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Development of Information-computational Infrastructure for Modern Climatology

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Abstract—The activities on the creation of information-computational infrastructure to support the climatic research initiated by academician V.P. Dymnikov are described. In particular, the solutions to the problem of working with big climatic and meteorological datasets are analyzed. The structure and functionality are presetned of the thematic web-GIS “Climate” whose software-hardware prototype operates at the Institute of Monitoring of Climatic and Ecological Systems of Siberian Branch of Russian Academy of Sciences. The system supports the interactive analysis of big climatic and meteorological datasets and the visualization of its results. The results of the analysis of aridity in South Siberia in the late 20th–early 21st centuries carried out using the web-GIS “Climate” prototype are presented.

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1. INTRODUCTION

The creation of information-computational infrastructure was started during the visit of academician V.P. Dymnikov to Tomsk in 2000. During the lecture he presented the estimates of expected volumes of climatic data which demonstrated that the traditional approach to the analysis of climatic datasets by their downloading from the remote archive and by their processing on the local computer is out of date. This initiated activities on the creation of the thematic information-computational infrastructure.

At the first stage, the team was formed which joins specialists from the Marchuk Institute of Numerical Mathematics (INM) of Russian Academy of Sciences (RAS), Institute of Monitoring of Climatic and Ecological Systems (IMCES) of Siberian Branch (SB) of RAS, Institute of Computational Mathematics and Mathematical Geophysics (ICMMG) of SB RAS, Research Computing Center of Lomonosov Moscow State University (RCC MSU), Siberian Regional Research Hydrometeorological Institute (SibRHMI), and Tomsk State University (TSU). This team established regular scientific and educational activities ENVIROMIS and CITES (http://www.scert.ru/ru/conference/). At the interdisciplinary international conferences on environmental observations, modeling, and information systems (ENVIROMIS) [22], the researchers of various specializations learn about the modeling and information technologies and their potential in solving problems from different areas. The young scientist schools on Computational Information Technologies for Environmental Sciences (CITES) [21] provide not only the general knowledge of the current state and development trends of this area but also the practical skills of computational climatic experiments and analysis of their results. International conferences with the same name accompanying the schools present the current state of this sphere in the country and in the world. It should be noted that since the first school was held V.P. Dymnikov has formed the set of general lectures which are usually given by

RAS members and special courses of lectures which describe in detail new and prospective directions of climatology development. Besides, the team has already completed several big international and national projects whose results are presented in [1, 2, 20].

It was clear already in the 20th century that the development of measurement technologies and climate models will lead to the formation of big data archives and will cause problems with the analysis of current and possible future environmental processes. The main datasets were received from satellites at that time, so the most significant progress in the provision of the whole set of works associated with the use of large environmental data volumes was made in the area of remote sensing. Concrete examples can be found on the websites of GEOSS geoportal (http://www.geoportal.org/) and Climate Change Initiative Program of European Space Agency (http://cci.esa.int/). The situation with the data of local measurements and climate modeling which are more demanded in climatology was not so critical. The volumes of data archives were not large and, due to the development of Internet, were easily downloaded to the user's computer where they were analyzed. The popularity of such approach led to the organization of data centers whose main task was to collect and store data and to provide the user's access to them. Although the total volume of archives in the largest data centers currently exceeds tens of petabytes, the only interactive service aimed at supporting the researcher's work is still the visualization of the selected dataset which allows revealing its usefulness for the further analysis.

At the same time, the propagation of Internet in the research community in the late 20th century stimulated the flow of general and topical studies aimed at the formation of the research environment on the Internet base. The approach is based on the three-layer architecture proposed by D. de Roure [14]: data–information (data provided with the description)–knowledge; the objective is to exempt specialists who need knowledge (results of studies) from transmitting large data volumes across the network. Such environment has many names: information-computational infrastructure, cyberinfrastructure, e-science (recently it has been more often called "virtual research environment" (VRE) [13, 19]). The main objective of this approach is to provide a user with the possibility of working with data at the place of their storage. For this purpose, it is necessary to build a single distributed system comprising data, standard and user's instruments for the processing, analysis, and visualization of results as well as computing resources where the type of processing chosen by the user is carried out, and provide the Internet access to the system through the convenient and user friendly interface. It was initially assumed that the key elements of such system are thematic web portals, and the ATMOS portal on atmospheric sciences became one of successful attempts to implement this approach [20]. Then it became clear that the virtual research environment must provide researchers with the possibility of joint work [25] and the use of Web 2.0 technologies. Since thematic data are spatial, the conclusion was made rather quickly that information-computational systems and the information-computational infrastructure of environmental sciences based on them should jointly use the potential of web and GIS technologies [11, 16, 26]. Such approach allows using powerful computing resources, providing the distributed access and processing of huge datasets, and keeping the clarity of analysis and its results typical of traditional GIS. The spatial dependence of data brings certain peculiarity to the development of this area with the intensive use of data [7].

Currently, all over the world significant efforts and resources are focused on the development of distributed and stable infrastructure for the open, permanent, and safe access to observational data and Earth system simulation results as well as for their qualitative description providing the remote analysis and visualization. One of the most functional systems for the processing and visualization of satellite data is GIOVANNI by NASA (http://daac.gsfc.nasa.gov/techlab/giovanni/) [12]. Several big international projects are aimed at developing new systems. In particular, the EVER-EST project (European Virtual Environment for Research–Earth Science Themes, http://ever-est.eu/) deals with the creation of VRE which satisfies the requirements of the community of scientists who deal with climate research, steady availability of natural resources, and natural disasters. In the framework of ESGF (Earth System Grid Federation) international collaboration, the ESG (Earth System Grid) virtual environment was developed which provides access to climatic data. The next step of its development is the creation of corresponding services [28]. The World Meteorological Organization (WMO) jointly with the European Commission in the framework of the Copernicus Climate Change Service (C3S, http://climate.copernicus.eu/) carries out such works aimed at providing climate services for interested parties.

Obviously, there is no system which can solve the whole range of problems in the area of climatic and environmental studies, and it is necessary to create thematic systems which satisfy standard requirements to the general scheme of interaction between spatial data, computing instruments for their analysis, and users. The reliable analysis of climate changes and of the response of nature and society to them requires skills in working with large data volumes, ability to "communicate" with computer systems and complex models, the knowledge of modern methods for the statistical analysis and of program languages of rather high level. Unfortunately, specialists in the neighboring thematic areas rarely possess these features, let alone decision-makers. The thematic VRE should help to solve this problem.

The next sections of the paper discuss the development of the information-computational infrastructure for modern climatology and describe some applied problems solved using the implemented elements of this infrastructure. In particular, the web-GIS "Climate" is described which is intended for the analysis of big climatic and meteorological datasets and for the visualization of its results as a base of the developed thematic VRE. The examples of VRE application for the detailed analysis of climate changes in Siberia and their consequences are provided. The directions are considered of activities on the creation of information-computational infrastructure for climatology. They should allow reaching the goal declared by WMO for the next decade is to create the system of climate services for the interested parties and population.

2. WEB-GIS "CLIMATE"

A base for the created thematic VRE is web-GIS "Climate" intended for the analysis of big climatic and meteorological datasets and for the visualization of its results [2]. It is a complex web-GIS application for climatic and environmental studies in a selected region which implements the integration of results of hindcast, forecast, and observations and provides researchers with interactive access to the instruments and results of the analysis. The user's access to the system is provided through the web portal http://climate.scert.ru/.

The architecture of the system prototype worked out in IMCES SB RAS [31] allows its operation on several hardware nodes which are connected with each other by data transfer channels. This enables forming the distributed computing network. The realization of this possibility is presented in [23]. Each node consists of four typical units: structured data archives and their metadata; the modular computing unit representing a set of software components providing the search, selection, processing, and visualization of spatial data; the geoportal which provides the start and control of execution of the computing unit and the communication with web mapping services; the web client providing users with the interactive graphic interface for the analysis and visualization tools.

The archives of spatially referenced geophysical data include simulation data of various spatial resolutions (reanalysis data, results of computations of climatic and meteorological models) and observational data (the series of weather station data, remote sensing data, etc.) accompanied by metadata describing their basic characteristics. The presence of metadata allows establishing the unambiguous correspondence between data and the procedures for their processing which is also maintained when the archive is supplemented with new datasets [30]. The computing unit provides the processing of spatial data and the presentation of its results for the user as files of the following formats: GeoTIFF, ESRI Shapefile, NetCDF (Network Common Data Form), EPS (Encapsulated PostScript), etc. The specialized geoportal provides access to all interactive tools through the user friendly GIS interface in a standard web browser.

The user chooses the dataset and geophysical characteristics to be analyzed, the method of analysis and its parameters as well as spatiotemporal domain interesting for her. The geoportal forms the task for data processing and recording to files and transfers it to the computing unit. Based on the task received, the computing backend prepares a computational pipeline and performs run and execution control of respective software components responsible for the selection and processing of spatial datasets. The results of processing are recorded to files in GeoTIFF (raster data) or ESRI Shapefile (vector data) formats and are transferred to the geoportal which displays them using the graphic user's interface in the form of corresponding map layers provided by WMS (Web Mapping Service) and WFS (Web Feature Service). Additionally, the same results can be obtained in NetCDF, PNG, and GML formats. The calculation of main statistical characteristics which indicate regularities of temporal and spatial variations in parameters is implemented in the system. The system functionality includes the computation of trends, the estimation of their statistical significance, and a correlation between meteorological parameters. The following climate change indices recommended by IPCC are also calculated: extreme values of temperature and precipitation and their probability characteristics. Besides, the system computes the characteristics of nonstationary distributions of different extreme values. The implemented set of computational procedures allows helps to get a rather complete idea about the peculiarities of changes in climatic characteristics in the region under study. Due to the modular organization, the system functionality may be extended by adding new modules created both by the developers and by the system users. The thematic VRE supports the joint development of applications by the distributed research teams and the training of students and postgraduates [3].

3. USING VIRTUAL RESEARCH ENVIRONMENT FOR ANALYSIS OF CLIMATE CHANGE AND ITS CONSEQUENCES IN SIBERIA

As new elements were created, the thematic VRE was applied to study climatic and environmental processes on the territory of Siberia. The results obtained using the modules for the calculation of standard statistical parameters integrated to VRE and indicating general trends in the regional climate change are given in [17, 18, 24, 29, 30]. For example, let us present some results of the analysis of dry and wet periods in South Siberia in the late 20th–early 21st centuries, where the modules for the calculation of extreme events integrated to VRE were actively used.

To assess hydrothermal conditions in South Siberia (50 –65 N, 60 –120 E) over the period of 1979–2010, the D.A. Ped' drought index S_i was used; it is the normalized parameter of the relationship between air temperature and total precipitation [9]:

$$S_i \quad \frac{T_i}{{}_T} \quad \frac{R_i}{{}_R}.$$

Here, $T_i = T_i - T_{\mathrm{norm}}$ is the temperature anomaly for the *i*th month; ${}_T$ is its standard deviation. The respective characteristics for precipitation are determined in a similar way. Calculations were based on ERA-Interim reanalysis data (ECMWF) [15] with the resolution of 0.75 along latitude and longitude.

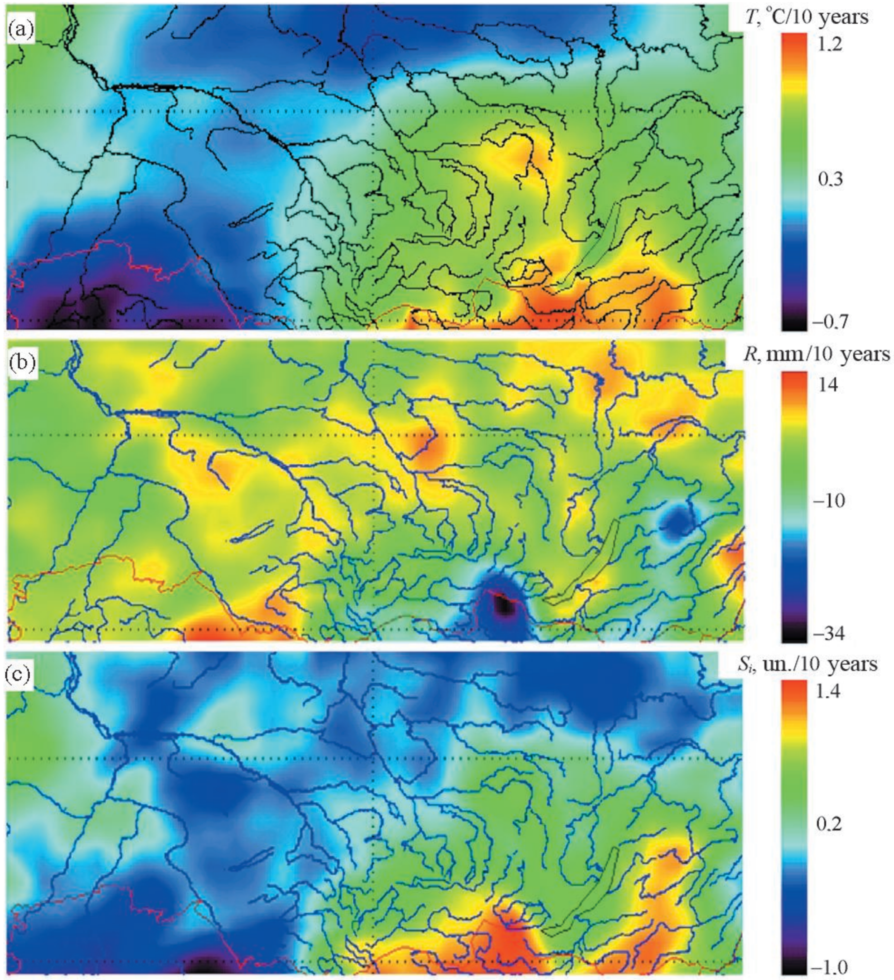
The use of reanalysis data allows obtaining the characteristics of hydrothermal conditions for the areas with a sparse observation network, unlike in the traditional approach to the analysis of catastrophic droughts [4, 6, 8]. To eliminate significant differences between the simulation results and precipitation measurement data, reanalysis data for May–September of each year were corrected [27] using the linear regression method based on observations at located in the region 127 weather stations with the most complete and homogeneous observation series.

The results of calculations demonstrate that the latitudinal distribution of monthly mean temperature is observed on the analyzed territory during the year. The distribution of its trends varies during the warm season. In May, the temperature rise with the rate of 0.3–0.7 C/10 years is observed in most of Siberia. In June and July, temperature drops in Western Siberia and rises in Eastern Siberia. The maximum contrast in the distribution of trends is observed in the south of the region in July. The coefficients vary from –0.65 in the southwest to 1.2 C/10 years in the southeast. The minimum absolute values of temperature trends are registered in the north. In August and September, monthly mean values of temperature increase in the west and southeast (by 0.4–0.8 C/10 years); statistically insignificant trends are typical of the rest of the territory. The same regularities in the spatial distribution of average long-term total precipitation are observed during all summer months. The maximum (to 125 mm) is registered in the mountains (the Altai, Western and Eastern Sayan, Chamar-Daban, and Stanovoe Uplands), and the minimum (<10 mm) is observed in the southwest of the region. Maximum and minimum total precipitation is observed on the whole territory in July and May, respectively. The trends in total precipitation during the warm season are bidirectional, they are negative in most cases. According to the results of analysis of index S_i, changes in hydrothermal conditions within the territory are characterized as follows. In May, aridity increases on most of the territory, the slight decrease in S_i is observed only in the mountain areas of Transbaikalia. In June, the moistening increases in the central areas of Western Siberia, whereas the south of Eastern Siberia becomes more arid. In July, contrasts increase: the trends in S_i in the region vary from –1.0 to 1.4 per decade. In August and September, the latitudinal distribution of trends is observed: from positive ones in the south to negative ones in the north of Siberia. The figure illustrates the most contrast change in the calculated trends.

The frequency of atmospheric droughts in South Siberia was estimated. The maximum and minimum values of the Ped's drought index, its variability (the difference between maximum and minimum values), the frequency of droughts of various intensity over the analyzed period, the duration and beginning of the dry period ($S_i > 1$) were computed for 1979–2017. The drought intensity is defined by the following classification: light (1 $S_i < 2$), moderate (2 $S_i < 3$), severe (3 $S_i < 4$), and extreme (S_i 4).

The analysis reveals that the maximum values of S_i (to 4.6) and, hence, the most intensive droughts are observed in August. They are localized in the northeast of the analyzed region and in the south of the West Siberian Plain. Northwest of the region is characterized by droughts with $S_i < 3$ in all months. The minimum values of S_i reaching –5 describe the state of overmoistening of the territory. In most cases, the value of the index was equal to –3…–4. The average interannual variability of S_i does not exceed 6–7.

In some months over the period under study the frequency of droughts reaches 38% for light droughts, 23% for moderate droughts, 7% for severe droughts, and 2% for extreme droughts. More than a half of extreme events fall on the period after 2000. Extreme droughts (S_i 4) were observed only in August on a



The changes in hydrothermal characteristics in South Siberia in July (1979–2010): (a) monthly mean air temperature; (b) total precipitation; (c) aridity index S_i.

small territory (in the northeast of the Central Siberian Plateau and in the Altai area). The frequency of severe droughts (3 S_i < 4) makes up not more than 5–7% and is patchy: in May, this is the territory adjoining the Bratsk and Ust'-Ilimsk reservoirs, the Stanovoe Uplands; in June, this is the Sayan Mountains; in July, this is the south of the West Siberian Plain; in August, this is the piedmont regions of the Sayan Mountains and the northern areas of the Central Siberian Plateau; in September, the frequency of severe droughts is not more than 1–2% on most of the territory. Moderate droughts (2 S_i < 3) are observed in all months of the vegetation period, and their frequency on most of the territory is not higher than 10%; the minimum (4%) is registered in May. The frequency of light droughts (1 S_i < 2) is maximum in Western Siberia in September (20–35%). In Eastern Siberia, their frequency in this month is by twice lower. From May to August, the frequency of light droughts in the whole studied region does not exceed 10–20%.

In some years, the continuous duration of droughts (at $S_i > 1$) on most of the territory can reach 3–5 months. Such situation was observed in Eastern Siberia in 1986, 2001, 2002, and 2007 and in Western Siberia in 1988, 1998, and 2012. After 2000 the frequency of droughts with the duration of more than 2 months has increased in the whole region. In the years when the drought duration does not exceed 2–3 months, the period with insufficient moistening begins in May–June in most cases.

Thus, increase in the duration of dry periods during the vegetation season and the frequency of extreme events (both dry and wet episodes) have been observed in South Siberia in the recent years. At the same time, the trends in S_i in summer are differently directed, and no significant change in hydrothermal conditions occurred in the recent 40 years on average. In general, the obtained results specify the previous estimates of the frequency, intensity, and area of droughts [5, 10]. The archives of characteristics calculated in the system in the form of map layers (to be opened in typical GIS) can be used for solving applied problems, in particular, for assessing the influence that changes in the hydrothermal conditions in the region make on the environment and economy.

4. CONCLUSIONS

The developed prototype of the virtual information-computational environment for the monitoring and forecasting of regional climatic and environmental changes allows the remote interactive analysis of big archives of heterogeneous geophysical data. The developed approaches enable integrating new archives and analytic procedures to VRE. The use of tested computational algorithms provides the reliability of results obtained in specific subject areas. The distributed architecture of VRE allows the operational addition of new computing nodes and data storage systems; it also provides the flexible information-computational support for the studies of climatic and environmental changes using modern web-GIS technologies. Due to the availability of the system via Internet and the possibility of analyzing data without special knowledge of programming, both a wide range of specialists in different areas of science and decision-makers will be able to solve problems of their subject area.

Certainly, to provide the adequate answer to modern challenges of the epoch of big climatic data and to solve the task formulated by WMO, that is, to organize the climate service as an analog of the weather service, it is necessary to organize the national center of climatic data and services provided with high-performance computing resources and large data storage systems. The presented prototype provides scientific and technological basis for the development of the thematic virtual research environment. Only such base allows the successful use of the results of modern climatology to elaborate measures for adaptation to the current and expected climate changes.

REFERENCES

1. A. A. Baklanov and E. P. Gordov, “Anthropogenic Risks: Monitoring, Management, and Correction of Anthropogenic Changes in Siberia. Computing Technologies,” in *Selected Reports of International Conference on Environmental Observations, Modeling, and Information Systems: ENVIROMIS-2006 (Tomsk, Russia)*, Part 3, Vol. 11 (2006) [in Russian].
2. E. P. Gordov, V. N. Lykosov, V. N. Krupchatnikov, I. G. Okladnikov, A. G. Titov, and T. M. Shul’gina, *Information-computational Technologies for Monitoring and Modeling of Climate Changes and Their Consequences* (Novosibirsk, Nauka, 2013) [in Russian].
3. Yu. E. Gordova, Yu. V. Martynova, and T. M. Shul’gina, “Using the Information-computational Web-GIS for Development Climate Change Monitoring and Modeling Skills for Students-climatologists,” Izv. Irkutskogo Gosudarstvennogo Universiteta. Nauki o Zemle, **9** (2014) [in Russian].
4. O. A. Drozdov, *Droughts and Moistening Dynamics* (Gidrometeoizdat, Leningrad, 1980) [in Russian].
5. A. N. Zolotokrylin, V. V. Vinogradova, and E. A. Cherenkova, “Dynamics of Droughts in European Russia under Conditions of Global Warming,” in *Problems of Environmental Monitoring and Modeling of Ecosystems*, Vol. 21 (Gidrometeoizdat, St. Petersburg, 2007) [in Russian].
6. A. N. Zolotokrylin and E. A. Cherenkova, “Trends towards Moistening of the Grain Belt of Russia in the Early 21st Century,” in *Problems of Environmental Monitoring and Modeling of Ecosystems*, Vol. 25 (IGKE Rosgidrometa i RAN, Moscow, 2013) [in Russian].
7. L. A. Kalinichenko, A. A. Vol’nova, E. P. Gordov, N. N. Kiseleva, D. A. Kovaleva, O. Yu. Malkov, I. G. Okladnikov, N. L. Podkolodnyi, A. S. Pozanenko, N. V. Ponomareva, S. A. Stupnikov, and A. Z. Fazliev, “Data Access Challenges for Data Intensive Research in Russia,” Informatika i Ee Primeneniya, No. 1, **10** (2016) [in Russian].
8. A. V. Meshcherskaya, V. G. Blazhevich, M. P. Golod, and I. G. Belyankina, “Long-term Variations in Aridity Indices during the Warm Season in the Main Agricultural Zone of the USSR,” Trudy GGO, No. 505 (1986) [in Russian].
9. D. A. Ped’, “On the Drought Index and Overmoistening,” Trudy Gidromettsentra SSSR, No. 156 (1975) [in Russian].
10. E. A. Cherenkova and A. N. Zolotokrylin, “On Comparability of Some Quantitative Drought Indices,” Fundamental’naya i Prikladnaya Klimatologiya, No. 2 (2016) [in Russian].
11. O. E. Yakubailik, “Internet GIS Portal,” Vychislitel’nye Tekhnologii, No. 3, **12** (2007) [in Russian].
12. S. W. Berrick, G. Leptoukh, J. D. Farley, and H. Rui, “GIOVANNI: A Web Service Workflow-based Data Visualization and Analysis System,” IEEE Trans. Geosci. Remote Sens., No. 1, **47** (2009).
13. L. Candela, D. Castelli, and P. Pagano, “Virtual Research Environments: An Overview and a Research Agenda,” Data Sci. J., No. 12 (2013).

14. D. de Roure, N. R. Jennings, and N. R. Shadbolt, “The Semantic Grid: A Future E-science Infrastructure,” in *Grid Computing: Making the Global Infrastructure a Reality*, Chapter 17.
15. D. P. Dee, S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A. J. Geer, L. Haimberger, S. B. Healy, H. Hersbach, E. V. Hylm, L. Isaksen, P. Kellberg, M. Kohler, M. Matricardi, A. P. McNally, B. M. Monge-Sanz, J.-J. Morcrette, B.-K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J.-N. Thepaut, and F. Vitart, “The ERA-Interim Reanalysis: Configuration and Performance of the Data Assimilation System,” Quart. J. Roy. Meteorol. Soc., **137** (2011).
16. J. M. Frans van der Wel, “Spatial Data Infrastructure for Meteorological and Climatic Data,” Meteorol. Appl., No. 7–8, **12** (2005).
17. E. P. Gordov, K. Bryant, O. N. Bulygina, I. Csiszar, J. Eberle, S. Fritz, I. Gerasimov, R. Gerlach, S. Hese, F. Kraxner, R. B. Lammers, G. Leptoukh, T. V. Loboda, I. McCallum, M. Obersteiner, I. G. Okladnikov, J. Pan, A. A. Prusevich, V. N. Razuvaev, P. Romanov, H. Rui, D. Schepaschenko, Ch. C. Schmullius, S. Shen, A. I. Shiklomanov, T. M. Shulgina, A. Z. Shvidenko, and A. G. Titov, “Development of Information-computational Infrastructure for Environmental Research in Siberia as a Baseline Component of the Northern Eurasia Earth Science Partnership Initiative (NEESPI) Studies,” in *Regional Environmental Changes in Siberia and Their Global Consequences*, Ed. by P. Ya. Groisman and G. Gutman (Springer, 2013).
18. E. P. Gordov, A. Z. Fazliev, V. N. Lykosov, I. G. Okladnikov, and A. G. Titov, “Development of Web Based Information-computational Infrastructure for Siberia Integrated Regional Study,” in *Environmental Change in Siberia*, Earth Observation, Field Studies and Modelling, Ser.: Advances in Global Change Research, **40** (2010).
19. E. P. Gordov, V. N. Krupchatnikov, I. G. Okladnikov, and A. Z. Fazliev, “Thematic Virtual Research Environment for Analysis, Evaluation and Prediction of Global Climate Change Impacts on the Regional Environment,” in *Proc. SPIE, Vol. 10035, 22nd Int. Symp. Atmospheric and Oceanic Optics: Atmospheric Physics, 100356J*.
20. E. P. Gordov, V. N. Lykosov, and A. Z. Fazliev, “Web Portal on Environmental Sciences “ATMOS”,” in *Advances in Geosciences*, Vol. 8 (European Geosciences Union, 2006).
21. E. P. Gordov, V. N. Lykosov, E. Yu. Genina, and Yu. E. Gordova, “International Conferences and Young Scientists Schools on Computational Information Technologies for Environmental Sciences (CITES) as a Professional Growth Instrument,” IOP Conf. Series: Earth and Environmental Science, **96** (2017).
22. E. P. Gordov, V. N. Lykosov, Yu. E. Gordova, and E. Yu. Genina, “Multidisciplinary ENVIROMIS Conferences as a Tool Connecting Climate Information Procedures and Users,” IOP Conf. Series: Earth and Environmental Science, **48** (2016).
23. E. P. Gordov, A. Shiklomanov, I. Okladnikov, A. Prusevich, and A. Titov, “Development of Distributed Research Center for Analysis of Regional Climatic and Environmental Changes,” IOP Conf. Series: Earth and Environmental Science, **48** (2016).
24. E. P. Gordov and E. A. Vaganov, “Siberia Integrated Regional Study: Multidisciplinary Investigations of the Dynamic Relationship between the Siberian Environment and Global Climate Change,” Environ. Res. Lett., No. 1, **5** (2010).
25. T. O’Reilly, “What is Web 2.0: Design Patterns and Business Models for the Next Generation of Software,” Meteorol. Appl., No. 1, **12** (2005).
26. G. Peng, J. L. Privette, E. J. Kearns, N. A. Ritchey, and S. Ansari, “A Unified Framework for Measuring Stewardship Practices Applied to Digital Environmental Datasets,” Data Sci. J., **13** (2014).
27. A. A. Riazanova, N. N. Voropay, I. G. Okladnikov, and E. P. Gordov, “Development of Computational Module of Regional Aridity for Web-GIS “Climate”,” in *The Open Access Volume of IOP Conf. Series: Earth and Environmental Science*, No. 1, **48** (2016).
28. J. L. Schnase, D. Q. Duffy, M. A. McInerney, W. P. Webster, and T. J. Lee, “Climate Analytic as a Service,” in *Proc. Conf. on Big Data from Space BiDS’14* (ESA–ESRIN, 2014).
29. T. M. Shulgina, Yu. E. Genina, and E. P. Gordov, “Dynamics of Climatic Characteristics Influencing Vegetation in Siberia,” Environ. Res. Lett., **6** (2011).
30. A. Titov, E. Gordov, I. Okladnikov, and T. Shulgina, “Web-system for Processing and Visualization of Meteorological Data for Siberian Environment Research,” Int. J. Digital Earth, No. S1, **2** (2009).
31. A. G. Titov, I. G. Okladnikov, and E. P. Gordov, “Architecture of a Spatial Data Service System for Statistical Analysis and Visualization of Regional Climate Changes,” IOP Conf. Series: Earth and Environmental Science, **96** (2017).