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Climate Change Impacts on Agriculture in Europe

Final Report of COST Action 734 'Impact of climate change and variability on European agriculture'

edited by
Simone Orlandini
Pavol Nejedlik

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CHAPTER I

REVIEW AND ASSESSMENT OF AGROCLIMATIC INDICES AND SIMULATION MODELS IN EUROPE

J. Eitzinger, S. Thaler, S. Orlandini, P. Nejedlik, V. Kazandjiev, V. Vucetic, T.H. Sivertsen, D.T. Mihailovic, B. Lalic, N.R. Dalezios, A. Susnik, C.K. Kersebaum, F. Rossi, A. Dalla Marta, C. Nendel, V. Vucetic

Abstract. Many agrometeorological tools are available for agricultural research as well as for operational applications such as for stakeholder decision making. These tools range from simple indices or empirical models to complex, mechanistic models. Complex models can be used to simulate and analyse the manifold interactions in the soil-plant-atmosphere system, for example in the important field of climate change impacts on agricultural production. However, all kind of model results are related to different uncertainties and limitations, such as trends in technology and human activities, models representation of reality, lack of knowledge on system responses or lack of calibration data. This review provides, based on an European wide survey an overview of most widely used agrometeorological tools in Europe in research and operational use, related case study results, observed trends, problems in operational application and recommendations.

1. Introduction

A review and assessment of agroclimatic indices (including meteorological, climatological, and agrometeorological indices, currently used in agrometeorology) as well as crop simulation models relevant for various European agricultural activities was carried out in the frame of the COST734 action. The survey was based on questionnaires and a literature review. The detailed results are described in the COST734 report (Orlandini and Nejedlik, 2008) and two journal publications (Orlandini *et al.*, 2008; Eitzinger *et al.*, 2009).

During the past decades several software tools were developed for agricultural research and decision making purposes. For example, crop and whole farm system modeling, pest and disease warning models/algorithms, models for irrigation scheduling or agroclimatic indices can help farmers in decision making for crop management options and related farm technologies. For research purposes, models can also be used to simulate and analyze the complex interactions in the soil-plant-atmos-

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phere system. For example, they can be used to simulate climate change impacts on crop water balance and crop yields. Nevertheless, these modeled systems include many uncertainties and limitations resulting from unknown trends in future technology and human activities, a simplified representation of reality, lack of knowledge on system responses and lack of calibration data. Several research studies were conducted in Europe and worldwide in the field of model development, improvements, or comparisons of models. However, there are still many improvements necessary for model applications and related uncertainties, e.g. for climate change impact studies, as the presented COST734 studies reveal.

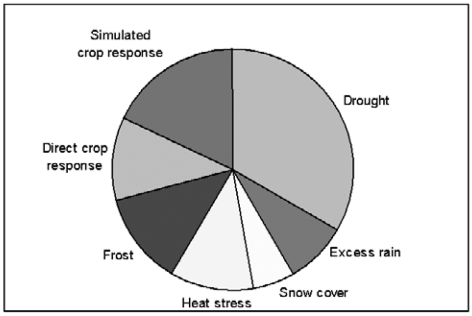
2. Agroclimatic Indices and Providers

Indices are explicitly defined by equations, whereas indicators reveal relationships used to quantify impacts. Both serve to simplify complex phenomena. Therefore, indicators can be converted into indices, once relationships are quantified and measurable. Indicators may also include output values from mechanistic models, which reflect simplified impact relationships.

Various indices are used in Europe for both operational and research applications. Indices are mostly used in agrometeorological monitoring and services operated by the national state bodies, such as in national meteorological and hydrometeorological institutes and their regional branches. Commercial agrometeorological services are scattered and usually focused on specific area such as extreme weather warning service or advisory services in case of plant protection against pests and diseases. In some cases, commercial companies selling products to farmers, such as weather stations, including also some technical support and agrometeorological services and/or forecasting models (mostly pest and disease warning and irrigation scheduling) as a service. Agrometeorological information is mostly produced by national bodies such as meteorological services, which run the meteorological networks, and so they are also the owners of the data. They usually cooperate with other national bodies or commercial companies such as agricultural extension services or insurance companies by providing them the data either free of charge or at low cost.

Research activities developing agrometeorological indices in Europe mainly focus on drought and crop responses such as phenology, and to a lesser extent, frost and heat stress (Fig. 1). The attention paid to research does not reflect the practical use of indices. For example, relatively little attention is paid to the operational monitoring of drought and heat stress, while the majority of countries report the research activities in this field.

Fig. 1. Frequency of reported application of agrometeorological indices in research related to their purpose, according to the COST734 survey (Eitzinger et al., 2009).



A large number of various indices including literature is reported in Orlandini et al. (2008).

Drought indices quantify the lack of water for specific periods of time, such as the negative deviation of precipitation from the normal in the case of meteorological drought indices. Meteorological drought indices, however, do not always reflect well the level of crop water shortage. Therefore, agrometeorological drought indices, focus on crop water balance of crop stands during the plant growth and development cycle. The general problem of these indices is to include both physical and biological properties of crops to reflect their sensitivity and limitations towards the lack of water supply during the vegetation period. A related problem is the definition of the time step used to calculate the particular indices. Therefore, each drought index performance is related not only to a specific application (e.g. for crop water stress detection, climatic water deficit, etc.) but also to the environmental conditions (e.g. different indices show different sensitivity under changing climatic conditions). Therefore, new studies also recommend a combined application of drought indices, optimized for the relevant environmental conditions, to improve the monitoring performance for various applications. An example is a combination of remote sensing based indices (e.g. perpendicular drought indices) with meteorological or agrometeorological drought indices. In Greece, for example, the two remote sensing based drought indices Reconnaissance Drought Index (RDI) for hydrometeorological drought and Vegetation Health Index (VHI) for agricultural drought (Kanellou *et al.*, 2009a) are preferred beside the existence of conventional drought indices such as Deciles of precipitation, RDI using precipitation and potential evapotranspiration, Palmer Drought Severity Index (PDSI) using precipitation, potential evapotranspiration and the available water capacity (Kanellou *et al.*, 2009b), the Standardized Precipitation Index (SPI) and the Rainfall Anomaly Index (RAI).

Most of drought indices focus on pastcasting, while few of them on nowcasting, as reported in the COST survey. These indices are often applied locally or regionally as they have to use multiyear measured values of the particular parameters recorded or calculated for a certain locality. Many of the indices in use are rather complex and deal with water balance components and precipitation measures. Indices including the calculation of water balance components are used with various modifications in almost all countries from national to farm level extent. Both indices, based on water balance components and on precipitation for a given period, are mainly produced by national weather services, as they run the meteorological networks at regional and national levels. Some institutes additionally use water balance outputs of crop models like WOFOST to define the days with the lack of water for specific crops.

Among the standard indices, the standardized precipitation index (SPI), Palmer drought severity index (PDSI), percent of normal precipitation and rainfall percentiles are in operational use among national services in Europe and at the Drought Management Center for South eastern Europe (DMCSEE). Relevant maps are published on the web page <http://www.dmcsee.org/>, and they are updated once per month.

Excess rain is mostly estimated from daily cumulated precipitation measurements. Further to this parameter, the rainfall intensity is measured either by pluviographs or by weight rain gauges providing online signal. The majority of rainfall parameters are issued by the standard forecast of each meteorological service, mainly at the regional scale. Many of the services also provide special rainfall maps in their pastcasting, forecasting and now casting, identifying the areas with high precipitation and/or anomalies. For instance, the INCA system has been applied in Austria since 2003 to spatial past-, now- and forecasting of various weather parameters and uses radar and station data to produce precipitation maps (http://www.zamg.ac.at/incaanalyse/). In Greece, for example, apart from high precipitation pastcasting maps, an operational-research application of the non-hydrostatic model LM-COSMO of HNMS (Hellenic National Meteorological Service) has been used for forecasting excess rain events and the simulation of severe thunderstorms (Avgoustoglou, 2002).

Heat stress is an important but complex phenomenon, depending on the definition and the sensitivity of the parameter. Factors such the height of temperature, duration, and rate of increase of the temperature as well as air humidity, radiation, and wind can modify the heat stress level of living organisms. The critical thresholds of temperatures for crops differ much and they vary also according to the plant development stage. A threshold of heat stress usually refers to the daily mean temperature, over which a detectable reduction of growth or damages on plant begins. In fact, heat stress for crops is strongly detected by the heat balance of various crop tissue, which again is influenced significantly by transpiration cooling. Drought can therefore decrease the critical air temperature level for crops regarding heat stress. Relevant indices should therefore consider the overall local climatic conditions and, if feasible, be calibrated crop specific. Heat stress prediction is naturally included in general weather forecasts, though there are very few services listed, which provide special heat stress related indices. A heat index forecast is provided, for example, by Hungarian Meteorological Service, which includes the forecast of daily average temperature above 25 °C. Synoptic conditions during heatwaves and the frequency of occurrence of such events can be estimated using the Intensity-Duration-Frequency (IDF) curves as applied in Greece in estimating related fire risk (see below).

Similarly, agrometeteorological *frost damage* depends on the temperature and the duration, while the temperature remains below the freezing point, and on the sensitivity of the recipient as well. However, the common detection and prediction of frost conditions considers the duration of temperatures below 0 °C and daily minimum values. Frosts are frequently classified as either advective or radiative, which also defines their impact on the different type of crops and the possibilities for frost protection. During radiative frosts, local orographic conditions can modify near surface temperatures considerably forming cold air lakes with a strong vertical temperature gradient. Often the frost line does not reach more than 1-2 m above ground, so that only the crops close to the ground are affected by frost. These aspects make local frost prediction very difficult, and only generalized, large scale based assessments can be given by operational services.

Frost events are both forecasted and monitored by the national meteorological services in all countries. A standard weather forecast usually includes the forecast of the frost or the possibility of ground frost occurrence. However, only few special indices in operational use focus on nowcasting and pastcasting in Europe. Frost forecast is usually issued at the national level for general purposes, while specific indices for local assessments are mainly used by farmers (e.g., for frost irrigation scheduling), consultants, and insurance companies. In Greece, for example, a high precision and resolution meteorological system was developed for short-term forecasting and nowcasting of significant weather. Among the extreme events, one shows the occurrence of frost on a 2x2 km grid for 7 days, recorded on an hourly basis.

Snow cover has several effects on crop growing conditions (e.g. soil temperature). On one hand, it brings a valuable protection of plants against hard frosts during the winter. On the other hand, long snow cover duration under unfavorable conditions can damage the crops by a forced occurrence of fungs and a delay of the growing period for example. Furthermore, a frequent change of snow cover, combined with freezing/thawing events can physically damage the roots of crops (e.g. in winter cereals). The indices or algorithms related to snow cover, beyond research applications, mostly focus on operational pastcasting, which, for example, is done daily at different spatial scales of 10x10 km grids in Finland to the regional and national scales in other European countries. In some cases, the water equivalent of the snow cover is announced, which permits to estimate the amount of the water being stored in the snow as a water source in spring. Specific snow conditions are frequently observed in the Alpine region for detecting risk of avalanches.

Further to the above described indices, several *specific agrometeorological indices* are in operational use and often focus on the assessment of growing conditions for crop management.

Relevant special weather forecasts for farmers and detailed information on crop growing conditions are provided by many European services, including institutional and commercial services. Daily forecasts are, for example, provided at the scale of 10x10 km by the Finish Meteorological Service and a private company in Finland. This information includes probability of rain and frost, rain amount, air and soil temperatures, relative humidity, wind speed and direction and an index describing weather conditions for plant protection. The German Weather Service (<www.dwd.de>) provides actualized 7-day forecasts up to 4 times a day, concerning the drying of hay and grain moisture of cereals and maize. Other parameters include potential and crop evpotranspiration, soil temperatures as well as soil wetness and workability trends. Additionally, recommendations are given for the sowing day of winter cereals, oats, potato, sugar beets, and maize for the upcoming 6 days. Some services provide information about the workability of the soil with regard to the depth of the frozen soil considering also the impact of frost on lumps of clay during the winter.

Operational hail supression and/or short term forecast is carried out in several countries mostly at the regional level. For example, an operational project has been carried out in Greece, the Greek National Hail Suppression Project (NHSP) weather modification program. The objectives were to reduce hail damage and at the same time to examine and study the thermodynamic, dynamic, and microphysical characteristics of the potential hail producing clouds. Instability indices are also calculated for operational hail forecasting in Greece. The assessment of the indices is objectively accomplished through multivariate statistical analysis. The indices with high loading and scores are considered to best detect convection for hail forecasting. Severity of hailstorms and distinction between hailstorms and rainstorms is assessed and indentified by developing a three-stage methodological procedure, which is based on empirical functional relationships between satellite METEOSAT IR parameters and weather radar parameters (Domenikiotis *et al.*, 2007). Also in some other countries specific radar services are installed for hail warning systems, such as in Serbia.

Forest/grass *fire indices* in various forms are mainly in use in Mediterranean countries. Considering the increasing occurrence of forest fire events under climate change conditions, a more frequent use of these indices is expected. The German Weather Service (DWD) provides a daily risk index for forest fire which combines several indices: a Swedish index (Angström), two German indices (Baumgartner, M-68), and the Canadian forest fire warning system (FWI: fire weather index, FFMC: fine fuel moisture code) (<http://www.agrowetter.de/Agrarwetter/Waldbrand_en.html>).

In Portugal the Meteorological Institute runs an operational system based on Canadian FWI (<https://www.meteo.pt/en/ambiente/risco_incendio>). The Slovak Hydrometeorological Institute provides forest fire warning and prediction by using M-68 method applied to local conditions (<http://www.shmu.sk/w/?page=5000>).

Remote sensing techniques are often used for monitoring and near-real time assessment of the affected area by forest fires, namely the Normalized Difference Vegetation Index (NDVI) and the Surface Temperature (ST), extracted by the meteorological satellite NOAA/AVHRR (Domenikiotis *et al.*, 2003).

3. Crop response, Pests and Diseases Monitoring

There are not many services in Europe monitoring the response of the crops to weather conditions regarding *crop growth and phenological development*. Operational phenological networks, which comprise a sufficient number of working stations, are mainly situated in the region of Central Europe (especially in Germany). These networks are run by meteorological services (e.g. at the German and the Austrian weather service: <www.dwd.de>, <www.zamg.ac.at>) and systematically monitor phenological development stages of selected plants, and in several cases, crop development including some pheno-metric parameters, pests and diseases, as well as yields. The use of the data is mainly in pastcasting. At the Austrian weather service (ZAMG) European phenological forecast maps are provided (<http://zacost.zamg.ac.at/phaeno_portal/phaenologieprognosen.html>) beside a phenological monitoring service and a data bank. A special set of parameters regarding the plant conditions close to the harvest is provided by the German Meteorological Service. Further to that, either standard (WOFOST) or specific (IPHEN) models are used to simulate the development of different plants. In some cases some parameters are monitored by remote sensing (e.g., greenness index). Remote sensing of phenological parameters is intensively used at the European scale by JRC Ispra within the MARS project.

Pests and diseases occurrence are widely simulated by using either specific algorithms (in most cases) or partial outputs of crop growth models. Several agrometeorological services provide operational *pest and disease warnings* for specific crops in many European countries. A significant part of pest and disease warnings are, however, carried out on a regional to local level (e.g. by agricultural extension services or by farm based systems using agrometeorological weather stations).

4. Process oriented Crop Simulation Models

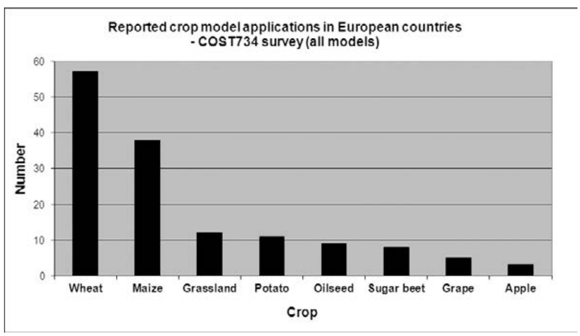
Mechanistic or process-oriented models have been applied in research for more than 50 years. The three most important "schools of development" from Australia, the Netherlands, and the United States include: (i) APSIM models (Asseng *et al.*, 2000), (ii) SUCROS based models (such as WOFOST) from the "School of De Wit" (Van Ittersum *et al.*, 2003), and (iii) the DSSAT family (such as CERES) of crop models (Jones *et al.*, 2003), although there are links between these models. The survey shows that the most frequently used process oriented crop models for research or operational applications in Europe are CERES, WOFOST, and STICS, showing nevertheless, differences among countries. WOFOST is the only model, which is operationally integrated at the European level for the European crop yield prediction system, covering all countries.

It can be seen at the beginning of the 21st century, that research applications dominate and that only few models are operationally applied. Often the number of national or European applications of the relevant models are related to established research institutions working on model developments. The main applications of crop models are found in climate change impact research on agriculture, whereas the operational applications focus on crop yield forecasting. The applications often include an assessment of the dependence of growth, development, and yields of crops on limitations of soil-water regime. The assessment of crop development and yield response to related timing of crop management such as fertilizing, cultivation, irrigation, plant protection, etc., is another application. They are rarely used for early warnings or mitigation of damages from extreme meteorological phenomena and processes.

Most crop simulation models in Europe are applied for annual crops, especially cereals and maize, reflecting the economically most important crops in Europe (Fig. 2). However, permanent grassland, potatoes, sugar beet, oilseeds, and others also play an important role regionally, which results in specific model applications.

Crop model applications are influenced by several uncertainties determining limitations of their use in research and practice (e.g., Eitzinger *et al.*, 2008). The main reported limitation for application of crop models in Europe is related to the input data. The reported most frequent problems are the availability or the low quality of the soil input data (especially for spatial model applications), the lack of long term biophysical crop data for model validation and calibration and, in some cases, the availability or costs of meteorological data. This is related to differences in socio-economic conditions and local administration of data among the different regions of Europe. The reliability climate scenarios or seasonal forecasts is another crucial point for the use of such models for operational purposes or for making long-term strategic decisions.

Fig. 2. Reported crop model applications (operational and research application, one count per model and country) according to the COST734 survey.



4.1 Spatial applications of models and indices

Spatial model applications, such as interfacing models with geographic information system (GIS), increase the possibilities of applying these models to regional planning and policy. Because of their relatively simple calculation methods, agroclimatic indices are often implemented in GIS in order to show spatial distribution and developments of the relevant calculated index. The most common examples of these are drought indices.

However, several crop models are applied on spatial scales beyond the field level. The most promising method to estimate crop yield over larger areas is combining crop growth models and remote sensing data (e.g. Bouman, 1995; Moulin *et al.*, 1998). The main benefit of using remote sensed information is that it provides a quantification of the actual state of crops for large areas, while crop models give a continuous estimate of crop growth and development over time. Only few applications of spatial crop growth monitoring systems are already operational in Europe. However, the general item of remote sensing data assimilation in crop models has been the subject of mainly methodological research in the last years. They have allowed to elaborate practical solutions, but the operational application is still limited by the large amount of data to be processed. The best known example of an operational application is the MARS Crop Yield Forecasting System (MCYFS) for food security in Europe and other parts of the world (<http://agrifish.jrc.it/marsstat/>), which is providing quantitative crop statistics at EU (for a 50x50 km^2 grid for NUTS units) and national levels, in near real time.

MCYFS was also adapted for national CGMS at a finer grid scale of 1x1 km^2 to 10x10 km^2 (for defined zones below NUTS level) for Belgium (B-CGMS; http://b-cgms.cra.wallonie.be/en/). B-CGMS is based on the existing European harvest forecasting system, but the data bases are supplemented and refined by Belgian physical (soil data) and technical (temperature sums, crop management) parameters. Satellite data are used for a quantitative estimate of production in B-CGMS, where at the European CGMS it is used for qualitative interpretation.

A national example of spatial agroclimatic monitoring is SIGA (Servicio de Información Geográfico Agrario-Service of Agrarian Geographics Information), an application running at the Ministry of Agriculture (Deputy Direction of annual crops) in Spain (Sanchez *et al.*, 2005). The application (SIGCH-GIS related to the management of annual crops) offers cartographic and alfanumerical information, thematic maps on agroclimatic variables, as well as information about the plan of productive regionalization of Spain for the application of the EC rules (EC-1251/1999) of the European Commission. There are also regional projects with similar characteristics like SITNA, such as a territorial information system developed by the regional government of Navarra region. SAgMIS is an internet based GIS information system managed by the Environmental Agency of the Republic of Slovenia, which includes in situ information on crop water balance and irrigation forecast. Maps of water balance for different areas in Slovenia and time scales can be obtained upon request (Sušnik and Kurnik, 2004).

5. Conclusions and recommendations

The COST734 survey enabled probably the most complete overview on the big number of models and indices currently used in Europe for different operational and scientific applications in agriculture. Due to their simplicity, agroclimatological indices are considered as valuable tools for research and operational applications. Particularly, the possibility of using wide temporal time steps (daily, weekly, monthly) makes these indices suitable for application with historical climatic series. There are few cases (e.g. drought indices, grapevine quality index), where indices also include thresholds describing the consequences of obtained values and recommended interventions needed to manage and to protect crops from climate related impacts. The results of the questionnaires pointed out their large use at European level for many purposes, spatial (regional, national) and temporal (nowcasting, past-casting, forecasting) scales. Especially for indices, it seems also to be clear, that there is a need of standardization and harmonization of applications in Europe in order to allow inter-comparison and to improve the interpretation of results.

The more complex approaches, namely process oriented models, are still very limited in operational applications (especially crop yield models), except for the more simple models (e.g. crop water balance models focusing on irrigation scheduling rather than on yield estimates), or widely applied models for pest and disease management. In research, however, process oriented crop models play a very important role in the assessment of global and climate change impacts on agriculture. A majority of these studies were carried out on a larger scale, neglecting the necessarily finer spatial resolution to be of relevance for local adaptation recommendations for farmers. One of the main difficulties for the spatial application of process oriented crop models in a high spatial resolution is the lack of model input data (not available, high costs, expensive data management, etc.). On the other hand, new methods are currently being developed to overcome these problems by using GIS and integrating remote sensing data. Only very few examples exist for operational crop yield forecasting which integrate all these available tools, and they are only used at the expert level.

Beside the effects of climate change on crop productivity, which are the dominating studies till now, it is recommended that the modeling community should also have a closer look on other aspects such as soil fertility, and environmental issues like groundwater recharge and water quality, soil carbon stocks, erosion, trace gas emissions, etc., in the future. Integrated modeling approaches are thus required and should reflect the most relevant interactions in the soil-crop-atmosphere system. Furthermore, we should also try to combine our modeling of climate change impacts with ideas and experiences of sustainable production.

6. Phenological monitoring using indices and models for evaluating crop responses to climate change and variability

6.1 Introduction

All species have responded to the changing climate throughout their evolutionary history. Nevertheless, the past climatic changes are commonly attributed to a relatively slow gradual process, which enabled a smooth process of biological adapting or replacement. There is now a concern on how different species and ecosystems will respond to the recent and rapid rate in climate development. Species of a particular ecosystem are adapted to the long prevailing climatic conditions and are quite vulnerable even to modest changes of the climate. Not only the warming trend combined with the spatially variable changes in precipitation influence the wild growing plants, but they also have already affected managed ecosystems (Easterling *et al.*, 2007).

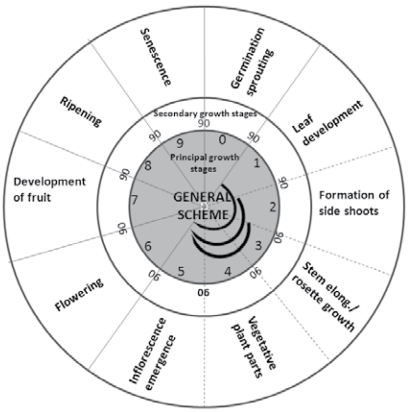
Increasing temperature and further changes in climate have already affected both physical and biological systems in all continents. Examples of observed changes include the increase of vegetation cycles and altitudinal shifts. These observations come from the monitoring of phenological manifestation of different plant species. Thus, phenology serves as a life cycle indicator reflecting the impacts of the weather on vegetation. The main driver of phenological development is temperature. A strong relation between plant development and temperature was firstly mentioned by Reaumur already in 1735 (Reaumur, 1735). Since then, this observation has formed the basis for any phenological model. Clear response of life cycle events to environmental changes have caused a strong increase of interest in phenological processes as an indicator for climate change impacts. However, the timing of phenological events is also of importance for agricultural crop management, as phenological development can be influenced e.g. by the sowing date (Porter *et al.*, 1987). Phenological data also play a key role for crop model calibration and validation.

Phenological data are of different kind. The most important precondition to get usable and comparable data is thus an exact definition of the phenological phases. There are several phenological scales in use but in recent decade the use of so called extended BBCH code (Growth stages of plants, BBCH Monograph), (Meier, 1997) is recommended. Based on Zadoks` (Zadok *et al.*, 1974) cereal code it is a system for a uniform coding of phenological similar growth stages of all mono- and dicotyledonous plant species.

The BBCH code (Fig. 3) uses a general scale so that it can be applied also to those plants for which no special scale is available. Clear and easily recognized external morphological characteristics are used to describe main (longer-lasting) phenological development stages, called principal growth stages. The secondary growth stages define a short step of development.

Agroclimatic indices are used to quantitatively define the available resources for the different agricultural needs. These needs are, for example, determined by physiological processes of the plants. The major drivers of the plant development are temperature and the availability of photosynteticaly active radiation while water availability rather limits plant growth. Indices characterizing the plant development can bring indirect information about the impact of climate variability and also about the conditions for further plant growing.

Fig. 3. Scheme of the BBCH code (Meier, 1997).



Principal Growth Stages	Description
0	Germination / sprouting / bud development
1	Leaf development (main shoot)
2	Formation of side shoots / tillering
3	Stem elongation or rosette growth / shoot development (main shoot)
4	Development of harvestable vegetative plant parts or vegetatively propagated organs / booting (main shoot)
5	Inflorescence emergence (main shoot) / Heading
6	Flowering (main shoot)
7	Development of fruit
8	Ripening or maturity of fruit and seed
9	Senescence beginning of dormancy

All basic principles of phenological indices and models are based on the tight relation between temperature, plant development and growth. Other factors like photoperiod and vernalization affect plant development on a smaller scale and their impact is not as clear as the temperature impact (Craufurd and Wheeler, 2009).

6.2 Indices and models used in phenology

While agrometeorological indices often use phenological parameters to determine the conditions for plant growth, deterministic crop models are fully based on the plant development modelling. Most frequent use of phenological parameters in agrometeorological practice has been found in Orlandini *et al.* (2008) concerning crop response to weather conditions. Phenological monitoring is done in different ways by using visual observing as well as remote sensing techniques. Monitoring of phenological development of particular crop often requires in situ observation either by the observer himself or by various types of cameras. There are not many services monitoring the response of the crops to the weather regarding the growth and phenological development. Operational phenological networks, which comprise a sufficient number of stations, mainly work in the region of Central Europe and in some Balkan countries. These networks are usually run by the Meteorological services (see Chapter I.3) and are differentiated. Agricultural crops and orchards are monitored in the whole vegetation cycle and report also on the occurrence of the pests and diseases and yields.

Traditional phenological methods which record the occurrences and development of individual species are complemented by the techniques studying the earth from space. This approach resulted in a new field of phenological monitoring that is based on observing the phenology of whole ecosystems and stands of the vegetation on a global scale.

The most successful of these approaches is based on observing the temporal change of a Vegetation Index like Normalized Difference Vegetation Index (NDVI). NDVI is utilizing the fact that the vegetation shows typically low reflection in the red (the related wave lengths are mostly absorbed by growing plants for photosynthesis) and strong reflection in the Near Infrared (Infrared is mostly reflected by plants due to their cellular structure). NDVI shows a strong correlation with the typical green vegetation growth stages (emergence, vigor/growth, maturity and harvest/senescence). Following its evolution through the vegetation cycle enables us to extract useful parameters on the growing season (start of season, end of season, length of growing season, etc.). Other growing season parameters could potentially be extracted, and global maps of any of these growing season parameters could then be constructed.

Satellite sensors usually provide medium spatial resolution but high temporal resolution. Thus, the indices derived from NDVI are essentially suitable at the regional and continental scales. The start of plant development is easily recognized, which enables to state the Start of Season (SOS). Remotely sensed start of the season and spring indices (SI), (Schwartz, 1997) based on the phenological model were used to formulate the Growth Efficiency Index (GEI) at the continental scale (Liang *et al.*, 2008). However, further to the relatively low spatial resolution, the impact of local climate brings considerable deviations at the local scale including the influence of the chilling unit phenomenon. Despite of the fact that different indices derived from the time series of image data showed a considerable progress at continental scale the regional and land cover differences in phenological change show that local driving mechanisms often dominate the effects of the global mechanisms in affecting the phenological profile (McCloy, 2010). However, remotely sensed indices like NOAA Global Vegetation Index (GVI) were not reported to be utilized in operational use in Europe.

The use of the indices and models based on the in situ measurements and observations remains the most efficient monitoring of plant development at the local scale. The plant stage is either directly observed or computed by using a model. Phenological models are usually embedded in the system of process oriented crop growth models (see Chapter I.4). The basic aim of phenological models is to derive the phenological stages from environmental parameters – mostly meteorological parameters.

Since the concept of heat units or thermal time was introduced by Reaumur, different methods of calculating heat units have been used in modeling phenological development of crops. The concept of heat units, measured in growing degree-days (GDD), has considerably improved the description and prediction of phenological events. However, the implementation of different methods of calculation led to different GDD estimates (McMaster and Wilhelm, 1997).

One of the examples of sophisticated methodological development of phenological model calibrated and validated on long-term phenological data and its application to estimate the future conditions is the PhenoClim model (Bartosova *et al.*, 2010) developed at the Institute of Agrosystems and Bioclimatology, Mendel University in Brno, Czech Republic. It is a part of a software package for agroclimatic utilization (Trnka *et al.*, 2009) with four tools (SoilClim, AgriClim, PhenoClim and snow MAUS) and works with the term of effective temperature calculated over a specific threshold for each plant. The methodological approach, calibration and validation of the model are described below.

6.3 PhenoClim – a phenological model for determination of phenological phases

Miroslav Trnka, Lenka Bartošová, Jan Balek, Branislava Lalic

PhenoClim enables detailed analysis of phenological development using meteorological parameters as predictors of phenological stages. It allows:

- to carry out quality control of observed data sets.
- to estimate phenological dates at various experimental sites where only limited observational data are available.
- to estimate effect of future climate conditions on onset and duration of phenological stages.

Six meteorological parameters in daily time steps are required for the analysis as inputs: maximum and minimum air temperature (°C), global solar radiation ($MJ.m^{-2}.day^{-1}$), amount of precipitation (mm), water vapor pressure (hPa) and wind speed ($m.s^{-1}$). In addition various predictors could be used including monthly index data (e.g. North Atlantic Oscillation index).

Phenological data for PhenoClim are required for primary calibration of the phenological model and usually consists of the date of analyzed phenological phase (e.g. first flower) or its duration (e. g. time from the first till full flowering) for each year. Input text file contains either one or two sets of dates (with years and first phenological phase, e.g. first flower) or two consequent phenological phases which are analyzed together (e.g. first flower and full flowering).

Model description:

Each species requires different sum of effective temperatures or degree days (T_S) (Chmielewski *et al.*, 2005) above certain threshold (T_{base}) that might be also species/cultivar specific. As the values of T_S and T_{base} are only rarely available, one of the primary functions of PhenoClim is to allow calculation of both parameters. In order to achieve this, observed data of particular phenological stage and high quality weather inputs are required.

Calculation of T_S has to be initially specified by the user either by using:

1. given date in phenological data file (when the sums between two phenological phases are calculated),
2. arbitrary date set in the interface (e.g. January 20, March 1, etc.),
3. calculated according to the conditions in the given year e.g. based on combination (or just one indicator) of mean, maximum and minimum temperature and snow cover presence/absence.

The model user has also to select which of available daily temperatures from input file (mean, maximum and minimum temperature) will be used to derive T_S. PhenoClim also allows to calculate the sum of global radiation and sum of precipitation (number of rainy days respectively) and to use them as predictors of phenological stage onset or duration.

As neither T_S nor T_{base} are a priori known the user has to define the range of potential T_{base}. Then PhenoClim calculates values of T_S for each T_{base} and compares it with the observed data. Usually the range of baseline values for each predictor is set by the user as well as the incremental step for testing.

Model calibration and validation:

Two independent data sets of phenological and meteorological data should be used for model calibration and validation. The user may select e.g. even years for calibration and odd years for verification or choose different periods (e.g. 1961-1981 for calibration and 1982-2009 for validation).

T_S and thresholds are determined for each year in the calibration dataset and then mean T_S is calculated for all tested T_{base} values. Using this mean T_S and T_{base} (value/values) the phenological stage onset/duration is estimated at first for calibration years. Obviously there is never 100% fit between observed and estimated phenological data, since the phenology depends on a complex of factors that cannot be fully covered by the

PhenoClim procedure. However, PhenoClim enables based on the calibration dataset, to select the most likely combination of T_S and T_{base} for any particular species. This is done through a set of statistical variables namely mean bias error (MBE), root mean square error (RMSE) and coefficient of determination (R^2).

RMSE is defined as an indicator of both random and systematic errors and MBE is an indicator of systematic errors (Davies and McKay, 1989), which are both determined in days. The same set of statistical variables is calculated for the validation dataset and the model user is able to select the best predictor(s) of a given phenophase and its values of effective T_S and T_{base}. These values can be then utilized for quality control or monitoring of ongoing phenological stages or for estimation of the onset of phenophases under expected climate conditions.

Demonstration, example of PhenoClim:

Common hawthorn (Crataegus monogyna) first flower and full flowering data from 1961-2009 with daily meteorological data from experimental site Vranovice (170 m a.s.l., 48°56´N, 16°35´E) are used as an example. For hawthorn, the range of base values was set between 0°C and 10°C for mean temperature, 0°C and 20°C for maximum temperature and -5°C and 10°C for minimum temperature with a step of 0.1°C. Start of calculation of temperature sums for hawthorn were determined by mean temperature of 2.5°C, minimum temperature of 0.0°C and maximum temperature of 5.0°C. For hawthorn, the even years from site Vranovice were used as fitting data. Odd years from the same experimental sites were used as verification data.

For hawthorn, the results of estimated parameters across the evaluated range (for weather parameters mean, maximum, minimum temperature, global radiation and precipitation) and the good fit of the model with the verification years (odd years, 1961-2009) are shown in Table 1. The mean temperature is the best predictor (RMSE and MBE reach the lowest values) of hawthorn's phenophases (first flower and full flowering) and of the relationship between observed data and simulated data (calculated using daily mean temperature). Results are shown in Fig. 4.

Using this weather parameter, the onset of phenophases was calculated for two other experimental sites Lednice and Lanžhot (Fig. 5). Chmielewski *et al.* (2005) used a similar phenological model for several species based on data recorded from 1961 to 2000. RMSE values for their model range between 2.7 to 8.2 days and MAE (Mean Absolute Error) range between 1.3 and 6.2 days. The authors mention that MAE is in a range which is common for phenological models even if they are much more sophisticated.

Tab. 1. Values of temperature sums and threshold with statistical variables for Common hawthorn first flower (RMSE=Root Mean Square Error, MBE – Mean Bias Error, R^2=coefficient of determination). For mean, maximum and minimum temperature the range of base values are shown.

Common Hawthorn/first flower					
	Treshold/°C	Sums/°C	RMSE/days	MBE/days	R^2
Mean T_S (0–10°C)	2.60	456.51	2.62	2.04	0.86
	0.00	683.96	3.16	2.63	0.87
	5.00	294.45	3.20	2.38	0.78
	10.00	89.85	4.47	3.29	0.63
Maximum T_S (0–20°C)	4.90	679.12	3.08	2.50	0.86
	5.00	670.73	3.16	2.58	0.85
	10.00	333.28	3.76	2.67	0.74
	0.00	1151.37	4.18	3.42	0.84
Minimum T_S (-5–10°C)	0.60	249.74	4.07	3.00	0.65
	0.00	287.44	4.17	3.25	0.64
	5.00	72.50	5.07	3.83	0.48
	10.00	6.75	5.56	4.29	0.47
Sums of global radiation ($MJ.m^{-2}.d^{-1}$)	0.90	987.42	5.67	4.46	0.40
	0.00	1091.23	5.76	4.42	0.42
	5.00	572.35	6.26	4.96	0.29
	10.00	269.54	6.39	4.67	0.31
Sums of precipitation (mm)	0.00	47.38	18.94	16.08	0.10
	10.00	2.21	31.56	23.71	0.02
	5.00	6.75	32.11	24.92	0.01

In a next step the validated model is applied for climate change scenarios. The onset of phenophases of Common Hawthorn under future climate conditions (2050 and 2100) was calculated using Global Circulation Models (GCMs) NCAR, HadCM and ECHAM (Fig. 6). Simulations for Emission Scenarios (SRES) A1b were used for the experimental site Lednice for high climate sensitivity. Results are in accordance with the recent changes in plant development and show expressive shifting of phenophases (first flower and full flowering) to earlier dates by 18 days in 2050 and by 44 days in 2100.

According to findings in the last decade, the predicted climatic changes will cause changes in development of many crops. This will influence the vegetation cycle and consequently also the farming practices and planning. Generally, both the start and the end of the vegetation season will shift to earlier/later dates respectively. This shift will strongly depend

Fig. 4. Comparison of observed and simulated phenological dates (by PhenoClim model) for site Vranovice using data from 1961 to 2009.

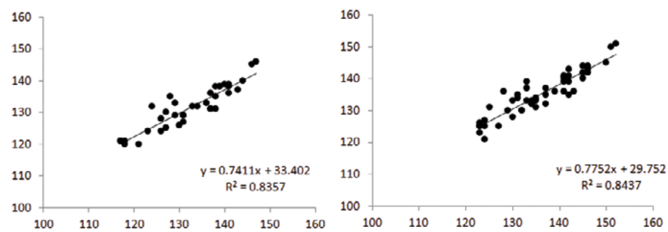


Fig. 5. Onset of simulated (experimental sites Vranovice, Lednice, Lanžhot) and observed (experimental site Vranovice) phenological phases first flower and full flowering of Common Hawthorn. Central bars indicate the range of mean std with average value being depicted by vertical line. The long bars indicate minimum and maximum values.

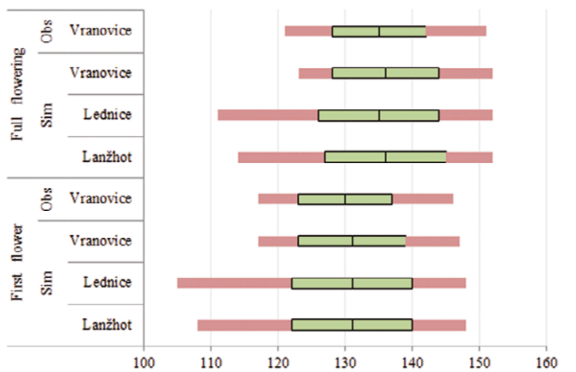
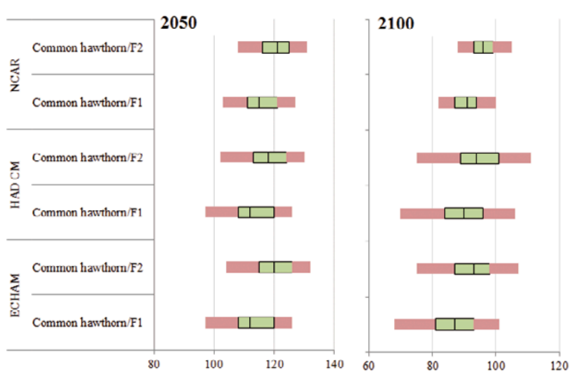


Fig. 6. Onset of phenophases first flower and full flowering of common hawthorn in 2050 and 2100; F1=phenophase “first flower”, F2=phenophase “full flowering”. Central bars indicate 25th and 75th percentile with median; long bars indicate 5th and 95th percentile.



on the local climatic conditions and on the particular plant and variety. Also differences could appear in different climatic regions. Table 2 shows an example of such a calculation using a process oriented crop model. Using the outputs of climate models the phenological stages of the particular plant (wheat) under the relevant climate scenarios were simulated.

Tab. 2. Day of year of anthesis (A) and maturity (M) for winter wheat (variety ANASTASIA) for 2040 and 2080 calculated by SIRIUS wheat model based on the outputs of climate scenarios assimilated from HadCM3 (H), ECHAM5 (M)and NCAR-PCM (N) climate models using the SRES-A2 scenario for greenhouse gas emissions (Lalic and Mihailovic, 2009).

	H2040		H2080		M2040		M2080		N2040		N2080	
	A	M	A	M	A	M	A	M	A	M	A	M
Banatski Karlovac	128,2	168,4	119,1	160,0	126,2	167,6	114,2	157,8	127,0	168,1	116,7	159,5
Kikinda	130,3	170,4	122,2	162,3	128,5	169,8	118,3	160,9	129,2	170,3	119,0	161,4
Subotica (Palic)	133,2	174,9	125,1	166,4	131,8	174,1	121,1	164,7	132,0	174,9	122,3	165,1
Novi Sad (Rimski Sancevi)	131,3	172,2	122,7	164,0	129,1	171,4	117,8	161,5	130,6	172,3	119,5	162,8
Sombor	130,2	170,7	122,1	162,8	128,5	170,2	117,3	160,4	129,4	170,6	118,9	161,4
Zrenjanin	128,5	169,1	119,6	160,4	126,6	168,5	115,1	158,4	127,4	168,9	116,3	159,3

Adaptation strategies in crop production are often determined by crop timing and related changes under climate scenarios. Therefore, monitoring, calculation and prediction of phenology will be a decisive task in applied agrometeorology in the future. Nevertheless, there are some more complex phenomena beyond the influence of temperature on the development of plants such as wintering or the length of the dormancy period.

6.4 Analysis of the Relationships between Climate and Grapevine Phenology in Europe

The aim of this COST734 study was first to give a concrete example of the analysis of relationships between climatic variables and the grapevine phenological stages (flowering and harvest) in some European regions, and secondly to verify the potential of climatic variables and indices as predictors of phenological development.

The meteorological variables used for this work were air temperature and the NAO index. Air temperature was derived from reanalysis, which were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado USA (http://www.cdc.noaa.gov/) and processed by the NCEP/NCAR Reanalysis Project. The NAO index is calculated from the difference of normalized sea level pressure between the Azores and Iceland. In particular, an extended version of the index (Jones NAO index), obtained for the winter half of the year by using a station in the south-western part of the Iberian Peninsula, was used (http://www.cru.uea.ac.uk/).

The dates of grapevine's phenological stages were provided by the main European viticultural regions thanks to the COST734 members. Flowering and harvest data were collected for different varieties, periods and localities: in Croatia (1961-2009) for flowering, in France (1945-2005) and Germany (1979-2008) and in Italy (1970-2006) for harvest, in Austria (1965-2008), Slovakia (1990-2008), and Ukraine (1959-2008) for both flowering and harvest.

Phenological data sets were statistically analyzed to find relationships with meteorological parameters. These were the main points of analysis:

- Analysis of the temporal trends of flowering and harvest stages according to varieties and localities;
- Qualitative analysis of the impact of air temperature on phenological stages;
- Correlation between NAO index and phenological stages.

Results

All temporal trends have a negative slope and are statistically significant – examples are shown in Figures 7 and 8. Anticipations (decadal change) were found for both harvest dates in Germany (-6.7 days), Austria (-3.5 days) and France (-3.3 and -7.3 days) (Table 3) and for flowering date in Italy (-4.4 days), Croatia (~ -2.6 days), Austria (-3.6 days) and Ukraine (-5.6 days) (Table 4).

In 2003, the year with the highest recorded air temperature and a persistent heat wave, the results show the highest degree of anticipation for all phenological stages under study. Strong evidence of the impact of temperature on grapevine development was found using data from France (Table 3), where the summer heat wave was most severe in Europe.

Positive statistical relations were found between air temperature and phenological stages. For an increase of 1 °C of air temperature, an anticipation between 3 to 10 days for flowering or between 3 to 11 days for harvest, was calculated (Table 5).

Statistical relations were calculated between NAO index and grapevine's phenological phases in the different countries (Table 6). In particular, significant impacts are detected only for Mediterranean areas such as in France, Italy (Fig. 9) and Croatia.

Fig. 7. Temporal trend of flowering in Austria (Riesling variety).

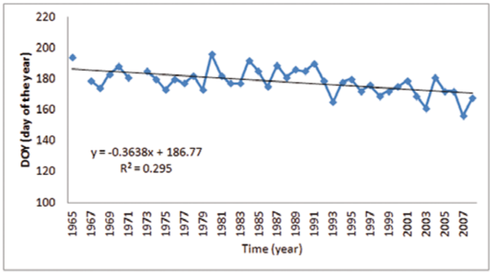
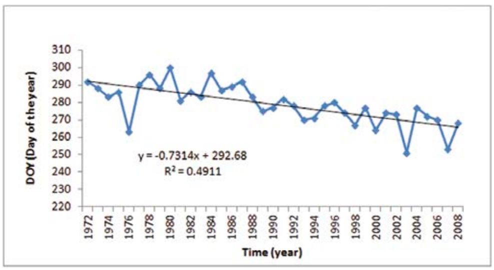


Fig. 8. Temporal trend of harvest in Germany (Müller-Thurgau variety).



Tab. 3. Harvest temporal trend (N.S.=no significant; ★=$P \leq 0.05$; ★★★=$P \leq 0.001$).

Country	Site	Grapevine variety	+/- Days x 10 years	p level
Italy	Montepulciano	Sangiovese	-0.3	N.S.
Germany	Bad Kreuznach	Riesling	-5.4	N.S.
	Weinsberg	Riesling	-9.5	N.S.
		Müller-Thurgau	-6.7	★★★
		Silvaner	-0.5	N.S.
		Lemberger	-0.4	★
Austria	Krems	Riesling	-3.5	★★★
Ukraine	Sevastopoli	Pinot gris180	1.1	N.S.
		Muscat white50	-4.5	N.S.
		Muskat white230	-0.8	N.S.
France	Chateauneuf	Grenache	-3.3	★★★
	Champagne	Pinot noir	-1	N.S.
	Alsace	Riesling	-7.3	★★★
	St. Emillon	Merlot	-1.5	★
Slovakia	Dolne Plachtince	Burgundy white	-1.8	N.S.
		Blue Frenkei	-7.3	N.S.
		Müller - Thurgau	-3.8	N.S.
		Blue Portugal	1	N.S.

Tab. 4. Flowering temporal trend (N.S.=no significant; *=$P \leq 0.05$; **=$P \leq 0.01$; ***=$P \leq 0.001$).

Country	Site	Grapevine variety	+/- Days x 10 years	p level
Italy	Montepulciano	Sangiovese	-4.4	**
Croatia	Hvar	Blatina	-2.9	***
		Plavac mali	-2.2	**
		Trbljan, Kuč	-2.6	**
	Daruvar	Chasselas dore	-2.9	***
		Riesling Italico	-2.8	***
Austria	Krems	Riesling	-3.6	***
Ukraine	Sevastopoli	Pinot gris180	-5.6	***
		Muskat white230	-0.3	N.S.
Slovakia	Dolne Plachtince	Burgundy white	-1.4	N.S.
		Blue Frenkei	-5.6	N.S.
		Müller - Thurgau	-4.7	N.S.
		Blue Portugal	-4.2	N.S.

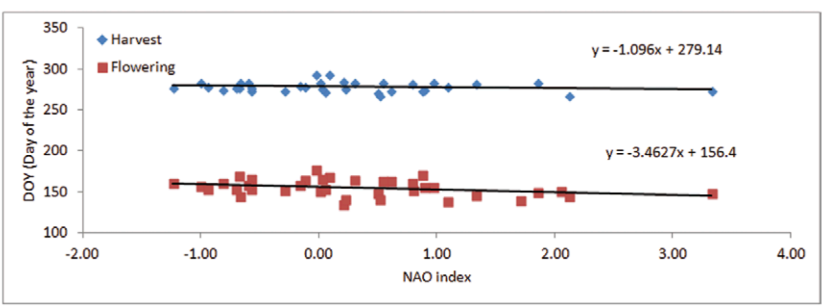
Tab. 5. Effect of air temperature on grapevine phenology.

Country	Site	Grapevine Variety	Flowering (days x 1°C)	Harvest (days x 1°C)
France	Chateauneuf	Grenache		-5.97
	Champagne	Pinot noir		-8.5
	Alsace	Riesling		-10.96
	St. Emillon	Merlot		-7.11
Italy	Montepulciano	Sangiovese	-9.74	-3.09
Croatia	Hvar	Blatinia	-3.94	
		Plavac mali	-4.37	
		Trbljan, Kuč	-6.05	
	Daruvar	Chasselas dore	-8.06	
		Riesling Italico	-7.72	
Austria	Krems	Riesling	-6.02	-4.01
Germany	Bad Kreuznach	Riesling		-3.03
	Weinsberg	Riesling		-2.21
		Müller-Thurgau		-7.15
		Silvaner		-1.32
		Lemberger		-6.19
Slovakia	Dolne Plachtince	Burgundy white	-6.42	-3.36
		Blue Frenkei	-5.34	0.96
		Müller - Thurgau	-5.43	-5.44
		Blue Portugal	-5.72	-5.15
Ukraine	Sevastopoli	Pinot gris180	-1.93	-5.26
		Muskat white230	-3.09	-4.22

Tab. 6. Impact of NAO index on phenological stage.

Country	Latitude	Longitude	Flowering (days x unit NAO)	Harvest (days x unit NAO)
France	44.88	0.15		-4.1
	48.78	4.42		-3.12
	44.05	4.82		-2.69
	48.07	7.37		-3.2
Germany	49.83	7.85		-2.69
	49.13	9.28		1.37
	49.13	9.28		-1.27
	49.13	9.28		-0.33
	49.13	9.28		-0.45
Italy	43.08	11.77	-3.46	-1.09
Austria	48.4	15.6	-0.18	-0.27
Croatia	43.1	16.27	-2.03	
	43.1	16.27	-1.27	
	43.1	16.27	-2.64	
	45.36	17.14	-1.17	
	45.36	17.14	-2.46	
Slovakia	48.2	19.3	-1.43	-1.75
	48.2	19.3	0.68	2.79
	48.2	19.3	0.29	-2.95
	48.2	19.3	0.25	-1.43
Ukraine	44.5	34.22	0.69	-3.85
	44.5	34.22	-0.39	0.51

Fig. 9. Linear regression between NAO index and phenologiocal stages in Italy.



Conclusions and recommendations

The results found in this study showed the key role that climate change has on phenological stages of grapevine. The meteorological variability influences the stages of development of grapevine with consequent impact on flowering and harvest. Advance of grapevine phenological phases (flowering and harvest) is strongly affected by the temperature increase and modulated by geo-climatic area and variety characteristics. The use of reanalysis temperature and NAO index data to analyse phenological temporal trends appeared highly effective.

Acknowledgement

Further to COST734 members this study was also supported by data from Ukraine provided by Svetlana Korsakova from Nikitsij Botanical Garden, Ukraina /korsakova@i.ua/.

6.5 Monitoring the Influence of Dormancy on Phenology of Fruit Trees

Pavol Nejedlik

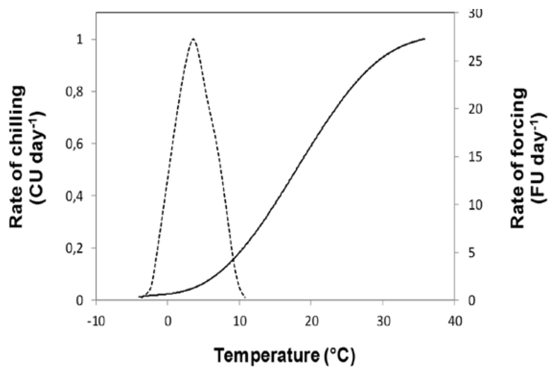
As indicated above, the air temperature is the most important environmental factor regulating the timing of vegetation cycle. The first step of the start of the seasonal growth of trees is leaf and flower bud burst. While the winter may look like a time of inactivity many things are actually going on with the trees and also some shrubs particularly with regard to the development of buds and flowers for the coming season. Once buds have entered dormancy, they will be tolerant to temperatures much below freezing and will not grow in response to mid-winter warm spells. These buds remain dormant until they have accumulated sufficient amount of rest time during cold weather, which can be expressed in so called chilling units (CU). Prevailing theory explains that the air temperature regulates the timing of bud burst in two ways. After growth cessation in late summer or early autumn, the buds are in a state of rest, i.e., their ontogenetic development toward bud burst stops or is slowed by the physiological conditions in the bud. It occurs after the physiological development of buds is overcome by prolonged exposure to chilling (Fig. 10).

There are two major hypotheses on how the chilling requirement (Tab. 7, p. 26) is connected to the onset of bud development. So called sequential approach says the chilling requirement must be fully met before bud development is enabled. In the parallel approach accumulated chilling affects the amount of forcing required for bud burst or the rate at which forcing accumulates at a given temperature, and the chilling and forcing phases may overlap. The coldness of the winter has a strong influence on many wild trees (Sarvas, 1974) and horticultural crops regarding quantity and quality of buds and flowers (Linsley-Nokes *et al.*, 1995; Niederholzer, 2009), as well as on the timing of flowering. Winter chilling is the term used to refer to how effective the coldness of winter has been. Chilling units are most meaningfully described and measured using an hourly time scale. Chill hours below a threshold are one of the most common methods for calculating chill.

Tab. 7. Chill unit requirements of orchards.

Varieties of stone fruit and chill units required	
Variety	Chill units required
"Snow Zee" Nectarine	900
"Early O,Henry" Peach	900
"Maycrest" Peach	600
Plum	400
Apple	300-400

Fig. 10. The rate of chilling and rate of forcing as a function of temperature.



Rate of accummulation of chilling unite (CU, dotted line) and forcing units (FU, solid line) as functions of temperature according to Sarvas (1972, 1974)

There is a certain number of simple models calculating the CU:

Simply Under Model – one hour below 6°C = 1 CU
45°F Model – one hour below 45°F = 1 CU
PCU Model – uses the correlation in between coldest month and CU accumulated

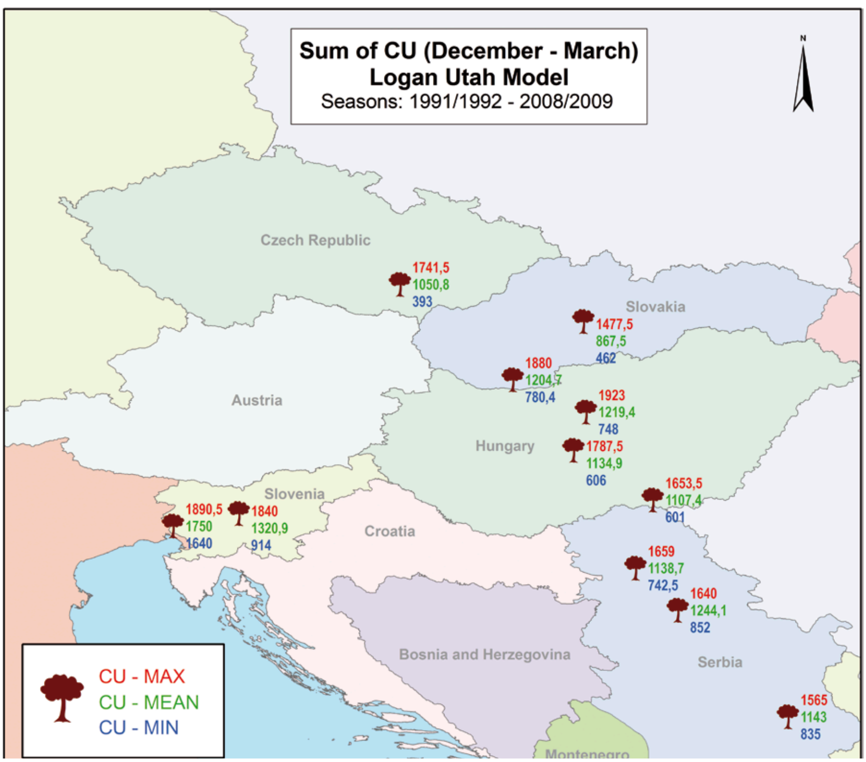
The most complex model is the (Logan) Utah Model:

Assumption: one_hour at 6° C gives the value of 1 chill unit (CU)
1 hour below 1.4° C = 0.0 chill unit
1 hour between 1.5 – 2.4° C = 0.5 chill units (CU)

1 hour between 2.5 – 9.1^{o} C = 1.0 chill units (CU)
1 hour between 9.2 – 12.4^{o} C = 0.5 chill units (CU)
1 hour between 12.5 – 15.9^{o} C = 0.0 chill units (CU)
1 hour between 16.0 – 18.0^{o} C = -0.5 chill units (CU)
1 hour over 18.0^{o} C = -1.0 chill units (CU)
(Richardson, Seeley, Walker – 2003)

There are some criteria suggested for the particular fruit trees used to determine how many CUs bring favourable conditions for the start and healthy development of the trees after the winter dormancy. An insufficient number of CU may lead to delayed foliation and in fruit trees also to reduced fruit set and increased buttoning and reduced quality of fruits (Sheard and KwaZulu-Natal, 2002).

Fig. 11. The number of chilling units calculated in South–East of Central Europe and North-West of Balkan, (Nejedlik and Tekusova, 2010).



In general, Europe does not belong to the regions with potential insufficient number of chilling units. In a case study, a calculation of the chilling units at selected stations in the area of South-East of Central

Europe and North-West of Balkan by using the Logan-Utah model is shown in Fig. 11. The average sum of CU does not bring any harm to the stone and pome fruits during dormancy. However, extreme values bring a certain insufficiency of CU. CU sums rather depend on the local climate defining the duration of the interval with a certain range of temperatures than on the mean temperature set by the elevation and regional climate.

The results show that extreme values bring the CU sums below the optimal level even in low elevations. The accumulated chilling units do not fully correspond with the severity of the winter season. The comparison of the number of accumulated chilling units with the onset of the first phonological phase in spring did not show any close correlation. However, the latest start of the bud burst in many localities happened mostly in the years with quite low number of chilling units. Nevertheless, other factors could play also a role to set favorable conditions for the trees to start the seasonal growth.

Conclusions and recommendations

Agrometeorology appears as an interdisciplinary science involving both physical and biological parts of the processes managing the development of the nature in its vegetation cycle. The indices and models dealing with plant development and growth play an important role in monitoring and prediction of the particular stages of the vegetation cycle. On top of their farming management applications, they also bring information for the market and in some ways can also serve as indicators of food security measures. Under European conditions, quality of the agricultural products and the level of effectivity of the production are both in the focus of the managing systems. The concept of the relation of the temperature and plant development formulated by Reamur has actually formed the first hint for agrometeorological modeling and it has been used so far in almost all agrometeorological models dealing with the plant development. Thus, phenological indices and in a way also simple models appeared quite soon. The dominant agrometeorological model systems concentrate mostly on crop productivity by using phenological concept of degree days. As it appears, further environmental components also influence plant development and plant growth at the level of the whole ecosystems, which requires rather the use of integrated model systems.

Climate change issues have brought a new point to the monitoring and modeling plant and animal development, while using the phenology as an indicator of ongoing changes. Long term phenological data sets are now used to describe the phenological respond to climate change of both wild and cultivated plants. An important progress in phenological monitoring is the formulation of the decadic code /BBCH/ widely accepted in the observing methodologies, which brings the opportunity either to directly observe or at least to express the observed data with a clearly defined unified method. This opens the possibility to use the observed data at both regional and global scales.

7. Crop model sensitivities to climatic variability towards a better yield assessment

Josef Eitzinger, Branislava Lalic

7.1 Introduction

The potential impacts of climate change on agricultural crop production are manifold and complex in general, and contain many uncertainties. Process oriented simulation models (also called mechanistic or dynamical models) are frequently used to assess the complex interactions of the soil-crop-atmosphere system at different scales. However, they only represent a simplification of the different involved processes and rely on defined boundary conditions. Therefore, simulation studies are limited in the validity of their results. In agriculture mostly specific aspects such as crop yields or yield risks under defined boundary conditions such as various climate scenarios, land use, and management scenarios were investigated using crop simulation models (e.g. Alexandrov *et al.*, 2002; Audsley *et al.*, 2006; Downing *et al.*, 2000; Eitzinger *et al.*, 2003; Fuhrer, 2007; Kersebaum *et al.*, 2005; Olesen and Bindi, 2004; Semenov and Porter, 1995; Parry, 2000; Wolf and Van Diepen, 1995).

Sources of uncertainties can also be detected at all scales of model application, including uncertainties based on a) model representation of involved processes as well as on b) model inputs (e.g. Trnka et al, 2005; Nonhebel, 1993). An example for the first type of uncertainties at the crop production level is the simulation of the crop water balance and root water uptake within the soil profile. Uncertainties in crop model inputs can be based on measurement errors or uncertain inputs based on other model outputs such as climate change scenarios from global climate models. Basically, model application is always a compromise between model simplification (uncertainty in simulated results increases with increasing simplification of simulated processes) and input data demand (in more complex models uncertainty of simulated results increases because of increasing number of input parameters, which are not always available or have a high degree of uncertainty in the data itself).

Many uncertainties in general are related to the scaling problem such as significant differences between the model inputs and their regionalization at the farmers field level such as soil input data from a low resolution soil map or weather input data from distant stations or from General Circulation Models (GCM's) (e.g. Trnka *et al.*, 2004). Another problem results from the fact that in many cases only the change in the mean weather parameters (e.g. of temperature and precipitation) are considered in climate scenarios used in impact simulation models, neglecting any potential change in climate variability (e.g. Olesen *et al.*, 2007; Torriani *et al.*, 2007; Luo *et al.*, 2010). Also many extreme weather events such as hail, which can have additional negative impacts on crop yields, are not directly represented by modeled climate scenarios. Regional climate scenarios (depending on the applied downscaling method) can considerably differ from GCM's on a regional basis and usually represent local conditions much better (including changes in climate variability or seasonal variations of temperature and precipitation), but often with a higher degree of uncertainty.

As mentioned above, a significant source of uncertainty results from the applied methods and models, as different crop models can have various sensitivities and levels of representation of certain soil-crop-atmosphere processes (Janssen, 1994; Jamieson *et al.*, 1998; Eitzinger *et al.*, 2004; Eitzinger *et al.*, 2012). These differences origin from the existence of various sources of knowledge of specific processes (which are changing over time and normally leading to an increasing number of model versions), but also from the differences in the implementation of a model driven by the requirements of a planned model application. The planned model application determines also the simulated time step (e.g. hourly, daily, monthly) and the model design for a certain spatial scale (e.g. single plant, field, region). Most crop models are designed for daily time steps and the field level scale which is the most appropriate approach also for climate change impact studies.

A well-known process related problem is, for example, the direct CO_2-effect, which is mostly considered as a fixed value in crop models, since it is mostly used to distinguish C3 from C4 crops. FACE (Free Air Carbon Experiments) experiments show a more complex picture and strong variability between cultivars and environmental conditions of which many processes are still not known and therefore difficult to simulate (Fuhrer, 2003; Kartschall *et al.*, 1995; Kersebaum *et al.*, 2008; Wolf *et al.*, 2002; Ewert *et al.*, 2002).

The already mentioned simulation of soil and crop water balance is another crucial point in dynamic crop growth models (e.g. Stenitzer *et al.*, 2007; Kroes and Roelsma, 2007). For example, there are different applied approaches for soil water balance simulation, reaching from the simple "cascade" approach (e.g. in DSSAT models) to complex soil water flow simulations based on soil water potentials, including e.g. the Richard's equation (e.g. SWAP model; Kroes and Van Dam, 2003). It means that more simple approaches are not always applicable to any soils (e.g. Stenitzer and Murer, 2003). However, they mostly show acceptable results for crop yield simulation in the more free draining soils (Eitzinger *et al.*, 2003) without significant capillary rise from groundwater tables. Another problem, empeding correct simulation of field and soil-crop water balances, is the difficult parameterization of interception (which usually represents, in agricultural crop stands, about 20% of precipitation in average) and surface runoff, which is determined by infiltration capacity of the soil and surface slope. These parameters can change soil water balance and crop available soil water considerably if not correctly described, and are often a source of deviation to measured soil water contents (beside the problem of site representative precipitation inputs).

Another soil-crop water balance related problem is the still highly empirical simulated process of root growth, which has a strong impact on soil water availability and use. For example, the interactions of root growth with certain soil properties (such as strong inhomogeneities, soil temperature, chemical properties or compacted layers) are mainly not considered as dynamical processes. Several studies compare different crop models in these aspects, e.g. Eitzinger *et al.* (2004) and Wolf *et al.* (1996). It is shown that the representation of root growth can have a strong feedback on simulated soil water contents with soil depth. The models should therefore be well calibrated on this aspect, which is, however, often not possible or can not be carried out easily under various soil conditions. In climate change impact studies for large areas, e.g. the European scale, simplified models or empirical procedures within complex models can be a source of uncertainty, such as applying transfer models for calculating soil water holding capacity (e.g. Gijsman *et al.*, 2002). These aspects are often not considered at all due to lack of data and resources.

Due to the different representations of dynamic processes, crop models (and other ecosystem models) often show different sensitivities to input parameters or different responses, when input parameters, such as weather or climatic conditions, are changing over time. In several studies crop model sensitivities to different model inputs are compared and estimated (Nonhebel, 1993; Dubrovský *et al.*, 2000; Eitzinger *et al.*, 2012). The model sensitivities should, however, reflect crop responses well to avoid biases in simulated model outputs, especially when input parameters vary over time.

7.2 Effects of Climate Extremes on Simulated Winter Wheat Yields in South-Eastern Europe under Changing Climate

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One of the main problems in estimating climate change effects on crops is the identification of limiting factors for crop growth in a specific environment and how their impact may change under changing climate. Previous experiences indicate that simple trend extrapolation of precipitation or temperature for next decades or centuries are not as useful information as, for example, a change in weather extremes or in seasonal weather patterns.

To investigate this problem, a related COST734 study focused on the identification of agroclimatic parameters, which best explain effects of climate change on winter wheat yield variability in the pannonian regions by use of a crop simulation model, considering the impact of soil type, past climate and future climate scenarios.

According to all GCMs, countries in South-Eastern Europe are facing serious climate change impacts. Since "Summer Drying Problem" in South-Eastern Europe is directly related to Pannonian lowland, the Vojvodina region, which is a part of Pannonian lowland situated in Northern Serbia, was chosen as a case study area. The aim of the study is to estimate if and how winter crops such as winter wheat might be affected from the changing climate conditions.

Future climate scenarios were assimilated from HadCM3, ECHAM5 and NCAR-PCM climate models using the SRES-A2 scenario for greenhouse gas (GHG) emission for both 2040 and 2080 integration periods. In order to calibrate and validate the Met&Roll weather generator, 4 -variable weather data series for six main climatic stations in the Vojvodina region were analysed. Grain yield of winter wheat and actual evapotranspiration were calculated using the SIRIUS wheat model.

Results

Table 8 shows the simulated crop yield changes under the applied climate scenarios for different atmospheric CO_2 concentrations and time periods at the considered Vojvodina weather stations, including the direct CO_2 effect on crop yield. The dominating soil type of the region is Phaozem.

Tab. 8. Relative change of simulated winter wheat yield in Vojvodina for 2040 and 2080 in comparison with the base period for the Phaozem soil type (-20-0% blue, 0-20% green, 20-40% light yellow, 40-60% gold yellow, 60-80% orange); (Climate scenarios: H=HadCM3; M=ECHAM5; N=NCAR-PCM); (Weather stations in Vojvodina: BK, KI, PA, RS, SO, ZR).

Phaozem												
2040						2080						
330			707			330			1050			
H	M	N	H	M	N	H	M	N	H	M	N	
-10.0	-8.4	-8.2	6.8	8.4	8.7	-11.2	-7.9	-5.9	39.8	45.7	49.5	BK
-8.22	-7.9	-3.8	5.4	5.2	11.1	-8.32	-5.6	-0.4	27.9	33.3	43.9	KI
-5.0	-6.2	11.4	12.6	11.5	32.7	-7.91	8.7	6.9	45.6	76.8	73.6	PA
-5.6	-4.6	-3.2	12.1	13.3	15.1	-8.8	-7.0	-2.1	45.6	49.0	56.9	RS
-3.7	-3.8	-0.7	14.3	14.3	18.1	-5.8	-3.7	-0.4	48.5	53.2	59.6	SO
-17.0	-16.8	-14.8	-1.4	-1.2	1.3	-19.1	-16.1	-13.6	27.9	33.0	38.1	ZR

The yield simulations in general (also for other soils not shown) mostly show slightly decreasing winter wheat yields during the 2040s and 2080s (up to -20%) if a direct CO_2 effect on crop growth is not considered (no change in atmospheric CO_2 concentration). Interestingly, for the 2080s, no further significant yield decrease is indicated, although there are higher winter temperatures compared to the 2040s. Considering the CO_2 effect (which affects positively photosynthesis and water use efficiency) for both 2040s and 2080s increasing yields are simulated and the increasing yield trend for the 2080s is about doubled compared to the 2040s due to the higher atmospheric CO_2-concentration. The decreasing yield during the 2040s and 2080s without any change in the CO_2-concentration can clearly be dedicated to a shortened growing season. However, it is not clear why there is almost no further decrease in the 2080s compared to the cooler 2040s. Similarly, for the scenarios including the CO_2-effect, the relative yield increase between the 2040s and 2080s is much larger (per ppm CO_2) than the increase between the 2040s and the reference period. Both periods have similar mean climate change signals in respect to the change in temperature, precipitation and atmospheric CO_2 concentration. An explanation could be that the influence of weather extremes, represented in the weather input data of the crop model, are changing in a way that negative impacts on crop yields decrease till the 2080s.

Therefore, in a further step the correlation coefficients between simulated crop yield and agroclimatic indices were calculated using AGRICLIM software (see Chapter II) and standard calculation procedures.

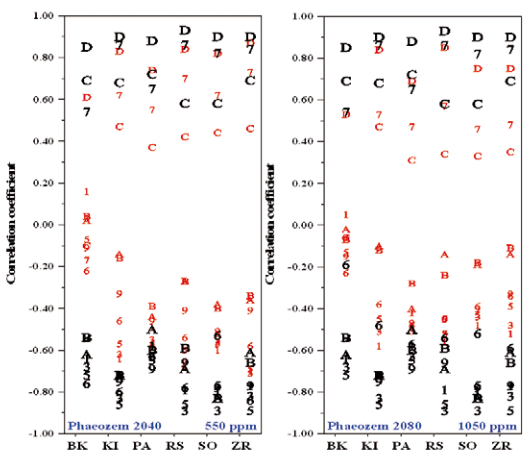
Correlation results for the Vojvodina region (Table 9) show high positive correlations between winter wheat yield and actual evapotranspiration, accumulated precipitation, and ratio between actual and reference evapotranspiration for April-June. Indices referring to negative impacts on yield are number of days with water deficit for April-June and number of summer and tropical days in May and June which can be regarded as indicators of extreme weather events (i.e. heat waves). Also, obtained correlations are the highest for phaozem, fluvisol and gleysol, but the lowest for solonchak, solonetz, leptosol and arenosol soils.

According to obtained results (Tab. 9) for the whole region and all soil types, indices describing number of days with water and temperature stress as well as accumulated precipitation and Eta during the growing season have the highest correlations with the simulated yields. The high positive correlations between yield and ETa, H, and AMJ6 can be notified as well as high negative correlations with AMJ1, AMJ2, AMJ3, AMJ4, TRDV, SUDV, TRDVI and SUDV. The latest indices, referring to negative impacts on yield, are also indicators of extreme weather events. Since impact of extreme weather on crop yield is extremely difficult to quantify, above mentioned indicators can be useful tools in future assessment studies.

Tab. 9. Agroclimatic indices, correlation coefficient to simulated winter wheat yield averaged for all stations and soil types in the Vojvodina region, Serbia under current climatic conditions (reference period 1985-2005). Denotation and symbols refer to these used in Figure 12 (NDWD=No. of days with water deficit).

Agroclimatic index	Denotation used	Symbol on graphs	Average correlation coefficient
Actual evapotranspiration	ETa	D	0.87
Acummulated precipitation during growing season	H	C	0.62
NDWD for April-Jun when ETa/ETr < 0.5	AMJ1	1	-0.68
NDWD for April-Jun when ETa/ETr < 0.4	AMJ2	3	-0.74
NDWD for April-Jun when ETa/ETr < 0.3	AMJ3	5	-0.76
NDWD for April-Jun ETa/ETr < 0.2	AMJ4	6	-0.70
ETa/ETr for April-June	AMJ6	7	0.74
No. of summer days in May	SUDV	9	-0.68
No. of tropical days in June	TRDVI	A	-0.64
Sum of effective temperatures above 10 °C	ET_10	B	- 0.63

Fig. 12. Coefficient of correlation between agroclimatic indices and simulated winter wheat yield for Phaeozem soil calculated with observed weather data for the 1985-2005 period (large symbols) and weather data generated from HadCM3 climate model outputs (small symbols). Denotations of codes are shown in Table 9.



The influence of soil type and climate scenarios differences on these correlations were then analyzed for the Vojvodina region. Figure 12 presents for the Phaeozem soil, the correlations changes between observed weather data (reference period 1985-2005) and the 2040s and 2080s HADCM3 climate change scenario generated weather data at various weather stations in Vojvodina.

In general, correlations are decreasing for the future climate scenarios, showing the lowest values for the 2080s period. These results mean that the negative impacts of the considered indicated weather extremes on crop yield will decrease for the winter wheat growing period. Similar results have been observed for the other soil types and applied climate scenarios (data not shown).

Considering the GCMs used in the study, annual temperatures in the Vojvodina region are expected to raise 1.3°C by 2040 and 2.4°C by 2080. Accumulated temperatures above 0°C during the winter wheat vegetation period in Vojvodina (October-June) are expected to be 8.6-12% higher up to 2040 and 17.8-25.67% higher up to 2080, in comparison to the reference period (1985-2005). Annual precipitation, up to the 2040, is expected to decrease only slightly with a range comprised between 1.9 mm (HadCM3) and 4.3 mm (ECHAM5). Most significant decrease of precipitation is expected during the summer (with the highest monthly precipitation rates during the annual cycle), while accumulated precipitation during the winter wheat vegetation period is expected to remain almost the same.

As a conclusion, the climatic changes seem to improve the winter wheat potential yields in this region, which will also be the case for other winter crops if an additional positive effect of increased CO_2-concentration is found. In our analysis, the negative impact of weather extremes related to heat and drought for winter wheat yields decreases with time, which is probably outbalancing partly (beside the direct CO_2-effect) the negative effect of a shortened growing period on biomass accumulation. On the other hand an earlier harvest in spring reduces the number and severitiy of heat waves on spring crops.

However, for summer crops this picture could be quite reversed due to the significant summer drying effect in these scenarios, where drought and heat related negative impacts could have a dominating effect on crop yields.

7.3 Crop model sensitivities to weather extremes and related uncertainties

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A crop model comparison on model sensitivity was carried out during the COST734 action, related to the influence of drought and heat episodes during sensitive crop stages for winter wheat and maize on simulated crop yield (Eitzinger *et al.*, 2012). Model input data used in this study represent two sites in Austria with different climate and soil conditions. Furthermore, 2 years with contrasting weather conditions (2003 and 2004) were considered for the sensitivity analysis for both winter wheat and maize growing periods. Additional scenarios modifing temperature, precipitation (during crop sensitive stages) and soil physical properties (reflecting impacts of different soil cultivations) were applied.

Figures 13 and 14 show the result for winter wheat and maize for the year 2003 with a significant drought and heat wave from May-August at the site located in an Austrian semi-arid region (Marchfeld).

Significicant differences between the considered crop models can be detected in the final simulated yields in case of drought stress during summer (shown for the case of maize), whereas the differences in the model sensitivity are much smaller in case of the impact of extreme temperatures. This supports the assumption that the simulation of soil water content and crop drought stress is still a main factor for uncertainties in crop simulation models.

In case of winter wheat (Fig. 14) the response to a change in extreme temperatures is similar (but less pronounced) with the respond to skipped precipitation during flowering, because less water stress occurred during the winter wheat flowering period. A much higher relative yield depression with respond to skipped precipitation was found with maize, where the flowering period occurred during the drought period (in June), later in the year. However, significant differences in simulated relative yield response are obvious between the models. The temperature differences for winter wheat were also larger than for maize (Fig. 13), which is probably because the temperatures did not reach the critical limits set for maize in all models.

Models can behave very differently regarding the simulated yield response, especially when weather extremes (such as drought) occur, even within relatively short periods (2 weeks in our study). The reasons for this behaviour are manifold. It could be due to a weak representativeness of simulated growth processes or soil water content or to a difference in model parameterization (e.g. critical limits to drought or heat stress for crop growth processes).

The effect of soil characteristics changes (bulk density) due to soil cultivation on these simulated differences and another simulation for a year with different weather conditions were also investigated and carried out. The model sensitivity to these applied changes for certain scenarios with drought effects are shown in Figures 15 and 16.

Fig. 13. Simulated yield response of maize to drought and heat conditions during flowering, simulated from crop models at a semi-arid site in Marchfeld (Austria) under plough cultivation in 2003 (Text in the columns indicate the applied changes of weather parameters during a 2 week period of crop flowering, compared to the real weather data: noP=no Precipitation, T=Increase in daily maximum and/or minimum temperatures).

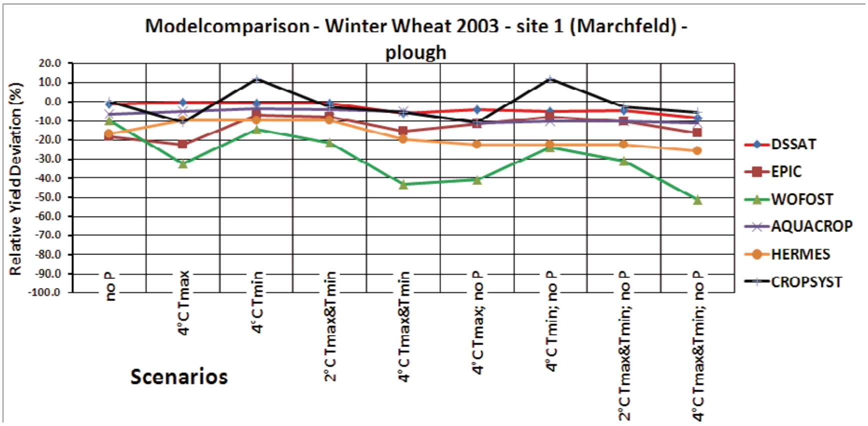


Fig. 14. Simulated yield response of winter wheat for drought and heat conditions during flowering, simulated from crop models at a semi-arid site in Marchfeld (Austria) with plough cultivation in 2003 (Text in the columns indicate the applied changes of weather parameters during a 2 week period of crop flowering, compared to the real weather data: noP=no Precipitation, T=Increase in daily maximum and/or minimum temperatures).

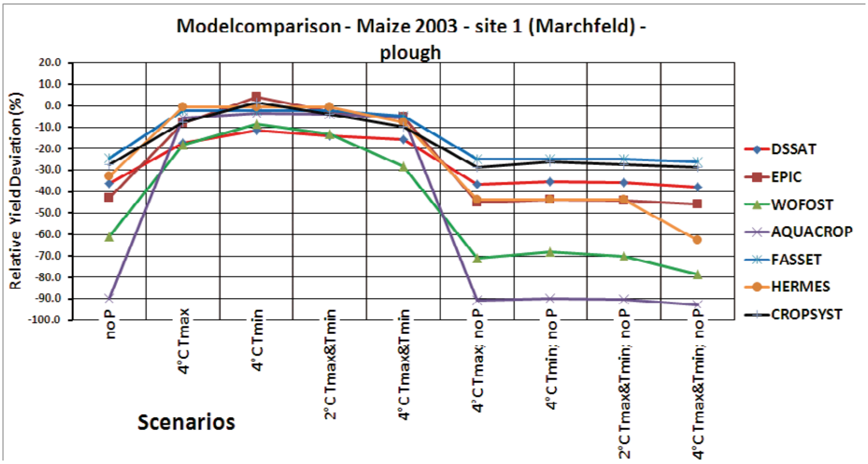


Fig. 15. Response scenariois simulated winter wheat yield by various crop models at a semi-arid site in Marchfeld (Austria) in 2003 in respect to different soil cultivation. The applied scenario is skipped precipitation during the 2 weeks flowering period for winter wheat.

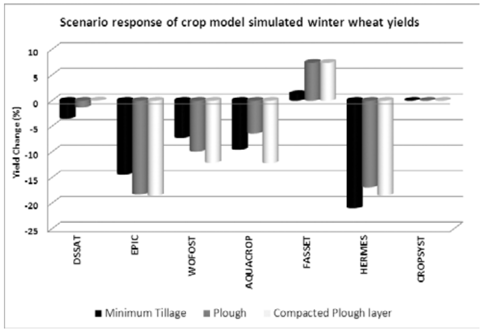
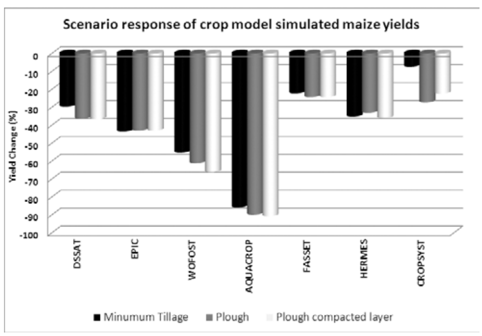


Fig. 16. Response in simulated maize yield by various crop models at a semi-arid site in Marchfeld (Austria) in 2003 in respect to different soil cultivation. The applied scenario is skipped precipitation during the 2 weeks flowering period for maize.



In some cases, crop models react differently to the effects of potential soil cultivation effects. In case of winter wheat, there is no uniform reaction between the models. Except for one, all models show a general yield decrease for the scenario with skipped precipitation during flowering, however, with no uniform response to the applied soil cultivation variants.

In the case of maize (Fig. 16), models behave uniformly (yield decrease on the applied scenario with skipped precipitation during flowering) probably because of a more severe drought stress. The response to the type of soil cultivation is also quite uniform. In most cases minimum soil cultivation shows the lowest yield depressions due to a better soil water storage capacity. However the range of yield depression still differs significantly between the models.

On one hand, it can be concluded that crop models can behave in a very different manner in yield decrease simulation due to water shortage, while the impact of extreme temperatures is much lower under the local climatic conditions. On the other hand, for conditions with low water stress such as winter crops (or irrigated crops), the impact of extreme temperature on simulated yield may dominate. Large differences in simulated crop yield are also possible, since in our case we used uncalibrated crop models for absolute yields simulations. Attention should thus be paid, while applying crop models for climate change impact studies, especially for local or regional studies where a better calibration and parameterization is necessary. A comparison of climate change impact studies based on different crop models has only a limited reliability, if the limitations are not considered in the interpretation of results.

8. Conclusions and recommendations

Considering the results and Know-How gathered from the above presented COST734 studies following recommendations can be given on applications of crop models and agroclimatic models and indices:

- A key set of reference of agroclimatic indices should be defined for European wide applications to allow international comparison of climate change effects.
- For regional applications or for applications where adaptation measures should be developed at the farm level, a careful calibration and parameterization of crop models or indices is necessary to avoid biased results. In the frame of climate change studies regional climate scenarios should be used.
- Large scale crop model or agroclimatic indices applications may show spatial biases in their results. Therefore, a model should be tested in view of the relevant application at various sites under different conditions (climate, soil, crop) to avoid spatial biases. Another condition is a spatial input data base with high resolution and representativeness (including soil, weather and climate scenarios, management and crop data).
- Under changing climate a change in climate variability can have significant impact on real as well as simulated crop yields and various agroecosystem processes. It should be considered in the climate scenarios used in agricultural climate change impact modelling, to decrease potential uncertainties in the study results.
- Different crop models may react differently to crop growth stress factors such as drought or extreme temperatures, soil conditions due to differences in simulated processes, and model parameterization. It is therefore recommended to test different crop models for application at a specific site for a specific purpose.

- Concerning the simulation of drought impacts on crop yields, the soil cultivation effects and root development and water balance parameters should be well simulated by crop models. A specific site and crop cultivar calibration is crucial under such conditions.
- Crop models should further be compared to each other and improved in scientific studies and model specific recommendations and their application potentials should be developed.
- Main crops such as maize or wheat can be simulated by several crop models. However, a cultivar specific calibration should be fostered for various environments, especially for those under climate change conditions or under the occurrence of climate stresses limiting crop growth conditions.
- The direct effects of weather extremes on crop growth and yield formation which are not caught by crop model, and their weather inputs should additionally be considered in crop modelling studies, especially in climate change impact studies.
- Agroclimatic indices can help to identify the type of extremes having impacts both on observed and simulated crop yield. These indices should additionally be used in order to better identify the climate related crop production risks especially under climate change scenarios.

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CHAPTER II

TRENDS OF AGROCLIMATIC INDICES AND SIMULATION MODEL OUTPUTS IN EUROPE

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Abstract. The availability of long-term meteorological and especially agrometeorological data across Europe is considered. Homogenization of climate data is then discussed and a case study from Bulgaria is presented. Statistical methods, for example, trend calculation and significant testing are also listed. Current trends of agrometeorological indices and simulation model outputs are presented in varios case studies, namely from Croatia, Slovakia, Poland and Spain.

1. Long-Term Meteorological and Agrometeorological Data Availability

The evaluation of climate impacts can be performed both on past and future data. There are different ways to analyze past climate, such as the use of historical long-term meteorological data, remote sensing and re-analysis. Historical long-term meteorological data are available at the meteorological services and some other weather related institutions. Typical meteorological elements with long-term records in each European country are air temperature and precipitation as well as wind speed and direction, solar radiation, air humidity, etc. The spatial resolution of the meteorological data varies depending on the density of the respective weather networks and/or the interpolation techniques applied. The data temporal resolution covers different time slices mainly during the 20^{th} century. Both monthly and daily values of the relevant meteorological elements. Most of the gridded weather data sets as well as data series from countries such as Germany, Finland were generally available for the COST 734 applications. However countries such as Bulgaria, France, Romania were able to provide mainly secondary data, including maps, various indices, etc.

In recent years, the availability and use of agrometeorological data from weather stations or networks have become more and more important for the management and planning of agricultural activities and for the decision support system (Hoogenboom, 2000). In fact, agrometeorological variables such as temperature, relative humidity, solar radiation, wind and precipitation heavily affect the characteristics of a given territory. These

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variables are then often used as input in many simulation models to investigate issues such as genotype improvement, environmental characterization, evaluation of potential production, prediction of the effect of climatic change and variability on crop growth and yield and definition of farm management techniques (Maracchi, 2003). The trend of these variables is not constant over the territory, but it changes depending on the geomorphologic and topographical characteristics of the landscape, which can induce really wide differences over a short distance. In particular, geographic coordinates, altitude above sea level, distance from bottom of valleys, slope and aspect affect the spatial distribution of weather variables.

In most European countries, phenological data are collected or have been collected in the past over several decades. Monitoring phenological phases is carried out in many European countries like Slovenia, Slovakia, Czech Republic, Switzerland, Germany, Austria, and others. Each country has its own database, in some cases still on paper, mostly on databank-systems, going back in many cases to the 1950s and a few very long time-series from single locations like bud burst of horse chestnut in Geneva since 1808 (Defila and Clot, 2001). Besides the scientific research in phenology that is now focused on climate warming and its impact on vegetation, pheno-data are used for crop modeling, pollen forecast and general information to the public via media and in schools. The observations should have been made following the same, similar, or at least comparable, rules and quality checks. Phenological phases reflect among other things the environmental characteristics of the climate in the region where they occur. Consequently, long series of phenological observations may be used for the detection of climate variability or climate change.

Obviously all European countries have historical long-term meteorological records. Differences in the field, however, are observed in the terms of their temporal and spatial resolution, area coverage, especially availability for end users. Some of the European institutions/countries are ready to provide primary weather data, while others at this stage are open to present mainly secondary data, including various indices, maps, etc. A possible solution of this problem is the application of gridded meteorological data sets, which are freely available on the internet. The same conclusion could be directed to the agrometeorological data, although its measurement is not so spread across the continent as the collection of weather data.

2. Data Homogenization

2.1 State of the art

Homogenization has become one of the basic elements of climatological studies (e.g. Szalai, 2000). An investigation of climatic change must be based on a homogeneous climatological time series (e.g. *Štepánek et al.*, 2000). A series is said to be homogeneous «if its variations are caused only by variations in weather and climate» (e.g. Conrad and Pollak, 1962).

Inhomogeneities in climate time series arise from non-climatic factors like changes in station location, changes in methods to calculate means, changes in observation practices, changes in instruments and in station environment. Each of these changes may require a separate homogenization strategy. The changes may cause stepwise and/or gradual biases in the climatological time series, making these series unrepresentative of the climate of the concerning area (e.g. Brandsma, 2000).

Beside the well-known use in the climate change studies, more and more users request long-term time series in homogenized form. Not only is this positive development the result of the work of the enthusiastic colleagues active on this field for a long time, but also the new observation methods. The overall trend shows a decrease of human observations, and a growing rate of automatization. In consequence, we often do not measure the same meteorological parameter, as earlier, only something similar to that, certainly new methods of observation are used, which imply rather different data quality problems, etc. The merging of satellite and radar information into the classical database could effect large breaks as well (e.g. Szalai, 2000).

The identification of local, regional and global climate change has become an important issue in climatology. Data homogeneity is strongly related to the climate change problem, which is at the centre of scientific and policy debates. It has been recognized and widely accepted that long and reliable observation series are required to address climate change issues and impact studies. Unfortunately, these high quality meteorological data series seldom exist, therefore it is imperative that homogenized data be used for theoretical and applied research (e.g. Mersich, 1999). As often clearly stated by the IPCC, there is an urgent and continuing requirement for high quality and consistently collected observation and related homogeneous data sets to understand climate change, verify assessments and models use to generate future climate scenarios (e.g. Scholefield, 1999).

It was already mentioned that the long-term climatological time series are often plagued with discontinuities caused by station relocation, installation of new instruments, etc. Several types of disturbances can distort or even hide the climatic signal. Therefore, it is quite natural that the data are tested in order to locate possible discontinuities. However, usually the detection of the homogeneity breaks is not enough. The breaks appear to be so common that rejection of inhomogeneous series simply leave too few and too short series for further analysis. The widely adopted practice is to make adjustments in the non-homogeneous climatological time series (e.g. Tuomenvirta, 1999).

There are several direct and indirect methodologies for homogeneity testing. The direct methodologies include, for example, use of metadata, side by side comparisons of instruments, statistical studies of instrument changes. The indirect methodologies consider use of single station data, development of reference time series, subjective and objective methods. The available objective methods include: Potter's method; Standard normal homogeneity test; two-phase regression; rank order change point test; Craddock test; Caussinus-Mestre technique; multiple analysis of series for homogenization (e.g. Alexandersson and Moberg, 1997; Peterson *et al.*, 1998; Szentimrey, 1999).

Various homogenization tests/techniques/software are applied in European countries:

- Standard Normal Homogeneity Test (e.g. in Croatia, Slovenia, Spain, etc.):
- Craddock test (e.g. in Austria, Slovenia)
- Caussinus-Mestre technique (e.g. in France, Bulgaria)
- AnClim – software (e.g. in the Czech Republic, Slovakia, Italy, Bulgaria, etc.)
- ClimDex – software (Italy).

Both, Craddock and SNHT tests (e.g. Alexandersson 1986, Craddock 1979) can be applied on yearly, seasonal or monthly time series of mean, minimum and maximum temperature, precipitation and sunshine duration. For both methods homogenous reference time series is needed. Craddock test is based on the analysis of von Neumann ratio, which is closely related to the first-order series correlation coefficient. If the series is homogenous with constant mean, von Neumann ratio is close to 2, otherwise it is smaller than 2. SMHT method uses T-test to analyse the shifts in mean and standard deviation of time series. The detected shifts should be approved in the history of the station and than they are adjusted. For temperature also daily data are homogenized using harmonic functions on monthly corrections.

The Caussinus-Mestre method, simultaneously accounts for the detection of unknown number of multiple breaks and generating reference series. It is based on the premise that between two breaks, a time series is homogeneous and these homogeneous sections can be used as reference series. Each single series is compared to others with the same climatic area by making series of ratio (e.g. for precipitation) and differences (e.g. for air temperature). These ratios or difference series are tested for discontinuities. When a detected break remains constant throughout the set of comparisons of a candidate station with its neighbours, the break is attributed to the candidate station time series (e.g. Caussinus and Mestre, 1997; Mestre, 1999, 2000; Peterson *et al.*, 1998). For detection purposes, the formulation described by Caussinus and Lyazrhi (1997) is used which allows the determination of a normal linear model with an unknown number of breaks and outliers. They formulated it as a problem of testing multiple hypotheses. At each step, one or two more breaks are added to the previous selected hypothesis. Analytical studies (e.g. Mestre, 1999) show that this double step procedure gives better detection results than the single step procedure for up-and-down breaks. Furthermore, a triple step procedure, much more greedy in terms of computation time, leads to small improvements (e.g. Mestre, 1999, 2000). The Causinus-Mestre method, with a double step procedure, is now the standard detection part of the homogenization method used in Météo-France (e.g. Moisselin and Mestre, 2002; Moisselin *et al.*, 2002). The knowledge of break positions can be a very interesting aspect for some users. For many applications (such as climate change studies) it is the first half-part of the problem. The other one, described below, is the break correction. A two factors linear model is proposed for correction purposes (e.g. Mestre, 2000). The series within the same climatic area are considered as affected by the same climatic signal factor at each time, while the station factor remains constant between two breaks. The model is applied after break detection. It provides the correction coefficient of a set of inhomogeneous series, through weighted least-squares estimation of the parameters. The weighted least squares allow correction of series with missing data. It also allows the data weighting, according to their supposed quality, which can be estimated, for example, with the correlation between the stations. The above formulation is equivalent to an exact modelling of the relative homogeneity principle. Given a set of inhomogeneous instrumental series, it allows unbiased estimations of the breaks affecting these series. This method does not require computation of regional reference series, and is currently the standard correction part of the homogenization method used at Météo-France (e.g. Moisselin and Mestre, 2002; Moisselin *et al.*, 2002)

Software packages such as AnClim-Pro, CLimDB, LoadData are frequently used nowadays, e.g. in Italy. The AnClim software:

- Input format: TXT files, working with one station at a time.
- Menu is ordered in a sequence (steps) to be taken during data processing: viewing data, adjusting (transformation), testing distribution, finding outliers, homogeneity testing (both absolute and relative homogeneity tests), analysis, filtering.
- managing the software: *Series Controler* (form in the right bottom corner: info about period, length of series, number of missing values, using monthly data or seasonal and annual averages), settings for the software: use menu *Options / Settings*, documentation can be found using menu *Help / Documentation*.

- Working with one series: graphs, outliers, statistical characteristics, testing.
- Working with two series: merging two series (using differences, ratios), graphs, outliers, statistical characteristics, testing.
- Time series analysis (mainly cyclicity).
- Filtering (smoothing) output data.
- Other tools: filling missing values, creating reference series, automatization.

LoadData – application for loading data from database (e.g. Oracle):
- Creating connection (using ODBC).
- Specification what to download (stations, elements, periods).
- Adjusting output (cross tables).
- Output to TXT files, Excel, AnClim.

Running LoadData application from the AnClim:
- Download wizard – guides through all the steps.
- Transformation to files suitable for AnClim automatically.

ProClimDB software:
- Used for processing whole datasets (all stations at a time).
- There are two main input files in the software: *Data* file (dbf file with all stations data) and *Data_info* file (list of stations with their geography, etc.).
- How to proceed: select a function, specify files, set options, run the function for a whole dataset.
- User has full control over the processing all the time, a lot of auxiliary output is created.
- First step of processing is getting information about all available stations, their period, etc., the other step is importing geography, then we can calculate statistical characteristics , correlations, reference series, outliers, etc. A lot of tools for managing dataset is available as well.
- Homogeneity testing in AnClim: after we export candidate and its reference series to TXT files (using ProClimDB), we can use automatization in AnClim – running homogeneity tests for differences (ratios) between candidate and its reference series for a whole dataset:
- It is recommended to use several tests: e.g. t-test (on differences), Man-Whitney-Pettit test (non-parametric test), SNHT (several modifications), Bivariate test, Vincent test (two-phase linear regression).
- Further it is useful to run the tests for several types of reference series: based on correlations, distances, regional average (good for temperature but in case of precipitations we can get only one meaningful type of reference series).
- Testing monthly, seasonal and monthly averages.

Results from homogeneity testing are put back to ProClimDB (imported to DBF file) and further processed:

- Numbers of inhomogeneities detections per individual years or groups of years are calculated (summed).
- Where the inhomogeneity detection using various tests, various reference series etc. coincides, we can regard such cases as very probable to be inhomogeneous, then to go to metadata and verify them etc.
- After we decide inhomogeneites, we can adjust them, and in the end to fill missing values.

ClimDex is a Microsoft Excel program designed to assist researchers in the analysis of climate change and detection. More specifically, ClimDex guides a user through a four-step analysis process, using a graphical user interface. This process consists of the following steps: 1. Quality Control; 2. Homogeneity Testing; 3. Calculate Indices; 4. Region Analysis.

Weather data in the Czech Republic that are certified for the use by various research teams are provided by the Czech Hydrometeorological Institute. These data are homogenized before handover to the user based on the metadata and information from surrounding stations. All certified data originate from a CLIDATA (<http://www.ataco.cz/clidata-web/introduction/introduction.jsp>) which is used for data quality control and is used for the administration of climatology stations and station observations. The access into the primary database is severely restricted and only homogenized and complete "so called technical series" are allowed to be used by researchers outside the CHMI. Experts of CHMI (e.g. Dr. Stepanek) conduct extensive research in the field of data homogenization and provide freely available software and know how (e.g. AnClim software package: <http://www.klimahom.com/software/AnClim.html>).

In Spain for precipitation: the SNHT and Wald-Wolfowitz tests are applied to the monthly precipitation values in stations with more than 20 years of data from 1960 (approximately 1200 series). For temperature: Mann test (applied to the monthly temperature values in stations with more than 20 years of data from 1960) as well as Petit test (applied to the monthly temperature values in stations with long series).

In Poland large variety of homogenization methods are generally accepted (e.g. Kożuchowski, 1990; Pruchnicki, 1987). In some cases, several methods are applied simultaneously for more accurate estimation of a given situation. For procedures of detection non-homogenous series we use the following methods: difference – quotient method,; parametric tests, i.e.: *T*-Student test, *F*-Snedecor test, etc.; non-parametric tests, i.e.: Smirnow test, Wald-Wolfowitz test (series test), Wilcoxon test, etc. In case of non-homogeneity detected in observation series, the following methods are applied to remove it, i.e.: difference – quotient method, double-mass method, isomer method, correlation method, Standard Normal Homogeneity Test developed by Alexandersson. Presently, there is no coordinated program of climate data homogenization. This process is conducted in different research centers, but the volume of published homogenous measurement series is small.

Dalezios *et al.* (2004) deal with tests on homogeneity of temperature and time series in Greece. The emphasis is placed on the identification of inhomogeneities in temperature and precipitation time series as well as on the specification of certain years, in which inhomogeneities occur. Moreover in this study correction factors are identified to artificially homogenize the time series. This accomplished by employing various homogeneity tests to monthly data over 37 years (1951-1987) at 31 stations over Greece which has been classified in 5 regions using Factor analysis. Pnevmatikos *et al.* (2006) worked on homogeneity and quality control of rainfall time series. They used different methods and techniques that have been developed in the past, for homogeneity adjustments of annual rainfall data of the 20th century in 36 Greek stations.

Several methods have been used in Switzerland (e.g. Auer *et al.* 2006; Begert *et al.*, 2005; Della-Marta, 2006). National weather data has been homogenized in the framework of the CLIMATE90 programme. The methods are described in Aschwanden *et al.* (1996).

2. Case study: Bulgaria

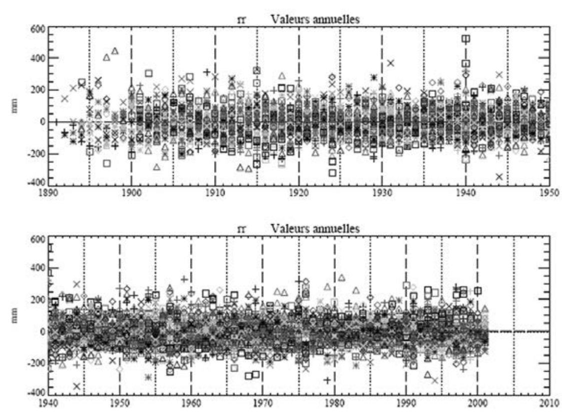
Since 1994, Météo-France has put significant efforts on search, data rescue and homogenization of long series of weather measurement. These efforts allowed to built-up a base of homogenized data (e.g. Moisselin and Mestre, 2002). The major goal of this case study to apply the French homogenization method on long-term series of average, minimum and maximum air temperature as well as precipitation and sunshine duration from Bulgaria. Specific objectives were: to control monthly data of average, minimum and maximum air temperature as well as precipitation and sunshine duration from selected weather stations in Bulgaria; to detect breaks and outliers within the collected and controlled time series; to correct the currently used climate long-term series according to the defined breaks and outliers in order to obtain homogenized climate series; to validate the respective breaks.

2.1 Data control

The common conditions of detection and correction were the need of correlated series and the homogenization procedure concerned only monthly data. At a lower time scale, correlations are considered insignificant. The homogenization process was performed on sets of 15 series of minimum and maximum air temperature, 20 series of average air temperature and precipitation and 15 series of sunshine duration, merged with geographical criteria.

The first step was the performance of a quality control of the long-term series of the weather elements used in the study. The control procedure was executed several times till appropriate data sets were obtained. The anomalies of monthly minimum, maximum and average air temperature as well as precipitation (Fig. 1) and sunshine duration for each year and station were compared and analyzed in order to locate and remove possible data errors. The obvious crude errors as well as some suspicious values of the above-mentioned weather elements were reported to the Division of Climatology and the Division of Weather Database. The updated data were again checked out by the controlling software. The remained errors and suspicious values this time were replaced by the respective value for missing data (i.e. -999.9). The control procedure was executed several times till appropriate data sets were obtained. The time periods of some weather stations including high density of missing annual values of minimum, maximum and average air temperature as well as precipitation and sunshine duration were dropped and not considered within the further study.

Fig. 1. Anomalies of annual precipitation, during application of data quality control



The second step in the homogenization procedure was to replace missing monthly values assuming that these values are very few and their replacement would not have any impact to the data series. The two factors linear model by means of the computed weighted least squares allows correction of series with missing data. For this purpose, the linear model was run with the option for correction of missing data.

The following step was to calculate the diurnal temperature range (DTR) from controlled data of minimum and maximum air temperature. The motivation for selecting also DTR was that DTR is often more sensitive to the homogeneity tests (e.g. Wijngaard, 2003). A reason is that breaks due to station relocations and changes in measuring techniques are usually radiation-related, with different effects on minimum and maximum air temperature. For example, Wijngaard *et al.* (2003) showed that a break that appears clearly in the DTR variable series may be only weakly apparent in the minimum and maximum air temperature. That is why, it was considered in our study to use also DTR series at least as reference series.

The next step was to calculate the respective differences for DTR, minimum, maximum and average air temperature as well as ratios for precipitation and sunshine duration. These differences and ratios were then tested to put into evidence breaks or outliers. The typical homogenization techniques are based on the assumption that climatic variations affect in the same way a homogeneous regional reference series, whose reliability cannot be proved. The different methods (e.g. Alexandersson, 1986; Førland and Hanssen-Bauer, 1994; Peterson and Easterling, 1994) for creating such series do not guarantee their perfect homogeneity.

2.2 Break detection

There is an easy way to get round the reference series. It is based on the simple statement that between two breaks a series is reliable (by definition), so these sections can be used as reference series (e.g. Mestre, 2000). Each single series is compared to others within the same climatic area by making a series of differences. These difference series are then tested for discontinuities.

At this stage, it is not known which individual series is the cause of a shift detected on a ratio or difference serie. However, it was already mentioned that according to the Caussinus-Mestre method, if a detected break remains constant throughout the set of comparisons of a candidate station in respect to its neighbours, it can be attributed to this candidate station. The detection of the outliers follows the same principle.

Difference and ratio series were computed and constituted between all weather stations, used in the study, and their respective neighbour weather stations. The breaks and outliers were then put into evidence by the double-step procedure applied within the Caussinus-Mestre method. For example, some detected breaks and outliers of minimum, maximum and average air temperature as well as precipitation and sunshine duration are shown in Figures 2-6. The black triangles indicate the position of the detected breaks in the difference and ratio series of the presented weather station versus the other weather stations, while A points out the outliers and the empty diamonds are representing missing data. The weather stations are ordered from the top to the bottom with respect to increasing values of the estimated standard deviation STD. Hence, in practice, the reliability of the comparisons slightly decreases from the bottom to the top.

The number of breaks detected within monthly precipitation and average air temperature series at the used weather stations is presented in Table 1.

Tab. 1. Breaks detected within monthly precipitation (P) and average air temperature (T) series at the Bulgarian weather stations used in the study

Station (name)	Breaks (number)		Station (name)	Breaks (number)	
	P	T		P	T
Belogradchik*	5	-	Nesebar*	4	-
Bjala Slatina*	4	-	Obr. Chiflik	4	4
Blagoevgrad*	3	-	Orjahovo	1	4
Boshurishte	2	7	Panagjurishte	4	3
Buch. prohod*	2	-	Pavlikeni	4	5
Burgas	2	6	Pernik*	1	-
Chirpan	4	1	Peshtera	0	6
Dupnitza	4	3	Petrich	6	6
Elena	1	3	Pirdop*	3	-
Elhovo*	5	-	Pleven	1	6
Elin Pelin*	3	-	Plovdiv	4	4
Gabrovo	4	6	Preslav*	7	-
Gor. Chiflik	2	4	Razgrad	2	2
Haskovo	3	2	Russe	3	2
Ivajovgrad*	1	-	Sadovo	3	5
Jambol*	2	-	Sandanski	5	1
Karnobat	2	1	Sevlievo	2	-
Kazanlak	5	3	Shumen	2	3
Kesarevo*	5	-	Sliven	0	1
Kjustendil	4	6	Smjadovo*	0	-
Knesha	1	5	Stara Zagora	4	5
Koprivshtitza	3	3	Svilengrad	0	3
Krumovgrad*	2	-	Teteven*	4	-
Kubrat*	0	-	Topolovgrad	6	-
Kurdjali	0	4	Tran	0	2
Lom	0	3	Varna*	1	-
Lucovit*	2	-	Vidin	0	3
Montana*	2	-	Vratza	4	1

Legend: * - stations with precipitation series only

Fig. 2. Homogenization of minimum air temperature data in 4 Bulgarian weather stations: ▼ – break; A – outlier; dash line – validated break and then corrected; ◇ – missing values

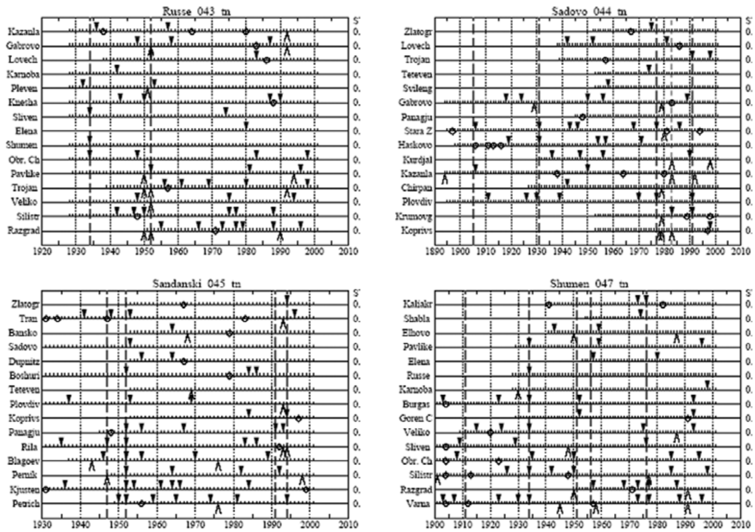


Fig. 3. Homogenization of maximum air temperature data in 4 weather stations: ▼ – break; A – outlier; dash line – validated break and then corrected; ◇ – missing values

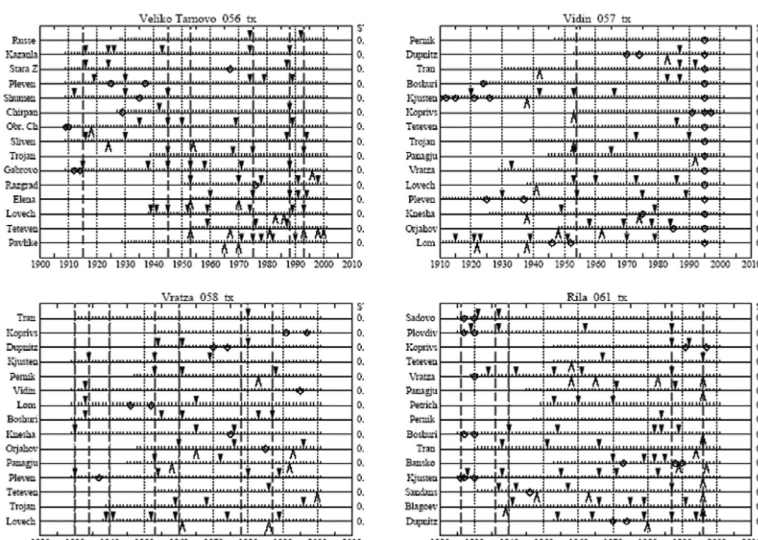
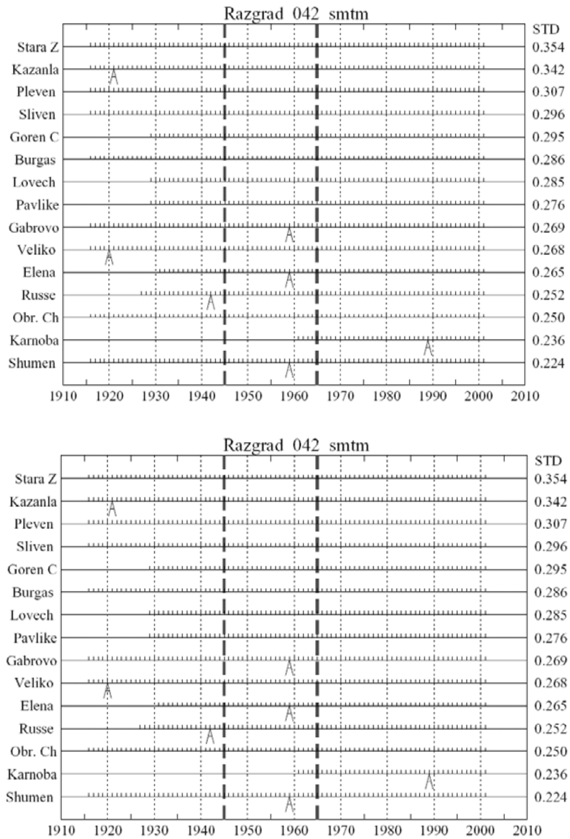


Fig. 4. First step (a) and end (b) of homogenization of monthly average air temperature data in station Razgrad (northeast Bulgaria); ▼ – break between Razgrad and a neighbour series; A – outlier; ◇ – missing data; dash line – validated break and then corrected



Several breaks during the 20th century can be detected easily in Figures 2-6, considering the relatively good alignment of breaks in average, minimum and maximum air temperature as well as precipitation and especially sunshine duration. For example, in weather stations Karnobat, Kazanlak and Kjustendil the breaks of sunshine duration data in 1970, 1985, 1980 and 1971 respectively, are obvious. In station Boshurishte the breaks of precipitation data in 1953 and 1969 can be easily detected. Station Razgrad is characterized with relatively well expressed breaks of average air temperature in 1945 and 1965. The weather stations Sandanski and Shumen are also faced by relatively well expressed breaks of minimum air temperature in 1952 and 1934 respectively, etc.

Fig. 5. First step (a) and end (b) of homogenization of monthly precipitation data in station Boshurishte (west Bulgaria); ▼ – break between Boshurishte and a neighbour series; A – outlier; ◇ – missing data; dash line – validated break and then corrected

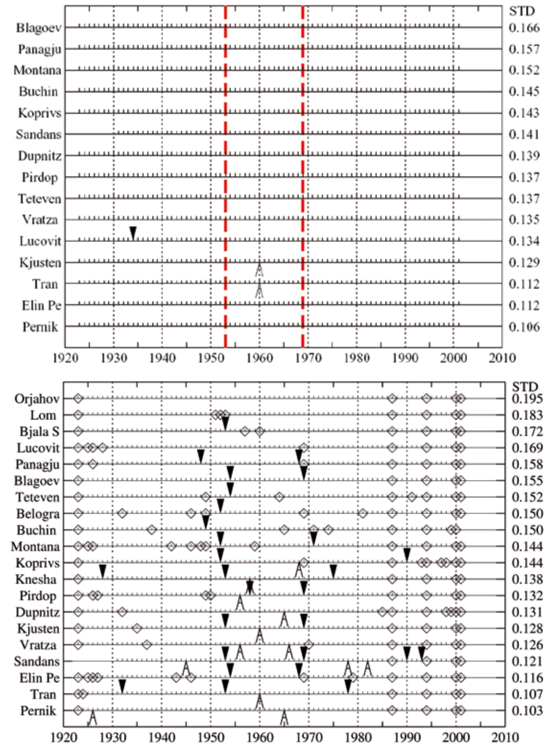
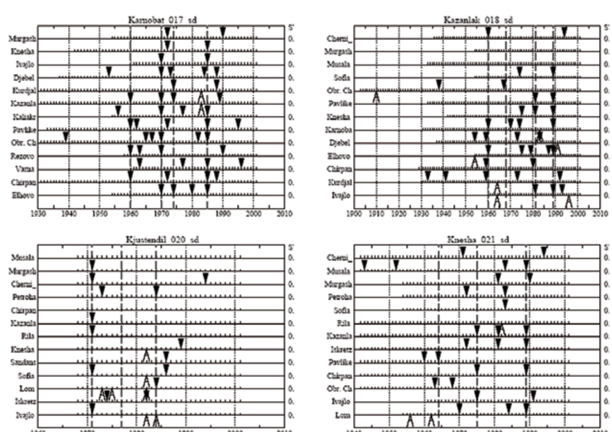


Fig. 6. Homogenization of sunshine duration data in 4 weather stations: ∀ – break; A – outlier; dash line – validated break and then corrected



2.2 Break correction

The knowledge of break positions for many applications including climate variability and change studies is the first important half of the final goal. The second part of the homogenization goal is the break correction. The two factors linear model was applied after break detection and validation. It was assumed that the series within the same climatic area are considered to be affected by the same climatic signal factor at each time, while the station factor remains constant between two breaks. The model computed the correction coefficients of a set of non-homogeneous series, through weighted least squares estimation of the parameters.

It was impossible to locate straightaway all possible breaks: the pronounced breaks hided smaller one's. Thus, the procedure of detection and correction of breaks and outliers was not automatic. It was iterative and the expert knowledge and strategy was very essential. Every time the expert team validated the breaks keeping in mind some statistical and climatological issues. The whole procedure of break detection and correction took a very long time, for example, it was run more than 15 times in order to locate, validate and correct all the breaks and outliers in the series of minimum and maximum air temperature.

During the first 7 runs all 49 weather stations with minimum and maximum air temperature series were used in order to detect, validate and correct the respective breaks and outliers mainly for the second half of the 20th century (1951-2000). Then only the weather stations with long-term temperature records (29 weather stations: including the period 1931-2000) were further applied within the homogenization procedure trying to better detect breaks and outliers during the first half of the 20th century. The DTR series were kept to a maximum as reference series in order to locate, validate and correct hidden breaks and outliers in minimum and maximum air temperature. It is necessary to emphasize that the principle of coherence between DTR and minimum and maximum air temperature series was valid under the homogenization process at this stage. When it was already not possible to follow this principle (after at least 10 homogenization runs were executed) the DTR series were dropped. In this way, the homogenization procedure continued separately on minimum and maximum air temperature series especially when the important execution of the validation of break and outlier positions was carried out.

On the other hand, the total procedure of break detection and correction of sunshine duration series was much easier and did not take such a long time (because of the smaller number of weather stations as well as the shorter length of the series) – it was run less than 10 times. The whole iteration of homogenization of average, minimum and maximum air temperature as well as precipitation and sunshine duration ended when all or most break risk was gone (Figg. 2-6).

The results of this study show that homogenization is important for building of reliable weather database in Bulgaria. It is obvious that homogeneous weather series of data are essential for research, especially for investigation in climate change and variability in the country. For producing high quality time series efficient measures for testing the homogeneity should be applied. The French homogenization procedure, which is applied in Météo-France, was proved in the study as an essential tool for climate change studies. By directly comparison of each climate long-term series to its neighbours, it was shown that problem with construction of homogeneous reference series does no longer exist. The applied methodology of homogenization is valuable for practical use such as on climate data in Bulgaria, even with missing metadata (as in the case of this study), and allows the detection of multiple breaks. Most homeogenization methods in Europe have been developed for the analysis of temperature and precipitation only. However, the Caussinus-Mestre method for the relative homogeneity testing of climatological series and the model performing correction of non-homogeneous climate series were also successfully tested on long-term series of sunshine duration. In fact, the executed homogenization was very useful for better understanding of average, minimum and maximum air temperature as well as precipitation and sunshine duration series in Bulgaria.

The homogeneous series do not replace uncorrected (raw) data. The homogeneous series can be changed in the future. The raw data can be used for completing missing data or to improve the break detection or correction. There are even some analyses, where unadjusted data are preferred (e.g. Peterson *et al.*, 1998). These are often station specific studies that do not involve long-term trend analysis. Therefore, it is important to preserve the original data as well as the homogeneity-adjusted versions. Also, the original data need to be preserved because new and better or improved approaches to homogeneity adjustments will probably be developed in the near future. During the last two decades, considerable work has been done on homogeneity testing and data adjustments and research will continue in this field.

More and more the need for reliable data both in space and time becomes apparent for too much is at stake to rely on inaccurate data. The very existence of our society is threatened. Therefore, it is important for all WMO members (including Bulgaria) to produce and make available homogeneous series of data and metadata.

One of the most important problem in the climate research is the quality of data. Long series of reliable climatological data are required in climatological studies on the natural climate variability and the effect of anthropogenic influences on recent climate. However, high quality climatological data seldom exist because in reality many types of disturbances can affect the respective climate series. Many efforts were put in this study for quality control on the Bulgarian series of minimum and maximum air temperature and sunshine duration. It should be stressed that the respective series were affected by different types of errors. Therefore, it is recommended that before any homogeneity testing of Bulgarian weather data to be applied, an extensive routine quality control needs to be performed.

Historical time series carry the information of natural and artificial variability. However, before climate variability can be studied all artificial biases have to be removed. This is a hard job but unavoidable. Although this problem could be treated by using one or several homogenization techniques, metadata will provide a better insight and explain the reasons of breaks and support the statistical test results. It is always advisable to compare what station history says and what data analysis identifies (e.g. Auer, 2003). Unfortunately, the lack of metadata was an important limitation in this study. That is why, some efforts at the National Institute of Meteorology and Hydrology are necessary in the field. The importance of metadata data was assumed by the WMO Commission for Climatology and the working group on Climate Change Detection (e.g. Niedzwiedz and Ustrnul, 2000). A proposal was given for Global Climate Observing System Surface Network Sites (e.g. WMO, 1999). Also WMO has stressed its strong interest in metadata recording for current measurements, but also in metadata recovery for historical time series. This interest is underlined by the establishment of a WMO Expert Team on Metadata for Climate Applications within the Commission for Climatology. The expert team members have been preparing guidelines on metadata and homogenization (e.g. Auer, 2003). These guidelines would be of help when respective metadata are gathered in Bulgaria.

3. Statistical Methods

3.1 Country examples

Bulgaria: for trend calculation the following statistics are applied: least squares; minimum absolute deviation; significance testing: confidence intervals for least squares, the Mann-Kendall and Spearman rank statistics. Least squares linear regression is a maximum likelihood estimate i.e. given a linear model, what is the likelihood that this data set could have occurred? The method attempts to find the linear model that maximises this likelihood. Least squares linear regression, like many statistical techniques, assumes that the departures from the linear model (errors) are normally distributed. Techniques that do not rely on such assumptions are termed robust. Non parametric correlation statistics are an attempt to overcome the limited resistance and robustness of the linear correlation coefficient, as well as the uncertainty in determining its significance.

Serbia applies time series analysis using quantitative parameters of chaos. This method includes deriving low attractors in atmospheric data time series and calculations corresponding quantities as the Lyapunov exponent, Kolmogorov entropy and Kaplan-Yorke dimension. It is also combining with filtering techniques for time series, particularly with the 4253H filter.

In the Czech Republic the statistical methods include standard statistical packages, ANCLIM (see above), neural networks, wavelet analysis packages as well as trend calculation: least squares; significance testing: confidence intervals for least squares, the Mann-Kendall and Spearman rank statistics; cluster analysis; various techniques for assessment links with the agrometeorologically relevant events and e.g. regional circulation patterns (e.g. GWL)

Slovenia uses Correlation analysis, Multiple regression analysis, Trend Calculation: Seasonal or monthly decomposition (Census 1 or 2); Significance Testing: Confidence intervals for least squares; STATISTICA software which needs a license.

Switzerland: trend analysis, Fourier and spectral analysis, and others, mostly using available FORTRAN routines (e.g. Visual Numerics, 2001; Press *et al.*, 1992). Recently, an increasing number of investigations have been carried out using the R language (R Development Core Team 2006.), which is becoming a standard. Of particular interest could be the studies on precipitation and the detection of extreme events in observed time series (Frei and Schär, 2001; Scherrer *et al.*, 2006; Schmidli *et al.*, 2002; Schmidli and Frei, 2006)

Spain: Trend Calculation: Least squares; Minimum Absolute Deviation; Significance Testing: Confidence intervals for least squares, the Mann-Kendall. Empirical Orthogonal Function and Principal Component. Composites. Statistical regression models (e.g. Rodríguez-Puebla *et al.*, 2007; Libiseller and Grimvall, 2002).

Slovakia: GIS analysis and standard statistical methods are used.

Poland: the basis for time series is generally adapted statistical methods. Calculations are performed by computer software of general use such as Excel, and more specialized such as STATISTICA, or original software written in specific research centers. Most applied methods (Kożuchowski, 1990) are: presentation of measurement data with empirical formulae and estimation of their compatibility with tests such as χ^2 or Kolmogorow-Smirnow test; spectral analysis of time-series data, harmonic analysis of time-series data, trend analysis, filters, tests of statistical significance in phenomena changeability research, empirical orthogonal functions (EOF)

In Italy, beyond the common statistical methods, indices for extremes (Klein Tank and Konnen, 2003) as in ECA&D (<http://eca.knmi.nl>) are applied. The most used statistical software is MATLAB. Some specific software for extremes is available from ECA&D (ClimDex).

Greece: According to Anagnostopoulou *et al.* (2006) analysis of changes in extreme rainafall have used both parametric and non –parametric methods. The parametric methods usually involve fitting a suitable distribution to the data then analyzing changes in the distribution's parameter. Non-parametric methods have utilized a large number of extreme rainfall indices. In the present study the Generalized Extreme Value (GEV) Distribution and the Pareto Distribution are applied and their results are analyzed. Daily precipitation data derived from 22 Greek stations evenly distributed in the Greek region have been used for the time period 1958-2000. The results derived from the analyses concern the threshold selection as well as the return period of extreme rainfall events in the study area. Skourkeas *et al.* (2006) focus on the estimation of mean maximum and minimum winter temperature over the Greek region, by applying a statistical downscaling method based on the CCA technique. Several test-hypothesis for the variance and the mean value were done between the observed and the estimated temperatures. The CCA approach is turned out to be a very useful multivariate technique for the construction of reliable linear models in downscaling methods.

3.2 Trend calculation and significant testing

The following text is an overview of linear regression methods for reference by members of the STARDEX project (Haylock, 2004; STARDEX, 2004).

Least squares: Least squares linear regression is a maximum likelihood estimate i.e. given a linear model, what is the likelihood that this data set could have occurred? The method attempts to find the linear model that maximises this likelihood.

Minimum absolute deviation. Least squares linear regression, like many statistical techniques, assumes that the departures from the linear model (errors) are normally distributed. Techniques that do not rely on such assumptions are termed robust. Least squares regression is also sensitive to outliers. Although most of the errors may be normally distributed, a few points with large errors can have a large affect on the estimated parameters. Techniques that are not so sensitive to outliers are termed resistant. A more resistant method for linear trend analysis is to assume that the errors are distributed as a two-sided exponential. This distribution, with its larger tails, allows a higher probability of outliers. The solution to this needs to be found numerically. Example code can be found in Press *et al.* (1986).

Three-group resistant line. This method derives its resistance from the fact that one of the simplest resistant measures of a sample is the median. Data are divided into three groups depending on the rank of the x values. The *left* group contains the points with the lowest third of x values. In a time series this is equivalent to the first third of the series. Similarly, the *middle* and *right* groups contain points with the middle and highest third of ranked x values respectively.

Logistic Regression. Linear regression has been generalized under the field of generalized linear modelling, of which logistic regression is a special case. This method utilizes the binomial distribution and can therefore be used to model counts of extreme events. Often in a series, the variance of the residuals (from the linear model) varies with the magnitude of the data. This goes against the assumptions of least squares regression, which assumes residuals to have constant variance, but is a natural element of the binomial distribution and logistic regression. Therefore data do not need to be normalized. The logistic regression model expresses the probability π of a success (e.g. an event above a particular threshold) as a function of time. Since the probability of a success is in the range [0,1], it needs to be transformed to the range $(-\infty, +\infty)$ using a link function. Model fitting can be done using a maximum likelihood method. Further information about logistic regression, together with an example using extreme precipitation in Switzerland, can be found in Frei and Schär (2001).

Linear Correlation. The *linear correlation coefficient* (Pearson product-moment coefficient of linear correlation) is used widely to assess relationships between variables and has a close relationship to least squares regression. It can be shown that the coefficient of determination is the same as the square of the correlation coefficient. The correlation coefficient can therefore be used to assess how well the linear model fits the data. Assessing the significance of a sample correlation is difficult, however, as there is no way to calculate its distribution for the null hypothesis (that the variables are not correlated). Most tables of significance use the approximation that, for a small number of points and normally distributed data, the following statistic is distributed for the null hypothesis like Student's t-distribution. The common basis of the correlation coefficient and least squares linear regression means that they share the same shortcomings such as limited resistance to outliers. See Wilks (1995) or Press *et al.* (1986) for further information.

Spearman rank-order correlation coefficient. Non parametric correlation statistics are an attempt to overcome the limited resistance and robustness of the linear correlation coefficient, as well as the uncertainty in determining its significance. If x and y data values are replaced by their rank, we are left with the set of points (i,j), i,j=1,N which are drawn from an accurately known distribution. Although we are ignoring some information in the data, this is far outweighed by the benefits of greater robustness and resistance. The Spearman rank-order correlation coefficient is just the correlation coefficient of these ranked data. Significance is tested as for the linear correlation coefficient using the last equation, but in this case the approximation does not depend on the distributions of the data. See Press *et al.* (1986) for further information.

Kendall-Tau. Kendall's Tau differs from the Spearman rank-order correlation in that it only uses the relative ordering of ranks when comparing points. It is calculated over all possible pairs of data points using the following:

$$\tau = \frac{concordant - discordant}{\sqrt{concordant + discordant + sameX}\sqrt{concordant + discordant + sameY}}$$

where concordant is the number of pairs where the relative ordering of x and y are the same, discordant where they are the opposite, sameX where the x values are the same and sameY where the y values are the same. τ is approximately normally distributed with zero mean and variance:

$$Var(\tau) = \frac{4N + 10}{9N(N-1)}$$

One advantage of Kendall's tau over the Spearman coefficient is the problem of assigning ranks when data are tied. Kendall's tau is only concerned whether a rank is higher or lower than another, and can therefore be calculated by comparing the data themselves rather than their rank. When data are limited to only a few discrete values, Kendall's tau is a more suitable statistic. See Press *et al.* (1986) for further information.

Resampling. Resampling procedures are used extensively by climatologists and could be used to assess the significance of a linear trend. The bootstrap method involves randomly resampling data (with replacement) to create new samples, from which the distribution of the null hypothesis can be estimated. Therefore no assumption needs be made about the sample distribution. If enough random samples are generated, the significance of an observed linear trend can be assessed by where it appears in the distribution of trends from the random samples. A problem, however, is that the maximum likelihood derivation of the least squares estimate for the linear trend assumed that data residuals about the line were normally distributed. Therefore if the distribution of the residuals is not Gaussian, then the least squares estimate is not valid. Still, bootstrapping could be used to test the significance of a least squares linear trend, given that this may not be the best trend estimate. An important assumption in resampling is that observations are independent. Zwiers (1990) showed that, for the case of assessing the significance of the difference in two sample means, the presence of serial correlation greatly affected the results. A method has been proposed by Ebisuzaki (1997) whereby random samples are taken in the frequency domain (with random phase) to retain the serial correlation of the data in each sample. It seems that various statistical methods and software are applied on time series in Europe. All this shows the existing of well organized capacity building as well as the opportunity to apply and develop know how in the field. However, a strategy for development of a common statistical approach analyzing time series from different European regions should be considered. In this sense, the achievement of consistent and/or coherent results in this sphere in the European Union and beyond would be more real.

4. Current Trends of Agroclimatic Indices, Simulation Model Outputs and Hazards: Case Studies

4.1 Croatia

4.1.1 Growing degree-days

The growing degree-days (GDD) for different temperature thresholds (5, 10, 15, 20 and 25°C) at Croatian stations with long-term time series of meteorological data (1901–2000) have been analyzed (Vučetić, 2009a). The range of the mean annual GDD for the 5 °C threshold is from approximately 2000 °C in the highlands to 4200°C in the mid-Adriatic. The results of the linear trend and the Mann-Kendall test indicate significant positive trends in annual GDD values at the 0.05 significance level for all thresholds in the northern and mid-Adriatic. A progressive test in the mid-Adriatic shows that the GDD for the 25°C threshold has

Tab. 2. Linear trend of growing degree-days (°C/100 years) for different temperature threshold (T) for selected Croatian stations during the year (Y), warm season (W, April-September), and cold season (C, October-March) for the period 1901-2000. Linear trends at the 0.05 significant level are bolded according to the Mann-Kendal test

	T = 5 °C			T = 10 °C			T= 15 °C			T = 20 °C		T = 25 °C	
Trend	Y	W	C	Y	W	C	Y	W	C	Y	W	Y	W
Zagreb-Gric	201.0	115.6	85.4	144.0	105.4	38.6	76.7	71.3	5.5	35.0	35.0	7.6	7.6
Osijek	13.4	3.3	5.3	12.9	-2.4	12.0	-1.4	-9.6	-0.1	-12.7	-12.6	-3.3	-3.3
Gospic	-14.0	-25.1	33.4	-28.2	-35.5	15.2	-28.3	-33.5	0.7	-2.4	-2.4	-0.5	-0.5
Crikvenica	220.9	143.9	73.6	177.7	140.1	34.2	142.2	127.9	11.6	94.0	93.8	21.1	21.1
Hvar	211.5	107.5	99.8	168.9	103.0	67.1	126.9	93.4	32.1	100.8	94.7	31.3	31.3

become significant since the early eighties and in the northern Adriatic since the early nineties. It is shown that the mid-Adriatic coast and islands are subject to the highest vulnerability to climate change in Croatia (Tab. 2). In this region, the growth in high temperatures and the risk of summer droughts account for high current vulnerability in agriculture and forestry. This vulnerable region has spread from the middle Adriatic to the northern Adriatic in the warm season, but there is no higher risk towards the inland mountains. If all available potential adaptation measures (particularly irrigation systems) were implemented in this region, the vulnerabilities could be brought to a lower level.

4.1.2 Modelling of maize production in Croatia

Maize is one of the most important agricultural crops in Croatian lowlands and was selected for research of the effect of climate warming on yields. The impact of present climate on maize yield was studied using DSSAT model (Decision Support System for the Agrotechnology Transfer) for central Croatia (Vučetić, 2009a, 2010). The linear trends of model outputs during the period 1949-2004 and the non-parametric Mann-Kendall test indicate that the beginning of silking has advanced significantly by 1.4 days/decade since the mid nineties, and maturity by 4.5 days/decade. It also shows a decrease in biomass by 122 kg/ha and in maize yield by 216 kg/ha in 10 years.

4.2 Slovakia

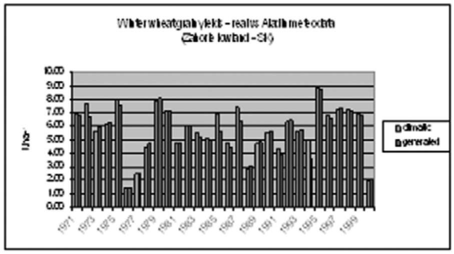
4.2.1 Sensitivity of field crop yields with respect to meteorological datasets

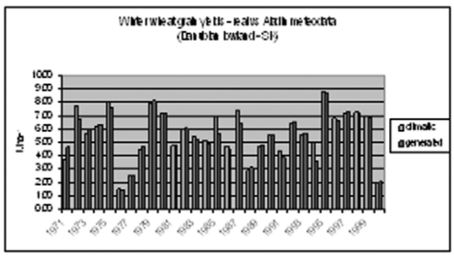
Variability of field crops yields were evaluated separately in Záhorie and Danubian Lowland. Yields were simulated with two different climatic datasets for the period of 1971-2000: data generated by Aladin model and with measured climatic data characteristic for the particular locality.

Winter wheat yields in Záhorie and Danubian Lowlands were simulated with two different climatic datasets for the period of 1971-2000: data generated by Aladin model and with measured climatic data characteristic for the particular locality. As seen from the results (Fig. 7, Tab. 3), model with generated data overestimates grain as well as upland biomass yields of winter wheat in Danubian Lowland (+24.69% in grain and +19.16% in upland biomass yields). On the other hand, model with generated data underestimates both grain and upland biomass winter wheat yields in Záhorie Lowland in comparison with usage of measured data (-3.41% in grain and -4.93% in upland biomass yields).

Spring barley yields in Záhorie and Danubian Lowlands were also simulated with two different climatic datasets for the period of 1971-

Fig. 7. Winter wheat grain yields and their deviations simulated according to generated and measured climatic data for Danubian lowland (grid 4522 vs. meteodata for Hurbanovo – left) and Záhorie lowland, (grid 5252 – vs. meteodata for Bratislava- right) – datasets in years 1971-2000





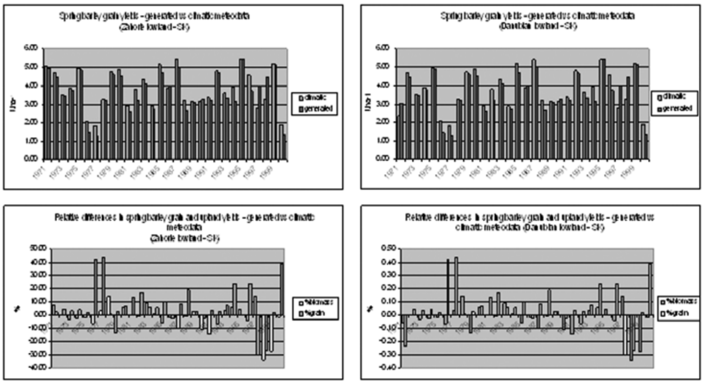
Tab. 3. Comparison of simulated winter wheat yields according to generated (Aladin) and climatic data for Danubian lowland (grid 4522 vs. meteodata for Hurbanovo,) and Záhorie lowland, (grid 5252 – vs Bratislava) – datasets in years 1971-2000

Winter wheat		Generated [t.ha^{-1}]		Measured [t.ha^{-1}]		Δ [t.ha^{-1}]		Δ [%]	
	Harvest	grain	upland biomass	grain	upland biomass	grain	upland biomass	grain	upland biomass
Záhorie lowland	26.7	5.55	11.70	5.73	12.26	-0.18	-0.56	-3.41	-4.93
Danubian lowland	25.7	5.93	12.89	4.59	10.55	1.34	2.34	24.69	19.16

2000 and the yields were finally compared (Fig. 8, Tab. 4.) Model with generated data overestimates grain as well as upland biomass yields of spring barley in Danubian Lowland (+13.07% in grain and +13.45% in upland biomass yields). Model with generated data underestimates grain yields of spring barley in Záhorie Lowland (-7.88%) and overestimates upland biomass (+ 2.19%) at the same time.

Corn maize grain yields in Záhorie and Danubian Lowland were also simulated with the climatic datasets for the period of 1971-2000 and with generated data and the yields were compared. Model with generated data overestimates grain yields of corn maize by 8.82 % in Danubian Lowland. Model with generated data underestimates grain yields of corn maize in Záhorie Lowland (-3.83%) (Tab. 5).

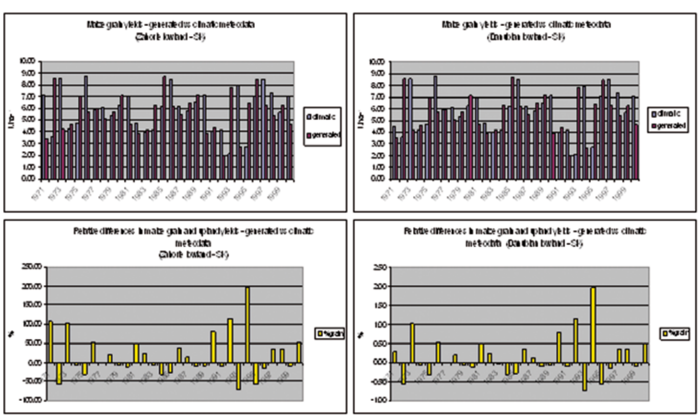
Fig. 8. Spring barley grain yields and their deviations simulated according to generated and measured climatic data for Danubian lowland (grid 4522 vs. meteodata for Hurbanovo – left) and Záhorie lowland, (grid 5252 – vs. meteodata for Bratislava- right) – datasets in years 1971-2000



Tab. 4. Comparison of simulated spring barley yields according to generated (Aladin) and climatic data for Danubian lowland (grid 4522 vs. meteodata for Hurbanovo,) and Záhorie lowland, (grid 5252 – vs Bratislava) – datasets in years 1971-2000

Spring barley		Generated [t.ha^{-1}]		Measured [t.ha^{-1}]		Δ [t.ha^{-1}]		Δ [%]	
	Harvest	grain	upland biomass	grain	upland biomass	grain	upland biomass	grain	upland biomass
Záhorie lowland	12.7	3.68	8.36	3.86	8.12	-0.18	0.24	-7.88	2.19
Danubian lowland	11.7	3.54	8.26	3.20	7.24	0.34	1.02	13.07	13.45

Fig. 9. Corn maize grain yields and their deviations simulated according to generated and measured climatic data for Danubian lowland (grid 4522 vs. meteodata for Hurbanovo – left) and Záhorie lowland, (grid 5252 – vs. meteodata for Bratislava- right) – datasets in years 1971-2000



Tab. 5. Comparison of simulated maize grain yields according to generated (Aladin) and climatic data for Danubian lowland (grid 4522 vs. meteodata for Hurbanovo,) and Záhorie lowland, (grid 5252 – vs Bratislava) – datasets in years 1971-2000

Maize		Generated [t.ha^{-1}]	Measured [t.ha^{-1}]	Δ [t.ha^{-1}]	D [%]
	Harvest				
Záhorie lowland	30.9	5.62	5.83	-0.21	-3.83
Danubian lowland	29.9	5.11	4.61	0.50	8.82

4.3 Poland

4.3.1 Standardized Precipitation Index (SPI) and its distribution in central-west Poland

In the last three decades, the growing tendency of extreme phenomena occurrences, including droughts, has been observed. Owing to the more frequent occurrences of long and deep droughts, increasingly more attention is devoted to drought monitoring and assessment. Droughts have the potential to strongly affect both natural environment and economy but the biggest losses are always noted in agriculture as the most water and climate-sensitive sector.

Presently, there are many indices that describe and classify droughts. Their availability and applicability depends, to a large degree, on the type of available data and length of observation time series. One of the relatively simple data series is Standardized Precipitation Index (SPI) developed by McKee, Doeskeni and Kleist in 1993.

Because the SPI values are normalized, the method can be used in different climate zones. In Poland, this indicator is used for drought monitoring in Kujawy region (central Poland), one of the driest regions in Poland. The original classification was modified by L. Labedzki (Bak, Labedzki 2004) for Polish conditions. As a result of this modification, it is possible to include low intensity droughts which, because of the characteristics of natural environment in central Poland (low precipitation totals especially during growing season compared to other regions of Poland), also affect crop yields. Labedzki's modification also enables to account for high precipitation variability of the analyzed area (Tab.6).

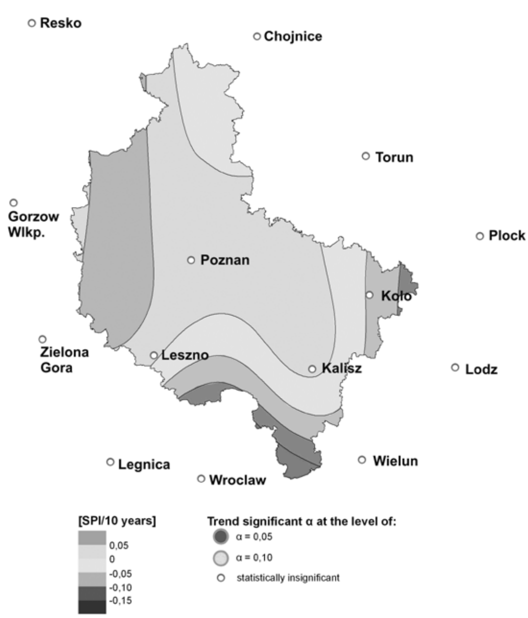
The SPI values were calculated from data collected by12 synoptic stations located in the central-west Poland (Wielkopolska region). The calculation was based on monthly mean values of precipitation (April-September, inclusive) and values of seasonal totals calculated for summer season (April-September) for the period of 1966-2005. The SPI values were calculated using free software available on the National Drought Mitigation Center website.

Tab. 6. SPI Values for central Poland

+2.0 and more	extremely wet
+1.50 to +1.99	very wet
+0.50 to +1.49	moderately wet
-0.49 to +0.49	near normal
-1.00 to -1.49	moderately dry
-1.50 to -1.99	severely dry
-2.00 and less	extremely dry

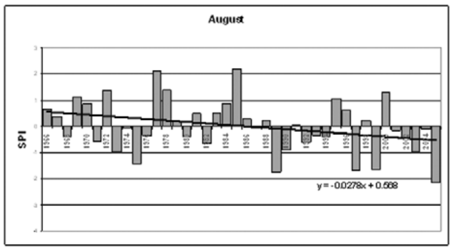
The results were then analyzed to determine dry period occurrences in the central-west Poland. The SPI values calculated for the entire summer season (6-month period) dropped to ≤ 2.00, i.e. indicating 19 extreme drought occurrences at 12 stations during the analyzed four decades. The lowest SPI value of -2.75 occurred in 1989 at the Torun station. Never did the extreme drought extend simultaneously to the entire analyzed area. During the driest year – 1992, extreme drought occurred in 54% of all analyzed stations. SPI trend calculated for summer season was increasing in the central and western parts of the analyzed area, while in all the remaining parts it was decreasing (Fig. 10). The changes were statistically insignificant in the entire analyzed area.

Fig. 10. SPI linear trend coefficients in summer season in central-west Poland (1966-2005)



SPI values for particular months of growing season indicated 46 extreme drought occurrences. Extreme droughts were most frequent in August (12) and September (10), and the least frequent in July (3) and May and June (6 each). SPI values trends were statistically insignificant in all stations. Negative trends were stronger but less frequent (40% of all trends). Figure 11 presents an example of visibly decreasing SPI value and its trend line.

Fig. 11. SPI values for August and its linear trend (Kolo station) (1966-2005)



4.3.2 Methods and assessment of growth season on example of Poland

All analyses of agroclimatic indices require a clear definition of the analyzed growing season. There are different methods for defining growing season, i.e. determination of its beginning and end. In Poland, many analyses of changes of agrometeorological indices are based on growing season defined as summer season (April 1st – September 30th). However, this definition is not satisfactory for analyses of relationship between climate parameters and vegetation development status and requires a more precise determination of time of beginning and end of vegetation growth. The most frequently used term in this context is thermal growing season defined as a number of days with the established temperature of ≥ 5°C (Kepinska-Kasprzak M., Mager P., 2010).

In case of lack of the daily data, beginning and end dates of growing season are determined on the basis of monthly mean air temperature values. In Poland, the method of G. Guminski (1950) is used. The method is based on the following assumptions:

- mean monthly air temperature is assigned to the 15th of each month,
- each month is 30 days long,
- month to month temperature change is linear,
- equations (1) and (2) allow to calculate the number of days (x), which added to the 15th day of each month preceding the threshold value indicates the beginning or end day of growing season:
- temperature increase:
  (1) $x = 30 [(t_p - t_1) / (t_2 - t_1)]$

- temperature decrease:
  (2) $x = 30 [(t_1 - t_p) / (t_1 - t_2)]$
  where:
  t_p – thermal threshold (5°C)
  t_1 – mean monthly temperature of the month preceding threshold value,
  t_2 – mean monthly temperature of the month following threshold value.

Higher accuracy results can be achieved using methods based on mean 24-hour temperature value. Huculak&Makowiec (1977) method based on 24-hour data is the most frequently used method in Poland. It is based on the following assumptions:

- the beginning of thermal growing season (TGS) in a given year is the earliest date of a series of days with the mean daily air temperature of ≥ 5.0°C that is the beginning of such cumulated series of daily mean temperature deviations from the threshold value of 5.0°C that do not have negative values up to the end of the first 6 months of a year,
- the end of TGS in a given year is a day directly preceding the earliest date after the beginning of TGS of a series of days with the mean daily air temperature of ≤ 5.0°C that is the beginning of such cumulated series of daily mean temperature deviations from the threshold value of 5.0°C that do not have positive values up to the end of the end of a year.

Results of analyses based on mean 24-hour air temperatures from 11 meteorological stations located in different parts of Poland from 1966-2005 are presented below. The aim of analyses was to determine whether there were any substantial differences between growing season understood as summer season (April 1st – September 30th) and thermal growing season. The analysis of the thermal growing season was based on the average, the earliest and the latest dates of beginning and end of thermal growing season (TGS) as well as its length. Some of the results presented below are part of the Polish National Project No **619/NCOST/09/2010/0**.

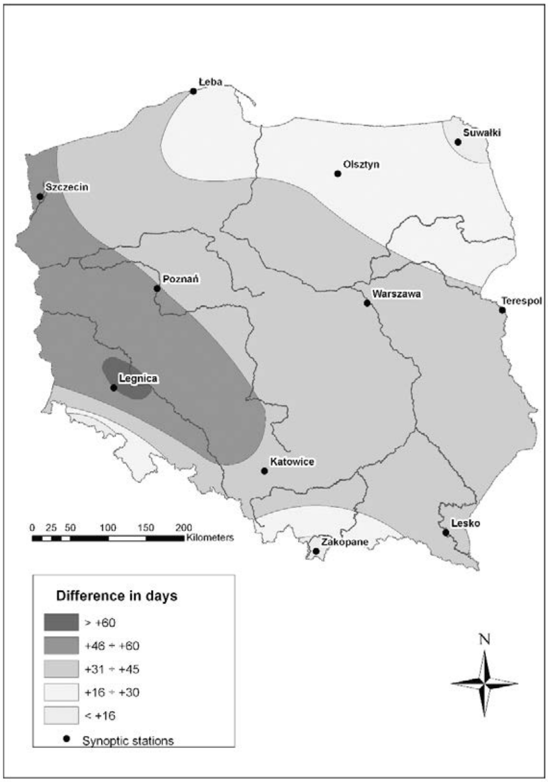
Length and dates of beginning and end of thermal growing season in Poland in 1966-2005 show visible zonal scheme oriented south west to north east (Fig. 12). The earliest date of beginning of thermal growing season was noted in south-west of Poland (before March 20) and the latest in north-east (1st and 2nd decade of April). Beginning of TGS, therefore, was registered ca. 10-15 days, on the average, prior to April 1st (i.e. beginning of summer season), while in north-east Poland and in the mountains by ca. 5-13 days after April 1st. Because vegetation growth in the west begins before "summer season", this fact should be taken into account in analyses of growing season and indices which describe GS. Date of beginning of thermal growing season – occurring later than beginning of summer season – in north east, on the other hand, makes it difficult to select appropriate methodological approach for analyses of the entire country (Tab. 7).

End of thermal growing season is the latest in south and west Poland (1^{st} decade of November on the average) and the earliest in north-east edges of the country and in the mountains (3^{rd} decade of October on the average). End date of thermal growing season occurs, therefore, later than that of summer season (i.e. September 30^{th}) in the entire area of Poland – the largest differences were noted in the west, smaller in north east, in the mountains and central Poland. However, it has to be noted that such late date of end of thermal growing season has no significant consequence for vegetation process, yielding and harvesting of crops. For example, harvesting medium-late and late potatoes takes place from October 5^{th} in central Poland to October 10-15^{th} in all other regions of the country. The average time of maize harvest in central Poland is September 20^{th} and in the north and in mountains – September 24-30^{th}, sugar beet harvest – from ca. 20 October in north-east Poland and mountainous areas up to 25-30 of October in south-east Poland. The average time of third harvest of red clover is on 10 of September in south-west Poland and on 15-20 of September in north Poland and montane areas. In Poland, therefore, from the point of view of agriculture, analyses based on summer season as the basic period do not bear significant error compared to analogous analyses based on thermal criterion ($T \geq 5.0°C$).

Still, because of the observed climate variability, there is a possibility that beginning and end dates of growing season (and consequently its length) can change (Impacts… 2004, IPCC… 2001). The analysis of changes of growing season in Poland in 1966-2005 indicates changes of beginning dates of growing season. Growing season begins visibly earlier in northern and western Poland (up to – 3.3 day/10 years, trend statistical significance $\alpha = 0.05$). In other parts of Poland, a weaker trend of belated beginning of GS (up to +1.5 day/10 years in southeast Poland) is noticed. In case of end dates of GS, there is a weak, statistically insignificant trend of its earlier occurrence. The result of the observed changes in beginning and end dates of GS is the statistically insignificant increasing trend of GS length in the northern and western parts of Poland.

Growing season length, determined by dates of beginning and end, affects crop selection and conditions of plant development and consequently the volume of crop yield. Shortening of growing season has negative impact on agricultural production. Belated beginning of growing season is particularly undesirable as it leads to accumulation of field works and belated spring sawing. Earlier end of growing season, on the other hand, is potentially harmful for cover crops and winter crops.

Fig. 12. Differences of length between thermal growing season and summer season



Tab. 7. Differences between thermal growing season and summer season in Poland in years 1966-2005

Region of Poland	**Growing season**								
	Beginning date			**End date**			**Length**		
	Thermal growing season	**Summer season**	**Difference**	**Thermal growing season**	**Summer season**	**Difference**	**Thermal growing season**	**Summer season**	**Difference**
	[date]	[date]	[days]	[date]	[date]	[days]	[date]	[date]	[days]
west	12.03. ÷ 21.03.	1.04	-11 ÷ -20	4.11. ÷ 9.11.	30.09	+35 ÷ +40	228 ÷ 241	183	+46 ÷ +60
central and east	27.03 ÷ 30.03.	1.04	-2 ÷ -5	1.11	30.09	+30 ÷ +32	214 ÷220	183	+32 ÷ +37
north and north-east	5.04 ÷ 10.04	1.04	+4 ÷ +9	31.10. ÷ 8.11	30.09	+31 ÷+39	210 ÷ 212	183	+27 ÷ +30
far north-east	12.04	1.04	+11	25.10.	30.09	+25	197	183	+14
montane area	16.04	1.04	+15	23.10.	30.09	+23	191	183	+8

Tab. 8. Changes in growing season in Europe

Area	Period	Observation materials	Growing seasons			Literature
			BGS	EGS	LGS	
Oceanic part of Scandinavian Peninsula	1982-2002	pheno+meteo	-3.0 day/dec.	delay	+4 to +5 day/dec.	Hogda K.A., Karlsen S.R., Solheim I. 2001
Continental part of Scandinavian Peninsula	1982-2002	pheno+meteo	-1 do -2 day/dec.	no changes	+1 do +2 day/dec.	Hogda K.A., Karlsen S.R., Solheim I. 2001
North Scandinavia	1969-1998	pheno (IPG)	small changes			Chmielewski F.M., Rötzer T. 2001; Chmielewski F.M., Rötzer T. 2002
West Estonia	1948-1999	pheno	-2 day/dec.	small changes	+2 day/dec.	Ahas R., Aasa A. 2006
Central and east Estonia	1948-1999	pheno	small changes			Ahas R., Aasa A. 2006
West and north Poland	1966-2005	meteo	-2 to -5 day/dec.	0 to -1 day/dec.	+2 to +4 day/dec.	Mager P., Kopec M. 2010
Central and southeast Poland	1966-2005	meteo	+1 to +2 day/dec.	-1 day/dec.	-1 to -2 day/dec.	Mager P., Kopec M. 2010
Central Europe	1969-1998	pheno (IPG)	-2.7 day/dec.	+1 day/dec.	+4 to +6 day/dec.	Chmielewski F.M., Rötzer T. 2001; Chmielewski F.M., Rötzer T. 2002
Central Slovakia	1930-1961 and 1987-2008	pheno	-1.5 day/dec.	-	-	Škvareninová J. et al.. 2009
Southeast Czech Republic	1940-2008	pheno	-2 day/dec.	-	-	Škvareninová J. et al.. 2009
Germany	1961-2000	pheno (IPG)	-2.3 day/dec.	-	-	Chmielewski F.M., Müller A., Bruns E. 2004
Germany,Austria,Switzerland (to h=950 m a.s.l.)	1982-2002	meteo	-0.9 to -2.1 day/dec.	+2,5 day /dec.	+1.1 to +4.9 day/dec.	Menzel A., Jakobi G., Ahas R., Scheinfinger H., Estrella N. 2003
Austria	1961-1990	meteo	-	-	+3 to +7 day/dec.	Hesenauer H., Nemani R.R., Schadauer K., Running S.W. 1999
Central England	1952-1990 and 1991-2000	pheno	70% of analyzed data -1.5 day/dec.	-	-	Fitter A.H., Fitter R.S.R. 2002
Southeast Europe	1969-1998	pheno (IPG)	small changes			Chmielewski F.M., Rötzer T. 2001; Chmielewski F.M., Rötzer T. 2002

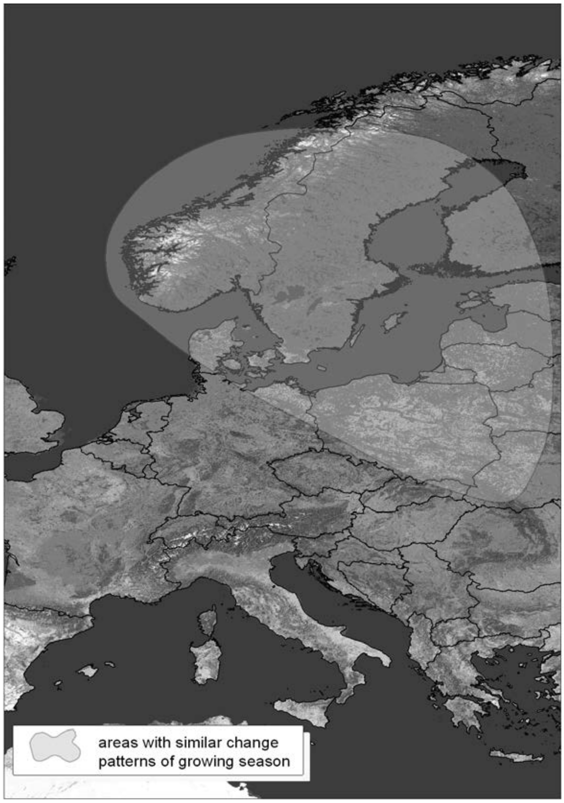
Abbreviations:
BGS – beginning of growing season
EGS – end of growing season
LGS – length of growing season
Obs. M. – observation materials
Pheno – phenological observations
IPG – International Phenological Gardens
Meteo- meteorological observations

Explanations:
-2.0 day/dec. – earlier BGS
+1.6 day/dec. – delay of EGS
+4 to +5 day/dec. – lengthening of LGS

One of the most interesting aspects of changes of thermal conditions in Poland is the fact that statistically significant increase of the mean annual air temperature has little impact on growing season length. This phenomenon can be explained by the specificity of changes of thermal conditions in Poland. The observed increase of air temperature is not evenly distributed throughout a year (Zmudzka, 2001) and manifests itself mainly in winters and summers thus not having any influence on length of growingseason (Kozuchowski, Degirmendžić, 2005). However, milder winters resulting from thermal inertia cause higher temperatures in spring months particularly in western regions of Poland (Kozuchowski, Zmudzka, 2001) where we also observe trend of earlier beginning date of GS.

Another method of determination of growing season is phonological observation. The majority of this type of study in Europe is based on results from International Phenological Gardens (IPG). IPGs are a unique network covering a large part of Europe (from the Scandinavian Peninsula to Macedonia and from Ireland to Finland) created for the observation of genetically identical shrubs and trees. The establishing of an international phenological observation programme was decided at

Fig. 13. Growing season in Europe



the first meeting of the Agrometeorological Commission of the WMO in 1953. The first phonological observations started at Offenbach (Germany) in 1959, and the number of IPGs increased up to more than 50 IPGs today. Identical species of trees and shrubs give an opportunity to conduct observation of phenological phases in different climate conditions. The observations have been conducted for over 40 years and include over 23 plant species.

Literature research allowed to collect information on changes of growing season in Europe (Tab. 8). In Europe, as in Poland, the trend of earlier date of beginning of growing period is more visible than the trend of changes of GS end dates. Spatial distribution of values of GS parameters in Poland shows the greatest similarity to patterns observed in the Scandinavian Peninsula and in Estonia (Fig. 13). In all these areas – in their western parts which are most exposed to influence of oceanic air masses, trends of earlier GS beginning dates are the strongest; while in their central and eastern regions the changes are weaker or absent.

4.4 Spain

4.4.1 Trends in temperature, precipitation, sun hours, wind and humidity for several climatic zones of Peninsular Spain

Data used in the study

Daily data of temperature, precipitation and sun hours, for the period 1950-2009 have been used in the trend analysis study for a total of 25 stations of the synoptic network of AEMET. The Climatic zones considered in the study were the following:

a. Galicia and Norther coastal zone (meteorological stations: Vigo-Peinador, Santiago Labacolla, Oviedo aeropuerto, San Sebastián Igueldo, Vitoria Foronda).
b. Northern Plateau (meteorological stations: León-Virgen del Camino, Burgos-Villafría, Salamanca-Matacán, Valladolid-Villanubla).
c. Southern Plateau (meteorological stations: Madrid-Barajas, Albacete-Los Llanos).
d. Guadiana and Guadalquivir river basins (meteorological stations: Badajoz-Talavera la Real, Sevilla-San Pablo, Morón-Base Aérea, Córdoba-airport, Almería- airport).
e. Ebro's river basin (meteorological stations: Logroño-Agoncillo, Zaragoza- airport, Huesca-Monflorite, Teruel).
f. Mediterranean coastal zone (meteorological stations: Reus, Valencia-Manises, Alicante-El Altet, San Javier (Murcia), Alcantarilla (Murcia), Almería airport, Palma de Mallorca-Son San Juan).

Summary of the trend study results

Northern and North Western zones

Temperature. There has been an increase of maximum and minimum temperatures averages, as much in the annual average as in the vegetative period (February to June, both included) average. Nevertheless, such temperature increases have not been even throughout the last 60 years period. Three different periods can be distinguished. In the first, approximately from 1950 to 1970, there was a decrease in temperature averages. In the second, from 1970 to 2000, there was a sustained increase. Along the third, the last ten years, temperature averages have remained constant. For the whole period (1950-2009), maximum temperature averages (annual and vegetative period) have increased slightly more than minimum temperature averages, over 1° C in both cases. In Galicia there has also been an increase in the number of hot days (maximum temperature over 30° C) and a decrease in the number of frost days (minimum temperature under 0° C). Along the Northern coastal zone there are no trends in these last two climatic elements.

Precipitation. There has been a small decrease in the amount of precipitation registered in annual periods or vegetative periods. It rains approximately a 10% less at present than in the 50's, and this decrease has taken place mainly from the 80's. Nevertheless there have not been changes in the (annual or vegetative period) number of days with precipitation, which suggest that it rains less when it does. In contrast, there has been a slight increase in the intensity of short duration showers. There are no trends in the number of days with thunder storm.

Sun hours. It seems that there has been an increase in the number of sun hours in the last 10 or 15 years, but there are no changes for the whole period. There is a negative trend in the first 30 years (1950-1980), and a positive trend afterwards (1980-2009) to recover in the last decade the annual sun hours of the 50's.

Wind. There are decreases in the wind run as well as in the gusts maximum speed, but changes in these two elements have been so marked as to suggest that there have been changes in the kind of measurement instruments or changes in the placement of the anemometer.

Northern Plateau

Temperature. There has been an increase of maximum and minimum temperature averages, as much in the annual average as in the vegetative period (February to June, both included) average. Such increase is bigger in maximum temperature averages, slightly over 1° C, than minimum temperature averages, slightly under 1° C. Three periods can be distinguished. In the first, approximately from 1950 to 1970, maximum and minimum temperature averages have been relatively high, similar to those of the present. A second period, from 1970 to 1990, with lower averages. And a third, from 1990 to 2009, in which temperature averages have recovered, and possibly surpassed those of the 50's and early 60's. It is to remark, that considering the period from 1970 to the present, the increasing trend is quite clear. For both periods (annual and vegetative), there has also been a small increase in the number of hot days (maximum temperature over 30° C) and approximately a 10 % decrease in the number of frost days (minimum temperature under 0° C).

Precipitation. In the last 60 years the amount of precipitation has decreased around a 15 % in the annual as well as in the vegetative period. For the vegetative period, there are no trends in the number of days with precipitation or with thunderstorms, but there is a slight increase of both in the annual period. It is to remark that there has been an accused decrease in the amount of precipitation (around 50%) registered in the months of February and March.

Sun hours. There is a negative trend in the first 30 years (1950-1980), and a positive trend afterwards (1980-2009) to recover in the last decade the annual sun hours of the 50's.

Wind. There is a decrease in the annual wind run and the gusts maximum speed in the four stations considered, but their temporal patterns are different. Interannual variability is quite high. In the stations of Salamanca and Valladolid there has been a marked change at the beginning of the 90's, which points to a change in measurement instrumentation or a change in the anemometer placement.

Southern Plateau

Temperature. There has been an increase of maximum and minimum temperature averages in the annual average and in the vegetative period (February to June, both included) average. The increases of maximum and minimum temperatures averages for the vegetative period have been of approximately 1.5° C, while the annual averages have experienced an increase of 1° C in maximum temperatures and an increase of 1.5° C in minimum temperatures. Along the 60 years (1950-2009) two periods can be distinguished. The first from 1950 to approximately 1970 in which there is a negative trend, and the second from 1970 to the present in which the trend is markedly positive. There has been an increase of 10 % in the annual number of hot days (maximum temperature over 30° C) and a 5 % decrease of frost days (minimum temperature under 0° C). For the vegetative period such percentages have been slightly bigger.

Remark. The data series of the Madrid-Retiro meteorological station goes back to the end of the XIX century. Although there have been 5 periods with different trends along the XX century, there is a clear increase in maximum and minimum temperatures annual averages. Minimum temperature annual averages have increased from 8° C, annual average at the beginning of the century, to 10° C at the end of the century. As for the different periods, there was no trend from 1900 to 1920 in minimum temperatures annual average. There was a positive trend in the period comprised between 1920 and approximately 1960. From 1960 to the middle of the 70's the trend was negative. There was a marked positive trend from the middle of the 70's to approximately 1990. Finally, there is no apparent trend from 1990 to 2009. It is to remark that the town's heat island effect have not been removed from the series o annual averages of minimum temperatures.

Precipitation. The patterns of evolution through time of the two meteorological stations are different. While in Madrid-Barajas there has been a clear decrease in precipitation along the last 60 years: it rains 30 % less in the vegetative period and in the annual year, rainfall in Albacete-Los Llanos has remained constant along that period (1950-2009), although there is a high interannual variability. There are no changes in the number of days of precipitation and the number of days with thunderstorms.

Sun hours. There is a negative trend from 1950 to the middle of the 80's, and a positive trend afterwards, although the annual sun hours in the last years have not reached the amounts of the 50's. *Wind*. Not enough data to get a conclusion.

Guadiana and Guadalquivir river basins

Guadiana river basin

Temperature. There has been an increase of maximum and minimum daily temperatures in the annual average and in the vegetative period (February to June, both included) average. In the Guadiana river basin three periods can be distinguished. The first, ranging from 1950 to the beginnings of the 70's, has a negative trend in maximum and minimum temperature averages. The second, from the beginnings of the 70's to the middle of the 90's, has a positive trend. And a third, from the middle of the 90's to the present, in which the temperatures have remained constant. Along the whole considered period (1950-2009) there has been an increase of 2° C in daily maximum temperature averages for the vegetative period, and an increase of 1° C in daily minimum temperature averages. There has been an increase in the number of hot days (maximum temperature over 30° C), while it has remained constant the number of frost days (minimum temperatures under 0° C). It is to remark that 2005 was the year with more frost days (24) in the whole period (1950-2009). If that value were removed of the series, the trend in the number of frost days would be negative. Taking into account that there are studies of temperature trends in the southern half of the Peninsula referring to the last 30 or 40 years, it should be noted that considering the period from 1970 to the present, the increasing trend is clear and sustained in the Guadiana and Guadalquivir river basins.

Precipitation. In the Guadiana river basin there has been a clear decrease along the last 60 years in the amount of precipitation in both periods, annual and vegetative. For the vegetative period there is a slight negative trend in the number of days with precipitation, but there is no trend in the annual period. There are no trends in the number of days with thunder storms. It is to remark that 2005 was the year with less precipitation (229 mm) for the whole period (1955-2009) of the series (Badajoz-Talavera la Real).

Sun hours. There is a negative trend from the 50's to the mid 80's, and a positive trend from the mid 80's to the present, to reach the annual sun hours of the 50's.

Wind. Three periods can be distinguished. The first from 1960 to 1980 with high interannual variability in annual wind run and average values in annual wind run. A second, between 1980 and 1990, with high interannual variability and high annual wind run values. The third, from 1990 to the present, has a small interannual variability and lower annual wind run values. In the first 20 years the average gusts maximum speed was around 90 km/h, and in the following 30 yeas it decreased to around 80 km/h.

Guadalquivir river basin

Temperature. There has been an increase of maximum and minimum daily temperatures in the annual average and in the vegetative period (February to June, both included) average. The increase in the annual and vegetative average daily maximum temperatures has been of 1° C, while it has been near 2° C in annual and vegetative average daily minimum temperatures. Two periods can be distinguished, the first from 1950 to the mid 70's with a negative trend and a marked interannual variability, and a second from the mid of the 70's to the present with a positive trend and lesser interannual variability. There has been an increase in the number of hot days (maximum temperature over 30° C) and a decrease in the number of frost days (minimum temperatures under 0° C). It is to remark that 2005 was the second year with more frost days (24, annual period) in the whole period (1950-2009), while there are no frost days in the last 4 years. There are no frost days in the last 10 years over the plains near the river in its lower half course.

Precipitation. It has been a clear decrease in the amount of precipitation in both periods, annual and vegetative. For the vegetative period such decrease is over 30 %, and it is approximately of 25 % for the annual period. There is a slight increase in the number of days with precipitation and no trend in the number of days with thunder storms. For the vegetative period there have been two periods, the first from 1950 to 1980 in which there is an accused interannual variability and a slight increase in the number of days with precipitation, but no trend in the amount of rainfall. And a second period, from approximately 1980 to 2009, in which there has been a decrease in interannual variability, rainfall amount and number of days with precipitation. It is to remark that, considering just the months of February and March, there have been a marked decrease in the amount of precipitation in both river basins and a decrease in the number of days with precipitation. *Sun hours.* There is a negative trend from 1950 to the mid 80's, and a positive trend from then to the present, to reach the year sun hours of the 50's.

Wind. Two periods can be distinguished: the first 30 years (1966 a 1996) and from 1996 to 2009. In the second period, the interannual variability of annual wind run is markedly bigger. In the opposite, the gusts maximum speed is around 110 km/h as average for the first 15 years, while it decreased suddenly to around 90 km/h in 1980. Such a sudden decrease points out to a change of measurement instruments. *Humidity.* In both annual and vegetative periods, there has been a decrease of average humidity in the Guadalquivir river basin between 1950 and 1979, and it has remained constant afterwards.

Ebro river basin

Temperature. Three periods can be distinguished in annual and vegetative period averages of daily maximum and minimum temperatures. A first, ranging from 1950 to the end of the 70's, in which the trend is slightly negative. A second, from the end of the 70's to the end of the 90's, with a marked positive trend. And a third, from the end of the 90's to the present, in which temperatures have remained constant. For the whole period (1950-2009), there is an increase in daily maximum and minimum temperature averages, in both annual and vegetative period. Daily maximum temperature averages have increased around 2° C, while daily minimum temperature averages have increased around 1° C. There has been an increase in the number of hot days (maximum temperature over 30° C) and a decrease in the number of frost days (minimum temperatures under 0° C) for both periods, annual and vegetative. It is to remark that, along the whole period (1950-2009), 2005 was the second year in number of frost days in the vegetative period (31 in Huesca), and the year with highest number of frost days in the annual period (76 in Huesca and 49 in Zaragoza). A displacement of about two weeks, to an earlier occurrence, has taken place in dates of the last frost day (although this has not happened in one of the stations (Logroño-Agoncillo) considered in the study).

Precipitation. There is no significant trend in the Ebro valley in the amount of precipitation, nor in the annual period and neither in the vegetative period, but there are increases in the number of days of precipitation, number of days of thunder storms and the interannual variability. It is to remark that the years 2007 and 2008 are, respectively, the first and the second in amount of rainfall for the whole period (1950 a 2009) in Logroño-Agoncillo. In the southern face of the Pyrenees (represented by Huesca meteorological station), there has been a decrease in the amount of precipitation (around 30 %) but no change in the number of days with precipitation. From 1970, the number of days with thunder storms has decreased.

Sun hours. There is a negative trend from 1950 to the beginning of the 80's, and a positive trend from then to the present. It seems that in the XXI century first decade there is a similar number of annual sun hours than in the 50's.

Wind. Data are discrepant in the stations considered. While there is a decrease in the gust maximum speed, from 120 to 100 km/h, in Zaragoza, there has been an increase, from 100 to 110 Km/h, in Huesca. In Logroño there has been a slight decrease both in the annual wind run and in gusts maximum speed.

Humidity. In the series of Zaragoza Airport meteorological station there has been a decrease, from 65% to 60 %, in the annual average.

Mediterranean coastal zone

Temperature. Two periods can be distinguished in annual and vegetative period averages of daily maximum and minimum temperatures. In the first, from 1950 to the beginning of the 70's, there is a negative trend. In the second, from the beginning of the 70's to the present, the trend has been positive. For the whole period (1950-2009), there has been an increase of approximately 1° C in daily maximum and minimum temperatures for both annual average and vegetative period average. There has been an increase in the number of hot days (maximum temperature over 30° C) and a decrease of around 50 % in the number of frost days (minimum temperatures under 0° C), in spite of 2005 being one of the years with more frost days in the whole period (1950-2009). In Valencia-Manises meteorological station, which series begins in 1966, the increase is more marked, around 2° C, due to no considering the decrease between 1950 and 1970. But in the last 5 years there has been an increase in the number of frost days in this station. A displacement of about two weeks, to an earlier occurrence, has taken place in dates of the last frost day.

Precipitation. There is no significant trend in the amount of precipitation in both periods, annual and vegetative, but there are increases in the number of days with precipitation and the number of days with thunder storms, while there is a decrease in the interannual variability (which, in general, is quite marked). There is a slight negative trend for the months of February and March. *Sun hours.* Three periods can be distinguished. The first, from 1950 to 1985, with a decrease in the number of annual sun hours. A second, from 1985 to 2000, with a marked increase; and a third, the last ten years, in which there is a decrease. Around 2000 the number of annual sun hours recovered the values of the 50's (around 3000), but at present the number is similar to that of the 70's (around 2800).

Wind. In Valencia-Manises meteorological station (series from 1966 to 2010), from 1966 to 1990 there is a negative trend in annual wind run and no trend in gusts maximum speed, but in the last 20 years the trend is positive in annual wind run and markedly decreasing in gusts maximum speed. There are two periods in Alcantarilla meteorological station, but in this case the trend is positive in the last 20 years for gusts maximun speed. In San Javier station, the trend is negative for the whole period in annual wind run, and there is no trend in gusts maximum speed.

Humidity. The three meteorological stations present quite different patterns, so it is not possible to extract a consistent conclusion.

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CAPITOLO III

POTENTIAL OF REMOTE SENSING TO SUPPORT THE ASSESSMENT OF CLIMATE CHANGE AND VARIABILITY ON EUROPEAN AGRICULTURE

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Abstract. An important objective of the COST 734 "CLIVAGRI" was to study the benefits of satellite remote sensing to assess climate change and variability impacts on agriculture. In the frame of WG2.1, satellite data records, e.g. series of observations over time that measures variables believed to be associated with climate variation and change, were surveyed and collected among European countries, based on a specific questionnaire, and the possibilities and limitations of the assessment of spectral climatic and biophysical data for agriculture warning purposes were reviewed.

During the study of satellite data availability and their resolution in time and space, long term archives of satellite data useful for agroclimatic studies were observed, software tools for exploitation of satellite archives and indices related to vegetation state which can be retrieved from archives of satellite data were also tested. Usually, remote sensing data are used in order to derive useful information such as vegetation indices and agroclimatic indices. Regarding to the combined methods in crop yield modelling, the incorporation of satellite data into crop simulation models has a number of applications in regional crop production assessment and forecasting. These approaches are more sophisticated but need high spatial and temporal resolution remote sensing data. In the near future, increase in the use of satellite data into crop simulation models is expected due to improvements in sensor capabilities (spatial resolution, hyper-spectral data).

Furthermore, examples of crop models using physical and biophysical variables from satellite remotely sensed data together with ground measurements to improve the crop growth modelling were applied and strategies / methods of remote sensing data assimilation in crop models were reviewed. Methodologies and key results of remote sensing applications for the detection of potential frost damage on agricultural vegetation using measured meteorological and agronomical data are also presented.

Finally a review of recent improvements in Earth Observation satellite data for agrometeorological modelling and the challenges for the operational assimilation of satellite image data in models, mentioning

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observations with a cloud-free and with a cloudy atmosphere, and a survey of the most important statements of the IPCC Fourth Assessment Report based mainly on the satellite-borne observations, are presented, with recommendations dedicated to different level of users.

1. Introduction

An important objective of the EU COST Action 734 "Impacts of Climate Change and Variability on European Agriculture – CLIVAGRI" is to study the benefits of satellite remote sensing to assess climate change and variability impacts on agriculture.

Agrometeorological data usually come from a very sparse meteorological network, sometimes incomplete and/or not always available. Satellite data are becoming important tools in agroclimate related studies due to the availability of the long time series. Characteristics of radiometers on-board meteorological and environmental satellites allow for determination of many parameters characterising the actual state of the biosphere and spatial and temporal changes. Satellite remote sensing has contributed to agricultural studies since the early seventies using optical data for the classification of agricultural crops and monitoring crop growth and crop development. Vegetation can heavily influence climate in terms of energy balance and, at the same time, it represents a sensitive indicator of the effects of climate change and man-made influences.

The leaf area index (LAI) is a major biophysical canopy parameter, which has an important role in vegetation physiological processes and ecosystem functioning. Assessment of crop LAI and its spatial distribution over agricultural land is of importance for addressing various agricultural issues such as: crop growth monitoring, vegetation thermal and hydric stress, crop forecasting, yield predictions and management practices. Long-term monitoring of LAI can also provide an understanding of dynamic changes in productivity and climate impacts on vegetation ecosystems.

Remote sensing is seen as an complementary tool to provide missing or inappropriate information regarding the achievement of sustainable and efficient agricultural practices. The estimation of LAI from satellite data is based on different algorithms and procedures, which used mainly spectral indices and radiative transfer model inversions (Broge and Mortensen, 2002).

LAI is generated globally from various sensors (AVHRR, MODIS, MISR, POLDER, SPOT-VGT, etc) with data at different spatial resolutions (250m to 1-3km) and temporal frequencies (4-day, 8-day and monthly). Some vegetation spectral indices-LAI relationships for example with NDVI, MSAVI2, and MTVI2 have proved to be reasonably efficient for estimating LAI with satisfactory absolute values and spatial variability.

Due to recent satellite availability, high resolution spatial and spectral (hyperspectral) data are being used to retrieve LAI and other biophysical and biochemical variables such as leaf chlorophyll and water content.

Crop models simulate crop growth under different environmental and management conditions, taking various limiting factors (e.g., soil, weather, water, nitrogen) into account in a dynamic way. These simulation models are good tools for diagnosing crop growing conditions, for predicting yield over large areas, to understand the spatial variability of crop behavior and to design tools for crop monitoring over large areas (Launay and Guérif, 2005).

Satellite remote sensing provides extensive spatial information on the actual growth status of the agricultural crops. The use of satellite-derived data throughout the crop's growing season is one of the methods that allow a spatial calibration of the crop model by locally estimating the missing information on model parameters (Batchelor *et al.*, 2002). Several methods of using remote sensing data with crop models have been explored (Delécolle *et al.*, 1992; Fischer *et al.*, 1997; Combal *et al.*, 2002; Haboudane *et al.*, 2004). The combined use of the assimilation of data acquired during crop growth, and of spatially distributed data obtained by remote sensing allows relevant simulations of the plant and soil state variables.

Yield assessment and forecasting is a research field of great importance. Accurate yield assessment can assist policies, decision making, management and mitigation strategies from national to farm level. The main methods for crop yield estimation and forecasting are remote sensing based methods, crop growth models, agroclimate models and statistical sampling methods (Ren *et al.*, 2008).

Crop growth models are successfully used to simulate the effects of agricultural practices and climatic conditions to crop growth and yield (Launay and Guerif, 2005). However, their predictive accuracy over large area is limited by the lack of spatially distributed information regarding weather conditions and crop characteristics. The extensive spatial information of remote sensing data contributes in minimizing this limitation. Thus, remote sensing data can be used for the spatial calibration of the crop model by locally estimating the missing information on model parameters (Batchelor *et al.*, 2002; Launay and Guerif, 2005).

The dedicated studies show that many useful techniques have been developed to obtain canopy state variables from remote sensing data, and for assimilating the acquired variables into crop models. However, for crop modeling and remote sensing data assimilation to be commonly used on a regular operational basis, a lot of effort has to be spent on bridging the gap between data availability and accuracy as well as between model and user requirements. This could be achieved by integrating satellite images with different spatial, temporal, spectral, and angular resolutions, and the fusion of optical data with data of different origin, such as LIDAR, radar and *in situ* measured parameters.

As remote sensing technology is evolving, this kind of research is being continued. Still, basic concepts and satellite derived parameters (e.g. reflectance, LAI, NDVI) are used, whereas the contribution of the spatial, temporal and spectral enhancement of the data to the accuracy of the predictions made is further examined.

The objective of this chapter is to examine the challenges for the operational application of satellite image data in agrometeorological models. The starting point is an assumption that remotely sensed data have been shown to be useful in such models, and subchapters illustrate this point.

2. Review and assessment of spectral climatic and biophysical data for agriculture warning purposes: Possibilities and limitations

L. Toulios and P. Struzik

2.1 Satellite Remote Sensing as a Tool for Monitoring of Climate and its Impact on the Environment – possibilities and limitations

Development of satellite remote sensing allowed for completely new possibilities in weather observations. Data coverage, both spatial and temporal was largely increased. Sensors installed on meteorological satellites were designed for measurement and observation of typical meteorological variables, which are also base for climate monitoring. Additionally, satellite sensors make possible observations of land and sea surface and their features related to actual state of surface – vegetation, temperature, moisture, chlorophyll concentration, suspended matter, wind etc (Struzik *et al.*, 2008).

Meteorological satellites have been present in space for almost 50 years. Such a long period allows for climatological studies based on remotely sensed observations of the Earth and atmosphere. The longest series concern cloud observations but continuous improvement of instruments made possible also: air sounding, land surface properties observations, oceans and seas monitoring, snow and polar ice caps observations and many other application.

Monitoring of climate require observations which are related to processes which are driving forces for possible changes. Space observations provide valuable information in global, continental and regional scale which helps to better understand processes which are hardly detected by point ground measurements. Especially important are satellite observations which help in key areas of uncertainty in understanding climate and Global Change, such as:

- Earth's radiation balance and the influence of clouds on radiation and the hydrologic cycle,
- Oceanic productivity, circulation and air-sea exchange,
- Transformation of greenhouse gases in the lower atmosphere, with emphasis on the carbon cycle,
- Changes in land use, land cover and primary productivity, including deforestation,
- Sea level variability and impacts of ice sheet volume,
- Chemistry of the middle and upper stratosphere, including sources and sinks of stratospheric ozone,
- Volcanic eruptions and their role in climate change.

For analysis of long term processes related to climate, tools with high stability and low uncertainty are required. The question is whether instruments placed onboard of meteorological satellites are characterised by enough level of mentioned parameters. Long term monitoring of vegetation status make possible to detect temporal changes in the timing of vegetation growth.

Most of the operational satellites were created as weather rather than climate platforms. As a result, long term absolute accuracy of satellite measurements was not a crucial issue. In the measurement of the climate variable it is vital for understanding climate processes and changes. However, it is not as necessary for determining long-term changes or trends as long as the data set has the required stability. And, when it comes to building satellite instruments, stability appears to be less difficult to achieve than accuracy. The difficulty arises because of the many known and unknown systematic uncertainties that are to be accounted for in the calibration of the instruments. Although excellent absolute accuracy is not critical for trend detection, it is crucial for understanding climate processes and changes.

During creation of satellite based Climate Data Records unique challenges appear:

- the need to manage extremely large volumes of data;
- restrictions of spatial sampling and resolution;
- accounting for orbit drift and sensor degradation over time;
- temporal sampling;
- difficulty of calibrating after launch (e.g., vicarious or onboard calibration);
- the need for significant computational resources for reprocessing.

A chronic difficulty in creating a continuous, consistent climate record from satellite observations alone is that satellites and instruments have a finite lifetime of a few years and have to be replaced, and their orbits are not stable. Most important is proper calibration of satellite sensors during their entire time. This can be done by pre-launch calibration, post-launch vicarious calibration and inter-calibration. Cloud cover is a major constraint on optical remote sensing, whether it is spaceborne, airborne or ground-based observation, particularly in cloudy regions.

2.2 Status of satellite climate and biophysical data for warning purposes for agriculture, in Europe

Climate variability and change is a global issue, which must be addressed with global models and global data are needed as input to these models. Earth Observation (EO) from space has a unique capacity to provide such global data sets continuously and consistently not only on this level, but also on the national and local levels and the use of alert and warning systems must be based on such data.

Some of the climate and biophysical variables essential for understanding and monitoring the climate system and the impact on agriculture can be efficiently observed from space, since this technology enables their systematic, global and homogeneous measurement. Climate and agriculture research is generally based on data collected for other purposes, primarily for weather prediction. To make these data useful for climate impact and warning studies, it is usually necessary to analyze and process the basic observational raw data and integrate into models.

The new generation of satellite sensors has brought an upgraded level of remote-sensed information to the user community thanks to a much better spatial, temporal, spectral and angular sampling of the radiative fields emerging from the surface of the Earth.

In the frame of COST 734, satellite data records, e.g. series of observations over time that measures variables believed to be associated with climate variation and change, were surveyed and collected among European countries, based on a specific questionnaire. The analysis of the data records which have been developed from operational satellite observations, presents the status of satellite climate and biophysical data for warning purposes for agriculture, in Europe (Toulios et al, 2008).

Among European countries there is a great heterogeneity in climate and biophysical data received from satellite sensors or collected as satellite-derived ready products. Some of them are currently collecting satellite data for years and these data records could be useful for models for climate change impact studies. SEVIRI/METEOSAT and AVHRR/NOAA are the most popular satellite sensors which provide climate and biophysical variables, among the surveyed countries. These two satellite systems are widely used by the European Meteorological Services, most countries having their own satellite reception systems. MODIS and ASTER onboard TERRA or AQUA platforms are preferred by a lot of the European countries due to easy accessibility via internet and because their improved spatial, temporal and spectral characteristics are appropriate for many agricultural applications.

The main variables that are collected in operational or experimental way are land surface temperature and NDVI (Normalised Difference Vegetation Index). In a second series of the climate variables are cloud products, snow cover, radiation, land cover, precipitation and SAF products. Evapotranspiration and albedo follows, and the rest variables only in specific cases (Air-stability, Storm detection, Ozone content, Vegetation Condition Index (VCI), Temperature Condition Index (TCI), Soil moisture, Modified Soil Adjusted Vegetation Index (MSAVI), leaf area index (LAI), Degree days, sea ice and sea wind).

There are differences between countries regarding the use of climate and biophysical variables, explained by the fact that the high level products (like evaporation, soil moisture, storm detection, etc) require quite complex algorithms or schemes. The SAF (Satellite Application Facility) products are not extensively used by many countries. It has also to be mentioned that in many countries the assimilation of satellite data into crop growth simulation models is still in an experimental stage.

NDVI is still considered one of the most successful of many attempts to simply and quickly identify vegetated areas and their "condition" and it remains the most well-known and used index to detect live green plant canopies in multispectral remote sensing data. In addition to the simplicity of the algorithm and its capacity to broadly distinguish vegetated areas from other surface types, the NDVI also has the advantage of compressing the size of the data to be manipulated by a factor two (or more), since it replaces the two spectral bands by a single new field. Nevertheless, it must be noted that the NDVI has tended to be over-used in applications for which it was never designed. For example using the NDVI for quantitative assessments raises a number of issues that may seriously limit the actual usefulness of this index if they are not properly addressed. The NDVI should be used with great caution in any quantitative application that necessitates a given level of accuracy. All the perturbing factors (atmospheric soil effects, anisotropic effects and spectral effects) that could result in errors or uncertainties of that order of magnitude should be explicitly taken into account; this may require extensive processing based on ancillary data and other sources of information. More recent versions of NDVI datasets have attempted to account for these complicating factors through processing.

The satellite-derived surface temperature (for land and sea), is also a broad used climate variable among the surveyed countries. Surface temperature is used in various agro-meteorological applications like: surface heat energy balance study, characterization of local climate in relation with topography and land use; mapping of low temperature for frost conditions or winter cold episodes; derivation of thermal sums (using surface temperature instead of air temperature) for monitoring crop growth and development conditions. Polar orbiting satellites in low orbit can provide much better spatial resolution and hence potentially more useful estimates of surface temperature than can other measurement methods.

Some variables like albedo, evapotranspiration, air-stability, storm detection, ozone content, soil moisture, sea wind and ice are used by a much reduced number of countries. This can be explain by the fact that the procedures used to retrieve such variables are still in experimental phase and do not satisfy the user requirements related with accuracy, spatial or temporal scales, etc. For example soil moisture is an important parameter for weather and climate prediction as well as for crop monitoring. Many efforts have been made for soil moisture estimation with space-borne sensors and in-situ measurements. These approaches measure soil moisture at different spatial scales and each of them have certain advantages and limitations. Microwave remote sensing measurements can provide physical retrieval of soil moisture in low vegetation areas, but have poor spatial resolution. Optical/IR measurements can be used to retrieve soil moisture at high spatial resolution statistically, but limited to clear days. In spite of these results, presently soil moisture retrieval with satellites is still not operationally available. The new generation of microwave remote sensing satellites (e.g. Terra SAR X) will provide soil moisture products in the near future.

3. Study of satellite data availability and their resolution in time and space, for the assessment of climate change and variability impacts on agriculture

P. Struzik, G. Stancalie, F.M. Danson, L. Toulios, Z. Dunkel and E. Tsiros

Satellite data useful for large scale agro-climatic analysis have been available since the start of operational meteorological satellite systems. Data are archived by different satellite operators and users. Selected archives are freely available or require only registration. Use of satellite data for long-term studies requires access to long time-series data. The purposes of this task are:

- Inventory of available long-term satellite data archives useful for agro-climatic analysis (NOAA/AVHRR, MODIS, other possibilities).
- Description of available indicators of vegetation status, derived from multispectral remotely sensed observations, which can be retrieved from long-term satellite data archives for further trend analysis.

The first step is inventory of available long-term satellite data archives containing data from visible and infrared sensors or processed products useful for agro-climatic analysis performed with the Web. This report is a summary of investigations presenting a guide for the users, where long-time series of satellite data for agro-climatic applications are available including the periods covered, areas covered, satellite sensors, available channels/products, spatial resolutions, focussing of freely available archives.

The second step is assessment of available indices and available in data archives together with guidelines on which indices can be processed from the data stored in archives representing different spectral channels.

3.1 Long term archives of satellite data useful for agroclimatic studies

Long term studies of temporal and spatial changes and characterisation of vegetation cover requires long series of satellite data produced by the same sensors or sensors which can be inter-calibrated with sufficient accuracy (NRC, 2004). The most useful satellite missions which comply with this requirement are meteorological satellites continuously operational since 1960. Also environmental satellites holding the same instrument like Terra and Aqua with MODIS instrument provide long time-series of data. Focusing on European coverage, the most interesting satellites are:

For more general studies (continental scale):

- Geostationary METEOSAT Second Generation (since 2003)

For regional studies (continental to country scale):

- Polar orbiting with AVHRR or similar instrument: NOAA (since 1978), METOP (since 2006, FengYun 1 – since 2002).
- Polar orbiting with MODIS instrument: Terra (since 2000), Aqua (since 2002).

For finer scale studies (country to sub-region scale): SPOT, LANDSAT, IRS, ASTER.

The most important parameters which are useful for agroclimatic analysis are:

- Pure VIS/NIR channels useful for construction of vegetation indices (VI).
- Processed vegetation indices (NDVI, LAI, SAVI, VCI and many others).

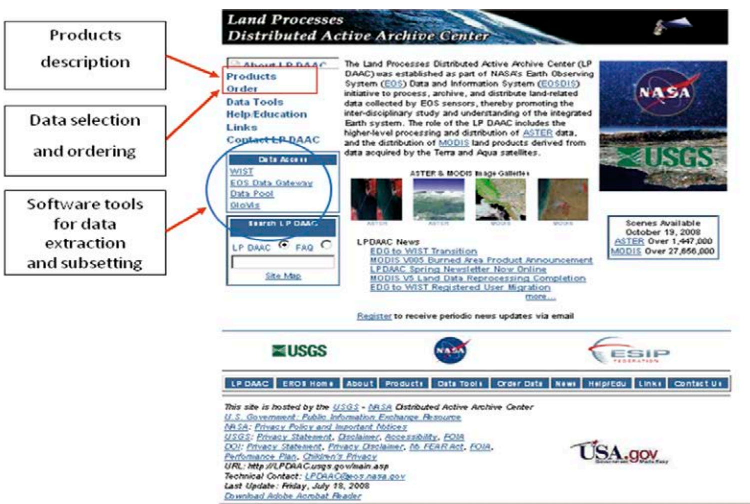
Due to possible climate change also time series of other parameters or phenomena related to agriculture may be analysed, such as:

- Land surface temperature, thermal anomalies (TCI).
- Radiation (Short Wave, Long Wave, FAPAR, etc.).
- Evapotranspiration.

- Land cover/change.
- Fire and burned area monitoring.

Analysis of vegetation anomalies resulting from possible climate change requires access to different types of services. Most important are long-term archives (Fig. 1) (preferably freely available) consisting of pure satellite channel data or various processed indices used for characterisation of the actual state of the biosphere. Taking into account ongoing studies, information from operationally available satellites in the form of data and products related to vegetation analysis are required. The third type of services important to users is software for satellite data searching, data extraction and presentation, due to the large variety of used formats. In this last case most recommended is software originally developed for the users of archives by operators of individual archives. Important advantage of such software is compatibility with data formats and free availability in case of free archives.

Fig. 1. Example of web archive interface (LP-DAAC). In the archive 70 different satellite products for land monitoring are available



3.2 Software tools for exploitation of satellite archives

Access to required satellite data and products is less difficult when specialized search engines and selection tools are applied. Administrators of individual archives provide many interesting tools which allow for:

- Product selection from archive
- Geographical area selection

- Time period selection
- Ordering products or direct connection to FTP site for download
- In some cases also visualization software based on distributed data format is available.

Typical tools helping with satellite products search and retrieval are listed in below:

- EUMETSAT Product Navigator
- Search and Preview Tool (www.landcover.org)
- USGS Global Visualisation Viewer GloVis
- NASA Warehouse Inventory Search Tool (WIST)
- LP DAAC MODIS Reprojection Tool on the Web (MRTWeb)
- LP DAAC Data Pool
- EOS Data Gateway

3.3 Indices related to vegetation state which can be retrieved from archives of satellite data

Parameters related to actual state of vegetation conditions, changes of cover, ongoing processes and resulting changes were investigated in the frame of many international research programmes and studies related to possible operational use of parameters for agroclimatic and agrometeorological applications (Heute *et al.*, 2006). Vegetation indices using spectral characteristics of green plants measured by satellite sensors are the most commonly used satellite products providing important observations related to: climate, land cover change, connected hydrological processes, management of natural resources and decision making processes for sustainable development (Schmidt and Karnieli 2002; Shin 2005).

Due to the long time-series of AVHRR data (Advanced Very High Resolution Radiometer) on board NOAA satellites, covering more than 30 years, applications were possible related to: global, continental and regional studies of agricultural primary production, annual variability expressed by changes in primary production and phenology cycle, related to climate change (Wood *et al.*, 2003; Shin and Kim, 2003; Peters *et al.*, 2002; Zhao and Schwartz, 2003).

As a result we can directly assess relations between global temperature trends (especially in temperate regions) and length of vegetation season. Thousands of scientific papers were based on satellite derived vegetation indices. Since the launch of Terra and Aqua satellites the possibility has emerged for use of moderate spatial resolution sensors with resolutions of 250m, 500m and 1 km using MODIS and SPOT Vegetation data. Investigations of ecosystem functioning at finer scales have been possible especially for homogeneous surface cover, not met at coarse resolution.

Satellite observations of vegetation combine visible channels placed at the chlorophyll absorbing part of spectrum and near infrared spectrum where leaf reflectance is more significant. As a result measurement of vegetation cover photosynthetic capacity can be observed and monitored for long periods. Use of those data requires capability for consistent processing of data sets covering longer periods and incorporation cloud detection filters and compensation for changing observation geometry, observation solar time, atmospheric influence and satellite sensor degradation (Broge and Leblanc 2000; Ramirez *et al.* 2007). Due to cloudiness, satellite vegetation products are averaged in time, producing composites based on data from periods of 7-16 days and applying resolutions from GAC/AVHRR 8 km (Kidwell 1997) to finer 0.25km MODIS/SPOT.

Vegetation indices are characterising the whole land surface, representing actual characteristics of land cover conditions. To satisfy needs of the users, techniques for elimination of atmospheric effects are applied (water vapour, ozone, aerosol etc.).

The most widely used indices are: NDVI, EVI, SAVI, ARVI and SARVI (Heute 1988, Kogan *et al.* 2003, Leeuwen *et al.* 2006). These indices represent the actual state of green vegetation. When analysing anomalies related to vegetation in comparison to longer periods, indices reflecting conditions are constructed: VCI, TCI, VHI or other anomalies.

3.4. Correlation between Climatic Water Balance and estimation of plant development stage based on satellite technologies (Case study for Poland)

P. Struzik and M. Kepinska-Kasprzak[1]

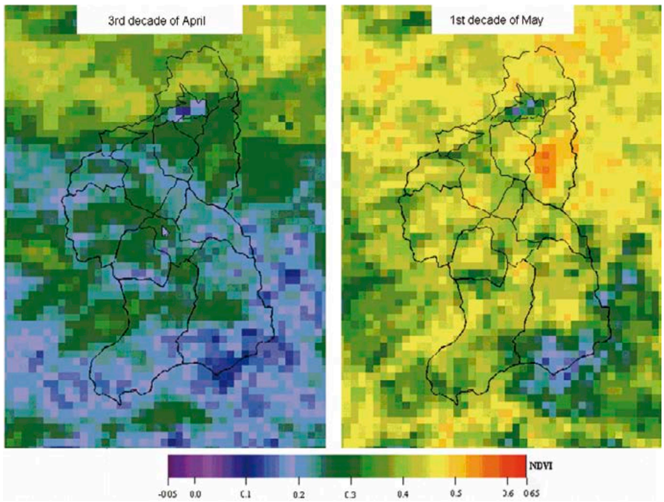
Climatic Water Balance (CWB) is one the indices characterizing atmosphere humidity. In agrometeorology, CWB is applied as an indicator of weather conditions during growth season and as an indicator of drought. Climatic Water Balance is a value derived from water input, i.e. precipitation and water loss caused by evapotranspiration. CWB, therefore, is a very general indicator of vegetation development stage. For the purpose of this study, standardized values of Climatic Water Balance based on the assessment of reference evapotranspiration, are calculated using the Penman-Monteith method (FAO 56), which allow for objective assessment of climatic water shortage and to compare different regions and time periods.

Satellite technologies, on the other hand, allow the nearly real time estimation of vegetation status and detection of impact of water deficit stress. The comparison of satellite data with the quantitative data of weather conditions that determine CWB will allow to evaluate just how

[1] The project was funded by the Polish Ministry of Science and Higher Education to support scientific projects of COST Action 734 members. The project was awarded ministerial funds for a period of 16 months – grant No. 619/N-COST/2010/0.

accurately does CWB reflect the actual vegetation stage. The result will also provide a valuable tool for monitoring drought.

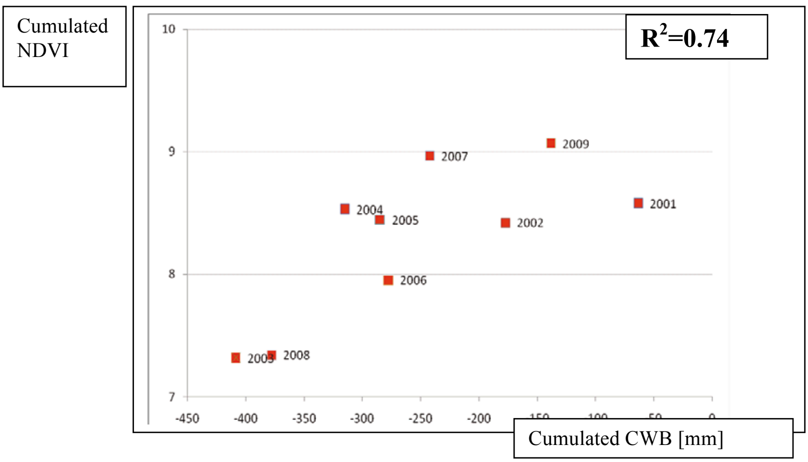
Fig. 2. Comparison of decadal NDVI values for Raba River catchment during Spring period (last decade of April and first decade of May)



Determination of the vegetation state is based on AVHRR/NOAA data, from which NDVI is determined for each day of analysed period. Clouds occurrence is a main limiting factor obstructing scene. To minimize cloud influence, data are grouped into decades (10 days periods) and MVC (Maximum Value Composition) technique is applied. The most important factor related to actual vegetation state is anomaly of actual values regarding to multi-annual mean for each individual decade. Data from whole period 1998-2009 were used for determination of mean, maximum and minimum NDVI values for each decade using full resolution of AVHRR data. Using those data as a reference, the VCI (Vegetation Conditions Index) were determined for each decade. VCI values reflects anomaly of vegetation state in comparison to the whole period, thus indicating positive or negative trends related to perfect conditions or less favorable situation connected to lack of water cased by drought or other factors having influence on vegetation development (e.g. temperature, sunshine, diseases etc). The study is carried out on data collected from two environmentally distinct areas in Poland: the Prosna, Dunajec and Raba river catchments. The Prosna catchment is almost entirely located in the central Poland lowlands and dominated by agricultural land. Dunajec and Raba catchment, are located in a highland and mountainous region. Example of NDVI distribution at the part of Raba catchment for two consecutive decades is presented in Fig. 2.

Climatic Water Balance and satellite data characterizing crop development stage are calculated for each decade of the vegetation season (Apr.-Sept.) of the period 1998-2009. Due to sparse satellite data for 1998-2000, for further analysis the period 2001-2009 was used.

Fig. 3. Comparison of cumulated decadal NDVI values (vertical axis) and cumulative decadal CWB values (horizontal axis) for selected station at Prosna catchment. Cumulative values for the period



Correlation between decadal CWB values and values of indices characterizing crop actual state determined on the basis of data acquired via satellite techniques were calculated and analyzed. The example of results is presented in Fig. 3. Good agreement (correlation coefficient = 0.74) was achieved between cumulated through vegetation season CWB and NDVI decadal values. Dry years are characterized by very low (negative) CWB and relatively low NDVI values, opposite effect was encountered for wet years, favorable for vegetation growth.

The second task was the comparison of daily evapotranspiration calculated with the Penman-Monteith method (ETo), and the actual evapotranspiration based on satellite data – based on 30 min Land-SAF product (ETc) (Figs. 4 and 5). This study was performed for whole year 2007.

The daily evapotranspiration values from Penman-Monteith and from satellite data were used as an input to hydrological model MIKE 11 NAM. Comparison of measured discharge with simulated discharge were slightly better for satellite product (R^2 = 0.95) comparing to Penman-Monteith (R^2 = 0.92).

Good results achieved with satellite derived evapotranspiration confirm the following benefits of this product:

Fig. 4. Distribution of yearly evapotranspiration determined from satellite (Land-SAF product) for the area of Prosna catchment

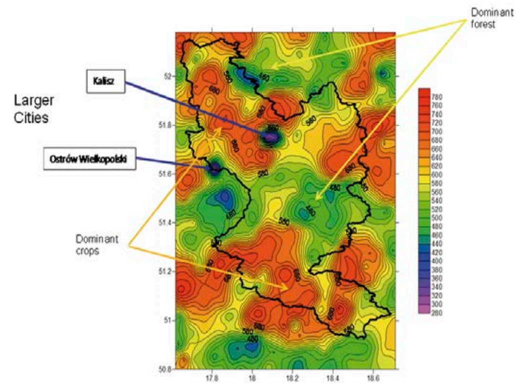
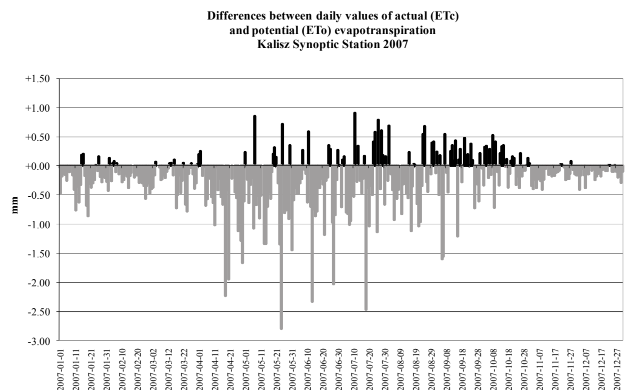


Fig. 5. Comparison of results obtained by Penman-Monteith and satellite method of calculation of evapotranspiration



- Good description of spatial distribution of evapotranspiration
- Possible use as an input to hydrological and agrometeorological models
- Economic benefits – dense network of ground measurements not required.

The realization of this project will gain further experience in application of satellite remote sensing techniques for real-time objective assessment of plant development stage. A basis for the implementation of satellite remote sensing into real-time assessment of crop status available to farmers (e.g. within agrometeorological protection service provided by IMGW) will be created. This project also contributes to drought mitigation in Poland. Real-time assessment of drought is of great practical significance in Poland where drought events are relatively regular and frequent causing large losses in agriculture. In case of drought, real-time assessment is extremely valuable as it provides opportunity for quick reaction such as applying necessary agrotechnical procedures.

4. Analysis of potential for assimilation of satellite data into models for the determination of current trends in agroclimatic indices based on spectral data – Remotely Sensed Indices in Crop Yield Modelling

E. Tsiros and N.R. Dalezios

Agriculture is highly dependent on environmental conditions and thus, a quantitative understanding of the climate of a region based on long time-series of meteorological data is essential for developing improved and efficient farming systems (Reddy, 1983). Nevertheless, complete and reliable meteorological long-series databases are difficult to find. Data loggers contribute to automatic recording of meteorological data, but still temporal gaps and discontinuities exist due to sensor failures or human errors (delayed upload of data, maintenance etc.) Thus, meteorological data usually come from a very sparse meteorological network, sometimes incomplete and/or not always available (Domenikiotis *et al.*, 2004).

Satellite remote sensing is contributing to agricultural studies since early seventies using optical data for the classification of agricultural crops and monitoring crop growth and crop development. In general, the application of remote sensing in agriculture falls broadly into three categories (Steven and Jaggard 1995): land classification and crop mapping; monitoring and forecasting of crop production and; identification of stress in crops and generally vegetation. Also, data from remote sensing platforms can be used to complement weather data in drought and crop yield assessments (Quarmby *et al.*, 1993; Hayes and Decker, 1996; Dalezios *et al.*, 2001; Domenikiotis *et al.*, 2004).

Crop yield can be considered as the productivity of a cultivated crop per unit area. In general, the area where a crop is cultivated is stable from year to year (e.g. Quarmby *et al.*, 1993). If field location changes on an annual basis due to crop rotation, identification of the field parcels is required (Steven and Jaggard, 1995). However, "productivity varies greatly from year to year with the weather and related factors to be the main source of variation" (Domenikiotis *et al.*, 2004).

Accurate production assessment on regional to national scales at a significant time period prior to harvest is becoming increasingly important in developing and developed countries (Domenikiotis *et al.*, 2006). Predictive relationships are quite difficult to derive, whereas incorporating vegetation physiology with spectral signatures depends on several logistical factors such as the cost and the temporal and spatial resolution of the associated satellite data (Domenikiotis *et al.*, 2004). Usually, the methods for estimating crop production are based on objective techniques such as crop growth modelling and remote sensing (Bouman, 1994).

4.1 Satellite data appropriate for long term monitoring

The way or better the techniques in which satellite remote sensing contributes to agricultural studies and the type of data used differentiate according to application needs. Remote sensing systems have difficulties in meeting the simultaneous requirements for high spatial and temporal resolution through the growing season to monitor individual fields (Domenikiotis *et al.*, 2004). The type of satellite data appropriate for crop monitoring and crop production assessment, agricultural drought monitoring and climate impact assessment are from remote sensing systems that provide low spatial and high temporal resolution data, since daily coverage and acquisition of data is needed for such applications. Also, long-series databases have to be available. Satellite data that fulfil the above requirements are NOAA/AVHRR and MODIS data. In most cases, daily data is aggregated to weekly or ten-day composite images.

4.2 Satellite remote sensing techniques for crop monitoring

Satellite remote sensing techniques in monitoring agroclimate are based on satellite derived parameters and indices. There are several approaches which can be classified as following (McVicar and Jupp, 1998):

- only remotely sensed imagery,
- combination of remote sensing products with meteorological variables, and
- crop yield modelling.

The first two approaches are usually preferred in monitoring, assessment, trend analysis and agroclimatic classification applications.

The interest for the remote sensing approach in crop yield modelling has been increased significantly during the last two decades. Satellite data can provide a better understanding of the spatial and temporal evolution of the parameters incorporated into models. Vossen (1994) divided the remote sensing methods into statistical, deterministic and combined. The statistical approach is based on indices computed from satellite data, averaged over a region or country and entered mostly in regression analysis. The deterministic approach consolidates the computation of Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI), Absorbed Photosynthetically Active Radiation (APAR) or Fraction Photosynthetically Active Radiation (FPAR) and biomass before yield assessment. The combined methods integrate remotely sensed information into crop growth models. The latter two methods require large amount of data (e.g. on plant physiology, soil and site specific characteristics, daily weather conditions), whereas the statistical methods have the minimum data requirements (Vogt, 1994).

One major application of remote sensing for agriculture is crop monitoring and the assessment of vegetation stress. Satellite derived indices and specifically vegetation indices have been extensively used for identifying stress periods in crops or vegetation generally (Steven and Jaggard, 1995; Kogan, 1995; Tsiros *et al.*, 2004).

The most commonly used vegetation indices in crop yield estimation are given below.

- Normalized Difference Vegetation Index (NDVI).
- Vegetation Condition Index (VCI) (Kogan, 1995).
- Temperature Condition Index (TCI) (Kogan, 1995).

The NOAA/AVHRR and MODIS derived NDVI has been extensively used in crop yield assessment/forecasting. A number of applications around the globe have denoted the importance of NDVI in crop yield modelling via statistical models (e.g. Benedetti and Rossini, 1993; Quarmby *et al.*, 1993; Dalezios *et al.*, 2001; Ren *et al.*, 2008). In most applications predictions and forecasts of yield were more than 80% accurate. The maximum predictive accuracy was near 95% and was obtained using MODIS data. The results showed that accurate predictions can be acquired 40-100 days prior to harvest.

Many researchers around the globe have used time-series of weekly or ten-day Global Area Coverage (GAC) NOAA/AVHRR NDVI images for deriving VCI and developed models relating the VCI data with crop yield (e.g. Hayes and Decker, 1996; Domenikiotis *et al.*, 2004, 2006; Tsiros, 2009). In most applications, the analysis of the difference between the estimated and the measured yields showed differences lower than 20% of the official value. The lower relative errors of the predicted yields were around 5%.

Lastly, applications based on the combined use of VCI and TCI have resulted to accurate yield predictions 30-100 days ahead of harvest (e.g. Dabrowska-Zielinska *et al.*, 2002; Tsiros, 2009). The use of multiple regression models relating VCI and TCI values with the final yield for yield assessment presented in most cases predicting accuracy higher than 95% regarding the upcoming yield.

4.3 Summary

Satellite remote sensing contributes in monitoring agroclimate with three main approaches. These are: the use of satellite data, the use of satellite data and meteorological data and crop yield modelling. Usually, remote sensing data are used in order to derive useful information such as vegetation indices and agroclimatic indices. In contrast to NOAA/AVHRR data, MODIS has higher spatial and spectral resolutions. Thus, this type of data is relatively better when downscaling is needed and can contribute to an increase in the accuracy of crop yield estimation.

On the other hand, NOAA/AVHRR data may have the disadvantage of low spatial and spectral resolution, but they provide higher number of overpasses per day and thus, they are potentially better instruments for near-real time applications. Also, NOAA/AVHRR data have been available since 1981 and long time-series exist. Thus, NOAA/AVHRR data are preferred in applications, where long time-series is needed.

Most statistical models are models relating indices describing the crop status with the final yield (crop yield models) and are applied with varying success for estimating the upcoming crop production. In most cases, estimation accuracy is higher than 90%. The favourite tool for remotely sensed crop yield modelling is regression analysis. When phenological observations are missing, correlation analysis is often used for identifying critical periods where crop conditions have direct impact to the final yield. The coefficients of determination (R^2) are not directly connected with important biophysical processes, and thus often present high variability depending on the type of crop been monitored, the area and period under investigation. However, the great advantage of these approaches is their simplicity. Even though they are not always very precise, they have the ability to recognize years with very high or very low yields many weeks prior to harvest.

Regarding to the combined methods in crop yield modelling, the incorporation of satellite data into crop simulation models has a number of applications in regional crop production assessment and forecasting. These approaches are more sophisticated but need high spatial and temporal resolution remote sensing data. In the near future, increase in the use of satellite data into crop simulation models is expected due to improvements in sensor capabilities (spatial resolution, hyper-spectral data).

5. Use of satellite remotely sensed data together with ground measurements to improve the crop growth modelling – Satellite data availability, methods and challenges for their assimilation in agrometeorological models and for the assessment of climate change and variability impacts on agriculture

G. Stancalie, A. Nertan, F.M. Danson and L. Toulios

Agroecosystems are defined as a spatially and functionally coherent unit of agricultural activity, oriented towards the production of food and/or other valuable goods such as timber, fibre or fuel, that includes the living and nonliving components involved in that unit as well as their interactions. According to Wood *et al.* (2000), agroecosystems are areas in which at least 30% of the land surface is dedicated to croplands or intensively managed pastures. In the last decades many agroecosystem models have been developed for numerous crop vegetation types, for different scales, and with a wide variety of applications.

The studied literature reveals that many valuable methods and techniques have been developed both for the retrieval of canopy state variables from satellite data, as for assimilating the retrieved variables in different crop models. For crop modelling and remote sensing data assimilation to be commonly used and on an operationally basis, a lot of effort have to be spent on bridging the unsuitability between data availability and accuracy, as well as, between model and user requirements. The increased EO image data availability, with different spatial, spectral and temporal resolutions, allows some new approaches regarding data integration and the fusion of optical satellite information with data of different other origins.

5.1 Crop models

The agroecosystem models, known as "crop models" or "crop growth models" incorporate biological and physiological parameters of plants and take into account the interactions between plants and their environment. In those models, vegetation state variables, such as phenological phases, dry mass, leaf water content, chlorophyll content and leaf area index (LAI) are linked to driving variables like weather conditions, nutrient availability and management practices. Usually, the models output is the final yield or accumulated biomass (Delécolle *et al.*, 1992; Weiss *et al.*, 2001).

The crop models are powerful tool for dealing with agro-environmental issues like: process-based or functional modelling of crops, land capabilities, crop water use efficiency, yields estimates, impact of climatic change on crop functioning, adaptation, mitigation, impact of agriculture on soil, water and air quality, impact of land use changes on agriculture, etc.

The crop models allow dynamic simulation of the behaviour of the soil-plant system (Fig. 6) and subsequently, they can give dynamic diagnostic information about soil and crop conditions.

The crop models have been developed at different spatial scales:

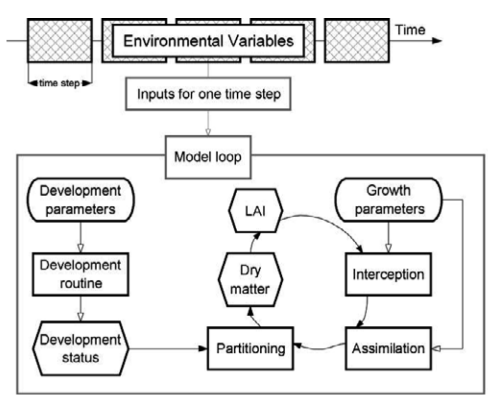
- large region (e.g. a country): yield estimates at different levels, yield responses to varying pedoclimatic and management conditions, water quality on very large watersheds, impact of global change;
- small region (county, watershed): yield estimates (producers associations), yield oscillations due to the interaction of various factors, (e.g. change in fertilization level), water consumption;

- field / farm: evaluation of crop structural models (able to provide more detail on the basic mechanisms of adaptation), decision making tools for crop management, precision agriculture, technological potential, impact of global change.

For the crop models at the regional scale, three basic approaches are available (Gommes, 2003):

- *operating models* use regional input data, considered as spatial averages of local point data. Due to the heterogeneity of the input data (e.g. solar radiation, surface temperature, rainfall) and the non-linear relationships between model inputs and outputs, these types of models are vulnerable to aggregation error (Hansen and Jones, 2000). Relatively simple process-based models can, however, produce accurate results using spatially averaged data (e.g. Wang and Engel, 2000; Challinor *et al.*, 2004);
- *crop simulation models on a grid*, in which all model inputs are interpolated to a common grid (Dorigo *et al.* 2007). The mathematical interpolation can be applied to the crop biophysical, biochemical, and agrometeorological parameters, as well as to weather data. A well known example for this approach is the EU MARS (Monitoring Agriculture with Remote Sensing) program, conceived to develop large scale operational tools in the field of agricultural information from dedicated methods for satellite image analysis and agro-meteorological models (Diepen *et al.*, 1998. Genovese, 1998; Boogaard *et al.*, 2002);
- *models which can be run at a limited number of weather (agro meteorological) stations*, in the case that most required inputs are actually available. This is the approach followed by AquaCrop FAO model (Raes *et al.*, 2009; Steduto *et al.*, 2009; Hsiao *et al.*, 2009).

Fig. 6. Simplified scheme of crop model (after Dorigo et al., 2007; adapted from Delécolle et al., 1992)



The approaches presented above can lead to important errors when many pre-processed inputs are used (e.g. weather grids). In addition, they all have to be calibrated against agricultural statistics data, thereby somehow losing the advantages associated with the complex scientific approach.

Their use of crop models is restricted by the uncertainties induced by their input parameters or initial conditions (Guérif and Duke, 1998). To provide more information useful for crop functioning models, remote sensing data can be supplied by different sensors, joining different wavelength regions (optical, microwave or thermal infrared) and different temporal frequency (Weiss *et al.*, 2000).

5.2 Physical and biophysical variables from remote sensing data which can be assimilated into crop models

Various EO data and derived parameters may be used to drive crop growth models. Table 1 presents the canopy state variables and soil characteristics accessible from remote sensing observations in several spectral domains: visible (VIS), near infrared (NIR), near and short wave infrared (SWR), thermal infrared (TIR), active and passive microwaves (μ-wave). The number of '+' indicates the potential accuracy with which the variable can be estimated.

In the solar reflective domain (i.e. from the visible to the short-wave infrared) canopy structure variables are mainly accessible such as vegetation reflectances/radiances and the inferred variables, leaf chlorophyll and water content, the fraction of absorbed photosynthetically active radiation (FAPAR), vegetation indices, etc.

Particularly promising results have been obtained by assimilating the LAI estimates derived from visible and near-infrared satellite data (Moran *et al.*, 1997; Guérif & Duke, 1998, Chen *et al.*, 2002, Haboudane *et al.*, 2002; Baret *et al.*, 2007). Fig. 7 presents an example of a LAI product, obtained from MODIS satellite data over Romania.

Unfortunately, the satellite data in the solar reflective spectrum are affected by atmosphere and cloudiness, which often prevents from their effective use for vegetation monitoring. To increase the probability of cloud-free acquisitions, satellite optical sensors with a short revisit time, with a moderate to high spatial resolution, some operating in tandem, can be used (MERIS/ENVISAT, ASTER/TERRA-AQUA, SPOT, IRS etc.).

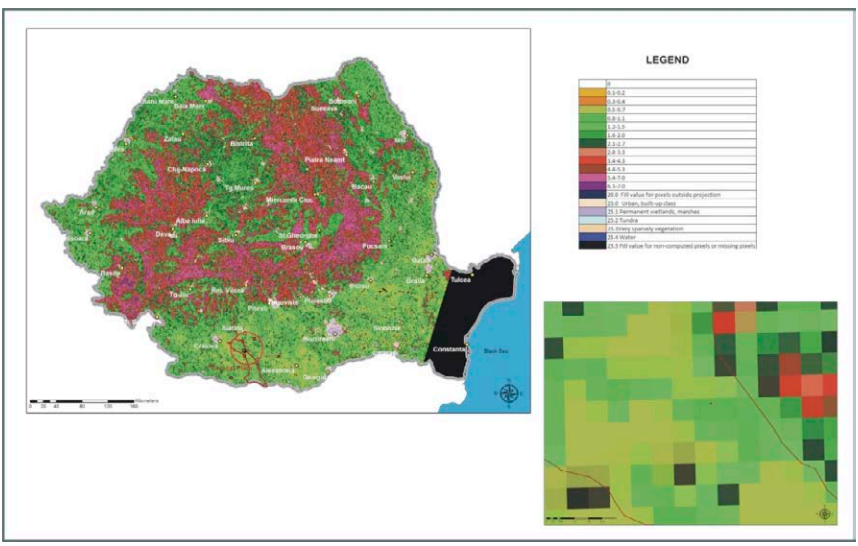
The TIR domain provides information on surface temperature, energy and water balance of the canopy and allow estimation of vegetation evapotranspiration or soil moisture, improving the assessment of drought stress or water use (Courault *et al.*, 2005). However, the use of these kinds of observations in crop models remain very limited (Olioso *et al.*, 2005).

The use of microwave (radar) data (e.g. provided by the ENVISAT Advanced Synthetic Aperture Radar) is based on the sensitivity of the mi-

Tab. 1. Canopy state variables and soil characteristics accessible from remote sensing data in several spectral domains. (after Baret et al., 2007)

BIOPHYSICAL VARIABLES		VIS-NIR-SWIR	TIR	μ-wave
Canopy structure	Leaf area index	+++	+	++
	fAPAR	+++		
	Cover fraction	+++	+	+
Leaf characteristics	Chlorophyll content	+++		
	Water content			++
	Temperature		+++	
Soil characteristics	Moisture	+		++
	Roughness	+		++
	Organic matter	++		
	Residues	++		

Fig. 7. MODIS LAI product in the test-area of Romania, on 03.07.2008



crowave backscattering coefficient to vegetation and soil parameters, such as foliar index, plant water content, soil moisture and roughness (Prevot *et al.*, 2003; Wigneron *et al.*, 2004; De Wit and Van Diepen, 2007). However, due to the long revisit time of ASAR sensor (i.e. 35 days) and to the impact of soil moisture and soil roughness on the backscattering coefficient, the retrieved crop vegetation information has a limited applicability in agrosystems characterization.

Consequently, a synergic use of optical and microwave satellite data (e.g. MERIS and ASAR) may significantly improve the potential of assimilating remote sensing derived information into crop growth models.

5.3 Using retrieved biophysical variables with crop models. Strategies / methods of remote sensing data assimilation in crop models

The complexity and integration of satellite information into crop functioning models presume two main levels (Guérif and Duke, 1998):

- Radiative transfer inversion methods allow the estimation of canopy state variables used in crop functioning processes: LAI, (fAPAR) using short-wave data, soil moisture using microwave data and evapotranspiration using thermal infrared data. Then, due to optimization techniques, the canopy state variable estimates can be used to force or recalibrate the crop model parameters.
- The process representing the crop functioning is considered by coupling a crop model with an adequate radiative transfer model. The coupled model is thus directly recalibrated in order to provide the best concordance between simulations and satellite measurements. The two models are connected through one common variable like LAI, assuming the input data from other known radiative transfer model (Moulin *et al.*, 1997; Guérif and Duke, 1998).

The limitations of using crop growth models over large areas consist in our ability to provide the required input parameters into the models. It is impossible to obtain plant and soil characteristics directly from in-situ observations over large areas. Thus, remote sensing is a performing tool for providing reliable information about crop processes over wide areas.

Remote sensing data assimilation represents a combination of models with remotely sensed observations. Depending on models and data used, different "strategies" of remote sensing data assimilation have been developed: forcing methods, model calibration, sequential correction of model predictions, variational methods etc.

There appear to be very few examples of operational data assimilation methods applied to crop or agrometerological models. Outstanding issues for operationalization include:

(i) lack of an appropriate satellite constellation,
(ii) lack of knowledge on spatial and temporal variation of cloud cover,
(iii) lack of operational approaches for atmospheric correction,
(iii) lack of sensors with SWIR wavebands.

The assimilation performance is influenced by many factors, like the number and timing of remote sensing data regarding the crop development

(Moulin *et al.*, 1998; Guérif and Duke, 2000) and the precision of the key variable simulating (e.g. LAI) using crop model. Taking into account this analysis, various assimilation strategies have been developed, in order to optimize the use of available images. Each strategy is defined by the parameter(s) to be re-estimated and the data to be used. Decision rules induce the choice of the strategy and are based on the number and timing of remotely sensed measurements, and on the suitability of the crop model validation.

It is necessary to understand the uncertainties in the crop models and in the ground measurements data. Beyond these errors, one should consider also the fact that the modality in which model variables are described in the remote sensing models may not be the same, as the way in which they are described in the ground measurements, used for calibration or validation. For example LAI measured on the ground using destructive methods does not take into account canopy clumping and is therefore different from the effective LAI measured from by indirect methods (e.g. LAI2000, hemispherical photographs) and estimated from remote sensing data inversion.

In many numerical weather prediction models, probabilistic approaches are widely accepted and advanced algorithms for sequential data assimilation such as nudging, variational and filtering methods have been developed. In contrast with this case, many crop models are generally deterministic, and offer little information regarding the uncertainties of the model states during simulation process, which is essential for a successful application of most sequential data assimilation algorithms. Probabilistic methods and data assimilation have been tested to crop growth models as well (Dorigo *et al.*, 2007; de Wit, and van Diepen, 2007). Particularly the use of the Ensemble Kalman filter to assimilate high resolution satellite observations of NDVI and land surface temperature in a crop growth model provided good results (Pellenq and Boulet, 2004).

An important aspect related with the operational assimilation of satellite image data in crop models is the calibration/validation procedures using ground data. It was noticed that in some cases (e.g. LAI parameter) the error of the ground observations is about the same size as the errors in the satellite estimates. The effects of cloud cover have to be also studied and quantified carefully.

6. Review of recent improvements in Earth Observation satellite data for agrometeorological modelling – Challenges for the Operational Assimilation of Satellite Image Data in Agrometeorological Models

F.M. Danson and L. Toulios

The main objective of this section is to examine the challenges for the operational assimilation of satellite image data in agro- meteorological models. The starting point is an assumption that remotely sensed data have been shown to be useful in such models and that it is meaningful to examine the factors that affect the availability of appropriate data and observations. Previous published research has shown that the key variables required for assimilation in agrometeorological models are either satellite radiance (or reflectance) or a range of inferred variables. Key inferred variables include leaf area index, FAPAR, surface temperature and various vegetation indices (Danson *et al.*, 2003; Bacour *et al.*, 2006).

Many surveys of user requirements for agricultural applications of remote sensing have been undertaken over the last 40 years and there is some consensus that, with the exception of precision agriculture applications, that the following characteristics are desirable in a European agricultural context:

- Spatial resolution: 10-30m.
- Temporal resolution: weekly or better.
- Spectral resolution: Landsat-like wavebands including the SWIR.
- Angular resolution: observations at different view angles may be desirable in some circumstances.

6.1 Observations with a cloud-free atmosphere

If we start by assuming a cloud free atmosphere, then three things determine whether we can observe a given location at a given time:

- Is the satellite in a position to make the observation? This is determined by the satellite orbit and the pointing capability of the platform; satellite orbits for environmental remote sensing are generally very similar; some platforms are highly agile while some have a fixed view angle. This is the 'revisit time'.
- Is the instrument activated? This is determined by the operational mode of the instrument; some instruments record data continuously (more or less), whilst others are only activated following user requests.
- Is the instrument functioning? Instruments have a finite lifetime after which they no longer function; some instruments have specific problems like Landsat ETM scan line corrector error; others like Landsat 5 TM can miraculously come back to life.

We can now consider what determines temporal resolution. The length of line of latitude 45 degrees (which goes through Bordeaux) is about 28,000km and satellites orbit every 100 minutes or so, or 14 orbits/day. We therefore need a swath width of about 2000km for daily coverage at 45 degrees north (for example Novi Sad, Serbia) (or 2800km at the equator). This is why Modis Terra/Aqua achieves near-daily global coverage (swath width 2300km)

We start by defining revisit time - how frequently could a given point be imaged, and repeat cycle - how frequently does ground track repeat). With no pointing capability the revisit time for Modis Terra is 1 day and repeat cycle is 16 days. With a pointing capability the revisit time for Ikonos is 1-5 days, and the repeat cycle 114 days. We know there is a 'trade-off' between spatial and temporal resolution, but there is another approach using satellite constellations such as the Disaster Monitoring Constellation (DMC). The DMC consists of series of 5 small satellites located in the same orbit and imaging large swaths of the Earth's surface to give a ones day repeat cycle and daily imaging potential of any area on the Earth with up to five satellites. This configuration significantly increases the observation opportunities for imaging sensors.

6.2 Observations with a cloudy atmosphere

Cloud cover prevents surface observations so that the probability of recording useful data is the product of observation probability, as previously discussed, and cloud free imaging probability. One question here is whether we need observations for specific *points*, or observations over given *areas* – since the probability of seeing a given point will always be higher than that of observing a prescribed area. Landsat ETM+ 16 day revisit/repeat cycle means 22 opportunities for observation per year. However with a cloud free frequency of 20%, typical of the UK we might expect only 4 or 5 cloud free images per year. With daily revisit like that provided by the DMC, and 20% cloud free frequency, we would expect 73 cloud free images per year (Armitage *et al.*, 2010).

Another approach is multi-sensor, multi-platform, multi-system data collection. To increase the frequency of observations of a given location it is possible to incorporate data from several sensors. Many of the newer satellite sensors have similar broad visible and near infrared wavebands (very few have a SWIR waveband). If the spectral response functions of two different satellite sensors are different it is possible to derive cross-calibration equations for vegetation indices computed from different sensors (Steven at al., 2003). This may not be necessary when variables are determined through a physical-based model inversion approach. Accurate radiometric and atmospheric correction is critical for multi-date, multi-sensor applications.

6.3 New sensors for agrometeorological applications

Based on a snapshot of the CEOS database there currently 40 satellites currently flying that have land-based observations (including ice) as their primary target (CEOS, 2010). Discounting very high resolution cartographic and SAR instruments, and the established series like Landsat, SPOT and IRS, there is a small number which may be suitable for agrometeorological observations. These include the ALOS AVNIR-2 (Advanced Visible and Near Infrared Radiometer), CBERS-2B CCD camera, THEOS (THailand Earth Observation Satellite). Other sensor with potential applications in agrometeorology includes SumbandilaSat, RapidEye, Formosat-2, IMS-1, Kompsat-2 and Pleiades-1.

7. Remote sensing applications for the detection of potential frost damage on agricultural vegetation

E. Savin, G. Stancalie, S. Oancea, D. Mihailescu, A. Mestre, J. Luis and L. Toulios

In the climatic change context numerous uncertainties regarding the intensity and the frequency of frost events have been noticed. The spatial modelling of minimum temperatures at fine scales using remote sensing data will allow the users to estimate the consequences of climatic changes and to plan reliable adapting methods (use of less sensitive varieties in the sectors more likely to experience spring frosts).

The analysis of meteorological data showed a high spatial variability for the low temperatures as well as damages due to frost events on all European countries. Protecting plants from the effects of lethally low temperature is a matter of considerable importance in agriculture and in horticulture production of high-value fruits and vegetables. This has lad to the intensification of efforts to map frost risk zones, to forecast frosts correctly, to monitor the onset of frosts and pinpoint areas most likely to be affected. Satellite remote sensing provides some unique opportunities in this regard.

7.1 Methodology of frost risk mapping using measured meteorological and agronomical data

A) Methodology used in Greece. Combining remote sensing data and GIS for assessing frost damages on crops (the CALIS case study)

The Calamities Information System (CALIS) is a modern system for monitoring the surface temperatures in space and time, with simultaneous monitoring of crop growth. It aims in localization of the effects of extreme temperatures (frost, heat excess) and drought, in the agricultural production and transmission of information to the users through internet.

The CALIS system combines Earth Observation data with low resolution information in a ready-to-use form. The system alerts the users, e.g. insurance companies, to crop damage and aids them to compensate individuals who have suffered. Night frost in early spring, late spring/summer drought and heat excess are the calamities which the system addresses (Medal et al, 1998a).

The impact of climate hazards on vegetation condition and subsequent damage is assessed using meteorological and Earth Observation satellite data, as well as complementary information such as agricultural statistics, land use maps, tables of phenological stage by region and ground data measurements.

The methodology is adapted to each climate hazard separately. The main scheme can be described as follows: Under normal conditions, a monitoring system runs and systematically generates synoptic trends. The monitoring system activates the alert system whenever risk factors are detected. The alert system automatically produces temperature maps of critical geographic areas, maps of high risk areas, maps of potential damages indication, maps of minimum temperatures, maps of drought index calculation, maps of maximum temperatures, etc. These products are generated by a processing chain and are put at disposal of the end-users. The end-users consult these products using an on-line server.

The CALIS system has been used successfully to assess the damage to crops in five pilot-sites in France, Spain and Greece, on several crops such as almond trees, olive trees, apple trees, pear trees, cherry trees, peach trees and vine trees (Medal *et al.*, 1998b; Toulios 2004).

B) Methodology used in Spain

In the Meteorological Application Department, (Agentia Estatal de Meteorologia) in Spain was elaborated an operational method for frost climatology in areas of agricultural interest (fruit zones) in order to establish adequate insurance policies. The method uses daily minimum temperatures data for the period 1970-2006 from several stations (synoptic and secondary stations, with professionals and volunteers) in each zone under study, as well as daily meteorological bulletins (with synoptic maps) from 1961 to 2006 to relate synoptically situations and minimum temperatures and to obtain a classification and frequency of cold spells.

It should be noted that most of the Spanish secondary stations contain a lot of errors as well as lags in their data. Besides, in some cases there was not synoptic station in the zone of study or near it. Therefore in those cases artificial series to represent daily minimum temperatures have been created. For frost risks for fruit trees, the study was focused on cold spells (irruption of air very cold and dry, which can cause black frost (that is not visible, there are no ice crystals due to lack of humidity).

C) Methodology used in Romania

The methodology used in Romania combines the use of meteorological data with satellite images for the minimum temperatures of the land surface estimation as well as for the frost damaged vegetation assessment. Usually, when an advection occurs and there is a frost risk situation, the minimum temperatures map is computed using the minimum air temperature values, measured by weather stations. This method can be improved using the satellite images derived products namely, land surface temperatures (LST) from TERRA/AQUA-MODIS, NOAA-AVHRR or MSG-SEVIRI sensors (Tait and Zheng, 2003). The notable advantage of using remote sensing data is the availability of information on areas where there are no in situ measurements (weather stations).

Satellite derived land use/land cover products are also useful for the delimitation of frost risk zones like agricultural fields, orchard and vineyard. Land use/land cover data were available from CORINE Land Cover 2000 (CLC2000) and MODIS image data. CORINE Land Cover 2000 is the European reference data set for land use/land cover. The satellite database used for the CLC2000 was IMAGE2000 and contained LANDSAT ETM+ images. Using GIS facilities all images can be georeferenced and used for an integrated analysis.

The LST maps were obtained from TERRA/AQUA-MODIS, NOAA-AVHRR or MSG-SEVIRI by applying specific algorithms (Li and Becker, 1993; Stancalie, 2005). Using satellite images for the frost event of 26-27 March 2009 the following working documents were elaborated:

- Maps with minimum soil surface temperature
- Maps of greenness difference from Normal Difference Vegetation Index (NDVI).

The main steps of satellite image data processing were:

- Image acquisition
- Image geo-reference
- Study zones selection
- Computation of real values
- Integration in the GIS environment.

7.2 Key results

The CALIS system used in *Greece* offers to the users:

- monitoring of extended areas in daily basis
- estimation of the intensity and spatial distribution of the "event"
- a first damage estimation
- objective picture of the "event"
- cooperation between the farmers and the Insurance Organizations
- speedup of decisions about the compensations to the farmers.

For the study of frost on daily basis (early morning) NOAA/AVHRR data were used. Some of the CALIS products in which the users can access through the Internet in case of frost are:

- Ground temperature maps for a given date on a given pilot-site
- "Sensitive" areas maps for a specific crop
- Potential damages maps at crop level in three scales
- Minimum temperature maps for a 2-7 days period for the specific area.

In *Spain*, for the zones vulnerable to the frost risk, the probability for a given period (season, month, ten days, week) of minimum temperature under the thresholds of 0°C, -2°C, -4°C and -6°C, have been estimated.

In the operational methodology the following issues were taken into account:

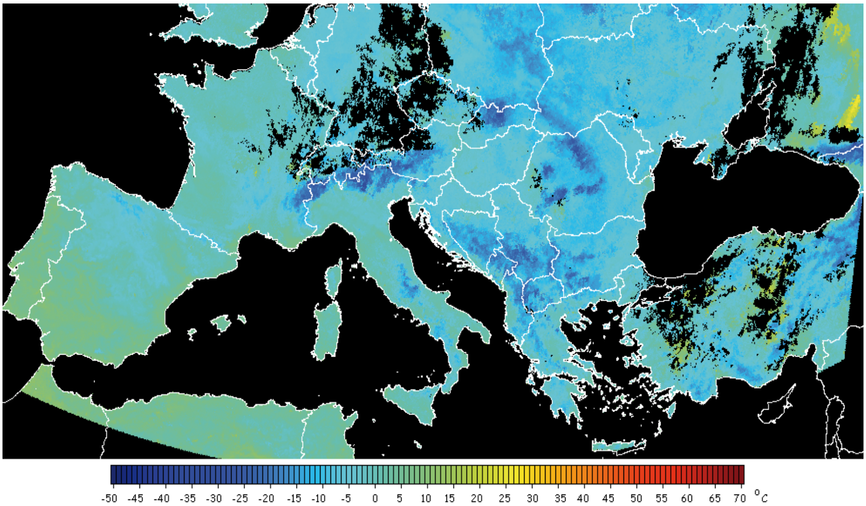
- Probability of occurrence of cold spells provoking damage, because the worst situations are those which cause a sharp drop of temperature, advection of cold air caused by a rapid temperature decrease.
- Persistence, length of frosts periods: probability of successive frost days and probability of periods of successive frost days.
- Frosts intensity (measured as descend of temperatures and time of the year).
- Size of the affected area by the frost (the area affected by frost should be big enough to cause significant damages).
- Trends in minimum temperatures in the areas under study.

For *Romania*, a study-case for the frost event of 26-27 March 2009 was conducted. For this case-study the satellite data used consisted in MSG-SEVIRI images LST – MODIS, LST – MSG products and NDVI from MSG.

The TERRA-MODIS/Land Surface Temperature and Emissivity (LST/E) products provide per-pixel temperature and emissivity values in a sequence of swath-based to grid-based global products (Caselles *et al.*, 1997). The MODIS/Terra LST/E Daily L3 Global 1km Grid product (MOD11A1), is tile-based and gridded in the Sinusoidal projection, and produced daily at 1km spatial resolution. There are three version of LST images databases, the last being V005.

The MODIS LST products are created as a sequence of products beginning with a swath (scene) and progressing, through spatial and temporal transformations, to daily, eight-day and monthly global gridded products. The MODIS LST products MOD11_L2, MOD11A1, and MOD11B1 have been validated at stage 1 with in situ measurements in more than 50 clear-sky cases in the temperature range from -10°C to 58°C and the column water vapour range of 0.4-4cm (Wan, 1999; Wan and Dozier, 1996).

Fig. 8. LST -MSG for 26 March 2009 over Europe



The MSG series is spin-stabilized, and capable of greatly enhanced Earth Observations. The satellite's 12-channel imager – SEVIRI, observes the full disk of the Earth with an unprecedented repeat cycle of 15 minutes in 12 spectral wavelength regions or channels. MSG - LST is a product realized by Land SAF and distributed via EUMETCAST.

LST is the radiative skin temperature over land. Land Surface Emissivity (EM), a crucial parameter for LST retrieval from space, is independently estimated as a function of (satellite derived) Fraction of Vegetation Cover (FVC) and land cover classification. The retrieval of LST is based on clear-sky measurements from MSG system in the thermal infrared window (MSG/SEVIRI channels IR10.8 μm and IR12.0 μm).

In order to reduce the cloud cover, a synthesis of 96 LST - MSG images for 26 March 2009 over Europe was first obtained (Fig. 8); then the LST was derived over Romania (Fig. 9).

Greenness difference map, computed using NDVI 10 days synthesis from SPOT VEGETATION images (1km resolution), proved to be a reliable satellite-derived information for the estimation of zones possible affected by frost. The greenness difference map was obtained using NDVIs synthesis for the decade 21-31 March 2009 and the decade 11-20 March 2009. In resulted map (Fig. 10) there are three classes: decrease of greenness, little or no changes and increase of greenness.

Comparing the greenness map with the minimum land surface temperature the correlation between zones with lower temperature and zones with no changes in vegetation development are high lighted.

Fig. 9. LST-MSG for 26 March 2009 over Romania

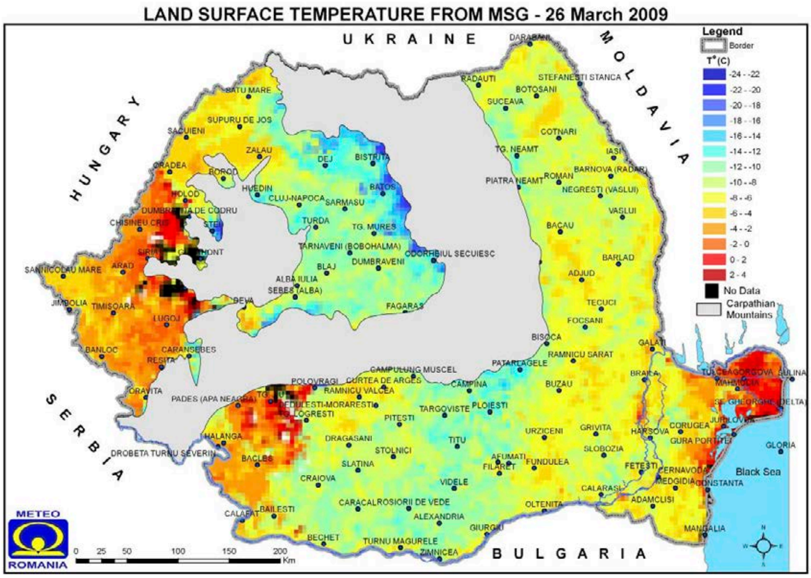
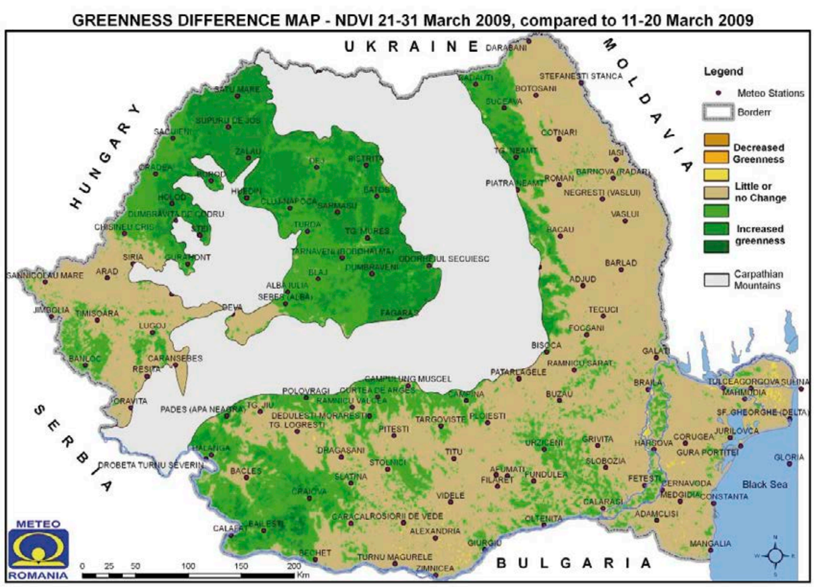


Fig. 10. Greenness difference map



7.3 Recommendations dedicated to different level of users, regions and crops

The analysis of meteorological data showed a high spatial variability for the low temperatures as well as of damages due to frost events. Indeed, important differences in the temperatures recorded at weather stations (in some cases a few kilometres apart, or coming from the same hill side) are observed. These contrasts are accounted for by numerous factors, the main ones being the atmospheric conditions, the local topography and the soil characteristics. In this context, an estimate of minimum temperatures at a fine scale using remote sensing data, mainly for the spring frost situations is very useful.

The use of satellite derived products, i.e. LST-MODIS and LST-MSG gave reliable estimations of land surface temperature. The use of MODIS-LST products, with high spatial resolution is an advantage for the situations with radiative frosts, with clear sky conditions.

For cloudy sky cases, the use of MSG LAND SAF LST products with a temporary resolution of 15 minutes allows clouds elimination using the temporal synthesis procedure. Greenness map difference proved to be a good indicator for the delimitation of frost damaged zones.

8. Remote sensing data assimilation in crop models

F.M. Danson and E. Tsiros

Simulation techniques are used to support field research and improve the efficiency of resource use in crop production (Arora and Gajri, 1998). Crop growth models are good tools for identifying growing conditions or predicting yield, since they simulate crop growth under different environmental conditions and varying agricultural practices. Nevertheless, the use of crop growth models is restricted by the lack of spatial information on model inputs (Launay and Guerif, 2005). Remotely sensed data provide continuous information in time and space and thus, the incorporation of satellite data into crop growth models has great potential.

A working definition of data assimilation (DA) is: «the set techniques that combine data with some underlying process model to provide optimal estimates of the true state and/or parameters of that model». There are several studies presenting the use of DA schemes that use remote sensing data to improve the performance of ecosystem or crop growth models (e.g. Quaife *et al.*, 2008; Knorr and Lakshmi, 2001).

8.1 Options for data assimilation

A key feature of data assimilation (DA) schemes, is that they use all the available information on the underlying model, the observations and observation operator, including estimates of uncertainty in both the model and the observations, to provide a best estimate of the true state of a system (Quaife *et al.*, 2008).

DA schemes are classified in two nominal categories, sequential and variational techniques. These categories include most of the DA methods. The sequential methods include Kalman Filters (KF), Ensemble Kalman Filters (EKF) and Particle Filters (PF). Sequential techniques are designed for real time systems, consider only historical observations, assimilate observation in a single time step and can lead to artificial high frequency components.

Variational methods use numerical minimization. Traditionally they are used for initial conditions but parameters may also be adjusted. In agricultural based parameters and in cases where the related model is simple enough, there is no need to use gradient descent and thus a differentiated model. An advantage of the variational techniques is that they minimize the RMSE and thus increase the accuracy of the optimum estimate. But, these techniques are not suitable for real time applications Nevertheless, when there is no interest in real time applications, variational techniques offer more flexibility.

High level products such as Leaf Area Index (LAI) are easier to assimilate because they are directly related to crop growth models and can be calculated by them. But, it is often difficult to quantify uncertainties and estimate the biases and inconsistencies caused by differences between the assumptions in LAI (or other product) estimation by satellite data and through the model outputs. Thus, there is a need to work with more "core" satellite observations. Using low level products (e.g. reflectance) can lead to a better understanding of the uncertainties, although they are more complex to utilize (Quaife *et al.*, 2008). This is achieved by avoiding the assumptions in the satellite product calculations. Lastly, the assimilation of high level products offers a simple and pragmatic way forward, whereas assimilating "raw" observations can ultimately provide better results but may be an unrealistic goal for many projects.

8.2 Combined use of remote sensing data and crop models

The strategies used by many remote sensing researchers over the last 20 years have often been referred to as "data assimilation" whereas strictly speaking they are generally radiative transfer model inversions providing input data for crop models. Crop models have two main types of output, agronomic variables (e.g., leaf area index, chlorophyll content) and environmental variables (e.g., water consumption, nitrate leaching). Remote sensing data and models are used in both areas, with the models applied at different scales, but with some parameters are difficult to obtain at coarse scale. It is important to know the size of input data errors and how they propagate, and also the 'model errors', that is, the accuracy with which the models represent the real world. An important recent trend has been the incorporation of prior information in model inversion strategies.

Strategies for using remote sensing data in crop models include:

- Forcing – this requires frequent data observations to adjust the model outputs using remote sensing data.
- Sequential correction – using updating to replace model data with observed data and filtering which takes into account earlier model states and data derived from remotely sensed data.
- Model calibration – where competition between model parameter may lead to an 'ill posed' inversion problem.

Three case studies illustrate these points:

Cereal yield estimation in Algeria using NOAA AVHRR data – with land use derived from finer resolution SPOT data. The method requires daily data, but on the other hand it requires little additional input information.

Sugar beet yield on field-by-field basis in France using SPOT data. The SUCROS model was used. Crop establishment is the key to spring growth and this is the most important period for crop monitoring – however the accuracy of the results were sensitive to LAI variation caused by water stress – since the crop model did not accurately explain the post stress response of the crop LAI. In this case there is still a need for high spatial and temporal resolution data.

Crop management in wheat – using the STICS model to evaluate the nitrogen application needs at within-field scale. Challenges in this example included the difficulty of parameterising the soil properties (29 of them) in the STICS model, and the small number of dates of the airborne (CASI) remotely sensed data. These lead to the adoption of Bayesian methods and the use of prior distributions in the model parameters. The outputs were the posterior distribution of variables (LAI and chlorophyll) and information on the spatial variability of these variables – which was used to provide N application recommendations. Test were undertaken to investigate whether cumulating observations over a number of years provided higher quality outputs, but it was found that one 'good year' was sufficient. Sensitivity analysis can be used to examine the importance of the model variables and to optimise data acquisition.

9. Satellite observations for climate science

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This section aims to surveys the most important statements of the IPCC Fourth Assessment Report (2007) based mainly on the satellite-borne observations, and to add several new results published after the Report. These climate-related applications of satellite remote sensing technology are sorted into four groups:

(i) external forcing factors,
(ii) detection of climate changes,
(iii) comparison of the present observed and the model-simulated climate and, finally,
(iv) testing the simulations of feedback mechanisms, determining the radiation balance of the atmosphere. The study of these applications led to the following conclusions:

9.1 Specifics of remote sensing in climate science

The use of remote sensing techniques from space is advantageous, since this is the only way to observe a wide range of geophysical parameters on a global scale to acceptable accuracy in a consistent and repeatable manner (Silvestrin, 2010). The satellite images have fairly high spatial resolution and high (though, costly) temporal resolution already achievable over vast areas. This technology allows us to measure locations of the Earth system impossible or difficult to access, mainly by the all-weather day-and-night capability for microwave sensing. This technology is able to measure several parameters at same time and it can be highly automatic, from acquisition to exploitation. One may even state that on a per-measurement basis, usually far less expensive than any other means of geophysical observations.

However, the technology has some caveats too (Silvestrin, 2010). One must always consider that remote sensing data are results of indirect measurements where the observed signal is always affected by more factors than just the one, targeted by the observation. Therefore, further assumptions and models are needed to interpret the measurements, e.g. to calibrate sensor, to remove perturbing effects, etc. The area of the measurement target is often relatively large, raising the representativity issue, considering surface heterogeneities.

The wavelengths in the two regions differ by around five orders of magnitude: features observed are very different and usually highly complementary. The two groups exhibit very different spatial resolutions: only tens of km for the microwave, whereas 1 km is easily achieved for the optical measurements. On the other hand, microwave sensing is little

Tab. 2. Absolute and relative differences between the recent (Trenberth et al., 2009) and previous (Kiehl and Trenberth, 1997) estimations (calculations were made by the authors of the present paper and they are rounded in Wm^{-2}). Components summarising other lines of the table are set in italics (calculations by Mika et al., 2010)

No.	Component (Wm-2)	New	Old	Diff.	Rel. Diff.
S1	Incoming Solar From the Sun	341	342	-1	0%
S2a	Reflected by clouds and atmosphere	79	77	2	3%
S2b	Reflected by the surface	23	30	-7	-23%
S2	Reflected Solar to the space	102	107	-5	-5%
S3	Absorbed by.(short-wave balance of) the atmosphere	78	67	11	16%
S4	Absorbed by (short-wave balance of) the surface	161	168	-7	-4%
S5	Shortwave balance at TOA (S1-S2)	239	235	4	2%
L1	Outgoing long-wave Radiation balance	239	235	4	2%
L2a	Long-wave emitted by the atmosphere	169	165	4	2%
L2b	Emitted LW by the clouds	30	30	0	0%
L2	Emitted LW from the atmosphere to Space	199	195	4	2%
L3a	Emitted LW from the surface to the space	40	40	0	0%
L3b	Emitted LW from the surface to atmosphere	356	350	6	2%
L3	Emitted LW from the surface: all	396	390	6	2%
L4	Back LW radiation from the atmosphere	333	324	9	3%
L5	LW balance of the atmosphere (L3b-L2-L4)	-176	-169	-7	4%
L6	LW balance at the surface (L4-L3)	-63	-66	3	-5%
N1a	Thermal (sensible heat)	17	24	-7	-29%
N1b	Evapotranspiration (latent heat)	80	78	2	3%
N1	Non-radiative energy balance of the atmosphere	97	102	-5	-5%
O1	Overall balance at TOA (S5-L1)	0	0	0	
O2	Overall balance of the atmosphere (S3+L5-N1)	-1	0	-1	
O3	Overall bal. at the surface (Net absorbed) (S4+L6-N1)	1	0	1	

affected by atmosphere and clouds (but rainfall may be a problem), and they can even penetrate vegetation, dry soil and snow. For the visible wavelengths clouds are obstacles, and daylight is also a condition. In the optical part of the spectrum various atmospheric corrections are needed to clear the targeted signal from other effects. In this respect, wide and partly unknown radiation parameters of the aerosol components are the problem (Silvestrin, 2010).

9.2 Detection of external forcing factors

The state of climate system largely depends on the radiation process, and human activity can primarily modify the radiation processes, too.

Tab. 3. Direct radiation effect by aerosols on the radiation balance of the Planet, estimated by satellite remote sensing (IPCC 2007: Table 3. abbreviated)

Satellite instrument	Measurement period	DRE (Wm^{-2})
MODIS, TOMS	2002	-6.8
CERES, MODIS	March 2000 –December 2003	-3.8 - -5.5
MODIS	November 2000 – August 2001	-5.7 ± 0.4
CERES, MODIS	August 2001 – December 2003	-5.3 ± 1.7
POLDER	November 1996 – June 1997	-5.2
CERES, VIRS	January 1998 – August 1998; March 2000	-4.6 ± 1.0
SeaWifs	1998	-5.4
POLDER	November 1996 – June 1997	-5 - -6
ERBE July 1987	July 1987 – June 1997	-6.7
Average (deviation)		-5.4 (±0.9)

Hence it was inevitable to know the actual radiation balance of the Planet with high accuracy. But, this is not so easy. Recently Trenberth *et al.* (2009) re-considered their earlier radiation balance estimations (Kiehl and Trenberth, 1997). The earlier period was based on observations from 1985-1989, whereas the recent estimates originated from March 2000 to May 2004 period.

As seen in Table 2, very few terms of the radiation balance are unchanged between the two estimates. In some cases the difference between the estimates is ca. 10 Wm^{-2}, sometimes over 20 %, in relative terms. The majority of the changes are likely caused by the uncertainty of the estimation, not by the climate variation of the Earth during this relatively short period.

The increasing greenhouse effect modified the balance by 2.3 Wm^{-2} since the beginning of industrial revolution. But, concentration of greenhouse gases is equally distributed over the World, due to their long residence time, and, furthermore, to our present knowledge the land use changes are less important forcing factors of the global radiation balance, we studied the remote sensing activities to characterise the influence of aerosol particles in details, only.

The direct effect of aerosols can be characterised by three different parameters:

(i) The optical thickness of aerosol, τ_{aer}, indicates the ratio of the Sun radiation which does not reach the surface: Using this parameter as a negative exponent of the e "natural number", we get this ratio.

(ii) The α albedo of a given aerosol layer shows the ratio of radiation reflected back towards the space in the given wavelength.

Finally, (iii) the ***DRE***, the common effect of natural and anthropogenic aerosols, indicates the surplus of outgoing energy from the Earth-atmosphere system compared to the situation without aerosols, at all.

There were at least 10 satellite missions since 1975 when the NOAA AVHRR observations became used to estimate τ_{aer} and α. Here we present just the satellite based estimation concerning the ***DRE*** influence in Table 3. The different methods have given similar values for the natural and anthropogenic direct radiation effect. The nine instruments, using much more different approximation, gave for this effect a -5.4 Wm^{-2}. Comparing this value with the other components of the radiation balance, we can express that their role is secondary beside the effect of cloudiness, atmospheric water content, or natural atmospheric greenhouse effect.

9.3 Changes of climate

There are a very large number of variables in the climate system. The most straightforward, and also realistic ones to observe by remote sensing, are listed in Table 4, according the present and future activity of the "ESA Climate Change Initiative" (Liebig, 2010). It is not possible to overemphasise the importance of multi-variable objective data on recent climate changes. Common sense, physical considerations and also the technical possibilities and constraints lead the decision on the priorities among these variables. The first two drivers are needed to have the maximum set of fairly independent physical state variables, as soon as possible.

Tab. 4. Essential climate variables as considered by the ESA Climate Change Initiative. Observation of the 11 bold-set variables is already in process (Liebig, 2010)

Atmosphere	Surface	Air temperature, precipitation, air pressure, water vapour, surface radiation budget, wind speed & direction.
	Upper air	*Cloud properties,* wind speed & direction, Earth radiation budget, upper air temperature, water vapour
	Composition	Carbon dioxide, methane & other GHGs, ozone, aerosol properties
Ocean	Surface	*Sea-surface temperature. Sea-level, sea-ice, ocean colour,* sea state, sea-surface salinity, carbon dioxide partial pressure
	Sub-surface	Temperature, salinity, current, nutrients, carbon, ocean tracers, phytoplankton
Terrestrial	*Glaciers & ice caps, land cover, fire disturbance,* fraction of absorbed photosynthetically active radiation, leaf-area index (LAI), albedo, biomass, lake levels, snow cover, soil moisture, water use, ground water, river discharge, permafrost and seasonally frozen ground	

9.4 Testing of climate reproduced by models

The climate system, the atmosphere, the lands, the oceans, the biosphere and solid water is one of the most complicated non-linear systems. No model is able to take every factor and space-time scales into consideration. Besides the lack of computer capacity, we have to consider the lack of knowledge derived from the limitations of the observation network. For this reason, testing climate models is very important. The simpler part of testing is to check whether the fields in the models, simulated with present external circumstances, fit reality. In this respect, one can find positive (successful) and negative (biased) examples, as well. Recently Mika *et al.* (2010) collected a set of examples in the framework of the present research. E.g. water vapour content of the atmosphere is simulated fairly well, indicating that this component is increasing parallel with the gradual warming of the Planet. For the negative examples one may mention the present position of various components of the cryosphere, where both the sea ice and even more the snow cover are simulated with large errors.

9.5 Testing climate model sensitivity

The aim of climate modelling is to project future climates in response to realistic changes in the external forcing factors. These external factors are influenced by many circumstances. Among others, they are the world population, the structure of energy industry, development difference between the regions, etc. The other uncertainty factor is how correctly we simulate the sensitivity of climate system, namely the expected temperature in response to given changes of the external factors. We are not really able to estimate the first uncertainty source, due to its complexity, but we can validate the climate sensitivity simulations through testing certain particular processes. These particular processes are the climate feedback mechanisms.

If we compare the uncertainty originated from different emission scenarios, on one hand, and from sensitivity differences of the models, on the other hand, we have to assess both uncertainty sources to be similar. Hence, decreasing the difference of climate models, reflecting better knowledge of the real sensitivity, would be equally useful from the point of view of the prediction as reduction of the uncertainty of future emissions.

Hence, it is a very important scientific task to test simulated feedbacks in the models, and absolute (comparison with some kind independent reference value) and relative (comparison of different models) study in which the satellite observation will have important role. Mika *et al.* (2010) presented two examples where the models seemed to underestimate the climate sensitivity of the actually investigated models, as they either underestimated the positive ice-albedo feedback mechanisms or overestimated the negative long-wave radiation feedback.

10. Conclusions and Recommendations

The use of remotely sensed data has many dimensions and the activity of the 'Working Group 2.1 – remote sensing' could examine only very small parts of the applications of remotely sensed information in the frame of agricultural meteorology; however the results could be useful not only among the members of the Action 734 but in a wider community of users. The results can be summarised in the following.

Satellite data offer an unprecedented potential for climate research provided that separate sensor/satellite data are integrated into high-quality, globally-integrated climate products. Also the influence of climate change on the biosphere can be monitored with use of satellite data. The presence of meteorological and environmental satellites in space since the 1960s allows for real climate change studies. The main issues are the accuracy and stability of satellite measurements. Actually, not all climates related variables can be traced with use of satellite sensors due to their accuracy. Much improved post-launch calibration of satellite instruments, and inter-calibration of similar instruments flying on different satellites is required to achieve continuity of observations. This requires overlapping periods of consecutive satellite missions. Other problems concern data management (processing and reprocessing). Rapid development of Earth observations results in extremely large volumes of satellite data. Regarding future missions, new more accurate sensors are envisaged.

The satellite data archives and tools which help with data search and further use of them show that a large variety of information is freely available for the users who would like to study vegetation temporal and spatial changes over the last 10-30 years. The information allows for selection of individual regions of interest located in any place on the Earth and to calculate or use available processed indices characterizing the state of vegetation or agrometeorological conditions. For global scale studies resolutions available start from 250 m (MODIS based) and extend to 16 km (GAC NOAA based). The most important feature of long term archives is the possibility to obtain or easily calculate anomalies and trends of investigated parameters, which allow for determination of biosphere changes in individual region. Such studies provide an opportunity to analyze possible climate change influences on agriculture.

Remotely sensed data have been shown to be a useful tool in the assessment of stress caused by adverse climatic conditions and in crop yield modelling. In specific, NOAA/AVHRR and MODIS data are powerful means for monitoring agro-environment and for crop yield assessment.

Knowledge of crop growth and development patterns is essential to improve management practices and maximize yield. Satellite data have a vast number of applications in determination of indices in order to model crop phenology and development. Stresses that have direct impact on plant development and on plant's biophysical processes can be adequately detected by satellite data and specifically by the use of vegetation indices. Thus, vegetation indices can be used for yield assessment and forecasting. The presented applications have indicated the growing potential and capabilities for assessing yield by use of remote sensing techniques.

Remote sensing techniques provide information about the present state of the crops, but not for the growth and development processes. In this respect, the assimilation of remote sensing data into crop growth models could improve the prediction of crop evolution.

The use of crop growth models over wide agricultural areas is limited due to present capacity to provide them the appropriate input parameters. It is very difficult to obtain plant and soil characteristics over large areas, directly from in-situ observations. Therefore, remote sensing data are a very useful tool to give information about crop processes over large areas. In this respect the characteristics of new satellite sensors regarding spatial resolution and temporal frequency to provide vegetation specific variables, operationally, are an important advantage.

For the operational assimilation of satellite image data in crop models there are some new approaches for data collection and analysis. The most promising solution seems to be the constellation of identical satellite in the same orbit. There are great expectations for improving remote sensing data assimilation into crop models based on the future offers of satellites/sensors with high spatial resolution and high time frequency (e.g. GMES, Sentinel 2, etc).

Recent reviews regarding the methods for retrieving biophysical properties showed that most radiative transfer inversion techniques are based on iterative optimization or neural networks methods. However, the inversion of radiative transfer models is a major problem which may induce significant uncertainties in the biophysical variables estimation when limited information is used. The improvement of the inversion process capabilities requires more information obtained from radiative transfer models, using of proper prior information on the canopy distribution and atmosphere variables, knowledge of uncertainties of the satellite measurements according to spatial and temporal constraints.

Usually, statistical approaches based on vegetation indices use only two or three spectral wavebands; whereas parameter retrieval based on canopy reflectance modelling, partial least squares regression models or artificial neural networks can use the complete spectral data space provided by the sensor. Consequently, it is important to choose an adequate inversion algorithm and/or merit function due to the fact that representation of bands in spectral ranges with high absolute reflectance may generate the retrieval of only the canopy variables that affect these wavelengths.

There are still a lot of limitations for the use of satellite image data in crop models, like the lack of short wave IR bands, the reduced availability of on-board storage and data transmission capabilities, the calibration/validation procedures and atmospheric corrections, etc.

Operational assimilation of data in agrometerological models will require new approaches to collection and analysis. There are probably enough platforms in space to collect daily 30m spatial resolution data for the whole of Europe. The effects of cloud cover need to be quantified and some areas of Europe may be too cloudy (<14% cloud free frequency) to allow weekly observations. Cloud free frequency may be seasonally dependent for some area, but there is poor information on this from a remote sensing perspective. The most promising solution is constellation of identical satellites in same orbit and the availability of small satellite technology opens the possibility of a *European AgriSatellite* constellation. Some of the current systems lack wavebands in the SWIR which are important for monitoring crop moisture condition and many have limited on-board storage and data transmission capabilities. Finally it should be noted that calibration and validation activities are critical and operational atmospheric correction for local areas is a pre-requisite.

The analysis of meteorological data showed a high spatial variability for the low temperatures as well as of damages due to frost events. Indeed, important differences in the temperatures recorded at weather stations (in some cases a few kilometres apart, or coming from the same hill side) are observed. These contrasts are accounted for by numerous factors, the main ones being the atmospheric conditions, the local topography and the soil characteristics. In this context, an estimate of minimum temperatures at a fine scale using remote sensing data, mainly for the spring frost situations is very useful.

The use of satellite derived products, i.e. LST-MODIS and LST-MSG gave reliable estimations of land surface temperature. The use of MODIS-LST products, with high spatial resolution is an advantage for the situations with radiative frosts, with clear sky conditions. For cloudy sky cases, the use of MSG LAND SAF LST products with a temporary resolution of 15 minutes allows clouds elimination using the temporal synthesis procedure.

Greenness map differences proved to be a good indicator for the delimitation of frost damaged zones. LSTs derived from MSG images, which cover all Europe, are available at each 15 minutes with a spatial resolution of 4km. As an example, a MSG-LST synthesis with 96 images of 26 March 2009 was realized and the clouds zones were successful eliminated.

Strategies for using remote sensing data in crop models include:

- Forcing – which requires frequent data observations to adjust the model outputs using remote sensing data.
- Sequential correction – using updating to replace model data with observed data and filtering which takes into account earlier model states and data derived from remotely sensed data.
- Model calibration – where competition between model parameter may lead to an 'ill posed' inversion problem.

High level remote sensing products are easier to assimilate. Nevertheless, working with more 'core' satellite observations such as low level products can provide better results, since assumptions made in the satellite product calculation are avoided. Lastly, the assimilation of 'raw' remote sensing data, although it can provide better results, is often an unrealistic approach due to the computing power required.

Though 'CLIVAGRI' mainly focuses on agricultural aspects of climate changes, the study on satellite based information on the climate change contributed to the key assumption of the project, namely to the reality and risk of the climate change, itself. The above tackled various aspects namely the external forcing factors, the observed changes, the validation of the models and the balance of positive and negative feedbacks. All demonstrate the strong potential of our present knowledge, but they also indicate its shortcomings. The latter are mainly connected to those spatially distributed processes where present observation networks are not sufficient to provide the required information, and present numerical models are still not able to resolve all spatial details required for transforming into global scale climate processes. Better resolution of both the space-borne observations and the climate modelling scenarios will likely improve the situation in the near future.

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CHAPTER IV

AVAILABILITY, ASSESSMENT AND DEVELOPMENT OF REGIONAL CLIMATE SCENARIOS FOR EUROPE

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Abstract. During the last decade, various projects have contributed to the development of regional climate scenarios for Europe. Three of these scenario repositories (IPCC-AR4, ENSEMBLES and CECILIA) and possibilities for application to agrometeorological studies were examined from different perspectives in the context of the WG 3 activities of COST 734.

1. Introduction

The IPCC Fourth Assessment Report (IPCC AR4) (Solomon *et al.*, 2007) suggests that, similarly to many other regions of the World, European countries could become vulnerable to global warming (Christensen *et al.*, 2007a). But although the broad response of global climate to increased greenhouse gas concentrations is well established, many unknowns remain in the regional details of climate projections for the 21st century. Moreover, the floods and droughts that affected many areas of Europe in recent summers stress the importance of the hydrologic cycle and the need to better understand the occurrence of precipitation extremes. Examples of this sort of events are the floods in the Czech Republic during the summer of 2002, with the Vltava river inundating Prague and causing severe and widespread damage, or the heat wave of summer 2003, one of the severest heat waves on record in central and western Europe causing both human losses and extensive damage to human activities and natural ecosystems (Kysely & Huth, 2004). A number of studies have linked the occurrence of extreme events to anthropogenic forcings (e.g. Beniston and Stephenson, 2004; Schär *et al.*, 2004; Pal *et al.* 2004; Meehl and Tebaldi, 2004). Impacts on agriculture and forestry affecting the economy of countries in the region were extensively studied as well (Menzel *et al.*, 2006).

While coupled atmosphere-ocean general circulation models (AOGCMs) provide a global view on climate change, their horizontal resolution is still too coarse to describe in detail processes affecting extreme events at the regional scale (Gates *et al.*, 1996). In order to enhance the global climate scenarios a number of regionalization techniques have been de-

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veloped (Giorgi *et al.* 2001). Dynamical downscaling refers to the use of limited-area, regional climate models (RCMs) driven with boundary conditions either from AOGCM results or, in the context of model verification, global reanalyses (Giorgi and Mearns, 1999). It has been shown that dynamical downscaling can significantly improve the simulation of extreme events (e.g. Huntingford *et al.* 2003; Frei *et al.* 2003). Methods ranging from canonical correlation analysis to stochastic weather generationform the basis of what is generally dubbed statistical downscaling (Calanca *et al.*, 2008). In recent years, statistical techniques have also been extended to the downscaling of extreme events (e.g. Busuioc *et al.*, 2008; Hundecha and Bárdossy, 2008).

Concerning the use of RCMs to develop regional climate change scenarios, significant progress was already achieved under the EC FP 5, with projects:

- "Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects" (PRUDENCE; http://prudence.dmi.dk) (Christensen *et al.*, 2007b);
- "Modelling the Impact of Climate Extremes" (MICE) (Hanson *et al.*, 2007);
- "Statistical and regional dynamical downscaling of extremes for European regions" (STARDEX; http://www.cru.uea.ac.uk/projects/stardex/);
- "Development of a European Multimodel Ensemble system for seasonal to inTERannual prediction" (DEMETER; http://www.ecmwf.int/research/demeter/) (Palmer *et al.*, 2004).
- PRUDENCE and DEMETER, in particular, formalized the concept of multi-model ensemble simulations, which was even more systematically taken up by the EC FP6 project
- ENSEMBLES ("Climate change and its impacts at seasonal, decadal and centennial timescales", van der Linden and Mitchell, 2009; http://ensembles-eu.metoffice.com/).

Within the framework of ENSEMBLES regional simulations were performed with a total of 15 regional models driven by a few different global models for basically the same domain and at a spatial resolution of 25km, which was twice as high as the resolution achieved in the PRUDENCE runs and an order of magnitude better than achieved with the IPCC AR4 global simulations. Although only the A1B emission scenario was considered for driving the experiments and only a limited number of AOGCM/RCM combination could be tested, the ENSEMBLES project delivered a considerable amount of updated information for further use in climate change analysis and impact studies across Europe.

Two additional projects were also implemented in the context of the EC FP6 to investigate climate change and impacts in Central/Eastern Europe:

- CECILIA ("Central and Eastern Europe Climate Change Impact and Vulnerability Assessment"; http://www.cecilia-eu.org/); and
- CLAVIER ("Climate Change and Variability: Impact on Central and Eastern Europe"; http://www.clavier-eu.org/).

In CECILIA, RCMs were applied at a resolution of 10 km to study the implications of climate change on hydrology, water quality and management, air quality, agriculture and forestry. In CLAVIER, simulations carried out at the same resolution were focused on climate change impacts on agriculture, tourism, energy and public sector industry and services.

2. Scope

Recalling the deliverables of WG 3 as outlined in the MoU of COST 734 (D1: Collection of climate scenarios for various European regions; D2: Assessment of scenarios uncertainties; D3: Development of future trends in (agro)climatic conditions), the main goal of the present report is to provide a summary of results obtained from a regional analysis of the IPCC AR4 scenarios and key findings from the ENSEMBLES and CECILIA projects.

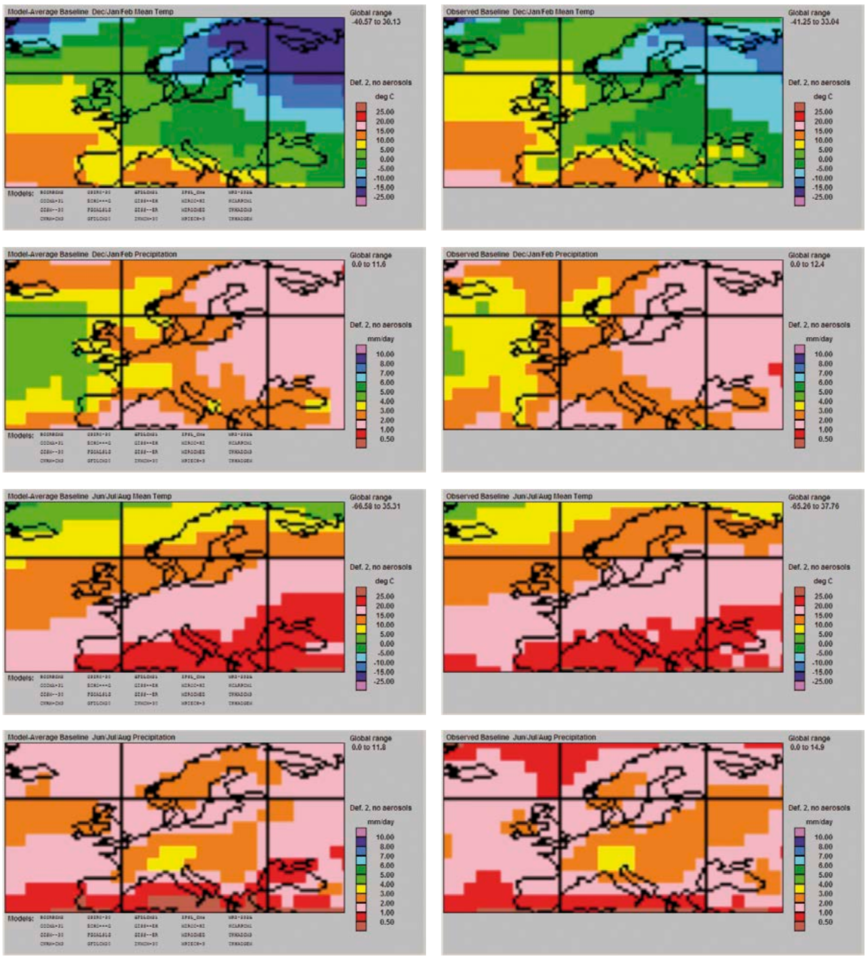
3. Devemopment of Regional Scenarios from Ipcc-Ar4 Global Climate Model Ouput

Although available only at a relatively coarse spatial resolution, the global climate model simulations completed in the context of the IPCC AR4 provide a quite unique opportunity to investigate climate change also in relation to variables not always discussed, but certainly of interest in agroclimatic studies, e.g. sea-level pressure, cloudiness, or soil moisture (see Solomon *et al.*, 2007, chapter 10, Supplement). The scenarios are available through the IPCC data portal (http://www.ipcc-data.org/)

To obtain regional climate scenario for Europe, the IPCC AR4 A1B global scenarios were used as input to the MAGICC/SCENGEN 5.3 software package (Wigley *et al.*, 2003, 2008; for details see http://www.cgd.ucar.edu/cas/wigley/magicc/). MAGICC/SCENGEN is a coupled gas-cycle/climate model (MAGICC; Model for the Assessment of Greenhouse-gas Induced Climate Change) that drives a spatial climate-change SCENario GENerator (SCENGEN). It has been largely used in the context of the IPCC process.

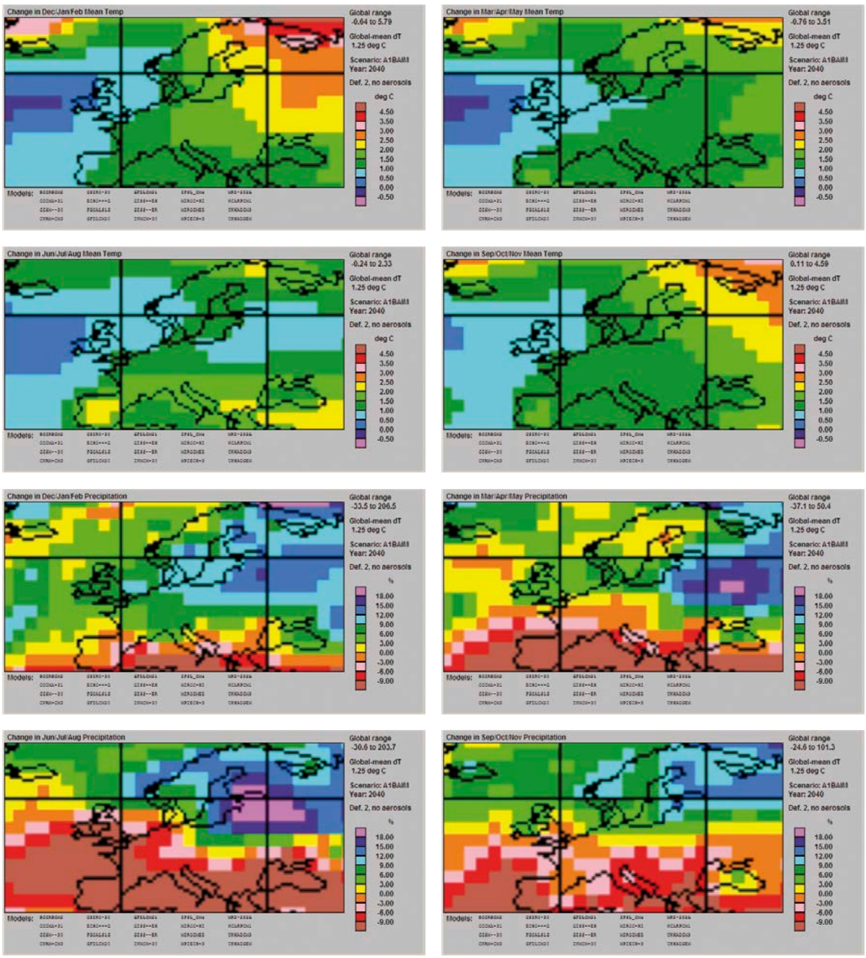
The global section of the package, the MAGICC, is based on an upwelling diffusion energy balance model calibrated by global sensitivity of the GCMs outputs. Global-mean temperatures from MAGICC are used

Fig. 1. Comparison of simulated (left column) multi-model ensemble mean seasonal temperature (upper row) and precipitation (lower row) with ERA-40 diagnostics (right column). The upper four panels refer to the winter season, the bottom four to the summer season. Time frame: 1980-1999



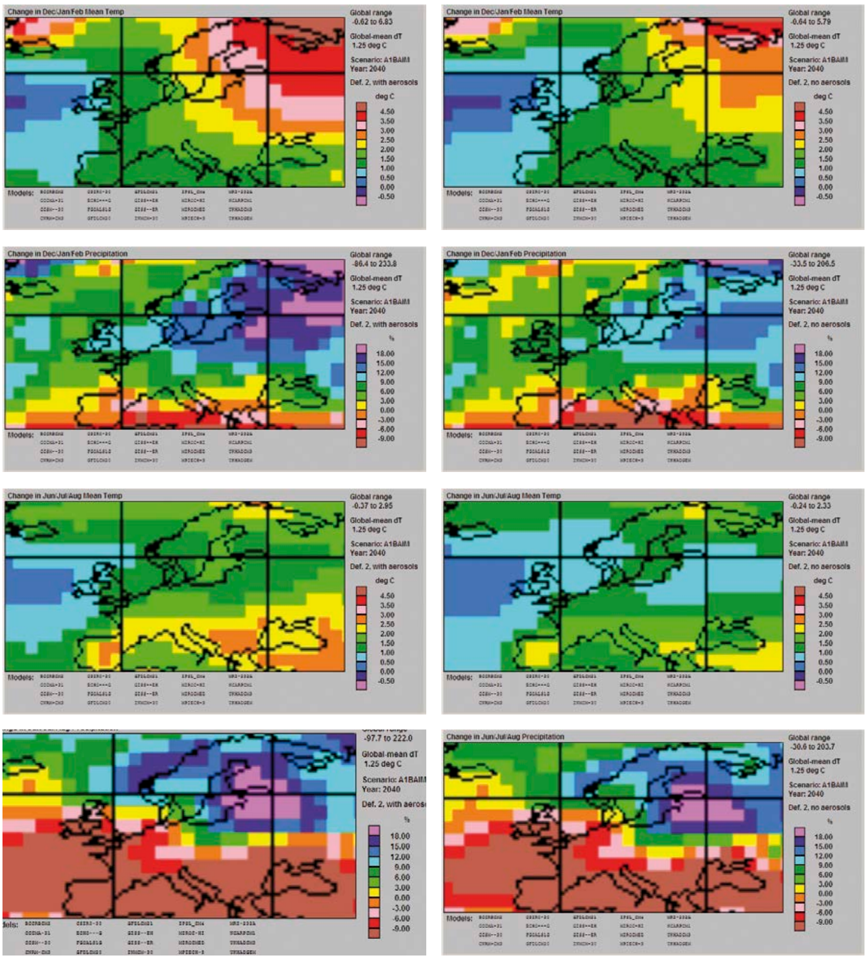
to drive SCENGEN, a scenario generator based on pattern scaling techniques (Santer *et al.*, 1990) and treating greenhouse-gas and aerosol forcings can be treated separately. Eventually, spatial patterns are normalized and expressed as changes per 1°C change in global-mean temperature. These normalized greenhouse-gas and aerosol components are appropriately weighted, added, and scaled up to the global-mean temperature defined by MAGICC for a given year, emissions scenario and set of climate model parameters.

Fig. 2. Model-mean changes in temperature (top) and precipitation (bottom) computed by the magicc/scengen for 2030-2049 compared to 1980-1999. The projected global change is 1.25 K.



For the present analysis, we firstly checked the reliability of simulated climate patterns for the reference period 1980-1999 by comparing the resulting fields with those obtained from the ERA-40 reanalyses (Uppala *et al.*, 2005). The winter and summer distributions of temperature as seen by MAGICC/SCENGEN are similar to the ERA-40 reanalysed fields (Fig. 1., upper quadrants), but in most regions of Europe there is a cold bias in the simulations. This bias is rather strong in Northern Europe (in the order of -8 K) but less pronounced for majority of the continent (less than -3 K).

Fig. 3. Effect of the aerosol loading on the projected changes in temperature (upper lines) and precipitation (lower lines) in winter (top panel) and summer (bottom panel) for the A1B scenario. Shown is the average of the 20 models, for 2030-2049 relative to 1980-1999. In the leaft column the aerosol load was decreased as compared to the default prescribed by magicc/scengen (Wigley, 2008)



Simulated fields of precipitation for the same reference period (Fig. 1., lower quadrants) do also capture the observed patterns, but there is an evident wet bias for most of Europe. This overestimation is around 10-15 % in average, but in Central Europe this error is more than 70 %. Although the wet bias remains, in summer the situation is improved, with only a 10% departure in the same Carpathian region showest the strongest bias during winter.

After this verification exercise, MAGICC/SCENGEN was used to generate seasonal climate change scenarios for 2030-2049, for both temperature and precipitation, assuming standard aerosol concentrations (Fig. 2), or prescribing a decrease of the atmospheric aerosol load (Fig. 3).

As seen in Fig. 2, with standard aerosol concentration the strongest warming areas are found in the north-east and north-west sectors of the European region, whereas there is very little warming in the Atlantic. Fig. 2 also reveals that the southern areas become drier, but the northern, especially the north-eastern sector, get wetter. The transition zone between drying in the south and wettening in the north undergoes a seasonal cycle. Note, moreover, that in summer and in autumn the Alpine-Carpathian region is projected to face a decrease in precipitation that, however, is partly compensated in the rest of the year.

Concerning the effects of a decrease in the aerosol loading of the atmosphere, Fig. 3 indicates that this results in particular in a stronger warming and wettening of North-Eastern Europe in winter, and a stronger warming of the sourthern countries in summer.

4. Regional Climate Simulations

4.1 The ENSEMBLES transient model runs

In ENSEMBLES 15 RCMs were run to generate transient climate scenarios for Europe at a spatial resolution of 25km (van den Linden and Mitchell, 2009). The 15 RCM simulations were driven with the lateral boundary conditions inferred from 7 AOGCM runs and assuming in most cases a A1B greenhouse gas emission scenario. The committed period for the transient runs was 1950-2050, but most of the simulations were extended to 2100. All simulations are available through the ENSEMBLES data portal (http://ensemblesrt3.dmi.dk/)

The overall change in the annual climate obtained as a mean of the RCMs ensemble shows the same patterns already disclosed by the PRUDENCE model runs (Christensen and Christensen, 2007), the IPCC AR4 (Christensen *et al.*, 2007a) and by Figs. 4 and 5 of this report, with northern Europe warming more significantly than southern Europe on an annual basis. As in the case of the IPCC AR4 model runs, the simulations completed in the framework of ENSEMBLES indicate a high degree of coherency across the spatial patterns of change simulated by the individual models. Again this is in line with the results obtained in PRUDENCE and appearing in the IPCC AR4 (Christensen *et al.*, 2007a).

As was the case for the PRUDENCE runs (e.g. Déqué *et al.*, 2007), the ENSEMBLES RCMs were extensively tested during the project (Chris-

Fig. 4. RCMs representation by means of Taylor diagrams over individual regions for temperature. All values were normalized. The reference is seen on the bottom axis at 1 standard deviation to the right of the origin. For further details concerning this type of representation please refer to Taylor (2001). Geographic areas: (BI) British Isles; (IP) Iberian Peninsula; (FR) France; (ME) Mid-Europe; (SC) Scandinavia; (AL) Alps; (MD) Mediterranean; (EA) Eastern Europe. For further details concerning the definition of the eight geographic areas see Christensen and Christensen (2007)

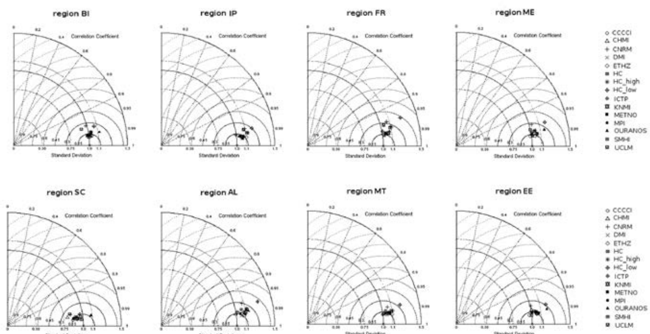
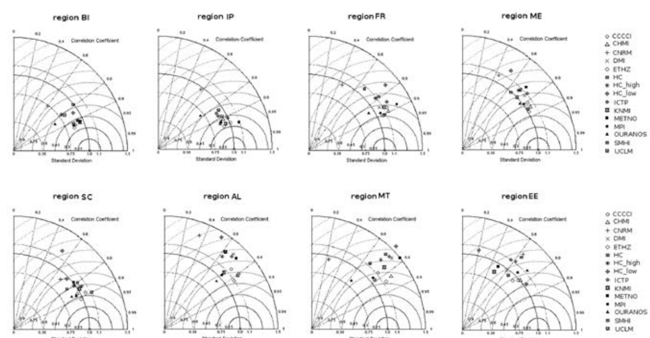


Fig. 5. Same as Fig. 4 but for precipitation



tensen *et al.*, 2010). ERA40 reanalysis fields (Uppala *et al.*, 2005) were used for driving the RCMs at the boundaries over the period of 1961 till 2000. All the RCMs simulations were performed on the same domain fully covering the European region. Relevant results from various verification activities can be found in Buser *et al.* (2010), Christensen *et al.* (2010), Coppola *et al.* (2010), Déqué and Somot (2010), Kjellström and Giorgi (2010), Kjellström *et al.* (2010), Lenderink *et al.* (2010), Lorenz and Jacob (2010).

In the following we present an analysis of results from 13 RCMs, whereby two additional members simulations were included for HadRM (high and low climate sensitivity). For final analysis time series of

Fig. 6. Mean seasonal bias of winter (left) and summer (right) temperature as simulated by a selection of 13 of the ensembles RCMs. The gridded data of Haylock et al. (2008) were used as a reference. Figure courtesy of Sven Kotlarski (ETHZ)

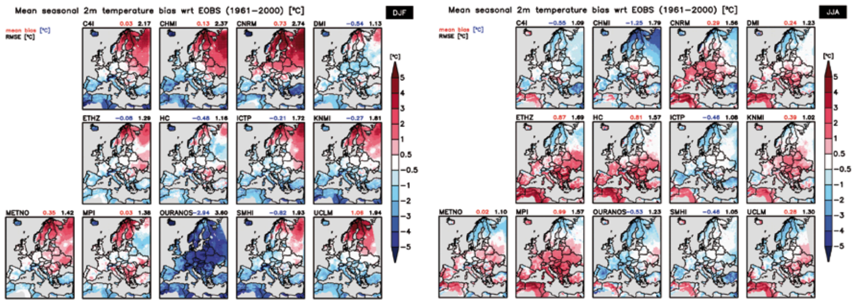
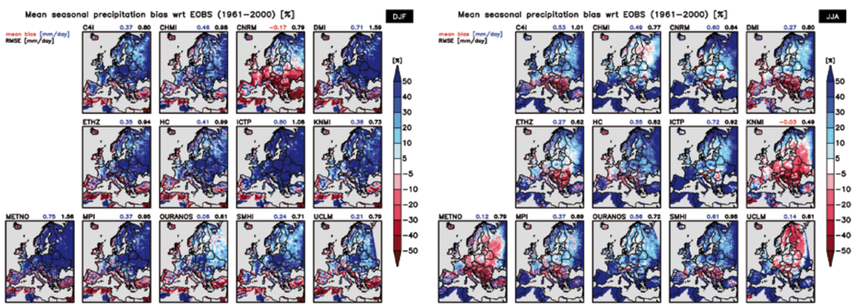


Fig. 7. Same as Fig. 6 but for precipitation. Figure courtesy of Sven Kotlarski (ETHZ)



monthly averages over so called PRUDENCE regions (Christensen and Christensen, 2007) were computed and compared to gridded fields extracted from the archive developed by Haylock *et al.* (2008) also in the context of ENSEMBLES. The results of the validation are presented in terms of Taylor's (2001) diagrams in Figs. 4 and 5 for temperature and precipitation, respectively. Quite good agreement can be seen for all the regions in temperature. However, for precipitation the results are not very good, especially for some regions.

The model performance can also be appreciated by looking at the geographic patterns of the seasonal (winter and summer) bias fields (simulation minus observation for temperature, resp. relative bias in % for precipitation) (Figs. 6 and 7) as developed by Kotlarski *et al.* (2011). A similar analysis, with in addition an examination of the model performance in simulating cloudiness can be found in Christensen *et al.* (2010).

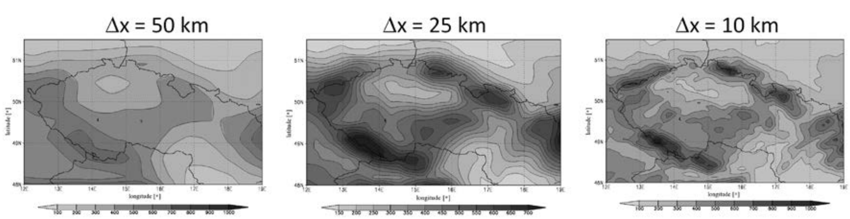
The main conclusions from these figures are the following: (a) except in one case, models show a significant warm bias (up to 5°C) over Scandinavia in winter; (b) similarly, most models show a warm bias (roughly 3°C) over extended portions of southern and south-eastern Europe in summer, opposing a cold bias over northern Europe; (c) most RCMs show a considerable wet bias (up to 50%) in winter across all of Europe; (d) concerning summer precipitation, the results are more variable, with a tendency for a wet bias over Scandinavia and a tendency for a dry bias in particular over south-eastern Europe. Note, however, that for summer precipitation there are numerous exceptions to this general picture, with for instance a few models producing a dry bias extending into Scandinavia.

4.2 The CECILIA *Project*

The main goal of CECILIA (Central and Eastern Europe Climate Change Impact and Vulnerability Assessment) was to provide climate change impacts and vulnerability assessment in targeted areas of Central and Eastern Europe (CEE) at very high spatial resolution (10 km). Two time slices were produced, a first focusing on the near future window of 2021-2050, the second one addressing 2071-2100. A secondary objective of this project was to adapt a few of the models used for ENSEMBLES, ALADIN-Climate and RegCM (Giorgi *et al.*, 2004a and 2004b) for very high resolution (grid spacing of 10 km) simulations over selected sub-domains.

Over CEE running the RCMs at very high spatial resolution is necessary to capture the complex topographic and land-use patterns associated with the Alps, Carpathians basin and smaller mountain chains and highlands. Fig. 8 shows that at a much more realistic and faithful depiction of the topography can be achieved by increasing the spatial resolution from 25 km (ENSEMBLES) to 10 km (CECILIA).

Fig. 8. Mapping of the topography of the Czech republic at the 50 (left) and 25 km (middle) resolution adopted in ensembles and at the 10 km (right) adopted in cecilia



For preliminary data assessment over CEE region, three sets of available climate projections were analyzed: the global model ensemble CMIP3 (completed in support of the IPCC AR4), and the regional model simulations completed for the EU projects PRUDENCE and ENSEMBLES. This analysis revealed not only the differences between individual data sources concerning the change patterns of change in CEE, but also demonstrated once more the existence of seasonal migration of the transition belt

Fig. 9. Relative change in seasonal precipitation (%) as simulated in cecilia for 2021-2050 relatively to 1961-1990 in (from left to right) winter, spring, summer and autumn. The color scale ranges from -50% (red) to +50% (blue)

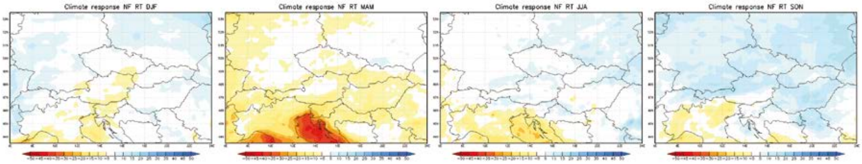
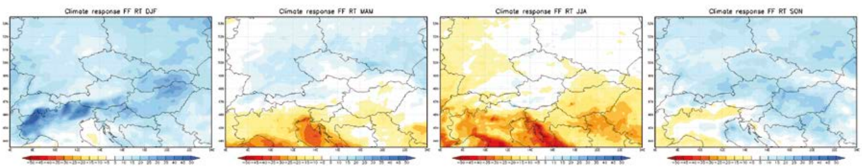


Fig. 10. Same as Fig. 9 but for 2071-2100



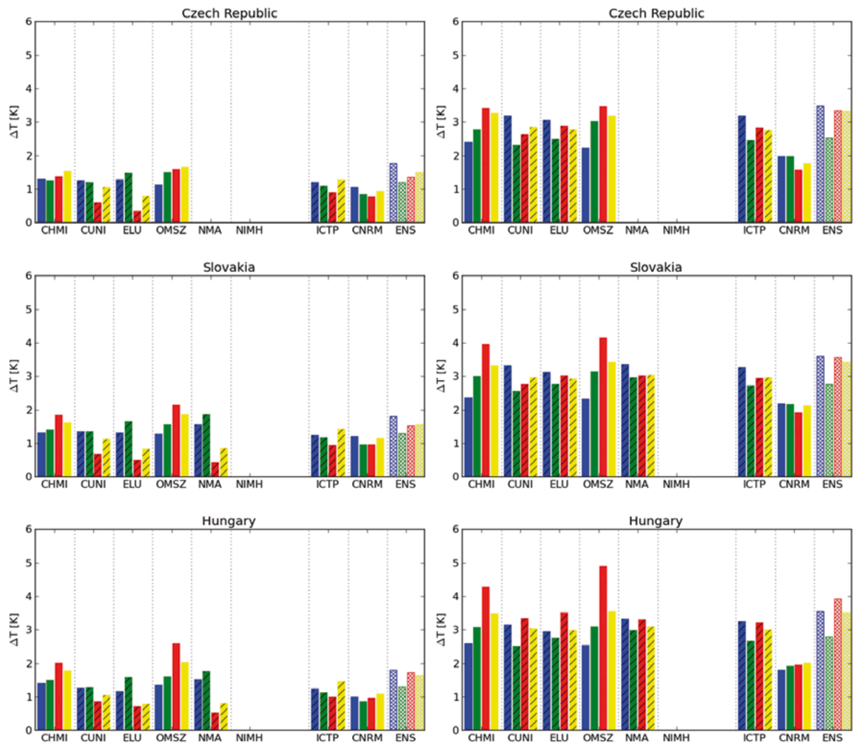
between the area with decrease in precipitation in the south and the one characterized by increasing precipitation in the north (see also Giorgi and Coppola, 2007).

Overall, changes projected by the CECILIA model runs (Figs. 9 and 10) were consistent with those of previous studies but the higher resolution of the CECILIA fields allowed for a much more realistic geographic differentiation, suggesting a higher potential for direct application to agrometeorological studies.

To account for uncertainties in boundary conditions, in CECILIA two pairs of AOGCMs/RCMs were tested, ARPEGE/ALADIN and ECHAM5/RegCM3. There were 6 modelling groups involved in the CECILIA simulations, all performed with 10 km resolution, but covering slightly different, yet overlapping domains. The partner CUNI, ELU and NMA used RegCM3, while CHMI, OMSZ and NIMH used ALADIN. For temperature, a high consistency between the projections by the models was found, with results in good agreement with previous findings. For precipitation, rather small changes were found for Central Europe.

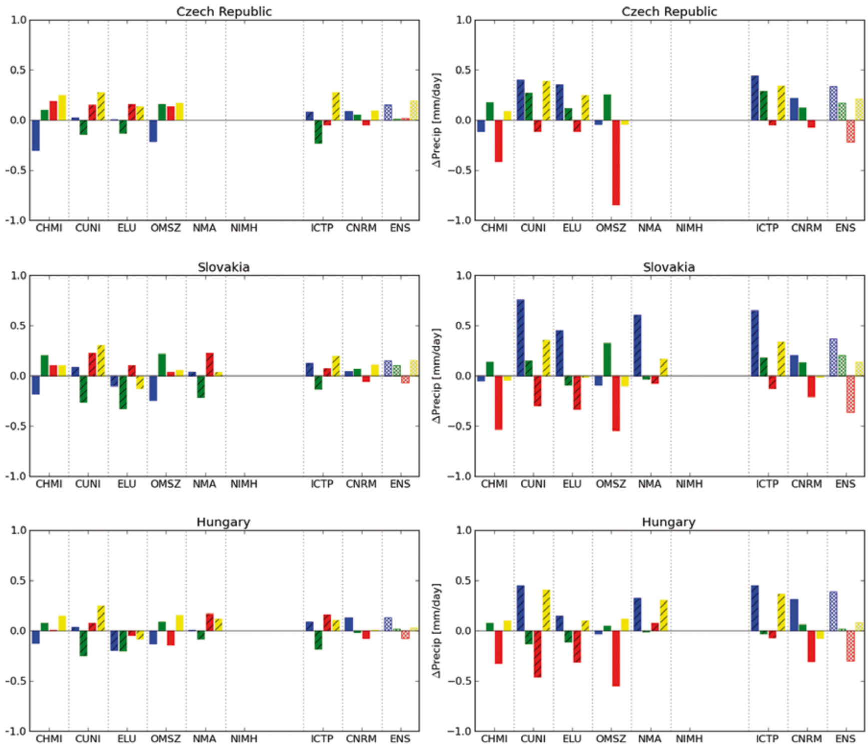
For a more detailed view, changes in surface temperature simulated for individual countries are presented in Figs. 11 and 12 for the Czech Republic, Slovakia and Hungary. For comparison, on the right hand side of the plots the results of the driving models are presented along with corresponding ENSEMBLES averages. While for temperature the results are more or less consistent with respect to both time slices (except for the fact that simulations driven with ARPEGE show a notably lower signal), for precipitation the scatter of the signal is much higher and, in the case of the ARPEGE-ALADIN chain rather inconsistent.

Fig. 11. Change in 2m temperature between 2021-2050 and 1961-1990 (left), and 2071-2100 and 1961-1990 (right) for the Czech Republic (top), Slovakia (middle) and Hungary (bottom). Blue=DJF, green=MAM, red=JJA, yellow=SON, hatched=RegCM-ECHAM couple, plain=aladin-arpege chain, ENS=average of 14 ensembles models



Another method for regionalizing the results was the application of statistical downscaling techniques. The primary objective was to make comparison of the methods on the common region (central European area along the Czech-Slovak-Austrian-Hungarian borders) against observed griddd data. From a technical point of view, the purpose was to compare individual downscaling methods, i.e. statistical downscaling techniques (multiple linear regression, multiple linear regression on data stratified by circulation types, canonical correlation analysis, various kinds of non-linear methods, including neural networks, classification-based methods, and stochastic downscaling approach) between themselves as well as with respect to the dynamical downscaling by the RCMs involved (models ALADIN-Climate/CZ and RegCM). Characteristics of the temporal and spatial structure were analyzed, namely, the 1-day lag autocorrelation (persistence) and spatial autocorrelation. It can be summarized that RC-Ms systematically overestimate persistance while underestimate spatial

Fig. 12. Same as Fig. 11 but for temperature



autocorrelations. This behaviour is different from statistical downscaling models, for which underestimation of both temporal and spatial autocorrelations is typical (for more details see CECILIA Final Report).

To construct specific regional climate change scenarios using full advantage of information from RCM simulations it was found that some method of bias correction has to be used, especially for precipitation. Different methods were tested and finally applied in most scenarios. The evaluation of their performance was done by comparing the original model data (reanalysis driven, control) and the corrected model data with observational data. A low-parametric method was implemented at CUNI and used to modify data representing daily maximum and minimum temperature and daily precipitation as generated by the RegCM3 and ALADIN-Climate/CZ models. The method was demonstrated to successfully rectify major systematic errors in the model data; it was able to reduce substantially the bias of mean values, amend the spread of the values and bring a more realistic number of dry/wet days in case of the precipitation series (Fig. 13). A substantial improvement was also achieved

Fig. 13. Distribution of values of daily precipitation in the series obtained by different downscaling methods, dynamical or statistical (displayed for a single grid point, located at 49°00' N, 15°28' E) – JJA season. The RCM runs as well as the statistical downscaling mappings were driven by the ERA-40 data

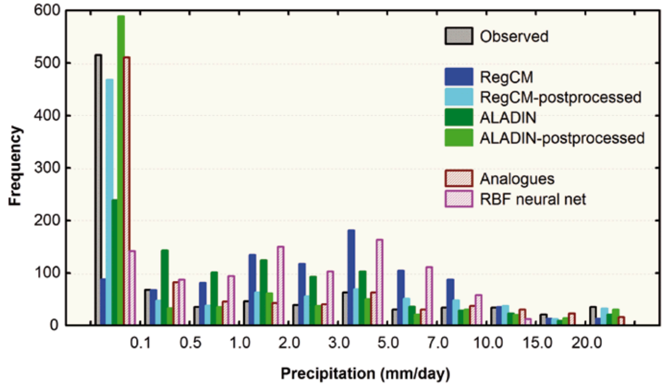
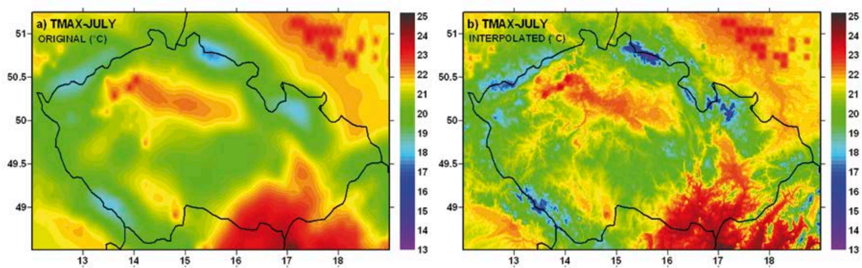


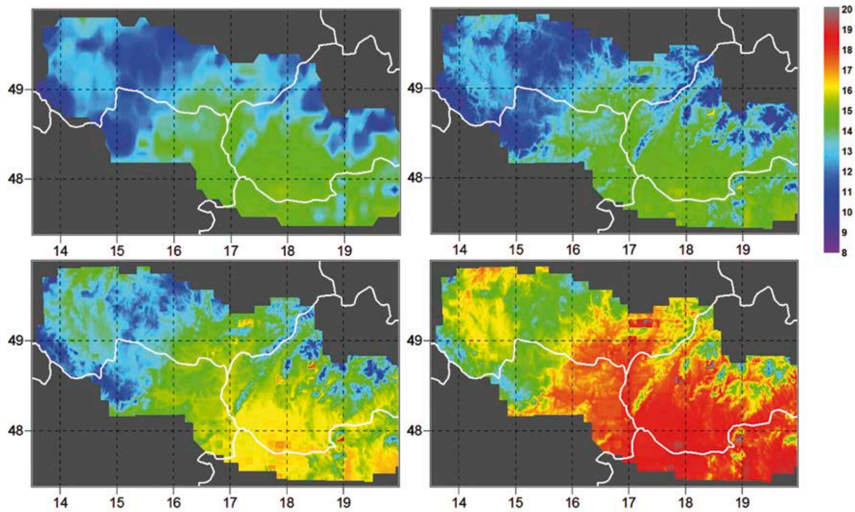
Fig. 14. Monthly maximum temperature in July, simulated by the RegCM model (left panel) and after the altitude-based localization of the model outputs (right panel) in 1km resolution



for the representation of extreme tails of the statistical distributions of the target variables, including the highest/lowest quantiles, important for reliable assessment of the occurrence of extreme phenomena. However, some of the problems associated with the RCM outputs remained unsolved even after the correction, at least to some extent (e.g., sometimes unrealistic temporal persistence in the time series and potentially distorted physical consistency of the multivariate fields).

Another important issue was the model output localization based on statistical downscaling techniques, developed and adapted for the CECILIA project. Attention was paid particularly to techniques that help compensating for a simplified representation of the terrain elevation in the RCMs. It was shown that localization can substantially improve all model outputs related to temperature, as in this case the relation to terrain elevation is very strong and well represented by the CECILIA region-

Fig. 15. Annual mean of maximum daily temperature (°C): Data simulated by the RegCM model after the bias correction (top left), localized data for the control period 1961-1990 (top right) and the future periods 2021-2050 (bottom left) and 2071-2100 (bottom right)



al models (Fig. 14). By using the model-simulated vertical gradient, the correction could be applied for the climate data in the control period as well as for simulations of the future, on daily basis. The localization was carried out and tested for precipitation data as well; in this case, however, the connection of daily/monthly precipitation sums to terrain elevation was weaker and less realistically simulated by the RCMs (especially the RegCM model). The eventual improvement achieved by precipitation localization was therefore rather small on average and its benefit usually less significant compared to sources of error not related to the elevation mismatch.

To obtain fields of temperature and precipitation both devoid of major systematic errors and detailed enough to be used for studies at very fine scales, bias-correction and localization were combined (see Fig. 15). The application was carried out for the outputs of the RegCM model, for maximum and minimum daily temperature and daily precipitation in the periods 1961-1990 (control climate), 2021-2050 (near future) and 2071-2100 (far future). While usually generating fields with spatial patterns close to reality, the procedure did not produce data which could be considered completely flawless. Specifically, insufficient density of the network of weather stations providing the observations seems to be a limiting factor for this type of postprocessing. In relation to the 10 km grid adopted in CECILIA, some areas were underrepresented or characterized by an anomalously behaving measuring site. This introduced artifacts and unrealistic values into the postprocessed climatic fields, located usually in a vicinity of a single node of the original model grid. It was concluded that the point-wise debias/localization approach, although actually retaining the maximum amount of details available from local observations, may therefore be replaced with a correction constructed for a broader local area in future postprocessing applications.

5. Development of Scenarios of Agroclimatic Conditions

As a contribution to the overall goal of WP3, possibilities to develop scenarios of agroclimatic conditions from the output of AOGCM or RCM simulations were also examined. We note that the assessment of agroclimatic conditions can be done along different lines of research, be it by obtaining information directly from an analysis of projections in daily mean temperature and precipitation, possibly but not necessarily in the framework of a climate classification (e.g. de Castro *et al.*, 2007), be it in terms s of agroclimatic indices (Fronzek and Carter, 2007; Trnka *et al.*, 2011), or then with the help of impact models, such as process-based models of grop growth (Minguez *et al.*, 2007; Olesen *et al.*, 2007) or models simulating the distribution of pests and diseases (Hirschi *et al.*, 2011). As a rule, the last two approaches require daily weather data at the local scale. Therefore, many of the efforts done in the past to derive scenarios of acgroclimatic conditions had a focus on downscaling.

For agroclimatic applications, the correction of climate model biases (see Figs. 6 and 7) also becomes of paramount importance, because application models are very sensitive to errors in the meteorological drivers. In the case of precipitation, deficiencies in the model formulations are reflected in errors affecting daily precipitation statistics (e.g. Frei *et al.*, 2003), precipitation extremes (Frei *et al.*, 2006), spatial precipitation patterns (Philips and Glecker, 2006) or inter-annual variability (Vidale *et al.*, 2007). Bias correction techniques for daily precipitation mounts alone, such as those proposed by Ines and Hansen (2006) or Schmidli *et al.* (2006), are insufficient to cope with the need of agricultural or hydrological decision problems, because they only address the statistical distribution of daily precipitation amounts, leaving the time structure of rainfall series uncorrected.

Statistical downscaling techniques, as summarized in Calanca *et al.* (2008) and discussed in the previous section, can be applied to overcome the disparity of scales addressed by RCMs and application models. Maraun *et al.* (2010) provide a exhaustive review of recent development concerning the downscaling of simulated precipitation fields.

A common approach to downscaling and bias correction is the development of daily weather data with the help of stochastic weather generators (Semenov and Barrow, 1997). Two such weather generators were extensively used in the framework of COST734, namely M&Rfi (formerly Met&Roll) (Dubrovsky *et al.*, 2004), a stochastic weather generator of the Richardson (1981) type used in support of the WG 4 activities (Trnka *et al.*, 2011) and also in a Swiss contribution to the Action (Samietz *et al.*, 2009; Hirschi *et al.*, 2011), and LARS-WG (Semenov, 2007; Semenov and Stratonovitch, 2010), a stochastic weather generator employed in studies complementing the WG 3 activities (e.g. Lazzarotto *et al.*, 2010; Spörri, 2010; Calanca *et al.*, 2011).

To facilitate the application of LARS-WG to agrometeorological studies, two important data sets were already integrated in this weather generator: the 25 km grids of interpolated daily precipitation, minimum and maximum temperatures and radiation from the European Crop Growth Monitoring System (CGMS) of the Joint Research Centre (JRC) in Ispra (Semenov *et al.*, 2010) and an ensemble of 15 global climate change scenarios obtained from the IPCC-AR4 scenario archive (Semenov and Stratonovitch, 2010). Efforts are currently undertaken to also integrate the ENSEMBLES RCM scenarios in LARS-WG (Calanca and Semenov, in prep.).

M&Rfi and LARS-WG were chosen because they have been in use for more than a decade, have been therefore extensively tested and proven to be reliable even with respect to the simulation of extreme events (Semenov, 2008). Although there are possibilities for application at the spatial scale (see e.g. Semenov and Brooks, 1999), a main limitation of both weather generators is that they remain point models. Extensions to multisite generation, as sketched e.g. in Wilks (1999) could become important in the future. Moreover, the possibilities of new types of approaches to the generation of precipitation (e.g. Burton *et al.*, 2008), the extension to the hourly scale (Fatichi *et al.*, 2011) should also be explored.

6. Summary and Recommendations

WP3 of COST734 examined the availability, assessment and development of regional climate scenarios for Europe. The main findings can be summarized as follows:

- *Existing regional climate scenarios for use in agroclimatic studies.* To be able to take advantage of both the progress in the field of climate modeling and a steadily increasing spatial resolution, we recommend to access the most recent datasets. For Europe these includes the in particular the products developed in the framework of ENSEMBLES, CECILIA and CLAVIER. ENSEMBLES offers for the first time transient climate simulations spanning the second half of the 20th century and in many case the whole of the 21st century at a spatial resolution of 25 km. These scenarios should therefore be particularly useful for studies dealing with the near-future impliacations of climate change.

- *New regional climate scenarios.* Although not completed at the time of writing, we also recommend to closely follow the activities within the CORDEX project, an effort sponsored by the World Climate Research Programme (WCRP) aiming at a COordinated Regional climate Downscaling Experiment. This new project will deliver the basis for the IPCC AR5, and ist product are likely to become a new benchmark. Details of the project can be found at http://www.meteo.unican.es/en/projects/CORDEX
- *Climate change scenarios at the national scale.* In CECILIA, results were already investigated with respect to individual countries (see e.g. Figs 10 and 11). At the time of writing other projects are on the way or have just been completed. As an example, we can mention the UKCP09 project (http://ukclimateprojections.defra.gov.uk/), which aims at providing targeted climate information for the UK, or the CH2011 project (http://www.c2sm.ethz.ch/services/CH2011/), which provides a new and thorough assessment of how this climate may change over the 21st century in Switzerland.
- *Reliability of regional climate scenarios.* In spite of undeniable progress, review of the results of ENSEMBLES and CECILIA as well as investigation coordinated by the Action indicated that users of regional climate simulations still have to face a variety of shortcomings, ranging from quite substantial biases even in simulated, long-term mean seasonal fields, to deficiencies in the representation of the temporal characteristics of precipitation. Even in the case of very high-resolution simulations such as those carried out in CECILIA, post-processing of simulated climatic fields remains of paramount importance.
- *Scenarios uncertainties.* Project such as DEMETER or ENSEMBLES have clearly shown that uncertainties in climate projections can be substantial. Quantifying this uncertainties and how they propagate is essential for impact studies. While ENSEMBLES provides an excellent baseline for dealing with uncertainties arising from different formulations and setups of global and regional climate models, not all of the uncertainties can be addressed with its products. In particular, almost all of the ENSEMBLES runs were carried out under the assumption of a A1B emission scenario, and therefore the implication of different emission pathways remain unexplored. In this respect, tools such as MAGICC/SCENGEN can be very useful.
- *Statistical downscaling.* The highest spatial resolution achieved with RCMs in recent projects or programmes dealing with the operational development of climate change scenarios was of 10 km in CECILIA. Even in this case it was shown that impact studies would significantly benefit from the application of statistical downscaling techniques, in

particular in areas characterized by complex topography. The choice of the downscaling technique should be dictated by specific needs. No unique approach can be recommended for the time being.

- *Development of agroclimatic scenarios*. Stochastic weather generators have been found to be particularly useful for the applications of climate change scenarios to agroclimatic studies. Two such weather generators were applied in projects coordinated by the Action, but we pointed out that there are many additional developments in the field of which end-uses could take advantage, in particular with respect to the generation of rainfall, refinenement of the temporal and the extensions to multisite generators.

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CAPITOLO V

IMPACTS AND ADAPTATION TO CLIMATE CHANGE OF CROPS IN EUROPE

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Abstract. So far a limited number of studies have examined the regional variation in Europe in terms of impacts and adaptation to climate change. In COST-734 WG4 several methodologies were applied to study the effects of climate change on European crop production and adaptations to climate change:

1) A questionnaire survey was used to gather and analyse standardised information on vulnerabilities, impacts and adaptation to climate change for selected crops for European environmental zones;
2) Analysis of site and regional crop data responses to climatic varibility;
3) A study of agroclimatic conditions under present and projected climate change conditions over most of the EU and neighbouring countries with special focus on variability and events with lower probability using a set of eleven agroclimatic indices; and
4) A comparison of a range of winter wheat crop simulation models against datasets from North to South in Europe to evaluate the ability of crop models to simulate crop yield responses across a wide range of climatic conditions.

The results indicate not only most vulnerable areas but also those that might profit from the expected changes. Surprisingly the expected impacts (both positive and negative) of climate change in Mediterranean are in several cases smaller than those expected for northern or central Europe. This is partly explained by the possibilities for shifting some of the crop cultivation into the winter season in the Mediterranean countries in a warmer climate. Probably the bleakest expectations could be found in responses from continental climate of Pannonian environmental zone. Still the adaptation strategies should be introduced to reduce negative effects and exploit possible positive effects of climate change. Both short-term adjustments (e.g. changes in crop species, cultivars and sowing dates) and long-term adaptations (e.g. water management, land allocation, farming systems and institutions) are considered as important across most zones. However, the differences in climate exposure, sensitivity, and adaptive capacity will differently affect agroecosystems across Europe.

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1. Introduction

Intensive farming systems in western and central Europe generally have a low sensitivity to climate change, because a given change in temperature or rainfall have modest impact (Chloupek *et al.*, 2004), and because the farmers have resources to adapt and compensate by changing management (Reidsma *et al.*, 2010). However, there may be considerable difference in adaptive capacity between cropping systems and farms depending on their specialisation (Reidsma *et al.*, 2007). Intensive systems in cool climates may therefore respond favourably to a modest climatic warming (Olesen and Bindi, 2002). On the other hand some of the farming systems currently located in hot and dry areas are expected to be most severely affected by climate change (Darwin and Kennedy, 2000). There is a large variation across the European continent in climatic conditions, soils, land use, infrastructure, political and economic conditions. These differences are expected also to greatly influence the responsiveness to climatic change (Olesen and Bindi, 2002; Trnka *et al.*, 2011).

To date, there have been a limited number of studies that have dealt with the expected changes in the agroclimatic parameters at the pan-European scale and many of these studies are review articles (Olesen and Bindi, 2002; Lavalle *et al.*, 2009; Bindi and Olesen, 2011; Olesen *et al.*, 2011). Conversely, some indications may be found from global-scale analyses which display consequences of climate change for the whole of Europe considered as one large region or two large entities (Parry *et al.*, 2004). Such studies directly estimated crop yield changes by using empirically calibrated crop simulation models. They provide quantitative estimates, but these are linked to a fixed set of hypotheses aiming at depicting the components of the world crop production. An alternative approach have considered sets of agroclimatic indices at various degree of complexity (e.g. Ramankutty *et al.*, 2002; Fischer *et al.*, 2002, 2005). The latter studies offer comprehensive views of changes changes for Europe. However, these studies had to rely on monthly datasets while many key processes in agrosystem take place on daily and even shorter time scales. There is therefore a need to supplement such crop modelling studies with assessment of changes in agroclimatic indices with the idea of elaborating an accessible and flexible tool allowing assessment of agroclimatic conditions (including role of variability and extremes) while keeping in mind the approaches being used has to be progressively developed.

The scale of the ongoing changes in European crop production is wide-ranging and cannot be fully covered by national studies that are usually not based on comparable methodologies. In COST-734 WG4 several methodologies were applied to study the effects of climate change on European crop production and adaptations to climate change:

1) A questionnaire survey was used to gather and analyse standardised information on vulnerabilities, impacts and adaptation to climate change for selected crops for European environmental zones (Olesen *et al.*, 2011);
2) Analysis of site and regional crop data responses to climatic varibility (Peltonen-Sainio *et al.*, 2011);
3) A study of agroclimatic conditions under present and projected climate change conditions over most of the EU and neighbouring countries with special focus on variability and events with lower probability using a set of eleven agroclimatic indices (Trnka *et al.*, 2011); and
4) A comparison of a range of winter wheat crop simulation models against datasets from North to South in Europe to evaluate the ability of crop models to simulate crop yield responses across a wide range of climatic conditions (Palosuo *et al.*, 2011).

2. Observed Impacts and Adaptation to Climate Change of Crop Production

2.1 Observed climate changes

Most of Europe has experienced increases in surface air temperature during 1901 to 2005, which amounts to 0.9 °C in annual mean temperature over the entire continent (Kjellström, 2004; Alcamo *et al.*, 2007). However, the recent period shows a trend considerably higher than the mean trend (+0.4°C/decade for the period 1977-2001, Jones and Moberg, 2003). For the past 25 years, trends are higher in central and north-eastern Europe and in mountainous regions, while the lowest temperature trends are found in the Mediterranean region (Klein Tank, 2004). Temperature is increasing more in winter than in summer (EEA, 2004; Jones and Moberg, 2003). An increase in temperature variability has been observed, primarily due to increase in warm extremes (Klein Tank and Können, 2003).

There are indications of changes in the rainfall pattern as indicated by the frequency of drought events during spring and early summer. There has been an increased occurrence of droughts in large parts of western and eastern Europe, with particularly large increases in the Mediterranean region (Trenberth *et al.*, 2007). Mean annual precipitation is increasing in most of Atlantic and northern Europe and decreasing along the Mediterranean (Klein Tank *et al.*, 2002). An increase in mean precipitation per wet day has been observed in most parts of the continent, even in areas getting drier (Frich *et al.*, 2002; Klein Tank *et al.*, 2002).

Other studies show that the number of stations with statistically significant trends towards drier conditions (in terms of available soil moisture), prevail in central Europe over those where either no trend at all or a tendency toward wetter conditions were noted (Trnka *et al.*, 2009).

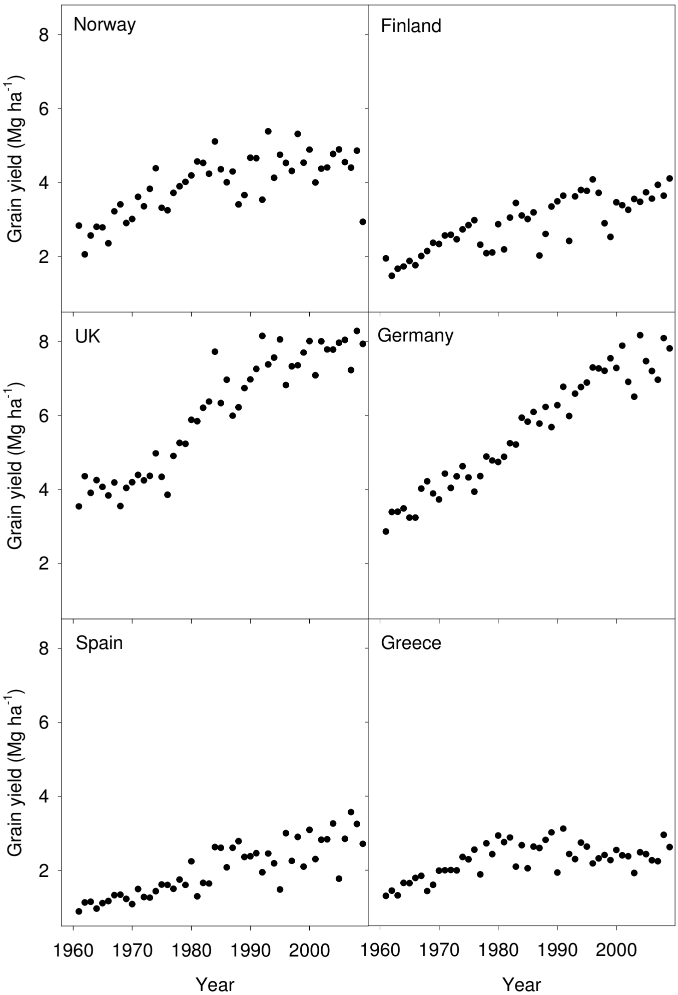
These shifts in intensity and frequency of drought in the region were shown to be largely driven by changes in near surface temperature (van der Schrier *et al.*, 2007) and associated with changes in circulation patterns (Trnka *et al.*, 2009). The droughts might be combined with extreme heat-waves as was the case in 2003, when large parts of Europe were exposed to summer temperature rises of 3 to 5 °C. This heat wave was associated with an annual precipitation deficit up to 300 mm, and the drought was a major contributor to the estimated reduction of 30% over Europe in gross primary production of terrestrial ecosystems (Ciais *et al.*, 2005). The heat wave also led to widespread reductions in farm income (Fink *et al.*, 2004).

2.2 Observed yield trends

The highest yields of both cereal and tuber crops are obtained in western Europe and the lowest yields in southern and eastern Europe. By far the largest cropping areas are found in eastern Europe, in particular in the Russian Federation and Ukraine. The cropping areas of eastern Europe are larger than the total of all other regions for wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), potato (*Solanum tuberosum* L.), and sugar beet (*Beta vulgaris* L.).

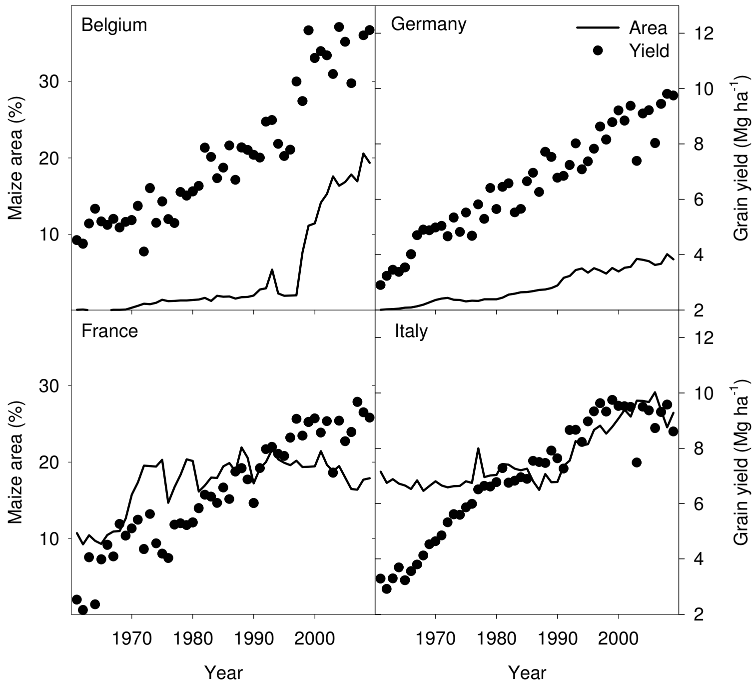
The development in national grain yields of wheat in the period 1961 to 2009 is shown in Fig. 1 for selected countries in northern, central and southern Europe (Olesen *et al.*, 2011). Yields in northern Europe are limited by cool temperature (Holmer, 2008), whereas yields in southern Europe are limited by high temperature and low rainfall (Reidsma and Ewert, 2008). Yields increased considerably during the period 1970 to 1990 due to improved technologies in all countries with the highest absolute increases in western and central Europe. The yield increases have levelled off considerably during the past 10-20 years. There seems to be a small yield increase during the past 10-20 years in Finland, whereas yields in Greece have been declining. Both effects may be climate related with increasing temperature being beneficial in Finland, but negative in Greece. The wheat yields in Germany and Greece seem to indicate an increased yield variability, which mostly likely is also related to climate. However, compared to its neighbouring countries Switzerland and Austria the stagnation of the yield trend in Germany starts about 10 years later due to a continued increase of yields in the new federal states of the former GDR during the 1990s. Stagnating wheat yields in France have been attributed to lower yields under the rising temperature (Brisson *et al.*, 2010), but changes in management may also have played a role in some countries (Finger, 2010). There are also clear indications that increasing temperature is causing grain yield reductions globally (Lobell and Field, 2007).

Fig. 1. National grain yield of wheat in northern, central and southern European countries for the period 1961 to 2009 (FAOSTAT database) (Olesen et al., 2011)



Grain yields in maize (*Zea mays* L.) have been increasing over the period 1961-2006 in both central and southern Europe (Fig. 2). The yield increases seem to be continuing in Belgium and Germany, even in recent years, where wheat yield increases have been levelling off (Olesen *et al.*, 2011). This has also resulted in a steadily increasing grain maize area in these countries and a northward shift of the grain maize cultivation in Germany. The yields of grain maize in France and Italy have not increased in recent years. This is most likely due to warmer climate and a higher frequency of droughts, which reduces the water available for irrigation,

Fig. 2. National grain yield and area of grain maize in four countries in northern and southern Europe for the period 1961 to 2009 (FAOSTAT database) (Olesen et al., 2011)



and since maize is predominantly an irrigated crop in these countries, this has impacted on both maize yields and the area cropped with maize.

Peltonen-Sainio *et al.* (2010) characterised the coincidence of yield variations with weather variables for major field crops using long-term datasets to reveal whether there are commonalities across the European agricultural regions. Long-term national and/or regional yield datasets were used from 14 European countries (total of 25 regions). Crops studied were spring and winter barley and wheat, winter oilseed rape, potato and sugar beet. Relative yield deviations were determined for all crops. Meteorological data on monthly means for temperature variables, solar radiation, accumulated precipitation and evapotranspiration were provided for the relevant agricultural regions of each country for 1975-2008. Harmful effects of high precipitation during grain-filling in grain and seed crops and at flowering in oilseed rape were recorded. In potato reduced precipitation at tuber formation was associated with yield penalties. Elevated temperature had harmful effects for cereals and rapeseed yields. Similar harmful effects of rainfall and high temperature on grain yield of winter wheat was found by Kristensen *et al.* (2011) in a study using observed winter wheat yields from Denmark.

3. Projected Impacts of Climate Change on European Crop Production

3.1 Projected climate changes

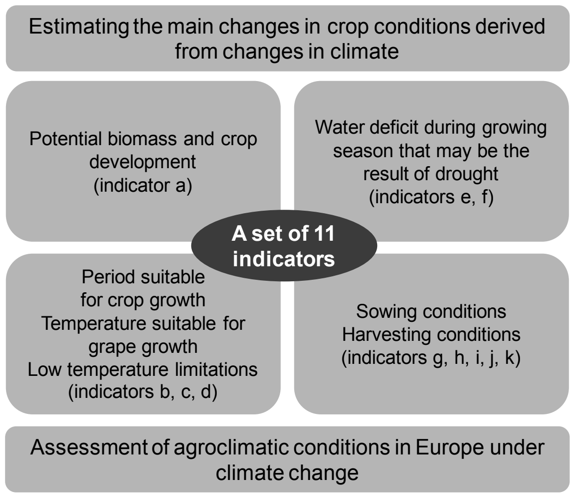
Most of the recent global climate model (GCM) experiment results, used in Europe for analysing effects on agricultural systems, are based on coupled ocean-atmosphere models (AO-GCM) (Olesen *et al.*, 2011). The main modelling uncertainties stem from the contrasting behaviour of different climate models in their simulation of global and regional climate change (Olesen *et al.*, 2007). These uncertainties are largely a function of the relatively coarse resolution of the models and the different schemes employed to represent important processes in the atmosphere, biosphere and ocean. There has recently been an increased effort in downscaling the coarse GCM results using regional climate models (RCM) with spatial resolutions of 50 km or less (Christensen and Christensen, 2007; Christensen *et al.*, 2007). This has led to improved quality in projections of regional climate changes in Europe.

The expected warming is greatest over eastern Europe during winter and over western and southern Europe in June-July-August (Giorgi *et al.*, 2004). The projected increase in summer temperature is very large in the south-western parts of Europe (exceeding 6 °C in parts of France and the Iberian Peninsula) by the end of the 21st century under the A2 emission scenario, which describes a heterogeneous world with high population growth, slow economic development and slow technological change. Generally for all emission scenarios and climate models, the mean annual precipitation increases in northern Europe and decreases in the South. But the change in precipitation varies substantially from season to season and across regions (Christensen and Christensen, 2007). There is a projected increase in winter precipitation in northern and central Europe, whereas there is a substantial decrease in summer precipitation in southern and central Europe, and to a lesser extent in northern Europe.

There is relatively little difference in projected climate changes between emission scenarios up to about 2050. Recent climate change projections for Europe based on GCMs and RCMs of the A1B scenario for 2050 show annual temperature increases relative to 1961-90 of 1.5 to 3 °C and 2 to 3 °C for northern and southern Europe, respectively (van der Linden and Mitchell, 2009). The corresponding projected changes in annual rainfall are 5 to 10% increase in northern Europe and 0 to 10% decrease in southern Europe. The A1B emission scenario describes a world of rapid economic growth, a global population that peaks in mid-century and more efficient technologies based on a balanced energy mix.

It is very likely that the frequency of drought spells and their severity will increase at least in some regions of Europe (the southern and central parts in particular), and recent projections of climate change impacts

Fig. 3. Overview of the methodological approach for using indicators for the evaluation of changes in agroclimatic conditions in Europe under climate change (Trnka et al., 2011)



support this hypothesis (e.g. Calanca, 2007). Recent results also indicate that variability in temperature and rainfall may increase considerably over large parts of central Europe (Christensen and Christensen, 2003; Schär *et al.*, 2004). Indeed, heat waves and droughts similar to the 2003 situation may become the norm in central and southern Europe by the end of the 21st century (Beniston and Diaz, 2004).

3.2 Projected impact on agroclimatological indicators

Trnka *et al.* (2011) used a set of agroclimatic indices (Fig. 3) to provide a general picture of agroclimatic conditions in western and central Europe (study domain of 8.5°W-27°E and 37°N-63.5°N) in terms of the basic weather elements that govern yield potentials and crop management. The results were obtained by analyzing data from 86 different sites representing agroclimatic conditions for most of the EU, clustered according to an environmental stratification of Europe. The analysis was carried out for the baseline (1971-2000) and future climate conditions (time horizons of 2030, 2050 and 5°C increase of global temperature) based on outputs of three global circulation models (Fig. 4). For many environmental zones, there were clear signs of agroclimatic condition deterioration in terms of increased drought stress and shortening of the active growing season, which in many regions become increasingly squeezed between a cold winter and a hot summer. This study shows that rainfed agriculture is likely to face more climate-related risks, although the analyzed agroclimatic indica-

Fig. 4. Changes in the median values of selected agroclimatic indicators relative to the 1971–2000 reference period for: a) 2030, assuming the A2 SRES scenario and a medium climate system sensitivity; b) the same as (a) but for 2050; and c) for global warming by 5 °C. The color shading represents the positive (green) and negative (red) impacts of these changes and the values represent the medians of all of the sites in a particular zone. The estimates are based on three GCM models, i.e., the ECHAM (E), HadCM (H) and NCAR (N) (Trnka et al., 2011). The environmental zones used were defined by Metzger et al. (2005)

a)

Environmental Zone	Effective global radiation change (%)			Effective growing days change (days)			Huglin index change (%)			Date of the last frost change (days)			Proportion of dry days in AMJ change (%)			Proportion of dry days in JJA change (%)			Proportion of sowing days - early spring change (%)			Proportion of sowing days - fall change (%)		
	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N
ALN	3	6	7	15	16	25	12	16	19	-5	-6	-8	0	0	1	-2	-2	-2	5	7	7	0	2	2
BOR	3	4	7	13	11	17	12	23	14	-4	-6	-4	-2	0	-1	-2	1	-6	4	5	5	3	4	5
NEM	4	5	4	14	9	20	12	22	13	-5	-5	-5	2	1	1	0	4	-3	5	5	6	5	6	7
ATN	0	0	3	7	3	17	11	15	11	-5	-7	-8	-1	-1	-3	7	11	3	4	3	5	3	3	4
ALS	0	1	3	4	2	8	12	16	10	-6	-9	-6	-1	-2	-2	8	9	3	5	5	3	4	4	5
CON	-3	-3	1	-1	-2	5	11	16	11	-4	-7	-5	-1	-1	-2	9	11	4	4	4	4	4	4	5
ATC	-2	-3	1	0	-4	7	11	16	10	-6	-9	-8	-3	-3	-6	9	14	5	2	3	3	2	1	3
PAN	-15	-11	-8	-18	-13	-9	11	15	10	-5	-6	-5	2	2	0	17	16	10	3	3	2	2	3	4
LUS	-9	-9	-3	-21	-21	-6	12	16	10	-6	-7	-6	4	5	3	22	23	8	3	2	1	2	2	3
MDM	-10	-7	-3	-10	-7	-3	12	15	10	-2	-3	-2	8	7	4	14	13	7	4	3	2	2	2	2
MDN	-10	-7	-2	-11	-5	-3	9	12	8	-24	-23	-20	8	6	3	9	7	4	2	1	1	1	-1	2
MDS	-15	-14	-7	-14	-10	-6	8	12	8	-10	-11	-11	8	8	5	1	1	1	-3	-2	-1	-5	-3	0

b)

Environmental Zone	Effective global radiation change (%)			Effective growing days change (days)			Huglin index change (%)			Date of the last frost change (days)			Proportion of dry days in AMJ change (%)			Proportion of dry days in JJA change (%)			Proportion of sowing days - early spring change (%)			Proportion of sowing days - fall change (%)		
	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N
ALN	4	8	11	31	29	47	23	29	35	-8	-10	-14	1	1	2	-2	-2	-2	11	11	11	2	3	5
BOR	7	8	10	23	16	33	22	42	27	-6	-11	-7	-2	-1	1	-7	2	-7	7	9	9	6	9	10
NEM	6	8	7	22	12	36	23	40	24	-6	-10	-7	1	1	1	3	11	-2	10	9	12	8	8	11
ATN	0	-1	5	14	5	31	19	28	21	-9	-11	-14	-4	-4	-6	15	21	6	6	6	8	5	6	5
ALS	-1	-1	4	4	0	14	22	30	19	-11	-15	-11	-2	-2	-2	16	18	5	7	8	5	7	6	8
CON	-6	-6	1	-2	-6	10	20	29	19	-8	-12	-10	-2	-2	-4	16	20	8	7	7	6	7	7	9
ATC	-3	-6	1	1	-9	11	19	28	18	-11	-15	-15	-5	-4	-8	15	24	8	4	4	4	4	3	5
PAN	-23	-19	-14	-24	-19	-14	19	28	18	-9	-11	-8	4	5	-1	26	25	18	5	5	4	1	4	6
LUS	-19	-17	-6	-40	-39	-15	22	29	18	-11	-11	-11	10	14	8	38	39	18	4	5	3	2	0	3
MDM	-18	-14	-6	-20	-15	-6	22	27	18	-4	-5	-4	12	10	5	22	21	11	5	5	2	3	3	3
MDN	-15	-11	-6	-16	-11	-4	16	21	14	-27	-28	-27	15	13	5	13	11	5	2	2	0	-1	1	2
MDS	-23	-23	-12	-22	-20	-10	15	21	14	-15	-18	-17	14	13	9	1	1	1	-8	-6	-4	-8	-6	0

c)

Environmental Zone	Effective global radiation change (%)			Effective growing days change (days)			Huglin index change (%)			Date of the last frost change (days)			Proportion of dry days in AMJ change (%)			Proportion of dry days in JJA change (%)			Proportion of sowing days - early spring change (%)			Proportion of sowing days - fall change (%)		
	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N
ALN	10	19	28	95	88	129	81	106	126	-33	-37	-40	-11	-14	-10	-2	-1	2	33	33	38	8	15	17
BOR	16	3	5	76	46	91	78	148	96	-22	-35	-25	1	8	10	2	27	8	31	37	39	19	28	30
NEM	7	-3	16	64	20	117	79	135	83	-31	-30	-33	-5	0	-10	31	48	5	34	32	36	16	22	26
ATN	-12	-11	7	28	8	80	64	92	71	-43	-46	-52	-11	-15	-23	49	54	14	20	17	24	10	12	11
ALS	-25	-22	5	-24	-28	18	71	97	61	-50	-53	-50	5	5	-7	60	61	20	15	12	5	11	10	18
CON	-24	-24	-3	-10	-17	21	66	95	63	-31	-39	-35	-5	-3	-13	46	52	23	17	17	14	11	13	18
ATC	-17	-24	-7	-15	-33	12	62	92	59	-45	-59	-56	3	10	-7	45	59	24	9	10	9	6	4	9
PAN	-47	-41	-28	-44	-30	-25	62	89	58	-31	-31	-27	21	22	4	47	48	37	13	13	10	-17	1	-2
LUS	-48	-48	-27	-102	-97	-64	71	94	57	-50	-52	-50	49	52	34	76	76	48	7	12	5	-2	-2	5
MDM	-46	-37	-18	-58	-48	-17	71	85	58	-15	-16	-13	35	29	9	43	43	29	4	7	5	-2	3	11
MDN	-42	-34	-18	-55	-38	-23	51	68	44	-37	-39	-36	45	38	18	17	17	10	2	2	0	-9	-2	3
MDS	-57	-56	-27	-62	-60	-31	48	67	45	-54	-52	-51	27	26	19	1	1	1	-27	-26	-16	-37	-24	-5

tors will most likely remain at a level that permits acceptable crop yields; however, results suggest that there is the risk of an increasing number of extremely unfavourable years in many climate zones, which will result in poor economic returns and increased risk in agricultural production.

3.3 Projected impact on crop yields

A set of qualitative and quantitative questionnaires on foreseen impacts of climate and climate change on agriculture in Europe was distributed

Fig. 5. Expected average scores for impacts of climate change on a range crop production limiting factors for five selected crops: a) winter wheat; b) spring barley; c) grain maize; d) grassland; e) grapevine. The scale used for scoring goes from -2 (large decrease) to +2 (large increase), and colour-coding reflects positive effect (green) or negative effect (red). The grey colour represents area without present crop production (Olesen et al., 2011). The environmental zones used were defined by Metzger et al. (2005)

a) winter wheat

	Growth Duration	Overwin-tering	Frost	Suitable harv.	Seasonal variability	Drought	Heat stress	Hail	Pest& Diseases	Weeds	Soil erosion	Nitrogen losses
ALN												
BOR	1.5	-1.0	0.0	-0.3	0.0	0.5	0.5	0.0	2.0	1.0	1.0	2.0
NEM	0.3	-0.8	-0.3	1.5	1.3	1.0	1.0	0.5	1.5	0.0	0.3	0.8
ATN	0.2	-0.8	0.0	-0.3	0.3	0.8	1.0	0.5	1.5	1.0	0.8	1.3
ALS	-0.5	1.0	-0.5	1.5	0.0	1.0	1.0	0.0	1.0	0.0	2.0	1.0
CON	-0.2	-0.4	0.0	0.4	0.5	0.4	0.9	0.2	1.4	1.0	0.6	1.3
ATC	-1.0	-0.7	-0.5	-0.3	0.8	0.3	0.3	0.5	0.3	0.5	0.5	0.5
PAN	-0.7	-0.3	0.0	-0.5	1.7	0.7	2.0	1.0	1.3	1.0	0.3	0.8
LUS	-1.0		0.0	1.0	1.0	1.0	1.0	0.0	0.0	1.0	1.0	0.0
MDM	-1.0	-1.0	0.0	-1.0	0.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0
MDN	-1.3	-0.5	-0.3	-0.5	0.3	0.8	0.5	0.1	0.5	1.0	0.8	0.8
MDS	-0.8	0.0	-0.3	0.3	0.5	0.8	0.8	0.3	0.0	1.0	0.5	0.5

b) spring barley

	Growth Duration	Overwin-tering	Frost	Suitable harv.	Seasonal variability	Drought	Heat stress	Hail	Pest& Diseases	Weeds	Soil erosion	Nitrogen losses
ALN	2.0		-1.0	-1.0	1.0	0.0	0.0	0.0	2.0	1.0	2.0	2.0
BOR	1.5		-0.5	-0.3	1.0	1.0	0.5	0.0	2.0	1.0	1.0	1.3
NEM	0.0		-0.5	1.3	1.3	1.8	1.3	0.5	1.5	0.0	1.7	1.5
ATN	0.8		0.3	0.0	1.3	0.8	0.8	0.5	1.5	1.0	1.0	1.3
ALS	-1.0		0.0	1.0	1.0	1.5	1.5	1.0	1.5	0.5	1.0	0.5
CON	0.0		0.3	0.2	0.8	1.0	0.9	0.3	1.3	0.8	0.7	0.8
ATC	-0.7		-0.7	0.0	1.0	0.0	0.0	0.3	0.0	0.3	0.7	0.3
PAN	0.3		0.3	-0.3	1.5	1.3	1.3	1.5	0.3	1.0	0.3	0.3
LUS	-1.0		0.0	1.0	1.0	1.0	1.0	0.0	0.0	1.0	1.0	0.0
MDM	-1.0		0.0	-1.0	0.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0
MDN	-1.3		0.0	-1.0	0.0	0.7	0.3	0.2	0.7	1.0	0.7	1.0
MDS	-0.5		0.0	0.0	-0.5	0.0	0.0	0.0	-1.0	0.5	-1.0	0.0

c) grain maize

	Growth Duration	Overwin-tering	Frost	Suitable harv.	Seasonal variability	Drought	Heat stress	Hail	Pest& Diseases	Weeds	Soil erosion	Nitrogen losses
ALN												
BOR	1.0											
NEM	0.0		-1.0	0.5	1.0	1.0	0.0	0.5	1.0	1.0	1.0	1.5
ATN	1.3		-1.0	0.0	0.5	0.3	0.0	1.0	1.5	0.0	1.0	-1.0
ALS	0.0		0.0	1.0	1.0	1.7	1.3	1.0	1.5	0.5	1.0	0.5
CON	-0.9		-0.8	0.4	0.7	1.2	0.6	0.3	1.3	0.6	1.0	0.6
ATC	0.3		-1.0	1.0	0.7	0.7	0.3	0.7	0.7	0.7	1.3	0.3
PAN	0.0		0.0	0.4	1.7	2.0	1.5	1.0	1.0	1.5	0.8	0.5
LUS	-2.0		-1.0	1.0	1.0	2.0	2.0	0.0	0.0	1.0	1.0	0.0
MDM	-1.0			0.0	0.0	1.0	1.0	1.0	0.0	0.0	0.0	1.0
MDN	-0.8		-0.7	-0.3	0.3	1.3	1.0	-0.1	0.5	0.8	0.8	0.8
MDS	-1.0		-0.3	0.3	0.0	0.3	0.3	0.3	0.5	0.5	0.3	0.3

d) grassland

	Growth Duration	Overwin-tering	Frost	Suitable harv.	Seasonal variability	Drought	Heat stress	Hail	Pest& Diseases	Weeds	Soil erosion	Nitrogen losses
ALN	2.0	-2.0	0.0	-1.0	2.0	0.0	1.0	0.0	-1.0	1.0	0.0	1.0
BOR	2.0	0.5	0.0	0.3	1.5	0.5	0.5	0.0	0.5	0.5	0.5	0.8
NEM	1.3	-1.0	-0.3	0.5	1.0	1.0	0.5	0.3	0.8	0.0	0.0	0.3
ATN	1.6	-0.6	0.0	0.5	0.8	1.0	0.4	0.0	0.3	1.0	0.3	0.5
ALS	1.1	0.0	0.0	1.1	1.3	1.8	1.3	0.5	1.0	0.3	0.5	0.7
CON	0.7	-0.4	-0.1	0.6	0.6	1.2	1.0	0.0	0.5	0.6	0.3	0.4
ATC	0.8	0.0	-0.3	0.0	1.0	0.5	-0.3	0.0	-0.3	0.3	0.0	0.3
PAN	0.7	0.0	0.0	0.3	1.5	1.3	1.0	0.5	0.7	0.0	0.0	0.3
LUS	1.0		0.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
MDM	0.0	0.0	0.0	0.5	0.5	1.0	0.0	0.0	0.0	0.0	0.0	0.0
MDN	0.5	-0.3	0.0	0.3	0.8	0.8	0.0	0.3	0.0	0.5	0.5	0.5
MDS	0.5	0.0	0.0	0.3	0.3	0.8	0.0	0.0	-0.3	0.2	-0.3	0.0

e) grapevine

	Growth Duration	Overwin-tering	Frost	Suitable harv.	Seasonal variability	Drought	Heat stress	Hail	Pest& Diseases	Weeds	Soil erosion	Nitrogen losses
ALN												
BOR												
NEM												
ATN	1.5	-1.0	-1.0	1.0	1.0	0.5	0.0	1.0	1.5	0.0	1.0	1.0
ALS	0.0	-0.5	0.0	0.0	1.0	2.0	2.0	1.0	1.5	1.0	0.0	0.0
CON	-0.2	-0.8	-0.3	-0.2	1.3	0.6	0.4	0.5	1.0	0.3	1.2	1.0
ATC	0.3	0.0	-0.3	0.3	1.0	0.7	0.3	1.0	1.0	0.5	1.0	0.5
PAN	0.3	-0.7	0.0	0.4	1.7	0.4	0.5	1.0	0.8	1.0	0.8	0.5
LUS	-1.0		1.0	1.0	1.0	0.0	0.0	1.0	0.0	1.0	1.0	0.0
MDM	-1.0	0.0	0.0	-1.0	0.0	1.0	1.0	1.0	0.0	0.0	0.0	1.0
MDN	-1.0	-0.3	0.3	-0.3	0.3	1.0	0.8	0.3	-0.5	0.8	0.8	0.8
MDS	-0.3	0.3	0.8	0.5	0.3	0.6	0.4	0.8	-0.3	-0.1	0.5	0.3

to agro-climatic and agronomy experts in 26 countries (Olesen *et al.*, 2011). Europe was divided into 13 Environmental Zones (EZ). In total, 50 individual responses for specific EZ were received. The questionnaires provided both country and EZ specific information on estimates of climate change impacts on the production of nine selected crops (winter wheat, spring barley, grain maize, grassland and grapevine).

The responses in the questionnaires show a surprisingly high proportion of negative expectations concerning the impacts of climate change on crops and crop production throughout Europe, even in the cool temperate northern European countries (Fig. 5).

The expected impacts, both positive and negative, are just as large in northern Europe as in the Mediterranean countries, and this is largely linked with the possibilities for effective adaptation to maintain current yields. The most negative effects were found for the continental climate in the Pannonian zone, which includes Hungary, Serbia, Bulgaria and Romania. This region will suffer from increased incidents of heat waves and droughts without possibilities for effectively shifting crop cultivation to other parts of the years. A wide range of adaptation options exists in most European regions to mitigate many of the negative impacts of climate change on crop production in Europe. However, considering all effects of climate change and possibilties for adaptation, impacts are still mostly negative in wide regions across Europe.

4. Adaptations to Climate Change in Europe

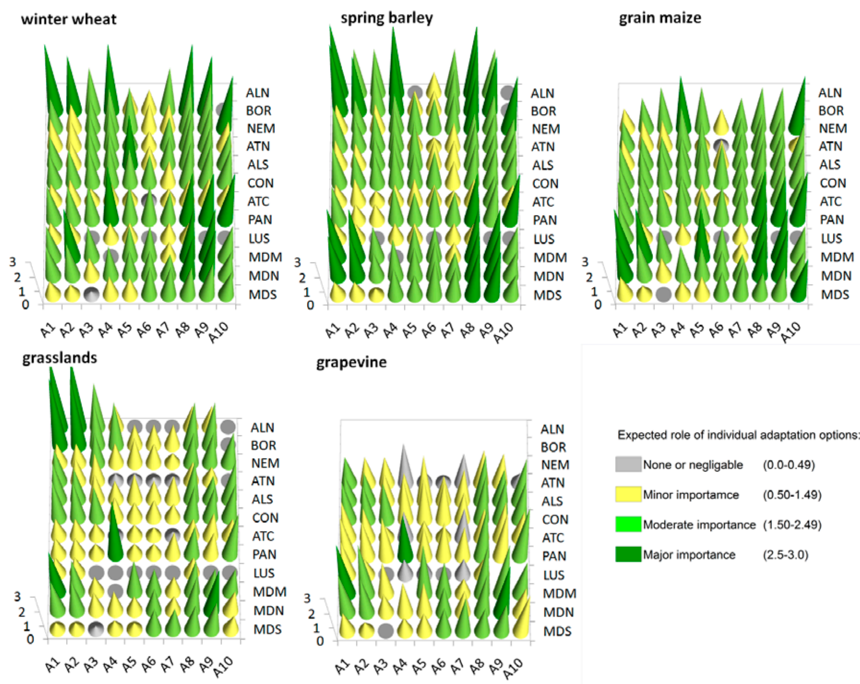
4.1 Adaptation measures

Olesen *et al.* (2011) surveyed the expectation for use of various adaptation options in European crop production (Fig. 6). The measures covered changes in cultivation timing, tillage practices, fertilisation practices, new cultivars, crop protection, seasonal forecasting and crop insurance.

Changes in timing of cultivation (including sowing and harvest) are expected to have minor to moderate effects for all five model crops evaluated by the respondents. In general, notable changes towards earlier sowing dates (and consequently of other field operations) are expected in order to avoid hot and dry periods during summer and use as much of the winter precipitation as possible. The anticipation of large shifts in timing of cultivation in the northern zones is probably enhanced by a pronounced prolongation of the growing season that will allow introduction of cultivars with longer seasonal duration.

Change in tillage practices under climate change here mostly focused on soil water conservation and protection against soil erosion (both water and wind), as these issues are believed to become increasingly impor-

Fig. 6. Expected importance of adaptation measures under the expected climate conditions for individual crops. The scale goes from 0 (none) to 4 (large). Legend: A1 Cultivation timing; A2 New tillage practices; A3 Modification to the fertilisation practices; A4 Modification of crop protection; A5 Introduction of new "climate-proof" cultivars; A6 Soil water conservation practices; A7 Focus on protection from soil erosion; A8 Operational monitoring of pests and diseases; A9 Seasonal agrometeorological forecast; A10 Introduction of crop insurance (Olesen et al., 2011). The environmental zones used were defined by Metzger et al. (2005)



tant (Falloon and Betts, 2010). Introduction of water-conserving tillage practices are assumed to be an important adaptation measure especially in case of wheat, barley and to some extent maize in the warm and dry zones, whereas the zones that are expected to experience increase of precipitation put more stress on erosion protection as soil water reserves are not expected to be replenished during winter months.

The expected shifts of fertilisation show an interesting north-south gradient with the northernmost zones expecting moderate to major changes in the fertilisation schemes both in arable crops (wheat, barley or maize) and perennials (grassland and partly grapevine). As the potential productivity of northern zones is expected to increase due to longer vegetation season, it will also require increased nutrient supply. However, the expected increase in precipitation may lead to higher risk of nitrogen and phosphorus leaching resulting in needs for modification of fertilisation and crop management practices to comply with EU environmental targets. The expectations for changes in fertilisation in drier zones are much lower.

The prospect of adaptation through cultivar changes is obviously smallest for grassland, whilst it is expected to be important in case of arable crops and in some zones also for grapevine. The new cultivars are expected to be more important in case of spring barley and grain maize.

The expected change in the crop protection efforts is one of the prominent adaptation measures, especially for wheat, barley, maize and partly grapevine. The economic benefit of crop protection and monitoring is quite low for grasslands (as are the risks). However, for wheat, barley and maize major changes in the crop protection schemes are expected. This emphasizes the need for pest and disease monitoring as one of the key adaptation responses. The focus on pests and diseases is a consequence of the likely northward spread of pests and diseases from warmer zones under climate change.

The changed climatic conditions, and according to some indications higher probability of unusual weather patterns, led most respondents to stress the role of seasonal forecasting as an adaptation tool. The seasonal forecasting is expected to be important in case of field crops and partly also grapevine, whilst in case of grasslands it is given minor priority probably for the same reasons as for phytopathological monitoring. For wheat, barley and maize the largest effect of seasonal forecasting is expected in zones, where relatively large inter-seasonal variations are more likely, and in case of Mediterranean zones the importance of seasonal forecasts likely result from increasing inter-annual variability in rainfall.

As crop insurance is seen as a quite effective tool for mitigating the effect of climatic hazards during the growing season, the highest importance has been reported for zones, where the climate impact is expected to be mostly negative.

4.2 Increasing resilience to climate change

The projected climate change does not seem to severely interfere with the possibilities of sowing and to less extent harvesting thus generally offering possibilities to adapt by changing sowing and harvesting dates in most European regions. The analysis shows that if the climate patterns will evolve according to the assumptions and scenarios we used, some of the currently highly productive agricultural regions in Europe may be at risk of reductions in suitability for rainfed crop production. This is particularly the case for Western France but also parts of South-Eastern Europe (Hungary, Bulgaria, Romania, Serbia etc.), where summers will become considerably hotter and drier reducing crop yields and increasing yield variability. In these regions winters will still be too cold to allow crop growth during winter. The Mediterranean zones will suffer from increase in dryness during spring and sharp decline in rainfed crop production potential adding a challenge to Mediterranean irrigation areas, where water use must become more efficient (Playan and Mateos, 2005).

Some of the recent studies taking into account potential impacts, adaptive capacity, and the vulnerability of farmer livelihoods indicate the agricultural sector in the Mediterranean region as vulnerable under most climate change scenarios (Metzger *et al.*, 2006). In accordance with this study we found that the Mediterranean region shows very little signs of positive impact of climate change on farming, as well as comparatively smaller adaptive capacity that is somewhat reflected in the adaptations already observed. On the other hand the respondents view the northern and north-western parts of Europe as the area, where the main gains (but also major challenges) are situated. However, the areas that came out as the most negatively affected in terms of changing conditions for crop production belong to the Pannonian (PAN) environmental zone rather than (to) the Mediterranean, which is worrying given the role that agriculture still plays in the national economies of countries located within the PAN zone (e.g., Romania, Bulgaria, Hungary, Serbia). Also parts of Austria, Czech Republic and Slovakia are expected to be highly negatively affected.

So far, research on climate change impacts in agriculture has given little emphasis to changes in frequency of extreme events. However, the impacts of increased climate variability on plant productivity are likely to increase yield losses above those estimated from changes in mean climate only (Porter and Semenov, 2005). This is primarily linked with changes in the frequency of extreme heat waves and changes in rainfall patterns, including more intensive precipitation events and longer dry periods. Changes in climate variability may be particularly difficult for many farmers to adapt to, and adaptation strategies to cope with variability may be different than from those dealing with changes in mean climate. Strategies for adapting to increased variability may include measures to avoid periods of high stress or measures that increase resilience of the system by adding diversity in the crop rotation and improving soil and water resources (Reidsma and Ewert, 2008).

5. Assessment of Uncertainties

5.1 Uncertainties related to climate change projections

The uncertainties and sources of variation in projected impacts of climate change on agriculture depend not only on the emission scenarios and climate models used for projecting future climates, but also on the impact models used, and the local soil and climatic conditions of the managed or unmanaged ecosystems under study. Olesen *et al.* (2007) addressed these uncertainties by applying different impact models at site, regional and continental scales, and by separating the variation in simulated relative changes in ecosystem performance into the different sources of uncertainty and variation using analyses of variance. The crop and ecosystem models used outputs from a range of global and regional climate models (GCMs and RCMs) projecting climate change over Europe between 1961-1990 and 2071-2100 under the IPCC SRES scenarios. The variation in simulated results attributed to differences between the climate models were, in all cases, smaller than the variation attributed to either emission scenarios or local conditions. The methods used for applying the climate model outputs played a larger role than the choice of the GCM or RCM.

For the projected changes in agroclimatic conditions under climate change (Trnka *et al.*, 2011), there were signs of agroclimatic condition deterioration and a need for adaptive measures to either increase soil water availability (e.g. by irrigation or various crop management options) or crop drought resistance in the majority of the zones. While the impacts are demonstrated on selection of three GCMs, these quite well represent a whole range of future projections. Fig. 4 shows some variation between GCMs in projected changes in agroclimatic indicators, but the differences in projected impacts are generally larger between environmental zones.

5.2 Uncertainties related to crop models

Reliability of simulated estimates of grain yield, its variability and other crop responses under different climatic conditions is essential for climate impact studies. Potential and actual impacts of climate on agricultural crops can be assessed by crop growth simulation as this technique can take the dynamic interactions between weather, soils, crops and management practices into account (Rötter *et al.*, 2011).

Palosuo *et al.* (2011) compared the performance of eight widely used, easily accessible and well-documented crop growth simulation models (APES, CROPSYST, DAISY, DSSAT, FASSET, HERMES, STICS and WOFOST) during 49 growing seasons of winter wheat (*Triticum aestivum* L.) at eight sites in North-western, Central and South-eastern Europe. Rötter *et al.* (2012) likewise compared the performance of these models against data of spring barley (*Hordeum vulgare* L.) at nine sites in Europe. The aim was to examine how different process-based crop models perform at field scale, when provided with a limited set of information for model calibration and simulation, which reflects the typical use of models in large area applications, and to present the uncertainties related to these kinds of model applications. Data distributed for the simulations consisted of daily weather data, basic information on soil properties, information on crop phenology for each cultivar, and basic crop and soil management information.

The results of Palosuo *et al.* (2011) showed a wide range of grain yield estimates for winter wheat provided by the models for all sites and years reflecting large uncertainties in model estimates. Some models on average underestimated observed yields, while other models overestimated yields. Also estimated dates of anthesis and maturity varied among models. Total above-ground biomass estimates did not follow the patterns of grain yield estimates and, thus, harvest indices were also different. The performance of individual models in predicting yields across sites was generally not satisfactory with only minimum calibration and lack of rigorous scrutiny of data for errors. However, models performed satisfactorily for the two sites with longer (> 10 years) yield series and well-documented field experiments. Mean predictions from the eight models were in good agreement with observations.

Results of Rötter *et al.* (2012) in spring barley show that models that were more accurate in predicting phenology also tended to be the ones better estimating grain yields. Total above-ground biomass estimates often did not follow the patterns of grain yield estimates and, thus, harvest indices were also different. Estimates of soil moisture dynamics varied greatly.

Precise protocols for conducting crop model comparisons are essential to ensure the comparability of the simulated results, and completeness and unambiguousness of the data. Generating and making accessible well-documented, harmonized and consistent datasets of weather, soil properties, crop development and growth and soil and crop management will be needed to further crop model development and evaluation.

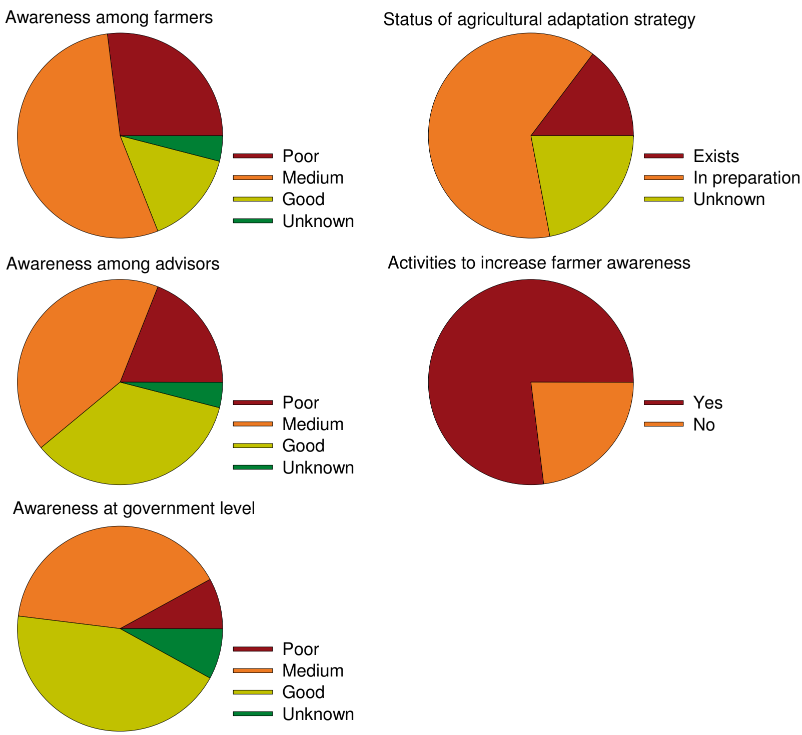
6. Awareness and Information Systems

Olesen *et al.* (2011) surveyed Europe for current awareness and use of information systems to cope with climate change. Respondents were asked to classify the status of

1) national adaptation strategy for agriculture,
2) awareness of climate change among farmers,
3) awareness of climate change among agricultural advisers,
4) awareness of climate change in government,
5) presence of specific actitivies to increase awareness among farmers, and
6) type of activities to increase awareness among farmers.

There is a top-down "gradient" in the collective knowledge on climate change impacts on agriculture with a higher level of understanding in governmental offices and a lower knowledge and awareness in case of extension services and individual farmers (Fig. 7). Only in one-third of the countries are the most affected group (farmers) considered to have a good understanding of the consequences of climate change on their enterprise and livelihoods. It also seems that the policy makers in most countries are not sufficiently informed about the risks associated with the climate change impacts for agriculture. This could be a possible explanation of a large discrepancy between the claimed awareness among government officials as almost 2/3 of the countries claim to have medium or good level of information on possible impacts, but only three countries reported an existing agricultural adaptation strategy. Although 75% of responding countries acknowledged activity aimed at increasing farmer awareness, there seems to be quite a long way to go before sufficient level of understanding is reached.

Fig. 7. Reported level of climate change awareness among farmers, agriculture advisors and government officials in 26 countries and the status of agriculture adaptation strategy and education programs for farmers (Olesen et al., 2011)



The level of information dissemination and the existence of warning systems show that a lot needs to be done in improving resilience of farming systems across Europe. The survey showed quite large differences between individual countries (and crops) but in general the use of decision support systems (DSS) is lower than expected. Whereas drought seems to be a pervasive problem across all zones and the risks will be higher under a changed climate, only half of the countries have some sort of DSS and only one fifth of the countries have a nation-wide drought monitoring scheme. The situation is even worse for heat-stress and weed management. On the other hand, selection of suitable crops or cultivars, crop protection and fertilisation schemes seems to be quite well supported by existing DSS with farm-based approaches in case of fertilisation and regional approaches in case of the crop protection.

One of the possible explanations of the present state is that the listed factors play an important role in the economy of every farm and direct benefits of DSS is well understood by farmers as it directly affects farm profitability. On the other hand accounting for drought or heat stress is less straight forward, and whilst information on this may be essential for decision makers, farmers are less inclined to demand such information. Surprisingly, in case of irrigation scheduling that has been always seen as one of the most efficient application of DSS, the results of the survey show a rather mixed picture. Whilst in some countries quite sophisticated DSS are applied (mostly in drier zones), in many countries where irrigation is used for wheat, maize, grasslands and grapevine production, there is no DSS system in place. This is in particular worrying, given the projected trends in droughts and irrigation needs.

7. Perspectives of European Agriculture Under Climate Change

The results of the studies undertaken in COST-734 indicate not only most vulnerable areas but also those that might profit from the expected changes (Olesen *et al.*, 2011; Trnka *et al.*, 2011). Surprisingly the expected impacts (both positive and negative) of climate change in Mediterranean are in several cases smaller than those expected for northern or central Europe. This is partly explained by the possibilities for shifting some of the crop cultivation into the winter season in the Mediterranean countries in a warmer climate (Minguez *et al.*, 2007). Probably the bleakest expectations could be found in responses from continental climate of the Pannonian environmental zone. Still the adaptation strategies should be introduced to reduce negative effects and exploit possible positive effects of climate change. Both short-term adjustments (e.g. changes in crop species, cultivars and sowing dates) and long-term adaptations (e.g. water management, land allocation, farming systems and institutions) are considered as important across most zones. However, the differences in climate exposure, sensitivity, and adaptive capacity will differently affect agroecosystems across Europe.

Policy will have to support the adaptation of European agriculture to climate change by encouraging resilience of cropping systems to increased climate variability and to more extreme weather conditions. This also includes investing in monitoring schemes, early warning systems and crop breeding. Policy will also need to be concerned with agricultural strategies to mitigate climate change through a reduction in emissions of methane and nitrous oxide, an increase in carbon sequestration in agricultural soils and the growing of energy crops to substitute fossil energy use, and this needs to be linked to the needs for adaptation to climate change (Smith and Olesen, 2010). The policies to support adaptation and mitigation to climate change will need to be linked closely to the development of agri-environmental schemes in the EU Common Agricultural Policy.

The adaptation to climate change has in particular to be factored in as part of the ongoing technological development in agriculture, including plant breeding (including molecular techniques), irrigation management, application of information and communication technology etc. However, such technologies should maintain and possibly improve soil quality and water resources, which are essential for improving resilience to climate change in cropping systems. In some cases such adaptation measures would make sense without considering climate change, because they help to address current climate variability. In other cases, the measures must be implemented in anticipation of climate change, because they would not be sufficiently effective if implemented as a reaction to climate change.

8. Recommendations for Research

Research on impacts and adaptation to climate change will have to deal with some "unknown aspects" that due to their complexity have not yet been studied in detail. These include the effect on secondary factors of agricultural production (e.g. soils, weeds, pests and diseases), the effect on the quality of crop and animal production, the effect of changes in frequency of isolated and extreme weather events on agricultural production, and the interaction with the surrounding natural ecosystems. It should also be noted that for obvious reasons most studies on climate change impacts have so far focused on crops. However, some livestock production systems, especially those involving grazing systems or use of fresh fodder, may be severely affected by climate change, and more studies on these systems are warranted.

There is a considerable need for increased attention on regional studies of impacts and adaptation to climate change in agriculture, since effects and responses have been shown by our study to be regionally specific depending on interactions with soils, current climate and cropping systems.

These studies should include assessments of the consequences on current efforts in agricultural policy for a sustainable agriculture that also preserves environmental and social values in the rural society. The research on adaptation in agriculture has not yet provided a generalised knowledge on the adaptive capacity of agricultural systems across a range of climate and socioeconomic futures. There is also a considerable need to better estimate the costs of various adaptation measures, and adaptation studies have to move from looking at potential adaptation to adoption, taking into account the complexity of farm-level decision-making, diversities at different scales and regions (including the entire food chain), and time-lags in responses and biophysical, economic, institutional and cultural barriers to change.

Decisions on responses to climate change in agriculture needs to address the uncertainties and the risks associated with the both climate change projections and their projected impacts (Frankhauser *et al.*, 2010). Many of those decisions heavily rely on agricultural modelling. Yet, it has been repeatedly argued that neither climate models nor crop models are fully up to the task (Soussana *et al.*, 2010), and Rötter *et al.* (2011) identify four research areas plus research capacity building as key to overcome deficiencies and improve the situation. The four research areas are model intercomparison, generation of new data for model improvement, methods for scaling, and uncertainty analysis. The authors further stress that the one to be most immediately addressed is to improve methods for quantifying and reporting uncertainties in simulated impacts.

9. Conclusions

Four different methodologies were applied to study the effects of climate change on European crop production and adaptations to climate change:

1) A questionnaire survey was used to gather and analyse standardised information on vulnerabilities, impacts and adaptation to climate change for selected crops for European environmental zones;
2) Analysis of site and regional crop data responses to climatic varibility;
3) A study of agroclimatic conditions under present and projected climate change conditions over most of the EU and neighbouring countries with special focus on variability and events with lower probability using a set of eleven agroclimatic indices; and
4) A comparison of a range of winter wheat crop simulation models against datasets from North to South in Europe to evaluate the ability of crop models to simulate crop yield responses across a wide range of climatic conditions.

The different methods complemented each other and provided a more holistic yet regionally differentiated picture of how climate change will play out for crop production in Europe.

Surprisingly the expected impacts (both positive and negative) of climate change in Mediterranean are in several cases smaller than those expected for northern or central Europe. This is partly explained by the possibilities for shifting some of the crop cultivation into the winter season in the Mediterranean countries in a warmer climate. Probably the bleakest expectations could be found in responses from continental climate of the Pannonian environmental zone. Policy will have to support the adaptation of European agriculture to climate change by encouraging resilience of cropping systems to increased climate variability and to more extreme weather conditions. This also includes investing in monitoring schemes, early warning systems and crop breeding. Research on impacts and adaptation to climate change will increasingly have to deal with some "unknown aspects" that due to their complexity have not yet been studied in detail. The research also needs much better to address the uncertainties associated with climate change projections of climate change impacts and adaptation in agriculture, including research to improve crop model predictions.

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