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SPATIAL AND TEMPORAL VARIABILITY OF PHENOLOGICAL PHASES IN ESTONIA

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TARTU UNIVERSITY
PRESS

Institute of Geography, Faculty of Biology and Geography, University of Tartu, Estonia.

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Opponent: Prof. Dr. Heino Tooming, EMHI, Tallinn

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CONTENTS

ORIGINAL PUBLICATIONS

I Ahas, R. 1999. Long-term phyto-, ornitho-, and icthyophenological time-series analyses in Estonia. International Journal of Biometeorology, 42: 119–123.

II Ahas, R., Jaagus, J. and Aasa, A., 1999. The Phenological Calendar of Estonia and its correlation with mean air temperature. International Journal of Biometeorology. Accepted.

III Ahas, R. 1998. Climatic change impact on seasonal cycles in nature: spatial and temporal variability of the phenological time-series in Estonia. — Climate Change Studies in Estonia, Kallaste, T., Kuldna, P. (eds.) SEI Tallinn, pp. 21–26.

IV Ahas, R. 1996. The seasonal dynamics of Estonian Landscapes: spatial and temporal variability of early-spring blossoming dates. Biometeorology, 14, Part 2, Volume 2. A. Hočevar, C. Črepinšek and L. Kajfež-Boga-taj (eds.), Proceedings of 14th International Congress of Biometeorology, Ljubljana, 1–8.09.1996, pp. 220–225.

V Ahas, R. and Aasa, A. 1999. Impact of landscape features on phenological phases in transitional zone from maritime to continental climate types of Northern Europe. Landscape Ecology. Submitted.

VI Jaagus, J. and Ahas, R. 1998. Spatial differences in climatic seasons in Estonia and their influence on phenological development of nature. 2nd European Conference on Applied Climatology 19 to 23 October 1998, Vienna, Austria. Österreichische Beiträge zu Meteorologie und Geophysik, 19. Zentralanstalt für Meteorologie und Geodynamik, Wien. ISSN 1016–6254, 6 pp.

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ABSTRACT

Ahas, R. 1999. *Spatial and temporal variability of phenological phases in Estonia*. Dissertationes Geographicae Universitatis Tartuensis No 10, Tartu University Press. Tartu.

The phytho-, orhnitho- and ichtyophenological time-series of the Estonian Naturalists Society and Estonian Meteorological and Hydrological Institute for 1948–1996 were analysed with the aim of studying space-time variations of selected time-series and the seasonality of Estonian nature.

The objectives of the Ph. D. dissertation were: 1) to develop and test methods for the analysis of space-time variation of phenological data in landscapes, 2) to analyse trends and the possible impacts of climate change in phenological time-series, and 3) to study regularities of spatial distribution of phenological phases in Estonia. For the study, the method of phenological calendars was introduced to describe the seasonality of nature. The method of phenological calendars lists the annual sequence of phenological phases in the form of beginning dates, their duration, and the intervals between phases. Those phenological parameters are compared and complemented with different available climatological data. In this study the mean air temperatures and statistics of climatic seasons were used. For the study of the phenology of landscapes (speed and pattern of distribution of phenophases) the special field observation programme was carried out in Estonia between 1995–1999.

The values of statistically significant linear trend show that the spring and summertime phenological phases have advanced and autumn phases have been delayed during the study period. The study of extreme (earliest and latest) years shows that 70% of the earliest dates of the 24 studied phases have occurred during the last 15 years, with an absolute maximum in 1990 with 8 extreme phases. The phenological spring has shortened (slope –0.23), the summer period has lengthened (slope 0.04), and autumn has lengthened too. The length of the growing season determined by the vegetation of rye has shortened (slope –0.09), which can be the result of changing agricultural technology. Correlation between beginning dates of phenological phases and the air temperature of the previous 2–3 months is relatively high (0.6–0.8). Studied +2 and –2°C scenarios and values of extreme years show that, for short-term variations of air temperature, the phenological development of nature remains within the limits of natural variation. Phenological maps show that these springtime phenophases spread in the landscape at a rate of 3–6 days per 100 km, with different rates in early and late springs. The maple has a steeper gradient on the north-eastern islands and the bird cherry on the western islands; the values of standard deviation have a similar spatial pattern. The distribution of phenological phases in Estonia is influenced by differences between the temperature regimes of the

Baltic sea and inland areas, different weather conditions in north-eastern Estonia, local altitude-impact of uplands with an absolute height of 150–300 m above sea level, and influences of bigger lakes and wetland areas.

Three seasonally different landscape types can be determined in Estonia on the basis of spring phenology 1) Relatively continental South-East Estonian Plain and uplands — have the earliest spring with the smallest deviations and stable intervals between phases. 2) Central, western and northern Estonian plains — with temperate influence of the temperature regime of the Baltic Sea, and big variations from year to year. Large variability is caused by the presence and duration of ice cover on the sea in cold springs, and direct access for warm air masses in early springs. 3) North-east Estonia — has the most boreal climate with longer snow cover and very late springs, influenced by arctic air masses, local effect of the Baltic Sea, uplands, and large wetlands.

1. INTRODUCTION

1.1. Objectives

Phenology is the study of annually recurring phenomena in the life-cycle of an organism or ecosystem, or of seasonal states of the physical environment. Phenology has emerged recently as an important focus for ecological research, primarily because of its considerable promise for addressing important questions concerning global modelling, monitoring and climate change (Schwartz 1999). Additional reliable methods and analyses of ground data sets are needed for models and the interpretation of data gathered by satellites. While the classical observation methods were considered old-fashioned and were criticised as unscientific, it turns out that the data on vegetation development provided by phenologists during the last centuries is about the most reliable information available for the evaluation of global trends in environmental parameters (Lieth 1997). Phenology has been a part of traditional natural sciences in Europe for centuries. There are many long time-series recorded by different observation programmes in Germany (Schnelle 1970), England (Crick & Sparks 1999), Russia (Schultz 1982), Switzerland (Defila 1992), Finland (Lappalainen 1994). The first phenological records in Estonia begin in the 18th century (Tarand & Kuiv 1994), followed by specially organised observation programmes in the 19th and 20th centuries (Eilart 1968; Lellep 1976, Ahas *et al.* 1998). Those phenological observation series were extended with the observation programmes of the Estonian Naturalists Society in 1922, and the Estonian Hydrological and Meteorological Institute in 1947. As a result of those observation programmes, the phenological time-series for Estonia have a good coverage and length, and have an important role to play in European phenological studies.

The objectives of the current Ph. D. dissertation are: 1) to develop and test methods for the analysis of space-time variation of phenological data in the landscape, 2) to analyse trends and the possible impacts of climate change in phenological time series, and 3) to study regularities of spatial distribution of phenological phases in Estonia. The study was initiated from the results of the MSc thesis “Geographical variability of the phenology of trees in Estonia” (Ahas 1994), which analysed the nomenclature and geographical variability of Estonian trees. As the next step, the current study differs in the quality and quantity of the data-series used, the methods of analysis, and the additional use of data from the specially organised field study programme. Also, in 1996 the Working Group on Phenology was set up to co-ordinate phenological studies between different institutions of the University of Tartu, the Estonian Meteorological and Hydrological Institute and the Estonian Agricultural University.

1.2. Phenology: methods and future perspectives

The importance of phenological studies is growing, together with the importance of studies of global change. Phenology, as the study of development stages of living nature and the physical environment, has its own methods, which have been developed very rapidly during the last decades (Schnelle 1955; Lieth 1974; Schultz 1981; Schwartz 1999). The recent development of phenological methods has been generated both by the field's promise for addressing important global change questions through modelling, and the need to calibrate biosphere related databases, now being generated from satellite remote sensing observations. The methods of global coverage studies of datasets obtained by satellite need to be downscaled and tied with local parameters of phenological and climatological databases. Therefore, the method of phenological calendars is introduced in phenological studies again (Defila 1991; Ahas 1999). The phenological calendar method was designed for the study of the seasonality of species, populations, ecosystems, or sites (Hopkins & Murray 1933; Schnelle 1955; Reader *et al.* 1974). The main method of those calendars was a graphically designed phenological spectrum and the study of the mean values of records (Schults 1981). These elements of descriptive phenology (Reader *et al.* 1974) were used for different studies and analyses of seasonality. Elements of phenological calendars have found applications in agriculture. These calendars of agriculture have: a list of phases, indicator species, and simple tools for phenological prognosis. Podolsky (1983) developed a method of phenological nomographs, and recommended that phenological indicator-calendars for agriculture be constructed on the basis of these nomographs. Today, the methods of phenology and seasonality studies have changed (Schwartz 1999), and there are many possibilities for studying the seasonality of nature and for composing calendars. The best quality and density phenological data is analysed and presented by Defila (1992) in the calendar of nature of Switzerland. In this calendar the statistical analysis of quartiles is combined with good graphical representation of calendars for different locations. Today, for large scale modelling, most phenologists use data obtained from satellites (White *et al.* 1997; Schwartz 1997) or special observation programmes (Kramer 1996). The integration of conventional and satellite-derived measures is needed in order to understand better the mid-latitude spring onset of photosynthesis, known as the "green wave" (Schwartz 1994; Schwartz 1998) and for modeling of vegetation dynamics for temporal ecosystems with high seasonality (Peterson & Roosaluste 1996).

For analyses of space-time variations of ground data-series, for comparing them with other locations, and for covering remote sensing data with ground series, co-ordinated observation series with unique methods are still needed.

For the analysis and comparison of data between geographical locations or years, the uniform method of calendars of nature, which can describe the full spectrum and rhythm of seasonality, must be developed further. For example, if we are interested in comparing the seasonal cycling of nature in Wisconsin and in Switzerland and in monitoring the possible effects of global change, we need a uniform method for monitor in these, even if we are dealing with different natural species or different climatic conditions. The phenological calendar (matrix of dates, intervals, duration etc) can be used in analyses, to record differences between years, periods, or locations. Climatic seasons and phenological phases can be used as good indicators, which enable the contribution of new information to studies on climatic change. For example, mean air temperature in summer (JJA) has not increased during the last century in Estonia (Jaagus 1998). At the same time, the results of this study revealed a significant lengthening of the summer season and the thermal growing season — by 11 and 13 days respectively (see Chapter 3). The start of climatic seasons in spring has tended to advance, and in the autumn period has been delayed. Similar trends have been observed in the whole Nordic region (Carter 1998).

2. ESTONIAN PHYTOPHENOLOGICAL DATABASE

2.1. Phenological data-series and observation methods

Phenological data-series used for the calendar originate from: the observation programme of the Estonian Meteorological and Hydrological Institute (EMHI), for 1948–1996; from the observation programmes of the Estonian Naturalists Society (ENS), for 1951–1997; long time-series of Hellenurme and Paide (Fig. 1); and from the phenological observation programme for this study (Fig. 2). Phenological phases were selected from a large quantity of data, according to three main criteria: 1) the quality of the observation series; 2) the possibility to get a better coverage of the whole growing season and 3) the length of the time-series.

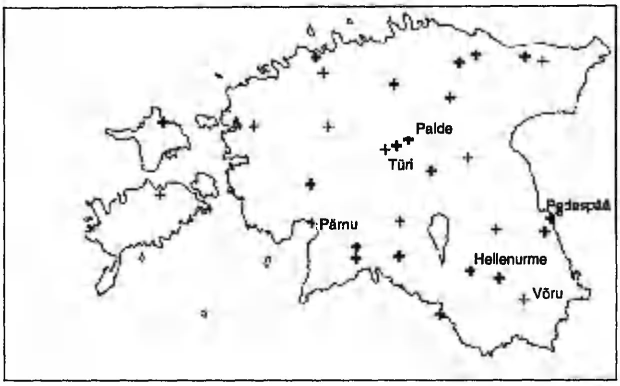

Fig. 1. Location map of phenological observation series used. + — EMHI; **+** — ENS.

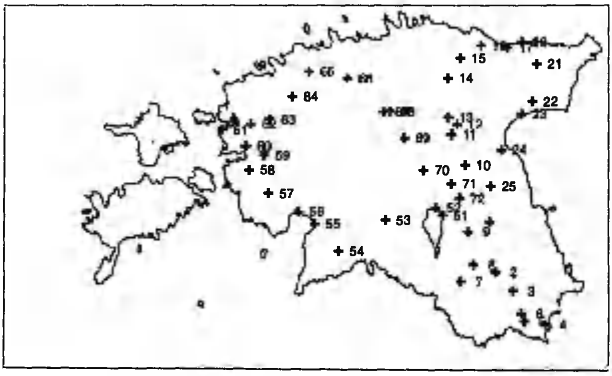

Fig. 2. Location and numbering of field observation sites in Estonia.

2.1.1. Agriphenological observation programme of EMHI (1948–1996)

The phenological phases of tree species analysed in this study were: 1) beginning of the sap rise of birch (*Betula pendula* Roth); 2) the beginning of the pollination of hazel (*Corylus avellana* L.), maple (*Acer platanoides* L.), birch (*Betula pendula* Roth), bird cherry (*Prunus padus* L.), lilac (*Syringa vulgaris* L.), oak (*Quercus robur* L.), rowan (*Sorbus aucuparia* L.), apple (*Malus domestica* L., variety *Antonovka*), and linden (*Tilia cordata* Mill.); 3) foliation of birch (*Betula pendula* Roth) and oak (*Quercus robur* L.); 4) defoliation of apple (*Malus domestica* L., variety *Antonovka*). The phenological phases of agricultural species studied were: ear of clover (*Trifolium pratense* L.); pollination of potato (*Solanum tuberosum* L.); nine phases of autumn sown rye (*Secale cereale* L.), Estonian variety *Sangaste* — beginning of vegetation, stalk formation (cereal), appearance of stalk node, ear, pollination, milky ripeness, waxy ripeness, full ripeness, harvesting.

All phenological observation data used was recorded in observation stations using the standard observation methods of the Agrimeteorological network, which are similar to the methodology used in the former USSR (Davitaja 1958). The beginning of a phenological phase was recognised when an activity was observed in 10% of the individuals of a population. About 10% of the data was interpolated due to obvious errors or gaps in observations. Interpolation of these time-series was carried out by correlation analysis, using the mean value of the two surrounding observation sites. Actual beginning of observation series is 1947, but the first observation year has very few records. Monthly mean air temperatures, used for the study, were observed at the same stations.

2.1.2. Phyto-, ornitho- and ichtyophenological observation programmes of ENS (1951–1997)

Phenological data-series from the observation programme of the Estonian Naturalists Society were selected as the data of the best quality and density (Ahas *et al.* 1998): the beginning of blossoming in five tree species (*Corylus avellana* L., *Acer platanoides* L., *Prunus padus* L., *Syringa vulgaris* L., *Sorbus aucuparia* L.). The ENS observation-series for the arrival of two bird species (*Motacilla alba* L., *Alauda arvensis* L.) in Elva between 1951 and 1996 were used for interpolation and lengthening of the time-series from Hellenurme (Fig. 1). Ichtyophenological time series by the ENS from the observation point at Pedaspää on Lake Peipsi were used in the study (Fig. 1). The phases selected were the start of spawning in two species of fish: pike (*Esox lucius* L.) and bream (*Abramis brama* L.).

The phytophenological observations of the ENS series were made with the standard methods described in the observation book (Eilart 1959; Ingerpuu *et al.* 1980); Orhnithophenological series are based on the observation manual, which is now published under the Estonian Ornithological Society. Ichthyophenological series are derived from the observation manual of Ristkok (1955). Phenological observation data is published in different books by the ENS.

2.1.3. Long observation-series of Hellenurme and Paide

For the analyses of long-term time-series only the best phenological observation-series from a limited number of observation points were selected and interpolated with time series of ENS and EMHI. Hellenurme series for 1965–1996 (Meitern *et al.* 1991; Ahas *et al.* 1998) and Paide series for 1917–1996 (Kiviorg 1972). The study is based on 8 common plant, fish, and bird species in two different observation sites: pollination of wood anemone, bird cherry, apple, and lilac, in Paide; arrival of skylark and white wagtail, in Hellenurme (Fig. 1).

2.2. Observation programme of landscape phenology

For evaluation of the current phytophenological database, for modelling and analysing green-wave phenology in Estonia, and for verification of the results of the study of spatial dispersion of phenophases, a special field observation programme was set up. During the years 1995–1999, phenological observations were carried out in 49 observation points in different landscape regions of Estonia (Fig. 2).

The observation programme of landscape phenology was initiated by the respective working group in the autumn of 1995 and finished its work in the spring of 1999. The 46 observation points were located in continental Estonia (Fig. 2). The objective of the observation programme was to study how phenological phases are distributed, and how they spread in the landscape. Therefore, the observation programme has a specific methodology and does not describe many specific aspects of phenology. For example, the observers do not record dates of phenological phases, they only record the appearance, or non-appearance, of a phase in the observation point. The observation table standard for spring observations included 6 development phases of 15 naturally occurring tree species, and the one for autumn observations included 5 development phases of 8 naturally occurring tree species. For the current analysis, the phases of: pollination of maple and bird cherry, were selected. The observation sites were chosen on the basis of the following parameters: visual (using binoculars) distance from the road, because of the tight timetable of observations; appearance of more than 2 adult specimens of the studied tree species; exposition of observation site. The phases were determined according to the methodology of agrimeteorological observations in Estonia. The observation sites differ from each other by the type of landscape, soil, moisture, and ecosystem. In cases of very different types of biotopes (wetland and forest) or topography (valley, plain, and hill) the observation sites were selected for the comparison of those different types (Ahas & Aasa, *submitted,* Publication V). The Estonian landscape is relatively flat with some glaciogenic uplands. The highest observation points are Haanja, in the south-eastern part of Estonia (No 6), 260 m above sea level and Emumäe (No 12), 140 m above sea level. Other observation points are located at an average height of 30–70 m above sea level; the lowest are in Western Estonia (No 55–62), located below 30 m above sea level.

3. METHODS

The phenological calendars method (Schnelle 1955; Lieth 1974; Hydrometeorological Printing House 1965; Schultz 1981; Podolsky 1983) was applied to analyse space-time variations of the calendar of Estonian nature. Beginning dates, as phenological variables, mark certain points in the annual cycle; they have a particular sequence and are closely correlated with phases of the same season. A recurrent annual cycle consists of a sequence of regularly exchanging phenological phases described in terms of beginning dates, durations and intervals. Every period distinguished in the annual cycle has its duration, for example, the thermal growing season, climatic seasons, or the pollination period of rye. An interval is defined as the period of time between any two phenological phases.

A phenological calendar contains common descriptive statistics (mean values, standard deviations, extreme values, ranges, parameters of distribution). At first, an average calendar was composed, using mean values of climatic seasons and phenological phases during the observed period. An annual circle where different seasons are distinguished, can graphically represent the calendar (Jaagus & Ahas 1998).

Spatial and temporal variation are analysed separately. Spatial standard deviations are calculated using observed data from a number of observation sites, at first, for every year individually, then, averaged by years. Spatial range means the difference between the latest and the earliest mean value among the stations or observation sites. Temporal standard deviation is found on the basis of a single time-series and then averaged by stations. Temporal range indicates the difference between the latest and the earliest year in the time-series (Ahas & Aasa, *submitted*, Publication V).

Regression analysis is used for estimation of trends and for correlation analysis to estimate statistical correlation between climatic seasons and phenological phases. Significance of correlation coefficients and slopes is estimated by means of t-statistic. The confidence level $P<0.05$ is considered to be sufficient for stating a significant correlation of trends (Ahas *et al. accepted*, Publication II).

The interpolation of phenological data collected with a route method had some specific aspects. As the map of observation sites (Fig. 2) shows, site locations are aligned on three main axes: north to south, east to west and northwest to southeast. This creates the need to use a special interpolation model for spatial interpolation of data. For interpolation of data from filed observations (Fig. 9–14 of Publication V), the software package Surfer 5.01 programme and the three interpolation ellipse model were used. The data was interpolated separately with every three ellipses, and the mean value of all three interpolations was used for the design of maps of 50 rows and 45 columns. Parameters of the three interpolation ellipses were: 1) R_1=52 000, R_2=152 000, A=–45°; 2) R_1=52 000, R_2=152 000, A=45°; 3) R_1=52 000, R_2=152 000, A=90°. Altitude of observation points is not considered. For the maps based on the results of the long time-series analyses, the statistics were calculated before interpolations. Because of good coverage with data, the maps of long time-series (Fig. 3–8 of Publication V) were interpolated with one circle (Ahas & Aasa, *submitted*, Publication V).

4. SPACE-TIME VARIATIONS OF THE ESTONIAN PHYTOPHENOLOGICAL CALENDAR

4.1. Phytophenological calendar

The analysed phenological calendar consists of the beginning dates of 24 phytophenological phases (Ahas *et al. accepted*, Publication II), occurring throughout the whole growing season (Table 1). Two phases: 'birch sap rising' and 'blossoming of hazel' are normally observed before the beginning of the growing season, during which daily mean air temperature is higher than 5°C (Jones & Briffa 1995). The order of chronological succession of phenological phases is common for all the years of the study period, and is the same for all observation sites. The only pheno-anomalies were observed in Võru for birch and linden pollination, which swapped places with their neighbouring phases in the phase sequence. Differences between the three stations studied are relatively small and are shown in Fig. 3 of Publication V.

The mean (arithmetic average) beginning dates and medians of phenological time-series do not differ more than 1–3 days, reaching a maximum for the pollination of hazel, which is a very variable early spring phase with the highest standard deviation (16.3). The high variability of early spring phases (sap rise of birch and pollination of hazel) is connected with snow cover and the length of winter, which is very variable in Estonia. The variability of data for the Türi station, in quartiles, is shown on Fig. 3 and the standard deviations in Table 1. Temporal variability of data is higher in spring and autumn; summer phases have smaller deviations, except for the pollination of rye, which has a standard deviation of 10.4 days. The variability of the parameters of climatic seasons, expressed in standard deviations, has a similar geographical distribution in Estonia (Jaagus & Ahas 1998). Relatively smaller standard deviations can be found for phenological phases in continental south-eastern Estonia (Võru).

The study of extreme (minimum and maximum) years (Table 1) shows that most of the earliest dates for spring have been observed during recent decades. 70% (17) of the earliest dates of the 24 studied phases have occurred during the last 15 years, with an absolute maximum in 1990 with 8 extreme phases. 25% of the latest dates of the 24 studied phases have occurred during the last 15 years and 58% (14 dates) during the first 15 years of the study period, with an absolute minimum in 1955 with 11 extreme phases.

Table 1. Phenological calendar studied (mean for 1948–1996): phenological phases (chronological order) and beginning dates in three observation stations, mean standard deviation and linear trend for the Türi station (* autumn sown rye, Estonian variety Sangaste; ** data series with many gaps; significant values of slope (p<**0.05**) are marked in bold)

Phenological phase	Average	Median	Slope	Min	Min year	Max	Max year	Stdev
Birch sap bleeding	5-Apr	6-Apr	**–0.441**	7-Feb	1989	24-Apr	1966	14
Pollination of hazel	11-Apr	14-Apr	**–0.399**	23-Feb	1990	6-May	1966	16.3
Beginning of veget. of rye*	17-Apr	16-Apr	0.116	28-Mar	1959	4-May	1956	8.6
Pollination of birch	10-May	11-May	**–0.181**	24-Apr	1990	4-Jun	1955	7.2
Foalition of birch	10-May	12-May	**–0.287**	22-Apr	1990	6-Jun	1955	8.1
Pollination of maple	12-May	12-May	–0.088	26-Apr	1990	4-Jun	1955	6.9
Pollination of bird cherry	19-May	20-May	**–0.168**	29-Apr	1990	8-Jun	1955	7.1
Foalition of oak	22-May	22-May	**–0.171**	6-May	1990	14-Jun	1955	7.7
Pollination of apple	29-May	31-May	–0.139	8-May	1990	22-Jun	1955	7.8
Pollination of oak	30-May	31-May	**–0.225**	6-May	1984	28-Jun	1987	9.2
Pollination of lilac	31-May	31-May	**–0.234**	2-May	1978	24-Jun	1955	9.1
Pollination of rowan	1-Jun	2-Jun	**–0.234**	16-May	1990	26-Jun	1955	7.7
Ear of rye	4-Jun	4-Jun	–0.115	22-May	1989; 1990	20-Jun	1955	6.4
Ear of clover	17-Jun	18-Jun	0.091	6-Jun	1963	8-Jul	1994	7.2
Pollination of rye	20-Jun	20-Jun	–0.035	6-Jun	1993	10-Aug	1991	10.4
Pollination of linden	13-Jul	14-Jul	–0.064	8-Jun	1948	28-Jul	1951	8.7
Milky ripeness of rye	14-Jul	13-Jul	–0.065	2-Jul	1989	31-Jul	1962	6.6
Pollination of potato	24-Jul	26-Jul	**–0.358**	4-Jul	1989	18-Aug	1955	8.9
Waxy ripeness of rye	31-Jul	31-Jul	0.122	18-Jul	1983	30-Aug	1987	7.9
Waxy ripeness of barley	8-Aug	10-Aug	–0.004	24-Jul	1975	20-Aug	1955	6.7
Full ripeness of rye	13-Aug	12-Aug	0.087	28-Jul	1988	6-Sep	1987	9.2
Rye harvest	17-Aug	16-Aug	0.036	27-Jul	1988	17-Sep	1987	11.8
Defoliation of apple**	19-Oct	20-Oct	0.026	6-Oct	1949	4-Nov	1967	7.9
End of vegetation of rye**	31-Oct	31-Oct	0.031	10-Oct	1992	23-Nov	1978	10.4

This explains the nature of the negative slope of the linear trend for those series. Extreme values for spring, summer, and autumn periods occur in different years. The earliest spring and summer occurred in 1990, and the earliest autumn in 1988. The latest spring was in 1955 and 1966, and the latest autumn in 1987. The absolute range of spring phases between earliest (1990) and latest (1955) years is relatively high. For example, the range of ‘pollination of maple’ for those years was 39 days and ‘pollination of oak’ 53 days; summer and autumn phases have similar amplitudes of variation between min and max values.

Spatial variations in the data from the three studied stations show that spring phenophases start the earliest in Võru. After the Gulf of Riga has warmed up, at the end of May, the phenological development in Pärnu begins to catch up with that in Võru. In early summer the phenological phases of the pollination of lilac, apple and rowan can very easily change their order, and the geographical variation of those phases is high too (Ahas 1999). For example, in years with a warm winter the pollination of lilac and apple starts in opposite order in Pärnu and Võru. This is a result of different winter conditions and is related particularly to the icecover of the Baltic Sea. Throughout the summer, only the most northern station, Türi, remains 2–4 days behind. In the autumn, the phenological phases in Pärnu are the latest due to the influence of a relatively warm sea.

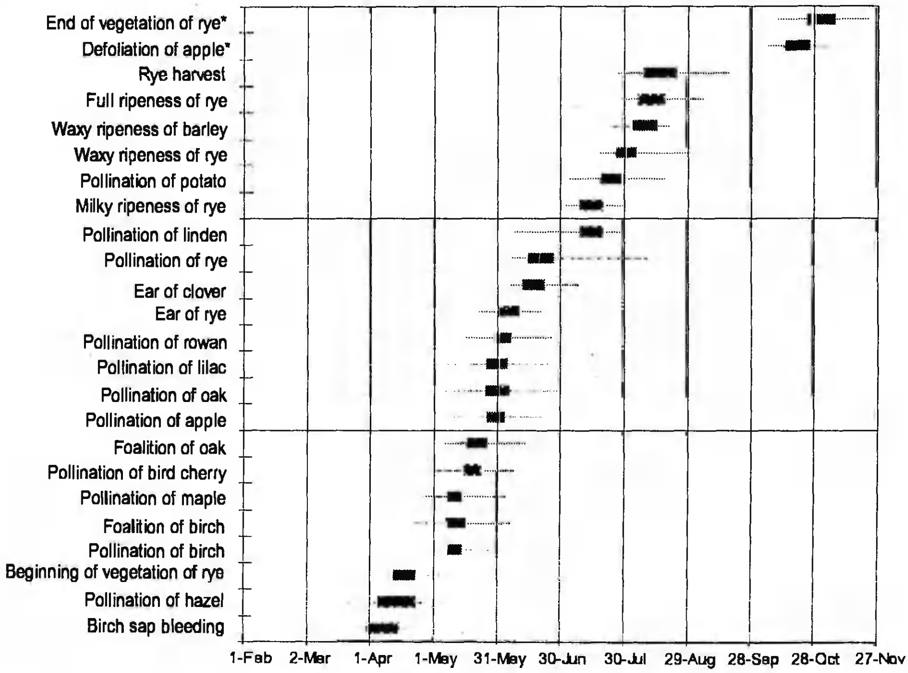

Fig. 3. Phenological calndar in Türi and variability of data in quartiles for 1948–1996.

Duration of homogeneous periods (phenological seasons) and intervals between phases are typical variables of phenological calendars. The phenological calendar of Türi (Fig. 3), by quartiles, shows different phenological seasons or homogeneous periods of the growing season. The phenological spring season begins with the vegetation of rye and ends with the pollination of apple. This period has shortened (slope –0.23). The summer period, between pollination of apple and harvest of rye, has lengthened, (slope 0.04), and autumn has length ened too. The length of the growing season of rye has shortened (slope –0.09), which is different from other similar studies and can be the result of the use of different methods or specific aspects of changing agricultural technology.

4.2. Temporal variability of studied time-series and possible impact of climate change

4.2.1. Phytophenological series

The results of the current study are similar to the changes in thermal growing season observed in Europe by the International Phenological Gardens programme (Menzel & Fabian 1999). For example over 30 years of observations in Europe, leaf unfolding has advanced 6 days and leaf colouring in fall has been delayed by 4.8 days. The slope of linear regression (b1) for the studied phenological calendar (Table 1) shows changes in time series during the study period. Most of the statistically significant values ($p<0.05$) of slope show that time-series have advanced, especially in the spring period. All statistically significant values of the trend are in spring between –0.1…–0.5. The slope of linear trend is different for seasons, with the biggest value for early spring and spring (Fig. 4). Autumn phases have been delayed, but these trends are not significant. This shows that there is a general tendency of lengthening of the vegetation period (Myneni *et al.* 1997).

Table 2 and Fig. 1–2 of Publication III present the temporal variability characteristics of some phenological phases observed in Paide (Central Estonia) between 1919 and 1995 (Ahas *et al.* 1998). Long-term changes in phenological phases have trends similar to those of climatic seasons. The start of phenological phases has advanced in spring. All the beginning dates have advanced, while the blossoming of wood anemone and of lilac have a trend significant on a 0.05 confidence level. During the last 78 years, spring has advanced 7.5 days on average.

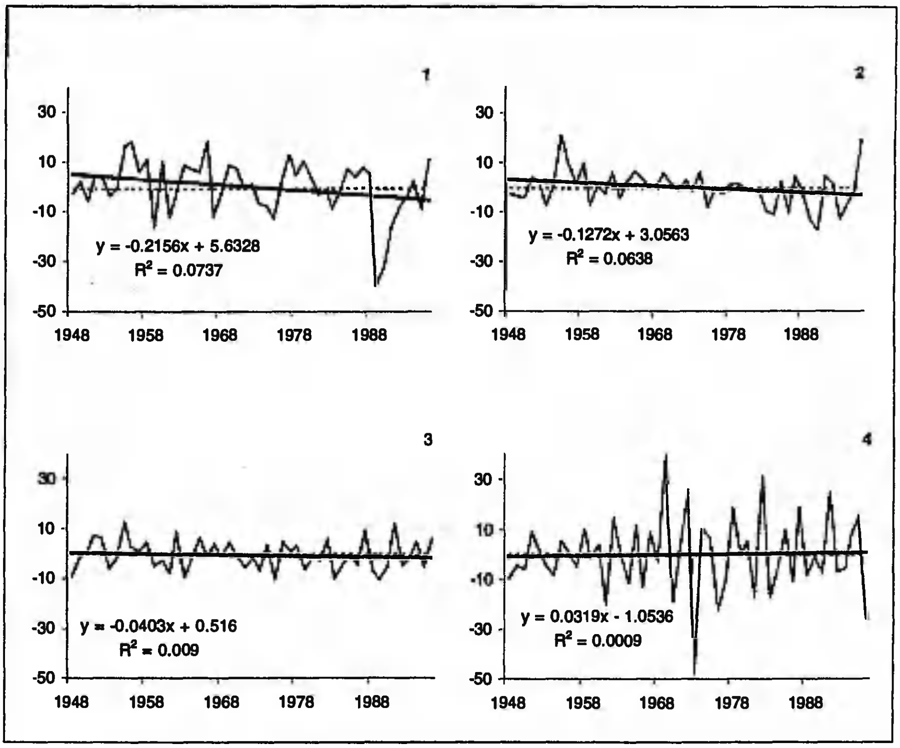

Fig. 4. The linear trend for mean values of studied phenological phases in Türi (1948–1996). Phases of: 1 – early spring; 2 — spring; 3 — summer; 4 — autumn.

4.2.2. Ichthyophenological series

The studied ichthyophenological time-series also exhibit a trend: during the 44 years studied, the beginning of spawning of pike has advanced 6 days and 8 days for bream (Fig. 3 Publication III). The regression analysis of fish phenology showed an advance of 9 and 15 days per 100 years respectively. For all ichthyophenological data the statistical confidence of the linear trend (t-statistic) is low (–0.92 and –1.13 respectively). Ichthyophenological observation series are not of the best quality due to many errors in the observation data.

4.2.3. Ornithophenological series

The analysis of ornithophenological time series (132 years) produced results opposite to those from the phyto- and ichthyophenological time-series; the arrival of the sky lark was delayed by 5 days and that of the white wagtail by 6 days, over the studied period (Fig. 4, Publication III) (Ahas *et al.* 1998). The result of linear regression analysis was, respectively, 4 and 5 days later per 100 years. The t-statistic value for the linear trend was 1.70 and 2.8 respectively.

The statistical short-coming of this method is that in phenological data analysis the use of linear regression is not the best method for periods of 100 years and longer (Gornik 1994). The long-period oscillations of climatic parameters (25–50 years) periodically reverse the direction of the linear trend at this scale. The analysis of ornithophenological time-series, and their description using a polynomial trendline (see Fig. 5, Publication III), shows that the long-term changes in phenophases are similar to the phyto- and ichthyophenological processes studied. The warm period at the end of the 19th century reverses the direction of the linear trend. The analysis of the white wagtail time-series over the same period as the phytophenological time-series suggests that its phenophase now starts 5 days earlier, which corresponds to the rest of the data studied. The problem lies in finding a relevant method and adequate period for analysis, giving the most representative output.

4.3. Spatial variability

4.3.1. Spatial distribution of long time-series

For analysis of the spatial distribution of phenological data, the time-series of maple and bird cherry, the 22 best quality data series from EMHI and ENS, over 48 years were selected (Fig. 1). Analyses of the pollination of maple and bird cherry in Estonia show the relatively big spatial differences of phenological phases in the spring period. Statistical analysis of time-series from all 22 observation sites gives mean beginning dates of 11th of May for the pollination of maple and 18th of May for bird cherry. Table 1 shows the statistics of 7 observation sites, geographically selected from those 22 (Ahas & Aasa, *submitted*, Publication V).

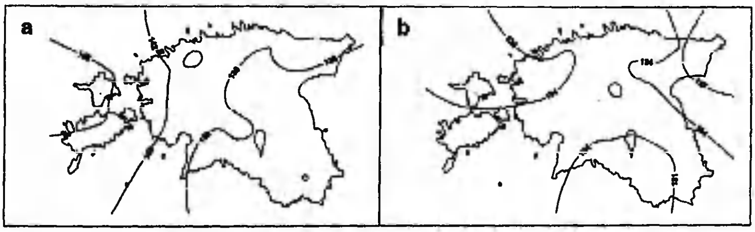

Fig. 5. Mean onset of pollination of maple (a) and bird cherry (b) in Estonia. (Julian days transformed into calendar dates 110=10 Apr, 120=20 Apr, 130=30 Apr, 140=20 May, 150=30 May).

The phenological maps of the studied time-series illustrate differences between the spatial patterns of the studied species (Fig. 5a and 5b). Maple is advancing to full bloom in southern Estonia (Valga, Polli, Võru), while in western and eastern Estonia it does so 3 days later and is even later in north-eastern Estonia (Jõhvi and Roodu). Bird cherry is advancing to full bloom one week after maple, with the earliest date in southern and south-eastern Estonia, developing in a north-westerly direction, with latest dates on the western islands.

The standard deviations of time-series are very homogeneous, between 7.1 and 7.7 days, except the beginning of pollination of maple in Valga, with 5,8 days. The spatial distribution of standard deviations is shown on the map of mean values for maple and bird cherry (Fig. 4a and 4b, Publication V). Like the beginning dates of phases, the spatial distribution of standard deviations has its specific pattern. The standard deviations of maple rise from west to east (north-east), and those of bird cherry from south to north-east.

The absolute minimum and maximum values of the studied time-series mean that the values of standard deviation are relatively high: 38 days on average, with a maximum of 52 days for maple in north-east Estonia. The absolute minimum year for most observation points is 1990 and the maximum year 1955. During the extreme years the differences in the distribution of the phenological phases of maple are not very big; the latest date is still in the north-east of Estonia (Fig. 5a and 5b, Publication V). Very early years exhibit fast development of phases throughout all the territory that is connected with the strong influence of warm air masses (Karing 1992). The pollination of maple is a phenomenon of the first hot and sunny days. The extreme values of 'pollination of bird cherry' show that in early and late years the distribution of phases is influenced by the temperature of the Baltic Sea, and proceeds from east to west, with an especially high gradient for the western islands (Fig. 6a and 6b, Publication V).

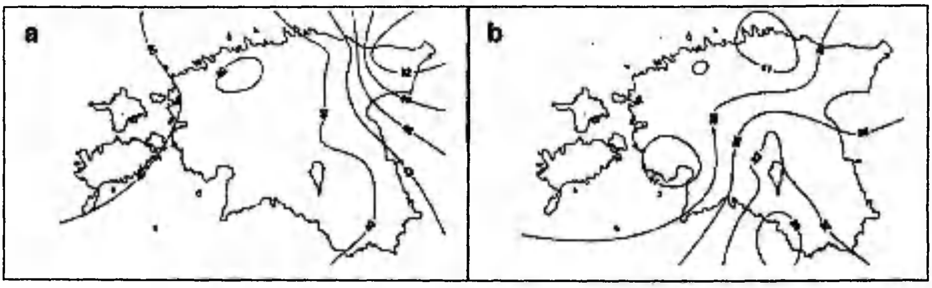

Fig. 6. Differences between minimum and maximum dates in days for maple (a) and bird cherry (b).

Mean intervals between minimum and maximum values demonstrate that in extreme years the studied phenological phases can start up to 3 weeks earlier or later. Intervals between early (1990) and late (1955) years are mapped in Fig. 6a and 6b. For maple, this interval grows towards the north-east, and for bird cherry, from south to north. The interval between phases of maple and bird cherry is very stable at 7–11 days, with a mean value of 9 days. The interval is growing from the south-eastern mainland (Valga, Tartu) to the north-east (Rakvere and Kohala) and the western islands (Kärdla, Karja) (Table 1 of Publication V). A similar effect is shown on the map of mean intervals, which has a strong gradient on the islands because of the very late dates for bird cherry (Fig. 8 of Publication V).

4.3.2. Field studies

The methodology of field studies was oriented to get maximum results on the spatial distribution of phenophases. Therefore we do not use the term 'beginning dates'. We have analysed the value of 'appearance of phenological phase' in certain observation points (Ahas & Aasa, *submitted*, Publication V).

Phenological maps of field observations show a big similarity between the distribution of phenological phases of both of the studied species. The beginning of pollination starts first in the southern and south-eastern part of Estonia, progressing towards the north-west. The last area to be reached is north-eastern Estonia. The difference between maple and bird cherry lies mainly in the speed and direction of development of phenophases. Onset of pollination of maple spreads very rapidly across Estonia and advances more towards the north-east. Pollination of bird cherry advances less rapidly; direction of development of the phase is influenced more by the Baltic Sea and therefore is more north-western.

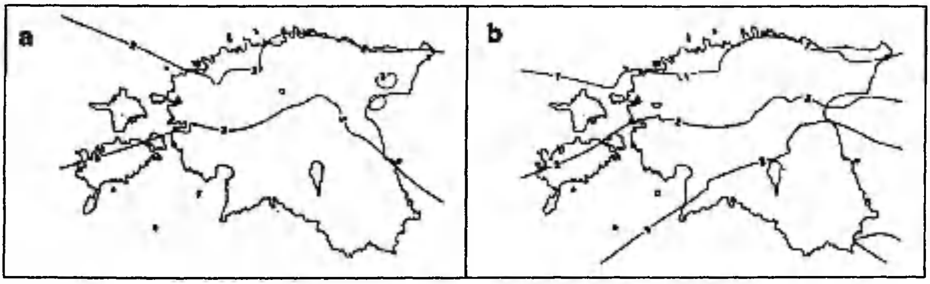

Fig. 7. Onset of pollination of maple: a) mean for all observations in 1996–1999 and b) 14 May 1999. Appearance of phases: 0 — not started; 1 — beginning of pollination; 2 — full bloom, 3 — end of pollination, 4 — phases finished.

The spatial pattern for the onset of maple pollination is described with the average for the whole study period (Fig. 7a) and with the average for the spring of 1998. The density of isolines on the map of mean values is low, but the direction of phenophases is described well with this line. Fig. 7b. shows the development of phases in a very slow spring, in 1999. The first observation shows local diversity of landscapes and exposition in southern Estonia and a very sharp border in the middle of continental Estonia. The second observation, after 2 weeks, shows that in the conditions of an unusually cold and sunny spring the onset of phases progresses very slowly and has a very high local micro-scale diversity, dependent on exposition and biotope character. The spring of 1998 was warm and the development of the onset of pollination of the maple was fast (Fig. 11a and 11b, Publication V). The direction of advance of the phase was to the north-east, which is typical for maple. The phase developed during 10 days across all of continental Estonia, which is the mean for the studied phenophases of this period in the database.

Onset of pollination of bird cherry is a very impressive phenological phase in the Estonian landscape, and therefore is described by many observation series. The map of the means of all observations and of the mean for 1998 (Fig. 12a and 12b) show that this phase, with its northerly direction of advance and two spatial isolines for the mean of 1998 spring, is similar to maple. The phenological maps of 1996 spring (Fig. 13a and 13b) show the movement of the onset of this phase towards the north and the relatively strong influence of the cold Baltic Sea and Lake Peipsi in eastern Estonia.

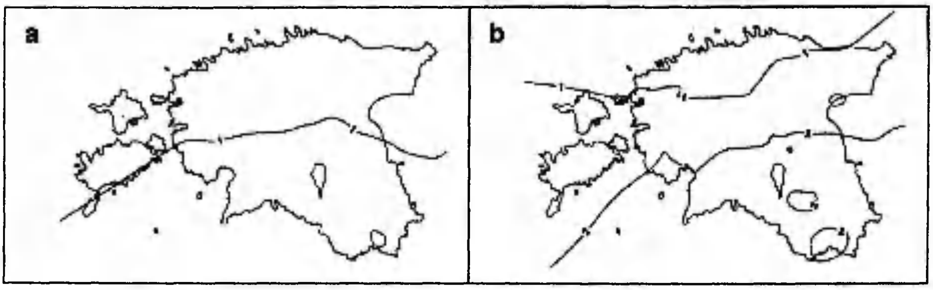

Fig. 8. Onset of pollination of bird cherry: a) mean for all observations in 1996–1999 and b) mean for 1998. (List of phases see Figure 7).

The similar influence of the temperature regime of the sea is seen on the map of phase onsets for 1998, and was mentioned in the study of time-series (Fig. 14a and 14b, Publication V). On those maps we can see the influence of the South Estonian Uplands, Central Estonian Wetlands, and the local impact of Lake Peipsi in eastern Estonia.

5. PHENOLOGICAL DATA AND CLIMATE

5.1. Correlation with climatic seasons

In many cases, the typical meteorological variables, such as monthly mean air temperature, are not the best variables to describe weather conditions associated with annual cycles in the organic world (Maak & von Storch 1997). Therefore, climatic seasons, characterised by their start date and duration, are applied (Jaagus 1997a). Instead of using measured values, qualitatively different periods of the year are distinguished according to strict criteria. The criteria for determining climatic seasons vary in different parts of the world (Flohn 1942; Lamb 1972; Hlavaè 1975; Kalnicky 1987; Sladek 1990; Lewik 1996). There is a tradition of analysing climatic seasons in Estonia (Raik 1963; Jõgi 1988; Jaagus 1996a).

A climatic season can be defined as an independent stage in the annual cycle of the climatic component of the geographic environment (Galahov 1959). Every season is expected to have its specific complex of weather types, atmospheric circulation, direction of weather changes, etc. In reality, climatic seasons begin at a different time every year, depending on weather conditions. A climatic calendar entails a complex of statistics that describe average annual cycles of climatic seasons (Jaagus & Ahas 1998). Phenological development in nature is closely related to weather conditions. Early and warm springs coincide with the earlier occurrence of phenological phases, and vice versa. Correlation coefficients between beginning dates of climatic seasons and phenological phases in Estonia, averaged over 9 stations between 1948 and 1996, are rather high (Table 2). They are marked in bold when the correlation is significant on a $P<0.05$ confidence level for each of the stations.

Due to thermal inertia, correlation between the start dates of late winter, early spring, and spring has been observed. For example, the beginning date of late winter influences whether the following spring will be early or late. Early spring is associated with the start of vegetation and the subsequent phases of rye. Harvesting of rye usually takes place in August and is therefore not connected with the start dates of climatic seasons in springtime.

The start of spring (i.e. the thermal growing season) has the highest correlation with phenological phases such as foliation of birch and blossoming of maple and bird cherry, which are observed from the end of April to the middle of May.

Table 2. Correlation coefficient (Corr.) between beginning dates of climatic seasons and phenological phases (in chronological order), averaged over 9 stations with parallel observations between 1947 and 1996, and mean difference (Diff.) between the correlation coefficients calculated for the periods 1972–1996 and 1947–1971. A value in bold means that correlation is significant on a P<0.05 confidence level for each of the stations.

Phase	**Late winter**		**Early spring**		**Spring**		**Summer**	
	Corr.	Diff.	Corr.	Diff.	Corr.	Diff.	Corr.	Diff.
Beginning of vegetation of rye	**0.53**	–0.06	**0.58**	–0.04	**0.39**	0.01	0.05	–0.10
Stalk formation of rye	0.47	0.00	**0.49**	–0.05	0.37	0.08	–0.02	–0.10
Foliation of birch	**0.46**	–0.03	0.39	–0.01	**0.55**	0.21	–0.06	–0.06
Blossoming of maple	**0.42**	0.07	**0.46**	–0.04	**0.55**	0.11	0.03	–0.27
Blossoming of bird cherry	**0.51**	–0.06	**0.53**	–0.19	**0.53**	0.09	0.14	–0.30
Appearing of stalk node of rye	**0.51**	–0.12	**0.54**	–0.02	0.37	0.09	0.02	–0.26
Blossoming of apple tree	**0.44**	–0.18	**0.48**	–0.40	**0.43**	0.02	0.32	–0.33
Blossoming of lilac	0.36	–0.32	0.40	–0.34	0.30	-0.04	**0.37**	–0.27
Blossoming of rowan	0.35	–0.37	0.37	–0.35	0.29	0.04	0.35	–0.33
Ear of rye	**0.40**	–0.27	**0.48**	–0.30	0.32	0.05	0.35	–0.27
Pollination of rye	0.36	–0.43	0.22	–0.33	0.30	0.06	**0.53**	–0.18
Milky ripeness of rye	0.39	–0.32	0.23	–0.25	0.31	0.22	**0.52**	–0.06
Waxy ripeness of rye	0.31	–0.36	0.20	–0.34	0.31	0.07	**0.44**	–0.08
Full ripeness of rye	0.31	–0.22	0.21	–0.36	0.26	0.11	**0.43**	–0.07
Harvesting of rye	0.25	–0.17	0.16	–0.34	0.31	0.16	0.33	–0.10

Phenological development of rye is less strongly correlated with the start of spring. The start of summer is strongly correlated with late phases of rye at the end of May and in June.

The longer the time interval from the beginning of a climatic season to the start of a phenological phase, the weaker is their correlation. This is clearly illustrated in Fig. 5, Publication VII, where lines show how the correlation between climatic seasons and phenological phases change with time. The phases are arranged in chronological order. It is also obvious that there is no correlation between the start date of summer and earlier phenological phases, i.e. stalk formation of rye and foliation of birch. To analyse the persistence of the correlation between the seasons and phases, the 50-year period has been divided into two halves and the same correlation coefficients have been calculated for them independently. Differences between correlation coefficients, averaged over the 9 stations, calculated for the periods 1972 to 1996 and 1947 to 1971 respectively, are presented in Table 2. They indicate that during the first period, correlation was remarkably higher than during the second period.

The difference is especially high for correlation coefficients between late winter and early spring, and some phenological phases in May and June. Greater differences are typical also for the beginning dates of summer. This means that correlation coefficients calculated for the period 1972 to 1996 are substantially smaller than the coefficients found for the period 1947 to 1971. Only the beginning date of spring has a higher correlation in the more recent time-series.

As a graphical summary of the results of the phenological calendar-analysis, several phenological annual circles can be drawn. Fig. 6 of Publication V presents the mean annual circle of climatic seasons in Estonia and of the phenological phases of autumn sown rye in spring and summer. Names of climatic seasons, in the inner circle, are typed in bold. The circle is oriented so that the winter solstice is located at 6 o'clock and the summer solstice is at 12 o'clock, coinciding with the beginning of the pollination of rye. Time progresses counter-clockwise.

5.2. Correlation with air temperature

Correlation between beginning dates of phenological phases and mean air temperature is relatively high (Fig. 4, Publication II) and this method is common for phenological studies (Roltsch *et al.* 1999; Wiegolaski 1999; Davitaja 1964). The studied phases are distributed throughout the growing season and therefore there is no uniform period with a mean air temperature used for the study (Ahas *et al. accepted*, Publication II).

Phenological phases have the highest correlation with the air temperature of the previous 2–3 months (Table 3). Due to the relatively high correlation (0.6–0.8), mean air temperatures can be used, as an alternative to the degree-days method, to analyse climate change impact on phenological phases or the phenological calendar. Value of change per 1°C of warming (Table 3) indicates the number of days by which the phase has advanced.

Temperature change has the smallest influence on spring phenophases (beginning of vegetation of rye, foliation of birch, pollination of maple), which depend more on the first sunny and warm days at the end of April or in May. Early spring (pollination of hazel) and summer phenophases (pollination of lilac and apple) are more influenced by temperature. The rate of change per 1°C is greatest for full ripeness of rye, with 6.7 days per degree of air temperature change in the corresponding period (May–July). The highest spatial differences are observed for the temperature correlation of the foliation of birch and pollination of maple. For these phases the correlation in Pärnu was much lower (correlation for maple 0.59) than in Türi or Võru (correlation for maple 0.85), which are less influenced by the cold sea water at the beginning of May.

Table 3. Correlation between phenological phases and mean air temperatures, with corresponding change per 1°C, in days

Phases	Türi			Pärnu			Võru		
	Correlation	Period (month)	Change per 1°C	Correlation	Period (month)	Change per 1°C	Correlation	Period (month)	Change per 1°C
Pollination of hazel	–	–	–	–0,83	II–IV	-6,2	–0,83	II–IV	-5,6
Beginning of vegetation of rye	–0,59	IV	–3,0	–0,59	II–IV	-3,1	–0,66	II–IV	-2,6
Foliation of birch	–0,80	IV	-3,9	–0,66	IV	-2,6	–0,74	IV	-3,2
Pollination of maple	–0,83	IV	-3,4	–0,59	II–IV	-2,1	–0,85	IV	-3,2
Pollination of bird cherry	–	–	–	–0,85	IV–V	–4,3	–0,82	IV–V	–4,3
Pollination of apple	–0,87	IV–V	-5,3	–0,82	IV–V	–4,4	–0,86	IV–V	–4,6
Pollination of lilac	–0,72	IV–V	-5,1	–0,91	IV–V	-5,2	–0,83	IV–V	–4,8
Pollination of rowan	–0,84	IV–V	-5,1	–0,81	IV–VI	-5,7	–0,74	IV–VI	-5,3
Ear of rye	–0,86	IV–V	–4,3	–0,86	IV–V	–4,2	–0,69	IV–V	-3,9
Pollination of rye	–0,71	V–VI	-6,0	–0,78	V–VI	-5,0	–0,66	IV–V	-3,2
Milky ripness of rye	–0,81	IV–VI	-5,3	–0,85	V–VI	-5,0	–0,81	IV–VI	-5,5
Waxy ripeness of rye	–0,68	V–VII	-5,2	–0,73	V–VII	-6,9	–0,76	IV–VI	-5,4
Full ripeness of rye	–0,74	V–VII	-6,7	–0,70	V–VII	-6,9	–0,76	IV–VI	-5,9
Full ripeness of rye	–0,74	V–VII	-6,7	–0,70	V–VII	-6,9	–0,76	IV–VI	-5,9

6. DISCUSSION

6.1. Impact of climate change

One important task of today's phenology is the evaluation of phenological databases and the reconstruction of past climates for the detection of possible climate changes and the interpretation of their impact upon the biosphere (Lieth 1997). The possible impact of climate change on the phenological development of nature has been studied for different time series in Europe. The most recent studies, using data from the International Phenological Garden network, show that the length of the growing season is changing and the phenological development of spring onset is advancing in Europe (Kramer 1994; Menzel & Fabian 1999).

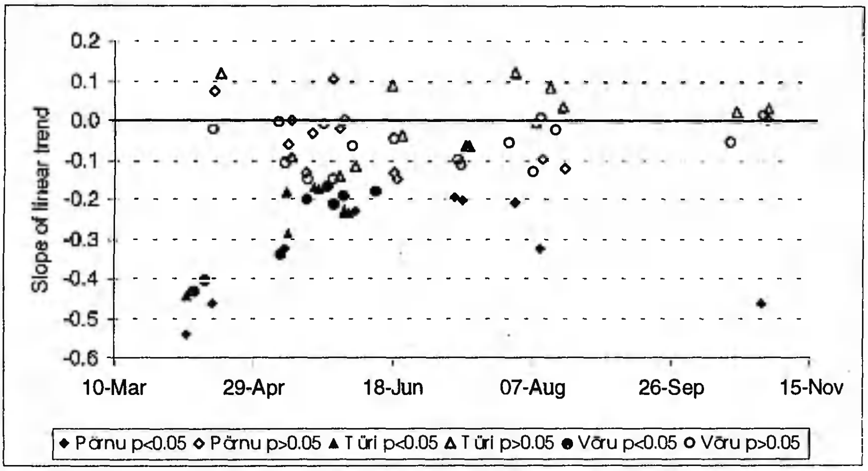

Fig. 9. The slope of linear trend for studied phenological phases in Türi, Pärnu and Võru (1948–1996).

Current analysis of the phenological calendar in Estonia shows the same effect (Fig. 9), except for the growing season as determined by the vegetation of rye. The growing period of rye is defined by the beginning of vegetation (16 April) and the end of vegetation (31 October) and can be influenced by agricultural techniques. Other spring phenophases and beginning dates of climatic seasons have advanced throughout the period in all the observation points in Estonia (Jaagus & Ahas 1998). For example, the pollination of hazel has advanced by 20 days during the last 48 years. The linear regression of onset of the pollina tion of bird cherry for the studied period has a statistically significant trend to advance in Estonia. Milky ripeness of rye, which is the mid July phase, has a similar trend with a higher deviation of values. The higher amplitude of variation of phenological data is one result of the impact of climate change (Ahas *et al.* 1998). This noticeable change can be considered to be a consequence of global warming (Tarand & Eensaar 1998). Mean air temperature in winter and in spring has increased more than 1°C during the last century (Jaagus 1996b).

The study of long time-series shows that contemporary spring in Estonia begins, on average, 8 days earlier than 80 years ago. The linear trend of the studied time-series, over this 80-year period, is statistically representative: t-Statistic between 1.7 and 3.2.

The blossoming of the studied plant species has advanced 3–14 days (over the 78 year time-series), or, according to the results of linear regression analysis, 0.5–1.7 days per 10 years. The most recent change in blossoming date was observed for the wood anemone — 14 days, and lilac — 9 days earlier.

The linear trend analysis for ornithophenological time series (132 years) produced opposite results to those from the phyto- and ichthyophenological time-series; the sky lark arrived 5 and the white wagtail 6 days later over the studied period. The statistical shortcoming of this method is that, in phenological data analysis, the use of linear regression is not suitable for periods of over 50 years. The long period oscillations of climatic parameters periodically reverse the direction of the linear trend at this scale. Using a non-linear trend for ornithophenological data sets gives more realistic results. The 3-d polynomial trend shows that the long-term changes of phenophase are similar to the phyto- and ichthyophenological processes studied. Every selected period from the 132-year observation period gives a different trend slope. Cold springs in the 1950-s and warm springs in the 1990-s have a noticeable influence on the studied periods. The seasonal cycles and periodical oscillations of phenological processes require more specific analytical tools (Ahas 1998).

6.2. Spatial distribution of phenological phases

Phenological phases and climatic seasons, in Estonia, are characterised by a remarkable variability in space and time. This is most pronounced during the winter season. The high year-to-year variations can be explained by high cyclonic activity in Northern Europe. Spatial differences are connected with high air temperature gradients, due to the influence of the Baltic Sea. As a rule, beginning dates of climatic seasons and phenological phases occur later than in the hinterland.

Hopkins's bioclimatic law (Hopkins 1918; Hopkins 1938) determines factors influencing the spatial distribution of phenological phases. The pattern of beginning dates of the climatic seasons and phenological phases, in Estonia, follows the same regularities. Onset of late winter and early spring seasons and phenophases spreads from south-west to north-east, onset of spring and summer — from south-east to north-west, and of autumn — from north-east to south-west. The distribution of all phenological phases is similar to the general directions in Eastern and Northern Europe mapped by Schnelle (1955) and Malosheva (1968). Similar influence of the Baltic Sea is also noticeable in phenological maps of Finland (Heikinheimo & Lappalainen 1997).

The results of the current study show that, as a rule, spatio-temporal variability of beginning dates of the climatic seasons is higher than that of phenological phases during the same period. It can be supposed that weather as an independent variable fluctuates within higher limits than phenological phases, which are influenced by weather conditions. Due to the physiological peculiarities of plants and local natural conditions phenological phases have an inertia that eliminates the influence of short-term weather fluctuations (Flint 1974).

On most observation trips, the most abrupt step in phenophases and changing seasonal aspects was recorded, on the way from Tartu to Rakvere, between observation points 10–13. Those points are located on the borderline between the South-East Estonian Plain (one of the earliest places) and Pandivere Upland (latest). There is a very great contrast in the natural landscape and across the climate. The strongest local influence was observed along the coastline of Lake Peipsi, at observation points No 23 and 24. The influence of the cold lake was discernible all the time, but on a very local scale, up to 1–2 km from the shoreline. The local influence of Lake Peipsi was also analysed in a study of phenological phases of ENS (Ahas 1999) and in the pattern of snow cover (Jaagus and Ahas 1998). The biggest influence of altitude was observed at observation points 5 and 6 at a height of 230 and 260 m on Haanja Upland (highest point 318 m), which is the highest landscape form in the Baltic region. The influence of elevation was distinguishable for early spring, when those relatively small influences of altitude have big effect on snow cover and soil frost (Jaagus 1997b). In spring, when the value of temperatures is close to 0°C, the difference of a few degrees has a big impact on the melting of snow and the surface. As result of this, relatively big regional differences occur even in latitudes of 100–300 meters of absolute height. After melting of the snow cover and ground, the relatively big local differences of microclimate and phenology will be smoothed-out due to the specific exposition regime and better moisture regime of those uplands.

Of special interest for the study, were the big wetland areas that play an important role in forming local meso- and microclimate. The most recognizable were the differences for wetland and forest areas of Central Estonia. Special observation points (66–69) were defined for the study of these local influences. The results of field studies and database analyses show that this landscape region has a different seasonal rhythm, which means that these observation points are under the influence of the inertia of the cold spring period, during middle of June. The local differences on the North Estonian Glint were studied at observation points Nos. 18 and 20, where the deep landscape barrier of the glint changes the microclimate and vegetation under and on it. The water temperature and airflow of the Gulf of Finland directly influence the area located under the glint.

6.3. Spatial pattern of extreme years

The spatial distribution of phenological phases differs from year to year. The analyses of mean values do not describe all aspects of seasonality in particular years or in extreme years. Therefore, the maps of phenological phases of normal, earliest (min), and latest (max) years are shown in Fig. 7. The maps show spatial differences between the min 1990 and max 1955 springs. These studies suggest that the direction of phenological phases changes. In early years the onset of the pollination of maple (e.g. 1990) is spreading very fast across Estonia, within two days, with little delay for north-eastern Estonia. Similarly the onset of the blossoming of bird cherry is very fast in early springs, but the direction of the advance of phases is shifting towards the western islands. The pattern of distribution of phenological phases for early and late years is analysed in a study of Finnish phenological time-series (Lappalainen 1994). In this study Lappalainen (1994) discusses differences between early, late, and mean years. The species studied had different patterns of phenophases. For example, for onset of pollination of bird cherry in Finland, the local influence of lakes is strong in early springs, and the pollination of birch is very strongly influenced by the Baltic Sea in early springs (Lappalainen 1994).

7. CONCLUSIONS

7.1 Methods

The method of phenological calendars was applied and tested for the study of space-time variations of phenological time-series and seasonality of Estonain nature. Seasonality of nature is described with the method of phenological calendars, which is the list of the annual sequence of phenological phases in the form of beginning dates, their duration, and intervals between phases. Those phenological parameters are compared and complemented with different climatological data available. The parallel use of phenological and climatic data is practical because of many gaps in phenological data-series and the need to have more variables for the measuring of seasonality. For the study of the phenology of landscapes (speed and pattern of distribution of phenophases), the special field observation programme was conducted. The objective of the observation programme was to study how phenological phases are distributed, and how they spread in the landscape. Therefore, the observation programme has a specific methodology and does not describe many specific aspects of phenology. The observers do not record dates of phenological phases, they only record the appearance, or non-appearance, of a phase at the observation point in Estonia. The observation table standard included 6 development phases of 15 naturally occurring tree species, for spring observations, and 5 development phases of 8 naturally occurring tree species, for autumn observations.

7.2. Trends

1) Linear regression of the studied phenological time-series shows that there has been a noticeable change (statistically significant linear trend) in the seasonality of Estonian nature during the studied period. Most of the statistically significant values ($p<0,05$) of slope of linear trend show that seasonal cycles have advanced, especially in the spring period. All statistically significant values of the trend are found in the spring period, with values between –0,2 and –0,5. Autumn phases have been delayed, but these trends have no significant values. This shows that there is a general tendency for the lengthening of the vegetation period. A remarkable change of 3–5 days per decade is recorded for phases of early spring such as birch sap rise, pollination of hazel, and foliation of birch. This trend is similar for all three stations studied and is connected with the phenomenon of changing winters: the greatest changes in Estonian climate are recorded for the winter period, that has become warmer during the last decades.

2) The study of extreme (minimum and maximum) years shows that 70% of the earliest dates of the 24 studied phases have occurred during the last 15 years, with an absolute maximum in 1990 with 8 extreme phases. 25% of the latest dates of the 24 studied phases have occurred during the last 15 years and 58% (14 dates) during the first 15 years of the study period, with an absolute minimum in 1955 with 11 extreme phases. The absolute range of spring phases is relatively high, the range of 'pollination of maple' for those years was 39 days and 'pollination of oak' — 53 days; summer and autumn phases have similar amplitudes of variation between min and max values.

3) Duration of seasons and intervals between phenological phases have changed too. The phenological spring has shortened (slope –0.23), the summer period has lengthened (slope 0.04), and autumn has lengthened too. The length of the growing season determined by vegetation of rye has shortened (slope –0.09), which can be the result of changing agricultural technology.

7.3. Correlations

1) Correlation between beginning dates of phenological phases and the air temperature of the previous 2–3 months is relatively high (0.6–0.8). Studied +2 and –2°C scenarios (Keevallik 1998), and values of extreme years, show that in the case of short-term variations of air temperature the phenological development of nature remains within the limits of natural variation. Phenological phases with the greatest changes will occur more than 10 days earlier (or later). For example, pollination of hazel (mean 13 April) will begin on 1 April in case of warming or on 26 April in case of cooling by 2°C.

7.4. Spatial distribution of phenological phases

The spatial distribution of the pollination of maple and bird cherry was analysed, in Estonia, on the basis of long time-series in 22 observation points, and on the basis of the special field observation programme in 46 observation points.

1) Spreading rate of phenological phases is very different in early and late years. Phenological maps show that the mean value of the rate of distribution of the springtime phenophases is 3–6 days per 100 km in relatively plain Estonia. In very early years the phenological phases move very fast, except for the western islands.

2) Direction of the onset of phenological phases is generally from south to north. The onset of maple phases is gradually directed more towards the north

east and bird cherry towards the north-west of Estonia. The main factors influencing the direction of development of phenophases are the temperature of the Baltic Sea, local influence of relief, and bigger lakes and wetland areas.

3) Landscape forms have the biggest influence in the Pandivere Upland, at a height of 100–140 m, and the Haanja Upland, at a height of 230 and 260 m. The influence of elevation was distinguishable for early spring, when the relatively small effects of altitude have a big effect on snow cover and soil frost. In spring, when the temperature is close to 0°C, a difference of a few degrees has a big impact on the melting of snow and the thawing of the ground surface. After the melting of the snow cover and thawing of the ground, the relatively big local differences in microclimate and phenology will be smoothed out because of the special exposition regime and better moisture regime of the uplands.

4) Three seasonally different landscape types can be determined in Estonia by spring phenology. 1) The relatively continental South-East Estonian Plain and uplands have the earliest spring with smallest deviations and stable intervals between phases. 2) Central, western and northern Estonian plains, with temperate influence of the temperature regime of the Baltic Sea and big variations from year to year. Big variability is caused by the presence and duration of ice cover on the sea in cold springs, and the direct access of warm air masses in early springs. 3) The north-east of Estonia has the most boreal climate, with longer snow cover and very late springs, caused by arctic air masses and, locally, by the Baltic Sea, uplands and large wetlands.

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REFERENCES

Ahas, R. 1994. Geographical variability of the phenology of trees in Estonia. MSc thesis on geography. University of Tartu, 86 pp. (In estonian with summary in english).

Ahas, R. 1996. The seasonal dynamics of Estonian Landscapes: spatial and temporal variability of early-spring blossoming dates. In: Biometeorology 14, Part 2, Volume 2. A. Hocevar, Crepinsek and L. Kajfez-Bogataj (eds.), Proceedings of 14th International Congress of Biometeorology, Ljubljana, 1–8.09.1996, p. 220–225.

Ahas, R. 1997. The impact of climatic changes on seasonal cycles in nature: the study of unusually late and early springs in Estonia. In: International Workshop on Prospects for Co-ordinated Activities in Core Projects of GCTE, BAHC and LUCC, S.C. van de Geijn and P.J. Kuikman (eds.), November 16–19 1997, Wageningen, p. 144–145.

Ahas, R. 1998. Limitations in the use of phenological time-series for climatic trend analysis. — Association of American Geographers, 94th Annual Meeting 1998. Boston. PROMEDIA Corporation. (CD).

Ahas, R., Tarand, A., Meitern, H. 1998. Temporal variability of the phenological time series in Estonia. In: Tarand A., Kallaste T. (eds.) Country Case Study on Climate Change Impacts and Adaptation Assesments in the Republic of Estonia. Report to the UNEP/GEF; Project No: GF/2200-96-45. Stockholm Environment Institute-Tallinn, Tallinn, p. 28–30.

Ahas, R. 1999. Long-term phyto-, ornitho-, and icthyophenological time-series analyses in Estonia. International Journal of Biometeorology 42: 119–123.

Ahas, R., Jaagus, J. Aasa, A. The phenological calendar of Estonia and its correlation with mean air temperature. Landscape Ecology. *Accepted.*

Ahas, R., Aasa, A. Impact of landscape features on phenological phases in transitional zone from maritime to continental climate types of Northern Europe. Landscape Ecology. *Submitted.*

Beruchashvili, N. L. 1994. Seasonal dynamics of landscapes of the Earth. Communications of Russian Academy Sciences, 6: 24–40.(In Russian).

Carter, T. R. 1998. Changes in the thermal growing season in Nordic countries during the past century and prospects for the future. Agricultural and Food Science in Finland 7: 161–179.

Crick, H. Q. P., Sparks, T. 1999. Climate change related to egg-laying trends. Nature 399: 423–424.

Davitaja, F. F. 1958. Agrometeorological problems. Moscow, Hydrometeorological Publishing House. pp. 91. (In russian with English Contents).

Davitaja, F. F. 1964. Prognosis of heat thresholds and selected questions of seasonal development of nature. Moskow, Gidrometeorologitsheskoe Izdatelstvo. 131 pp. (In Russian).

Defila, C. 1991. Phänologie der Schweiz. Inaugural-Dissertation. Zürich. 235 pp.

Defila, C. 1992. Pzlanzenphänologische Kalender ausgewählter Stationen in der Schweiz / Calendriers phytophänologiques en Suisse 1951–1990. Beiheft zu den Annalen der Schweizerischen Meteorologischen Anstalt.

Eilart, J. 1959. Phytophenological observation manual. Estonian Naturalists Society, Tartu, 16 pp. (In Estonian).

Eilart, J. 1968. Some aspects of history of phenology in Estonia. In: Lumiste, Ü. (ed.) Teaduse ajaloo lehekülgi Eestis. Tallinn, Academy of Sciences, 1: 169–176. (In Estonian with summary in german and russian).

Flint, H. L. 1974. Phenology and Genecology of Woody Plants. In: Lieth H (ed.) Phenology and seasonality modeling. Ecological Studies 8, Springer-Verlag, New York, p. 83–97.

Flohn, H. 1942. Witterung und Klima in Deutschland. Verlag von S. Hirzel, Leipzig.

Galahov, N. N. 1959. Study on structure of climatic seasons of a year. Izdatel'stvo Akademii Nauk SSSR, Moscow (In Russian).

Gornik, W. 1994. Investigations into the Problems of Finding a Mean Value in Phenological Data Series. Arboreta Phaenologica, 47, pp. 11–14.

Heikinheimo, M., Lappalainen, H. 1997. Dependence of the flower bud burst of some plant taxa in Finland on effective temperature sum: implications for climate warming. Ann. Bot. Fennici 34: 229–243 .

Hopkins, A. D. 1918. Periodical events and natural law as guides to agricultural research and practice. Monthly Weather Review Supplement No. 9. Washington D.C. pp. 5–41.

Hopkins, A. D. 1938. Bioclimatics — a science of life and climate relations. U.S. Dept. Agr. Misc. Publ. 280.

Hopkins, A. D. and Murray, M. A. 1933. Natural guides to the beginning, length and progress of seasons. Acta Phaenologica. 2. 1933. 33–43.

Hydrometeorological Printing House 1965. Natural calenders of North Western USSR. Geographical Society of USSR, Leningrad, Hydrometorological Printing House. (In Russian).

Ingerpuu, N., Krall, H., Ksenofontova T., Lellep, E., and Pihlapuu, L. 1980. Phytophenological observation manual. Estonian Naturalists Society, Tartu, 16 p. (In Estonian).

Jaagus, J. 1996a. Changes in climatological calendar during the last century in Tartu, Estonia. In: Wennerberg G (ed.) European conference on applied climatology. Abstract volume. SMHI, Norrköping, pp. 128–129.

Jaagus, J. 1996b. Climatic trends in Estonia during the period of instrumental observations and climate scenarios. In: Punning J. M. (ed.) Estonia in the system of global climate change. Institute of Ecology 4/1996, Tallinn, pp. 35–48.

Jaagus, J. 1997a. Long-term changes in climatological calendar. In: Frey, T. (ed.), Temporal changes in Estonian nature and environment. Problems of contemporary ecology. Short communications of the Estonian 7th Conference in Ecology, Tartu pp. 41–46. (In estonian with english summary).

Jaagus, J. 1997b. The impact of climate change on the snow cover pattern in Estonia. Climatic change, 36, pp. 65–77.

Jaagus, J. 1998. Climatic fluctuations and trends in Estonia in the 20th century and possible climate change scenarios. In: Kallaste, T., Kuldna, P. (eds.) Climate change studies in Estonia. Stockholm Environment Institute-Tallinn, Tallinn, pp. 7–12.

Jaagus, J. and Ahas, R. 1998. Spatial differences in climatic seasons in Estonia and their influence on phenological development of nature. 2nd European Conference on Applied Climatology 19 to 23 October 1998, Vienna, Austria. Österreichische Beiträge zu Meteorologie und Geophysik, 19. Zentralanstalt für Meteorologie und Geodynamik, Wien. ISSN 1016–6254.

Jaagus, J., Ahas, R. Space-time variations of climatic seasons and their correlation with the phenological development of nature in Estonia. Climate Research, *Accepted.*

Jõgi, J. 1988. On seasonal rhythms in formation of micro-climate. In: Keskpaik, A., Noorkõiv, R. (eds.) Problems of geography in Estonia. Estonian Academy of Sciences, Tallinn, pp. 62–66. (In Estonian).

Jones, P. D., Briffa, K. R. 1995. Growing season temperatures over the former Soviet Union. J. Climatol 15: 943–959.

Kalnicky, R. A. 1987. Seasons, singularities, and climatic changes over the midlatitudes of the Northern Hemisphere during 1899–1969. J. Clim Appl Meteorol 26: 1496–1510.

Karing, P. 1992. Air temperature in Estonia, Tallinn, 78 p. (In Estonian).

Keevallik, S. 1998. Climate change scenarios for Estonia. In: Tarand, A., Kallaste, T. (eds.) Country Case Study on Climate Change Impacts and Adaptation Assesments in the Republic of Estonia. Report to the UNEP/GEF; Project No: GF/2200-96-45. Stockholm Environment Institute-Tallinn, Tallinn, p. 30–35.

Kiviorg, L. 1972. Long phenological observation series in Paide and observer Ernst Saks. Diploma paper in Geography, University of Tartu, 92 p. (In Estonian with abstract in Russian).

Kramer, K. 1994. Selecting a model to predict the onset of growth of *Fagus sylvatica.* J. Appl. Ecology 31: 172–181.

Kramer, K. 1996. Phenology and growth of European trees in relation to climate change. Thesis Landbouw Universiteit Wageningen, Wageningen, 157 p.

Lamb, H. H. 1972. Climate: present, past and future. Vol. 1. Fundamentals and climate now. Methuen, London.

Lappalainen, H. 1994. Examples of plant phenological events in Finland and their relation to temperature. Memoranda Soc. Fauna Flora Fennica 70: 105–121.

Lellep, E. 1976. Phytophenological observations in Estonia. In: Krall, H. (ed.) Phytophenological observations in Estonian SSR 1952–1970. Estonian Naturalists Society, Abiks Loodusevaatlejale No. 71: 9–16. (In Estonian with abstract in German and Russian).

Lewik, P. 1996. Thermal seasons of the year in Southern Poland — tendencies of the terms and duration. Zeszyty Naukowe Uniwersitetu Jagiellonskiego, Prace Geograficzne, 102: 355–358.

Lieth, H. 1974. Purposes of phenology book. In: Lieth, H. (ed.), Phenology and seasonality modeling. Ecological Studies 8, Springer-Verlag, New-York, pp. 3–19.

Lieth, H. 1997. Aims and methods in phenological monitoring. In: Lieth, H. and Schwartz, M. D. (eds.), Phenology in Seasonal Climates I, Progress in Biometeorology, Backhuys Publishers, Vol 12. Leiden, pp. 1–21.

Maak, K., von Storch, H. 1997. Statistical downscaling of monthly mean air temperature to the beginning of flowering of *Galanthus nivalis* L. in Northern Germany. International Journal of Biometeorology 41: 5–12.

Malosheva, T. C. 1968. Methodological manual for composition of phenological maps. Leningrad. 59 p. (In Russian).

Menzel, A. and Fabian, P. 1999 Growing season extended in Europe. Nature 397: 659.

Meitern, H., Rootsmäe, L., Tarand, A. 1991. Ornitophenological observations from earlier years. Estonian Naturalists Society, Abiks loodusvaatlejale No. 91: 95. (In estonian with summary in russian and german).

Myneni, R. B., Keeling, C. D., Tucker, C. J., Asar, G., Nemani, R. R. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. Nature 386: 698–702.

Podolsky, A. S. 1983. New Phenology: Elements of Mathematical Forecasting in Ecology. John Wiley & Sons, New York.

Raik, A. 1963. Climatic seasons in Estonia. Acta et commentationes Universitatis Tartuensis, 144, p. 33–44. (In Estonian with summary in English).

Reader, R., Radford, S. R., Lieth, H. 1974. Modeling Important Phytophenological Events in Eastern North America. In: Lieth, H. (ed.) Phenology and seasonality modeling. Ecological Studies 8, Springer-Verlag, New York, pp. 329–342.

Ristkok, J. 1955. Ichyothophenological observation manual. Estonian Naturalists Society, Tartu, 6 p.

Roltsch, W. J., Zalom, F. G., Strawn, A. J., Strand, J. F., Pitcairn, M. J. 1999. Evaluation of several degree-day estimation methods in California climates. International Journal of Biometeorology 42: 169–176.

Schnelle, F. 1955. Pflanzenphänologie. Probleme der Bioklimatologie 3 Akademische Verlagsgesellschaft, Leipzig 299 p.

Schnelle, F. 1970. Beiträge zur Phänologie Europas II. 4 Mittelwertskarten. Gesamtvegetationszeit und 3 Vegetationsabschnitte Berichte des Deutschen Wetterdienstes, Nr. 18.

Schultz, G. E. 1981. General phenology. Nauka, Leningrad, p. 91–146. (In Russian).

Schultz, G. E. 1982. Geographische Phänologie in der UdSSR. Wetter und Leben 34: 160–168. (In German).

Schwartz, M. D. 1994. Monitoring global change with phenology: the case of spring green wave. Int. J. Biometeorol 38: 18–22.

Schwartz, M. D. 1997. Spring Index Models: An Approach to Connecting Satellite and Surface Phenology. In: Lieth, H. and Schwartz, M. D. (eds.) Phenology of Seasonal Climates, Backhuys Leiden. p. 23–38.

Schwartz, M. D. 1998. Green-wave phenology. Nature 394: 839–840.

Schwartz, M. D. 1999. Advancing to full bloom: planning phenological research for the 21st century. International Journal of Biometeorology 42: 113–118.

Sladek, I. 1990. Changes of duration and timing of some temperature seasons of the year in Prague. In: Brazdil, R. (ed.) Climatic change in the historical and the instrumental periods. Masaryk University, Brno, p. 194–196.

Tarand, A., Eensaar, A. 1998. Air temperature. In: Tarand, A. and Kallaste, T. (eds.) Country Case Study on Climate Change Impacts and Adaptation Assessments in the Republic of Estonia. Tallinn. p. 17–21.

Tarand, A., Kuiv, P. 1994. The beginning of rye harvest — a proxy indikator of summer climate in the Baltic area. Paleoclimate Research 13: (Sp. issue 8), Academie der Wissenschaften und der Literatur. Mainz.

White, M. A., Thorton, P. E., Running, S. W. 1997. A continental phenology model for monitoring vegetation responses to interannual climatic variability. Global Biogeochemical Cycles 11 No 2, p. 217–235.

Wiegolaski, F.-E. 1999. Starting dates and basic temperatures in phenological observations of plants. Int J. Biometeorol 42: 158–168.

FENOLOOGILISTE FAASIDE AJALIS-RUUMILINE VARIEERUVUS EESTIS

SUMMARY IN ESTONIAN

Parasvöötme loodus ja inimtegevus on väga tugevasti mõjutatud aastaaegade vaheldumisest. Elus- ja eluta looduse aastaajalise arengu seaduspärasusi ja mõjusid uurib fenoloogia. Viimastel aastakümnetel on fenoloogilise uurimistöö olulisus tõusnud seoses globaalsete muutuste uurimisega. Fenoloogiline monitooring on üks väheseid, mis suudab oma aegridadega kirjeldada eluslooduses toimuvaid pikaajalisi muutusi. Fenoloogilise uurimistöö aluseks on kvaliteetsed vaatlusandmed. Eestis on käesoleval sajandil kogunud kvaliteetset fenoloogilist andmestikku Eesti Loodusuurijate Selts (ELUS) ning Meteoroloogia ja Hüdroloogia Instituut (EMHI). Oma kvaliteedilt ja tiheduselt on nimetatud andmestik võrreldav maailma parimatega Saksamaal ja Šveitsis.

Käesoleva uurimistöö eesmärgiks on: 1) arendada ja testida fenoloogiliste aegridade analüüsi meetodeid, 2) uurida kliimamuutuste võimalikku mõju fenoloogilistele faasidele ning 3) looduse fenoloogilise arengu geograafilist varieeruvust Eestis. Töö on magistritöö (1994) edasiarendus. Täienenud on andmebaas. On loodud välitööde programm, metoodika ja uurimisteemad on oluliselt muutunud.

Töös kasutati ELUS-i ja EMHI andmestiku paremat osa: kevad- ja suvekuude fenofaase. Andmestiku valiku põhiliseks kriteeriumiks oli vaatlusridade pikkus ja andmete homogeensus. Välitöödel (1995–1999) vaadeldi fenofaase kogu Mandri-Eesti ulatuses, et analüüsida faaside maastikulise leviku seaduspärasusi. Saksa ja Vene teadlaste loodud fenoloogilise kalendri metoodikat kohandati Eesti andmestike ja nüüdisaegsete andmetöötlusvahenditega. Lisaks fenoloogiliste andmete kasutamisele analüüsiti keskmisi õhutemperatuure ja klimaatilisi aastaaegu vastaval uurimisperioodil. Analüüside tulemusel selgus, et looduse kevadine ja suvine areng on viimase viiekümne aastaga keskmiselt 2–5 päeva varasemaks nihkunud, lineaarne trend on statistiliselt usaldusväärne. Kõige rohkem on muutunud varakevadiste faaside (3–5 päeva dekaadi kohta) ja kõige vähem on muutunud sügiseste faaside algusaeg. Pikaajaliste aegridade ajaline varieeruvus on viimastel aastatel suurenenud, eriti on suurenenud varaste (soojade) kevadete ja suvede hulk. Näiteks on 70% Türil vaadeldud faaside äärmusaastatest esinenud viimase 15 aasta jooksul. Samas on hiliseid (külmi) kevadeid ja suvesid olnud vähem ja absoluutsed miinimumid jäävad 1955. aastasse.

Fenofaaside ruumilise varieeruvuse vaatlustulemuste analüüs näitas, et kevadised fenofaasid levivad Eestis keskmise kiirusega 3–6 päeva 100 km kohta, soojadel ja külmadel kevadetel ning suvedel on faaside levikukiirus isesugune.

Faasid levivad põhja–lõuna suunas, olles vastavalt aastaajale ja aasta iseloomule kallutatud kirde või loode suunas. Loodesuunalise mõju põhjustab Läänemere temperatuurirežiim, kirdesuunalise kaldumise aga Pandivere kõrgustiku ja jahedama õhutemperatuuri mõju. Kõrgustike mõju looduse fenoloogilisele arengule on märgatav Haanja ja Pandivere vaatluspunktides ning üksikutel juhtudel ka Otepääl. Fenoloogiline areng pidurdub kõrgustikel 1–3 päeva 100 meetri kohta. Kõrgustike ja ümbritsevate tasandike vahe on hästi märgatav varakevadel, siis on ka üsna väikeste kõrgusevahede mõju lume sulamisele oluline. Samuti on märgata erinevusi suurte Vahe-Eesti soode ja rabade piirkonnas.

Sesoonsuse tüübilt on võimalik Eesti jagada kolme piirkonda: 1) varaseima fenoloogilise arenguga ja väikese varieeruvusega Lõuna-Eesti, 2) tugevama merelise mõjutusega ja suurema varieeruvusega Lääne ja Kesk-Eesti ning 3) hiliseima fenoloogilise arenguga ja suurima varieeruvusega Kirde-Eesti.

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ORIGINAL ARTICLE

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Long-term phyto-, ornitho- and ichthyophenological time-series analyses in Estonia

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Abstract This study analyzes a long-term phenological time series for the impact assessment of climate changes on Estonian nature and for the methodological study of the possible limitations of using phenological time series for climate trend analyses. These limiting factors can influence the results of studies more than the real impact of climate changes, which may have a much smaller numeric value. The 132-year series of the arrival of the skylark (*Alauda arvensis*) and the white wagtail (*Motacilla alba*), the 78-year series of the blossoming of the wood anemone (*Anemone nemorosa*), the bird cherry (*Padus racemosa*), apple trees (*Malus domestica*) and lilacs (*Syringa vulgaris*), and the 44-year series of the spawning of pike (*Esox lucius*) and bream (*Abramis brama*) were studied at three selected observation points in Estonia. The study of the phenological time series shows that Estonian springs have, on the basis of the database, advanced 8 days on average over the last 80-year period; the last 40-year period has warmed even faster.

Key words Phenology · Climate change · Time series

Introduction

Phenology is important in climate change studies for the downscaling of global models, remote-sensing, and impact assessment. Due to the nature of phenological data (dates, length and intervals of phenophases) and the seasonal cycling of nature, special methods and limitations apply to the use of simple time-series analyses in phenology. Even when using simple statistics in climate change studies, we have to know the ecology of the studied species, make an evaluation of the data series, and eliminate the impacts of different limiting factors, such as the regional aspects of climate and landscape, soil types, climatic seasons, and extreme climatic conditions (Schwartz 1997). In some cases these factors may influence the results more than the real impact of climate change, which may produce much smaller effects.

The current study analyzes long-term phenological time series to assess the impact of climate change on Estonian nature and for the methodological study of the possible limitations of using phenological time series for climate trend analyses. Using simple analytical tools, this study makes a first evaluation of the data and methods that may be suitable for future studies of phenological calendars and time series.

Data and methods

Phenological database

For the long-term time-series study only the best quality phenological observation series from a limited number of observation points were selected. Spring phenophases were selected for analysis due to the availability of good observation series and because the effect of climate change is more pronounced in springtime in Estonia. The study is based on eight common plant, fish, and bird species at three different observation points (Table 1).

For the study of extreme years and for the geographical information system (GIS) analyses the blossoming dates of *Corylus avellana*, *Acer platanoides* and *Sorbus aucuparia* were also used. These phenological data-series are from the observation programme of the Estonian Naturalists Society (1951–1996), the Estonian Meteorological and Hydrological Institute (1947–1996) and from long-term Hellenurme and Paide records. The records of the Estonian phenological database were also used since it has data on more than 100 plant, bird, fish, mushroom and insect species from 150 sites, mostly from the 1950s. The longest phenological data-series have been reconstructed for rye harvests and date back to the 17th century (Tarand and Kuiv 1994).

Methods

The checking of data sets and the interpolation of the time series was carried out by correlation analysis using the mean value of the three surrounding observation points. About 10% of data points were interpolated due to gaps in observations or errors. Late (cold), early (warm) and normal springs were selected on the basis of the standard deviations of the phenological data of the eight species studied and the beginning of climatic seasons (Jaagus

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Table 1 Long-term observation series: the species and phases studied, duration of the observations and the location of observation points

Species and phases	Period	Location
Arrival of skylark (*Alauda arvensis L.*)	1865–1996	Hellenurme
Arrival of white wagtail (*Motacilla alba L.*)		South Estonia
Blossoming of wood anemone (*Anemone nemorosa L.*)		Paide
Blossoming of bird cherry(*Padus racemosa L.*)	1919–1996	Central Estonia
Blossoming of apple tree (*Malus domestica L.*)		
Blossoming of lilac (*Syringa vulgaris L.*)		
Spawning of pike (*Esox lucius L.*)	1952–1996	Pedaspää, Lake
Spawning of bream (*Abramis brama L.*)		Peipsi, East Estonia

Table 2 Linear regression statistics of the phenological time series studied

Phenological phase	Period (years)	Change (days)	Regression (all period)	Regression 1952–1996
Arrival of skylark (*Alauda arvensis*)	132	5	0.04	–0.34
Arrival of white wagtail (*Motacilla alba*)	132	6	0.05	–0.28
Blossoming of wood anemone (*Anemone nemorosa*)	78	–14	–0.17	–0.29
Blossoming of bird cherry (*Padus racemosa*)	78	–4	–0.05	–0.19
Blossoming of apple tree (*Malus domestica*)	78	–3	–0.047	–0.14
Blossoming of lilac (*Syringa vulgaris*)	78	–9	–0.11	–0.24
Spawning of pike (*Esox lucius*)	44	–6	–0.11	–0.11
Spawning of bream (*Abramis brama*)	44	–8	–0.15	–0.15

1997b) over the period 1952–1996. The data sets for springs classified as early (1959, 1975, 1984, 1990, 1993), late (1955, 1969, 1978, 1985, 1987) and normal (1958, 1968, 1970, 1977, 1979) were compiled and both the temporal and spatial variability of phenophases was investigated.

The temporal variability of data was studied using a phenological calendar-analysis method: the phenological phases of 1 year were analyzed as one calendar unit with phenological dates, durations and intervals (Ahas 1997). For statistical analyses of phenological data, the methods of analyis used for the International Phenological Garden data were studied (Gornik 1994; Kramer 1996). For statistical analyses, the Excel 97 standard module was used. The spatial analysis of the blossoming dates of common tree species was carried out using statistical analysis and the GIS package IDRISI. Additional IDRISI modules were used for the subsequent analysis of the charts.

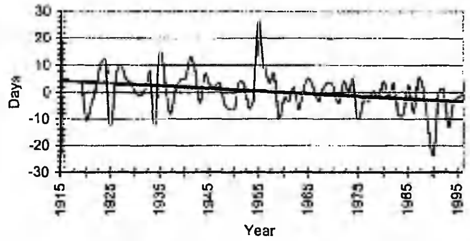

Fig. 1 The mean values of changes in the phytophenological time series for all species studied

Results

Trend analyses

The study of phenological time series shows that contemporary spring in Estonia begins, on average, 8 days earlier than it did 80 years ago. The general results of the study are presented in Table 2. The standard deviation of data sets is between 7.9 (arrival of skylark) and 11.4 (spawning of bream). The linear trend of the studied time series over this 80-year period is statistically representative: t-statistic between 1.7 and 3.2.

The blossoming of the studied plant species has advanced 3–14 days (over the 78-year time series) or, according to the results of linear regression analysis, 0.5–1.7 days per 10 years. The most recent change in blossoming date was observed for the wood anemone (14 days earlier) and lilac (9 days earlier). Phytophenological time series were found to be the most representative in the current study (Fig. 1).

The studied ichthyophenological time series also exhibit a trend: the beginning of spawning for pike and bream was 6 days and 8 days earlier, respectively, over the 44 years studied. The regression analysis of the spawning of fish showed an advance of 0.9 and 1.5 days per 10 years, respectively.

Using the linear-trend analysis for the ornithophenological time series (132 years) produced opposite results to those from the phyto- and ichthyophenological time series; the sky lark arrived 5 days later, and the white wagtail 6 days later over the studied period. The result of linear regression analysis was respectively 0.4 and 0.5 days later per 10-year period.

The statistical shortcoming of this method is that in phenological data analysis, the use of linear regression is not suitable for periods of over 50 years. The long period oscillations of climatic parameters periodically reverse the direction of the linear trend at this scale.

The lengths and periods of phenological time series

Using a non-linear trend for ornithophenological data sets gives more realistic results. The 3-d polynomial

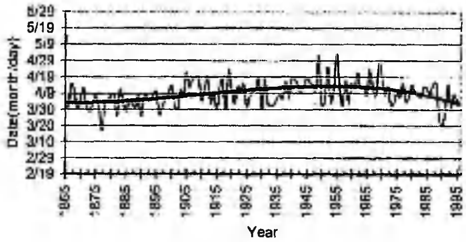

Fig. 2 Arrival date of white wagtail (*Motacilla alba*) and its linear and polynomial (3-d) trend in Hellenurme

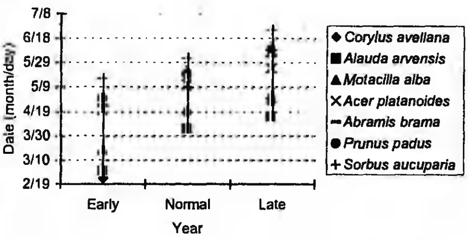

Fig. 3 The mean phenological dates of the beginning of blossoming of trees, arrival of birds and the start of spawning of fish in early, normal and late springs in Estonia

trend (Fig. 2) shows that the long-term changes of phenophase are similar to the phyto- and ichthyophenological processes studied. Every selected period from the 132-year observation period gives a different trend slope. Cold springs in the 1950s and warm springs in the 1990s had a noticeable influence on the studied periods. This is one of the reasons for the common use of phenological data series from the 20th century for climate change studies. The last column of Table 2 gives the regressions of studied data sets for the period 1952–1996. The influence of the cold and warm periods mentioned above is most noticeable in bird and plant data regressions over longer periods. The positive values of long ornithophenological series become negative, and the negative values of phytophenological data sets increase. This case (Fig. 2 and Table 2) demonstrates the risks of using linear trends and mean values for studying phenological time series. The seasonal cycles and periodic oscillations of phenological processes require more specific analytical tools.

Influence of different seasons

The impact of climate oscillations and climate changes on phenological cycles varies for different seasons of the year. Some seasons can change periodically to a considerable degree, especially in regions and seasons that are close to frost point, or depending upon water salinity. But in many cases the impact of climate change is very slight: differences in one season will be compensated for by the duration, temperature or cloudiness of the following periods, our phenological time series do not describe actual changes.

In Estonia, wich has a moist continental mid-latitude climate, climatic changes have most recently affected the late winter and early spring stages. The length (presence) of snowcover on inland areas and the icecover of the Baltic Sea is decreasing (Jaagus 1997b; Tarand and Eensaar 1998). The early spring phenological phases of plant and bird species exhibit a noticeable advancing trend, like the blossoming of the wood anemone 1.7 days earlier per 10 years. At the same time, the length of spring and the duration of phenophases is increasing and most differences will be smoothed during long and relatively cold springs (see Fig. 3). The study of the climatic seasons of Estonia (Jaagus 1997b) describes similar trends for the beginning of climatic seasons: late winter and early spring are changing faster than spring and summer.

Influence of extreme climatic conditions

In extremely late (cold) and early (warm) springs, the swings in phenological dates are much greater than is possible due to the impact of long-term climate change. The phenological calendar, the beginning, length and order of phenological phases is influenced for the whole season. Sometimes the differences are noticeable during the entire vegetation period, and in some species even the following year's development will be influenced. The extent of differences between early, normal and late springs was studied for a simple phenological calendar (Fig. 3). The selection of extreme years was made on the basis of phenological time series and climatic seasons in Estonia.

The mean difference in phenological dates between early and late springs is 17–23 days. In some cases the differences can be more than 2 months. For example, between the 1955 late and the 1989 early springs in Estonia the mean difference for all studied phases was 48 days, and for sensitive early spring phases, such as the blossoming of the wood anemone, even 62 days. As mentioned in previous chapters, early springs are normally long and cold; late springs can be very short and climatic summer can start with the development of all spring phenophases at the same time. The study of phase intervals shows that early springs phases are extended over a longer time period (average 51 days) than in late years (average 42 days). The extreme years show different rates of climate interactions on life forms. The plant species studied were the most sensitive to extreme spring influences; the average difference between early and late springs was 23 days, and for the early spring phase, for blossoming of the wood anemone the difference was 32 days and for pollination of hazel the difference was 37 days. The difference between the arrival dates of the birds (*Motacilla alba*, *Alauda arvensis*) for early and late springs was on average –17 days, and for the start of the spawning of the fish species (*Esox lucius*, *Abramis brama*), –11 days.

The most stable interval between the phenophases of extreme and normal years is between the spawning dates of the two studied fish species: 49–51 days. The mean standard deviation of the data series studied is 10.7 for early, 9.2 for late and 5.9 for normal springs.

The study of extreme springs shows that the possible impact of climate change is much smaller than the natural oscillations of the seasons. Natural species have adapted to these variations, and some negative impact of extremes can show up on the food-chain and ecosystem levels (studied as pest phenology in agriculture and forestry). However, essentially few extreme years can change our trends and mean values. The phenological shortcoming of the study of extreme years is that every year has its own specific rhythm and speed. For objective results we must find methods that account for the specifics of each individual year.

Spatial differences and the impact of climate change

The long-term trends in the data and the possible impact of climate change is influenced by regional climate subtype (Ahas 1996). In Estonia the influence of climate change is very different for coastal and inland areas (Fig. 4). The time series of the blossoming of the four plant species studied in coastal (Pärnu) and inland (Hellenurme) areas show different rates of change. The linear trend of phenological data shows that in coastal regions spring is advancing about two times more rapidly than in inland areas. The regression of mean values for the period 1952–1996 for coastal areas is –2.6, and for inland areas is –1.4. Only the late spring phenophases such as that of apple tree and lilac blossoming exhibit smaller differences between different climatic regions.

The study of the deviations of the data from the mean values showed great differences between the marine and continental climatic regions of Estonia. The largest deviations in the blossoming dates were associated with the coastal regions that have a marine climate. The standard deviation of the phenological dates is greater for early springs and is especially high in West Estonia with its more maritime climate subtypes. The spatial consequences of extreme springs are phenologically noticeable during June and July.

The blossoming of the four plant species studied was dispersed over about 35 days in the coastal regions, and in the more continental inland regions over 26 days. The large variability in the data from the coastal regions is generally connected with the temperature regime and ice cover of the Baltic Sea (Karing 1992). In the case of a cold winter and stable ice cover, the following spring will be very late in the region, while at the same time the inland areas warm up faster and spring will arrive much earlier. In the case of a winter without ice cover, the Baltic Sea is warmer and spring will start earlier in the coastal regions than in the more stable inland regions. The influence of a warm sea is especially pronounced for the early spring phenophases. The larger variations observed in the phenological data for a marine climate changes the hypothesis that the marine influence is a generally stabilizing seasonal factor.

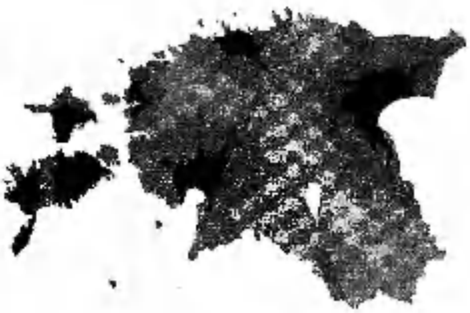

Fig. 4 Spatial differences of early and late springs for the beginning of blossoming of the studied plant species in Estonia. Scale unit: 1 day per gray-scale tone (light-dark)

Conclusions

The study of phenological time series shows that Estonian springs have, on the basis of the database, advanced 8 days on average over the last 80-year period; the last 40-year period has warmed even faster. The rate of changes has been different on temporal and regional scales; differences grow with the length of the time series used and with geographical distance. In order to use phenological time series for climate change studies we have to know all of these dimensions, aspects and limiting factors. The few aspects studied here demonstrate the risks of using a linear regression analysis of phenological time series and show the importance of the methodological development of phenology:

A. Warming rates and seasons – seasons and periods of the year have different sensitivities to climatic oscillations.

B. Stabilization and compensation – phenological seasons have stabilization periods compensate to for extreme conditions.

C. Response of life-forms – the climate-organism interactions are different for life-forms and species.

D. Extreme years – the natural variation of springs is much greater than the possible rate of climate change.

E. Regional climate – climatic subtypes can give very different trends for climate change, even within a small area.

Due to the nature of phenological data (dates, length and intervals of phenophases) and the seasonal cycling of nature, phenologists have used special scientific methods that were developed in the 1960s and 1970s (Lieth 1974; Podolsky1983; Schultz 1982). Modern methods using the possibilities offered by new statistical modeling and information technology advances have not yet been conceived. The use of methods developed for use in climate modeling, remote sensing, and GIS is hampered by the specific character of raw phenological data. Phenology has to develop new, appropriate study methods step by step, beginning with simple analyses and data sets.

References

Ahas R (1996) The seasonal dynamics of Estonian landscapes: spatial and temporal variability of early-spring blossoming dates. In: Hoe var A, Repinšek Z, Kajfe-Bogataj L (eds) Biometeorology 14, Part 2, Volume 2A, Proceedings of 14th International Congress of Biometeorology, Ljubljana, September 1996, pp 220–225

Ahas R (1997) The impact of climatic changes on seasonal cycles in nature: the study of unusually late and early springs in Estonia. In: van de Geijn SC, Kuikman PJ (eds) International workshop on prospects for co-ordinated activities in core projects of GCTE, BAHC and LUCC, S.C., November 1997, Wageningen, pp 144–145

Gomik W (1994) Investigations into the problems of finding a mean value in phenological data series. Arboreta Phaenologica 47:11–14

Jaagus J (1997a) The impact of climate change on the snow cover pattern in Estonia. Climatic Change 36:65–77

Jaagus J (1997b) Long-term changes in climatological calendar. In: Frey T (ed) Temporal changes in Estonian nature and environment. Problems of contemporary ecology. Short communications of the Estonian 7th Conference in Ecology, 8–9 May 1997, Tartu, pp 41–46

Karing P (1992) Air temperature in Estonia (in Estonian). Valgus, Tallinn, p 78

Kramer K (1996) Phenology and growth of European trees in relation to climate change. Thesis. Landbouw Universiteit Wageningen, Wageningen, p 157

Lieth H (1974) Phenology and seasonality modeling. Ecological Studies 8, New York, p 444

Podolsky AS (1983) New phenology: elements of mathematical forecasting in ecology. John Wiley & Sons, New York, pp 255–263

Schultz GE (1982) Geographische Phänologie in der UdSSR. Wetter und Leben 34:160–168

Schwartz MD (1997) Spring index models: an approach to connecting satellite and surface phenology. In: Lieth H, Schwartz MD (eds) Phenology of seasonal climates. Backhuys, Leiden, pp 23–38

Tarand A, Kuiv P (1994) The beginning of rye harvest – a proxy indicator of summer climate in the Baltic area. Paleoclim Res 13. Akademie der Wissenschaften und der Literatur, Mainz, pp 61–72

Tarand A, Eensaar A (1998) Air temperature. In: Tarand A, Kallaste T (eds) Country case study on climate change impacts and adaptation assessments in the republic of Estonia. SEITallinn, UNEP Tallinn, pp 17–21

II

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The phenological Calendar of Estonia and its correlation
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The phenological calendar of Estonia and its correlation with mean air temperature

Abstract Phenological calendar with 24 phenological phases was compiled for three meteorological stations in Estonia for the period 1948-96. We analyzed the length of the vegetation period, the order of phenological phases, and the variability and possible changes for the two incremental climate changes scenarios (+/- 2°C), and compared with examples of extreme years. The values of statistically significant linear trend show that the spring and summertime phenological phases shift earlier and autumn phases have moved later during study period. The study of extreme (minimum and maximum) years shows that 70% of the earliest dates of the 24 studied phases have occurred during the last 15 years with an absolute maximum in 1990 with 8 extreme phases. The phenological spring has shortened (slope –0.23), the summer period has lengthened (slope 0.04), and autumn has lengthened too. The length of the growing season determined by vegetation of rye has shortened (slope –0.09), which can be the result of changing agricultural technology. Correlation between beginning dates of phenological phases with the air temperature of the previous 2-3 months is relatively high (0.6-0.8).

Studied +2 and -2 C scenarios and values of extreme years show that in case of short time variations of air temperature the phenological development of nature remains within the limits of natural variation.

Key words: Phenology · Phenological calendar · Estonia · Seasonality · Plant phenology

Introduction

The occurrence of regularities in the seasonal cycling of nature, alternating of hot and cold seasons, is one of the most important climatic factors influencing the plant and animal kingdoms as well as human activity in mid latitudes. Phenology is the study of annually recurring phenomena in the life cycle of an organism or the physical environment (Schultz 1981, Kramer 1996). Seasonality of nature is described with the method of phenological calendars (Schnelle 1955) which is the list of annual sequence of phenological phases in form of beginning dates, duration of them and intervals between phases. Beginning dates as phenological variables mark certain points in the annual cycle. They have a particular sequence and they are closely correlated with phases of the same season. A recurrent annual cycle consists of a sequence of regularly interchanging phenological phases described in terms of beginning date, duration and interval. Every period distinguished in the annual cycle has duration; intervals are defined as the time periods between any two phenological phases. Calendars of nature describe the seasonality of biological (living) and physical components of nature, for example species, populations, ecosystems, sites or regions. As the result of study of the phenological calendars the homogenous periods of the seasonal cycle are normally defined as (phenological) seasons and marked with indicating phenological phases.

In current study the phenological calendar is defined as the list of beginning dates and selected statistics of phenological phases, their duration and the intervals between them which are analysed. Most phenologists use the method of phenological calendars. F. Schnelle (1955) introduces it methodologically; the first determination of phenological seasons was made by Ihne (1895) and developed by Hopkins and Murray (1933). The methods of Schnelle (1955), Davitaja (1964), Lieth (1974), Schultz (1981) and Defila (1992) show that there is no uniform method of composing a phenological calendar, determining seasons or of analysing seasonality with method of phenological calendars. There are many methods and possibilities in phenology for analysing possible climate change impact and correlation between beginning dates and climatic

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parameters (Defila 1992, Schwarts 1999). It is possible to analyse only phenological time series as indicators of climate change or climate-organism interactions (Ahas 1999, Menzel and Fabian 1999, Sparks 1999). Phenologists study correlations with climatic seasons (Jaagus and Ahas 1998), diurnal mean air temperature (Maak and Storch 1997, Wielgolaski 1999), or with the common method of cumulative sums of temperature (Roltsch et al 1999).

The Estonian calendar of nature consists of data of 8 climatic seasons and 52 phenological phases from 1948-96 collected from more than 20 observation points. In the current study only 3 observation points with best-selected data were used for analyses. The main objective of this study was to analyse 1) the temporal variability of phenological calendars in Estonia, 2) their correlation with mean air temperature and 3) sensitivity to the impact of possible climate changes. To analyse the phenological calendar, the order of phenological phases, variability of beginning dates, and the length of the vegetation period and determined seasons was studied. Possible climate change impact was analysed for +/-2° C scenarios (Keevallik 1998).

Data and methods

Estonia is located between 57.5°N and 59.5°N on the eastern coast of the Baltic Sea. The western part of Estonia lies under the direct influence of the sea while in the central and eastern parts the climate gradually becomes more continental. Phenological data series used for the calendar originate from the observation programme of the Estonian Meteorological and Hydrological Institute (1948-1996). For the final study only 24 phytophenological phases were selected for three stations: 1) Türi (58°49'N, 25°25'E) in more continental Central Estonia; 2) Pärnu (58°22'N, 24°31'E) with a marine climate in the south-west of Estonia and 3) Võru (57°51'N, 27°01'E) in continental South-Eastern Estonia (Fig. 1). Phenological phases (Table 1) were selected according to two main criteria: 1) the quality of the observation series and 2) if possible to give a good coverage of the whole growing season. A high density of phenological phases was discovered for May and June. Observations were particularly scarce in the autumn. Table 1 contains data of phenological calendars only for the Türi station; the other two stations are relatively similar in all statistics and therefore are not published here. All phenological observation data used was recorded using Agrimeteorological observation station methods, which are similar to the methodology used in the former USSR (Davitaja 1958). Monthly mean air temperatures used for the study were observed at the same stations. The beginning of a phenological phase was recognised when an activity was recognised

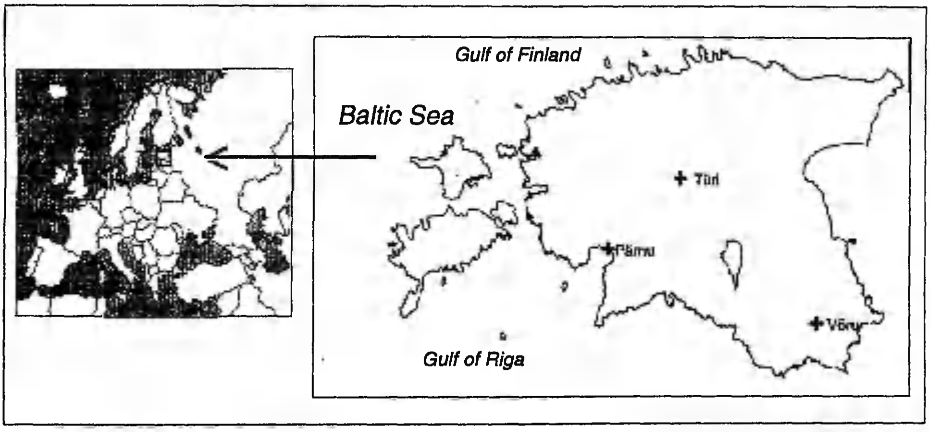


Fig. 1. Location map of Estonia in Europe and observation sites

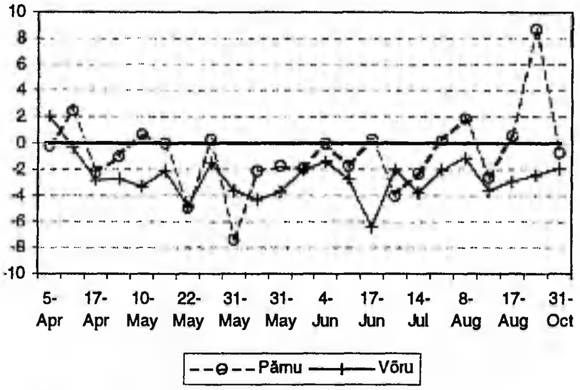
when an activity was observed in 10% of the individuals of a population. About 10% of the data was interpolated due to clear errors or gaps in observations. Interpolation of these time series was carried out by correlation analysis using the mean value of the two surrounding observation points.

The phenological phases of tree species analysed in this study were: 1) beginning of sap rising of birch *(Betula pendula* Roth*)*; 2) the beginning of pollination of hazel *(Corylus avellana* L.*)*, maple *(Acer platanoides* L.*)*, birch *(Betula pendula* Roth*)*, bird cherry *(Prunus padus* L.*)*, lilac *(Syringa vulgaris* L.*)*, oak (*Quercus robur* L.), rowan *(Sorbus aucuparia* L.*)*, apple *(Malus domestica* L., variety *Antonovka)*, linden (*Tilia cordata* Mill.); 3) foliation of birch *(Betula pendula* Roth*)*, oak (*Quercus robur* L.); 4) defoliation of apple (*Malus domestica* L., variety *Antonovka)*. The phenological phases of agricultural species studied: ear of clover (*Trifolium pratense* L.); pollination of potato *(Solanum tuberosum* L.); nine phases of autumn sown rye (*Secale cereale* L.), Estonian variety *Sangaste* - beginning of vegetation, stalk formation (cereal), appearance of stalk node, ear, pollination, milky ripeness, waxy ripeness, full ripeness, harvesting.

The statistical analysis of the data was carried out with the standard tools of MS Excel 97: average, standard deviation, min, max, quartiles, correlation, regression and trends were calculated. Impact of possible climate change on the phenological calendar in Estonia is analysed on the basis of correlation between phases and monthly mean air temperatures. In the first stage, correlation between phases and temperature during different periods was estimated and the period with the highest correlation was determined. Using linear regression analysis, changes in beginning dates of the phases per one degree C of change in mean temperature were calculated.

Climate change scenarios for Estonia, based on results of different general circulation model experiments, indicate a significant warming due to the increase of the greenhouse effect (Keevallik 1998). An increase of monthly mean air temperature of 2-4°C for the year 2100 was projected on average. In this study, two incremental climate change scenarios - equal increase and decrease of mean temperature by 2°C - were applied for the estimation of the sensitivity of the phenological calendar to climate change. Hence, it is assumed that the current correlation between mean air temperature and start of phenological phases will be similar within these limits of climate change.

Fig. 2. Differences of phenological calendar between observation points. 0 line marks the average for the Türi station



Results

1. Phenological calendar

The analysed phenological calendar consists of the beginning dates of 24 phytophenological phases occurring throughout the whole growing season (Table 1). Two phases: birch sap rising and blossoming of hazel are normally observed before the beginning of the growing season when daily mean air temperature is higher than 5°C. The order of phenological phases in chronological succession is common for all the years of the study period and is the same for all observation points. The only pheno-anomalies were observed in Võru for birch and linden pollination, which swapped places, in the sequence of phases, with their neighboring phases. Differences between the three stations studied are relatively small and are shown on Figure 2.

The mean (arithmetic average) beginning dates and medians of phenological time series do not differ more than 1-3 days, reaching a maximum for the pollination of hazel which is a very variable phase in early spring with the highest standard deviation (16,3). The high variability of early spring phases (sap rise of birch and pollination of hazel) is connected with snow cover and the length of winter, which is very variable in Estonia. The variability of data for the Türi station in quartiles is shown on Fig. 3 and the standard deviations in Table 1. Temporal variability of data is higher in spring and autumn; summer phases have smaller deviations, except for the pollination of rye which has Standard deviation of 10,4 on 20.06. The variability of the parameters of climatic seasons, expressed in standard deviations, has a similar geographical distribution in Estonia (Jaagus and Ahas 1998). Relatively smaller standard deviations of phenological phases can be found in continental South-Eastern Estonia (Võru).

The study of extreme (minimum and maximum) years (Table 1) shows that most of earliest dates of spring have been observed during recent decades.

70% (17) of the earliest dates of the 24 studied phases have occurred during the last 15 years, with an absolute maximum in 1990 with 8 extreme phases.

Table 1. Phenological calendar studied (mean for 1948-1996): phenological phases (chronological order) and beginning dates in three observation stations, mean standard deviation and linear trend for the Türi station.

Phenological phase	Average	Median	Slope	Min	Min year	Max	Max year	Stdev
Birch sap bleeding	5-Apr	6-Apr	**-0.441**	7-Feb	1989	24-Apr	1966	14
Pollination of hazel	11-Apr	14-Apr	**-0.399**	23-Feb	1990	6-May	1966	16.3
Beginning of veget. of rye	17-Apr	16-Apr	0.116	28-Mar	1959	4-May	1956	8.6
Pollination of birch	10-May	11-May	**-0.181**	24-Apr	1990	4-Jun	1955	7.2
Foalition of birch	10-May	12-May	**-0.287**	22-Apr	1990	6-Jun	1955	8.1
Pollination of maple	12-May	12-May	-0.088	26-Apr	1990	4-Jun	1955	6.9
Pollination of bird cherry	19-May	20-May	**-0.168**	29-Apr	1990	8-Jun	1955	7.1
Foalition of oak	22-May	22-May	**-0.171**	6-May	1990	14-Jun	1955	7.7
Pollination of apple	29-May	31-May	-0.139	8-May	1990	22-Jun	1955	7.8
Pollination of oak	30-May	31-May	**-0.225**	6-May	1984	28-Jun	1987	9.2
Pollination of lilac	31-May	31-May	**-0.234**	2-May	1978	24-Jun	1955	9.1
Pollination of rowan	1-Jun	2-Jun	**-0.234**	16-May	1990	26-Jun	1955	7.7
Ear of rye	4-Jun	4-Jun	-0.115	22-May	1989; 1990	20-Jun	1955	6.4
Ear of clover	17-Jun	18-Jun	0.091	6-Jun	1963	8-Jul	1994	7.2
Pollination of rye	20-Jun	20-Jun	-0.035	6-Jun	1993	10-Aug	1991	10.4
Pollination of linden	13-Jul	14-Jul	-0.064	8-Jun	1948	28-Jul	1951	8.7
Milky ripeness of rye	14-Jul	13-Jul	-0.065	2-Jul	1989	31-Jul	1962	6.6
Pollination of potato	24-Jul	26-Jul	**-0.358**	4-Jul	1989	18-Aug	1955	8.9
Waxy ripeness of rye	31-Jul	31-Jul	0.122	18-Jul	1983	30-Aug	1987	7.9
Waxy ripeness of barley	8-Aug	10-Aug	-0.004	24-Jul	1975	20-Aug	1955	6.7
Full ripeness of rye	13-Aug	12-Aug	0.087	28-Jul	1988	6-Sep	1987	9.2
Rye harvest	17-Aug	16-Aug	0.036	27-Jul	1988	17-Sep	1987	11.8
Defoliation of apple*	19-Oct	20-Oct	0.026	6-Oct	1949	4-Nov	1967	7.9
End of vegetation of rye*	31-Oct	31-Oct	0.031	10-Oct	1992	23-Nov	1978	10.4

* autumn sown rye, Estonian variety Sangaste; ** data series with many gaps; *** significant values of slope ($p<0.05$) are marked in bold

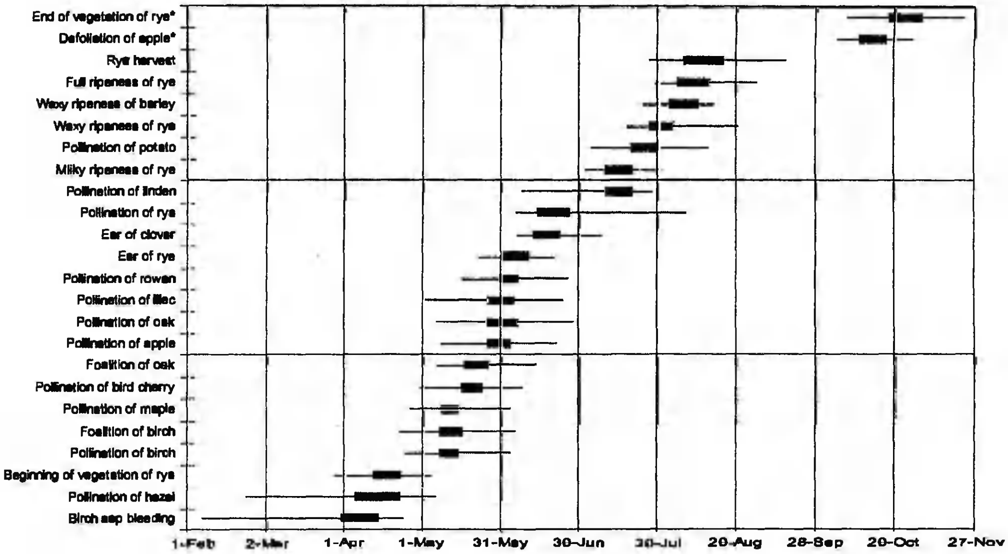


Fig 3. Phenological calendar in Türi and variability of data in quartiles for 1948-1996

25% of the latest dates of the 24 studied phases have occurred during the last 15 years and 58 % (14 dates) during the first 15 years of the study period, with an absolute minimum in 1955 with 11 extreme phases. This explains the nature of the negative slope of the linear trend for those series. Extreme values for spring, summer, and autumn periods occur in different years. The earliest spring and summer occurred in 1990, and the earliest autumn in 1988.

The latest spring was in 1955 and 1966 and the latest autumn in 1987. The absolute range of spring phases is relatively high between earliest (1990) and latest (1955) years. For example the range of pollination of maple for those years was 39 days and pollination-of-oak 53 days; summer and autumn phases have similar amplitudes of variation between min and max values.

Spatial variations in the data from the three studied stations show that spring phenophases start the earliest in Võru. After the Gulf of Riga has warmed up, at the end of May, the phenological development in Pärnu begins to catch up with that in Võru. In early summer the phenological phases of the pollination of lilac, apple and rowan can very easily change their order, and the geographical variation of those phases is high too (Ahas 1999). For example, in years with a warm winter the pollination of lilac and apple starts in opposite order in Pärnu and Võru. This is a result of different winter conditions and is related particularly to the ice cover of the Baltic Sea. Throughout the summer only the most northern station, Türi, remains 2-4 days behind. In the autumn, the phenological phases in Pärnu are the latest due to the influence of a relatively warm sea. The slope of linear regression (b1) (Table 1) shows changes in time series during the study period. Most of the statistically significant values ($p < 0,05$) of slope show that they have been shifted earlier especially in the spring period (Fig. 5). All statistically significant values of trend are in spring period with value between -0,1 ... -0,5. Autumn phases have moved later but these trends have no significant values. This shows that there is general tendency of lengthening of the vegetation period.

Duration of homogeneous periods (phenological seasons) and intervals between phases are typical variables of phenological calendars. The phenological calendar of Türi (Fig. 3) by quartiles shows different phenological seasons or homogeneous periods of the growing season. The phenological spring season begins with the vegetation of rye and ends with the pollination of apple. This period has shortened (slope –0.23). The summer period, between pollination of apple and harvest of rye, has lengthened, (slope 0.04), and autumn has lengthened too. The length of the growing season of rye has shortened (slope – 0.09), which is different from other similar studies (Menzel and Fabian 1999) and can be the result of the use of different methods or specific aspects of changing agricultural technology.

2. Correlation of phenological dates and mean air temperature

Correlation between beginning dates of phenological phases and mean air temperature is relatively high (Table 2, Fig. 4). The studied phases are distributed throughout the growing season and therefore there is no uniform period with mean air temperature used for the study.

Phenological phases have the highest correlation with the air temperature of the previous 2-3 months. Due to the relatively high correlation (0.6-0.8), mean air temperatures can be used as an alternative to the degree-days method to analyse climate change impact on phenological phases or the phenological calendar. Value of change per 1°C of warming (Table 2) indicates the number of days by which the phase begins earlier.

Table 2. Correlation between phenological phases and mean air temperatures, with corresponding change per 1°C, in days.

Phases	Türi			Pärnu			Võru		
	Corre-lation	Period (month)	Change per 1°C	Corre-lation	Period (month)	Change per 1°C	Corre-lation	Period (month)	Change per 1°C
Pollination of hazel	-	-	-	-0,83	II-IV	-6,2	-0,83	II-IV	-5,6
Beginning of vegetation of rye	-0,59	IV	-3,0	-0,59	II-IV	-3,1	-0,66	II-IV	-2,6
Foliation of birch	-0,80	IV	-3,9	-0,66	IV	-2,6	-0,74	IV	-3,2
Pollination of maple	-0,83	IV	-3,4	-0,59	II-IV	-2,1	-0,85	IV	-3,2
Pollination of bird cherry	-	-	-	-0,85	IV-V	-4,3	-0,82	IV-V	-4,3
Pollination of apple	-0,87	IV-V	-5,3	-0,82	IV-V	-4,4	-0,86	IV-V	-4,6
Pollination of lilac	-0,72	IV-V	-5,1	-0,91	IV-V	-5,2	-0,83	IV-V	-4,8
Pollination of rowan	-0,84	IV-V	-5,1	-0,81	IV-VI	-5,7	-0,74	IV-VI	-5,3
Ear of rye	-0,86	IV-V	-4,3	-0,86	IV-V	-4,2	-0,69	IV-V	-3,9
Pollination of rye	-0,71	V-VI	-6,0	-0,78	V-VI	-5,0	-0,66	IV-V	-3,2
Milky ripness of rye	-0,81	IV-VI	-5,3	-0,85	V-VI	-5,0	-0,81	IV-VI	-5,5
Waxy ripeness of rye	-0,68	V-VII	-5,2	-0,73	V-VII	-6,9	-0,76	IV-VI	-5,4
Full ripeness of rye	-0,74	V-VII	-6,7	-0,70	V-VII	-6,9	-0,76	IV-VI	-5,9
Full ripeness of rye	-0,74	V-VII	-6,7	-0,70	V-VII	-6,9	-0,76	IV-VI	-5,9

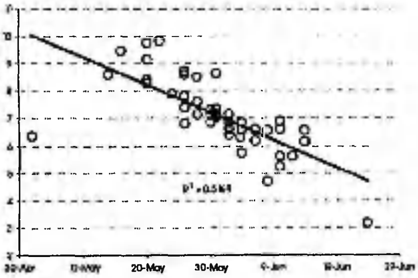


Fig. 4. Correlation of pollination of lilac in Türi station with mean air temperature of April and May

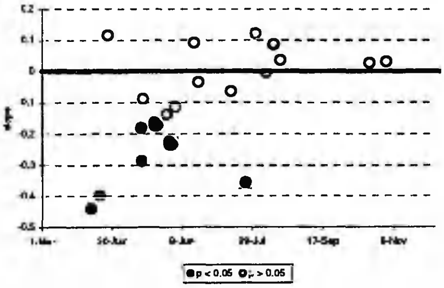


Fig. 5. Slope of linear trend for phenological phases in Türi.

Temperature change has the smallest influence on spring phenophases (beginning of vegetation of rye, foliation of birch, pollination of maple) which depend more on the first sunny and warm days at the end of April or May. Early spring (pollination of hazel) and summer phenophases (pollination of lilac and apple) are more influenced by temperature. The rate of change per 1°C is greatest for full ripeness of rye with 6.7 days per degree of air temperature change in the corresponding period (May-July). The highest spatial differences are observed for the temperature correlation of foliation of birch and pollination of maple. For these phases the correlation in Pärnu was much lower (correlation for maple 0.59) than in Türi or Võru (correlation for maple 0.85) which are less influenced by the cold sea water at the beginning of May.

Discussion

1. Impact of climate change

Most recent studies using data from the International Phenological Garden network show that the length of the growing season is changing and the phenological development of spring onset is advancing in Europe (Menzel and Fabian 1999). Current analysis of the phenological calendar in Estonia shows the same effect, except for the growing season as determined by the vegetation of rye. This period is defined by the beginning of vegetation (16 April) and the end of vegetation (31 October) and can be influenced by agricultural technologies. Other spring phenophases and beginning dates of climatic seasons have advanced throughout the period in all the observation points in Estonia (Jaagus and Ahas 1998). For example, the pollination of hazel has advanced by 20 days during the last 48 years. The linear regression of onset of the pollination of bird cherry (Fig 6) for studied period has statistically significant trend to become earlier in Estonia. Milky ripeness of rye that is the phase of mid of July has similar trend with higher deviation of values (Fig 7). The higher range of deviations of phenological data is one result of climate change impact (Ahas 1998). This noticeable change can be considered to be a consequence of global warming. Mean air temperature in winter and in spring has increased more than 1°C during the last century (Jaagus 1996). Studied +2 and -2 C scenarios show that in reality the phenological development of nature remains within the limits of natural variation (Fig. 8). For example, in the case of a 4°C warmer spring the phenological phases will still stay in the limits of the studied extreme years (min 1975 and max 1955) (Figure 4). Extreme events usually last only a few months of year and organisms can survive these conditions. The calendar of nature (Table 1) shows that only very extreme years like minimum 1990 and maximum 1955 have a longer influence than just one season. 2. The phenological calendar as a method to record and compare seasonality

The phenological calendar method was designed for the study of the seasonality of species, populations, ecosystems or places (Hopkins 1933, Schnelle 1955, Reader et al 1974). The main method of those calendars was a graphically designed phenological spectre and the study of mean values of records (Schults 1981). Those elements of descriptive phenology (Reader et al 1974) were used for different studies and analyses of seasonality.

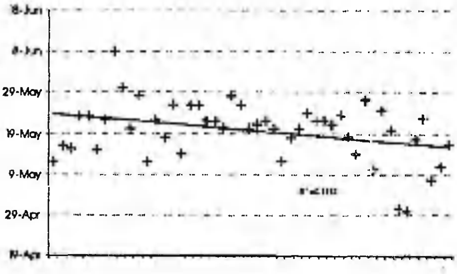


Fig 6. Linear regression for onset of the pollination of bird cherry in Türi for 1948-1996

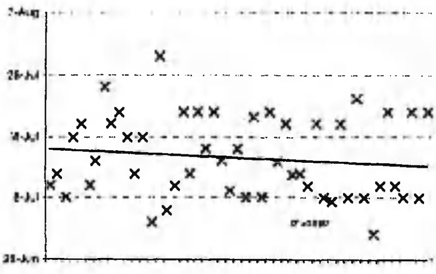


Fig 7. Linear regression for onset of the milky ripeness of rye in Türi for 1948-1996

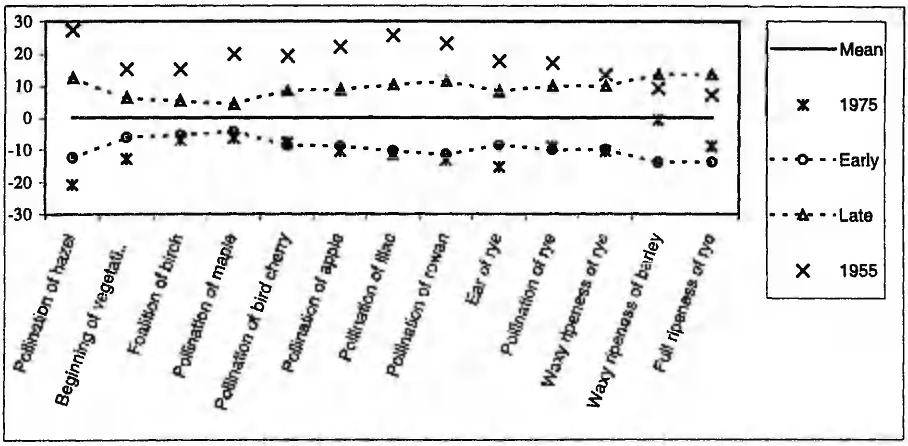


Fig. 8. Change of phenological calendar for Pärnu in days. 0 - level: average for study period; early +2 °C scenario; late -2 °C scenario; 1975 extrememin year; 1955 - extreme max year.

Elements of phenological calendars have been used for applications in agriculture.

Those calendars of agriculture have a list of phases, indicator species, and simple tools for phenological prognosis. The Podolsky (1983) developed method for phenological nomograph and recommended on bases those nomograph to compose phenological indicator-calendars for agriculture. Today, the methods of phenology and seasonality studies have changed (Schwartz 1999) and there are many possibilities for studying the seasonality of nature and for composing calendars. The best quality and density phenological data is analysed and presented by Defila (1992) in the calendar of nature of Switzerland. In this calendar the statistical analysis of quartiles is combined with good graphical representation of calendars for different locations. Today, most phenologist use data obtained from satellites for large scale modelling and forecasting (White et al 1997). For analyses of space-time variations of ground data series, for comparing them with other locations, and for covering remote sensing data with ground series, co-ordinated observation series with unique methods are still needed. For the analysis and comparison of data between geographical locations or years, the uniform method of calendars of nature, which can describe the full spectrum and rhythm of seasonality, must be developed further. For example, if we are interested in comparing the seasonal cycling of nature in Wisconsin and Switzerland and in monitoring the possible effects of global change we need a uniform method to monitor these, even if we are dealing with different natural species and different climatic conditions. The phenological calendar (matrix of dates, intervals, duration etc) can be used in analyses to record differences between years, periods, or locations.

Conclusions

1) Linear regression of the studied phenological time-series (Table 1, Fig. 4) shows that there has been a noticeable change (statistically significant linear trend) in seasonality during the studied period, between 1948 and 1996. Most of the statistically significant values ($p < 0,05$) of slope show that they have been shifted earlier, especially in the spring period (Fig. 4). All statistically significant values of trend are in spring period with value between -0,2 and -0,5. Autumn phases have moved later but these trends have no significant values. This shows that there is general tendency of lengthening of the vegetation period. A remarkable change of 3-5 days per decade is recorded for phases of early spring such as birch sap rise, pollination of hazel and foliation of birch. This trend is similar for all

three stations studied (Fig. 1) and is connected with the phenomenon of changing winters: the greatest changes in Estonian climate are recorded for the winter period that has become warmer during last decades (Jaagus 1997).

2) The study of extreme (minimum and maximum) years (Table 1) shows that 70% of the earliest dates of the 24 studied phases have occurred during the last 15 years with an absolute maximum in 1990 with 8 extreme phases. 25% of the latest dates of the 24 studied phases have occurred during the last 15 years and 58 % (14 dates) during the first 15 years of the study period, with an absolute minimum in 1955 with 11 extreme phases. The absolute range of spring phases is relatively high, the range of pollination-of-maple for those years was 39 days and pollination-of-oak 53 days; summer and autumn phases have similar amplitudes of variation between min and max values.

3) Duration of phenological seasons and intervals between phases is changing too. The phenological spring has shortened (slope –0.23), the summer period has lengthened (slope 0.04) and autumn has lengthened too. The length of the growing season determined by vegetation of rye has shortened (slope –0.09), which can be the result of changing agricultural technology.

4) Correlation between beginning dates of phenological phases with the air temperature of the previous 2-3 months is relatively high (0.6-0.8). Studied +2 and -2 °C scenarios and values of extreme years show that in case of short time variations of air temperature the phenological development of nature remains within the limits of natural variation. Phenological phases with greatest changes will occur more than 10 days earlier (or later). For example, pollination of hazel (mean 13 April) will begin on 1 April in case of warming or on 26 April in case of cooling of 2 C (Fig 7).

References

Ahas R, Tarand A, Meitern H (1998) Temporal variability of the phenological time series in Estonia. In: Tarand A, Kallaste T (eds) Country Case Study on Climate Change Impacts and Adaptation Assesments in the Republic of Estonia. Report to the UNEP/GEF; Project No.: GF/2200-96-45. Stockholm Environment Institute-Tallinn, Tallinn, p 28-30

Ahas R (1999) Long-term phyto-, ornitho-, and icthyophenological time-series analyses in Estonia. International Journal of Biometeorology 42:119-123

Crick HQP and Sparks T (1999) Climate change related to egg-laying trends. Nature 399:423-424

Davitaja (1958) Agrometeorological problems. Moscow, Hydrometeorological Publishing House. P 91. (In russian with English Contents)

Davitaja F F (1964) Prognosis of heat thresholds and selected questions of seasonal development of nature. Moskow, Gidrometeorologitsheskoe Izdatelstvo. 131 p. (In Russian)

Defila C (1992) Pflanzenphänologische Kalender ausgewählter Stationen in der Schweiz / Calendriers phytophänologiques en Suisse 1951-1990. Beiheft zu den Annalen der Schweizerischen Meteorologischen Anstalt 30/L, Zürich, 233

Defila C (1991) Phänologie der Schweiz. Inaugural-Dissertation. Zürich. 235 p.

Hopkins AD and Murray MA (1933) Natural guides to the beginning, length and progress of seasons. Acta Phaenologica. 2. 1933. 33-43

Ihne E (1895) Über phänologische Jahreszeiten, Naturw., Wehchenschr. 10. Berlin

Jaagus, J. (1996) Climatic trends in Estonia during the period of instrumental observations and climate scenarios. In: Punning J. M. (ed) Estonia in the system of global climate change. Institute of Ecology 4/1996, Tallinn. Pp 35-48

Jaagus J (1997) The impact of climate change on the snow cover pattern in Estonia. Climatic change 36:65-77

Jaagus J, Ahas R (1998) Spatial differences in climatic seasons in Estonia and their influence on phenological development of nature. 2nd European Conference on Applied Climatology 19 to 23 October 1998, Vienna, Austria. Österreichische Beiträge zu Meteorologie und Geophysik, 19. Zentralanstalt für Meteorologie und Geodynamik, Wien. ISSN 1016-6254

Keevallik S (1998) Climate change scenarios for Estonia. In: Tarand A, Kallaste T (eds) Country Case Study on Climate Change Impacts and Adaptation Assesments in the Republic of Estonia. Report to the

UNEP/GEF; Project No.: GF/2200-96-45. Stockholm Environment Institute-Tallinn, Tallinn, p 30-35.Schwartz MD (1999) Advancing to full bloom: planning phenological research for the 21st century. International Journal of Biometeorology 42:113-118

Kramer K (1996) Phenology and growth of European trees in relation to climate change. Thesis Landbouw Universiteit Wageningen, Wageningen

Lieth H (1974) Purposes of phenology book. In: Lieth H (ed) Phenology and seasonality modeling. Ecological Studies 8, Springer-Verlag, New York, p 3-19

Maak K and von Storch H (1997) Statistical downscaling of monthly mean air temperature to the beginning of flowering of Galanthus nivalis L. in Northern Germany. International Journal of Biometeorology 41:5-12

Menzel A and Fabian P (1999) Growing season extended in Europe. Nature 397:659

Podolsky AS (1983) New Phenology: Elements of Mathematical Forecasting in Ecology. John Wiley & Sons, New York

Reader R, Radford S R, Lieth H (1974) Modeling Important Phytophenological Events in Eastern North America. In: Lieth H (ed) Phenology and seasonality modeling. Ecological Studies 8, Springer-Verlag, New York, p 329-342

Roltsch WJ, Zalom FG, Strawn AJ, Strand JF, Pitcairn MJ (1999) Evaluation of several degree-day estimation methods in California climates. International Journal of Biometeorology 42:169-176

Schnelle F (1955) Pflanzen-Phänologie. Akademishe Verlagsgesellschaft, GEEST und PORTIG K.-G., Leipzig, p 166-210

Schultz GE (1981) General phenology. Nauka, Leningrad, p 91-146 (in Russian)

Schwartz MD (1998) Green-wave phenology. Nature 394:839-840

Schwartz MD (1999) Advancing to fullbloom:planning phenological researchfor the 21st century. International Journal of Biometeorology 42:113-118

White MA, Thorton PE, Running SW (1997) A continental phenology model for monitoring vegetation responses to interannual climatic variability. Global Biogeochemical Cycles 11 No 2, 217-235

Wiegolaski F-E (1999) Starting dates and basic temperatures in phenological observations of plants. Int J Biometeorol 42:158-168.

III

Ahas, R. 1998.
Climatic change impact on seasonal cycles in nature:
spatial and temporal variability of the phenological time-series in Estonia.
Climate Change Studies in Estonia, Kallaste, T., Kuldna, P. (eds.)
SEI Tallinn, pp. 21–26.

Climatic change impact on seasonal cycles in nature: spatial and temporal variability ot the phenological time-series in Estonia

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Abstract

The study includes analysis of phenological time-series in Estonia to assess the climate change impact on Estonian nature. Long-term time-series of the beginning of flowering of five tree species *(Corylus avellana, Acer platanoides, Padus sylvatica, Syringa vulgaris, Sorbus aucuparia)*, the arrival of two bird *species (Motacilla alba, Alauda arvensis)* and the beginning of spawning of two *fish species (Esox lucius, Abramis brama)* were used. Three aspects of the climate change impact on phenological phases were studied: 1) temporal variability of long-term phenological observation series; 2) spatial dispersion of phenophases; 3) phenological phases in unusually late and early springs. Time-series, GIS analysis and phenological calendar-analysis methods were used in the study.

1. Introduction

The current study analyses long-term phenological time-series with the aim to estimate the impact of climate change on Estonian nature. Variations in phenological data indicate the climate change impact on nature and help to predict the climatic change impact on different ecosystems. Three aspects of the climate change impact on phenological phases were studied: 1) temporal variability of long-term phenological observation series; 2) spatial dispersion of phenophases; 3) phenological phases in unusually late and early springs. Time-series, GIS analyses and phenological calendar-analysis methods were used (Ahas, 1997). The study of phenological time-series shows that spring in Estonia begins, on the average, 9 days earlier than it did 100 years ago, extreme climatic conditions in spring influence the length and order of phenological phases (phenological inversion). Analysis of the spatial dispersion of phenophases in early and late springs reveals very different rates and directions of seasonal development.

2. Data

1) The following phenological data-series from the observation programme of the Estonian Naturalists Society (1951-1996) and the Estonian Meteorological and Hydrological Institute (1947-1996) were selected as data of the best quality and density: the beginning of blossoming of five tree species *(Corylus avellana L., Acer platanoides L., Prunus padus L., Syringa vulgaris L., Sorbus aucuparia L.)*, the arrival of two bird species *(Motacilla alba L., Alauda arvensis L.)* and the start of spawning of two fish species *(Esox lucius L., Abramis brama L.)*.

2) For the long-term time-series study only the best phenological observation series from a limited number of observation points were selected. The study is based on 8 common plant, fish, and bird species in three different observation points. The species studied and the locations of observation points are listed in Table 1. Spring phenophases were selected for analysis due to the good observation series available and because the effect of climate change in Estonia is stronger in spring. The long-term time-series (more than 50 years), most valuable for climate change studies have been collected by organisations and families. The longest phenological data-series have been reconstructed for rye harvests and date back to the 17th century (Tarand, 1994).

3) For evaluation of the current phytophenological database and verification of the research results of spatial dispersion of phenophases, a special field study programme was undertaken. During 1995-1997 phenological observations were carried out in 49 observation points in different landscape regions of Estonia.

Table 1. List of long-term observation series, sites and phenophases

Phenological phase	Observation period	Total years	Observation point
Blossoming of wood anemone *(Anemone nemorosa)*	1919-1996	78	Paide (Central Estonia)
Blossoming of bird cherry *(Padus racemosa)*	1919-1996	78	Paide (Central Estonia)
Blossoming of apple tree *(Malus domestica)*	1919-1996	78	Paide (Central Estonia)
Blossoming of lilac *(Syringa vulgaris)*	1919-1996	78	Paide (Central Estonia)
Spawning of pike *(Esox lucius)*	1952-1996	44	Pedaspää (Lake Peipsi)
Spawning of bream *(Abramis brama)*	1952-1996	44	Pedaspää (Lake Peipsi)
Arrival of skylark *(Alauda arvensis)*	1865-1996	132	Hellenurme (Southern Estonia)
Arrival of white wagtail *(Motacilla alba)*	1865-1996	132	Hellenurme (Southern Estonia)

3. Methods

The interpolation of time-series was carried out by the method of correlation analysis and using the mean value of the three surrounding observation points. About 10% of data were interpolated due to gaps in observations or errors.

The spatial analysis of the blossoming dates of common tree species was carried out using the statistical analysis and the GIS package IDRISI. Interpolation of phenological data from various observation points into Estonian cartogrammes was performed with the interpolation module of IDRISI. For the subsequent analysis of the cartogrammes, different types of IDRISI modules were used. Analysis of the phytophenological database and data gathered during the special field observations revealed general trends of spatial and temporal variability of the studied phenophases in Estonia. The data gathered in field observations confirmed our results obtained from the statistical and GIS analyses of the phytophenological database (Ahas, 1996).

Late (cold), early (warm) and normal springs were selected on the basis of the standard deviation of phenological data and the beginning of climatic seasons (Jaagus, 1997) over a certain period of time. The data sets for springs classified as early (1959, 1975, 1984, 1990, 1993), late (1955, 1969, 1978, 1985, 1987) and normal (1958, 1968, 1970, 1977, 1979) were composed and both the temporal and spatial variability of phenophases were investigated.

Temporal variability of data was studied using the phenological calendar-analysis method: the phenological phases of one year were analysed as one calendar unit with phenological dates and intervals (Ahas, 1997).

4. Temporal variability of phenophases

4.1. Phytophenological series

The general results of the study are presented in Table 2. The blossoming of the studied plant species has advanced 3-14 days (for the 78 year time-series) or according to the results of linear regression analysis 5-17 days per 100 years.

Phytophenological time-series were found to be the most representative in the current study (see Figure 1 and Figure 2). The t-statistical value of the blossoming date of wood anemone is -3.74 and for lilac -2.85. This confirms the statistical reliability of the linear trend.

Table 2. Climate change statistics (linear regression) produced by phenological analysis

Phenological phase	Period (years)	Regression	t Statistics	Change per studied period (days)	Change per 100 years
Blossoming of wood anemone *(Anemone nemorosa)*	78	-0.17	-3.74	-14	-17
Blossoming of bird cherry *(Padus racemosa)*	78	-0.05	-1.29	-4	-5
Blossoming of apple tree *(Malus domestica)*	78	-0.047	-1.1	-3	-5
Blossoming of lilac *(Syringa vulgaris)*	78	-0.11	-2.85	-9	-11
Spawning of pike *(Esox lucius)*	44	-0.11	-0.92	-6	-9
Spawning of bream *(Abramis brama)*	44	-0.15	-1.13	-8	-15
Arrival of skylark *(Alauda arvensis)*	132	0.04	1.7	5	4
Arrival of white wagtail *(Motacilla alba)*	132	0.05	2.88	6	5

Figure 1. The date of blossoming of wood anemone *(Anemone nemorosa)* and its linear trend in Paide

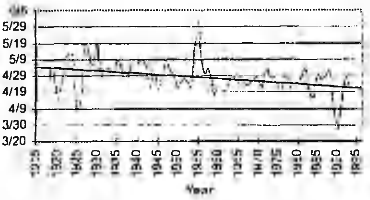
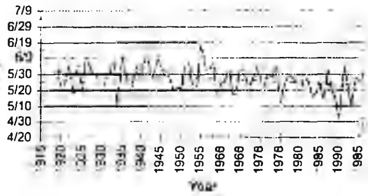
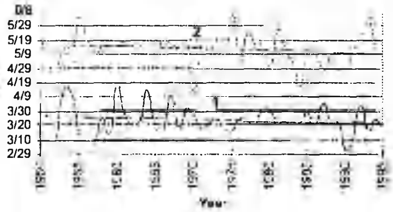


Figure 2. The date of blossoming of lilac *(Syringa vulgaris)* and its linear trend in Paide



4.2. Ichthyophenological series

Figure 3. The icthyophenological time-series of the beginning of spawning for *pike (Esox lucius)*(1) and bream *(Abramis brama)* (2) and their linear trends



The studied ichthyophenological time-series also represent a trend: the beginning of spawning for pike, 6 days earlier, and for bream 8 days earlier during the period of 44 years (see Figure 3.). The regression analysis of fish phenology showed an advance of 9 and 15 days per 100 years, respectively. The statistical reliability of the linear trend (t-statistics) is low for ichthyophenological data (-0.92 and -1.13, respectively). Ichthyophenological observation series are not of the best quality due to many errors in the observation data.

4.3. Ornithophenological series

Analysis of the ornithophenological time-series (132 years) produced results opposite to those obtained from the phyto- and ichthyophenological time-series, the sky lark arrived 5 days later and the white wagtail 6 days later (see Figure 4). The respective results of the linear regression analysis were 4 and 5 days later per 100 years. The t-statistical value of the linear trend was 1.70 and 2.8.

The statistical shortcoming of this method is that linear regression in phenological data analysis is not the best method for periods longer than 100 years (Gornik, 1994). Long-term oscillations of climatic parameters (25-50 years) periodically reverse the direction of the linear trend in this scale (see Figure 4).

Figure 4. Arrival date of white wagtail *(Motacilla alba)* and its linear trend in Hellenurme

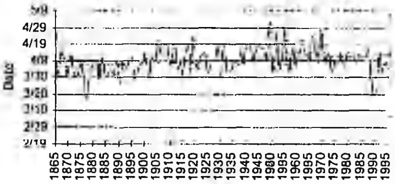
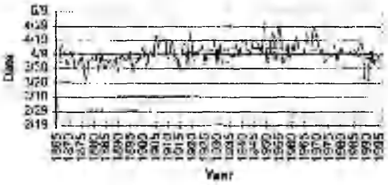


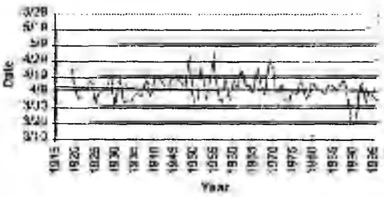
Figure 5. Arrival date of white wagtail *(Motacilla alba)* and its polynomial trend (3-d) in Hellenurme



Analysis of the ornithophenological time-series and their description using a polynomial trend line (see Figure 5) demonstrates that long-term changes in phenophase are similar to the phyto- and ichthyophenological processes (see Figures 1, 2. 3). The warm period at the end of the 19th century reverses the direction of the linear trend.

Analysis of the white wagtail time-series over the same period as the phytophenological time-series shows that its phenophase now begins 5 days earlier, corresponding to the other respective results. The problem is to find a method and period for analysis with the most representative output.

Figure 6. Arrival date of white wagtail *(Motacilla alba)* and its linear trend in Hellenurme (the period is the same as for the phytophenological data-series in Fig. 1 and 2)



5. Spatial variability of phenophases

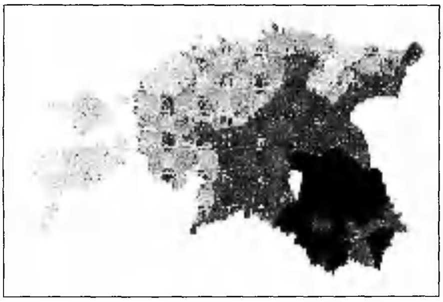
The beginning of flowering is graduated in a south-northern direction with some influence from the marine climate which reflects the distribution direction in a north-western direction. The marine influence is weaker in inland areas with a more continental climate warm-up (May-June). The rate of progression of the early spring phenophases (like the flowering of the *Corylus avellana* and *Acer platanoides*) is faster (4-8 days per 300 km) than that of the phenophases with a higher activating temperature level (10 days or more for *Padus sylvatica*, *Syringa vulgaris* and *Sorbus aucuparia*).

The Estonian landscape forms (uplands with 100-300 m of absolute elevation) change the normal distribution of phenophases. The average inhibition of the blossoming dates is about 1 day per 100 meters of absolute elevation. In very warm and early spring the blossoming of the five tree species in the uplands began earlier than on the plains. This can be explained by the better exposure and different water regime in the uplands (the spring meltwaters flow away quickly and the ground dries more rapidly).

The study of the deviations in the data from the mean values revealed great differences between the marine and continental climate regions of Estonia. The largest deviations in the blossoming dates were met in coastal regions with a marine climate. The blossoming of the 5 tree species was dispersed over about 35 days in the coastal regions, and over 26 days in the more continental inland regions. The large variability in the data of the coastal regions is generally connected with the temperature regime and ice cover of the Baltic Sea (Karing, 1992). A cold winter and stable ice cover is followed by a very late spring in the region, while inland areas warm up faster and spring arrives much earlier. When winter is without ice cover, the Baltic Sea is warmer and spring begins in the coastal regions earlier than in the stable inland. This influence of the warm sea is especially great on the early spring phenophases like the blossoming of *Corylus avellana* and *Acer platanoides*. The larger variations observed in the phenological data under a marine climate changed the hypothesis that the marine influence is a generally stabilising seasonal process.

The relief forms raise the standard deviation of data. The standard deviation of data is bigger in upland areas (100-250 m). The more variable spring aspects can be caused by differences in exposure, snow cover, and the water regime. The water regime and soil moisture have a large influence on the phenophases during the year. For example, very warm and dry springs change the direction of dispersion of the phenophases and can result in the inversion of the early-spring phenological phases.

Figure 7. Beginning of blossoming of *Prunus padus L.* in late spring. Scale unit: three days



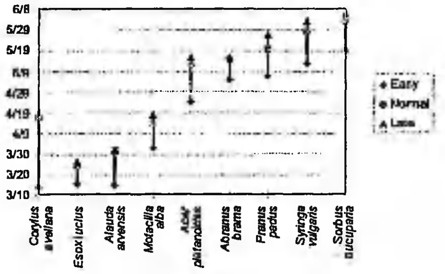
6. Study of unusually late and early spring in Estonia

Phenological calendar-analysis show that extreme climatic conditions in spring influence phenological dates and the length and order of phenological phases (see Figure 8). The 5 tree species were the most sensitive (average difference between early and late spring 23 days), in particular the early spring phase pollination of *Corylus avellana* -37 days. The difference between the arrival dates of the birds *(Motacilla alba, Alauda arvensis)* in early and late spring was on an average 17 days and that of the spawning of the fish species *(Esox lucius, Abramis brama)* 11 days. Examination of the phase intervals reveals that in early spring phases are extended over a longer period (on the average 51 days) than in late years (on the average 42 days) (see Figure 8).

The interval between the spawning dates of the two fish species is stable in early, late and normal years, being 49-51 days. The mean standard deviation of the data-series is 10.7 for early, 9.2 for late and 5.9 for normal springs.

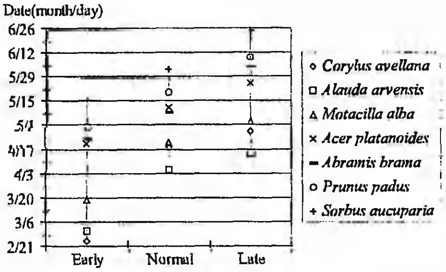
Figure 8. Duration of phenophases in early, normal and late spring

Variation of phenophases (mean)



Analysis of the spatial dispersion of phenophases in early and late springs produces most different rates and directions of seasonal development. The extremely warm and early springs in Estonia show a very rapid geographical dispersion of phases (Figure 10). The blossoming of the tree species progresses at a speed of 2-4 days per 300 km or across the total north-southern extent of the Estonian territory. This speed is much higher than in normal springs – about 8-10 days. The inversion of phenological phases was found in warm springs, especially for early phases such as the blossoming of *Coryllus avellana* and *Acer platanoides*.

Figure 9. The mean phenological dates of the beginning of blossoming of trees, arrival of birds and the start of spawning of fish in early normal and late spring in Estonia



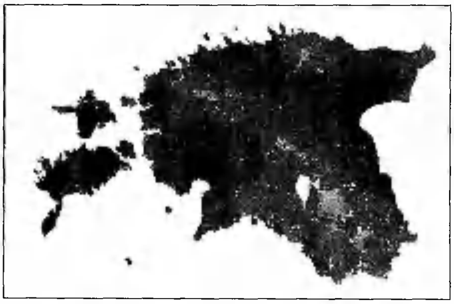
These phases have a low activating temperature and in the case of sunny days or the presence of warm air-masses the phases started in abnormal directions of dispersion and order. For very warm and early springs, the general geographical variations of the phenophases are smoothed early. In the second half of June the entire Estonian territory is in a homogeneous phenological phase without large geographical variations.

Years with a normal spring and weather conditions have the largest geographical differences phenologically. The blossoming of the tree species begins in the South-Estonian plains and disperses throughout the country within 8-10 days. The differences between the coastal regions with a marine climate and the more continental inland regions are great; the phenological phases in the Estonian uplands are retarded by about 1 day per 100 meters of absolute elevation. The geographical differences of the phenological aspects can be seen until first part of July. In normal years, the entire Estonian territory is in same phase of seasonal development by the middle of July.

The extremely cold and late springs in Estonia can be divided phenologically into two types. In the first case that is caused by domination of cold air-masses, the spatial differences are the smallest. The phenological development of nature is slow in all geographical regions, both coastal and inland. Only in the middle of May does the higher solar activity create geographical differences between the regions. In the second case that is caused by cold winter and domination of high-pressure systems, the coastal areas with a more marine climate remain cold longer and it is cloudier due to the great temperature differences. The inland areas and uplands are heated by solar radiation. Spring begins earliest in the south-facing uplands and plains. The differences in the blossoming dates of the studied tree species can be 15-20 days between the coastal and inland regions and these differences can be prolonged until mid-summer. In some cases, the different phenological aspects caused by cold spring were present in Estonia until the beginning of August.

The standard deviation of phenological dates is greater in early spring and is especially high in western Estonia with its more maritime climate subtypes. The spatial consequences of extreme springs are phenologically noticeable during June and July.

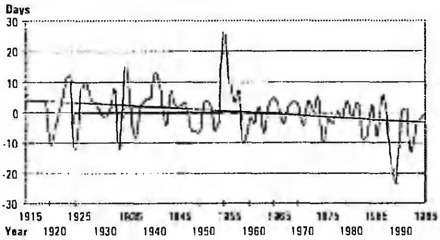
Figure 10. Spatial differences of early and late springs regarding the beginning of blossoming of the five studied tree species. Scale unit one day



7. Conclusions

The current study demonstrates that the analysis of spatial and temporal variations of phenological data is important for every level or scale of phenological study. The Estonian case study shows that the influence of the temperature regime of the Baltic Sea, the low uplands and other relief forms, as well as years with abnormal weather make it very difficult to determine general means and trends. For example, the speed of dispersion of the phenophases varied between 3 and 22 days per 300 km of NW-SE extent of the Estonian territory. Figure 11 shows the mean value of changes for all phytophenological time-series discussed in the paper. The linear trendline is statistically representative (t Statistic - 2.7) and the time-series is the one of the best quality. Spring has advanced 8 days earlier over the past 78 years. The study of phenological time-series shows that Estonian springs have advanced 3-14 days over the last 78 years, the last 40 years have warmed even faster.

Figure 11. The mean values of changes of phyto-phenological time-series



It is difficult to find these changes from the analysis of phenological data-series. The study of the phenological calendars of extreme years and reconstruction of longer time-series may reveal the pattern of these changes (long-term climate oscillations or human impact). Phenological differences between early and late spring can be greater than one month, spatial dispersion of phases is extremely variable. If springs are naturally so variable it is logical that the possible impact of other minor climatic changes will be smoothed by the same mechanisms that operate in the naturally extreme years.

For analysis of these processes with the help of geographical information systems, it is essential to select right methods and scales. For future studies it is important to develop the methodology and principles of phenological regionalisation of the study area. The second important direction for future studies is the estimation of phenological and climatological seasons of the year and the study of the phenological calendars in every homogeneous region (Podolsky, 1983). This classical method of phenology, the study of phenological calendars, enables analysis of climatological and phenological data concurrently. Analysis of phenological calendars will provide new starting points for future works with GIS systems and modelling of phenological processes.

References

Ahas, R. (1996). The seasonal dynamics of Estonian landscapes: spatial and temporal variability of early-spring blossoming dates. – In: *Biometeorology* 14, Part 2, Volume 2. A. Hocevar, Ccrepinsek and L. Kajfez-Bogataj (eds.), *Proceedings of 14th International Congress of Biometeorology, Lyublyana, 1-8.09.1996*, pp. 220-225.

Ahas, R. (1997). The impact of climatic changes on seasonal cycles in nature: the study of unusually late and early springs in Estonia. – In: *International Workshop on Prospects for Co-ordinated Activities in Core Projects of GCTE, BAHC and LUCC*, S.C. van de Geijn and RJ. Kuikman (eds.), November 16-19, 1997, Wageningen, pp. 144-145.

Gornik, W. (1994). Investigations into the Problems of Finding a Mean Value in Phenological Data Series. – *Arboreta Phaenologica*, 47, p. 11-14.

Jaagus, J. (1997). Long-term changes in climatological calendar. Temporal changes in Estonian nature and environment. – *Problems of contemporary ecology. Short communications of the Estonian 7th Conference in Ecology*, (ed. T.Frey), Tartu: 41-46.

Karing, P. (1992). Õhutemperatuur Eestis. [*Air temperature in Estonia*.] Tallinn, 78 p.

Kramer, K. (1996). *Phenology and growth of European trees in relation to climate change. Thesis Landbouw Universiteit Wageningen*, Wageningen, 157 p.

Podolsky, A.S. (1983). *New Phenology: Elements of Mathematical Forecasting in Ecology*. John Wiley & Sons: 255-263.

Tarand, A., Kuiv, P. (1994). The beginning of rye harvest – a proxy indicator of summer climate in the Baltic area. – In: *Paleoclimate Research 13, (Sp. issue 8)*, Academie der Wissenschaften und der Literatur. Mainz, pp. 61-72

IV

Ahas, R. 1996.
The seasonal dynamics of Estonian Landscapes: spatial and
temporal variability of early-spring blossoming dates.
Biometeorology, 14, Part 2, Volume 2. A. Hočevar, C. Črepinšek and
L. Kajfež-Bogataj (eds.),
Proceedings of 14th International Congress of Biometeorology,
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THE SEASONAL DYNAMICS OF ESTONIAN LANDSCAPES: SPATIAL AND TEMPORAL VARIABILITY OF EARLY-SPRING BLOSSOMING DATES

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ABSTRACT. The long term phenological observation series of the blossoming dates of *Corylus avellana, Acer platanoides, Padus sylvatica, Syringa vulgaris* and *Sorbus aucuparia* was used for a study of the seasonal dynamics of Estonian landscapes. With the help of the GIS packet IDRISI, the direction and speed of the dispersion of phenophases and the seasonal differences between different landscape regions was studied. The spatial and temporal variability of phenophases was studied separately for cold, normal and warm springs. The results of the study were verified with a special field observation program in 1995-1996.

Key words: Landscape phenology, long-term phenological observation series, GIS.

1. INTRODUCTION

The spatial dispersion of phenophases is influenced by very different natural conditions such as geographical co-ordinates, landscape type, exposure, climatic parameters, vegetation type, human impact, etc. The seasonal dynamics of landscapes also vary greatly depending on the weather conditions for the spring studied (cold, normal, warm). The differences from year to year are particularly large in temporal climate regions with high cyclonic activity like Estonia (Karing, 1992). In a study of the seasonal and temporal variability of phenological data we have to accept all the natural conditions listed before.

2. DATABASE AND METHODS

In current study, the long term (1947-1991) phytophenological observation series of the Estonian Naturalists Society and the State Agrometeorological Stations were used. The blossoming dates of common tree species *Corylus avellana, Acer platanoides, Padus sylvatica, Syringa vulgaris* and *Sorbus aucuparia* were studied with the help of statistical analysis and the geographical information system IDRISI. In the analysis of the general mean values and dispersion, the early, normal and late springs were separated. The analysis of the spatial and temporal variation of phenophases was done separately for the different spring types. The interpolation of phenological data from various observation points into cartogrammes for Estonia was done with a type module for the interpolation of IDRISI. For the following analysis of the cartogrammes, different type modules of IDRISI were used (IDRISI, 1992). For evaluation of the current phytophenological database and verification of the results of this study, a special field observation program was undertaken. During 1995 and 1996 phenological observations were carried out in 49 observation points in different landscape regions of Estonia (Figure 1.)

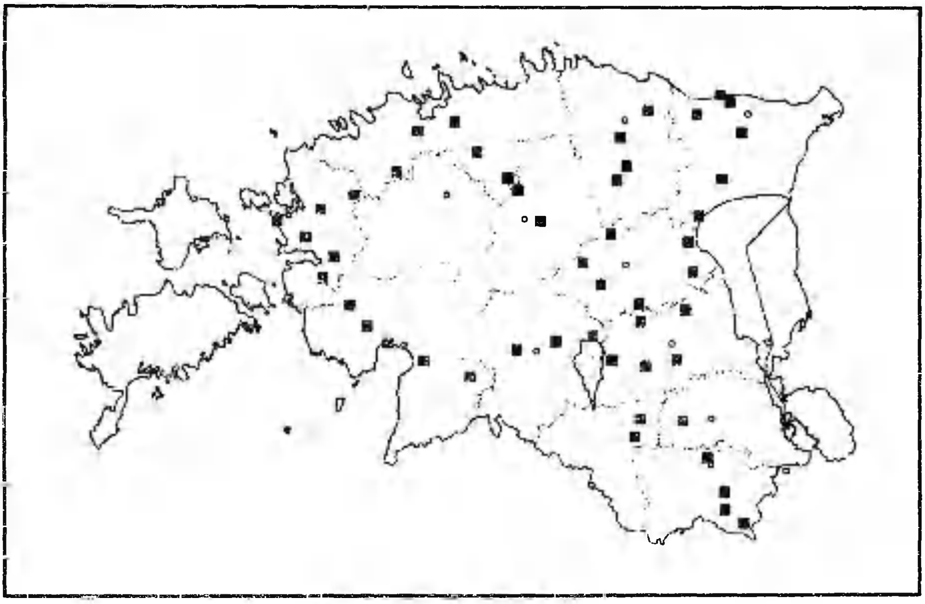

Fig.1 Distribution of the observation points of established observation programme (1995).

3. RESULTS

Analysis of the phytophenological database and data gathered during the special field observations revealed the general trends of the spatial and temporal variability of the studied phenophases in Estonia. The data gathered on field observations did confirm our results from the statistical and GIS analysis of the phytophenological database.

3.1. Spatial dispersion of phenophases

The beginning of flowering disperses in south-north direction with some influence by the marine climate which will deflect the distribution direction in a north-western direction. The marine influence is more deficient after the inland areas with a more continental climate warm up (May-June).

The speed of the early spring phenophases (like the flowering of the *Corylus avellana* and *Acer platanoides*) is faster (4-8 days for 300 km) than the phenophases with a higher activating temperature level (10 days or more for *Padus sylvatica, Syringa vulgaris* and *Sorbus aucuparia*).

The Estonian relief forms (uplands with 100-300 m of absolute elevation) change the normal distribution of the phenophases. The average inhibition of the blossoming dates studied is about 1 day per 100 meters of absolute elevation. In very warm and early springs the blossoming of the tree species studied started earlier in the uplands than on the plains. This result can be explained by the better exposure and the different water regime in the uplands (the spring meltwaters will flow quickly and land will dry more rapidly).

3.2. Variability of the data

The study of the deviations in the data from the mean values showed great differences between the marine and continental climate regions of Estonia. The largest deviations in the blossoming dates were connected with the coastal regions with a marine climate. The blossoming of the 5 tree species studied was dispersed over about 35 days in the coastal regions, and in the more continental inland regions over 26 days. The large variability in the data of the coastal regions is generally connected with the temperature regime and ice cover of the Baltic Sea. In the case of a cold winter and stable ice cover, the following spring will be very late in the region, while at the same time the inland areas are heated faster and spring will arrive much earlier. In the case of a winter without ice cover, the Baltic Sea is warmer and spring will start in the coastal regions earlier than in the stable inland. This influence of the warm sea is especially high for the early spring phenophases like the blossoming of *Corylus avellana* and *Acer platanoides*. The larger variations observed in the phenological data in a marine climate changed the hypothesis that the marine influence is a generally stabilizing seasonal processes.

The relief forms raise the deviations in the data from the general mean value. The more variable spring aspects can be caused by differences in exposure, snow cover, and the water regime. The water regime and soil moisture have a large influence on the phenophases during the year. For example, very warm and dry springs change the direction of the dispersion of the phenophases and can result in the inversion of the early-spring phenological phases.

3.3. Differences between warm, normal and cold springs

The extremely warm and early springs studied in Estonia have a very rapid geographical dispersion of phases. The blossoming of the tree species studied will disperse with a speed of 2-4 days per 300 km or the total north-south extent of Estonian territory. This speed is much higher than in normal springs - about 8-10 days. The inversion of phenological phases was found in warm springs, especially for early phases such as the blossoming of *Coryllus avellana* and *Acer platanoides*. These phases have a low activating temperature and in the case of sunny days or warm air-masses the phases started in abnormal directions of dispersion and order. For very warm and early springs, the general geographical variations of the phenophases will be smoothed early. In the second half of June the entire Estonian territory will be in a homogeneous phenological phase without large geographical variations.

Years with a normal spring and weather conditions have the largest geographical differences phenologically. The blossoming of the tree species studied will start in the southern Estonian plains and will disperse throughout the country within 8-10 days. The differences between the coastal regions with a marine climate and the more continental inland regions are great; the phenological phases in Estonian uplands are decreased by about 1 day per 100 meters of absolute elevation. The geographical differences of the phenological aspects can be seen until first part of July. In normal years by the middle of July the entire Estonian territory is in same seasonal development.

The extremely cold and late springs in Estonia can be divided phenologically into two types. In the first case, caused by the domination of cold air-masses, the spatial differences are the smallest. The phenological development of nature will be slow in all geographical regions, both coastal and inland. Only in the middle of May will the higher solar activity create geographical differences between the regions. In the second case, caused by a cold winter and domination of high-pressure systems, the coastal areas with a more marine climate will remain cold longer and it will be cloudier due to the great temperature differences. The inland areas and uplands will be heated by solar radiation. Spring will start in the south-facing uplands and plains of Estonia. The differences of the blossoming dates of the studied tree species can be 15-20 days between the coastal and inland regions and these differences can be prolonged until the mid-summer. In some cases of cold springs, the different phenological aspects were present in Estonia until the beginning of August.

4. DISCUSSION

The analysis of the spatial and temporal differences of the phenological development of Estonian nature showed that the methods for such study must be specially selected for every geographical region and scale. The use of general mean values for the description of a specific region or season or year can be a cause for misunderstanding of the phenological processes and regularities (Gornik, 1994). The Estonian example is a good description of the need for such methodology - even on such a small and flat country like Estonia, there are great seasonal differences between regions and years with different weather (Karing, 1992). The general question concerns the principles of phenological regionalisation for the different levels and scales. The climatic and landscape regions do not describe all the phenological processes and homogeneous areas, especially in the case of years with very different weather (from the norm). The study of these years can reveal the reality of our seasonal processes - the differences are very large and there is no possibility of using one general mean. Professor Podolsky used a special system for estimating the different natural conditions and modeling the results (Podolsky, 1984). The phenological nomograms he created did describe a number of natural conditions.The problem is that if we would like to add more values to the phenological nomogram (like spatial dimensions), the model becomes too complicated.The next step in this area of research must be the connection of the phenological nomograms and the GIS system. From the point of view of phenology as applied science, the very difficult systems and models cannot be practical.The classical method of phenology - the estimation of phenological seasons and the study of phenological calendars together with climatic parameters provide the chance for the future development of phenology.This method provides a logical way to study phenological and climatological processes in parallel with statistical methods, GIS and satellite images (Elagin, 1983). The current problems with GIS studies in other sciences as in phenology is the sensitivity of choosing the right scale and study methods. Use of the wrong scale or methods in GIS can create very wrong results and misunderstandings.

5. CONCLUSIONS

The current study shows that the analysis of the spatial and temporal variations of phenological data is important for every level or scale of phenological study. The Estonian case study shows that the influence of the temperature regime of the Baltic Sea, the low uplands and other relief forms, as well as years with non-average weather will make it very difficult to determine general means and trends. For example, the speed of dispersion of the phenophases studied varied between 3-22 days for the 300 km of the total territory of Estonia. For the use of geographical information systems in the analysis of these processes, the selection of the right methods and scale is key. For future studies it is important to develop the methodology and principles for phenological regionalisation of the study area.The second important direction for future studies is the estimation of phenological and climatological seasons of the year and the study of the phenological calendars for every homogeneous region. This classical method of phenology, the study of phenological calendars, provides the possibility of analyzing climatological and phenological data concurrently. The analysis of phenological calendars will give new starting points for future works with GIS systems and the modeling of phenological processes. The field observation program in 1995 and 1996 showed that the studied phenophases, interpolated and analyzed with the GIS packet IDRISI do act similarly in real nature as in the cartogrammes. In future studies of the dispersion of the phenological phases it will be important to use special GIS program together with satellite images of studied phenological aspects.

6. REFERENCES

Elagin, I. N., 1983. Distantsionnaja fenologija. Nauka, Novosibirsk, p.12-17. *(in Russian)*

IDRISI. 1992. Version 4.0. Technical Reference. 213 p.

Gornik, W., 1994. Investigations into the Problems of Finding a Mean Value in Phenological Data Series. Arboreta Phaenologica, 47, p. 11-14.

Karing, P., 1992. Air temperature in Estonia. Tallinn, 78 p. *(in Estonian)*

Podolsky, A. S., 1983. New Phenology: Elements of Mathematical Forecasting in Ecology. John Wiley&Sons, p. 255-263.

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Impact of landscape features on phenological phases in transitional zone from maritime to continental climate types of Northern Europe.
Landscape Ecology. Submitted.

Landscape Ecology (Submitted)

Impact of landscape features on phenological phases in transitional zone from maritime to continental climate types of Northern Europe

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Abstract

We analysed the spatial distribution of the pollination of maple (*Acer platanoides* L.) and bird cherry (*Prunus padus* L.) in Estonia on the basis of data from time series for 1948-1996, in 22 observation points, and from the special field observation programme 1996-1999, in 46 observation points. Phenological maps show that these springtime phenophases spread in the landscape at a rate of 3-6 days per 100 km, with different rates in early and late springs. The maple has a steeper gradient on north-eastern islands and the bird cherry on the western islands; the values of standard deviation have a similar spatial pattern. The distribution of phenological phases in Estonia is influenced by differences between the temperature regimes of the Baltic sea and inland areas, different weather conditions in north-eastern Estonia, local altitude-impact of uplands with an absolute height of 150-300 m asl., and influences of bigger lakes and wetland areas. Three seasonally different landscape types can be determined in Estonia on the basis of spring phenology 1) Relatively continental South-East Estonian Plain and uplands - have the earliest spring with the smallest deviations and stable intervals between phases. 2) Central, western and northern Estonian plains - with temperate influence of the temperature regime of the Baltic Sea, and big variations from year to year. Large variability is caused by the presence and duration of ice cover on the sea in cold springs, and direct access for warm air masses in early springs. 3) North-East Estonia - has the most boreal climate with longer snow cover and very late spring, influenced by arctic air masses, local influence of the Baltic Sea, uplands, and large wetlands.

KEY WORDS: Phenological phases ·Estonia ·Landscape factors · Phenological maps· Climate change

1. Introduction

Spatial distribution of phenological phases and phenological differences between geographical locations are the result of ecological factors influencing the development of organisms or the physical environment. Those spatial differences have been the subject of phenological mapping throughout the history of phenology. The most interesting analyses of the spatial aspects and factors influencing the distribution of phenophases are defined by the bioclimatic law of Hopkins (1918). Hopkins defined the speed and direction of phenological phases for the Northern American plains with the help of different gradients, and analysed regularities. The analyses of phenological maps by Schnelle (1955 p.71-83) in Europe was a new step in the development of this theory. His work also had very good analyses of altitude and latitude gradients in European plains and mountain areas. In a book on seasonality, edited by Lieth (1974), different aspects of phenological mapping and computerised mapping on the basis of a wide network of ground observations were discussed. At the same time, the studies of the spatial diversity of phenological phases found a new source of quality with the organisation of the network of International Phenological Gardens (IPG) by F. Schnelle. These stations set very high methodological standards, as they use tree species of the same clone and trees with similar age and method of planting (Schnelle 1970).

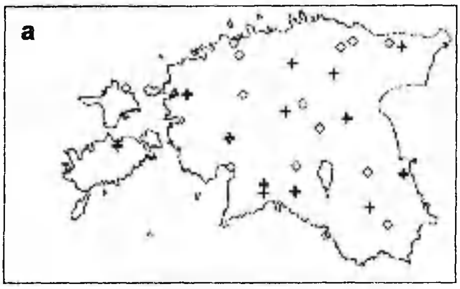

Figure 1. Location of Estonian pheno-logical observation series of 1948-96 used for time series analyses. Bold crosses – bird cherry, crosses - maple, quadrates – both species.

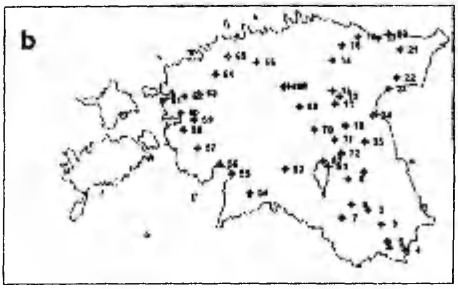

Figure 2. Location and numbers of field observation sites in Estonia.

At the same time, in the Soviet Union, regular observations of phenological parameters by a network of Agrimeteorological stations were begun. The phenological research in the USSR was co-ordinated and organised by the Geographical Society of the USSR (Schultz 1982), and good analyses of phenological maps for different areas, and methods for their composition (Hydrometorological Printing House 1965, Malosheva 1968) were published. The special theme of seasonal dynamics of landscapes is connected with the works of Georgian geographer Berutchashvili and his studies on modelling the seasonal dynamics of the Earth's landscapes, and with the theory of Stexes - seasonal development stages of landscape (Beruchashvili 1994). The calendar of nature of Switzerland has a different approach and density of data for landscape scale phenology, described with phenological calendars of geographical locations (Defila 1992).

The phenology of landscapes has been described in several of the studies mentioned above, and there are some studies in which the phenology of landscapes is a subject of special interest. Those studies describe movement of onset of phenological phases or "green wave" and model phenological events on landscapes using data of ground observations and remote sensing data sets (Schwartz 1997, White et al 1997). The "green wave phenology" became into heart of discussions of climate change during last years and this theme has relatively new approach on description of landscape scale changes in nature (Myneni et al 1997, Schwartz 1998). The distribution of phenological phases on landscape, speed and direction of it can indicate many aspects of local climate which is the result of climate-surface interaction. The study of spatial aspects of phenological phases in Estonia shows that there are different transition zones between continental and maritime

climate of Northern Europe which have very specific spatial pattern (Karing 1992, Jaagus 1997, Jaagus and Ahas 1998, Ahas 1999).
The main objective of the current study is to analyse following aspects ofthe spatial distribution of spring phenological phases in Estonia: 1) spatial pattern of phenological phases of common trees species; 2) direction and speed of the spread of phenological phases on the Estonian landscape; 3) spatial differences between different phenological phases and years. The second objective is to compare the spatial data of existing phenological databases and of neighbouring countries with the results of organised field observations.

2. Data and observation programme

The observation programme of landscape phenology was initiated by the respective working group in the autumn of 1995 and finished its work in the spring of 1999. The 46 observation points were located in continental Estonia (Figure 1). The objective of the observation programme was to study how the phenological phases are distributed, and how they move, in the landscape. Therefore, the observation programme has specific methodology and it does not describe many specific aspects of phenology. For example, the observers do not record dates of phenological phases, they only record the appearance of a phase or not in the observation point. The observation table standard included 6 development phases of 15 natural tree species for spring observations and 5 development phases of 8 natural tree species for autumn observations in Estonia. The observation sites were selected on the basis of the following parameters: visual distance from road (binoculars were used for observations) because of the tough timetable of observations; appearance of more than 2 adult species of studied tree species; exposition of observation site. The phases were determined according to the methodology of Agrimeteorological observations in Estonia, which is similar to that used previously in the whole of the Soviet Union. The observation sites differ from each other by type of landscape, soil, moisture, and ecosystem. In cases of very different types of ecosystems (wetland and forest) or landscapes (valley, plain, and hill) the observation sites were selected for the comparison of those different types. One weakness of the observations is that they were made irregularly, depending on when the observer had sufficient free time to carry them out. The phenological observations carried out by the author were made using a route system method. every year from 1995 to 1999 2 – 4 routes in spring were made.The route of the first day of observations had a length of 650 km for observation points 1-25 in eastern Estonia. The route of the second day, with a length of 630 km, was for observation points in western Estonia (points 51-72). The routes of the first and second days were observed in the same order throughout. The route method has some specific problems with timing, namely, the observation series are not made at one time. First day observations, 1-25, started at 7-9 a.m. and were finished at 6-7 p.m. Second day observations, points 51-72, were started 7-9 a.m and finished 6-8 p.m. Because the seasonal development of nature is very fast in the spring and autumn periods (after the equinox the length of day and night is changing fast) the observation data include some differences which happened in nature during the observation day or between the first and second days. It is complicated to eliminate or calculate, from the data, those differences between days, so they are included.

Especially big differences during one day and between two days can occur in the observation of spring phenophases on very hot and sunny days. For example, on 4.05.98 the weather was warm, and during the observation day the pollination of maple developed from the phase of "full bloom" to "end of bloom" in observation point 1, and during the second observation day (5.05.98) the bird cherry advanced to bloom. This speed of development was very fast and not normal. An example of a very slow and cold spring is the spring of 1999. Between two observation dates, on 27.04 and 14.05, the phenological phases did not develop at all.

The phenological data used were collected from different sources. Main time series of the studied tree species for 1948-1996 came from the Estonian Meteorological and Hydrological Institute (EMHI) (Figure 1). For the creation of phenological maps, additional data set from observation series of the Estonian Naturalists Society (ENS), for period of 1951 to 1996, was used. In the current study the two selected common tree species were maple (*Acer platanoides* L.) and bird cherry (*Prunus padus* L.). Of the studied phases of those species, the phases which were selected as common and most observed for all phenological data were: beginning of pollination (bloom) (1); full bloom (2); end of pollination (3). Numbers after phases is the code for data analysis, two more codes was used for marking phases before beginning of pollination - (0) and after end of pollination - (4).

For statistical analysis, data of 7 observation points (Table 1) of EMHI and ENS were selected on the basis of spatial diversity: Valga, Tartu, Pärnu, Saku (all EMHI) and Kärdla, Rakvere, Kohala (ENS), for period 1948-1996.

3. Methods

The interpolation of phenological data collected with a route method observation series had some specific aspects. As the map of observation sites (Figure 1) shows, siter locations are aligned on three main axes: North to South, East to West and Northwest to Southeast. This creates the need to use a special interpolation model for spatial interpolation of data. For interpolation of data from filed observations (Figure 9-14), the Surfer 5.01 was used, and the three interpolation ellipse model was used (Figure 2). The data was interpolated separately with every three ellipses and the mean value of all three interpolations was used for the design of maps of 50 rows and 45 columns. Parameters of the three interpolation ellips: 1) R_1=52000, R_2=152000, A= -45°; 2) R_1=52000, R_2=152000, A= 45°; 3) R_1=52000, R_2=152000, A= 90°.

The distance between the northernmost (No 20) and southernmost (No 4) observation points is 200 km, and between the westernmost (No 61) and easternmost (No 21), 220 km. Altitude of observation points is not calculated for interpolation. The Estonian landscape is relatively flat with some glaciogenic uplands. Highest observation points are: Haanja in the south-eastern part of Estonia (No 6), 260 m above sea level; Emumäe (No 12), 140 m. Other observation points are located at an average height of 30-70 m above sea level and the lowest are in Western Estonia (No 55-62) which are located below 30 m above sea level. But, it is known that even those small differences of elevation make a difference for all parameters of meso- and microclimate and phenological development (Jaagus 1997; Jaagus, and Ahas 1998).

For created maps of the results of the long time-series analyses, the statistics were calculated before interpolations. Because of good coverage with data, the maps of long time-series (Figure 3-8) were interpolated with one circle.

4. Results

4.1. Long time-series

For statistical analysis of the time series of maple (*Acer platanoides*) and bird cherry (*Prunus padus*), the 22 best quality data series from EMHI and ENS, over 48 years (1948-1996), were selected. Analyses of the pollination of maple and bird cherry in Estonia show relatively big spatial differences of phenological phases in the spring period. The statistical analyses of time series demonstrate that the mean beginning date of maple for whole 22 observation points was 11 May, and for bird cherry 18 May. Table 1 shows statistics of 7 geographically selected observation points of those 22

Table 1. Statistics of phenological phases of five selected observation sites in Estonia (for 1948-96)

Observ. site	Phase	average	min	max	stdevp
Valga	Maple	9-May	25-Apr	22-May	5.8
Tartu	"	10-May	23-Apr	28-May	7.4
Pärnu	"	12-May	26-Apr	8-Jun	7.7
Kärdla	"	13-May	23-Apr	1-Jun	7.5
Saku	"	13-May	24-Apr	4-Jun	7.1
Rakvere	"	10-May	19-Apr	1-Jun	7.7
Valga	Bird cherry	16-May	26-Apr	4-Jun	7.2
Tartu	"	17-May	28-Apr	6-Jun	7.3
Pärnu	"	19-May	30-Apr	8-Jun	7.2
Kärdla	"	24-May	4-May	14-Jun	7.3
Saku	"	22-May	30-Apr	11-Jun	7.8
Rakvere*	"	20-May	30-Apr	9-Jun	7.3

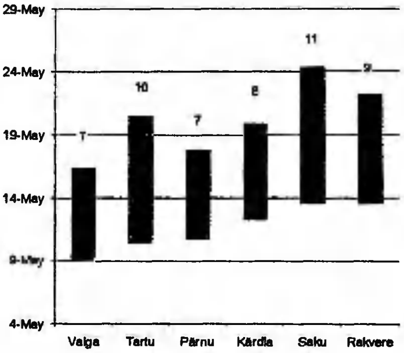

Figure 3. Intervals between onset of pollination of maple and bird cherry in five selected observation sites in Estonia

The phenological maps of the studied time-series illustrate differences between the spatial pattern of studied species (Figure 3). Maple is advancing to full bloom in southern Estonia (Valga, Polli, Võru), while in Western and Eastern Estonia it does so 3 days later and is even later in North-Eastern Estonia, with observation points of Jõhvi and Roodu. Bird cherry is advancing to full bloom one week after maple with the earliest date in southern and south-eastern Estonia, developing in a north-westerly direction, with latest dates on the Western islands.

The standard deviations of time series are very homogeneous, between 7.1 and 7.7 days, except the beginning of pollination of maple in Valga with 5,8 days. The spatial distribution of standard deviations is shown on the map of mean values for maple and bird cherry (Figure 4). Like the beginning dates of phases, the spatial distribution of

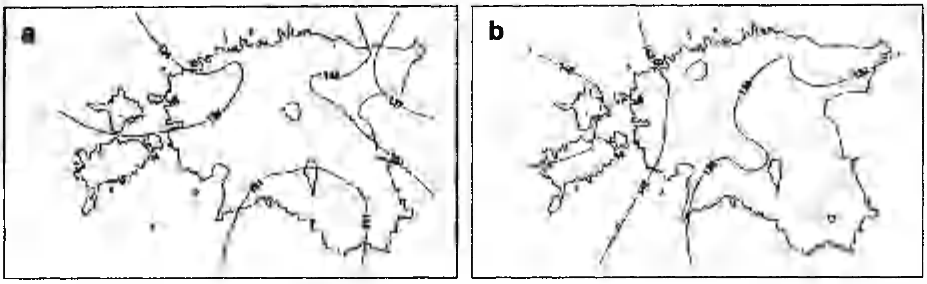

Figure 3. Mean onset of pollination of maple (a) and bird cherry (b) in Estonia. (Julian days transformed into calendar dates 130 = 30 Apr, 140 = 20 May).

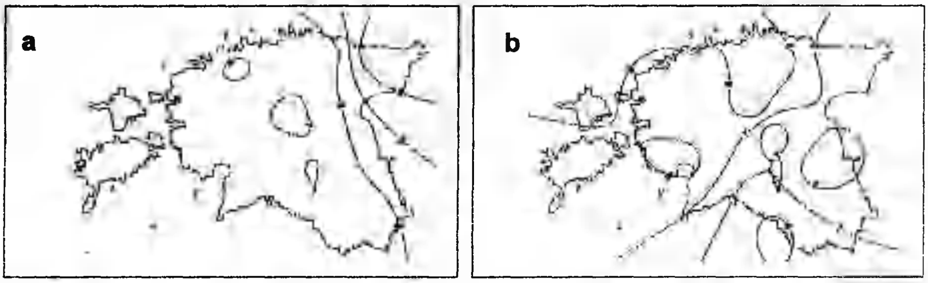

Figure 4. Standard deviations (number of days) of pollination of maple (a) and bird cherry (b) in Estonia.

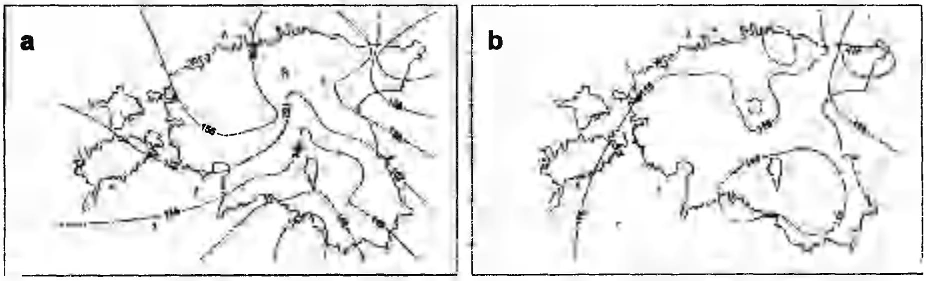

Figure 5. Onset of pollination of maple: a) max year - 1955 and b) min year - 1990. (Julian days transformed into calendar dates 110 = 10 Apr, 120 = 20 Apr, 130 = 30 Apr, 140 = 20 May, 150 = 30 May).

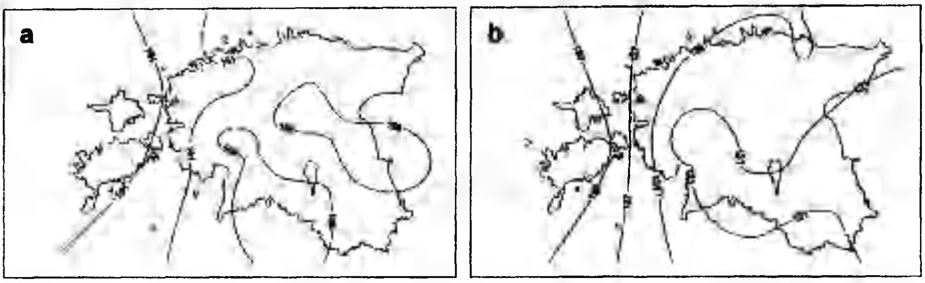

Figure 6. Onset of pollination of bird cherry: a) max year - 1955 and b) min year -1990. (Julian days transformed into calendar dates 120 = 20 Apr, 130 = 30 Apr, 140 = 20 May, 150 = 30 May, 160 = 10 June).

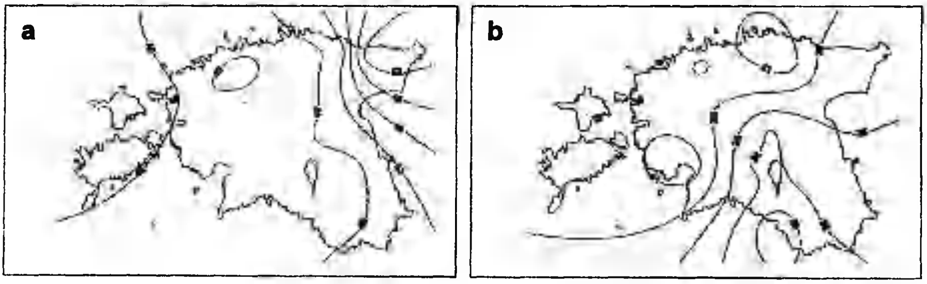

Figure 7. Differences between minimum and maximum dates in days for maple (a) and bird cherry (b).

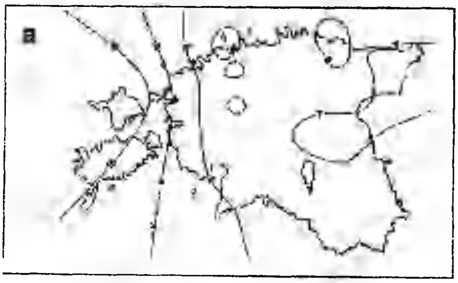

Figure 8. Mean interval between onset of pollination of maple and bird cherry in days.

standard deviations has its specific pattern. The standard deviations of maple rise from west to east (north-east) and bird cherry from south to north-east.

The absolute minimum and maximum values of the studied time-series show that those values are relatively high, 38 days on average and with the largest value, of 52 days, for maple in north-east Estonia. The absolute minimum year for most observation points is 1990 and the maximum 1955. During the extreme years the differences in the distribution of phenological phases of maple are not very big; the latest date is still in the north-east of Estonia (Figure 5). Very early years exhibit fast development of phases for all territory that is connected with the strong influence of warm air masses. The "pollination of maple" is a phenomenon of the first hot and sunny days. The extreme values of "pollination of bird cherry" show that in early and late years the distribution of phases is influenced by the temperature of the Baltic Sea and proceeds from east to west, with an especially high gradient for the western islands (Figure 6).

Mean intervals between min and max values demonstrate that the studied phenological phases can start up to 3 weeks earlier or later in extreme years. Intervals between early (1990) and late (1955) years are mapped in Figure 7. For maple, this interval grows towards the north-east, and for bird cherry, from south to north. The interval between phases of maple and bird cherry is very stable at 7-11 days, with a mean value of 9 days. The interval is growing from the south-eastern mainland (Valga, Tartu) to the north-east (Rakvere and Kohala) and islands (Kärdla, Karja) (Table 1). A similar effect is shown on a map of mean intervals, which has a strong gradient on the islands because of the very late dates for bird cherry (Figure 8).

4.2. Field studies

The methodology of field studies was oriented to get maximum results on the spatial distribution of phenophases. Therefore we do not have exact beginning dates for observation points. We have analysed the value of "appearance of phenological phase" in certain observation points.

Phenological maps of field observations shows a big similarity between the distribution of phenological phases of both studied species. The beginning of pollination starts in the southern and south-eastern part of Estonia, progressing towards the north-west. The latest area of the appearance is north-eastern Estonia. The difference between maple and bird cherry lies mainly in the speed and direction of development of phenophases. Onset of pollination of maple has very fast development over Estonia and advances more towards the north east. Pollination of bird cherry advances less rapidly, direction of development of the phase is more influenced by the Baltic Sea and therefore has a north-western direction.

The spatial pattern for the onset of pollination of maple is described with the average for the whole study period (Figure 9 a) and with the average for the spring of 1998 (Figure 9 b). The density of isolines on the map of mean values is low, but the direction of phenophases is described well with this line. Figures 10 a and 10 b show the development of phases in a very slow spring in 1999. The first observation (Figure 10 a) shows local diversity of landscapes and exposition in southern Estonia and a very sharp border in the middle of continental Estonia. The second observation (Figure 10 b), after 2 weeks,

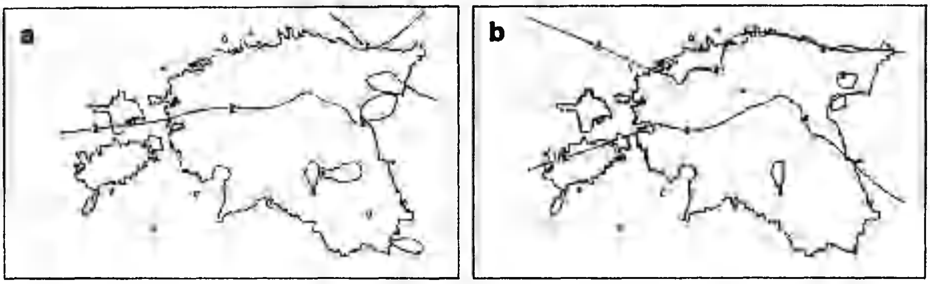

Figure 9. **Onset of pollination of maple: a) mean for all observations on 1996-99 and b) mean for 1998. Appearance of phases: 0 - not started; 1 - beginning of pollination; 2 - full bloom, 3 - end of pollination, 4 - phases finished.**

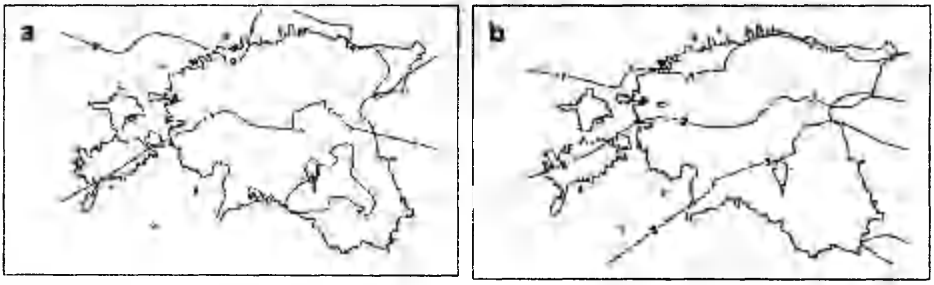

Figure 10. **Onset of pollination of maple: a) 27 Apr 1999 and b) 14 May 1999. (List of phases see Figure 9).**

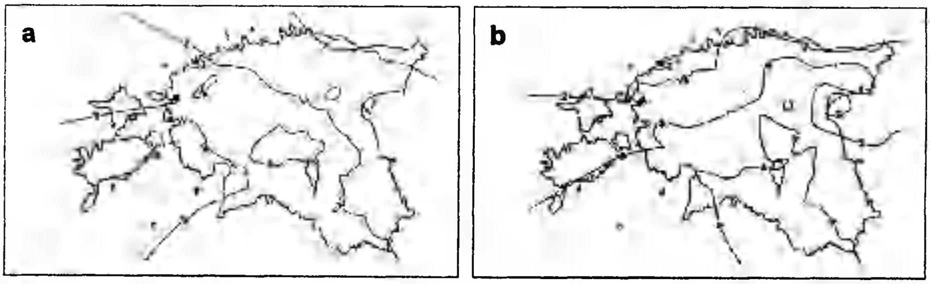

Figure 11. **Onset of pollination of maple: a) 4 May 1998 and b) 13 May 1998. (List of phases see Figure 9).**

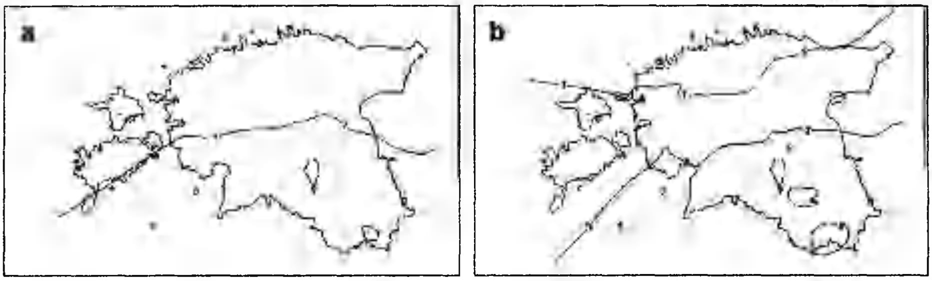

Figure 12. Onset of pollination of bird cherry: a) mean for all observations on 1996-1999 and b) mean for 1998. (List of phases see Figure 9).

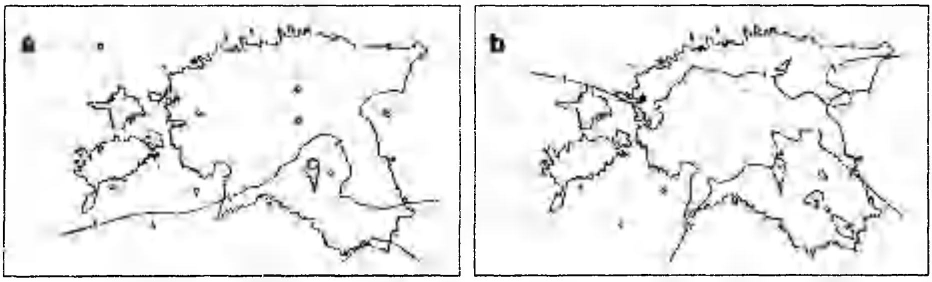

Figure 13. Onset of pollination of bird cherry: a) 13 May 1996 and b) 21 may 1996. (List of phases see Figure 9).

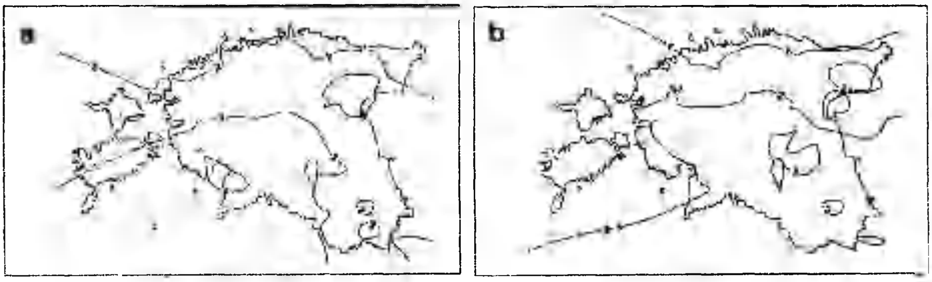

Figure 14. Onset of pollination of bird cherry: a) 4. June 1997 and b) 13 May 1998. (List of phases see Figure 9).

shows that in the conditions of an unusually cold and sunny spring the onset of phases progresses very slowly and has a very high local micro-scale diversity according to exposition and ecosystem. The spring of 1998 was warm and the development of the onset of pollination of the maple was fast (Figure 11 a and 11 b). The direction of progress of the phase was to the north-east, which is typical for maple. The phase developed during 10 days across all of continental Estonia, which is the mean for phenophases of this period studied from database.

Onset of pollination of bird cherry is a very impressive phenological phase in the Estonian landscape, and therefore it has many observation series. The mean map of all observations and the mean for 1998 (Figure 12 a and 12 b) show that this phase, with its north direction and two spatial isolines for the mean of 1998 spring, is similar to maple. The phenological maps of 1996 spring (Figure 13 a and b) shows moving of the onset of this phase towards the north with the relatively strong influence of the cold Baltic Sea and Lake Peipsi in Eastern Estonia. The influence of the sea is seen on the map of phase onsets of 1998 (Figure 14 b) and was mentioned in the study of time series (Figure 7 a and b). Figures 14 a and b show different development stages of phases in 1997 and 1998. On those maps we can see the influence of the Southern Estonian Uplands, Central Estonian Wetlands, and the local impact of Lake Peipsi in Eastern Estonia.

5. Discussion

5.1. Observations of phenological phases

The most abrupt step in phenophases and changing seasonal aspects was recorded, on most observation trips, on the way from Tartu to Rakvere, between observation points 10-13. Those points are located on the borderline between the South-East Estonian Plain (one of the earliest places) and Pandivere Upland (latest). There is very great contrast in the natural landscape and across the climatic barrier. The strongest local influence was observed along the coastline of Lake Peipsi at observation points No 23 and 24. The influence of the cold lake was discernible all the time but on a very local scale, up to 1-2 km from shoreline. The local influence of Lake Peipsi was also analysed in a study of phenological phases of ENS (Ahas 1999) and in the pattern of snow cover (Jaagus and Ahas 1998). The biggest influence of altitude was observed in observation points 5 and 6 at a height of 230 and 260 m on Haanja Upland (highest point 318 m), which is the highest landscape form in the Baltic region. The influence of elevation was distinguishable for early spring, when those relatively small influences of altitude have big effect on snow cover and land frost (Jaagus 1997). In spring when the value of temperatures is close to 0° C the difference of few degrees makes big differences on melting of snow and surface. As result of this the relatively big regional difference occur even in latitudes of 100 - 300 meters of absolute height. After melting of the snow cover and ground the relatively big local differences of microclimate and phenology will be smoothed down because especial exposition regime and better moisture regime of those uplands.

Of special interest for the study, were the big wetland areas that play an important roll in forming local meso- and microclimate. The most recognisable were the differences for wetland and forest areas of Central Estonia. Special observation points (66-69) were defined for the study of these local influences. As the results of field studies and database analyses show, this landscape region has a different seasonal rhythm. Those observation points are under the influence of the inertia of the cold spring period during middle of June. The local differences on the North Estonian Glint were studied in observation points Nos. 18 and 20, where the deep landscape barrier of the glint changes the microclimate and vegetation under and on it. The water temperature and airflow of the Gulf of Finland directly influence the area located under the glint.

5.2. Spatial pattern of extreme years

The spatial distribution of phenological phases differs from year to year. The analyses of mean values do not describe all aspects of seasonality in particular years or extreme years. Therefore the maps of phenological phases of normal, minimum, and maximum years is shown on Figure 7. The maps show spatial differences between min 1990 and max 1955 spring. These studies show the change of the direction of phenological phases changes. In early years the onset of the pollination of maple (e.g. 1990) is spreading very fast across Estonia, within two days with little delay for north-eastern Estonia. Similarly the onset of the blossoming of bird cherry is very fast in early springs, but the direction of the advance of phases is shifting towards the western islands. The pattern of distribution of phenological phases for early and late years is analysed in a study of Finnish phenological time series (Lappalainen 1994). In this study Lappalainen (1994) is discussing differences between early, late and mean years. The species studied had different patterns of phenophases. For example, for onset of pollination of bird cherry in Finland the local influence of lakes is strong in early springs, and the pollination of birch is very strongly influenced by the Baltic Sea in early springs (Lappalainen 1994). The changes of length of vegetation period and intervals between phases can show even more important trends of natural processes (Menzel and Fabian 1999). The length between studied phases of maple and bird cherry show that there is relatively big difference of distribution of those phases (Figure 8). The big gradient in Western Islands is result of impact of the Baltic Sea on bird cherry.

5.3. Phenology of landscapes

The study of the phenology of maple and bird cherry shows that the distribution (speed, direction) of a phenological phase has its regular and irregular aspects which we can measure and analyse like other variables. In Estonian landscapes the influence of altitude, latitude and territorial factors is very small and it is difficult to record it. The only stronger influence is a spring and summertime gradient in an east-west direction caused by the difference between the temperature of the Baltic Sea and the Russian Plain, and some direct impact from cyclonic activity from the Atlantic. For the study of those differences in Estonia, it is important to analyse differences between local factors and processes influenced on a larger scale.

The comparison of phenological maps of Europe and the Russian Plain shows differences and similarities of direction and speed of phenological phases (Schnelle 1955; Hydrometorological Printing House 1965). Those phenological maps of Central and

Eastern Europe show that development of phases has a general direction from south-west to north-east, with small variations for different phases. The Estonian phenological maps demonstrate the same tendencies, only the local influence of the Baltic Sea is changing the direction of phases to the north-west, with latest dates on the islands. Lappalainen (1994) mapped phenological phases of Finland for 1818-1955. Those maps show that the spatial pattern of bird cherry in Finland is similar to that in Estonia (Lappalainen 1994, p. 112). There is a possibility to verify and discuss the theory of phenological regions of Central Europe made on the basis of phenological mapping of the vegetation period (Schnelle 1955, 158-165, Appendix: Map 4). By this theory Estonia lies in the region of the intersection of three different types of seasonality in the northern part of Central Europe, and analyses of phenological maps in the current study show that there are similar types of seasonal patterns in Estonia (Figure 3-9). The first type of seasonality has the earliest beginning-dates with relatively continental climate and longer growing season, in South-East Estonia. Schnelle defined this region as having a beginning date of spring after 20. May and a growing season length of up to 80 days. The next type of seasonality is described for Central and West Estonia, with a bigger inertia from the temperature regime of the Baltic Sea, long and cold spring and warm autumn. Schnelle (1955) defined this region as having a growing season length of up to 70 days and with a beginning date of spring after 20 May. The last region is North and especially North East Estonia which has a very different phenological rhythm. The influence of northern air masses retards the onset of spring and advances the onset of autumn and winter compared to other parts of Estonia. At the same time the growing season is shortest in Estonia. As a result of climatic influences there is a majority of boreal ecosystems in this region. Schnelle (1955) describes this type of seasonality for all of northern Estonia, the phenological analyses of this study show that this region may be the north eastern part of Estonia, since most of northern and north western Estonia is more influenced by the soft climate of the Baltic Sea.

6 Conclusions

The spatial distribution of the pollination of maple (*Acer platanoides*) and bird cherry (*Prunus padus*) was analysed in Estonia on the basis of long time-series, in 22 observation points, and the special field observation programme, in 46 observation points.

1) Rate of spread of phenological phases is very different in early and late years. Phenological maps show that the mean value of the rate of distribution of the springtime phenophases is 3-6 days per 100 km in relatively plain Estonia. In very early years the phenological phases move very fast, except for the western islands.

2) Direction of the onset of phenological phases is generally from south to north. The onset of maple phases is gradually directed more towards the north east and bird cherry towards the north west of Estonia. The main factors influencing the direction of phenophases are the temperature of the Baltic Sea, local influence of relief, and bigger lakes and wetland areas.

3) Landscape forms have the biggest influence in the Pandivere Upland, at a height of 100-140 m, and the Haanja Upland, at a height of 230 and 260 m. The influence of elevation was distinguishable for early spring, when the relatively small effects of altitude have big effect on snow cover and land ground frost. In spring, when the value of temperatures is

close to 0 C a difference of a few degrees causes a big differences in the melting of snow and the thawing of the ground surface. After the melting of the snow cover and thawing of the ground, the relatively big local differences in microclimate and phenology will be smoothed out because of the special exposition regime and better moisture regime of the uplands.

4) The three, seasonally different, landscape types can be determined in Estonia by spring phenology. 1) The relatively continental South-East Estonian Plain and uplands have the earliest spring with smallest deviations and stabile intervals between phases. 2) Central, western and northern Estonian plains with temperate influence of temperature regime of Baltic Sea and big variations from year to year. Big variability is caused by presence and duration of ice cover of sea on cold springs and direct access of warm air masses on early springs. 3) North-East of Estonia has most boreal climate with longer snow cover and very late spring influenced by arctic air masses, local influence of Baltic Sea, uplands and large wetlands.

References

Ahas. R., 1999. Long-term phyto-, ornitho-, and icthyophenological time-series analyses in Estonia. International Journal of Biometeorology 42:119-123.

Beruchashvili, N.L. 1994. Seasonal dynamics of landscapes of the Earht. Communications of Russian Academy Sciences , 6:24-40.(in Russian).

Defila, C., 1992. Pzlanzenphänologische Kalender ausgewählter Stationen in der Schweiz / Calendriers phytophänologiques en Suisse 1951-1990. Beiheft zu den Annalen der Schweizerischen Meteorologischen Anstalt.

Hopkins, A.D. 1918. Periodical events and natural law as guides to agricultural research and practice. Monthly Weather Review Supplement No. 9. Washington D.C. pp 5-41.

Hydrometorological Printing House 1965. Natural calenders of North Western USSR. Geographical Society of USSR, Leningrad, Hydrometorological Printing House. (In Russian).

Jaagus, J. 1997. The impact of climate change on the snow cover pattern in Estonia. Climatic change 36:65-77.

Jaagus, J. and Ahas, R. 1998. Spatial differences in climatic seasons in Estonia and their influence on phenological development of nature. 2nd European Conference on Applied Climatology 19 to 23 October 1998, Vienna, Austria. Österreichische Beiträge zu Meteorologie und Geophysik, 19. Zentralanstalt für Meteorologie und Geodynamik, Wien. ISSN 1016-6254.

Karing, P. 1992. Air temperature in Estonia, Tallinn, 78 p. (in Estonian).

Lappalainen, H. 1994. Examples of plant phenological events in Finland and their relation to temperature. Memoranda Soc. Fauna Flora Fennica 70:105-121.

Lieth, H. 1974. Purposes of phenology book. In: Lieth, H. (ed), Phenology and seasonality modeling. Ecological Studies 8, Springer-Verlag, New-York, p 3-19 .

Malosheva, T.C. 1968. Methodological manual for composition of phenological maps. Leningrad. 59 p. (In Russian).

Menzel, A., Fabian, P. 1999. Growing season extended in Europe. Nature 397:659.

Myneni, R.B., Keeling, C.D., Tucker, C.J., Asar, G., Nemani, R.R., 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. Nature 386:698-702.

Schnelle, F. 1955. Pflanzenphänologie. Probleme der Bioklimatologie 3 Akademische Verlagsgesellschaft, Leipzig 299 p.

Schnelle, F. 1970 Beiträge zur Phänologie Europas II. 4 Mittelwertskarten. Gesamtvegetationszeit und 3 Vegetationsabschnitte Berichte des Deutschen Wetterdienstes, Nr. 18.

Schultz, G. E. 1982. Geographische Phänologie in der UdSSR. Wetter und Leben 34:160-168. (in German).

Schwartz, M.D. 1994. Monitoring global change with phenology: the case of spring green wave. Int. J. Biometeorol 38:18-22.

Schwartz, M. D. 1997. Spring Index Models: An Approach to Connecting Satellite and Surface Phenology. In: Lieth, H. and Schwartz, M. D. (eds) Phenology of Seasonal Climates, Backhuys Leiden. pp 23-38.

Schwartz MD 1998. Green-wave phenology. Nature 394:839-840.

White, M.A., Thorton, P.E., Running, S.W. 1997. A continental phenology model for monitoring vegetation responses to interannual climatic variability. Global Biogeochemical Cycles 11 No 2, 217-235.

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Jaagus, J. and Ahas, R. 1998.
Spatial differences in climatic seasons in Estonia and their influence
on phenological development of nature. 2nd European Conference on Applied
Climatology 19 to 23 October 1998,
Vienna, Austria. Österreichische Beiträge zu Meteorologie und
Geophysik, 19. Zentralanstalt für Meteorologie und Geodynamik,
Wien. ISSN 1016-6254, 6 pp.

Spatial differences in climatic seasons in Estonia and their influence on phenological development of nature

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Introduction

Climate in boreal zone is characterised by a marked seasonality, alternation of hot and cold seasons. Regularities in seasonal development of nature are one of the most important climatic factors influencing on the vegetable and the animal kingdom as well as on human activity. To study the seasonality more carefully, it is necessary to use a term of climatic season. It can be defined as an independent stage in the annual cycle of the climatic component of the geographic environment. Every season has its specific complex of weather types, atmospheric circulation, direction of weather changes etc. In reality, seasons begin every year at different time depending on weather conditions. The main characteristics of climatic seasons are their beginning date and duration.

Estonia is located between 57.5°N and 59.5°N on the eastern coast of the Baltic Sea. Despite of its small area there are observed remarkable climatic differences. The western part of Estonia lies under the direct influence of the sea while in the central and eastern parts climate is gradually changing to more continental. The main objective of this study is to estimate spatial variability in parameters of climatic seasons in Estonia and to determine its influence on pattern of phenological development of nature.

Definition of climatic seasons

Eight climatic seasons are distinguished in Estonia (Raik, 1963; Jaagus, 1996). In addition to the four main seasons - spring, summer, autumn and winter - two intermediate seasons between autumn and winter (late autumn, early winter), and two ones between winter and spring (late winter, early spring) are described.

Climatic seasons of the warm half-year are determined according to the course of diurnal mean air temperature. *Spring* begins after the permanent increase of diurnal mean air temperature above +5°C that means the start of vegetation period. *Summer* corresponds to a period where diurnal mean air temperature is permanently higher than +13°C. It is a favourable period for cultivation of termophilic plants. *Autumn* begins after permanent drop of diurnal mean air temperature below +13°C, and *late autumn* - after its permanent drop below +5°C.

Snow cover is the main factor determining climatic seasons during the cold half-year. *Early winter* starts after the first formation of snow cover. It embraces the period with unstable snow cover). *Winter* itself begins after the formation of permanent snow cover. *Late winter* is a period of snow melting in spring. *Early spring* begins after final disappearing of snow cover.

Data sources and methods

Beginning date and duration of the climatic seasons at 19 stations during 1946-1997 are determined strictly following the criteria. In addition, data from four other stations having shorter observation series are included into analysis of spatial variability.

These series are extended using data from neighbouring stations with the highest correlation.

Phenological database consists of observation data obtained from the Estonian Naturalists Society (1951-1996) and the Estonian Meteorological and Hydrological Institute (1947-1996). In this study, there are used the times series having the best quality and spatial coverage: the *beginning of blossoming of four tree species*, and the *stalk formation, ear and pollination of autumn sown rye* in 19 observation points in Estonia.

The main descriptive statistics are calculated for every station. Correlation between stations is analysed. Maps of these statistics are drawn. Beginning date and duration of the climatic seasons is correlated with a number of phenological parameters.

Territorial analysis of climatic and phenological data are realised in two ways. At first, beginning dates of climatic seasons and phenophases are correlated using observation data from single stations. Then, due to a certain irregularity of phenological network, IDRISI raster images of climatic and phenological parameters are generated. Correlation and regression analysis between time series of the images has been made using the earlier elaborated methodology (Jaagus, 1997).

Spatial variability of beginning dates and duration of the climatic seasons

Results of statistical analysis demonstrate a significant spatial variability in parameters of climatic seasons in Estonia. Mean beginning dates of climatic seasons in averaged by the 23 stations during the 52-year observation period are presented in the first row of the Table 1. Mean values averaged by six different climatic regions in Estonia as well as extreme values, their difference (range) and standard deviations are presented below. The same characteristics for duration of the climatic seasons can be found from Table 2.

It is obvious that there are two main factors influencing on the pattern of parameters of climatic seasons in Estonia. The first one is latitude and the second one is the Baltic Sea. In the southern parts of Estonia climatic seasons in spring period begin up to 6-8 days earlier, and in autumn period - later than in the northern parts. Cooling in autumn starts from the inland parts of North Estonia but differences in south-north direction are less than during spring period. Due to the thermal inertia of the sea beginning of the seasons in the coastal areas is shifted to the later time.

The north-eastern part of Estonia has the coldest climate. Warming in spring occurs the most slowly and cooling in autumn - the most rapidly. Mean duration of the winter season is up to 40 days longer than in West Estonian Archipelago. South-east Estonia is characterised by the earliest beginning of spring and summer. Coastal areas of Estonia have quite different climatic conditions. The coldest ones are, of course, typical for the northern coast, the coast of the Gulf of Finland. Spring and summer start especially late there. South-western coast (Gulf of Riga) has the longest summer season in Estonia. Climate on the West Estonian Archipelago is the most maritime and very much different from the other parts of Estonia.

The highest spatial variability of beginning dates of the climatic seasons is observed in case of summer and winter seasons (Fig. 1-2). Mean ranges of spatial differences are 17 and 40 days, correspondingly. These maps demonstrate very clearly the direction of moving and arriving of climatic seasons. The beginning of summer moves from south-east to north-west while the beginning of winter moves from north-east to south-west.

The most remarkable territorial inhomogeneities are caused by the thermal influence of the Baltic Sea. On the islands of West-Estonian Archipelago, autumn begins 1-2 weeks later, late autumn - 1.5-2.5 weeks, early winter - 1.5-3 weeks and winter - 2-4.5 weeks later than in East Estonia. The highest values are obtained from stations located on the western coast of the islands that are under the influence of the central ice-free part of the sea during the whole winter. Therefore, late winter begins 5-8 days earlier. But warming in spring is much slower due to the influence of cold water in the sea. For example, summer begins up to 17 days later than in the continental Estonia.

Standard deviation in Tables 1-2 illustrates temporal variability of parameters of climatic seasons. The highest temporal variability is typical for seasons of cold half-year. Snow cover amount varies from year to year very much. The most stable are beginning dates of spring and autumn.

Table 1. Mean and extreme values, ranges and standard deviations of average beginning dates of climatic seasons in Estonia during 1946-1997

	Late winter	Early spring	Spring	Summer	Autumn	Late autumn	Early winter	Winter
Estonia	**2-Mar**	**4-Apr**	**24-Apr**	**4-Jun**	5-Sep	**27-Oct**	**14-Nov**	**21-Dec**
SE-Estonia	1-Mar	3-Apr	20-Apr	29-May	4-Sep	23-Oct	10-Nov	14-Dec
NO-Estonia	5-Mar	8-Apr	23-Apr	2-Jun	31-Aug	21-Oct	8-Nov	5-Dec
N-coast	2-Mar	5-Apr	26-Apr	7-Jun	5-Sep	26-Oct	13-Nov	24-Dec
Central	3-Mar	6-Apr	22-Apr	1-Jun	1-Sep	22-Oct	10-Nov	14-Dec
SW-coast	2-Mar	3-Apr	25-Apr	2-Jun	11-Sep	1-Nov	17-Nov	27-Dec
W-islands	28-Feb	30-Mar	28-Apr	11-Jun	13-Sep	5-Nov	24-Nov	7-Jan
Earliest	26-Feb	27-Mar	20-Apr	27-May	30-Aug	20-Oct	7-Nov	2-Dec
Latest	7-Mar	10-Apr	30-Apr	13-Jun	14-Sep	7-Nov	29-Nov	11-Jan
Range	10	15	10	17	15	18	22	40
St. deviation	23.8	14.0	8.1	12.7	9.2	11.6	14.0	25.3

Table 2. Mean and extreme values, ranges and standard deviations of average duration (in days) of climatic seasons in Estonia during 1946-1997

	Late winter	Early spring	Spring	Summer	Autumn	Late autumn	Early winter	Winter
Estonia	33	**20**	**41**	**93**	**51**	**18**	**37**	**72**
SE-Estonia	32	17	39	98	49	18	34	79
NO-Estonia	34	14	41	90	50	18	27	91
N-coast	34	21	42	90	52	18	41	69
Central	34	15	41	92	51	19	34	80
SW-coast	32	23	38	101	51	16	41	65
W-islands	31	29	44	94	54	19	44	52
Earliest	29	12	37	85	49	14	23	46
Latest	36	32	47	102	55	23	47	96
Range	6	21	10	17	6	9	24	50
St. deviation	20.1	13.5	14.5	15.6	14.7	12.7	27.8	30.6

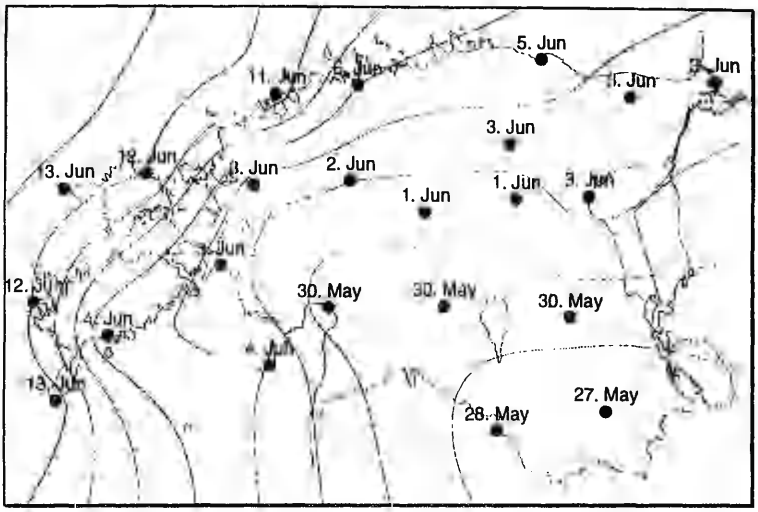

Fig. 1. Mean beginning date of summer in Estonia during the period 1946-1997

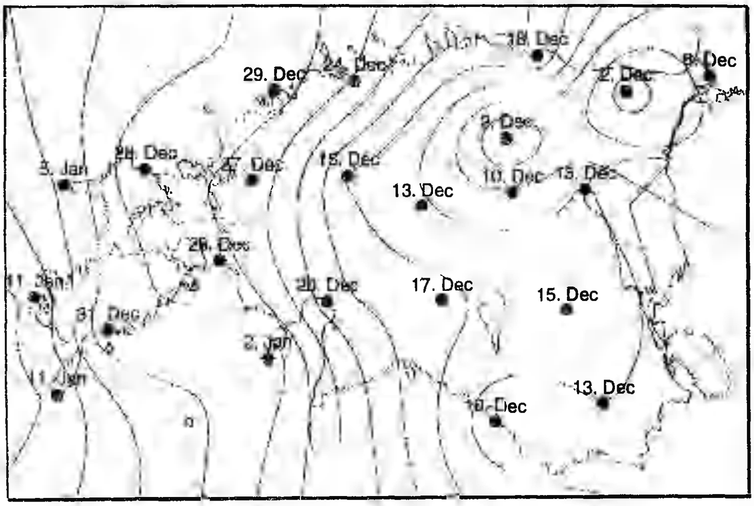

Fig. 2. Mean beginning date of winter in Estonia during the period 1946-1997

Spatial variability of phenological development of nature

Pattern of beginning dates of the climatic seasons in Estonia reflects very clearly spatial differences in seasonal development of nature, especially in spring. Table 3 presents the same statistics, as in Tables 1-2, for studied phenological phases observed during the period 1952-1995 in 19 observation points averaged by the same six climatic regions in Estonia. The analysis of spatial variability of phenophases demonstrated substantial differences between regions of maritime and continental climate in Estonia. The highest temporal variability in phenological data is typical for the coastal regions (W-islands, SW-coast and N-coast). Mean values of standard deviation of the studied phenophases varies from 7 days in inland up to 12 days on the western islands. Time intervals between the blossoming and leaf formation of the tree species, and between single phases of autumn sown rye in the coastal region is 35% longer, in the average, than in the inland regions.

The large temporal variability in the coastal regions is generally connected with temperature regime and ice cover of the Baltic Sea. In the case of a cold winter and stable ice cover, the following spring starts very late. But continental areas warm up faster and spring arrives much earlier. In case of warm winter and very early climatic spring (winter without sea-ice), the phenological spring, especially blossoming of *Corylus avellana* and *Acer platanoides*, starts in the coastal regions even earlier than in continental area.

Table 3. Mean and extreme values, ranges and standard deviations of average beginning of phenological phases studied for 1952-1995.

	Hazel (*Corylus avellana)* pollination	Winter sown rye stalk form.	Winter sown rye ear	Winter sown rye pollination	Maple *(Acer platanoides)* pollination	Bird cherry *(Prunus padus)* pollination	Rowan *(Sorbus aucuparia)* pollination
Estonia	**11. Apr**	**2. May**	**4. Jun**	**19. Jun**	**12. May**	**19. May**	**3. Jun**
SE-Estonia	10. Apr	27. Apr	2. Jun	16. Jun	9. May	14. May	28. May
NO-Estonia	15. Apr	6. May	4. Jun	22. Jun	14. May	21. May	6. Jun
N-coast	12. Apr	8. May	7. Jun	22. Jun	14. May	21. May	6. Jun
Central	12. Apr	5. May	4. Jun	21. Jun	12. May	17. May	4. Jun
SW-coast	10. Apr	1. May	5. Jun	19. Jun	12. May	21. May	1. Jun
W-islands	8. Apr	30. Apr	4. Jun	18. Jun	16. May	24. May	8. Jun
Earliest	12. Mar	14. Apr	24. May	8. Jun	24. Apr	2. May	19. May
Latest	30. Apr	17. May	16. Jun	26. Jun	20. May	26. May	14. Jun
Range	49	33	23	18	26	24	26
St. deviation	20.4	11.6	9.8	11.5	13.7	12.3	14.7

The beginning of phenological phases in spring spreads from south-east to north-west (Fig. 3). It is caused by the local cooling effect of the sea in coastal regions. The general direction of the *green wave* (beginning of spring) in Estonia is different from the all-European trend from south-west to north-east (Kramer, 1996). Different scale of study area and the influence of the Baltic Sea can explain it. The rate of progression of the early spring phenophases (flowering of the *Corylus avellana* and *Acer platanoides*) is faster (4-8 days for 300 km) than that of the later phenophases (10-15 days for 300 km in case of autumn sown rye, *Prunus padus* and *Sorbus aucuparia*).

Regional differences of the phenological data are influenced also by landscape inhomogeneities, such as uplands with 100-300 m of absolute elevation. They change the normal distribution of the phenophases (Ahas, 1996). The average inhibition of the blossoming dates studied is about 1 day per 100 meters of absolute elevation. Pandivere upland in North Estonia is the coldest region where spring phenophases are observed in the latest time, and where autumn begins earlier than in the rest of the country.

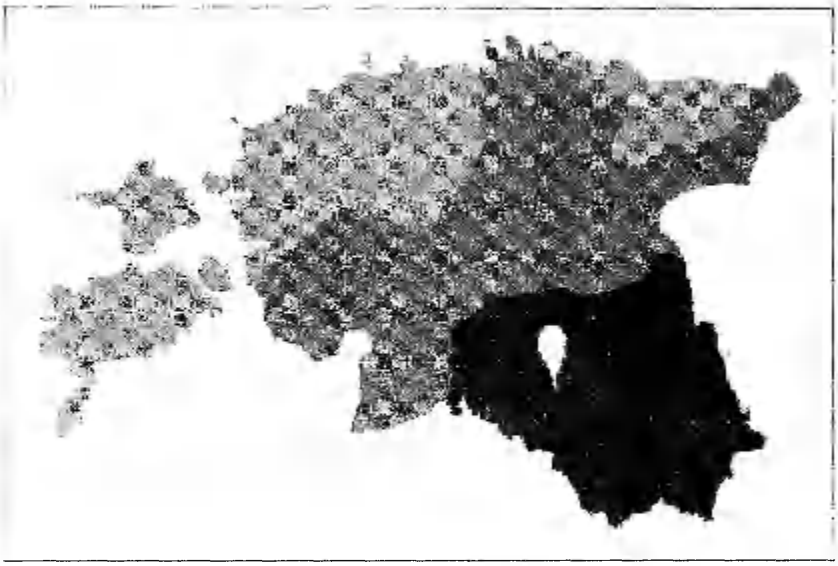

Fig 3. Mean beginning of blossoming of five tree species studied (1951–1996). Scale unit: three days.

Correlation between climatic seasons and phenological phases

Preliminary results of territorial correlation and regression analysis indicate a significant relationship between beginning dates of climatic seasons and phenological development of nature. Among the climatic seasons the highest correlation is characteristic for the beginning of early spring and summer. A dense correlation exists between the beginning date of summer, and the late spring/early summer phenophases, such as blossoming of *Sorbus aucuparia*, ear and pollination of autumn sown rye.

The correlation between climatic seasons and phenological data is the highest in continental southern Estonia. Lower correlation is typical for North-East Estonia. It can be explained by more frequent advection of cold arctic air in spring.

References

Ahas, R., 1996. The seasonal dynamics of Estonian Landscapes: spatial and temporal variability of early-spring blossoming dates. *Biometeorology*, 14, Part 2, Volume 2. A. Hocevar, Ccrepinsek and L. Kajfez-Bogataj (eds.), Proceedings of 14th International Congress of Biometeorology, Ljubljana, 1-8.09.1996, pp. 220-225.

Jaagus, J., 1996. Changes in climatological calendar during the last century in Tartu, Estonia. In: *European conference on applied climatology. Abstract volume.* (Ed. G. Wennerberg). SMHI, Norrköping, pp. 128-129.

Jaagus, J., 1997. The impact of climate change on the snow cover pattern in Estonia. Climatic change, 36, pp. 65-77.

Kramer, K., 1996. Phenology and growth of European trees in relation to climate change. *Thesis Landbouw Universiteit Wageningen*, Wageningen, 157 pp.

Raik, A., 1963. Climatic seasons in Estonia. *Acta et commentationes Universitatis Tartuensis*, 144, pp. 33-44. (In Estonian, summary in English).

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Jaagus, J. and Ahas, R., 1999.
Space-time variations of climatic seasons and their correlation
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Climate Research. Accepted.

Space-time variations of climatic seasons and their correlation with the phenological development of nature in Estonia

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ABSTRACT

In this paper the spatial and temporal variability of climatic seasons and phenological phases in Estonia is estimated, and correlation between them is analysed. The beginning dates and durations of eight climatic seasons at 23 stations, and of 16 spring and summer phenological phases in Estonia between 1946 and 1998 have been used for data analysis. Homogeneity of long-term series of climatic seasons has been tested using SNHT. The time series can be considered nearly homogeneous. The phenological calendar-method was applied. Significant spatial and temporal variability of climatic seasons was determined. The thermal influence of the Baltic Sea is the main factor in the formation of spatial differences. Due to the comparatively cold sea-surface, spring season lingers in coastal regions. On average, beginning of summer is observed first in south-east Estonia, at the end of May. In North Estonia summer starts at the beginning of June, and in coastal areas at the middle of June. The onset of springtime phenological phases has a pattern similar to that of the beginning dates of spring and summer. The onset migrates over Estonia from south-east to north-west. In coastal areas, climatic seasons during the autumn period start 1–5 weeks later than in continental Estonia. This spatial difference increases from the beginning of autumn towards the beginning of winter. Climatic seasons in the spring period have tended to start earlier as we progress from 1891 to 1998. At the same time, seasons in the autumn period tend to start later. In conclusion, the summer season has lengthened significantly (by 11 days), while winter has contracted by 30 days. Correlation between start dates of climatic seasons and phenological phases is rather high in Estonia. In most cases, correlation coefficients are statistically significant at a 0.05 confidence level. The highest values are typical for seasons and phases that occur nearly at the same time. In general, the space-time variability of phenological phases is much lower than that of climatic seasons on the same period.

KEY WORDS: Climatic season, phenology, phenological calendar, climate change, Estonia

1. INTRODUCTION

Uneven distribution of solar radiation during the year causes the alternation of hot and cold seasons which is the main feature characteristic of climate in mid latitudes. The seasonality of weather conditions, in turn, causes seasonal cycles in living nature.

Typical meteorological variables, such as monthly mean air temperature, are not the best variables to describe weather conditions associated with annual cycles in the organic world. Therefore, climatic seasons, characterised by their start date and duration, are applied. Instead of using measured values, qualitatively different periods of the year are distinguished, according to strict criteria. A climatic season can be defined as an independent stage in the annual cycle of the climatic component of the geographic environment (Galahov 1959). Every season is expected to have its specific complex of weather types, atmospheric circulation, direction of weather changes etc. In reality, climatic seasons begin at a different time every year depending on weather conditions. A climatic calendar entails a complex of statistics that describes average annual cycles of climatic seasons. The criteria for determining climatic seasons vary in different parts of the world (Flohn 1942; Temnikova 1958; Lamb 1972; Hlavač 1975; Kalnicky 1987; Sladek 1990; Lewik 1996). There is a tradition of analysing climatic seasons in Estonia (Raik 1963; Jõgi 1988; Jaagus 1996).

Phenological phases, which are closely correlated with climatic parameters, have recently emerged as an important focus for ecological research in global modelling, monitoring and climate change studies (Schwartz 1999; White *et al.* 1997). The detection of the impact of climate change on phenology and the length of the growing season is possible using observation series (Menzel & Fabian 1999; Crick & Sparks 1999) or phenological data obtained by satellites (Myeni *et al.* 1997; Schwartz 1998). For the analysing and modelling of phenology, scientists use climate parameters such as mean temperature, cumulative sums of daily mean temperatures and precipitation (Schnelle 1955; Maak & von Storch 1997; Heikinheimo & Lappalainen 1997; Roltsch *et al.* 1999), and other aspects, such as length of day or chilling requirement (Flint 1974; Kramer 1994). The calendars of nature method (Schnelle 1955; Schultz 1981) in phenology gives more possibilities for the study of seasonality and interrelation between phenological phases of the same or different species (Lieth 1974). Phenological calendars give the possibility to analyse three different parameters describing phenological phases according to beginning dates, duration and intervals (Jaagus 1996; Ahas 1997) or to combine calendars with temperature threshold nomograms with determined values (Podolsky 1983).

The main objective of this study is to estimate spatial and temporal variability of seasonality in Estonian nature. To achieve this, a calendar of nature consisting of data on climatic seasons and phenological phases has to be composed. The calendars of nature method should be applied to analyse the variability of seasonality and the interrelation between climatic seasons and phenological phases in Estonia.

2. MATERIALS AND METHODS

Estonia is located between 57.5°N and 59.5°N on the eastern coast of the Baltic Sea (Fig. 1). Despite its small territory (45 215 km^2), it is characterised by remarkable spatial differences in climatic conditions and in the phenological development of nature.

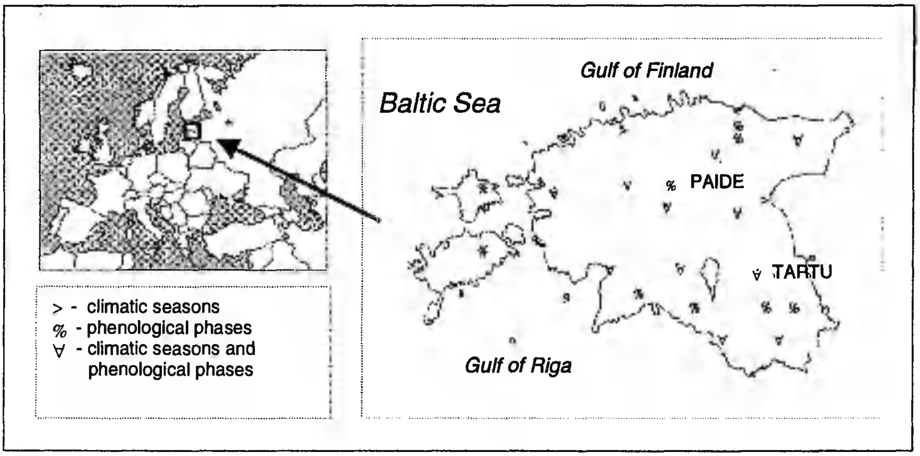

Fig. 1. Location map of Estonia in Europe and of observation sites in Estonia.

The western part of Estonia lies under the direct influence of the sea while in the central and eastern parts climate gradually becomes more continental.

Beginning (or start) dates of climatic seasons have been determined for 19 stations in Estonia during the period 1946–1998. There have been some gaps that have been filled using data from the neighbouring station with the highest correlation of start dates. Data from four additional stations with shorter observation periods (starting between 1959 and 1964) have also been included in the analysis of spatial variability. The duration of climatic seasons has been calculated as the difference between the beginning dates of two successive seasons.

Temporal variability, trends, and periodical fluctuations of the long-term series of climatic seasons have been analysed using data from Tartu between 1891 and 1998. Tartu is located in south-eastern Estonia (58°23'N, 26°43'E). It is characterised by a temperately continental climate representative of the majority of continental Estonia. The station was relocated within the city twice (1893, 1926). Since 1951, the meteorological station has been located at the airport, 10 km south of Tartu.

The homogeneity of the time series of climatic seasons was carefully analysed. There is no analogous data available that can serve as a reference series to test homogeneity of the start dates of climatic seasons in Tartu between 1891 and 1998. Therefore, only absolute tests such as the well-known von Neumann ratio can be used (Buishand, 1982). With the null hypothesis of a constant mean it can be shown that the mean of the ratios is equal to 2. For a non-homogeneous record the mean tends to be smaller than 2. Owen (1962) gives a table of percentage points of von Neumann ratio for normally distributed samples.

Another possibility for studying the homogeneity of a series of climatic seasons is to use air temperature data, since the start of climatic seasons depends directly on air temperature. When air temperature series are homogeneous, the time series of climatic seasons should be likewise.

The Standard Normal Homogeneity Test (SNHT) was applied in this study to analyse the time homogeneous reference series (Alexandersson 1986; Steffensen 1996; Alexandersson & Moberg 1997). The test is performed on a ratio or difference series between the candidate station and a reference series. For a homogeneous time series, the test statistic should not exceed a critical t-value on a fixed confidence level. The SNHT calculates adjustment statistics for data homogenisation. They were not applied as corrections to non-homogeneous series in this study. They were used only for the estimation of the influence of breaks in the homogeneity of time series of climatic seasons.

The following homogeneity tests were carried out in this study:

- SNHT for beginning dates of climatic seasons at the 23 stations, the reference series consisting of the mean values of the six nearest stations. The results indicated that the data of most stations is homogeneous. In the case of some stations, inhomogeneities during the first or last years of the time series were revealed.
- SNHT for monthly mean air temperature at the 23 stations, the reference series consisting of the mean values of the six nearest stations. The temperature series at 11 stations are entirely homogeneous. At the other stations, the main cause of inhomogeneity was relocation of the station. Adjustment statistics automatically calculated by the SNHT lie between ±0.5°C.
- SNHT for monthly mean air temperature in Tartu between 1891 and 1998. The time series from other stations in Estonia, from the closest stations in Finland and Sweden obtained from the NACD data set (Frich *et al.* 1996), and the long-term homogenised series from Uppsala and Stockholm (Moberg & Bergström 1997) were used as reference series. Test results determined a significant break in 1950 (all seasons except winter), which corresponds to the relocation of the Tartu station to the airport. Adjustment statistics were –0.2 to –0.4°C (maximum change in spring, minimum in autumn).
- Von Neumann ratios for start dates of climatic seasons in Tartu between 1891 and 1998. The values tend to be near 2.0, indicating homogeneity of the time series. The highest deviations occurred for the beginning date of early winter and winter. But their absolute values — 1.8 and 2.2 respectively — are above the critical level that indicates that the time series are homogeneous.

In conclusion, the homogeneity test results demonstrate that data of climatic seasons in Estonia are nearly homogeneous. The breaks in air temperature series of 0.2–0.5°C do not cause significant inhomogeneity in time series of start dates of climatic seasons. The main break in the air temperature series in Tartu after 1950 is accounted for the time series analysis of climatic seasons.

Phenological data were obtained from observation programmes conducted by the Estonian Meteorological and Hydrological Institute (1946–1995) and by Estonian Society of Naturalists (1951–1995). For this study, data of the best quality and coverage was selected:

- the start of pollination of six tree species: hazel (*Corylus avellana* L.), maple (*Acer platanoides* L.), bird cherry (*Prunus padus* L.), lilac (*Syringa vulgaris* L.), rowan (*Sorbus aucuparia* L.), apple (*Malus domestica* L., variety *Antonovka*) and foliation of birch (*Betula pendula* Roth);
- nine phases of autumn sown rye (*Secale cereale* L.), Estonian variety *Sangaste.* Its development phases are defined as follows: beginning of vegetation — fresh green leafs, daily maximum of air temperature above +5°C; stalk formation (cereal) — formation of the lowest stalk node (3–5 mm above node); appearance of stalk node — stalk node is 0.5 cm above the surface, detected manually; ear — half of spike (head of grain) is out of leaf sheath; pollination — opened flower calyxes and anther is visible; milky ripe-

ness — grain has fully developed, inside of grain is soft, plant is still green; waxy ripeness — grain is yellow, grain is strong; full ripeness — grain is strong; harvesting.

There are 17 observation sites for most of the tree species and 10 for rye (Fig. 1). Because of the lack of data with a similar density and quality, only spring and summer phenophases are analysed in this study. The beginning of a phenological phase is recognised when the phase has been reached by 10% of the observed plants. About 10% of the data was interpolated due to clear errors or gaps in observations. Interpolation of time-series was carried out by correlation analysis using the mean value of the two neighbouring observation points of the highest correlation.

To analyse long-term changes, the following time series of phenological data in Paide (central Estonia) are used: blossoming of bird cherry, apple, lilac and wood anemone (*Anemone nemorosa* L.) during the period 1919–1996 (Ahas *et al.* 1998).

The phenological calendars method (Schnelle 1955; Lieth 1974; Schultz 1981; Podolsky 1983) was applied to analyse space-time variations of the calendar of Estonian nature. Beginning dates as phenological variables mark certain points in the annual cycle. They have particular sequence and they are closely correlated with phases of the same season (Gerstengarbe & Werner 1999). A recurrent annual cycle consists of a sequence of regularly exchanging phenological phases described in terms of beginning dates, durations and intervals. Every period distinguished in the annual cycle has its duration, for example, thermal growing season, climatic seasons, or pollination period of rye. Intervals are defined as time periods between any phenological phases.

A phenological calendar contains common descriptive statistics (mean values, standard deviations, extreme values, ranges, parameters of distribution etc.). At first, an average calendar was composed using mean values of climatic seasons and phenological phases during the observed period. The calendar could be graphically represented by an annual circle where different seasons are distinguished.

Spatial and temporal variation are analysed separately. Spatial standard deviations are calculated using observed data from a number of observation sites, at first, for every year individually, then averaged by years. Spatial range means a difference between the latest and the earliest mean value among the stations or observation sites. Temporal standard deviation is found on the basis of a single time series and then averaged by stations. Temporal range indicates a difference between the latest and the earliest year in the time series.

Regression analysis is used for estimation of trends and for correlation analysis to estimate statistical correlation between climatic seasons and phenological phases. Significance of correlation coefficients and slopes is estimated by means of t-statistic. The confidence level $P<0.05$ is considered to be suitable for significant correlation of trends. Spatial interpolation using kriging is applied for the drawing of maps.

3. DETERMINATION OF CLIMATIC SEASONS

Essentially, climatic seasons are similar to ordinary phenological phases determined and recorded according to beginning dates. Determination of climatic seasons must follow some important principles. A season should be internally uniform and clearly different from other seasons. The influence of weather conditions on the seasonal development of nature is the leading criterion for dividing a year into climatic seasons. Determination of seasons must also be as simple as possible using uniform criteria. These recommendations permit one to use a large data set and to minimise subjectivity in the determination of start dates of climatic seasons.

Eight climatic seasons have been distinguished in Estonia (Raik 1963; Jaagus 1996). In addition to the four main seasons — spring, summer, autumn and winter — two intermediate seasons between autumn and winter (late autumn, early winter) and two between winter and spring (late winter, early spring) have been distinguished.

Constant temperature thresholds are the most frequently used possibility for determining climatic seasons. Sladek (1990) for example applied the simplest method by using only two temperature thresholds — 0°C and +15°C for the differentiation of four main seasons. For more detailed analysis, it is useful to divide spring and autumn into two parts which separate the thermal growing season.

Climatic seasons of the warm half-year are determined according to the pattern of daily mean air temperature. **Spring**, which begins after the permanent increase of daily mean air temperature above +5°C, indicates the start of the thermal growing season (Jones & Briffa 1995; Carter 1998).

Summer corresponds to a period where daily mean air temperature is consistently higher than +13°C. It coincides with the period favourable for the growth of thermophilic plants. A temperature threshold of +15°C is not a suitable criterion for the summer season in Estonia. During extremely cold summers daily mean air temperature does not permanent rise above this limit.

Autumn begins after a sustained drop of daily mean air temperature below +13°C. It is characterised by an increased frequency of cloudy and rainy days, by the first night frosts, and by maturation of apples and summer crops. **Late autumn** begins with the end of the thermal growing season after the sustained fall of daily mean air temperature below +5°C.

Weather conditions in Estonia are very variable with non-linear seasonal changes in air temperature. Periods of higher and lower temperature usually alternate. Dates when the daily mean air temperature crosses certain thresholds (+5°C or +13° in this study) are determined following procedures used by meteorological services for many decades. For example, high temperatures in the middle of May are often followed by colder days in the first half of June. In this case, positive and negative deviations from +13°C should be summed. If the total of positive deviations is greater than of negative ones, an earlier start of summer, in May, must be determined. If the sum of negative deviations from +13°C is greater during the subsequent cold period, the beginning of summer takes place later, after the cold period in June.

Snow cover is the main factor in determining the climatic seasons during the cold half-year. **Early winter** (or pre-winter) starts with the first formation of snow cover and with the first cold days when daily maximum temperature remain below zero. It embraces the period with unstable snow cover when freezing and melting alternates. In years when the first snow does not melt after a few days but remains for the entire winter, the early winter season is omitted.

Winter itself begins after the formation of permanent snow cover. The continuous period with cold weather before the formation of snow cover is included in the winter season. Permanent snow cover is defined according to the criteria applied in the former Soviet Union (Drozdov *et al.* 1989). These include, for instance, the existence of snow cover during one month as a minimum. Due to intensive cyclonic activity, winter is quite unstable in Estonia, and is characterised by frequent thaws. During some winters, especially in coastal regions, permanent snow cover does not form at all. In this case, early winter transforms directly into late winter. In which case, it will be more justified to observe winter as one long climatic season (early winter+winter+late winter). But, to avoid gaps in time series and to ease data processing, winter is distinguished every year, although its duration may be less than one month.

Late winter is a period of snow melting in spring. It includes also short periods when snow cover reforms after the disappearance of the permanent snow cover. The start date of the snow melting period is the day after which the occurrence of non-melting days (daily maximum temperature below zero) does not exceed the number of melting days. **Early spring** begins after the final disappearance of snow cover.

In cases of extraordinary early formation of temporary snow cover in late autumn or its extremely late formation in early spring, these periods were not included into early winter or late winter, if when they were separated from them by warmer periods with daily mean air temperature above +5°C.

4. SPATIAL VARIABILITY

Start date and duration of the climatic seasons in Estonia are characterised by a remarkable spatial variability. Statistics of spatial variability are presented in Table 1. Spatial mean start date and duration of climatic seasons are found by averaging mean values at the 19 stations calculated for the period 1946 to 1998. Spatial range here means the difference between the earliest (longest) and the latest (shortest) mean values of the stations. Spatial standard deviations are computed, at first for every year, and then they are averaged over time. Statistics for phenological phases from 10–17 observation sites are found in the same way.

Table 1. Statistics of spatial variability for start dates of climatic seasons determined at 19 stations and for phenological phases determined at 10–17 stations in Estonia between 1946 and 1998

Climatic season	**Spatial average**		**Spatial range**		**Standard deviation**	
	Start date	Duration	Start date	Duration	Start date	Duration
Late winter	1-Mar	33	7	7	4.5	7.4
Early spring	3-Apr	21	12	18	6.2	8.7
Spring	24-Apr	41	11	9	4.6	7.6
Summer	4-Jun	94	18	14	7.2	8.8
Autumn	6-Sep	51	14	5	5.9	7.8
Late autumn	27-Oct	18	17	8	6.8	9.0
Early winter	14-Nov	38	21	19	8.6	15.8
Winter	22-Dec	69	35	42	14.9	16.4
Phenological phase	Beginning date		Beginning date		Beginning date	
Pollination of hazel	12-Apr		4		4.6	
Beginning of vegetation of rye	14-Apr		8		4.6	
Rye stalk formation	2-May		9		6.2	
Birch leaf formation	6-May		10		3.8	
Flowering of maple	11-May		11		3.6	
Flowering of bird cherry	19-May		9		3.3	
Flowering of apple tree	27-May		9		3.4	
Flowering of rowan	31-May		7		3.1	
Pollination of rye	18-Jun		5		3.2	

The highest spatial variability for the start dates of winter (5 weeks) is due to the warming effect of the Baltic Sea. In the coastal regions winter begins 3–5 weeks later than in the inland parts of continental Estonia. Macro-scale synoptic processes resulting the lowest spatial variability for the start dates of late winter. Due to advection of a warmer air, snow melting begins more or less at the same time over the whole territory of Estonia.

The range of spatial variability of phenological phases in Estonia is rather constant — 7–10 days on average. This range is smaller than that of the start dates of climatic seasons. This can be explained by the wider spatial coverage of data on climatic seasons, and the use of using more data from coastal stations.

There are three different patterns of climatic season start dates of during a year. The earliest beginning of late winter and of early spring is observed on the western coast of Saaremaa Island (Fig. 1a). Usually, this region remains under the influence of the ice-free part of the Baltic Sea throughout the winter. Therefore, the snow cover is thin and melts earlier than in continental Estonia. The longest duration of snow cover occurs in the north-east of Estonia. The start of the two climatic seasons migrates from south-west to north-east. The comparatively high spatial variability in the beginning date of early spring is due to substantial local differences in the final melting of snow cover. the spatial distribution of the start date of early spring is similar to that of the beginning of the vegetation period of autumn sown rye (Fig. 1b) and other phenological phases occurring at the same time (pollination of hazel).

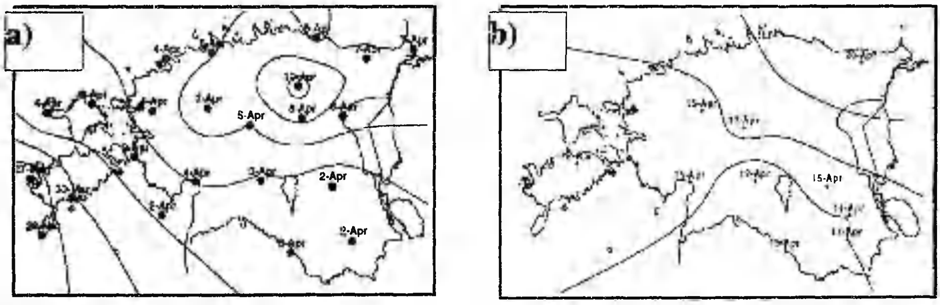

Fig. 1. Mean start date of early spring (a) and of vegetation of rye (variety *Sangaste*) (b) (isoline interval 2 days).

The another pattern is observed for the spring and summer dates (Fig. 2a). These seasons begin first in the south-east of Estonia. This can be explained by different factors: greater influence of warm air coming from the south and south-east, lesser influence of the arctic inflow from the north and north-east, lack of the influence of the cold Baltic Sea, and more intensive solar radiation. The latest starts of spring and summer are observed on the northern and western coasts of Estonia. Coastal regions are the coldest in spring due to the thermal inertia of the sea surface. The mean difference in the beginning of summer between south and north Estonia is 1–2 weeks, while the difference between the South-East and coastal stations of the West Estonian Archipelago is up to 18 days. The spatial pattern of springtime phenological phases has a pattern similar to the beginning of spring and summer. Typical phenological phases during the same period are the onset of blossoming of rowan, lilac, and apple trees (Fig. 2b).

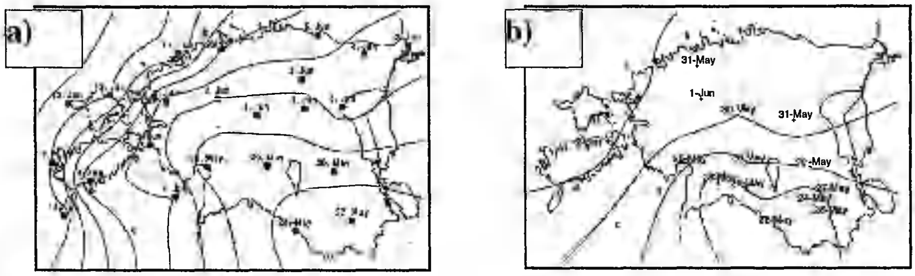

Fig. 2. Mean start date of summer (a) and the beginning of apple tree blossoming (variety *Antonovka*) (b) (isoline interval 2 days).

Spatial differences marking the start of climatic seasons during the second half-year are even more remarkable. They are increasing from the beginning of autumn up to the beginning of winter. Cooling starts in the northern and north-eastern part of the mainland (Fig. 3). This region is the most frequently affected by the inflow of cold arctic air from the north-east. The coastal regions of west Estonia are characterised by much higher temperatures. The spatial difference increases from 14 days in autumn to 35 days in winter (Table 1). On the islands of the West-Estonian Archipelago, autumn begins 1–2 weeks later, late autumn — 1.5–2.5 weeks, early winter — 1.5–3 weeks, and winter — 2–5 weeks later than in East Estonia.

The duration of climatic seasons is also characterised by a high spatial variability (Table 1). Early spring is much longer in the coastal regions due to the cooling effect of the sea. Significant spatial differences are observed in the mean duration of summer. Summer in South Estonia is 10–12 days longer than in North Estonia. The longest summer is observed in the coastal zone of the shallow Gulf of Riga where sea-surface temperature increases substantially during summer. Early winter and winter have the highest spatial variability (Table 1). In coastal areas, winter is nearly two times shorter than in Northeast Estonia.

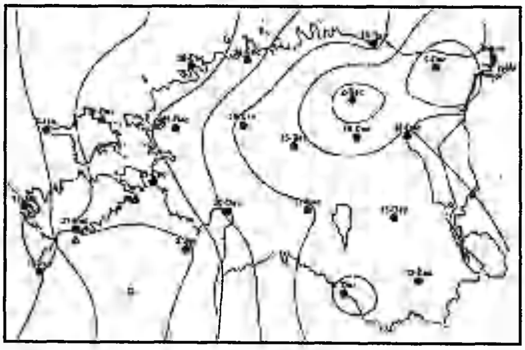

Fig. 3. Mean start date of winter displaying the largest spatial differences — 35 days — between eastern (continental) and western (marine) Estonia (isoline interval 5 days).

5. CORRELATION BETWEEN START DATES OF CLIMATIC SEASONS AND PHENOLOGICAL PHASES

Phenological development in nature is closely related to weather conditions. Early and warm springs coincide with the earlier occurrence of phenological phases, and vice versa. Correlation coefficients between beginning dates of climatic seasons and phenological phases in Estonia averaged over 9 stations (Fig. 1) between 1947 and 1996 are rather high (Table 2). They are marked in bold when the correlation is significant on a $P<0.05$ confidence level for each of the stations.

Table 2. Correlation coefficient (Corr.) between beginning dates of climatic seasons and phenological phases (in chronological order) averaged over 9 stations with parallel observations between 1947 and 1996, and mean difference (Diff.) between the correlation coefficient calculated for the period 1972–1996 and for 1947–1971. Bold value means that correlation is significant on a $P<0.05$ confidence level for each of the stations

Phase	Late winter		Early spring		Spring		Summer	
	Corr.	Diff.	Corr.	Diff.	Corr.	Diff.	Corr.	Diff.
Beginning of vegetation of rye	**0.53**	–0.06	**0.58**	–0.04	**0.39**	0.01	0.05	–0.10
Stalk formation of rye	0.47	0.00	**0.49**	–0.05	0.37	0.08	–0.02	–0.10
Foliation of birch	**0.46**	–0.03	0.39	–0.01	**0.55**	0.21	–0.06	–0.06
Blossoming of maple	**0.42**	0.07	**0.46**	–0.04	**0.55**	0.11	0.03	–0.27
Blossoming of bird cherry	**0.51**	–0.06	**0.53**	–0.19	**0.53**	0.09	0.14	–0.30
Appearing of stalk node of rye	**0.51**	–0.12	**0.54**	–0.02	0.37	0.09	0.02	–0.26
Blossoming of apple tree	**0.44**	–0.18	**0.48**	–0.40	**0.43**	0.02	0.32	–0.33
Blossoming of lilac	0.36	–0.32	0.40	–0.34	0.30	–0.04	**0.37**	–0.27
Blossoming of rowan	0.35	–0.37	0.37	–0.35	0.29	0.04	0.35	–0.33
Ear of rye	**0.40**	–0.27	**0.48**	–0.30	0.32	0.05	0.35	–0.27
Pollination of rye	0.36	–0.43	0.22	–0.33	0.30	0.06	**0.53**	–0.18
Milky ripeness of rye	0.39	–0.32	0.23	–0.25	0.31	0.22	**0.52**	–0.06
Waxy ripeness of rye	0.31	–0.36	0.20	–0.34	0.31	0.07	**0.44**	–0.08
Full ripeness of rye	0.31	–0.22	0.21	–0.36	0.26	0.11	**0.43**	–0.07
Harvesting of rye	0.25	–0.17	0.16	–0.34	0.31	0.16	0.33	–0.10

Due to thermal inertia, correlation between start dates of late winter, early spring and spring has been observed. Therefore, the correlation coefficients in Table 2 are somewhat similar. The highest correlation is characteristic of beginning dates of climatic seasons and phenological phases that occur simultaneously. For example, the beginning date of late winter influences whether the following spring will be early or late. Early spring is associated with the start of vegetation and the subsequent phases of rye. Harvesting of rye usually takes place in August and is therefore not connected with the start dates of climatic seasons in springtime.

The start of spring (i.e. the thermal growing season) has the highest correlation with phenological phases, such as foliation of birch, and blossoming of maple and bird cherry, which are observed from the end of April to the middle of May. Phenological development of rye is less strongly correlated to the start of spring. The start of summer is strongly correlated with late phases of rye at the end of May and in June.

The longer the time interval from the beginning of a climatic season to the start of a phenological phase, the weaker is their correlation. This is clearly illustrated in Fig. 5 where lines show how the correlation between climatic seasons and phenological phases changes with time. The phases are arranged in chronological order. It is also obvious that there is no correlation between the start date of summer and earlier phenological phases, i.e. stalk formation of rye and foliation of birch.

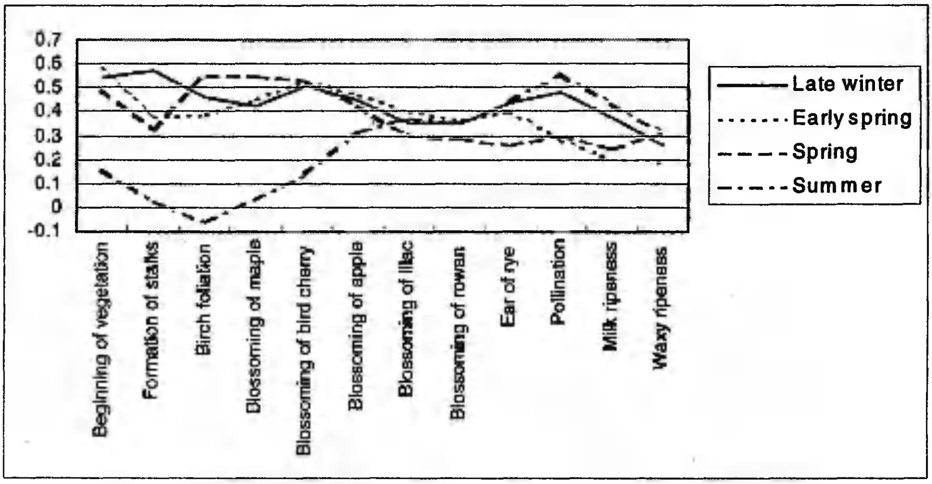

Fig. 5. Correlation coefficients between beginning dates of climatic seasons and phenological phases in Estonia.

To analyse the persistence of the correlation between the seasons and phases, the 50-year period has been divided into two halves and the same correlation coefficients have been calculated for them independently. Differences between correlation coefficients averaged over the 9 stations calculated for the periods 1972 to 1996 and 1947 to 1971, respectively, are presented in Table 2. They indicate that during the first period correlation was remarkably higher than during the second period.

The difference is especially high for correlation coefficients between late winter and early spring, and some phenological phases in May and June. Greater differences are typical also for the beginning dates of summer. This means that correlation coefficients calculated for the period 1972 to 1996 are substantially smaller than the coefficients found for the period 1947 to 1971. Only the beginning date of spring has a higher correlation in the more resent time series.

As a graphical summary of the results of the phenological calendar-analysis, several phenological annual circles can be drawn. Fig. 6 presents the mean annual circle of climatic seasons in Estonia and of the phenological phases of autumn sown rye in spring and summer. Names of climatic seasons in the inner circle are typed in bold. The circle is oriented so that the winter solstice is located at 6 o'clock, and the summer solstice is at 12 o'clock, coinciding with the beginning of the pollination of rye. Time progresses counter-clockwise.

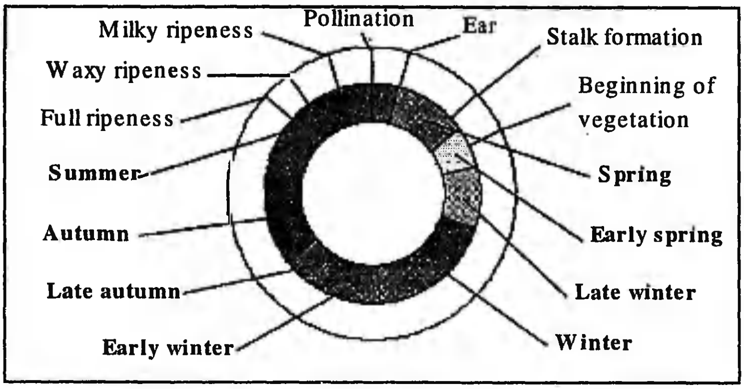

Fig. 6. Mean annual circle of climatic seasons in Estonia (inner circle) and of phenological phases of autumn sown rye in spring and summer (outer circle).

6. TEMPORAL VARIABILITY OF THE LONG-TERM SERIES

Long term changes in climatic seasons were analysed using data from Tartu station during the period 1891 to 1998. The time series and their linear trends are presented in Fig. 7. Statistics of the temporal variability of climatic seasons are shown in Table 3.

The lowest year-to-year variability is typical for the start dates of autumn and spring. This is probably due to the rapid change in the length of the day, sunshine duration, solar radiation, and air temperature during equinoxes in high latitudes.

Table 3. Statistics of temporal variability for beginning date and duration of climatic seasons in Tartu between 1891 and 1998. Significant changes by linear trend on a P<0.05 level are marked in bold

Climatic season or period	**Average**		**Range (days)**		**Standard deviation**		**Change by trend**	
	Start date	Duration	Start date	Duration	Start date	Duration	Start date	Duration
Early spring	2-Apr	20	69	65	14.7	14.0	–6	1
Spring	22-Apr	41	48	81	10.0	16.7	–5	–3
Spring in total		61		92		18.5		–2
Summer	2-Jun	93	68	74	13.7	16.7	–8	**11**
Autumn	2-Sep	48	39	67	8.5	13.3	3	5
Late autumn	20-Oct	22	51	65	11.4	15.6	**8**	–9
Autumn in total		70		72		15.4		–4
Early winter	11-Nov	29	66	125	13.4	25.1	–1	**18**
Winter	11-Dec	82	118	136	25.3	32.5	**17**	**–30**
Late winter	3-Mar	30	104	88	21.9	19.2	–13	7
Winter in total		141		100		20.6		–5
Growing season		182		77		16.3		**13**

Consequently, seasonal changes in living nature at that time are the fastest and most fixed in time in comparison with other times of the year. The highest temporal variability is characteristic for the beginning of early winter, winter and late winter. Greater cyclonic activity means that weather conditions are the most variable during the winter season.

Results of linear regression analysis of long-term series in Tartu indicate the presence of some long-term tendencies. Changes in trend in Table 3 mean differences between trend values calculated for years 1998 and 1891. Negative changes show a tendency for climatic seasons to start earlier and vice versa. Significant changes in linear trend on a $P<0.05$ level are marked in bold.

Climatic seasons during the first half of the year tend to begin earlier, while seasons of the second half (except early winter) have been starting later. A statistically significant trend was determined only for the beginning date of late autumn and winter. Their beginning dates have shifted from 16 to 24 October and from 2 to 19 December, respectively. Trends in late winter and summer time series are not significant due to the high temporal variability of the time series.

Long-term variability of the duration of climatic seasons is even higher than that of start dates (Table 3). Duration is determined by two beginning dates and this increases its temporal variability. The durations of winter and early winter are the most variable.

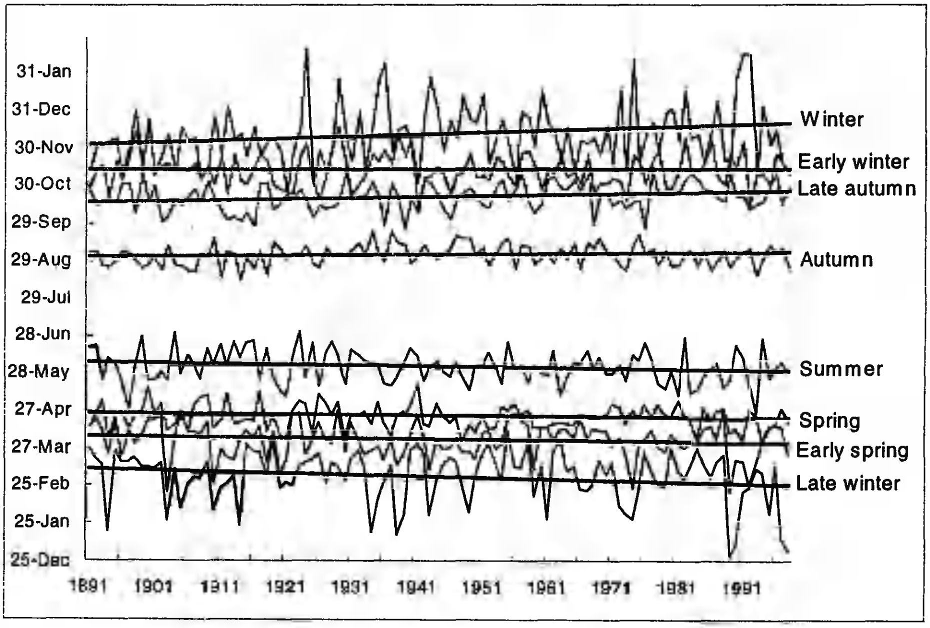

Fig. 7. Long-term series and linear trends for start dates of climatic seasons in Tartu (1891–1998).

The summer season has lengthened by 11 days during the 108-year period. Other significant trends were obtained for early winter, winter and the whole thermal growing season. The shortening of the winter season by 30 days is significant even on a $P<0.01$ level. All the long-term tendencies observed in Tartu are in a good accordance with the trebd of increasing mean air temperature during winter and spring seasons (Jaagus, 1998), and with the trend of decreasing spatial mean snow cover duration (Jaagus, 1997).

Long-term changes in climatic seasons are depicted in Figure 8. The inner circle represents the mean distribution of the seasons by trend at the beginning of the period, and the outer circle — at the end. The obvious lengthening of summer and shortening of winter can easily be observed.

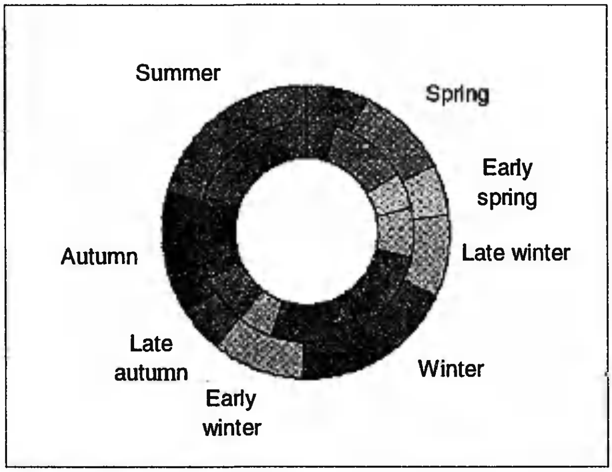

Fig. 8. Annual circle of climatic seasons in Tartu for years 1891 (inner circle) and 1998 (outer circle) calculated by linear trend.

To analyse temporal fluctuations of the studied trends, the whole observation period is divided into two equal parts. The same statistical measures as in Table 2 are calculated for the periods 1891 to 1944 and 1955 to 1998. During the first period, significant positive trends on a $P<0.01$ confidence level were found for the start dates of autumn and winter. They have shifted towards a later time by 12 and 27 days, respectively. The period 1945 to 1998 is characterised by a remarkable tendency for late winter and early spring to begin earlier (by 32 and 18 days).

Generally, results of long-term trends of climatic seasons in Estonia coincide with results obtained for different sites in North Europe (Carter 1998) and in the former Soviet Union (Jones & Briffa 1995). The duration of the thermal growing season has lengthened by 11 days in Tartu during the period 1891 to 1998 and by 1-3 weeks in Fennoscndia between 1890 and 1995.

Table 4 and Fig. 9 present the of temporal variability characteristics of some phenological phases observed in Paide (Central Estonia) between 1919 and 1995 (Ahas et al. 1998). Long-term changes in phenological phases have trends similar to those of climatic seasons. The start of phenological phases has shifted earlier in spring. All start dates have shifted earlier while the blossoming of wood anemone and of lilac have a trend significant on a 0.05 confidence level. Spring has advanced 7.5 days on average during the last 78 years.

Table 4. Statistics of temporal variability for beginning dates of phenological observation series in Paide from 1919 to 1995

Phenological phase	Average	Standard deviation	Earliest date	Latest date	Slope	Change by trend	t-statistic
Blossoming of wood anemone	119	10.3	86	159	–0.17	–14	**–3.74**
Blossoming of bird cherry	139	8.7	121	161	–0.05	–4	–1.29
Blossoming of apple	147	9.0	127	169	–0.05	–3	–1.10
Blossoming of lilac	148	7.9	125	169	–0.11	–9	**–2.85**

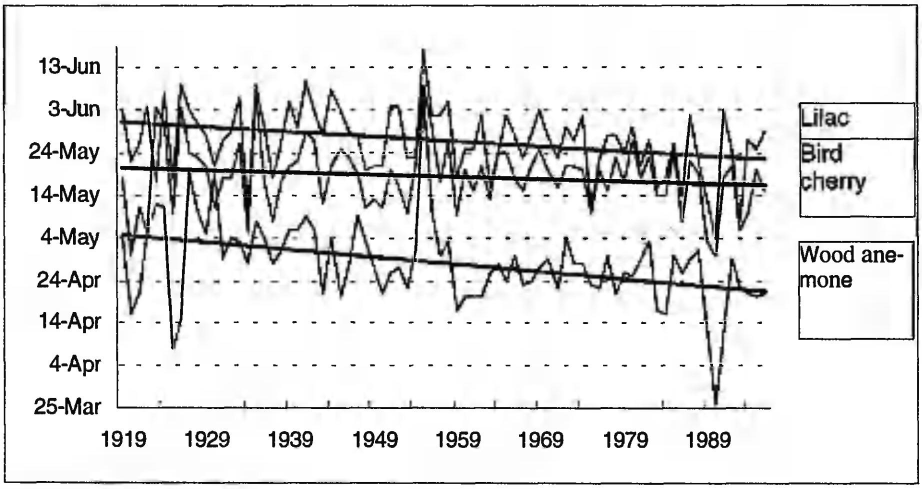

Fig. 9. Long -term series and linear trends of blossoming dates in Paide (1919–1995).

These results are similar to the changes in thermal growing season observed in Europe by the International Phenological Gardens (Menzel & Fabian 1999). For example, leaf unfolding has advanced 6 days and leaf colouring in fall has been delayed by 4.8 days per 30 years of observations in Europe.

7. DISCUSSION AND CONCLUSIONS

7.1. Determination of climatic seasons

Seasonal changes in weather conditions usually proceed gradually. Therefore, it is not easy to separate climatic seasons in the annual cycle. In any case the choice is arbitrary. Traditional criteria for determining climatic seasons, used over many decades in Estonia are applied in this study. Here, they are specified and adapted only for the processing of a large amount of data. The results of this study, showing in general quite a close correlation between beginning dates of climatic seasons and phenological phases, confirm the validity of the criteria used.

The main disadvantage of using air temperature thresholds is that, in some cases, small differences in air temperature between neighbouring stations could lead to big differences in the start dates of climatic seasons. This happens when seasonal change of air temperature is not gradual but oscillatory, with alternating strong positive and negative anomalies. Consequently, a climatic season can begin either on the rising (or falling) slope of the first wave or of the next one. The period of these temporal waves may be more than one month.

The beginning dates of the studied phenological phases have a similar spatio-temporal pattern as the studied climatic seasons. These phases can be used to determine seasons in parallel with the temperature threshold method. Phenological phases are a result of natural factors causing seasonality in living nature; they delimit periods with similar weather conditions that can be observed as climatic seasons. Therefore, many authors use phenological phases for the determination of seasons (Schnelle 1955; Schultz 1981).

The use of temperature thresholds for the determination of the winter season is more contestable. Snow cover is a complex climatic and Phenological phenomenon that is an even more important factor for characterising weather conditions in winter. It has a very great influence on plants, animals and human activity in Estonia.

In the regions of temperate continental climate, differentiation of early winter and late winter is justified. They present qualitatively different weather types and have a different impact on living nature. During mild winters, especially on the coasts of the West Estonian Archipelago, permanent snow cover is not formed. In that case, it is better to distinguish one winter period including early and late winter seasons.

The criteria used for the determination of climatic seasons in Estonia can also be applied in other regions with a similar climate (Dfb according to Köppen-Geiger). It can be assumed that they would work quite well in central latitudes of Fennoscandia and on the major parts of the East European plain. There is no sense nor possibility to elaborate the same system of climatic seasons for regions with different climate types. Phenological phases can serve as a more universal source for the determination of the natural seasons in large territories, for example for all continental Europe (Schnelle 1955; Menzel & Fabian 1999).

7.2. Spatio-temporal variability

Climatic seasons and phenological phases in Estonia are characterised by a remarkable variability in space and time. This is most pronounced during the winter season. The high year-to-year variations can be explained by high cyclonic activity in Northern Europe. Spatial differences are connected with high gradients of air temperature due to the influence of the Baltic Sea. As a rule, start dates of climatic seasons and phenological phases occur later than in the hinterland.

The Hopkins's bioclimatic law (Hopkins 1938) determines factors influencing the spatial distribution of phenological phases. It is oriented for North America but the main principles are also valid for Europe. The pattern of beginning dates of the climatic seasons and phenological phases in Estonia follows the same regularities. Onset of late winter and early spring seasons and phenophases spreads from south-west to north-east (Fig. 2), onset of spring and summer — from south-east to north-west (Fig. 3), and of autumn — from north-east to south-west (Fig. 4). The distribution of all phenological phases is similar to the general directions in Eastern and Northern Europe mapped by Schnelle (1955). Similar influence of the Baltic Sea is also noticeable in phenological maps of Finland (Heikinheimo & Lappalainen 1997).

The results of the current study show that, as a rule, spatio-temporal variability of beginning dates of the climatic seasons is higher than that of phenological phases during the same period. It can be supposed that weather as an independent variable fluctuates within higher limits than phenological phases, which are influenced by weather conditions. Due to physiological peculiarities of plants and local natural conditions phenological phases have an inertia that eliminates the influence of short-term weather fluctuations.

7.3. Long-term changes

Climatic seasons and phenological phases can be used as good indicators able to contribute new information to studies on climatic change. For example, mean air temperature in summer (JJA) has not increased during the last century in Estonia (Jaagus 1998). At the same time, the results of this study revealed a significant lengthening of the summer season and the thermal growing season — by 11 and 13 days respectively (Table 3, Fig. 8). The start of climatic seasons in the spring period has tended to shift earlier and in the autumn period has shifted later. Similar trends have been observed in the whole Nordic region (Carter 1998).

The same trends are also typical for long-term springtime phenological phases in Paide between 1919 and 1996 and other observation sites in Estonia (Ahas 1998; Ahas 1999). As a result, the spring onset of phenophases occur significally earlier 3–14 days (Table 4, Fig. 9). The greatest changes can be observed on early spring phases: pollination of hazel and blossoming of wood anemone. This result is similar to the results of analyses of the International Phenological Gardens (IPG) network data for 1959–1993, which shows that spring phenophases have advanced by 6 days and autumn phenophases have been delayed by 4.8 days (Kramer 1996; Menzel & Fabian 1999).

Correlation between beginning dates of climatic seasons and phenological phases in Estonia is high. In most cases, correlation coefficients are statistically significant at a 0.05 confidence level. The highest correlation is for seasons and phases that occur almost at the same time.

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LITERATURE CITED

Ahas R. (1997) The impact of climatic changes on seasonal cycles in nature: the study of unusually late and early springs in Estonia. In: van de Geijn, P. J. Kuikman (eds.) International Workshop on Prospects for Co-ordinated Activities in Core Projects of GCTE, BAHC and LUCC, S.C., November 16–19, 1997, Wageningen, pp. 144–145.

Ahas R. (1999) Long-term phyto-, ornitho-, and icthyophenological time-series analyses in Estonia. International Journal of Biometeorology 42: 119–123.

Ahas R., Tarand A., Meitern H. (1998) Temporal variability of the phenological time series in Estonia. In: Tarand A., Kallaste T. (eds.) Country Case Study on Climate Change Impacts and Adaptation Assesments in the Republic of Estonia. Report to the UNEP/GEF; Project No.: GF/2200-96-45. Stockholm Environment Institute-Tallinn, Tallinn, p. 28–30.

Alexandersson H. (1986) A homogeneity test applied to precipitation data. J Climatol 6: 661–675.

Alexandersson H., Moberg A. (1997) Homogenization of Swedish temperature data. Part I: homogeneity test for linear trends. J. Climatol 17: 25–37.

Buishand T. A. (1982) Some methods for testing the homogeneity of rainfall records. J. Hydrol 58: 11–27.

Carter T. R. (1998) Changes in the thermal growing season in Nordic countries during the past century and prospects for the future. Agricultural and Food Science in Finland 7: 161–179.

Crick H. Q. P., Sparks T. (1999) Climate change related to egg-laying trends. Nature 399: 423–424.

Drozdov O. A., Vasilyev V. A., Kobysheva N. V., Raevskij A. N., Smekalova L. K., Shkol'nyj E. P. (1989) Klimatologija. Gidrometeoizdat, Leningrad (in Russian).

Galahov N. N. (1959) Study on structure of climatic seasons of a year. Izdatel'stvo Akademii Nauk SSSR, Moscow (in Russian).

Flint H. L. (1974) Phenology and Genecology of Woody Plants. In: Lieth H (ed.) Phenology and seasonality modeling. Ecological Studies 8, Springer-Verlag, New York, p. 83–97.

Flohn H. (1942) Witterung und Klima in Deutschland. Verlag von S. Hirzel, Leipzig.

Frich P., Alexandersson H., Ashcroft J., Dahlström B., Demarée G. R., Drebs A., van Engelen A. F. V., Førland E. J., Hanssen-Bauer I., Heino R., Jónsson T., Jonasson K., Keegan L., Nordli P. Ø., Schmidt T., Steffensen P., Tuomenvirta H., Tveito O. E. (1996) North Atlantic climatological dataset (NACD version 1) — Final Report. Danish Meteorological Institute, Scientific Report 96-1.

Heikinheimo M., Lappalainen H. (1997) Dependence of the flower bud burst of some plant taxa in Finland on effective temperature sum: implications for climate warming. Ann. Bot. Fennici 34: 229–243.

Hlavaè V. (1975) Eine neue Methode zur objektiven Beurteilung der Säkularen Schwankungen und Abnormalitäten der Lufttemperatur und der Sonnefleckenrelativzahlen und ihre Anwendung für die 200jährige Prager Temperaturreiche. Geofysikalni Sbornik 23: 371–565.

Hopkins A. D. (1938) Bioclimatics — a science of life and climate relations. U.S. Dept. Agr. Misc. Publ. 280 .

Jaagus J. (1996) Changes in climatological calendar during the last century in Tartu, Estonia. In: Wennerberg G (ed.) European conference on applied climatology. Abstract volume. SMHI, Norrköping, p. 128–129.

Jaagus J. (1997) The impact of climate change on the snow cover pattern in Estonia. Climatic change 36: 65–77.

Jaagus J. (1998) Climatic fluctuations and trends in Estonia in the 20th century and possible climate change scenarios. In: Kallaste T., Kuldna P. (eds.) Climate change studies in Estonia. Stockholm Environment Institute-Tallinn, Tallinn, p. 7–12.

Jones P. D., Briffa K. R. (1995) Growing season temperatures over the former Soviet Union. J Climatol 15: 943–959.

Jõgi J. (1988) On seasonal rhythms in formation of micro-climate. In: Keskpaik A., Noorkõiv R. (eds.) Problems of geography in Estonia. Estonian Academy of Sciences, Tallinn, p. 62–66 (in Estonian).

Kalnicky R. A. (1987) Seasons, singularities, and climatic changes over the midlatitudes of the Northern Hemisphere during 1899–1969. J. Clim. Appl. Meteorol. 26: 1496–1510.

Kramer K. (1994) Selecting a model to predict the onset of growth of *Fagus sylvatica*. J. Appl. Ecology 31: 172–181.

Kramer K. (1996) Phenology and growth of European trees in relation to climate change. Thesis Landbouw Universiteit Wageningen, Wageningen.

Lamb H.H. (1972) Climate: present, past and future. Vol. 1. Fundamentals and climate now. Methuen, London.

Lewik P. (1996) Thermal seasons of the year in Southern Poland — tendencies of the terms and duration. Zeszyty Naukowe Uniwersitetu Jagiellonskiego, Prace Geograficzne, 102: 355–358.

Lieth H. (1974) Purposes of phenology book. In: Lieth H. (ed.) Phenology and seasonality modeling. Ecological Studies 8, Springer-Verlag, New York, p. 3–19.

Maak K., von Storch H. (1997) Statistical downscaling of monthly mean air temperature to the beginning of flowering of Galanthus nivalis L. in Northern Germany. International Journal of Biometeorology 41: 5–12.

Menzel A., Fabian P. (1999) Growing season extended in Europe. Nature 397: 659.

Moberg A., Bergström H. (1997) Homogenization of Swedish temperature data. Part III: The long temperature records from Uppsala and Stockholm. J. Climatol. 17: 667–699.

Podolsky A. S. (1983) New Phenology: Elements of Mathematical Forecasting in Ecology. John Wiley & Sons, New York.

Raik A. (1963) Climatic seasons in Estonia. Acta et commentationes Universitatis Tartuensis, 144: 33–44 (in Estonian, summary in English).

Roltsch W. J., Zalom F. G., Strawn A. J., Strand J. F., Pitcairn M. J. (1999) Evaluation of several degree-day estimation methods in California climates. International Journal of Biometeorology 42: 169–176.

Schnelle F. (1955) Pflanzen-Phänologie. Akademishe Verlagsgesellschaft, GEEST und PORTIG K.-G., Leipzig, p. 166–210.

Schultz G. E. (1981) General phenology. Nauka, Leningrad, p. 91–146 (in Russian).

Schwartz M. D. (1998) Green-wave phenology. Nature 394: 839–840.

Schwartz M. D. (1999) Advancing to full bloom: planning phenological research for the 21st century. International Journal of Biometeorology 42: 113–118.

Sladek I. (1990) Changes of duration and timing of some temperature seasons of the year in Prague. In: Brazdil R. (ed.) Climatic change in the historical and the instrumental periods. Masaryk University, Brno, p. 194–196.

Steffensen P. (1996) Standard normal homogeneity test for Windows. User guide. Danish Meteorological Institute. Technical Report, 96–13.

Temnikova N. S. (1958) Climate of the Latvian S.S.R. Gidrometeoizdat, Riga (in Russian).

White M. A., Thorton P. E., Running S. W. (1997) A continental phenology model for monitoring vegetation responses to interannual climatic variability. Global Biogeochemical Cycles 11 No 2, 217–235.

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*Jaagus, J. and Ahas, R., 1999. Space-time variations of climatic seasons and their correlation with the phenological development of nature in Estonia. Climate Research. Accepted. pp. 1–25.

*Ahas, R., Aasa, A. 1999. Impact of landscape features on phenological phases in transitional zone from maritime to continental climate types of Northern Europe. Landscape Ecology. Submitted. pp. 1–15.

*Ahas, R., Jaagus, J. and Aasa, A., 1999. The phenological calendar of Estonia and its correlation with mean air temperature. International Journal of Biometeorology. Accepted. pp. 1–10.

*Ahas, R. 1999. Long-term phyto-, ornitho-, and icthyophenological time-series analyses in Estonia. International Journal of Biometeorology, 42: 119–123.

Ahas, R., Tarand, A. and Meitern, H. 1998. Temporal variability of the phenological time series in Estonia. — Country Case Study on Climate Change Impacts and Adaptation Assesments in the Republic of Estonia, Tarand, A., Kallaste, T. (eds.). Report to the UNEP/GEF; Project No.: GF/2200-96-45. SEI Tallinn, pp. 28–30.

*Ahas, R. 1998. Climatic change impact on seasonal cycles in nature: spatial and temporal variability of the phenological time-series in Estonia. —

Climate Change Studies in Estonia, Kallaste, T., Kuldna, P. (eds.) SEI Tallinn, pp. 21–26.

Ahas, R. 1998. Limitations in the use of phenological time-series for climatic trend analysis. — Association of American Geographers, 94th Annual Meeting 1998. Boston. Promedia Corp. (CD).

* Jaagus, J. and Ahas, R. 1998. Spatial differences in climatic seasons in Estonia and their influence on phenological development of nature. 2nd European Conference on Applied Climatology 19 to 23 October 1998, Vienna, Austria. Österreichische Beiträge zu Meteorologie und Geophysik, 19. Zentralanstalt für Meteorologie und Geodynamik, Wien. ISSN 1016-6254, 6 pp.

Ahas, R. 1997. The impact of climatic changes on seasonal cycles in nature: the study of unusually late and early springs in Estonia. In: International Workshop on prospects for Co-ordinated Activities in Core Projects of GCTE, BAHC and LUCC, S. C. van de Geijn and P. J. Kuikman (eds.), November 16–19 1997, Wageningen, pp. 144–145.

* Ahas, R. 1996, The seasonal dynamics of Estonian Landscapes: spatial and temporal variability of early-spring blossoming dates. Biometeorology, 14, Part 2, Volume 2. A. Hočevar, Čerepinsek and L. Kajfež-Bogataj (eds.), Proceedings of 14th International Congress of Biometeorology, Ljubljana, 1–8.09.1996, pp. 220–225.

Ahas, R., 1994. Geographical variability of the phenology of trees in Estonia. Tartu, 1994. MSc Thesis (in Estonian). 74 pp.

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DISSERTATIONES GEOGRAPHICAE UNIVERSITATIS TARTUENSIS

1. Вийви Руссак. Солнечная радиация в Тыравере. Тарту, 1991.
2. Urmas Peterson. Studies on Reflectance Factor Dynamics of Forest Communities in Estonia. Tartu, 1993.
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