related to a subject under study, and a collection of thematic educational materials should be included into a specific course accessible to a student. A targeted VLL
based on the web-GIS platform “Climate” is successfully used for teaching meteorology and climatology students at Tomsk State University [9]. The results showed that students who have completed the courses embedded in the system demonstrate strong knowledge in the field of climate change and its possible consequences. To obtain these results, students were tested at the beginning of the course and after its completion. However, due to the need of registration to gain access to the VRE and its educational functionality the audience coverage was rather small.

In this paper we describe some steps in recent development of the “Climate” platform aimed at meeting the challenges listed above. First, we briefly present its architecture, major components, and workflow. Calculation of some characteristics useful for applications is not supported by the above-described version of the system. That is why its analytic functionality was extended. This extension is described in Section 3. Also, the use of the platform requires some basic knowledge of climatology and meteorology. This fact, as well as the level of available computational resources, led to the necessity of preliminary registration of potential users, which significantly decreases the platform potential. That is why a new Web-portal structure solving this problem was elaborated. It provides each group of users with resources available in this thematic VRE relevant to their skill level. This structure is described in Section 4. Then a new computational functionality targeted at the region well-being is described in more detail. Also, we present a new Web-portal structure which provides each group of users with resources relevant to their skill level and available in this thematic VRE.

2. WEB-GIS “CLIMATE”

The web GIS platform “Climate” provides Earth system science specialists with tools for processing and analysis of geospatial datasets and visualization of results. The platform's dedicated software framework comprises three key components: a server-side computational backend; a server-side middleware represented by the geoportal; and a web mapping client based on an AJAX technology and a specialized JavaScript library containing typical widgets. Geospatial datasets are processed by a set of validated software modules running by the backend. Results are represented by overlapped raster and vector cartographical layers accompanied by corresponding binary data. The platform “Climate” functionality includes basic and complex statistical analysis of data, while the online geo-information system (GIS) instruments allow the user to combine and map georeferenced results over a chosen cartographical basis. It does not require profound programming skills of the users, and it provides the users with reliable and practical online instruments for integrated research of climate and ecosystem changes through a unified web interface.

The “Climate” platform architecture represents a typical client-server structure where, in the general case, the server might be a set of geographically distributed standalone nodes [10] providing common (federated) interface (API) and client applications (basically, Web-GIS client). On the node level the server part of the architecture includes a high-performance computing system with a data storage attached. It is represented by two tiers: a resources tier including data and metadata; and a server applications (middleware) tier.

The client part of the architecture is based on a modern graphical web browser. It is represented by a single client applications tier.

The resources tier of the platform “Climate” includes data and metadata basic components. The data component contains datasets located on the data storage system either in the form of collections of netCDF files or PostGIS databases. The metadata component is represented by the metadata database (MDDB), which describes geospatial datasets and their processing routines and provides effective functioning of the system [11]. The database contains structured spatial and temporal characteristics of the available geospatial datasets, their locations and configurations of the software components for data analysis. According to the chosen data storage model, spatial datasets are mostly represented by collections of netCDF files grouped by spatio-temporal features and placed in a hierarchy of directories in data storage systems. Each netCDF file stores one or more variables containing values of meteorological parameters in a given spatio-temporal domain. Files in a dataset are usually named according to a unified pattern to provide their automatic search. Along with data
variables, netCDF files contain horizontal, vertical, and time domain grids. A dataset collection is defined as a collection of datasets created by an organization within the framework of the same research project but specified on different spatial and/or temporal grids or for different modeling scenarios. The collection may consist of one dataset.

The server applications middleware tier consists of two basic software components: a computational backend and a geoportal. The computational backend contains data processing and visualization software components. The data processing is a key software component containing computational modules based on the GNU Data Language (GDL, http://gnudatalanguage.sourceforge.net/) and Python and providing integral geospatial data statistical processing as well as API to handle netCDF, Hierarchical Data Form (HDF), ESRI Shapefile data files and PostGIS databases. Depending on the result type required, the visualization component of the backend generates files in the following formats: GeoTIFF, ESRI Shapefile, Encapsulated PostScript, CSV, XML, netCDF, and float GeoTIFF.

The Spatial Data Infrastructure (SDI) geoportal contains two basic components: a web portal and a geoserver (http://geoserver.org). The geoserver provides cartographical web services such as Web Mapping Service (WMS), Web Feature Service (WFS), and Web Processing Service (WPS). In general, the web processing service provides a standard HTTP interface for remote configuring and launching the data processing software modules and presenting results in generic formats. The services can be used by either standard GIS environments or web applications.

The web portal serves as a connection point between different SDI elements (geospatial data, metadata, services and client applications). Its main feature is providing a unified API for client web applications which comply with the conventional Boundless/OpenGeo architecture [12]. The web portal provides the server-side part of the Web-GIS client application which complies with the general INSPIRE (INfrastructure for SPatialInfoRmation in Europe, https://inspire.ec.europa.eu) requirements to geospatial data visualization and implements computational processing services for support of solving tasks in climate monitoring.

The currently available archive of geophysical data includes the first and second editions of NCEP/NCAR reanalysis, JMA-CRIEPI JRA-25 and JRA-55 reanalyses, ECMWF ERA-40 and ERA Interim reanalyses, NOAA-CIRES reanalysis of the Twentieth century, GMAO Modern Era-Retrospective analysis for Research and Applications (MERRA), two precipitation datasets from APHRODITE’s project and the DWD Global Precipitation Climatology Centre, correspondingly, NCEP Climate Forecast System Reanalysis (CFSR), data obtained using a model “Planet Simulator” for historical period and climatic projections up to 2100, as well as observations from weather stations located in the territory of the Russian Federation. Recently some MODIS (MODerate Image Spectroradiometer) Terra and Aqua Land Products (https://lpdaac.usgs.gov/) and INMCM4 [13] model climatic projections were integrated into the software complex by means of MDDB and administrative web console. Flexibility of the system allows easy and fast expansion of the number of datasets available for processing and visualization.

The computational modules allow calculating the basic statistical parameters (mean, standard deviation, maximum and minimum values of meteorological parameters) and indicators of the temporal structure of meteorological series (repeatability and continuous duration of atmospheric phenomena with values of meteorological parameters above or below the specified limits within the specified time range) reflecting the regularities of random variables in time and space. In addition, computational modules for calculating indices of climate change (http://cccma.seos.uvic.ca/ETCCDMI/indices.shtml) were developed. They allow one to extract information about extreme values of daily temperature and daily precipitation amount, and their probability characteristics. Some indices are calculated for fixed thresholds related to specific applications. Other indices are based on thresholds, which vary depending on the location of observation posts. In these cases, the threshold values are defined as respective percentiles of data series [14]. Features of the temporal dynamics of climatic indices are defined by long-term components of time series, trends allowing one to assess the change tendency of meteorological
values, by assessment of the statistical significance of identified trends, as well as by the degree of correlations between weather events. This sequence of procedures, including calculation of climatic parameters and studying their spatial and temporal dynamics, allows one to obtain the most complete picture of features of occurring fluctuations of the climate system in the studied region. The functionality of the computational backend can be easily extended on-demand by new modules developed by both developers and users. The computational backend contains data processing and visualization software components based on the GNU Data Language (GDL, http://gnudatalanguage.sourceforge.net/) and Python. Geospatial datasets are processed by a specialized set of validated software modules running within the framework of the computational backend.

The client applications tier provides a unified framework for browser-based Web-GIS applications, and platform’s Web-GIS client. The Web-GIS client interface is similar to interfaces of conventional GIS applications like uDig, QuantumGIS, etc. The application can display cartographical information provided by the platform “Climate” geoservices as well as WMS layers available from various data providers, such as the National Snow and Ice Data Center (https://nsidc.org/), the Socioeconomic Data and Applications Center (http://sedac.ciesin.org/), and others. The web-GIS client functionality also includes specialized wizards that allow the platform user to easily create various configurations for the computational backend in the XML format.

The web GIS platform “Climate” is used in studies of the ongoing Siberian climate change and its impact [15-17].

3. New computational functionality targeted at a region’s well-being
A description of extreme events requires the use of special statistics. A correct statistical description of extreme precipitation and temperature can be obtained using the concepts of extreme value statistics (EVSs) [18]. Software implementation of EVSs in the R language (package “extRemes”) allows statistical modelling of maximum values based on a non-stationary generalized extreme value distribution. The values required for risk assessment can be calculated using this distribution function. This is a probability of the value of an observed variable to exceed a certain level. These levels are frequently expressed as return levels $r_T$ for a certain return period $T$. $r_T$ is defined as the level which is exceeded, on average, every $T$, i.e., with probability $\frac{1}{T}$. After integration of the relevant analytics into the web-GIS “Climate”, this functionality was used to calculate 100-year return levels of July maximum precipitation based on ECMWF ERA Interim (figure 1a) and APHRODITE JMA data (figure 1b) for the Southern Siberia region (52.5-60° N, 75-95° E).

Figures 1a and 1b show similar behavior of the calculated characteristic, but the APHRODITE JMA results (figure 1b) have more details and higher values in some regions.

The analysis of trends in meteorological observations is one of the most common activities in climate change studies. Quantile regression provides a well-defined statistical framework for estimating the rate of change not only in the mean as in ordinary regression, but in all parts of the data distribution. Given a random variable $Y$ with a cumulative continuous distribution function $F_Y(y)$, the quantile function $Q_Y(r)$ is defined from $F_Y(y)$ as $Q_Y(r) = F_Y^{-1}(r)$. The quantile is defined as the value $Q_Y(r)$ such that $P[Y \leq Q_Y(r)] = r$, $0 \leq r \leq 1$. Then, considering the conditional distribution of $Y$ given $X = x$, the conditional quantile function $Q_{Y|X}(\tau; x)$ verifies $P[Y \leq Q_{Y|X}(\tau; x)] = \tau$. Whereas ordinary regression is based on the conditional mean function $E[Y|X = x]$ and minimization of the respective residuals, quantile regression is based on the conditional quantile function and minimization of the sum of asymmetrically weighted absolute residuals $\sum_{i=1}^{n} \rho(\tau)|y_i - Q_{Y|X}(\tau; x = x_i)|$, where $\rho$ is the tilted absolute value function. The calculation of quantile regression is implemented in the R language by the software package “quantreg” [19]. Quantile values of interest are set between 0 and 1.
Figure 1. 100-year return levels of July maximum precipitation for the Southern Siberia region: a - ECMWF ERA Interim data, 0.75x0.75 horizontal grid, 1979-2007, b - APHRODITE JMA data, 0.25x0.25 horizontal grid, 1979-2007.

Based on ECMWF ERA 40 data, trends of maximum January temperature for the Southern Siberia region (50-65° N, 60-120° E) are shown in Figure 2. The results obtained show that the maximum January temperature at quantile 0.05 changed (both decreased and increased) to a greater extent in comparison with (b) and (c) almost everywhere. The temperature at quantile 0.95 is changed to a lesser extent.

Figure 2. Maximum January temperature trends based on ECMWF ERA 40 data (2.5x2.5 horizontal grid, 1961-2002): a - at quantile 0.05, b - at quantile 0.5, c - at quantile 0.95.
The calculation of correlations between two variables is based on computation of the Pearson correlation coefficient which is a measure of the linear correlation between two variables. A novel software module calculating the Pearson correlation coefficient between daily, monthly, seasonal, and annual values of investigated meteorological variables was integrated into the system. Initially two input datasets are reduced to the same time grid selected by the user. Also, the correlation coefficient can be calculated for meteorological variables from two different datasets. If the input data are set on different spatial grids, the input data are interpolated to a grid with a higher spatial resolution. Figure 3 presents a special form for the calculation of the correlation index between different parameters (the air temperature obtained from ERA Interim reanalysis and meteorological stations datasets). In this case of meteorological station data and regular data, interpolation is performed for regular grid data to the coordinates of meteorological stations.

![Figure 3. Web-GIS client. Selection of a pair of meteorological parameters and processing type.](image)

4. Novel web portal structure

In the report of the World Economic Forum on global risks in 2014, the top ten concerns are the risks associated with the climate factor. Northern Eurasia makes significant input into these risks [2]. The monitoring data of the current climate in Russia show that in recent years the trend towards warming has significantly increased [20]. Considering data for 2016, the average annual temperature in the territory of the Russian Federation continues to grow more than 2.5 times faster than the global one, at a rate of 0.45° C over 10 years, and especially rapidly in the polar region, where the growth rate reaches 0.8° C in 10 years. Now the global climate change has led to an average increase in the frequency of dangerous hydrometeorological events in Russia, such as floods, heavy snowfalls and snowstorms, accompanied by storm and even hurricane winds, strong prolonged frosts, ice, and late spring frosts. In a warm period, heavy rains with thunderstorms, hail and squally winds, or severe droughts are not uncommon. The number and strength of extreme climate manifestations is growing every year. For example, in many regions of Russia at the beginning of the 21st century the frequency
of catastrophic floods increased by 15% compared to the last decade of the 20th century. In 2016 988 dangerous hydrometeorological phenomena (including agrometeorological and hydrological) were noted in the territory of the Russian Federation, 380 of which caused significant damage to the economy and even health of the population. Since forewarned is forearmed, scientifically grounded information about the current and expected climate changes in the region of residence will prepare the general public to expected consequences and will stimulate search for ways to adapt to them. An information package is developed to raise the public awareness of the climate change and promote understanding of the ongoing processes, which will underpin the process of adaptation to such changes on the regional scale.

To simplify using the “Climate” system potential by the population, regional stakeholders, and decision makers, a novel web portal structure was implemented. Now the system allows four user levels. The first one is the general public. For its needs, a special basic course in climate and processes taking place in it was developed aimed at regional climatic literacy level rising of the population and stakeholders. The second level is students and PhD students taking their course in meteorology and climatology. It comprises lecture courses and computational trainings. For the third level, decision-makers, a special database of calculated key regional climate characteristics is put together to give a basis for building adaptation strategies. These three levels are open-access ones. The fourth level is designed for specialists in climate and environmental sciences. It gives access to huge geophysical data resources, system tools (climate and weather models), and services for processing and visualization to perform calculations independently or in a joint scientific team.

To develop environmental literacy of the general public, a special course is designed, which consists of a set of environmental topics. These are, e.g., the difference between weather and climate, climate processes and drivers, climate change and its manifestation on different scales, extreme climatic phenomena and climate risks. Thus, within the framework of the course the basic concepts and problems of contemporary climate change and their possible consequences are set out and illustrated. All materials have been developed in accessible language to educate the public. The course also includes links to popular science network resources on topical issues of Earth sciences and several practical tasks to be performed for a selected region. In general, popularizing knowledge about climate change and explaining the trends of climate change and ways to adapt to them stimulates active participation of the society in environmental protection. In addition, this information package collects, processes, and disseminates reliable environmental information and incorporates the best scientific achievements into practice. At present, there is a serious lack of resources informing the population about the current and expected climate changes and their consequences in Russian. Therefore, we tried to fill this gap in a targeted open portals module. Translation of the course into English is not goal-oriented now, since there exist huge information resources for users with different levels of training in it. Relevant links are also provided to the users.

It is estimated that under the influence of global warming some regions of Russia will suffer from extremely high temperatures and droughts in summer. This will affect the productivity of crops and the state of forestry. In the North the melting of permafrost will accelerate, and floods will intensify. The average annual temperature in the territory of the Russian Federation continues to grow. Annual reports of the Hydrometeorological Center of the Russian Federation highlight and raise the awareness of the exposure and vulnerability of different industry and economy sectors to climate change [20]. Thus, regional decision makers should review strategies for the development of the transport infrastructure and construction projects, as well as the electric power sector policy and planning under the new conditions. As it was already mentioned, the global climate change has already led to an average increase in the frequency of dangerous hydrometeorological events in Russia, and according to a plausible scenario the number of such extreme climate events will increase. To build resilience to climate change and its regional manifestations, we need to assess the environmental, economic, political, and social consequences of the global climate change for the region and develop measures to adapt to these changes and reduce their negative impact.
To develop an effective adaptation strategy and measures to reduce the negative consequences of extreme climate manifestations, accurate knowledge of the geography of climatic extremes, the frequency of their occurrence and intensity is needed. Since the frequency of such events is small to obtain the necessary information, it is necessary to analyze such phenomena using modern approaches of the probability-statistical apparatus and detailed initial meteorological information accumulated during the period of instrumental observations for the territory of the region under study.

To provide regional decision makers with information required for targeted activity, a set of relevant climatic characteristics was calculated based on the “Climate” web-GIS for Siberian region, and an open database of those has been created for subsequent analysis of the ongoing climate changes by regional decision makers. This database provides them with quantitative references for assessing future climate and environmental risks and adapting the region’s development policies to these risks (figure 4).

The different characteristics of the air temperature and amount of precipitation recommended by WMO for analysis of extreme climatic events are represented in this database. These characteristics provide information on the maximum/minimum temperature and precipitation values, information on the frequency and duration of different extremes, identify the number of days when the temperature or precipitation exceeds some threshold (abnormal heat/cold wave, abnormal precipitation etc.).

In every group, the characteristics are calculated using different datasets (ERA-40, ERA Interim reanalysis, data of APHRODITE’s Water Resources Project, data of weather stations, etc.) and the data set used is included into characteristic’s description. Also, trends are calculated for every characteristic from every dataset for the period characterized by the greatest climate change. This will allow users to get a more detailed insight.

Figure 4. Web-page with links to a set of relevant climatic characteristics calculated for Siberian region.
There are links to download data files with calculated characteristics in different formats (netCDF, GeoTIFF, WMS and WFS links) in the database. If there is a need to work with some characteristic further, a user can download data files and load them into a third-party software. The most popular and easy to use software for working with netCDF-files is Panoply (https://www.giss.nasa.gov/tools/panoply/) developed by the NASA Goddard Institute for Space Studies. For a more detailed analysis one can use the NCL (NCAR Command Language) [21] designed specifically for scientific data analysis and visualization. Further work with GeoTIFF files, WMS, and WFS links is possible in a desktop GIS (QGIS, ArcGIS, etc.). It should be noted that the user needs to set the color legend manually when working with GeoTIFF files in GIS. The user can also download legend files as SLD files to provide a color coding of data in corresponding GeoTIFF files using a desktop GIS supporting such legend format.

5. Conclusions

The above-described version of the web GIS “Climate” possesses additional functionality to allow qualified users to analyze the consequences of the ongoing and projected climatic changes in Northern Eurasia. The thus elaborated portal structure is user-friendly and adjusted to users with different levels of knowledge. The present version of the thematic virtual research environment will be used in studies supported by the NEFI program.

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