Computation of Information for Environmental Management from the Results of Regional Climate Model Simulations

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Abstract

Regional Climate Models (RCM's) have recently been developed and they have provided results which downscale the results of General Circulation Models. CLIME is one project, which exploits these results in further modeling and development of support tools for environmental management. This paper concentrates on computing weather patterns and "climate migration" from the results of the RCM's for inclusion in the CLIME Decision Support System (DSS). The computational process is based on mathematical definitions of a weather pattern and climate. The prevalence of weather patterns and their spatial extent was studied using tabulating and spatial visualizations. The results have been incorporated into a web-based tool as interactive visualizations. The results reinforce the impression that for the IPCC scenario A2, under which emissions are high, the climate change is predicted to be stronger. The results also show that, at least using the selected discretization, the climate at one location is often dominated by only a few weather patterns. According to the results the predicted future climate is in some cases very similar to current climate at some other geographical location. This climate migration analysis is implemented as an interactive visualization in the CLIME DSS. It is argued that if an environmental DSS includes application tools, e.g., for what-if analyses, it should also include tools, with which the user can improve his/her knowledge and, subsequently, comprehension on the relevant issues. Interactive visualization is an example of such a tool.

1. Introduction

There is now a wide-spread consensus among scientists that the climate change will incur a profound change in our environment. Environmental managers are concerned with the effects of the climate change on the quality, quantity, and sustainability of environmental resources. Water resources have a central role in environmental management because the hydrological cycle is an important driver of environmental processes and because of the importance of water to nature and to humans. Environmental management, which is based on science and engineering, depends on good data, information, and knowledge; on suitable methods for the analysis of this data; and on useful methods and tools with which to gain insight into management problems. The basic scientific tools, which are used to assess and predict the climate change, are the Atmospheric-Ocean General Circulation Models (GCM's). Current GCM's are used to simulate the global climate at a spatial scale (cellsize) of ~300 km. Regional Climate Models (RCM’s) use the output of GCM’s and downscale their results to a local level, i.e., to a spatial scale of ~20–50 km. Recently RCM simulations have been produced in joint European projects, such as PRUDENCE (Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects[1]).

1.1 CLIME

CLIME (Climate and Lake Impacts in Europe[2]) is a research project in which researchers from nine European countries and from the New York City Department of Environmental Protection participate. CLIME belongs to a cluster of projects (CatchMod[3]), which are planned to produce analyses, methods, and tools for European water managers for their task in implementing the European Water Framework Directive[4].

In CLIME a watershed model GWLF (Haith et al., 1992), which is augmented with a dissolved organic carbon transport (DOC) model (Naden and Watts, 2001), and lake models PROBE (Svensson, 1998) and PROTECH (Reynolds et al., 2001) are used to study the hydrological and ecological response of watersheds and lakes to climate. The combined use of these models allows the simulation of runoff and other hydrological processes; of leaching of nutrients and DOC from watersheds; of physical processes of lakes; and of the phytoplankton ecology of lakes. The models are run with meteorological time series representing current and future climates, the future climate being generated with the RCM’s. Socio-economics of lake management is studied in CLIME by sociologists and systems analysts.

Lake managers are represented in CLIME by an advisory board comprising people employed by state agencies and other organizations responsible for environmental management. The objective of CLIME is to develop a suite of methods that can be used to manage lakes and watersheds under future as well as current climatic conditions. One important result of CLIME will be a Decision Support System (CLIME DSS), which will comprise tools designed to help lake managers to understand the possible change that will occur in his/her lake and conduct simple what-if analyses. The first vehicle for understanding climate change and its effects in CLIME DSS is interactive visualization and the second vehicle is a set of Causal Bayesian Networks (CBN’s), which are based on analysis of expert knowledge and simulation model results.

One goal which was set forth in the development of the CLIME DSS, is that the lake manager should be supported with readily understandable insights on how the climate is predicted to change and how those changes may affect lakes. A hypothesis was developed that climate affects processes in watersheds and in lakes through the weather patterns that occur often or dominate. Furthermore, the response of lakes in a same geographical area is shown to be synchronous in some cases (George et al., 2000). The dominant weather patterns are important from the point-of-view of long-term lake management. Knowledge on similarities between lakes and their responses helps lake managers to plan their activities.

1.1 Scope, objective, and organization

This paper concentrates on preparation of information for the CLIME DSS from the results of the RCM’s. The computational process can be divided into three parts: (i) the computation and analysis of the weather patterns, (ii) the computation of “climate migration”, and (iii) the

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[1] http://prudence.dmi.dk/ (accessed May 24, 2005)

[2] http://clime.tkk.fi (accessed May 24, 2005)

[3] http://www.harmoni-ca.info/ (accessed May 24, 2005)

[4] Directive 2000/60/EC, http://europa.eu.int/comm/environment/water/water-framework/index_en.html (accessed May 24, 2005)

computation of the input variable distributions for the Causal Bayesian Networks (CBN's), which are utilized in the CLIME DSS. The objective of this paper is to present methods which condense a large amount of data in such a way that the results are useful from the point of view of lake and watershed management. The development of the CBN's will be described in forthcoming publications and the user interface of the CLIME DSS is still under development.

The paper is organized as follows. First, materials and methods which were used in the study are described. Second, the results are described in three subsections under the results section. The first subsection describes the CLIME-DSS to make the context of the other results comprehensible. The second and third sections describe the main computational results. The validity of the results is discussed in the last section before conclusion, acknowledgements, and references.

2. Materials and Methods

2.1 The Regional Climate Model Simulations

Climatic conditions may vary substantially on a relatively small area, depending on the geographical characteristics of the region. Global circulation models operate on a too coarse a resolution to be able to take into account these regional features accurately enough. A regional climate model is able to describe the climatic conditions of a specified region more precisely. The main processes included in the RCM's include atmospheric processes, ocean processes, land and lake processes, as well as chemical and vegetation processes (Samuelsson, 2004).

RCM's used in CLIME include the RCAO model (i.e. *Rossby Centre Regional Climate Model*, which has been developed by the Swedish Meteorological and Hydrological Institute) and the HadRM3p model (i.e. *Hadley Centre Regional Climate Model*, which has been developed by the U.K. Met Office). These models operate on grids with a cellsize of ca. 50km. The geographic regions covered by the models are shown in Figure 1. The state of the atmosphere and its development within the geographic domain of a RCM depends on the global atmospheric conditions (Samuelsson, 2004). For PRUDENCE and CLIME, the boundary conditions for the RCM's were provided by GCM's and the RCM simulations were run for a control period of 1960-1990 and for a scenario period of 2070-2100. The GCM's HadAM3h and ECHAM4/OPYC3 were used with the RCAO model (model runs RCAO-H and RCAO-E, respectively) and the GCM HadAM3p was used with the HadRM3p model. To produce the datasets the scenario period was run using two IPCC (Intergovernmental Panel on Climate Change) emission scenarios, A2 and B2. In A2, population growth is assumed to stay low during this century. Energy use, GDP growth, etc. are, for their part, assumed to be high. B2 represents an intermediate alternative of all the IPCC scenarios: population growth, energy use, GDP growth, etc. are all considered moderate in the coming decades (Nakicenovic and Swart, 2000).

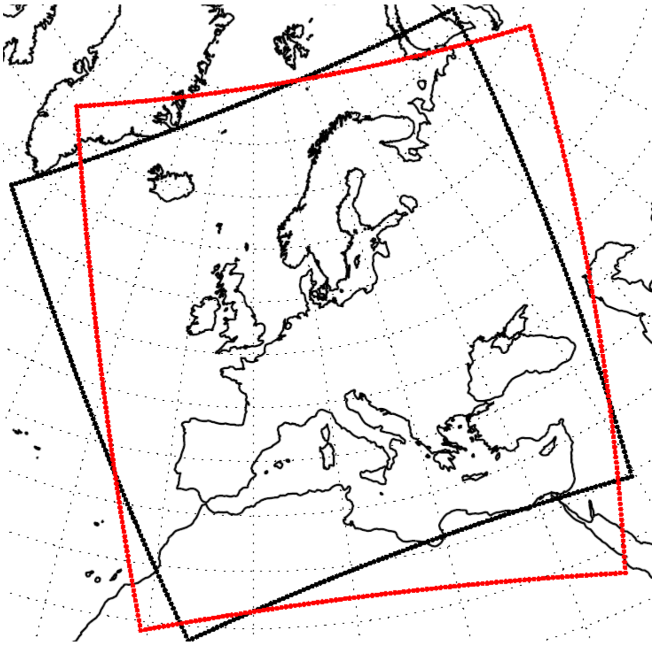

Figure 1. The geographical domain of RCAO (black) and that of HadRM3p (red) (from Samuelsson, 2004).

The RCM simulations provide values for a variety of meteorological variables, including temperature, precipitation, evaporation, wind speed, cloudiness, radiation, snow cover, soil moisture, and runoff.

The datasets that were used in this study were downloaded from the PRUDENCE website. The downloaded NetCDF[5] data files were first converted to ARFF[6] files for data mining and subsequent processing using a Perl module PDL::NetCDF[7] and a small Perl program. All data processing was done with small Perl programs developed by demand. The visualizations were made with the help of libral[8] and its Perl interface.

2.1 Weather Patterns

The computation and analysis scheme of weather patterns was based on a discrete representation of the weather at a given site and on a given day ("type of day"). In this scheme, the climate of a site is characterized using the numbers of different types of days in different seasons.

The selected characterization of climate is different from the usual characterization of climate with average seasonal values of selected meteorological variables. The advantage of the selected approach is that the important processes from the point of view of watershed and lake management often have a diurnal cycle and are thus represented well only in short time scales. Daily time scale is appropriate, and established practice in the case of hydrological simulation models and in investigating the effects of rainfall events. Environmental managers and those scientists, who do field work, also have a good understanding of what is the significance of a particular type of a day for the processes going on in the environment.

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[5] network Common Data Form, see http://my.unidata.ucar.edu/content/software/netcdf/index.html (accessed May 24, 2005)

[6] Attribute-Relation File Format, see http://www.cs.waikato.ac.nz/~ml/weka/arff.html (accessed May 24, 2005)

[7] http://cpan.org/authors/id/DHUNT/ (accessed May 24, 2005)

[8] Raster Algebra Library, http://libral.sf.net (accessed May 24, 2005)

In order to compute the discretizations, the number of variables was first reduced. The RCM simulations produce as an output as many as 18 variables. Six variables were selected because of their importance from the point of view of relevant processes in watersheds and in lakes. These were precipitation [mm/d], runoff [mm/d], snow water equivalent [mm], soil moisture [mm], 2-meter air temperature [°C], and 10-meter wind speed (average length of the wind vector) [m/s]. In Tables 1. and 2. these are referred to as Precip, Runoff, Snow, Soil, Temp, and Wind respectively. Second, the RCM output grid data were converted from numerical to categorical, i.e., ordinal data. The categories for these variables were defined after simple data mining, consisting mainly of visual inspection of the data, and, again, based on knowledge on relevant processes in watersheds and in lakes. The Weka[9] software was used for the data mining.

The six variables were classified into the following categories: 1) precipitation: no precipitation [0..0.1), some precipitation [0.1..5), heavy precipitation [5..∞); 2) runoff: no runoff [0..0.1), some runoff [0.1..4), heavy runoff [4.. ∞); 3) snow: no snow 0, snow >0; 4) soil moisture: dry soil < 210, wet soil ≥ 210; 5) air temperature: freezing (-∞..0), cold [0..10), warm [10°C..20°C), hot [20°C.. ∞°C); 6) wind speed: still < 3:, windy ≥ 3. This classification gives a total of 3 x 3 x 2 x 2 x 4 x 2 = 288 different daily weather patterns. In the computations the year was divided into four seasons winter (Dec-Feb), spring (Mar-May), summer (Jun-Aug), and fall (Sep-Nov).

Using the discretization the climate of a site can be expressed as a vector, whose elements denote weather patterns and the values of the elements denote the probabilities of these patterns (for an example see Table 1).

In this study, the similarity between two climate vectors is computed as a Euclidean distance.

3. Results

3.1 The CLIME DSS

The CLIME DSS comprises a Java applet and a server. The applet is capable of downloading climate visualizations; CBN's and associated a priori, possibly spatial, distributions from the server; and displaying all these to the user. The server is implemented as an extension to a standard web server[10], and it provides a set of XML files describing the structure of the DSS tools to the applet; and all the spatial and other data for the DSS tools. The BNJ[11] code for CBN's was included in the applet thus making it capable of computing *a posteriori* distributions of the CBN's. The user interaction capability of the DSS applet is especially relevant for this paper since the climate migration tool, which is described below, is an interactive spatial visualization tool.

3.2 Climate Change as a Change in Weather Patterns

Computation of the number of days with different weather patterns at different locations reveal that often a season is dominated by just one weather pattern, i.e., 20 % ... 50 % of the days in one season have the same weather pattern, and a season is typically very well characterized by four or five weather patterns ("types of days"). This is, however, very site dependent. An example of a relative number of different types of days at a site is shown in Table 1, where the number of weather patterns is limited to five in each season. The patterns were se-

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[9] http://www.cs.waikato.ac.nz/~ml/weka/ (accessed May 24, 2005)

[10] mod_perl tools (http://perl.apache.org/, accessed May 24, 2005) and XML::DOM modules were used.

[11] Bayesian Networks in Java, available from http://bnj.sourceforge.net/ (accessed May 24, 2005).

lected by identifying those five patterns that had greatest share of occurrence in any of the three climates.

Table 1. The relative number of different types of days in the RCM cell at 60.2 °N, 25.2 °E (the cell in which Helsinki is) under the current conditions (C) and under two future scenarios (B2 and A2), using the model run RCAO-E. Changes exceeding 10 units of percentage are shown in bold face.

Season	Precip	Runoff	Snow	Soil	Temp	Wind	C	B2	A2
winter	some	no	snow	wet	freezing	windy	**23 %**	**12 %**	**8 %**
winter	some	no	snow	wet	freezing	still	**23 %**	**9 %**	**6 %**
winter	some	some	no	wet	cold	windy	**1 %**	**11 %**	**18 %**
winter	some	some	snow	wet	cold	windy	9 %	13 %	10 %
winter	heavy	heavy	no	wet	cold	windy	0 %	5 %	9 %
spring	some	some	no	wet	cold	windy	5 %	12 %	15 %
spring	no	no	no	wet	cold	windy	6 %	12 %	13 %
spring	no	no	no	wet	cold	still	8 %	10 %	10 %
spring	some	no	no	wet	cold	windy	4 %	10 %	10 %
spring	some	some	no	wet	cold	still	4 %	7 %	5 %
summer	some	no	no	dry	warm	windy	19 %	24 %	22 %
summer	some	no	no	dry	warm	still	16 %	21 %	19 %
summer	no	no	no	dry	warm	still	16 %	16 %	17 %
summer	no	no	no	dry	warm	windy	9 %	8 %	8 %
summer	heavy	some	no	dry	warm	windy	8 %	8 %	7 %
fall	some	no	no	dry	warm	windy	6 %	12 %	12 %
fall	some	some	no	dry	warm	windy	6 %	9 %	10 %
fall	some	no	no	dry	warm	still	4 %	8 %	9 %
fall	heavy	some	no	dry	warm	windy	4 %	8 %	8 %
fall	some	some	no	wet	cold	windy	5 %	7 %	5 %

To gain even a more condensed, spatial picture of the changes predicted to occur in Europe, a change of ten or more units of percentage was defined as “significant”. For example, for Helsinki there are only three, in this sense, significant changes (see Table 1). Figure 2 shows the spatial distribution of the number of significant changes, and Figure 3 shows the spatial distributions of the number of significant changes in different seasons.

To identify those significant changes in weather patterns that also have a substantial spatial extent, the number of cells experiencing a given significant change was computed. The ten changes having the largest spatial coverage are listed in Table 2. In Figure 4 the spatial extent of two changes (increase in dry, hot, and still summer days and the increase in wet, cold, and windy winter days) is depicted.

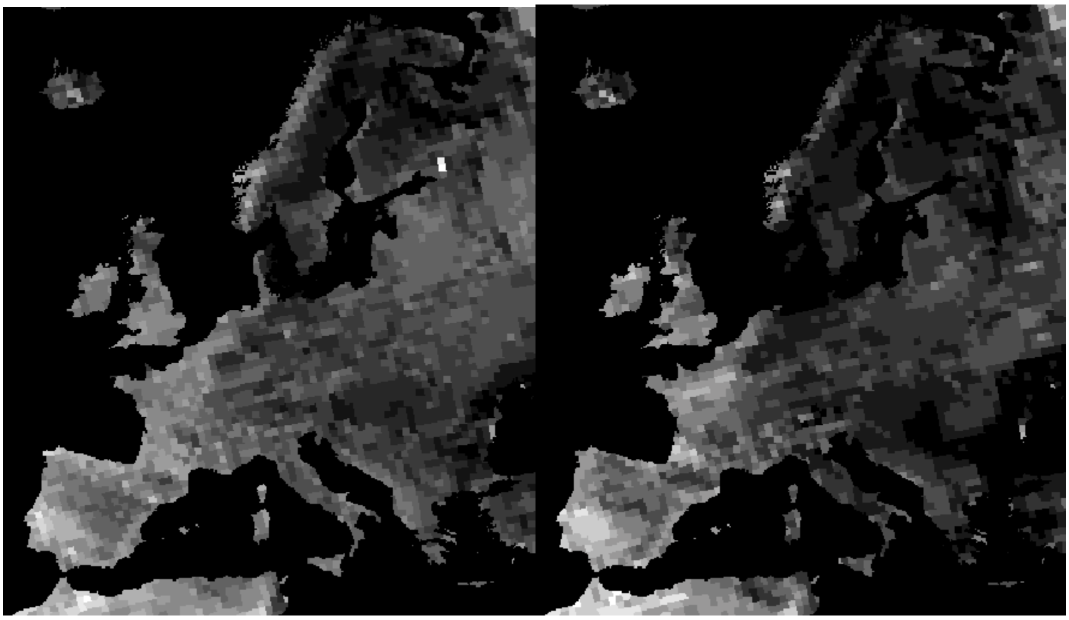

Figure 2. Comparison of spatio-temporal distribution of significant changes in weather patterns in Europe according to RCAO-E model runs under climate scenarios A2 (left) and B2 (right). The grey-scale is independently adjusted in each image (max cell value in A2 is 13 and in B2 is 9).

Table 2. The number of grid points (n) showing significant change in similar weather patterns in Europe according to RCAO-E, climate scenario A2, model runs.

Season	Precip	Runoff	Snow	Soil	Temp	Wind	Change	n
summer	no	no	no	dry	hot	still	increase	1635
summer	no	no	no	dry	warm	still	decrease	846
fall	no	no	no	dry	hot	still	increase	793
spring	no	no	no	dry	hot	still	increase	648
summer	no	no	no	dry	hot	windy	increase	585
winter	some	no	yes	dry	freezing	windy	decrease	533
winter	some	no	yes	wet	freezing	windy	decrease	492
winter	some	some	no	wet	cold	windy	increase	441
winter	some	no	yes	wet	freezing	still	decrease	425
spring	no	no	no	dry	hot	windy	increase	404

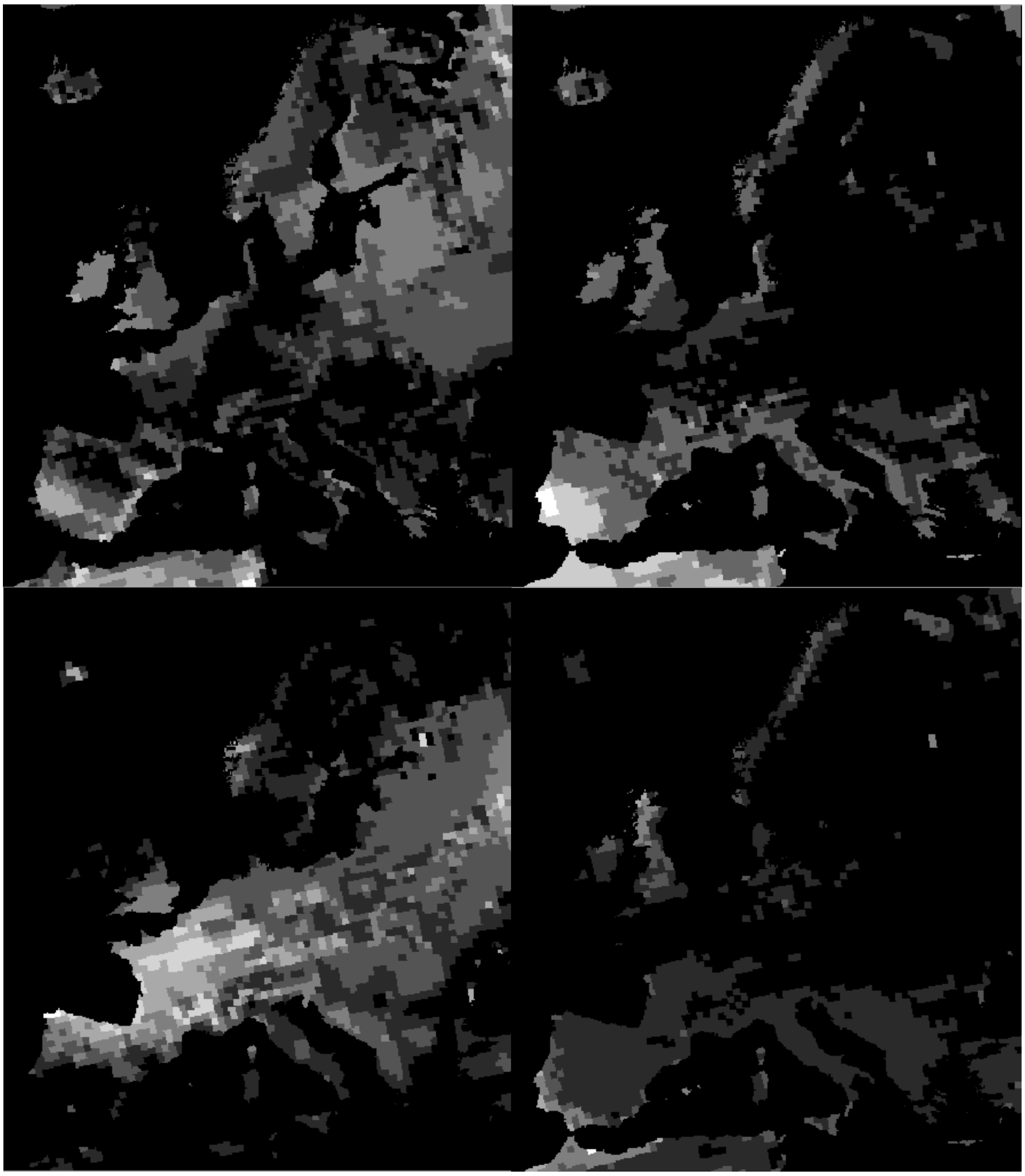

Figure 3. Comparison of spatial distribution of significant changes in weather patterns in different seasons (winter=above left, spring=above right, summer=below left, fall=below right) in Europe according to RCAO-E model runs under climate scenario A2. The grey-scale is independently adjusted in each image (max cell value in spring raster is 5 while in others it is 6).

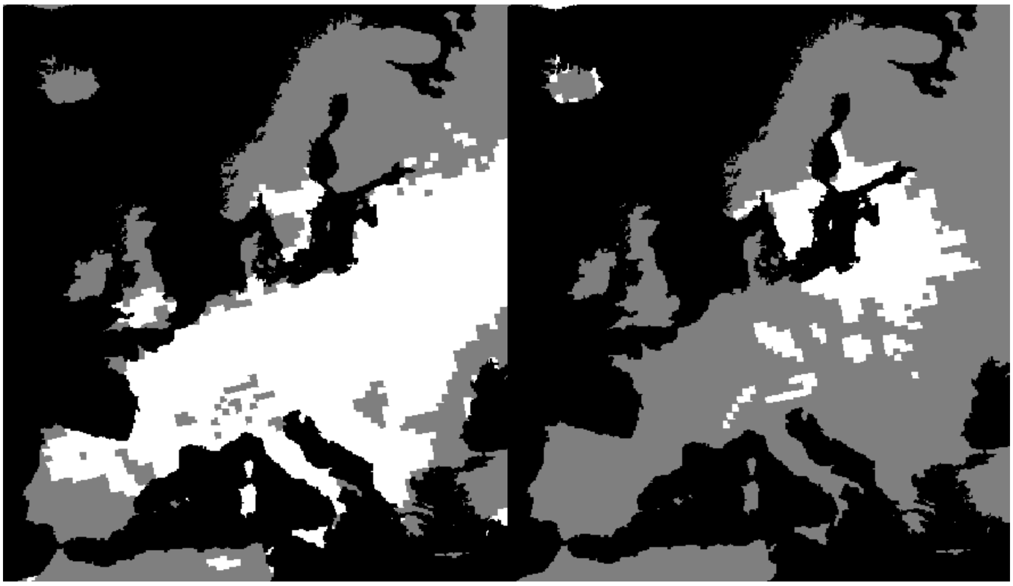

Figure 4. The spatial extent (white) of the significant change in two weather patterns in Europe according to RCAO-E model runs under climate scenario A2. The image on the left is the increase in dry, hot, and still summer days and the image on the right is the increase in wet, cold, and windy winter days.

3.3 Similarity of Current Climate at One Site with Future Climate at Another Site

The similarities between the predicted future climate at a given site, and the current climate at all sites within the geographical domain of the RCM grids was studied as follows. The similarities between the future climate at one grid cell and the current climate at all other cells were computed, and the coordinates of that cell where the current climate most resembled the future climate in the cell under study were stored. The similarity measure (Euclidean distance) depicting the magnitude of resemblance between the two climates was also stored. This analysis was repeated for all cells.

The result of the above computation yields information about “climate migration”. Climate migration is visualized in the CLIME-DSS as an arrow that points to the study location, with the tail of the arrow indicating the location where the current climate most resembles the future climate in the study location. Figure 5 shows the interactive climate migration tool. The climate migration analysis tool is an interactive visualization. The user first selects the climate scenario and climate model and then clicks on the map. The software (CLIME DSS Java applet) draws an arrow and an icon, which depicts the magnitude of resemblance, so that the end of the arrow points to the selected pixel. The user may then change the climate scenario or the climate model and the arrow changes respectively but points to the same location.

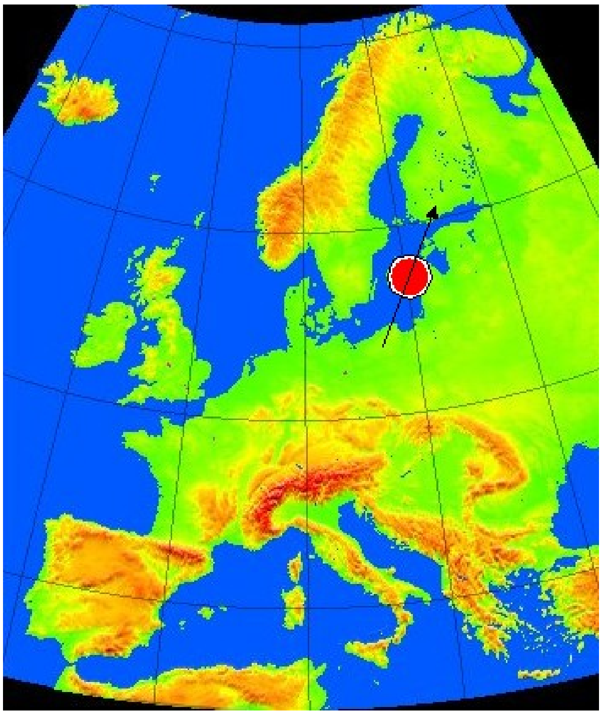

Figure 5. The interactive climate migration tool showing the location (tail of the arrow) where the current climate is most similar to the predicted future climate of the selected site (head of the arrow) and the level of the similarity (the amount of red in the white circle). The controls which are used to select the RCM and the climate scenario are not shown.

4. Discussion

The DSS has long been a debated subject, especially among natural scientists (e.g. Balloffet and Quinn, 1997). In CLIME the philosophy of developing and using a DSS builds on the results of pedagogical research (Bloom et al., 1964) and especially on the taxonomy Bloom (1964) developed. According to this taxonomy, and transferring it to the domain of environmental DSS's, the abilities and skills which are required from a manager of an environmental resource, can only be developed in certain steps. For example, comprehension can be built only on the top of knowledge, and application skills can be built only on the top of comprehension. This means that there has to be support and tools for all skill levels described in Bloom's taxonomy in a DSS. For example, interactive applications should not be provided in DSS's without information and tools with which the user can first develop required comprehension and knowledge. The visualization tools described in this paper assist the users to capture the essence of the climate change, and allows the users to exploit their expert reasoning in drawing conclusions about the ecological impacts.

The computational procedure described in this paper can be called data mining since it aims "to find unsuspected relationships and to summarize the data in novel ways that are both understandable and useful" (Hand et al., 2001). The exercise is computationally too demanding for interactive use within the Java applet of the CLIME DSS, but the visualizations can be computed off-line and the tool can download and present them to the user in an interactive way. The highly interactive visualization is currently limited to the climate migration tool. In addition to the computational burden, also the bandwidth of a network presents challenges. Consequently, careful planning is required in deciding what to include in visualization data sets. For example, in the climate migration analysis only the coordinates of that cell having the most similar current climate (as compared to the future climate of the study location) was stored in the visualization data set.

The visualization of the climate migration presents an interesting challenge. It would be desirable to be able to characterize the spatial distribution of the degree of resemblance between the two (future and current) climates. This could be achieved e.g. by presenting a colored map where different colors correspond to different levels of similarity. The amount of data required for such a presentation is relative to the square of the number of grid cells and thus easily leads to too large datasets to be transferred over the network.

The classification and categorization method used in this study is solely based on subjective reasoning like expert knowledge and decisions taken after using visual data mining tools. It would be interesting and valuable to study the sensitivity of the results to the categorization intervals. For example, visualizations of the type shown in Figure 4 are presumably quite sensitive to differences in discretization of the variables.

The results reinforce the impression that for the scenario A2, under which emissions are high, the climate change is predicted to be stronger. For example, for the scenario A2 the shift to snow-free, windy days with above zero temperature in Helsinki is more pronounced than under scenario B2 (Table 1).

There is an interesting division of Europe in the number of weather patterns that will change from the current to the future climate. Western Europe is predicted to experience change in a greater number of weather patterns than eastern Europe. This division is more pronounced under scenario B2 (see Figure 2). As Figure 3 shows, the division between western and eastern Europe can mainly be attributed to changes occurring during the winter season.

The results indicate that the most noticeable effect of climate change is the large increase in the number of hot and calm summer days. This effect is visible quite uniformly over the whole continental Europe (Figure 4). On the shores of the Baltic sea, there will be more wet, cold, and windy winter days in the future.

The climate migration analysis shows that in some cases the predicted future climate is very similar to current climate at some other geographical location.

5. Conclusion

Capturing the essence in the climate change for a specific purpose and over an entire continent is not a straight forward problem. This is due to the large amount of data, and the complexity in the assessment of the impacts of interest. This paper presents a methodology based on daily weather patterns that provides one avenue in characterizing the climate change over large geographical regions.

6. Acknowledgements

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