A phenology-based reconstruction of interannual changes in past spring seasons

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Received 23 November 2006; revised 26 July 2007; accepted 21 September 2007; published 27 December 2007.

[1] Plant phenological observations are accurately dated information of seasonal vegetation variability in midlatitude climates. In order to extend phenological records into the past and assess climate impacts on vegetation on long timescales, there is a need to make use of historical observations of plant phenology. Here we present a continuous, annually resolved reconstruction of a statistical 'Spring plant' defined as the weighted mean for the flowering of cherry and apple tree and budburst beech from plant phenological observations across a range of sites in Switzerland from 1702 to 2005. The reconstruction indicates a statistical reconstruction uncertainty (±3.4 days) at interannual timescale. The earliest and the latest year were observed in 1961 (14 April) and 1879 (13 May), respectively. In the context of the last 300 years, the recent three decades do not show a preponderance of very early years as expected from increased spring temperatures. Most of the years in the period after 1990, however, are earlier than the reconstruction mean (27 April). The 1940s, 1910s, 1890s and the early 18th century are periods with similarly early starts of spring season in comparison with the recent decades. Moving linear trend analysis shows unprecedented agreement towards earlier spring onsets in observed and temperature-based, reconstructed plant phenological records in the late 20th/early 21st century. Our reconstructed 'Spring plant' provides long-term evidence of vegetation variability for comparisons with temperature measurement and other spring onset indicators such as snow melt. The multicentennial long record offers a high potential for applications in long-term climate impact studies and vegetation model validations.

Citation: Rutishauser, T., J. Luterbacher, F. Jeanneret, C. Pfister, and H. Wanner (2007), A phenology-based reconstruction of interannual changes in past spring seasons, *J. Geophys. Res.*, *112*, G04016, doi:10.1029/2006JG000382.

1. Introduction

[2] Biophysical and biochemical vegetation processes play an important role in the climate system as they dynamically respond to climate forcings. They are also a major driver in the global water and carbon cycle and important for surface albedo property [e.g., *Seneviratne et al.*, 2006; *Fischer et al.*, 2007; *Cox et al.*, 2000]. Interannual changes in vegetation influence agricultural and socioeconomic factors such as crop suitability, yield, epidemiology of pests, food quality, as well as the duration of the pollen season [*Peñuelas and Filella*, 2001]. Plant phenology, the science of the timing of recurring plant development stages or phases such as flowering, leafing or leaf fall, has been found to be a relevant tool to document and to investigate environmental and climate impacts on plants and ecosystems in more detail [*Schnelle*, 1955; *Menzel*, 2002; *Schwartz*, 2003]. Phenological stages describe the rhythm of annual seasonal development and interannual changes in midlatitude climates (e.g., F. Jeanneret, The rhythm of seasonality: A phenological season diagram, submitted to Analele Universiatii de Vest din Timisoara, Seria Geograpfie, 2007).

[3] The advance of spring events has been documented for marine, freshwater and terrestrial groups in all parts of the world including all major oceans [*Parmesan*, 2006; *IPCC*, 2007]. In temperate and cold zones, the spring season is particularly sensitive because changes in growth activity are adapted to intrannual day length variability and reinforced by increasing temperatures [*Larcher*, 2003]. Atmospheric teleconnection indices such as the North Atlantic Oscillation or Arctic Oscillation influence both temperature and, thus, also phenological patterns [*Buermann et al.*, 2003; *Menzel et al.*, 2005b]. Precipitation can not be considered as a major driving factor in Northern Hemisphere midlatitudes [*Buermann et al.*, 2003] as it usually does not significantly explain variance in predicting spring plant development [e.g., *Sparks and Carey*, 1995]. The availability of water affects ecology on different hierarchical levels (from genomic to community and ecosystem) in a complex manner [*Heisler and Weltzin*, 2006; *Weltzin et al.*,

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0148-0227/07/2006JG000382

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2003] and becomes more important in arid and semi-arid regions where water supply is limited [*Peñuelas et al.*, 2004]. There is also an abundant number of summer and autumn phenological observations [e.g., *Chuine et al.*, 2004; *Menzel et al.*, 2006; *Meier et al.*, 2007].

[4] Vine harvest dates have recently been used for seasonal summer temperature reconstructions [*Chuine et al.*, 2004; *Menzel*, 2005; *Guiot et al.*, 2005; *Le Roy Ladurie et al.*, 2006; *Meier et al.*, 2007]. For autumn changes it is more difficult to establish statistically significant correlations with climatic drivers as there are fewer observations and several important factors such as summer temperature and precipitation as well as early frost events [e.g., *Menzel*, 2003; *Menzel et al.*, 2006; *Estrella and Menzel*, 2006; *Gange et al.*, 2007]. However, *Gange et al.* [2007] recently found that average first autumnal fruiting date of 315 english species was earlier, while last fruiting date was later.

[5] Recent work draws a globally coherent picture of changing growing seasons that is in agreement with temperature rise. *Parmesan and Yohe* [2003] and *Root et al.* [2003] analyzed trends in natural systems both derived from plant and animal phenological observations. They found major shifts due to known physiological constraints. The trends can be found for single species as well as for plant and animal communities [*Walther et al.*, 2002]. The observed changes have been physically linked to local or regional climate change through correlations between climate and biological variation, experimental manipulations and basic physiological research [*Parmesan*, 2006]. *Menzel et al.* [2006] confirmed the meta-analyses and presented evidence of coherent temperature and phenological trend patterns by analysing more than 125'000 European plant phenological records from a data set for 1971–2000. They confirmed that the pattern of observed change in spring efficiently matches measured warming across 19 European countries. Finally, modelling studies attribute the changes to human activity. *Root et al.* [2005] discerned a statistically significant two-step attribution: human activities contribute to temperature changes and human-changed temperatures are associated with changes in plant and animal phenological traits.

[6] The spring season can be described by many different means such as phenological observations, remote-sensing derived indices or temperature threshold indicators (see *Linderholm* [2006] for a review). During the recent past, plant phenological observations have shown consistent trends towards earlier spring dates in Europe [e.g., *Menzel and Fabian*, 1999; *Defila and Clot*, 2001; *Menzel and Estrella*, 2001; *Sparks and Menzel*, 2002; *Menzel et al.*, 2006], North America [e.g., *Beaubien and Freeland*, 2000], Korea [e.g., *Ho et al.*, 2006], and, however less pronounced, in China [e.g., *Chen and Pan*, 2002; *Chen et al.*, 2005]. Two studies have shown trends for phenological statistical spring indicators in Germany and Switzerland: *Chmielewski and Rötzer* [2002] used an indicator of the beginning of the growing season defined by four phenological phases that occur rather simultaneously. *Studer et al.* [2005] defined a combination of 15 phases occurring between early March and early July. The shift towards earlier appearance of spring events mirrors warming trends of late winter and spring temperatures [*Badeck et al.*, 2004; *Studer et al.*, 2005; *Schwartz et al.*, 2006; *Luterbacher et al.*, 2007; *Xoplaki et al.*, 2005]. Changes in vegetation indices from satellite imagery analyses also agree with these findings [*Myneni et al.*, 1997; *Schwartz*, 1998; *Stöckli and Vidale*, 2004; *White et al.*, 2005].

[7] Three independent spring indicators for the Swiss Plateau region from 1965–2002 illustrate the common signal between phenology, green-up and temperature (Figure 1). Observed plant phenology as a multispecies estimate derived from applying empirical orthogonal function (EOF) analysis on a combination of 15 plant phenological spring phases [*Studer et al.*, 2005], February–April mean temperatures of Zurich (Switzerland) [*Begert et al.*, 2005] and NDVI-derived start of season time series (1982–2002) of selected pixels in the Swiss plateau region [*Stöckli and Vidale*, 2004] highly correspond in their variability. Phenological observations significantly correlate with temperature ($r = -0.82$, $p < 0.001$) and earlier onset of greening as observed from satellite observations ($r = 0.89$, $p < 0.001$). Thus, changing temperatures influence the variability of specific plant sites observed from the ground as well as the spatially integrated date of green-onset as seen from space.

[8] However, it is crucial to collect evidence for earlier periods. Satellite imagery cannot be used as it only reaches back a couple of decades. Spring (March–May) temperatures have been reconstructed back to 1500 [*Xoplaki et al.*, 2005]. Within the last half millennium, European spring temperatures of the decade 1998–2007 are very likely to be the warmest of Europe [*Xoplaki et al.*, 2005; *Luterbacher et al.*, 2007] (updated). Coldest springs appeared during the Late Maunder Minimum (1687–1716). The last approximately 100 years have experienced the largest spring temperature increase within the last half millennium with approximately +0.1 K/decade. In addition, *Xoplaki et al.* [2005] report that anomalous warm springs have become more extreme in recent decades.

[9] Evidence of unprecedented temperature rise and variability as well as observed recent phenological trends points to the need for long-term phenological records. However, only a few long and continuous phenological time series are known [*Ahas*, 1999; *Defila and Clot*, 2001; *Rutishauser*, 2003; *Schaber and Badeck*, 2005; *Menzel et al.*, 2005a; *Rutishauser and Studer*, 2007; *Aono and Kazui*, 2007]. A greater number of historical phenological observations are available for Europe, North America and Asia during certain periods, but are neither continuous [e.g., *Leopold and Jones*, 1947; *Erkamo*, 1952; *Lindsey and Newman*, 1956; *Bradley et al.*, 1999], accessible in English [e.g., *Zhu and Wan*, 1973; *Zhu*, 1973; *Yoshino*, 2004] or end in the course of the 20th century [e.g., *Margary*, 1926; *Schnelle*, 1950; *Arakawa*, 1955; *Schnelle*, 1981; *Pfister*, 1984; *Aono and Omoto*, 1994; *Sparks and Carey*, 1995; *Walkovszky*, 1998; *Holopainen et al.*, 2006]. Complete recordings of phenological observations and especially long time series become increasingly important as critical sources of information for climate impact research [*Larcher*, 2003; *IPCC*, 2007]. Long-term independent plant phenological evidence is crucial to assess the stationarity of climate impact processes. Except the very recent work of *Aono and Kazui* [2007], no continuous long-term time series covering several centuries exist to date. Thus, there is very little evidence to assess vegetation-climate interac-

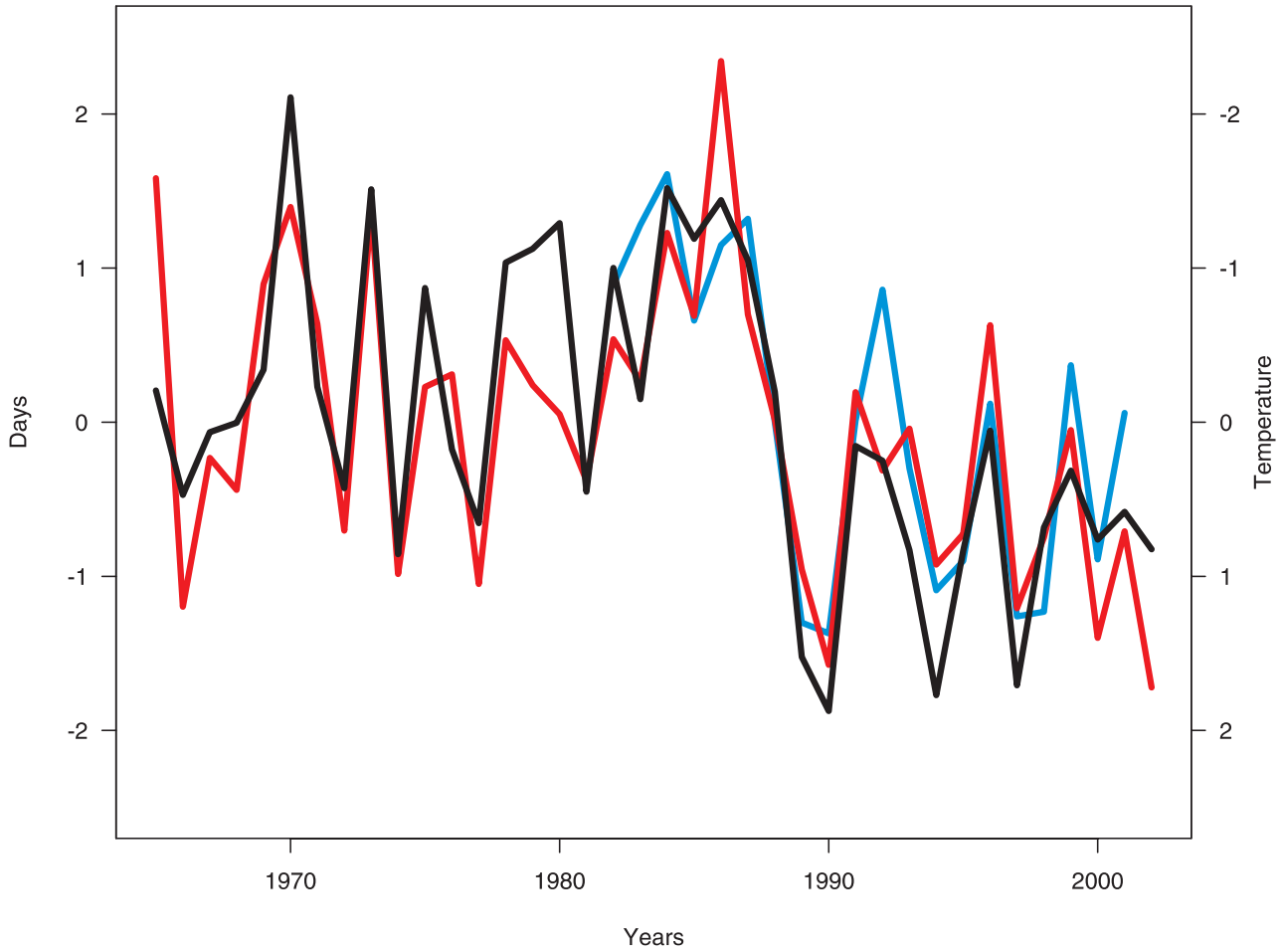

Figure 1. Comparison of spring season indicators: observed spring phenology (black line, 1965–2002) [*Studer et al.*, 2005], NDVI-derived green-up date (blue line, 1982–2002) [*Stöckli and Vidale*, 2004], and February-April mean temperature at Zurich (red line, 1965–2002) [*Begert et al.*, 2005]. Indicators are standardized with their individual mean and standard deviation (left scale: standardized days; right scale (inversed): standardized degrees Celsius).

tions continuously from preindustrial times to the present anthropogenically influenced environment.

[10] Here,we present a statistical approach to reconstruct century-long, annually resolved and continuous phenological time series of a statistical 'Spring plant'. We use records from the extended Swiss Plateau region starting in 1702. Historical documentary observations since the 1700s (http://www.euroclimhist.com) [*Pfister and Dietrich-Felber*, 2006], the century-long, ongoing time series of the flowering of the cherry tree at Liestal (northwestern part of Switzerland) [*Defila and Clot*, 2001] and a modern, nation-wide Swiss Phenological Network after 1951 (http://www.meteoswiss.ch) [*Defila and Clot*, 2005] provide suitable data. Based on historical availability we select phenological spring phases that have been observed during three centuries. Subsequently, we present a method to reconstruct a statistical 'Spring plant' from single phenological phases by fitting linear regression transfer functions. We demonstrate the possibilities and limitations with the example of phenological observation of the Swiss Plateau region and address associated uncertainties. Finally, we discuss the need and application of long-term phenological observations in the framework of global change research.

2. Data and Methods

2.1. Data Sources

[11] The study area includes the extended Swiss Plateau region (Figure 2). It comprises a range from plain to subalpine regions where phenological observations have been made (200–1000 m a.s.l.). The Plateau area is well defined in the north with the Jura mountains and the Alps in the south. The general circulation of the prevailing winds is enforced by the topographical features.

[12] We used data for the period 1702–2005. 3919 phenological records with 1037 historical observations are available before 1951 (Table 1). We define historical observations as plant phenological observations that comprise specific additional temporal and characteristical information in comparison to modern plant phenological network observations [*Rutishauser*, 2007]. First, the term historical contains temporal information. Historical observations are made prior to modern phenological networks were installed.

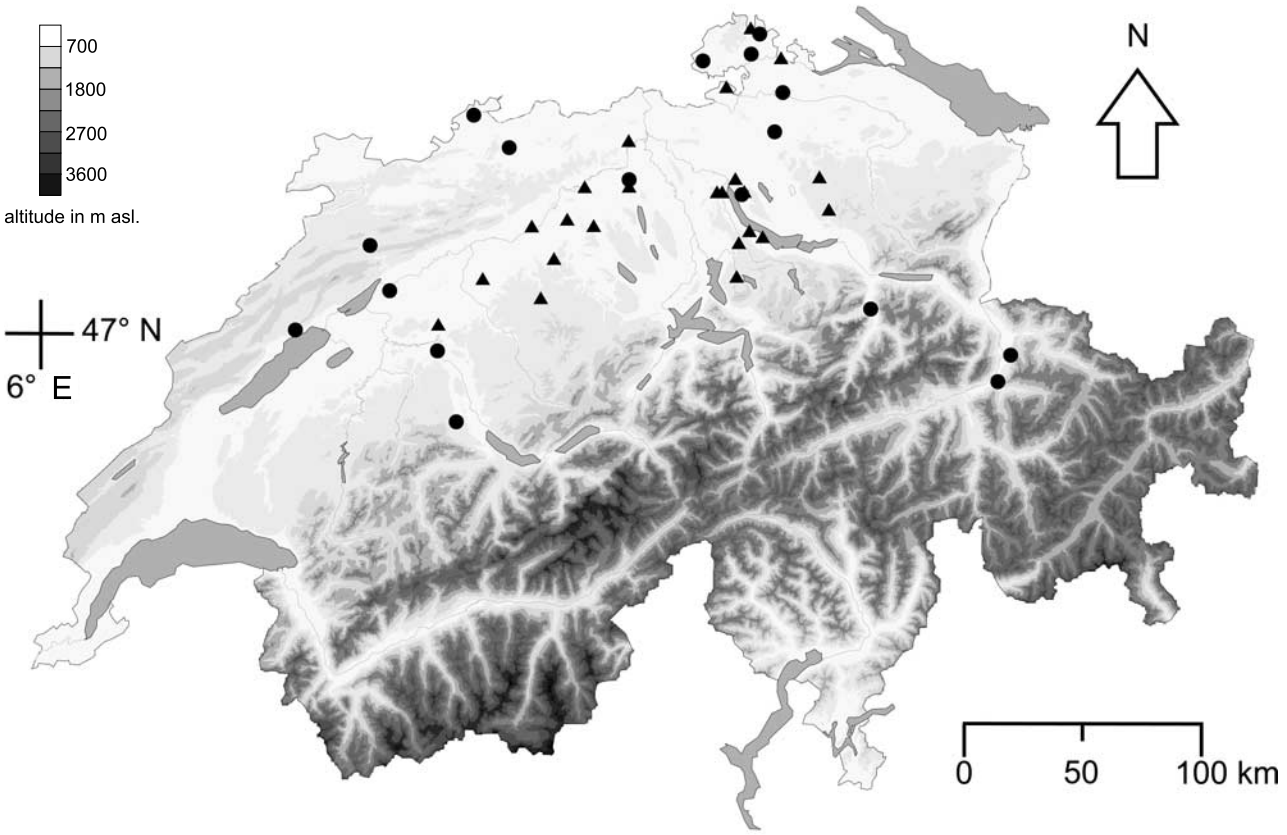

Figure 2. Location of phenological observation sites: Swiss Phenological Network 1951–2005 (triangles) and historical sites from Euroclimhist (points). Darker grey shaded areas show altitudes above the highest observation site (850 m asl.).

The start of the modern network period varies considerably among continents and countries, e.g., 1951 for Switzerland and 2006 for the NPN-USA [*Betancourt et al.*, 2007]. Second, the term historical also contains information about the nature of the phenological observation made. This aspect comprises the context that observations were made in and the place, namely personal or public archives, where the records are preserved at. Historical observations include data of present-day or past amateur naturalists or "closet phenologist" (T. Sparks in *Whitfield* [2001]) that were not strictly gathered according to modern, systematic guidelines. Thus, historical observations contain a higher amount of subjectivity. However, *Schnelle* [1955, p. 55] concluded from his vast experience with phenological observations that the most precise observations are made by genuine amateurs "for pleasure". Thus, historical observations that are often personally motivated absolutely contain reliable phenological observations. Within the systematics of paleoclimate reconstructions, historical plant phenological observations have been made with weather and climate observations and descriptions and early instrumental measurements. Historical phenological observations are classed with the group of documentary records (see *Brazdil et al.* [2005] for a review).

[13] On the basis of availability we selected the general spring phases flowering of the cherry (Prunus avium) and apple (Malus domesticus) tree, budburst of beech (Fagus sylvatica) and flowering of grape vine (Vitis vinifera). The first three phases each represent a spring event within two weeks at the end of April and beginning of May. The mean flowering date of cherry and apple tree for 1951–2005 is 23 April (standard deviation sd 10 days) and 7 May (sd 9 days) respectively, and 28 April for the budburst of beech (sd 7 days). The flowering of grape vines represents a rather late spring event with a mean date of 21 June (sd 13 days). Thus, grape vine has not been included in the definition of spring but is used in the reconstruction. Historical plant phenological observations were extracted from the Euroclimhist database [*Pfister and Dietrich-Felber*, 2006] and

Table 1. Historical and Recent Phenological Observations of the Extended Swiss Plateau Region[a]

Period	Location	Altitude	Phase	N (P, M, F, V)	Observer	Source
1702–1748	Neuchatel	447	V	44 (0,0,0,44)	NN	*Pfister* [1984]
1721–1738	Winterthur	442	P,F	41 (18,0,13,0)	Rieter	*Pfister* [1984]
1739–1842	Zollikon	480	V	125 (0,0,0,125)	NN	*Pfister* [1984]
1748–1794	Tavannes	795	F	20 (0,0,20,0)	NN	*Pfister* [1984]
1765–1783	Gurzelen	591	P, F	29 (19,0,10,0)	Sprüngli	*Pfister* [1984]
1774–1818	Glarus	472	P	45 (45,0,0,0)	NN	*Pfister* [1984]
1780–1827	Bern	540	P	40 (40,0,0,0)	Studer	*Pfister* [1984]
1785–1802	Sutz	463	P, F, V	46 (17,0,14,15)	Sprüngli	*Pfister* [1984]
1803–1813	Marschlins	534	M	7 (0,7,0,0)	von Salis	*Pfister* [1984]
1824–1863	Chur	585	V	40 (0,0,0,40)	NN	*Pfister* [1984]
1828–1838	Lenzburg	405	P	10 (10,0,0,0)	NN	*Pfister* [1984]
1840–1854	Bern	540	M	13 (0,13,0,0)	Nuscheler	*Pfister* [1984]
1854–1874	Basel	259	P	21 (21,0,0,0)	Huber	*Pfister* [1984]
1852–1875	Oberneunforn	470	P,V	29 (12,0,0,17)	Korradi	*Pfister* [1984]
1869–1881	Bern State	459–866	P, M, F	41 (14,13,14,0)	NN	*Vassella* [1997]
1881–1939	Schaffhausen	400	P	51 (51,0,0,0)	Streckeisen	*Pfister* [1984]
1881–1932	Lohn	640	P,V	67 (39,0,0,28)	NN	*Pfister* [1984]
1881–1940	Hallau	430	P,V	133 (60,0,0,73)	NN	*Pfister* [1984]
1894–2005	Liestal	320	P	112 (112,0,0,0)	Heinis	*Pfister* [1984]
1951–2005	Swiss Plateau	370–860	P, M, F, V	219 (55,55,55,54)	NN	*Defila and Clot* [2005]

[a]Period of available observations; location of observation; altitude of the observation site; phase, available phenological phases (P, Prunus; M, Malus; F, Fagus; V, Vitis); N, number of phenological observations (respective phases); observer, name of observer (NN, not known). Bern State observations are regional averages from a total of 105 Prunus, 53 Malus and 75 Fagus. Swiss Plateau values are regional averages from a total of 866 Prunus, 827 Malus, 883 Fagus and 306 Vitis observations.

from *Vassella* [1997]. All observations were thoroughly checked, digitized and published [*Pfister*, 1984; *Vassella*, 1997]. For 1951–2005, the phases of the same plant species were extracted from the Swiss Phenological Network database [*Defila and Clot*, 2005].

[14] For the first years of 1702–1713, only one observation/year is available. Subsequently, two to eight observations/year were recorded for several phases at different places. For the periods 1780–1810 and 1850–1920, more than five observations/year are recorded. Some stations recorded long continuous series of a single phase such as Zollikon after 1739 and the ongoing record of Liestal since 1894. For long records the name of the observer is not known and thus no information about the number of observer changes is available. From other stations (e.g., Winterthur, Gurzelen/Sutz, Bern, Schaffhausen), observations of several phases were made by one single observer. In addition, there is precise information about the observer written in the historical document. Therefore, we can assume that the same person observed the entire span of the record. The altitude of the observation sites range between 259 and 820 m a.s.l. Columns 4 and 5 of Table 1 describe the characteristics of the available phase and the respective number of years when this phase was observed at the particular site. Most observations were made by personal motivation of the observers except the 1864–1881 period in the State of Bern when forest wardens collected phenological observations assigned by state officials [*Vassella*, 1997].

[15] After 1951 we used observations of the Swiss Phenological Network covering the same area as the historical records [*Defila*, 1992]. The number of stations reporting per year varies between 3 and 23. After 1965 at least 15 observing stations per year are available. The observation sites span an altitude range of approximately 300–850 m a.s.l. In general, there are fewer observations of vine than of trees. There has been a decline in network observations recently as many observers are getting older and have not been replaced.

[16] For validation and interpretation, we compare our reconstructed statistical 'Spring plant' with independent, rarely available phenological long-term observations, temperature-based reconstruction for the flowering of the cherry tree and European spring temperature reconstructions. Observations include three observed regional average phenological series for southern Germany and Switzerland 1882–1998 [*Menzel et al.*, 2005b] and three single phases from Geisenheim, Germany [*Menzel et al.*, 2005a].

[17] *Menzel et al.* [2005b] averaged several plant phenological phases into three seasonal indicator series for southern Germany and Switzerland (47.5–50° N and 7.5–10.5° E) 1882–1998. Seasons contain several phases depending on the mean appearance date. 'Early spring' includes flowering of hazel, snowdrop, willow, coltsfoot (mean: 4 March). 'Late spring' includes flowering of blackthorn, red currant, sweet cherry, leaf unfolding of larch, rowan berry, birch (mean: 17 April). 'Early summer' includes elder, locust, raspberry (mean: 30 May). *Menzel et al.* [2005a] provide almost complete records of single phenological phases from a single site (Geisenheim, Germany) 1900–2000. Phases are the beginning of flowering of red currant (Ribes rubrum L., mean: 9 April), lilac (Syringa vulgaris L., mean: 25 April) and horse chestnut (Aesculus hippocastanum L., mean: 28 April). In addition, we use a temperature-based reconstruction of the flowering of the cherry tree for 1761– 2000 [*Chmielewski et al.*, 2004] and a temperature reconstruction for European land areas [*Luterbacher et al.*, 2004; *Xoplaki et al.*, 2005].

2.2. Reconstruction Method

[18] Figure 3 shows the conceptual framework to reconstruct long-term phenological records. After preprocessing we define a 'statistical plant' that can be represented by

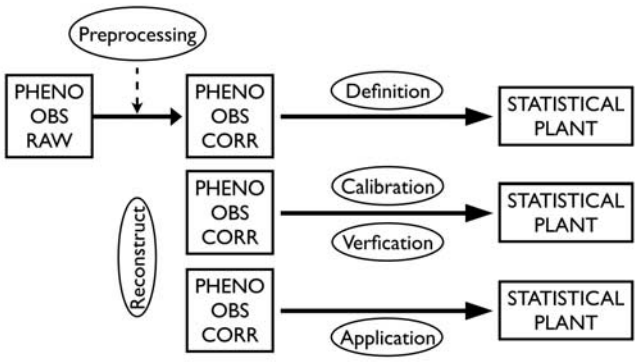

Figure 3. Methodological concept for the application of historical phenological observations to reconstruct 'statistical plants'. The available data (PHENO OBS RAW) are preprocessed. The corrected observations (PHENO OBS CORR) are used to (1) define the statistical plant (STATISTICAL PLANT), (2) to calibrate and verify transfer functions, and (3) to apply the transfer functions to the historical data to reconstruct the defined observed phenological 'statistical plant'.

individual phenological phases. Subsequently we calibrate, verify and apply statistical transfer model in such a way that single plant phenological phases can reconstruct a predefined regional average of the 'statistical plant'. In this study we consider plant phenological spring phases and call the 'statistical plant' subsequently 'Spring plant'.

2.2.1. Data Preprocessing

[19] Preprocessing includes the removal of statistical outliers, altitude corrections and calculating regional averages. Other local impact factors such as soil type or exposition can usually not be corrected because of missing information in the records. For outlier removal we apply the 30-day-rule as proposed by *Schaber and Badeck* [2002]. Observations are considered as outliers when estimated residuals of the linear models were larger than or equal to 30 days. In this study we removed 8 of 2890 network observations from the calibration period 1951–2005 (software of *Schaber* [2003]).

[20] For altitude corrections we applied the approach of *Bissolli and Schnadt* [2002] by fitting linear regression models and using the slope as altitude gradients. In our analysis station series were corrected to a reference altitude level of 500 m a.s.l.. Gradients are 2.6 days/100m and 2.5 days/100m for cherry and apple respectively and 0.9 days/100m for beech budburst.

[21] Regional averages are calculated after *Schaber and Badeck* [2002] that found that two-way crossed linear mixed models with random station effects a_i and fixed year effects b_j most appropriately describe the common interannual phenological variability (x_{ij}) in the region of interest:

$$x_{ij} = m + a_i + b_j + \epsilon_{ij} \tag{1}$$

where m is a constant and ϵ_{ij} are independent identically distributed random errors with assumed expectancy $E(e_{ij}) = 0$ and common variance σ_e^2 (software of *Schaber* [2003]).

2.2.2. Calibration and Application Reconstruction Models

[22] We define the 'Spring plant' S_{def} for each year in the calibration period 1951–2005 such that:

$$S_{def} = \frac{1}{n}\sum_{k=1}^{n} K_k \tag{2}$$

where K_k are the available phenological observations for S_{def} and n are the number of observations in each year (Figure 3, top). The number of observations per year n and the combination of the available phases can change for every year.

[23] For the 1951–2005 period, we calculate regional average series for the selected phenological phases P where the subscript l indicates the respective phases (equation (1)). We calibrate transfer functions between the 'Spring plant' S_{def} and regional average series of P_l (Figure 3, middle). For each regional average series of the phenological phase P_l we estimate regression parameters α_{Rl} and β_{Rl} that

$$S_{def} = \alpha_{R_l} + \beta_{R_l} P_l + \epsilon_{R_l} \tag{3}$$

ϵ_{Rl} is the phase-specific error term. Transfer functions can be calibrated for any phenological phase in addition to the phases selected for the 'Spring plant'.

[24] We then apply the transfer function to the phenological observations for the 1702–2005 period (Figure 3). We transform the observations K_k with the phase specific transfer functions P_l into single observations of the 'Spring plant' K_l such that

$$K_l = \alpha_{R_l} + \beta_{R_l} K_k + \epsilon_{R_l} \tag{4}$$

[25] Finally, we apply equation (1) to the single observations of the statistical plant K_l such that S_{recon} represents the annual values of a regional average series of the statistical plant:

$$S_{recon} = m + a_i + b_j + \epsilon_{ij} \tag{5}$$

[26] In this reconstruction we defined the 'Spring plant' S_{def} as the average of the flowering of apple and cherry tree and budburst of beech (K_k in equation (2)). Phase-specific transfer functions (equation (3)) were fitted for each phenological phase (Prunus, malus, fagus and vitis) for the calibration period 1951–2005.

2.2.3. Verification of Reconstruction Models

[27] For uncertainty estimates, we cross-validated [*Michaelsen*, 1987] each phase-specific transfer function in the period 1951–2005. In our analysis each year was withheld once from the data set and the transfer model was performed with the retaining years. Subsequently, we calculated root-mean-square error (RMSE) [*Wilks*, 1995] and reduction of error (RE) [*Lorenz*, 1956; *Cook et al.*, 1994] measures for each phase-specific transfer function. The RE-test statistics is

$$RE = 1.0 - \left[\frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x}_c)^2}\right] \tag{6}$$

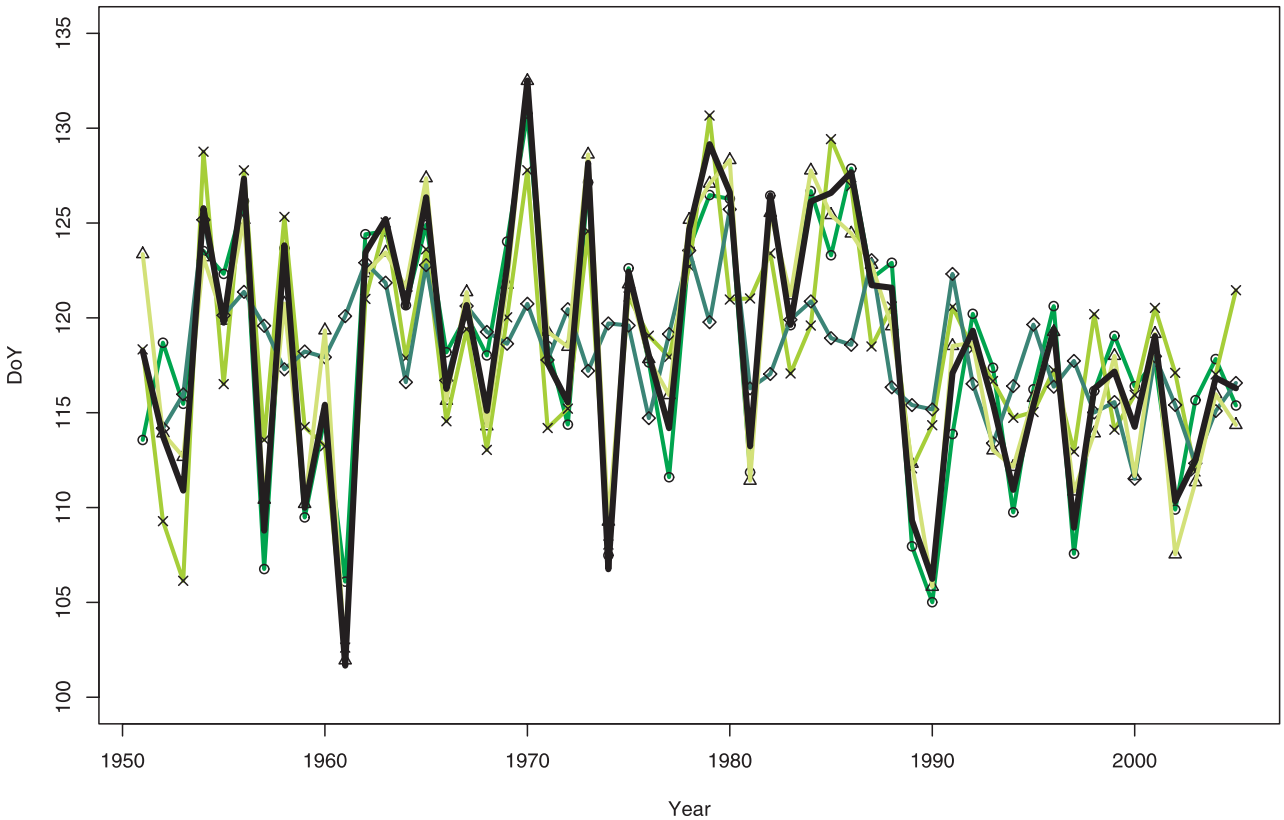

Figure 4. Temporal evolution of the selected phenological phases of the Swiss Phenological Network 1951–2005. Bold line shows the defined statistical 'Spring plant'. Reconstructions of 'Spring plant' values from the single phenological phases flowering of the cherry tree (Prunus avium; circles), flowering of the apple tree (Malus domesticus; triangles), budburst of beech (Fagus silvaticus; crosses) and flowering of vine (Vitis vinifera; diamonds). DoY indicates the Day-of-Year in days since 1 January.

where n is the length of the verification period, x_i represents the observations and $\hat{x}_i$ their estimates in the verification period. $\bar{x}_c$ represents the mean of the calibration period. The RE statistics describes the relation of the squared reconstruction error to the squared anomalies from the climatological mean. Here we adapt the RE statistics to the cross-validaton set up. In consequence, x_i are reconstructed 'Spring plant' values using the transfer function over the full 1951–2005 period, $\hat{x}_i$ are independent estimates of n cross-validation models and $\bar{x}_c$ is the mean of the defined 'Spring plant' S_{def}. The range of RE is from $-\infty$ to + 1. Zero represents the long-term mean. Increasingly positive RE-values represent increasing skill of the regression. A RE of + 1 is a perfect reconstruction whereas a RE of −1 is a random guess from a properly fitted distribution. Values between $-1 < \mathrm{RE} < 0$ is better than a random choice, but worse than the long-term mean. In addition, we calculated observation variability for the calibration period 1951–2005 as the average of the phase-specific, 2-standard error limits of all K_I.

[28] For smoothing, we apply a 20-year gaussian filter. Uncertainties for the 20-year gaussian filtered reconstruction of the 'Spring plant' are estimated using the mean 2-standard deviation range of S_{dev} from the calibration period 1951–2005 after making it consistent with Gaussian white noise [*Mann et al.*, 1998; *Briffa et al.*, 2002; *Xoplaki et al.*, 2005]. For comparisons of different long-term records, we apply moving trend window analysis [*Menzel et al.*, 2004]. Slopes of linear regression are calculated for each 30-year period around a center year that is shifted with a 1-year time step.

3. Results

[29] Figure 4 shows the 'Spring plant' as defined from the available data (bold line) and the reconstructions of the respective phase-specific regional averages in the period 1951–2005. The individual phases clearly represent the interannual variability of the defined 'Spring plant'. Early (e.g., 1961, 1974, 1990) and late springs (e.g., 1970, 1979, 1986) of the 'Spring plant' are well represented by three of

Table 2. Reconstruction Skill of the Individual Phases for the Estimation of the Statistical 'Spring Plant'[a]

Phase	SDest, days	R2, %	RMSE_{CV}, days	RE_{CV}
Cherry	10.3 ± 1.8	91	1.9	0.6
Apple	10.8 ± 1.9	92	1.9	0.5
Beech	12.0 ± 2.5	73	3.4	0.9
Vine	6.1 ± 1.5	20	6.1	0.03

[a]SDest indicates the 2-standard deviation range of the reconstructions when the transfer function is applied to all individual stations 1951–2005 (data uncertainty; see Figure 5). R2 is the variance of the 'Spring plant' explained by the respective single phase regression model. RMSE_{CV} and RE_{CV} indicate the root-mean-squared error and reduction of error of the cross validated 'Spring plant' reconstructions (statistical uncertainty; see 'Methods' for details).

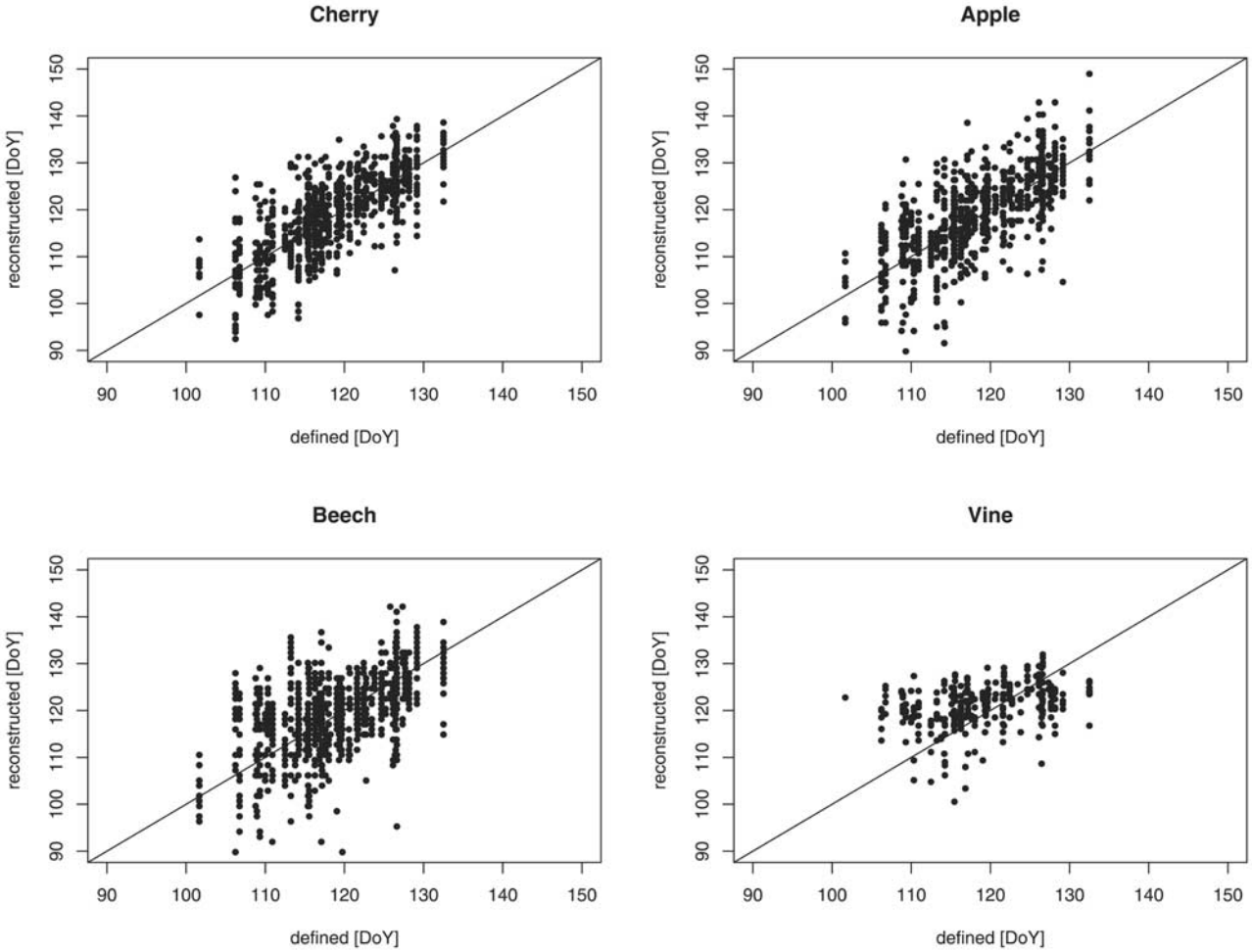

Figure 5. 'Spring plant' against reconstructed values from individual phases of cherry and apple tree flowering, budburst of beech and flowering of vine. DoY indicates the Day-of-Year as days since 1 January (see Table 2 for statistics).

the single phases. Cherry, apple and beech explain 91, 93 and 75% of the 'Spring plant' variance respectively (Table 2). The error (RMSE) is between 1.9 and 6.1 days for cherry and vine respectively resulting in a mean reconstruction uncertainty of ±3.4 days. RE values are all positive indicating reconstruction skill better than the long-term mean (1951–2005). However, Vitis (diamonds) only explains 20% of the 'Spring plant' variance and shows the lowest RE score (0.03) due to lower interannual variability (standard deviation of the estimates, SDest, 6.1±1.5, Table 2) than the phases included in the 'Spring plant'.

[30] Taking into account observation variability in the period 1951–2005 and applying the transfer functions to all stations (Figure 4 and Table 2), we reconstruct 'Spring plant' values within a variability of 6.1 ± 1.5 to 12 ± 2.5 days for grape vine and beech respectively (Figure 5). Observation variability for the reconstruction period are calculated as the mean of each phase with a value of ±10 days.

[31] The statistical transfer functions are applied to the historical observations in order to reconstruct spring variability back to 1702 (Figure 6). The mean appearance dates for the calibration period (1951–2005, "observed") and the reconstruction period (1702–1950, "reconstructed") are both on 28 April (DoY 118). The 20-year gaussian filtered curve shows decadal changes (bold line) with associated smoothed 2-standard errors of ±3.6 days. Dashed horizontal lines indicate the ±2-standard deviations of the calibration period of ±10 days and the vertical line shows the beginning of the calibration period. In this record, the earliest observation occurred in 1961 (14 April) whereas the latest 'spring' was observed in 1879 (13 May; Table 3).

[32] The most recent 30 year do not show a cumulation in extreme years as the interannual variability of the spring dates is low in comparison with earlier periods. However, the 1975–2005 interval is characterized by a large number of early years. Most of the years after 1990 are before the reconstruction mean. Similar conditions were only prevalent during the period 1702–1729 though with higher uncertainties due to a smaller number of observations. Groups of late single years are seen in the 1960s, 1875 and 1850s when spring appears more than half a week later than in the reconstruction mean. The 20-year gaussian filtered curve highlights periods of early and late years (Figure 6). The 1940s, 1910s and 1890s generally experienced earlier springs. The 1730s show even earlier springs than the

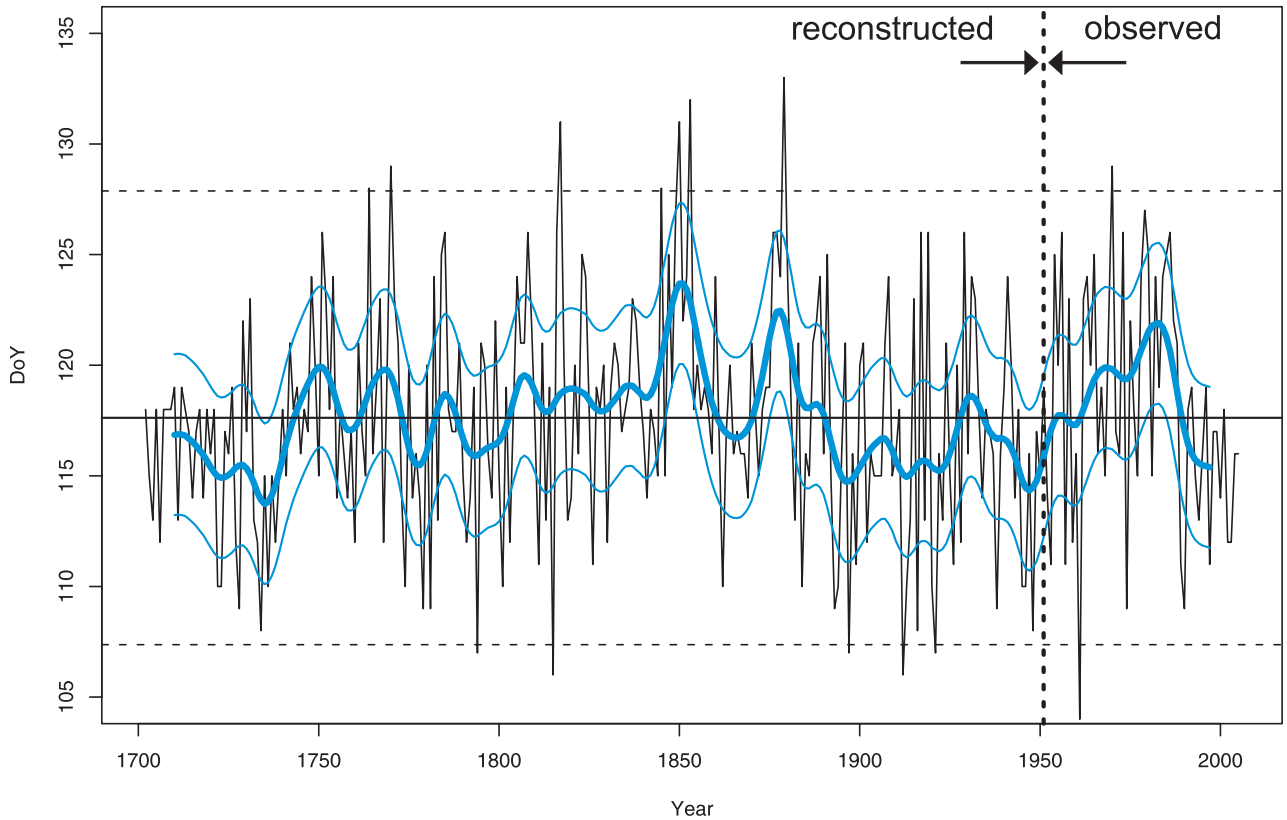

Figure 6. Statistical 'Spring plant' for the Swiss Plateau region 1702–2005. Twenty-year gaussian filter shows decadal changes (bold blue line) with associated reconstruction uncertainties (thin blue lines) according to *Mann et al.* [1998], *Briffa et al.* [2002], and *Xoplaki et al.* [2005]. Horizontal line shows the long-term mean (27 April; DoY 117). The dotted lines indicate the 2-standard deviation range of ±10 days of the entire period (1702–2005). Vertical dotted line indicates change of observations: reconstructed from historical phenological observations before 1951, observed from Swiss Phenological Network after 1951. DoY indicates the Day-of-Year as days since 1 January.

present. This is in agreement with recent evidence from different European areas that springs in the 1730s were among the warmest [e.g., *Xoplaki et al.*, 2005; *Jones and Briffa*, 2006]. Late periods occurred in the 1960s and generally around the mid 19th century. The 1860s and 1845–1853 are the two periods in the record with latest springs.

[33] In order to assess the reconstructed phenological 'Spring plant' we compared it to eight independent spring and early summer indicators (Figure 7). First, correlations were calculated between the reconstructed 'Spring plant' and three observed regionally averaged phenological seasons for southern Germany and Switzerland 1882–1998 (Figures 7a–7c [*Menzel et al.*, 2005b]). All correlations are highly significant ($p < 0.001$). 'Late spring' phases indicate strongest correlations with the Swiss 'Spring plant' whereas 'early spring' and 'early summer' phases are less well correlated. As expected, correlations are highest with records that are close and averaged over several phenological phases (Figures 7a–7c). The season closest to the mean onset date of the Swiss 'Spring plant', late spring (mean 17 April), explains 74% of the variability of the 'Spring plant'. Only one of five phases that are included in the 'early spring' season, flowering of the cherry tree, is part of both records. Early spring and summer observations are not as well correlated. These comparisons give us confidence that the concept of a representative, 'Spring plant' can reproduce phenological variability.

[34] Figures 7d–7f show comparisons between three single phases at the western-central German location of Geisenheim [*Menzel et al.*, 2005a]. Highest correlation was found with red currant and horse chestnut (Figures 7d–7f) even though only horse chestnut has a similar onset date in late April like the 'Spring plant'. In addition, we compared the 'Spring plant' with two temperature indicators. The temperature-derived (February–April mean) reconstruction

Table 3. Ten Earliest and Latest Single Years of the Swiss 'Spring Plant' 1702–2005

Earliest Years	Day	Date	Latest Years	Day	Date
1961	104	14 Apr	1879	131	11 May
1815	105	15 Apr	1817	130	10 May
1794	107	17 Apr	1853	130	10 May
1779	108	18 Apr	1917	130	10 May
1781	109	19 Apr	1919	130	10 May
1974	109	19 Apr	1891	129	9 May
1990	109	19 Apr	1929	129	9 May
1897	110	20 Apr	1970	129	9 May
1912	110	20 Apr	1770	128	8 May
1921	110	20 Apr	1850	128	8 May

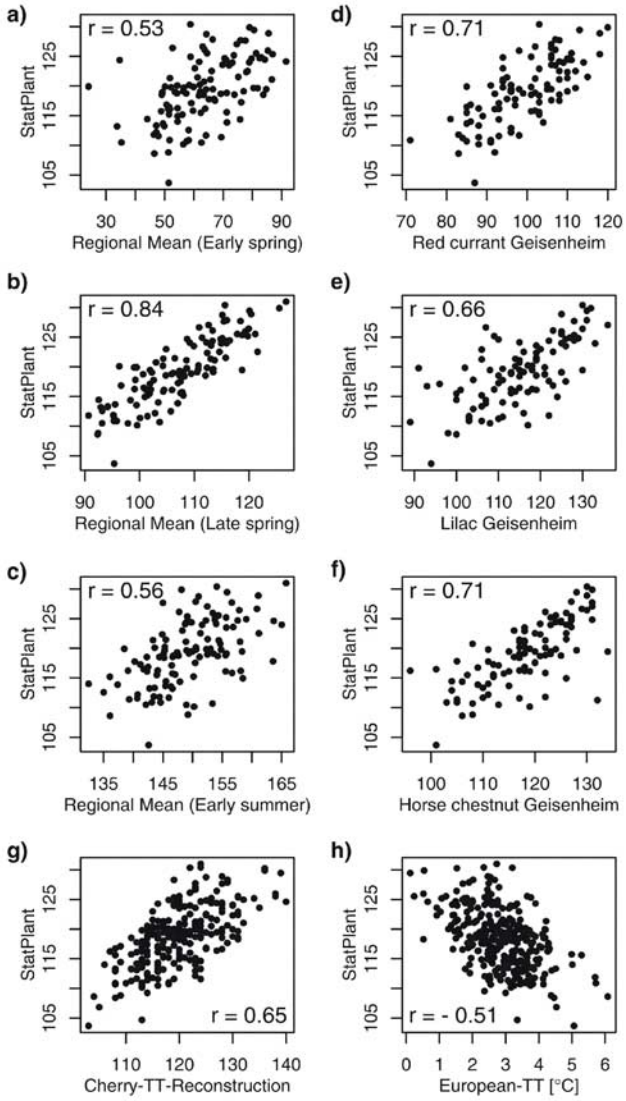

Figure 7. Comparisons of the Swiss 'Spring plant' [StatPlant] with other spring indicators. The common variability is described by Pearson's correlation coefficients r (all correlations are significant at the 99% level). Units are number of days since 1 January. (a–c) Regional, observed average of three selected phenological phases representing 'early spring', 'late spring' and 'early summer' for southern Germany and Switzerland 1882–1998 [*Menzel et al.*, 2005b]. (d–f) Three single phases at Geisenheim (Germany) 1900–2000 [*Menzel et al.*, 2005a]. (g) Reconstructed flowering of the cherry tree in Germany 1761–2000 [*Chmielewski et al.*, 2004]. (h) Spring (February–April) temperatures [°C] for European land areas 1702–2005 [*Luterbacher et al.*, 2004; *Xoplaki et al.*, 2005]. See section 'Data Sources' for details of all indicators [*Luterbacher et al.*, 2007].

of the flowering of the cherry tree corresponds well with the observed 'Spring plant' (Figure 7g, $r = 0.65$, $p < 0.001$ [*Chmielewski et al.*, 2004]). The correlation is somewhat lower but still significant when the phenological reconstruction is compared with European February–April mean land temperatures (Figure 7h [*Luterbacher et al.*, 2004, 2007; *Xoplaki et al.*, 2005]).

[35] For further comparisons we applied moving trend analysis to three independent but similar spring indicators (Figure 8). The indicators include the 'Spring plant', a long-term single phenological record (beginning of flowering of red currant) at Geisenheim, Germany, and a temperature-derived reconstruction of the flowering of the cherry tree for Germany. The moving linear trend series of the reconstructed Swiss 'Spring plant' shows a pronounced trend of more than three days/decade for the 1975–2005 period towards earlier spring events. Regarding the past 300 years, the periods of 1935–1960, 1850–1870 and 1770–1810 show also negative trends of more than 2 days/decade. Positive trends of more than 2 days/decade are found for the years 1950–1970 and 1870–1900. A less pronounced tendency towards later springs can be found between 1920–1935 and 1790–1850.

[36] For the 20th century linear trend series for the single phenological record and the temperature derived reconstruction are also available. All three linear trend series show a general agreement with more positive trends until the 1970s and a sudden change to negative trends and earlier onsets afterwards (Figure 8). The Geisenheim record exceeds all the previously observed trends in the past 30-year period (blue line). The other two analyzed records stay within the range of the past 250 years. For the last decades and the 1940s, the statistical plant shows similarities to the temperature-based reconstruction (red line). For the 1960s, the two observed indicators of Switzerland and Germany have both positive trend coefficients whereas the temperature-based reconstruction shows a period of negative signs.

[37] In summary, the statistical 'Spring plant' derived from cherry and apple tree flowering, beech budburst and vine flowering back to 1702 show the earliest spring on 14 April 1961 (earliest decade 1730–1740) and the latest spring on 13 May 1879 (latest decade 1845–1855). The current conditions are only similar in the period 1702–1729 though based on fewer observations per year. Generally earlier springs occurred also in the 1940s, 1910s and 1890s whereas late periods are documented for the 1960s and the mid 19th century and correspond well with independent phenological observations and temperature-based reconstructions.

4. Discussion

[38] There is ample evidence that plant phenological observations follow the variability of other independent spring indicators such as temperature and the onset of greenness as derived from satellite imagery (Figure 1). Despite the high correlation of interannual variability, intraseasonal decoupling can lead to distinct differences in the development of single years (e.g., 1980, 1986). However the length of many phenological records is limited to a few decades. Here we tackle the question of data limitations and reconstruct a multi centennial phenological 'Spring plant' record. This record not only allows us to put current temperature-impact analyses in a long-term perspective but also to describe more complex impact factor combinations.

[39] Whilst using historical phenological observations we have to be aware of the limitations that arise from the finite

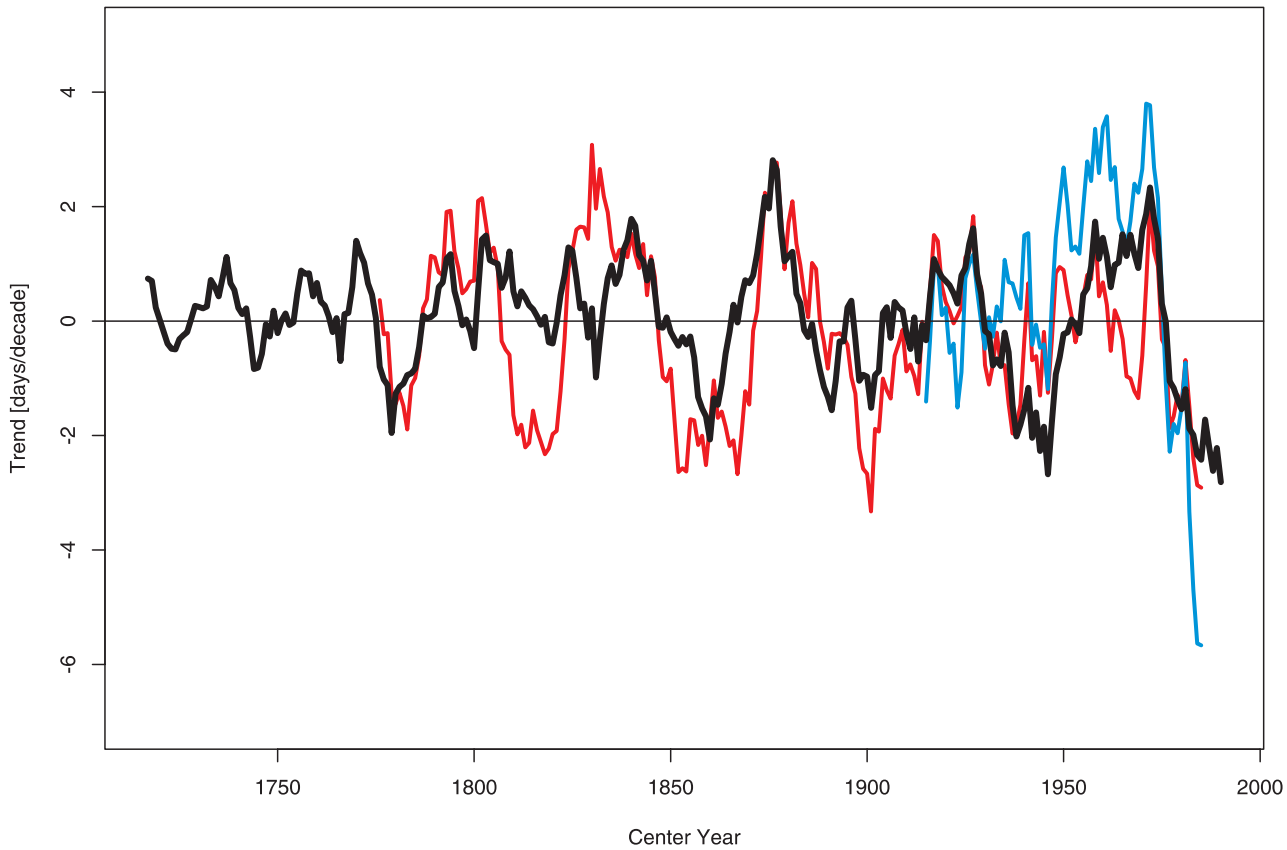

Figure 8. Thirty-year moving trend windows of the statistical 'Spring plant' for Switzerland (black line), the reconstruction of the flowering of the cherry tree from German February–April mean temperatures (red line) [*Chmielewski et al.*, 2004] and an observed single phenological spring phase (beginning of flowering of red currant Ribes rubrum L.) at Geisenheim, Germany (blue line) [*Menzel et al.*, 2005a].

availability of sources (Table 1 and Figure 2). In order to overcome the data limitations, we defined a statistical 'Spring plant' that accounts for historical availability of specific plant phenological phases. Similar approaches were used by *Studer et al.* [2005] and *Chmielewski et al.* [2004]. However, these studies aimed at integrating several phenological phases into a more robust mean 'statistical plant' for late 20th century. Thus, we combine the arguments of *Studer et al.* [2005] and *Chmielewski et al.* [2004] with the limited number of historical data.

[40] For the 1965–2002 period, spring indicators from Figure 1 are correlated with the 'Spring plant'. It clearly follows the statistically more complex spring index based on 15 phenological phases of *Studer et al.* [2005] very well ($r = 0.93$, $p < 0.001$). Correlations at interannual timescale between the 'Spring plant' and the satellite-derived indicator and February–April mean temperatures at Zurich return highly significant correlations ($r = 0.85$; $p < 0.001$). Thus, the approach of selecting key phenological phases applied here yields statistical coherence with phenological indices based on more data [*Studer et al.*, 2005] and satellite observations [*Stöckli and Vidale*, 2004]. Furthermore, spring temperature as the main driver of theses indicators has strong power for explaining vegetation variability during the green-up in spring.

[41] In addition to the three spring phases that defined the statistical 'Spring plant', we also included a fourth phase (flowering of the grape vine) even though this phase describes a rather late phenological spring event. But flowering of grape vine is prominent in historical documentary sources and has often been recorded. *Pfister* [1984, 1999] and *Pfister and Dietrich-Felber* [2006] provide historical phenological observations that were soundly checked and analyzed with historical source critical methods. The limitations of availability balance the valuable information of directly observed phenological variability.

[42] In order to overcome the limitations, we developed a processing chain for historical phenological observations (Figure 3). The two most important steps are combining single phenological records to regional time series (Figure 3; preprocessing) and defining and reconstructing a statistical 'Spring plant'. By combining three spring phases with each other we derived a mean, regionally averaged time series of spring variability that follows the methodological proposal of *Häkkinen et al.* [1995] and *Schaber and Badeck* [2002]. Despite the nonprofessional data construction and its often noncontinuous character our assessment has produced useful information and a robust indicator of spring variability. The method based on a linear model of the analysis of variance and maximum likelihood estimations was considered preferable to simple arithmetic mean [*Häkkinen et al.*, 1995]. It was considered the most suitable way to overcome systematic linear effects of differences in observers, genotypes, geography and microclimate within a defined region.

Still, *Holopainen et al.* [2006] successfully applied simple arithmetic means of standardized phenological station series into regional averages and reconstructed a phenological climate proxy series for southern Finland back to 1750.

[43] *Schaber and Badeck* [2002] tested all proposed methods with independent data from three regions in Germany. They support the findings of the Finnish study [*Häkkinen et al.*, 1995] and additionally tested the methods in the framework of linear models by Monte Carlo experiments of synthetic data. We confirm the feasibility of the results by *Schaber and Badeck* [2002] with Swiss data. The calculations of regional individual phase averages showed good results for the Swiss network data. Confidence intervals for a phase-specific regional average series lie between 7.5, 7.2 and 6.5 days for cherry, apple and beech respectively (Figure 5).

[44] In an additional step, we calibrated linear regression models between the regional single phase averages and the defined statistical 'Spring plant' (Figures 4 and 5). Assuming constant linear relationship between phenological phases and the statistical plant, we reconstructed an indicator of spring variability of a defined area for the time before the establishment of phenological networks. The uncertainty of the observations is much larger (6.1–12 days) in contrast to the statistical uncertainty derived from the variance of the residuals (Table 2). The statistical error by itself leads to an uncertainty of 1.9 to 6.1 days (Table 2). The combination of a quantitative uncertainty range of well-defined modern network observations (1951–2005) and the sound qualitative documentary source analysis gives us a total uncertainty estimate for the calibration period 1951–2005 of ±10 days (Figure 6). On a decadal timescale, uncertainties are approximately ±3.6 days when we account for autocorrelated effects of the filtering.

[45] In the long-term perspective, we have the unique possibility to assess changes in phenological times series. In 1989 for example, a wide spread shift towards earlier onsets of spring is documented in many European phenological time series [e.g., *Studer et al.*, 2005]. Our 'Spring plant' also shows a clear shift of about two weeks and a subsequent high number of early spring onsets mostly below the reconstruction mean (Figures 4 and 6). However, the change seems not unique in its amplitude. Throughout the record we note extreme changes such as 1961–1962 and 1879–1880. The period 1910–1925 shows a longer period of high amplitudes including two of the ten earliest years in the record and three late years (see also Table 3).

[46] Phenological spring observations show high correlations even over large distances. The single records at Geisenheim, Germany (Figures 7d–7f) significantly correlate despite the large distance of 500 km. Red currant and horse chestnut correspond best, explaining 50% of the variance of the Swiss 'Spring plant'. Both phases appear in April even though one appears in the beginning (red currant; 9 April) and the other one at the end of the month (horse chestnut; 28 April). Lilac (25 April) in turn has a very similar appearance date as the 'Spring plant' but only explains 44% of the variance.

[47] There is evidence that phenological variability is influenced by temperatures over a large spatial area (Figures 7g and 7h). When temperatures are averaged over a large region such as the European land area (Figure 7h [*Xoplaki et al.*, 2005]) correlation and, thus, temperature impact decreases. Temperature alone explains 25% of the 'Spring plant' variance. On the other hand, the comparison between the 'Spring plant' with the temperature-based reconstruction for Germany (Figure 7g) shares more than 40% of the variance of the 'Spring plant' 1761–2000. If a temperature record closer to the phenological observation area is chosen, then more than 60% of the phenological variability can be accounted for by temperature alone (Figure 1).

[48] Analyses of the Swiss 'Spring plant' relating to dates before 1900 are only possible with the temperature-based reconstruction of phenological events such as Figure 7g or with reconstructed temperature [*Xoplaki et al.*, 2005]. Peaks of trends are in phase (1860s, 1800s, 1780s) or out of phase (1890s, 1840s). Differences in amplitude are shown for the 1820s and 1870s whereas the turn to the 20th century, the 1850s, 1830s and 18th century agree in amplitude and trend sign. This is an indication that the temperature impact at different spatial scales has not been stable over time.

[49] The independent time series of the 'Spring plant' offers the means for comparisons with other spring indicators. We choose moving linear trend analysis on three independent time series (Figure 8). There is evidence that the end of the 20th century shows unprecedented agreement of observed and temperature-based cherry flowering reconstructions with strong negative trend signs. The magnitude of the observed records diverge when the Swiss 'Spring plant' shows a trend of −3 days/decade and the Geisenheim record a much stronger trend of −6 days/decade.

[50] Still, our findings correspond with the vast majority of studies across the Northern Hemisphere in sign and magnitude [e.g., *Parmesan*, 2006]. However, earlier periods of the analysis depict a more complex situation. After the 1930–1960 period the trends of the two observed records ('Spring plant' and red currant at Geisenheim) agree in sign and magnitude whereas the temperature-based reconstruction of the German cherry record does not show the strong positive trend of 1950 to 1970. Moreover, it shows negative trends in the period 1945–1975. In general, the Swiss 'Spring plant' shows similar trends as all of the other indicators (Figure 8).

5. Conclusions and Potential Application

[51] We present a reconstruction of a statistical 'Spring plant' that describes central European spring variability back to 1702. This reconstruction is solely based on historical phenological observations and is therefore entirely independent from other spring indicators derived from climate variables such as temperature measurements or climate and vegetation model results. The statistical 'Spring plant' is defined as the weighted average of apple and cherry tree flowering and budburst of beech. It has been reconstructed as a representative for the Swiss Plateau region by applying mixed linear model estimations for regional averages and regression models that reconstruct the annual 'Spring plant' value. The uncertainty range at interannual timescales is ±10 days and ±3.6 days at decadal timescales. The current 30 years of reveal a large number of early years.

[52] The earliest observation of the 'Spring plant' occurred in 1961 (14 April) whereas the latest 'spring' was observed in 1879 (13 May). Within the context of the past 300 years, the recent decades do not show a cumulation of extreme years but a large number of early years. Most of the years in the period after 1990 are before or very close to the long-term mean. Periods of earlier springs are also documented for 1900 and the 1940s and especially for 1700–1750. The temperature based reconstruction of cherry flowering dates in Germany and the long-term records from Geisenheim (Germany) starting in the 1880s show significant correlations with the Swiss 'Spring plant'.

[53] Moving linear trend analysis puts the development of the last 30 years into a century scale perspective on three long-term phenological records (Swiss 'Spring plant', Geisenheim flowering of red currant, German temperature-based reconstruction of cherry flowering). The most recent decades reveal unique agreement of all three records analyzed. In the context of the last 300 years, current trends Swiss 'Spring plant' and reconstructed German cherry flowering do not show unique magnitude in trends.

[54] With this new method estimating 'Spring plants' from a vast range of historical documents we have derived a unique phenological record to separate past interannual, decadal natural variability from anthropogenic impacts. Future analysis will have to focus on quantifying the influence of major climate parameters on the onset of spring and describe stationarity and nonstationarity in climate-plant-interactions (C. Schleip et al., Impact of climate change on summer and spring phenology in Switzerland in the last 250 years, submitted to *Journal of Geophysical Research*, 2007). It must also include large scale circulation and phenology interactions as they might provide additional evidence on the influence of pressure patterns that govern plant phenological changes in spring. Phenological observations will contribute significantly to the understanding of past climate-plant interactions and will help verify results from coupled climate models. Linking plant spring development with climatic drivers will lead to a better understanding of climate-vegetation-interactions.

[55] **Acknowledgments.** We thank all past and present plant observers for their effort in observing and recording phenological stages of a wide range of species. This research is supported by the Swiss National Science Foundation (project "Past, Present and Future Climate Impact on Spring and Summer Vegetation-a Phenological Approach" contract 205321-105691/1) and through its National Center of Competence in Research on Climate (NCCR-Climate), project "Paleoclimate Variability and Extreme Events PALVAREX". The publication was financially supported by the Foundation Marchese Francesco Medici del Vascello. Data of the Swiss Phenological Network were provided by Meteo Swiss. Thanks to Sibylle Studer and Reto Stöckli for providing the PCA-Index and NDVI time series for Figure 1 and Frank-M. Chmielewski for the temperature-based German cherry flowering reconstruction. We appreciate comments of the editors, David Inouye and an anonymous reviewer that helped to improve the quality of the manuscript.

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