Development of a "cloud" thematic software complex for analysis of climatic and environmental changes

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Abstract. The architecture and basic elements of an information and computing software complex for processing and statistical analysis of spatial geophysical data archives are discussed. The basic elements of this complex are now represented by several software procedures for searching, selecting, and preprocessing of spatial data arrays, and some components of a geoportal and a graphical user interface. The modular structure of the computational backend of this software complex and the metadata database provide easy extension of complex's functionality. This ability has been used for the integration of some advanced procedures for mathematical and statistical analysis, processing and graphical representation of the results in the form of graphs, diagrams, and fields on a map of the territory of interest in this software complex.

1. Introduction

The growth of environmental data volumes up to the petabyte level and the need to store, search, retrieve, process, visualize, and analyze such geospatial datasets make traditional approaches questionable. This has required new distributed data access and processing technologies to be created, and turned this IT area into a new scientific field that has recently appeared: data intensive application domain, in which relevant approaches and tools are developed [1-5]. Geospatial datasets used in climate and environmental research require application of a spatial data infrastructure (SDI) approach [6]. This approach, in particular, includes the development of a web portal (geoportal) [7-8] considered as a single access point to the SDI resources [9-10]. It provides a functionality of searching geographic information resources, data sampling and processing, as well as cartographical visualization services along with corresponding client applications [11]. Such data processing infrastructure, frequently called virtual research environment [12, 13], should also employ the Web 2.0 standards providing multidisciplinary geographically dispersed research teams with functional capabilities to perform joint investigations [14].

It is generally accepted that the development of client applications as integrated elements of such infrastructure should be based on the use of modern web and GIS technologies [15-17]. According to the general requirements of the INSPIRE Directive to geospatial data visualization [18], it is necessary to provide such features as data overview, image navigation, scrolling, zooming and graphical overlay, as well as displaying map legends and related meta information. That is, the basic functionality of a standard GIS well-known and widely used by potential users should be provided. The benefits of the web-based GIS technologies are obvious: theoretical independence on the web browsers and operating systems, automatic software location and upgrade, combined use of geographically distributed data

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sources, and joint use of centralized data warehouses. To perform reliable analysis of responses of natural ecosystems and society to ongoing climate changes, professional skills and expertise are needed to deal with complex numerical models, modern statistical analysis methods, and programming techniques. Such skills are not very typical for specialists engaged in related scientific fields. The application of web-GIS technologies provides the environmental scientists and decision makers with reliable comprehensible tools for investigating climate change impacts using a well-known graphical user interface.

There are several computational and/or information web systems working with geophysical data linked to environmental science. Some of them deal with analysis of real-time meteorological observational data [19]. Some of them like NASA's GES-DISC Interactive Online Visualization ANd aNalysis Infrastructure (GIOVANNI), (http://daac.gsfc.nasa.gov/techlab/giovanni/) [20] are designed for analysis and visualization of satellite data. One of the most flexible web-GIS is a Regional Integrated Hydrological Monitoring System (RIMS) created at the University of New Hampshire, USA [21, 22]. As a fully integrated advanced system for online analysis of heterogeneous climate, hydrology, and remote sensing data, the RIMS was a successful attempt to realize a multi-functional GIS as a web application using MapServer (http://mapserver.org/). The RIMS is widely used for various research projects [21, 23] including NEESPI (Northern Eurasian Earth Science Partnership Initiative, http://NEESPI.sr.unh.edu/). The main feature of the RIMS is that it deals directly with geospatial datasets instead of the corresponding cartographical images and allows access to the displayed data at each pixel of the map, as well as search and access to the data aggregated by certain space and/or time criteria.

Rapidly increasing volumes of information during the past decade have significantly decreased the effectiveness of a single-server Web GIS. Despite several attempts, in the field of Earth sciences informatization there is still no high-performance tool for integrated study of global and regional climate change providing unified user and application interfaces and combining rich abilities for processing, analyzing, and visualizing datasets obtained from various sources. In this paper, some new results of development of an online software complex for distributed "cloud" processing and advanced statistical analysis of large environmental datasets are presented. In particular, we described in detail the architecture and some already created elements of the developed software complex for analyzing environmental and climatic changes realized within the earlier proposed dedicated framework for the development of thematic information-computational web GISs aimed at the processing of large volumes of spatial data [24].

2. Architecture

The proposed software complex is to respond to three types of user queries: simple, specific, and in-depth. More than 90% of the queries for climatic and environmental data services are quite simple. The users request the spatial pattern of one or more variables, their temporal dynamics, and a suite of their basic statistics. They may also ask for specific analyses (e.g., "what if") made online. Scientists prefer to do their own assessments and require original (but preprocessed) data and comprehensive information about their specifics and quality (metadata). Only in rare situations an in-depth analysis for specific issues is required from the Data Services. The first two types will be handled on-line, and the third type of requests will be processed in-house by several dedicated software packages on the order-response basis. The software complex staff collects (or projects) typical requests for the third most demanding type of queries, and develops a suite of software packages to allow expediently addressing them.

Summarizing the approach adopted, we developed a software complex with the following features:

- geoportal with user-friendly and intuitive clear graphical user interface (GUI) as a single access point to the distributed archives of spatial data and tools for their processing;
- "cloud" data analysis and visualization by a flexible but powerful data processing engine with verified data processing routines;

- export of processing results and metadata as an image (PNG, JPEG, GIF, GeoTIFF), as NetCDF files, and by means of Web Mapping Service (WMS) and Web Feature Service (WFS).

To meet the above requirements, an architecture defining the major hardware and software components of the software complex and major components of its geoportal, thematic web client and web services providing access to the cloud computing resources of the software complex are developed. The software complex is focused on "cloud" distributed processing of large climatic spatial datasets. It can be deployed on several hardware platforms interconnected by high-speed data transfer channels (LAN, Internet). Each of these complexes consists of four typical blocks (Figure 1):

- resources represented by structured archives of geophysical data and corresponding metadata;
- a modular computational backend (core) represented by a set of software modules providing search, selection, processing, and visualization of spatial data, linked using a common application programming interface (API);
- a geoportal implementing logic of web applications, providing communication with cartographic web services, operations with a metadata store, as well as running a computational core;
- a web-GIS client that works on the user side in a modern web browser and provides an interactive graphical interface to the analysis and visualization tools.

Archives of geophysical datasets can be represented as low- and high-resolution modeling data (reanalysis, global and regional climatic and meteorological models) and observational data (series of observations at weather stations, remote sensing data of the Earth, etc.) given on various space-time domains and presented in different data formats. They are preprocessed and stored in high-performance storage systems according to the selected storage model and are accompanied by a set of metadata describing their major characteristics (space-time domain, spatial and temporal resolution, the list of characteristics presented in each archive, units of measurement, technical information necessary for functioning of software component for searching, sampling, and preliminary processing of data arrays). A Network Common Data Form (netCDF) was chosen as the main data format for gridded geospatial data in our data archive. This format is formally acknowledged by scientific institutions (including UCAR (University Corporation for Atmospheric Research, http://www2.ucar.edu/) and OGC (Open Geospatial Consortium, http://www.opengeospatial.org/) as a standard candidate for storing geospatial data and stimulating data exchange in binary form. It is perfectly suited for storing geospatial data and supported by a wide range of commercial and open source software.

Gridded datasets are stored in data storage systems as collections of netCDF files and arranged in a strict hierarchy of directories:

/<data root directory>/
<data collection name>/
<spatial domain resolution>/
<time domain resolution>/
<files and directories with data>

Here <*data root directory*> is a root location of data collections, <*data collection name*> is the name of the directory containing a single data collection, <*spatial domain resolution*> is the name of the directory containing data with the same horizontal resolution, and <*time domain resolution*> is the name of the directory containing data with the same time step. All data files (sometimes grouped in subdirectories) are located deeper in the hierarchy. The names of files and subdirectories are not regulated and determined by the individual specifics of a dataset. Every data file contains one or more multi-dimensional arrays of meteorological parameters. Data are stored in working nodes or in connected data storage systems (Local data) according to the "data awareness" principle. The data awareness is the knowledge about all data that are available within each working node and where these data are located [25]. According to this information, datasets are processed locally, on the nodes containing them. A detailed description of the data storage and processing model is given in [26].

Based on the developed architecture, some basic elements of the software complex providing access, search, and retrieval of data from the data archives were implemented. Collection and preparation of representative fragments of some spatial data archives were carried out, and methods for their preliminary processing were chosen and implemented. The set of data available for processing can be easily expanded. Modules of the computational core for writing data processing results into EPS, GeoTIFF, ESRI Shapefile, and NetCDF files were developed. Some elements of the graphical user interface that provide basic GIS functionality, integration with the geoportal software, and joint presentation of the results on a Google Maps basic layer (http://code.google.com/apis/maps/) were developed as well.

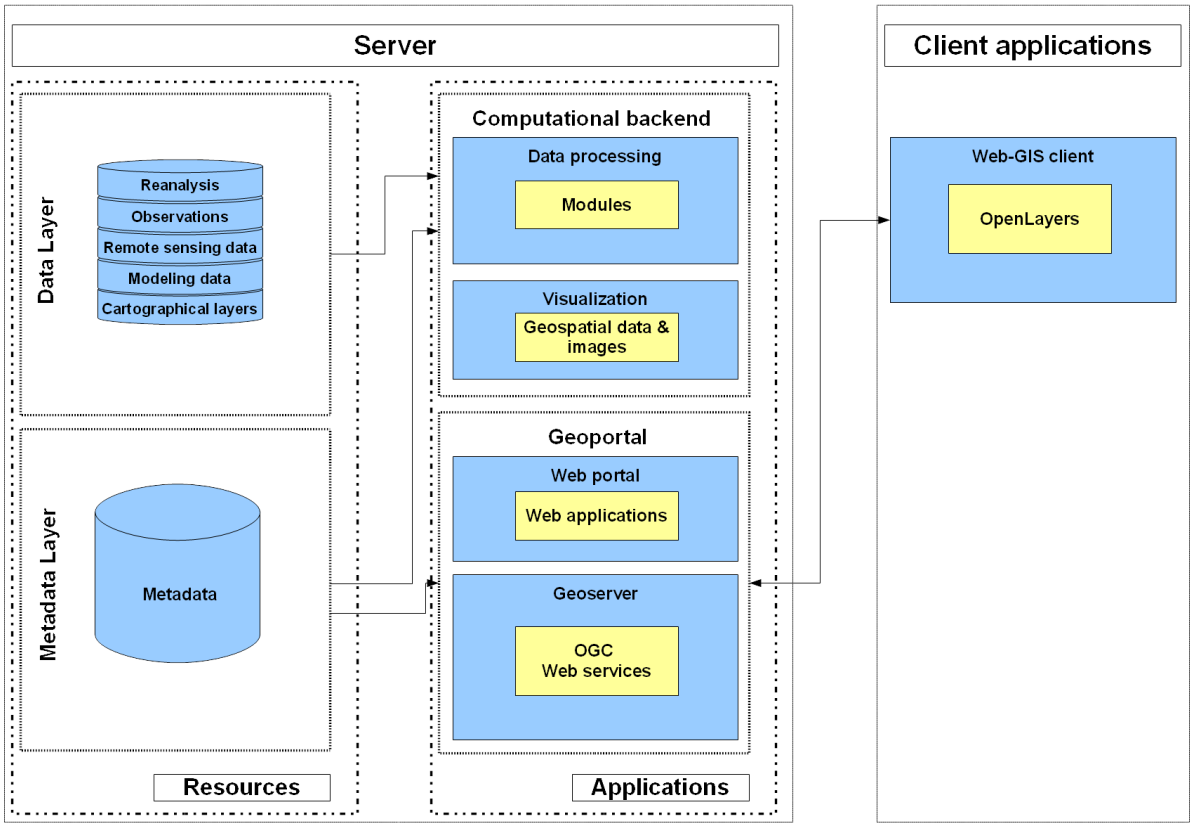


Figure 1. General architecture of the developed software complex.

3. Elements of the software complex

3.1. Metadata database

To describe the geospatial datasets and their processing routines and to provide effective functioning of the software complex, a dedicated metadata database (MDDB) was developed. This database contains the spatial and temporal characteristics of the available geospatial datasets, their locations, and run options of the software components for data analysis. Tables in the MDDB are divided into "technical" and "interface" ones. The technical tables contain data for computing software components. The interface tables hold a textual multilingual content for the graphical user interface.

Each climate dataset in the MDDB is uniquely identified by its four major characteristics: the name of the data collection, the resolution of the horizontal grid, the resolution of the time grid, and the name of the modeling scenario (if applicable). Each dataset includes one or several data arrays containing the values of various meteorological parameters given on spatial and temporal grids. Information about all datasets available for analysis is stored in the MDDB. It is used to locate data

files and provide metadata on request. Geospatial data processing is performed by a set of dedicated computing modules. These modules are run in accordance with a pipelined call sequence. This sequence is prepared by the web portal on the basis of user interactions with the graphical user interface. The MDDB contains a description of various call sequences and their options. Since some data analysis routines are designed to process only specific meteorological parameters, the connections between the computing modules and data arrays are also stored in MDDB.

Thanks to the MDDB, the processing abilities of the software complex and GUI elements can be modified "on-the-fly", without modification of the source codes. All new abilities become available to the users immediately after the metadata insertion, thus providing rapid and sustainable development of the software complex. To add and edit metadata in the MDDB, a dedicated web application (administrative web console) was developed and integrated into the complex (see Figure 2). It allows one to view, add, modify, and remove metadata in the MDDB supporting the database consistency.

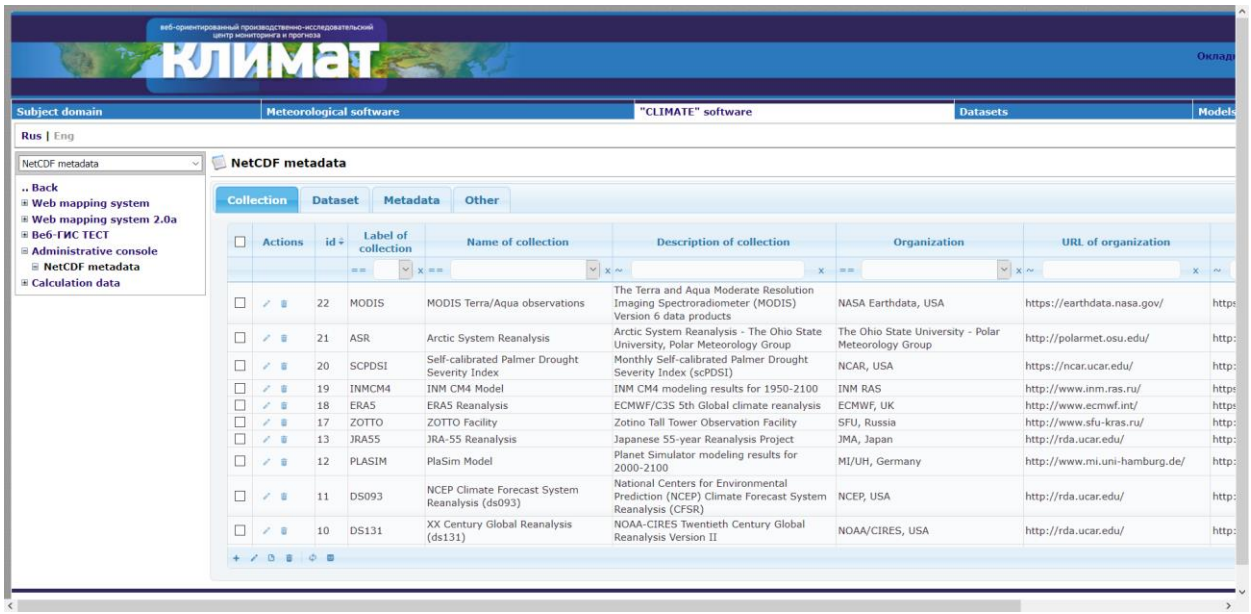


Figure 2. Administrative web console GUI.

3.2. Modular computational core

One of the key components of the software complex is a specialized computational backend representing a standalone software toolset. It is written in GNU Data Language (GDL, http://gnudatalanguage.sourceforge.net/) and Python (http://python.org) programming languages providing integral geospatial data mathematical processing and visualization functionality, as well as API to work with NetCDF/HDF, ESRI Shapefile data files and PostGIS databases. The computational backend contains the following key components:

- data input / output components;
- geospatial data processing components;
- graphical visualization components.

The computational backend manager controls the general application workflow, thus providing ordered calls of the data processing modules and their data exchange. The computational pipelines are prepared based on a special XML file (task file) describing the sequence of calls of data processing and visualization routines. Task files are generated by the Web-GIS client according to selections of the end user in GUI. The modular structure of the computational backend and MDDB provide easy expansion of the functionality of the complex by new data processing routines. In particular, special software adapters allow one to connect to other modules of the computational backend routines written in R language. These adapters utilize the dedicated Python-package RPy2 (http://rpy2.readthedocs.io)

and provide two-way data and instructions transfer between the computational core and procedures in the Python and R packages. As a result, the computational core can call new procedures implemented in R language and perform spatial data processing using them. Depending on the result type required, the backend produces output files in the following formats: GeoTIFF, ESRI Shapefile, Encapsulated PostScript, CSV, XML, NetCDF, and float GeoTIFF. The output files produced are passed to the Web-GIS client and presented to the end user.

3.3. Web-GIS client

The Boundless/OpenGeo architecture was used as a basis for the development of the Web-GIS client. The cartographical web application (Web-GIS client) for work with the archive of geospatial NetCDF datasets contains 3 basic tiers:

- tier of NetCDF metadata in JSON format;
- middleware tier of JavaScript objects implementing methods to work with NetCDF metadata, XML file of the selected calculation configuration, WMS/WFS cartographical services;
- graphical user interface tier representing JavaScript objects realizing a general application business logic.

NetCDF metadata tier. The web-GIS client metadata tier represents a set of interconnected JSON objects created on the basis of MySQL metadata relations and presenting the NetCDF datasets information (spatial and temporal resolutions, available meteorological parameters, acceptable processing procedures, etc.). Generally there are two kinds of objects: objects with a structure conforming to the corresponding MDDB relations, for instance, object of measurement units; and objects based on complex SQL queries to metadata relation sets that allow fast retrieval of necessary information using the MySQL indices as associative array keys.

The structure of JSON objects was chosen considering the efficiency of filling out graphical user interface interactive forms and the optimization of the process of creating and editing an XML task.

It might be concluded that by the approach chosen the processes of interaction between the user and MDDB via the Web-GIS graphical interface were optimized.

Middleware tier of JavaScript objects. This tier implements methods to work with NetCDF metadata, the XML task file and the WMS/WFS cartographical services, and appears to be a middleware which connects the JSON metadata and graphical user interface tiers. The methods include such procedures as:

- loading and updating of metadata JSON objects using AJAX technology;
- creating, editing, serialization of the XML calculation task object;
- launching and tracking the task execution process located on the remote calculation node;
- working with the WMS/WFS cartographical services: obtaining the list of available layers, presenting layers on the map, exporting layers into various formats according to the user request, obtaining and presenting the layer legend with the selected SLD style applied.

Graphical user interface. The tier is based on the conjunction of JavaScript libraries, such as OpenLayers, GeoExt and ExtJS, and represents a set of software components either standalone (information panels, buttons, list of layers, etc.) or implementing a general application business logic (menu, toolbars, wizards, mouse and keyboard event handlers, and so on). The graphical interface performs two main functions: providing functional capabilities for editing the XML task file and visual presentation of the cartographical information for the end user. It is designed to be similar to the interfaces of such popular classic GIS applications as uDig, QuantumGIS, etc. It should be noted that geospatial data cartographical services based on the Geoserver software can be used in the Web-GIS client as well as in standard desktop GIS applications.

3.4. Integration of advanced statistical tools

New software tools for statistical analysis of time series of spatial climatological datasets were developed and integrated into the software complex. To provide effective processing and data handling by the online tools, metadata describing the processing routines were added into the MDDB. Reliable algorithms from the packages "extRemes" [27], "quantreg" (https://cran.r-project.org/web/packages/quantreg/), and "copula" [28] implementing time-dependent statistics of extremes, the quantile regression and copula approach were used as a basis for this tool. These packages were written in R language (https://www.r-project.org/), and they provide a flexible API for integration into a third-party software. Since the major components of the modular computational core were written in GDL, it is practically impossible to directly call R procedures from them. However, thanks to special software adapters, connections between the GDL and Python and between the GDL and R routines were established. This allowed one to perform combined data processing using the GDL, Python, and R routines within the framework of the same processing pipeline.

3.5. Integration of new datasets

Recently some MODIS (MODerate Image Spectroradiometer) Terra and Aqua Land Products (https://lpdaac.usgs.gov/) and INMCM4 [29] model climatic projections were integrated into the software complex by means of the MDDB and administrative web console.

The Terra and Aqua combined MODIS Land Cover data product provides a spatially aggregated and reprojected global land cover type at yearly intervals (2001-2016) derived from different classification schemes using supervised classifications of reflectance data. International Geosphere-Biosphere Programme (IGBP), University of Maryland (UMD), and Leaf Area Index (LAI) classification schemes were used. Maps of the land cover data product are provided at yearly intervals at a spatial resolution of 0.05-degree (5,600 meter) for the entire globe from 2001 to 2016. Additionally, sub-pixel proportions of each land cover class in each 0.05-degree pixel is provided along with the aggregated quality assessment information for each of the three land classification schemes. The Terra MODIS and Aqua MODIS Vegetation Index (VI) values are given at two primary vegetation layers at monthly intervals at a spatial resolution of 0.05-degree for the entire globe from 2000 to 2018. The first is the Normalized Difference Vegetation Index (NDVI), which is referred to as the continuity index to the existing National Oceanic and Atmospheric Administration-Advanced Very High-Resolution Radiometer (NOAA-AVHRR) derived NDVI. The second vegetation layer is the Enhanced Vegetation Index (EVI), which has improved sensitivity over high biomass regions. The total volume of the collection is 63 GB.

The INMCM4 model collection contains sets of 29 climatic characteristics at daily and monthly intervals at 2x1.5 spatial grid for the entire globe from 1950 to 2100. Climatic projections were calculated for the scenarios RCP 4.5 and RCP 8.5. The volume of the collection is 1.1 TB.

These datasets were placed on the data storage systems, and corresponding metadata were added to the MDDB of the software complex using an administrative web console, thus making them available for analysis and visualization.

4. Results

To date there is no formalized description of the MDDB for large sets of geospatial meteorological and climatic data. The architecture presented above is the first attempt to address this problem crucial for the data intensive domain. The designed MDDB provides: 1) a graphical user interface with content for the elements; 2) a geoportal with data needed to generate correct task files; and 3) a computational core with information about the structure and location of spatial data sets allowing one to read and process them efficiently. The MDDB organizes information on the available data sets, facilitates automatic retrieval of data files, and improves the scalability and flexibility of computations.

The developed Web-GIS client is based on the architecture Boundless / OpenGeo. The first version of the GUI uses interrelated JavaScript libraries, OpenLayers, GeoExt, and ExtJS, and represents a set

of software components including independent components (dashboards, buttons, layer lists) and those implementing the general logic of the software application (menus, toolbars, wizards, mouse and keyboard event handlers, etc.).

The first application of the developed MDDB and user interface showed that their combined use facilitates expanding of the set of data archives available for analysis and adding new statistical processing procedures [30].

The results obtained show that the developed software complex and tools will be useful for decision makers and specialists working in affiliated sciences, with the focus of their work as socio-economic and ecological impact assessment, adaptation strategies, science policy administration, and other climate related activities. On this basis they will get reliable climate-related characteristics required for studies of economic, political, and social consequences of global climate change at the regional level.

5. Conclusions

The above-obtained and anticipated project results will create a pathway for the development and deployment of thematic software complexes focused on interdisciplinary studies of international research teams.

The software developed in this work will be used to process various heterogeneous datasets including observations and reanalysis products. It is aimed to perform space-time analysis of recent and possible future dynamics of global and regional climates with special emphasis on extreme climatic phenomena in the Northern Extratropics.

This complex incorporates many modern components, such as a web geoportal, distributed storage of spatial datasets, reliable software for processing and delivery of information. It will give an opportunity to scientists, professionals, and decision-makers to utilize various geographically distributed and georeferenced resources and processing services via a general web browser. Particularly, it will allow carrying out simultaneous analysis of several georeferenced thematic data sets using modern statistics, thus identifying the responses of ecological processes to climate change.

Although this software complex is aimed at environmental and climatic investigations, the approaches used in its development are quite general and can be applied to other thematic fields where spatial data processing and analysis are required.

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