EUROCLIM: MONITORING THE CRYOSPHERE TO IMPROVE CLIMATE CHANGE MODELLING

Rune Solberg

Norwegian Computing Center, P.O. Box 114 Blindern, 0314 Oslo, Norway
Phone: +47 2285 2500 ; Fax: +47 2269 7660
E-mail: rune.solberg@nr.no; Web: http://remotesensing.nr.no, http://euroclim.nr.no

ABSTRACT

One of the potentially greatest threats to human beings is climate change. Climate scenario modelling indicates that our environmental conditions will change with increasing speed in the coming years with one of the most significant changes being a warming of the global climate. However, although there will be warming on the global scale there will be large regional variations in climate that will affect various parts of the world differently. In fact, Europe is maybe the most sensitive region of the world and it is not known whether we will experience regional cooling or warming in a future warmer world in general.

The EuroClim system will be an advanced tool for climate monitoring and scenario modelling for the support of a sustainable development and protection of the environment in Europe. The European cryosphere (i.e., masses of sea-ice, snow, and glaciers) will be the main indicator system. Snow and ice variables are extracted from satellite data and processed by advanced algorithms. The cryospheric information is applied in a regional climate model and statistical tools extract the information needed by the users – like extreme weather and changes in the length of the growing season.

1. INTRODUCTION

Most likely, global warming will change the living conditions in Europe significantly. The population distribution may change and the weather will show more extreme conditions, like flooding and hurricanes. The Arctic ice cover, high-mountain seasonal snow cover and glaciers will be monitored by EuroClim over decades in order to continuously assess the climatic health of Europe. Observations already indicate that the Arctic may be free of sea ice in summer within 50-100 years. Therefore, it is of great importance to monitor the cryosphere in order to make updated climate scenarios and be able to take the necessary measures in time to limit the consequences to European citizens.

The main objective of the EuroClim project is to develop an advanced climate monitoring and prediction prototype system for Europe, which will contribute to Europe's ability to reduce possible man-made climate changes and to take the necessary measures to limit the consequences of climate change to human lives and the society in general. The EuroClim system includes sub-systems for extraction of cryospheric variables from in situ and remote sensing data. Cryospheric variable products are stored in an advanced, distributed database system connecting all the storage and processing sites comprising the EuroClim network. Each database in the network is an innovative storage system for multi-dimensional raster data. Sub-systems for climate modelling and statistical analysis apply the cryospheric variables in order to generate trend estimation, scenario analysis, uncertainty assessments, etc. A web-based system presents the results – from cryospheric products to high-level information showing possible climate changes and consequences thereof.

The project is establishing a 20-year historic database of selected cryospheric variables in order to have a baseline dataset for climate modelling and statistical analyses. The database will be updated continuously by the EuroClim system. About each year, a new climate-modelling scenario will be computed based on the updated cryospheric

Presented at 3rd EARSeL LIS SIG Workshop, Observing our Cryosphere from Space: Techniques and Methods for Monitoring Snow and Ice with regard to Climate Change, March 11-13, 2002, Bern, Switzerland

database. The cryospheric observations will be used to tune the climate modelling such that observations and modelling results match reasonably well for the time period covered by the database. Based on the tuned model, scenarios for 50-100 years will be computed. A regional coupled ocean-atmosphere model, covering Europe, with a global coupled model of coarser resolution making the boundary conditions, is applied.

EuroClim is a EU RTD project within the IST programme. Ten European research institutes and companies participate in the three-year project, which started in September 2001. Project partners with national operational responsibilities have committed themselves with assistance from the industrial partners in the consortium to make EuroClim an operational long-term monitoring system if the prototype system is a technical and cost-effective success.

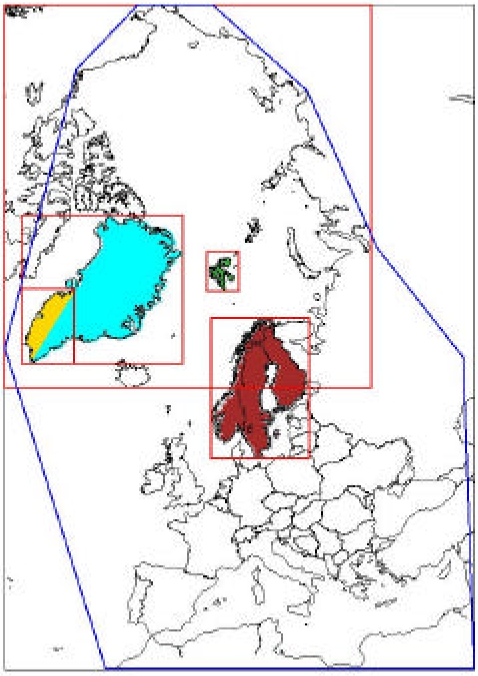

Figure 1*: The initial plan for regions of the cryosphere to monitor: The Arctic Ocean, Greenland, Svalbard and Scandinavia*

2. CRYOSPHERIC VARIABLE RETRIEVAL

2.1. Remote sensing of sea ice

The sea-ice variables to monitor include sea ice concentration and sea ice thickness. Sea ice concentration will be based on a multi-sensor algorithm using Bayes theory to combine SSM/I, scatterometer data and in the future AVHRR. The AVHRR algorithm outputs probability of sea ice. This is done in a two-step algorithm. First a physical threshold technique is used to provide a cloud mask. Then, a maximum likelihood classifier is used on the clear pixels to determine the probability of sea ice. The SSM/I algorithm is a smooth combination of the NASA-Team algorithm and the Bootstrap (Comiso) frequency mode algorithm. This ensures an optimum performance over both marginal and consolidated ice. There are many options for combining the two algorithm estimates, however, it is important that the virtues of each algorithm be retained. This means that the NASA-Team algorithm should be given very little weight at low concentrations, while the opposite should be the case over high ice concentrations.

For sea ice thickness, a correlation has been demonstrated between backscatter gradients in a SAR image and the sea ice thickness distribution (Kerman et al., 1999). This offers enormous potential for inferring ice thickness and hence (from correlations between successive images) ice fluxes in the Arctic. At the same time a radical improvement in ice characterisation from passive microwave data (SSM/I) has occurred due to the introduction (Comiso, 1990) and first use (Massom et al., 1999) of a cluster-analysis technique which makes use of all 7 frequency-polarisation combinations in the instrument to divide the Arctic into radiometrically distinct regions using neural network analysis.

New multi-sensor satellites (e.g. Envisat), and the data processing techniques developed in this project, aim to make operational measurements possible before the launch of ESA's Cryosat that will measure sea ice thickness precisely by using altimeter data, but only will operate for 3 years.

2.2. Remote sensing of seasonal snow

The snow variables to monitor include snow cover area, albedo, snow wetness and snow temperature. A large range of methods has been developed for snow-cover mapping. Spectral unmixing is currently one of the most accurate algorithms (see e.g. Nolin 1993). However, it is supervised and very time consuming. A new approach to spectral unmixing has been proposed by Solberg (2000a). The method measures certain features in potential endmember spectra in order to predict the actual endmembers and the amount of them (e.g., snow cover area). The method has so far only been tested on field spectrometer data.

SAR data has demonstrated the capabilities of detecting the extent of wet snow cover in mountainous areas (Shi et al., 1997). In mountainous areas the topography significantly affects the geometry and radiometry in the SAR image, thus geocoding and calibration using Digital Elevation Models (DEM) are required in order to relate the data to signature data. Enhanced snow cover mapping accuracy has been obtained by using coherence in addition to SAR intensity information (Strozzi et al., 1999).

Dry, weakly metamorphosed snow reflects most of the incoming shortwave radiation back into space. During snowmelt the albedo decreases rapidly and may drop from about 80% to about 10% within few weeks, completely changing the surface energy balance. Snow spectral albedo cannot be measured accurately through the whole optical part of the spectrum due to strong atmospheric interference in parts of the spectrum and the anisotropic behaviour of the reflectance. The standard way to model the spectral reflectance is by means of the model of Warren and Wiscombe (Warren and Wiscombe 1980; Wiscombe and Warren 1980). The model is calibrated by giving grain size and the content of impurities. However, the strong anisotropic effects of strongly metamorphosed snow must be taken into account to determine the actual spectral reflectance, which is not done by this model. Nolin et al. (1994) applied a discrete-ordinates radiate transfer model to calculate the reflected energy for a wide range of solar and viewing geometries. Experimental results showed that it overestimates the reflectance for all observation angles, and that the deviation from true reflectance increases with observation angle. The model was not usable for observations angles greater than 60°. There were similar problems for low solar incidence angles. The model was not able to characterise the backscatter peak at 180° relative azimuth angle. The project aims at developing a complete empirical model for the bi-directional spectral reflectance covering the wavelengths from 400 nm to about 10 µm. Currently, any model is far from doing that.

Melt onset is usually defined as the time of the first release of water from the snowpack and there are several approaches for measuring the first presence of liquid water. There are two optical approaches suitable for measuring or predicting the presence of liquid water (Solberg et al. 1997). The first is to very accurately measure the temperature of the snowpack and determine the point in time when it reaches 0° C. There are only a few cases of publications covering temperature measurements of the snow surface (e.g., see Key et al. 1997), and error sources and obtainable accuracy for snow has not yet been well determined. The other method is a more direct. The subtile changes in the snow spectrum (1000 and 1200 nm) from the presence of liquid water can be measured by spectrometer as shown by Green and Dozier (1996) on AVIRIS data. They demonstrated that it is possible to detect very small amounts of liquid water and possible to estimate the actual water volume very well. However, the method overestimates the amount of liquid water when vegetation is present (the water in the vegetation is measured too).

Since microwaves are very sensitive to free water in snow, the onset of snowmelt can be detected using SAR data (Koskinen et al., 1997). RADARSAT data has also been applied for assessing the potential of detecting the onset of snow melt. Algorithms using multiparameter C-band SAR data to estimate the wetness in the snow cover have been proposed.

2.3. Remote sensing of glaciers

Small glaciers are responding on changes in climate, e.g. on air temperature and precipitation, on a decadal scale. Therefore, such glaciers are an important climate change indicator. Glacier mass balance measurements are used to monitor whether glaciers are retreating or advancing. The traditional method for mass balance measurements is by direct in situ stake measurements at the end of the accumulation and ablation seasons, respectively. In the late 1980ies and early 1990ies attempts were made to use optical satellite remote sensing as a tool for locating the equilibrium line altitude (ELA) on these glaciers (Winther, 1993). However, the presence of superimposed ice, which is common on many Svalbard glaciers, made it impossible to locate the ELA with required accuracy. Radar satellite data in combination with ground-penetrating radar have shown promising results. Engeset (1998) showed that the use of SAR data improved the localisation of the ELA because of the penetrating capabilities into the snow/ice of radar signals compared to optical signals.

3. CLIMATE DATA MODELLING AND STATISTICAL SPACE-TIME ANALYSIS

Numerous global climate simulations have been carried out during recent years, but still with rather course resolution (about 300 km) due to limited computer resources. Regional climate models have during the last decade been utilized with success to improve the regional quantitative estimates of, e.g., climate change. Regional models are capable to reproduce the large-scale behaviour of the driving global models, and are been run with resolution of about 30 to 70 km for periods of up to 30 years.

The project will apply the regional model REMO with boundary conditions from ECHAM (Jakob 1995). Both are coupled atmosphere-ocean models. An approach is currently being developed for improving the model parameterisation using satellite-measured cryospheric variables. The model output and cryospehric observations will be compared and the model parameterisation modified accordingly in an iterative manner until model results and observations show reasonable agreement.

Reliable trend estimation is one of the statistical problems the project will focus on. The analysis of environmental time series data at a fixed point in time has received generous attention in the statistics literature. To draw objective scientific conclusions about a trend, both the trend estimate and a measure of its uncertainty must be given. This often leads to adjustments for temporal correlation in the data. Formal methods for trend assessment rely heavily on the assumed parametric form for the trend. Often, there may be little scientific support for assuming that the parametric form is, e.g., linear. Alternatively, we may estimate a non-parametric trend through a local regression approach (Hastie and Loader, 1993; Høst 1999).

In the past decades, the analysis of spatial patterns at a fixed point in time has been subject to extensive studies. Driven in part by the demand for quantitative methods for large-scale environmental monitoring, joint space-time modelling is currently an active research area for which there is no commonly accepted state of the art. Some alternative methods include Bayesian approaches (Handcock and Wallis, 1994), the space-time decomposition model by Høst et al. (1995) and the hierarchical Bayes approach by Wikle et al. (1998).

4. THE EUROCLIM SYSTEM CONCEPT

The principal system components and the major data flow between them are sketched in Figure 2. Input to *Cryospheric Variable Extraction* is remote sensing data, in situ data and ancillary data. Cryospheric variables are extracted and stored into the *System database*. Space-time data sets are retrieved from the database and analysed by the *Climate Modelling* and *Statistical Analys*is giving the climatic information required. The *Web Server* provides user access to the EuroClim system.

The distributed EuroClim approach is not to assume new unrealistic international structures of responsibility, but adapt to the current organisational situation. The distributed approach gives us the freedom to arrange for suitable pipelines for extracting the cryospheric variables from the different sets of raw data (snow, sea ice, glaciers). Each pipeline is likely to be operated within one organisation. Even though we expect data volumes to be high for some of these processing pipelines, the distributed design gives us the benefit of the network speed of Local Area Networks. The cryospheric extraction processing still should have access to auxiliary and meteorological data even if they reside in remote storages.

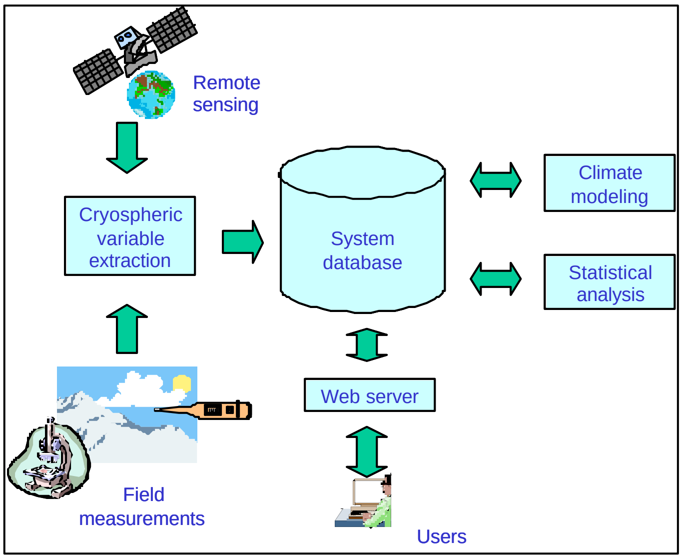

***Figure 2**: Principal EuroClim system components and the dataflow between them*

There already are a community of national organisations and authorities taking care of cryospheric parameter retrieval, data storage/handling and analysis/information extraction. The EuroClim system is going to be distributed in the sense that it provides for a set of databases, each holding a part of the total information included in the overall system. The cryospheric variables will be stored in a common map projection in raster format in the RasDaMan databases. The 4-dimensional (space-time) functionality of the database makes it possible to extract time series of data for a selected area in a simple manner. The database also has a multi-spatial functionality, which makes it possible to combine data from various sources of different spatial resolution, including point sources (Baumann 1999).

5. DATA AND INFORMATION TO USERS

Two groups of potential users for the results of the EuroClim system concept have been selected. The first of these are the *operational users* or organisations that would want to have raw parameter data and have their own means of analysing and interpreting it. These include national scientific research institutions with responsibilities to their national government. The second group is the general *public* who just require a summarised presentation of the data produced by the EuroClim system.

The operational users will use information from the EuroClim system to investigate their own questions. To do this, they will need to know how the system operates and the source of the input data. Typically, after determining what data is available for a particular time and location through a quick-look graphical interface, they will then want to download the data in a format suitable for input into their own models and simulations. They may also use EuroClim on behalf of environmental lobby groups such as Green Peace and the World Wildlife Fund, non-governmental organisations with regulatory powers such as the European Environmental Agency (EEA) and environmental agencies in individual states. They may also provide information on behalf of government ministries, the EU and the United Nations IPCC (Intergovernmental Panel on Climate Change).

Public users do not require access to the detailed data from the system. The group includes casual users from the general public who will have an interest in environmental issues and require a graphical presentation of the system outputs. Many members of the public do not understand very clearly global warming concepts and how Europe will be affected in the future. EuroClim will provide the public with accurate and objective information that promotes their wider understanding of the situation.

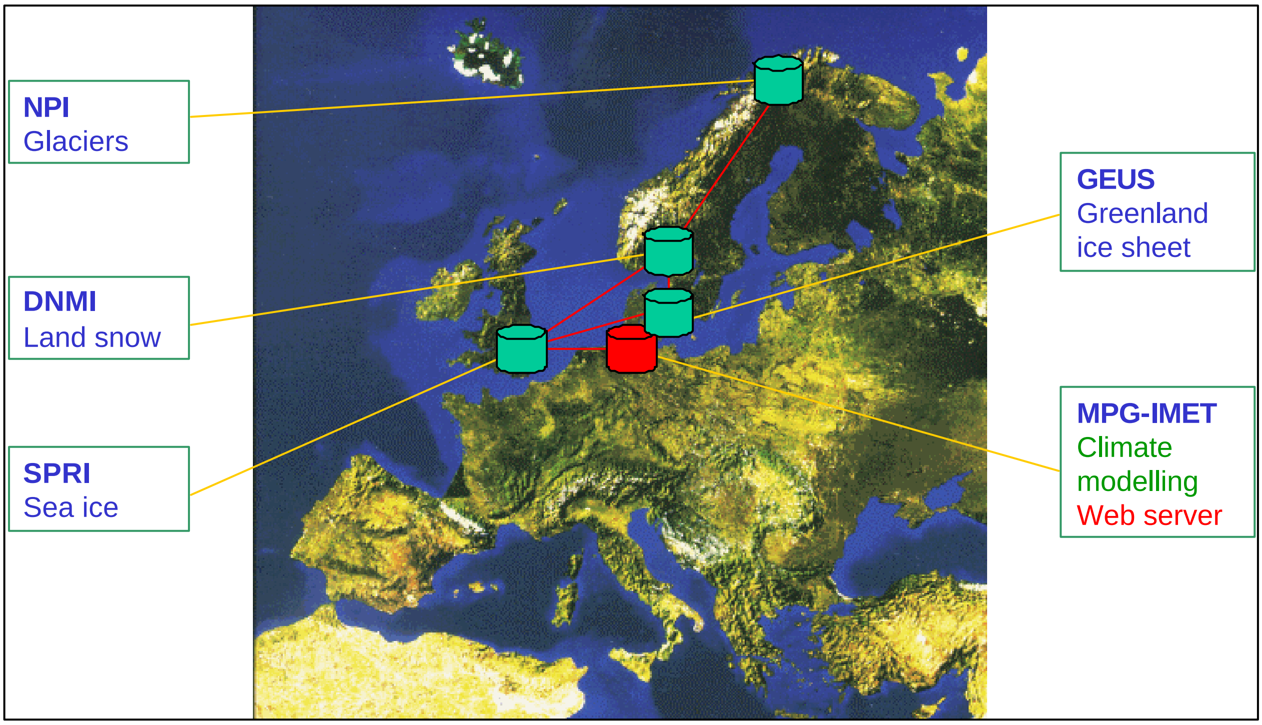

Figure 3*: The actual data bases planned for the EuroClim network*

The public will require simple access to information presented graphically and in an interesting way that will hold their interest. As well as being presented with basic information and trends, they should be given a certain level of interactive control to select different scenarios of warning, to see its effect on, say, sea levels, glaciers, weather patterns, etc. There may also be a need to support the visual information with simple guidance on interpreting it. It may also be possible for the public to email questions for environmental experts to answer.

6. THE CONSORTIUM

The ten members of the EuroClim consortium are the following institutes and companies (keywords describing each member's role in the project is given):

- Norwegian Computing Center (Norsk Regnesentral), NR: Norwegian research institute. Project coordination, remote sensing of snow, statistics and system design.
- Loughborough University – HUSAT Research Institute, LU-HRI: British research institute. Man-technology aspects, user needs, evaluation.
- Active Knowledge, AK: German company. Database system for multidimensional data.
- Norwegian Meteorological Institute (Det norske meteorologiske institutt), DNMI: Norwegian weather services institute. Remote sensing of snow and ice, regional climate modelling.
- Geological Survey of Denmark and Greenland (Danmarks og Grønlands Geologiske Undersøgelse), GEUS: Danish research and operational institute. Glaciology on Greenland.
- Max Planck Institute for Meteorology (Max-Planck Institut für Meteorologie), MPG-IMET: German research institute. Global and regional climate modelling.
- NORUT Information Technology (NORUT Informasjonsteknologi AS), NORUT: Norwegian research institute. Remote sensing of snow and distributed GIS.
- Norwegian Polar Institute (Norsk Polarinstitutt), NPI: Norwegian research and operational institute. Remote sensing of snow and glaciers, system verification.

- University of Cambridge – Scott Polar Research Institute, UCAM-SPRI: British research institute. Sea ice in the Arctic.
- Kongsberg Spacetec AS, KSPT: Norwegian company. Main IT partner. System design, development and implementation.

7. CONCLUSIONS

Initiatives to reduce the effects of anthropogenic climate changes will impose restrictions to people's freedom of action. The strength of the means that are necessary depends on the seriousness of the situation. A late identification will cause harsh and unpleasant efforts. Through identification and monitoring of key climate variables, the EuroClim project will provide an early-warning system for climate change, helping politicians to take necessary measures in time to limit the negative consequences on safety, health and life quality. The establishment of a system for long-term monitoring and continuous updating of climate change indicators is crucial to ensure the necessary continuity. Increased knowledge about natural climate variability and the development of methods and models will contribute in risk assessment and risk abatement.

The European cryosphere (the Arctic region, high-mountain areas with seasonal snow and glaciers, including Greenland) will be the focus of the main indicator system. Snow and ice variables are extracted and processed by advanced sensor technology and algorithms and applied in regional climate models and statistical models in order to predict changes and run scenario analyses. Project partners with national operational responsibilities have committed themselves, with assistance from the industrial partners in the consortium, to make EuroClim an operational long-term monitoring system if the prototype is a technical and cost-effective success.

ACNOWLEDGEMENTS

The author likes to thank his colleagues in the "pilot team" in the consortium for their contributions to the first ideas and initial development leading to the EuroClim concept: Jason Baragry (NR), Peter Baumann (AK), Asgeir Finnseth (NORUT), Øystein Godøy (DNMI), Tore Guneriussen (NORUT), Nick E. Hughes (UCAM-SPRI), Gudmund Høst (NR), Martin Maguire (LU-HRI), Knut Helge Midtboe (DNMI), Kjell Arne Mikalsen (KSPT), Ole B. Olesen (GEUS), Ernst Maier-Reimer (MPG-IMET) and Jan-Gunnar Winther (NPI).

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