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Exceptional European warmth of autumn 2006 and winter 2007: Historical context, the underlying dynamics, and its phenological impacts

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[1] Updated European averaged autumn and winter surface air temperature (SAT) timeseries indicate that the autumn 2006 and winter 2007 were extremely likely (>95%) the warmest for more than 500 years. In both seasons, the European SAT anomaly is widespread with anomalies up to three standard deviations from normal. The anomalous warmth is associated with strong anticyclonic conditions and warm air advection from south west. Phenological impacts related to this warmth included some plant species having a partial second flowering or extended flowering till the beginning of winter. Species that typically flower in early spring were found to have a distinct earlier flowering after winter 2007. **Citation:** Luterbacher, J., M. A. Liniger, A. Menzel, N. Estrella, P. M. Della-Marta, C. Pfister, T. Rutishauser, and E. Xoplaki (2007), Exceptional European warmth of autumn 2006 and winter 2007: Historical context, the underlying dynamics, and its phenological impacts, *Geophys. Res. Lett.*, *34*, L12704, doi:10.1029/2007GL029951.

1. Introduction

[2] Reconstructed seasonal surface air temperature (SAT) indicates the late 20th/early 21st century European climate being very likely warmer than that of any time during the past centuries [*Luterbacher et al.*, 2004; *Xoplaki et al.*, 2005; *Casty et al.*, 2007]. The recent regional warming has already affected physical and biological systems [*Intergovernmental Panel on Climate Change (IPCC)*, 2001]. Prominent temperature driven changes in nature are observed impacts on plant phenology, such as an earlier start of spring in mid and higher latitudes of the northern hemisphere [e.g., *Menzel and Fabian*, 1999; *Sparks and Menzel*, 2002; *Menzel et al.*, 2006; T. Rutishauser et al., A phenology-based reconstruction of interannual changes in past spring seasons, submitted to *Journal of Geophysical Research,* 2007]. Warmer autumns have impacts on the timing and secondary flowering of some species [e.g., *Gange et al.*, 2007] or on animals that might miss the signal to reduce their winter activity or leave too late to warmer areas [*Walther et al.*, 2002]. The exceptionally strong continental warming trend and lengthening of the growing season over the last decades were recently attributed to anthropogenic influence [e.g., *Stott*, 2003; *Christidis et al.*, 2007]. The exceptional hot European summer of 2003 [e.g., *Luterbacher et al.*, 2004; *Schär et al.*, 2004; *Büntgen et al.*, 2006] had enormous adverse social, economic and environmental effects. More recently, the autumn 2006 (AU06) and the winter 2006/2007 (WI07) were in many parts of Europe the warmest on record (e.g., M. Beniston, Entering into the "greenhouse century": Recent record temperatures in Switzerland are comparable to the upper temperature quantiles in a greenhouse climate, submitted to *Geophysical Research Letters,* 2007, hereinafter referred to as Beniston, submitted manuscript, 2007) causing problems to alpine tourism due to exceptionally low snow amounts, exacerbating drought conditions and water shortages in parts of the Mediterranean [*Xoplaki et al.*, 2004] with impacts on hydropower production and agriculture. Here we study the exceptionally warm European AU06 and WI07 from a climatological and dynamical point of view, shed light on how exceptional this period is in the context of the past centuries and address impacts on phenology. Finally we put the current warm conditions in the context of future climate change in Europe.

2. Data and Methods

[3] We used the European autumn and winter SAT reconstructions back to 1500 by *Luterbacher et al.* [2004] and *Xoplaki et al.* [2005], which were statistically estimated using a combination of long instrumental data and temperature index series derived from documentary evidence [e.g., *Brázdil et al.*, 2005]. The European data were updated using monthly values from September 2006 to February 2007 [*Hansen et al.*, 2001]. A one-sided Welch t-test [*Welch*, 1947] was used to assess the significance of the difference between the AU06 and WI07 and previous best estimates of extremes back to 1500 (see auxiliary material[1]). Other sources of climate information come from the 12th and 13th century chroniclers who used quasi objective indicators in the cryosphere and the biosphere to document extreme climate anomalies. In this way, the magnitude of warm winter anomalies can be assessed from phenological observations and from observed absence of snow and frost [*Pfister et al.*, 1998]. For the analysis of the spatial structure, the anomalies of SAT and geopotential height at 500 hPa

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[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2007gl029951. Other auxiliary material files are in the HTML.

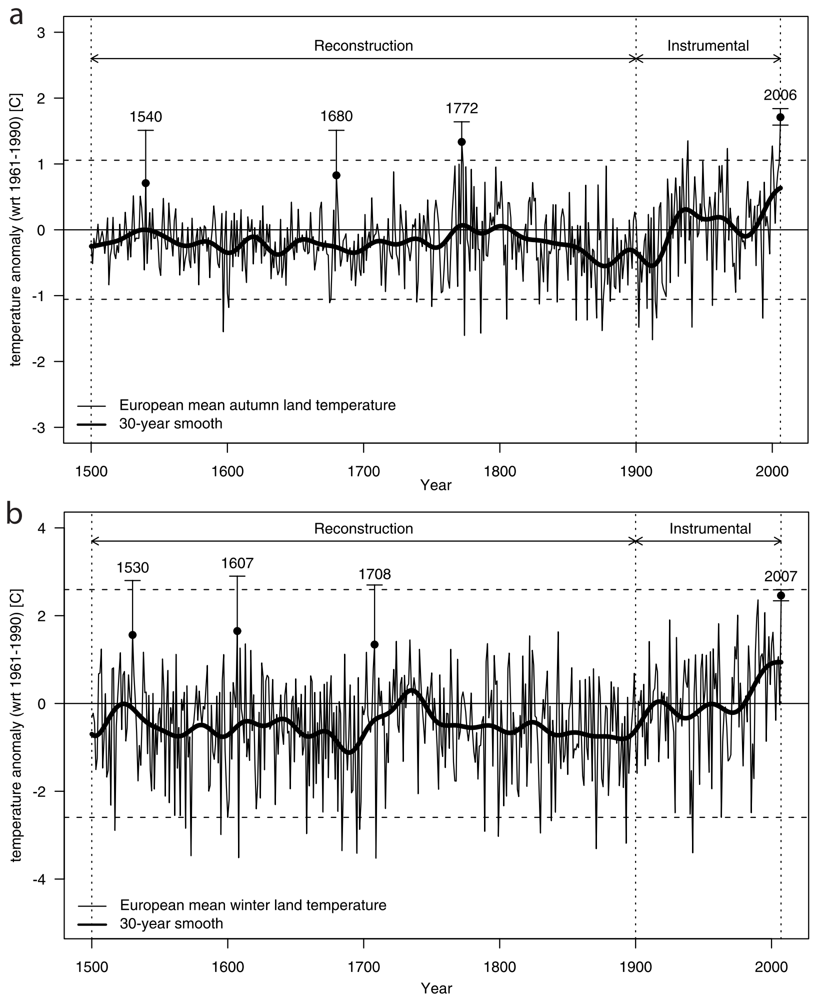

Figure 1. (a) Autumn (SON) averaged-mean European SAT anomalies (wrt 1961–1990) from 1500 to 2006, defined as the average over the land area 25°W–40°E and 35°N–70°N (thin black line). The values for the period 1500 to 1900 are reconstructions [*Xoplaki et al.*, 2005]; data from 1901 to 2006 are gridded instrumental data. The thick black line is a 30-year smooth 'minimum roughness' constraint calculated according to *Mann* [2004]. The dashed horizontal lines are the 2SD of the period 1961–1990. The warmest European pre-industrial autumns together with the +2 SE are denoted. (b) As Figure 1a but for Winter (DJF) 1500–2007.

(Z500) are calculated from the operational analyses of ECWMF and, before September 2002, ERA-40 data [*Uppala et al.*, 2005]. The SAT datasets are combined using a lapse rate of 6 K/km. Precipitation data are taken from the GPCC dataset [*Rudolf et al.*, 2007], North Atlantic Oscillation Index (NAOI) values stem from the NOAA Climate Prediction Center.

[4] Plant phenology serves as an integrating meteorological instrument, and thus can function as a bio-indicator for climate change. A systematic European overview of phenological impacts of the exceptionally warm European AU06 and WI07 is not possible at this stage as immediate data reporting has only been established in a few countries. Here we use German phenological data from the German Meteorological Service, the area which had the strongest temperature anomaly during both seasons. Data was taken from the immediate reporting program SOFORT (1992-February 2007) and the annual reporting program ANNUAL (1951–2003). Timeseries of the first flowering of common hazel (*Corylus avellana* L.) and snowdrop (*Galanthus nivalis* L.) were created by combining SOFORT and ANNUAL datasets. The response to winter monthly, two-monthly and seasonal mean SAT (HadCRUT3v [*Brohan et al.*, 2006]) in Germany was tested by linear regression.

3. Results and Discussion

[5] The AU06 (WI07) anomaly (wrt 1961–1990) averaged over the entire European land masses was around 1.7°C (2.4°C) warmer. At this scale, both seasons exceeded around 3 standard deviations (SD, wrt 1961–1990). The whiskers in Figure 1 show the plus 2 standard errors (SE) for the warmest autumns and winters of the preinstrumental period. The uncertainties inherent in those reconstructions take into account unexplained variance in the instrumental calibration period, partly uncertainties in the documentary data as well as the decrease of data back in time [*Luterbacher et al.*, 2004; *Xoplaki et al.*, 2005; *Küttel et al.*, 2007]. However, it is possible, that the earlier uncertainties are underestimated for various other reasons [*Jones et*

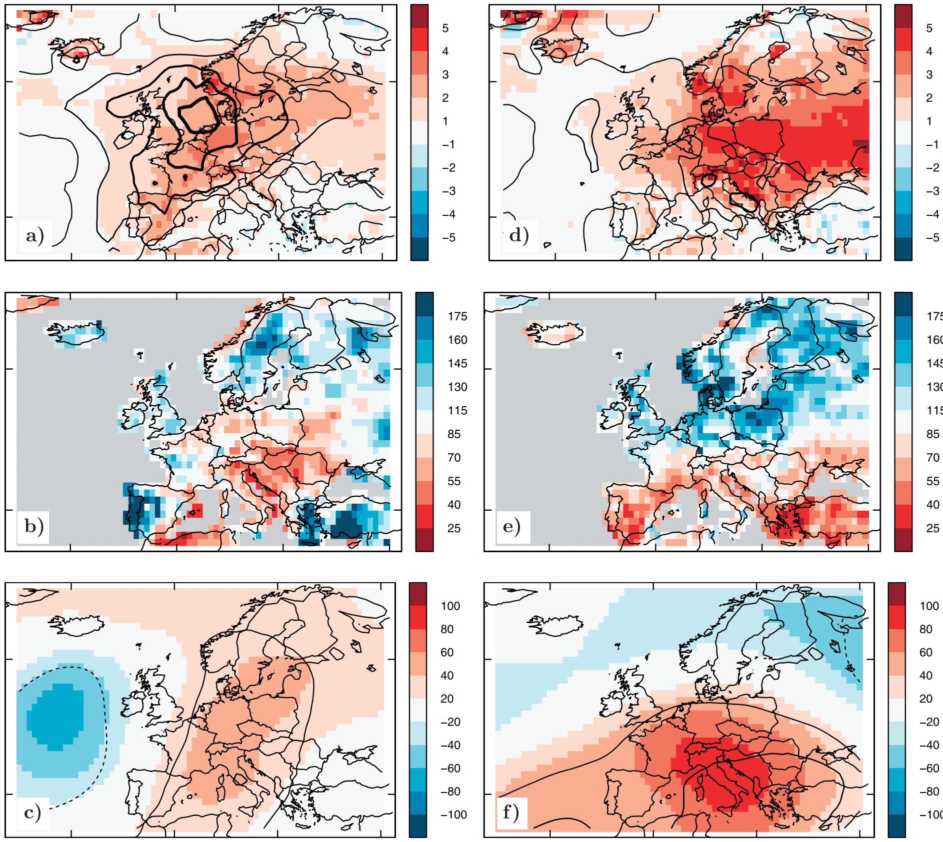

Figure 2. (a) Anomalies (wrt 1961–1990) of AUT06 SAT (°C), (b) precipitation (% of 1961–1990), and (c) Z500 (gpm). Contour lines display anomalies normalized by the 1961–1990 interval. Contour spacing is 1 unit with increasing thickness with stronger SD, zero line is omitted. (d–f) As in Figures 2a–2c but for WI07.

al., 2001; *Küttel et al.*, 2007]. According to the Welch *t*-test both the AU06 and WI07 are extremely likely (>95% probability; following the IPCC 4th Assessment Report on Addressing Uncertainties recommendations) the warmest autumn and winter for more than the last half millennium. The tests were performed for three other extreme years per season in the reconstruction (Figure 1 and auxiliary material). If we analyze the combined half year season of SAT September 2006-February 2007 by applying the same test between prominent half year extremes, we find that it is virtually certain (>99% probability) the warmest for more than 500 years. Extending further back chroniclers reported between 1100 and 1500 the occurrence of several extremely warm winters which may have matched or exceeded temperatures in WI07, at least at a regional scale (e.g. 1186/87, 1205/06, 1360/61) [*Pfister et al.*, 1996, 1998; *van Engelen et al.*, 2001]. None of these, however, was preceded by an extremely warm autumn. The closest analogue to AU06 and WI07 seems to be 1289/90. According to the anonymous writer of the Annals of Colmar and Basel there was an uninterrupted transition from autumn into spring, as the trees retained their leaves until the appearance of new ones; strawberries were eaten at Christmas; and the vine produced leaves, stalks and even blossoms in the middle of January. In Vienna fruit trees in January were flowering "like in May" [*Pfister et al.*, 1998].

[6] Figure 2 presents the anomalous spatial distribution of SAT, precipitation and Z500 for AU06 and WI07. For AU06, the SAT shows a strong overall positive anomaly (Figure 2a, up to 4SD over the land). Below normal precipitation (Figure 2b) occurred mainly over central Mediterranean and eastern Europe; remaining areas were above normal, especially over the Iberian Peninsula and the eastern Mediterranean. The anomaly patterns of SAT and precipitation are consistent with the Z500 field (Figure 2c): Warm air was advected towards western Europe from the eastern subtropical Atlantic, a region with anomalous warm SSTs at that time (not shown). Anomalies in surface pressure similar to Z500 indicate a barotropic structure of this trough. The individual months of AU06 indicate similar SAT anomalies, thus contributing evenly to the anomalous seasonal mean pattern (not shown). However, monthly Z500 indicate that the SAT anomalies are associated with different circulation conditions. There are negative anomalies of Z500 over the central North Atlantic in September and October (with NAOI values of −1.62 and −2.24 respectively). In November, the negative anomaly is located further north and the positive Z500 anomaly over western Europe is stronger (NAOI +0.44). Nevertheless, all these circulation configurations can be linked to warm air advection from the subtropical Atlantic.

[7] The largest WI07 SAT anomalies were located over central Europe (Figure 2d), exceeding 2 SD in central and eastern Europe and the Balkans. But SAT in elevated Alpine sites were not exceeding winter 1989/1990, mainly due to missing Foehn and inversion situations [*MeteoSwiss*, 2007].

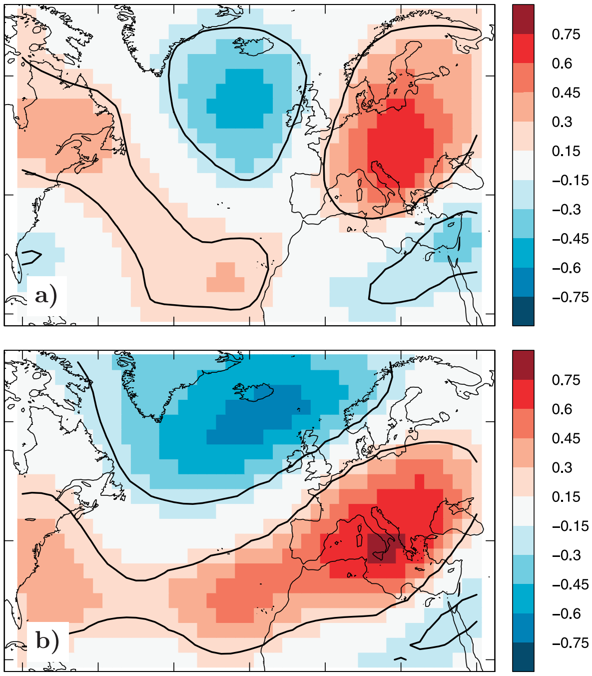

Figure 3. Spatial correlation between detrended HadCRUT3v [*Brohan et al.*, 2006] SAT averaged over the region 5°–15°E, 46°–52°N and NCEP Z500 of the 3-monthly average for (a) SON and (b) DJF over the period 1958–2005 (shaded). Contour lines indicate 90% significance level.

The WI07 Z500 anomaly (Figure 2f) helped the advection of anomalous warm air from the central and subtropical Atlantic. Precipitation reveals a distinct north south gradient, negative anomalies over the entire Mediterranean region (in large areas less than 40% of the 1961–1990 period) and positive in northern Europe (Figure 2e). Intraseasonal analyses indicates that December and January contributed most to the seasonal SAT anomaly (NAOI +1.34 and +0.22). In February, the strongest SAT anomaly was over southwestern Europe with a negative Z500 anomaly over the central North Atlantic (NAOI −0.47).

[8] Further links between SAT and circulation are explored in a correlation analysis between seasonal HadCRUT3v SAT (averaged over Germany, 5°E–15°E, 46°N–52°N; the location of the strongest absolute and relative anomalies) and Z500 over 1948–2005 for both seasons independently (Figure 3). For a more comprehensive study for the Mediterranean see *Xoplaki et al.* [2004]. For autumn (Figure 3a), high central European temperatures are associated with negative Z500 anomaly south of Iceland and a positive anomaly over large parts of Europe. This configuration promotes the advection of warm air from the eastern subtropical Atlantic and the western Mediterranean Sea towards Europe. For winter, however (Figure 3b), warm SAT is linked to a positive NAOI with anomalous southwesterlies and the advection of warm (and humid) air masses. The similarity of the correlation patterns with the corresponding observed Z500 anomalies in AU06 and WI07 (cf. Figures 2c and 2f, note the differing domains) confirms that advection processes had a large role in producing the extraordinary SAT anomalies. Extreme seasonal climate anomalies, such as the presented seasons cannot be easily pinned to a single cause. *Philipp et al.* [2007] show that distinct changes in autumn circulation patterns can explain around 36% of the interannual variability. These changes have had a significant influence on the long-term trend of European autumn SAT during the past 150 years. Other contributing factors could be associated with the general tropospheric warming due to climate change [*IPCC*, 2001] and, possibly, regions of anomalous SST in the source regions of the advected air. Alternatively, *Stott et al.* [2004] show that anthropogenic changes in the atmospheric composition have at least doubled the risk of the hot European summer of 2003. Climate change projections suggest an increase of SAT over western Europe and also to some extent an increase of interannual SAT variability for autumn [*Scherrer et al.*, 2005, 2007; Beniston, submitted manuscript, 2007]. For the past decades, many simulations are inconsistent with observations. In particular, the models show a stronger warming in autumn SAT than observed and simulated winter SAT show no decrease in interannual variability [*Scherrer et al.*, 2005, 2007]. Thus, AU06 and WI07 might reduce these inconsistencies between observations and concurrent climate model simulations.

[9] The warm AU06 and WI07 was very likely the cause of unusual phenological events. Figure 4 displays the spatial pattern of departures of hazel (Figure 4a) and snowdrop (Figure 4c) flowering dates in 2007 from long-term averages in Germany. In 2007 all stations show an advance of hazel (snowdrop) spring events up to 64 (62) days. Annual mean phenological anomalies (1951–2007, Figures 4b and 4d) demonstrate that in 2007 hazel (snowdrop) flowering was on average 37.6 (22.2) days earlier, which is unique since the start of the timeseries in 1951. SOFORT data (1992–2007) was also analyzed separately. Here (Figures 4b and 4d, red curve), the start of flowering in 2007 was also early compared to the 1992–2006 average dates (hazel: −31.7, snowdrop: −15.4 days), however almost comparable advances are found in 1994 and in 1999. It must be noted that only the first (in time) 70% (hazel) and 80% (snowdrop) of all observed onset dates in each year were averaged, since till the end of February 2007 only these percentages of SOFORT observations were available. Monthly mean January/February SAT explains 75% (72%) of the common variance of hazel (snowdrop) flowering in 1951–2007 (Figures 4b and 4d). Regression analysis indicate (not shown) that hazel (snowdrop) flowering responds to 1°C warmer February by 11.3 days (8.3) earlier flowering. These strong regressions underline the statistical and functional linkage between winter temperatures and the onset of early spring phases. Linear regressions of flowering dates against year (1951–2007) demonstrate an advancement of onset dates in the second half of the 20th century (hazel, −0.41 days/year, R^2 = 0.17, snowdrop, −0.28 days/year, R^2 = 0.14. Other prominent phenological impacts comprise accelerated development of winter crops (E. Bruns, DWD, personal communication, 2007), and continued flowering of perennial herbaceous plants till December. The impact of recent warming (1990–2007) is visible in the dataset: in 14 (hazel) and 13 (snowdrop) years of this 18 year period, flowering was earlier than the long-term average. Phenological impacts elsewhere in Europe included; in the Netherlands, 240 wild plant species and over 200 cultivar species were still observed in flower in the first

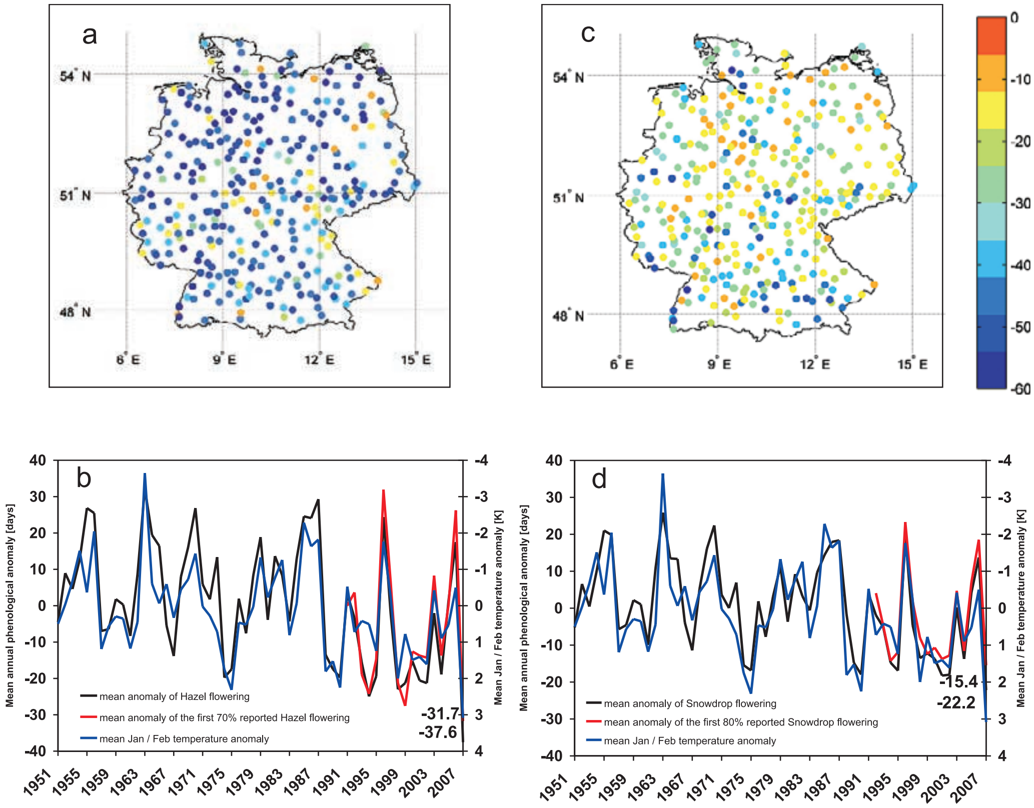

Figure 4. Start of flowering (a and b) of common hazel and (c and d) of snowdrop in Germany. Figures 4a and 4c show deviations of onset dates in 2007 from long-term average (1961–1990) [days], and in Figures 4b and 4d, black indicates mean annual anomalies in 1951–2007 of 40+ stations, red indicates mean annual anomalies of the SOFORT network for the first 70% (flowering of hazel) and 80% (flowering of snowdrop) observed records, and blue indicates mean January/February temperature anomalies.

15 days of December (A. van Vliet, personal communication, 2007, http://www.natuurkalender.nl/). In Switzerland, second flowering of horse chestnuts end of October in Geneva, later leaf fall of beech, and up to 30 to 40 days earlier flowering of common hazel was reported [*Defila*, 2007; C. Defila, personal communication, 2007]. Internet information on recent recording within the British phenological network also suggest an earlier start of first spring events (http://www.naturescalendar.org.uk).

4. Conclusions

[10] We provide evidence that the recent European AU06 and the WI07 (full September 2006-February 2007) were extremely likely (virtually certain) to be the warmest for more than half a millennium. The anomalous warmth, and exceptionally dry conditions in parts of the Mediterranean and central Europe is related to advection of warm air masses from the Eastern subtropical Atlantic as well as strong anticyclonic conditions over large parts of the continent. Other factors could include land-atmosphere interaction, snow-albedo feedback, sensitivity to remote SST anomalies, ocean currents, as well as anthropogenic influences.

[11] The warm AU06 and WI07 had a great impact on the phenology of many plant species. The flowering dates of hazel and snowdrop were well advanced, however, in comparison with records, not all species reveal extraordinarily early events. A general advance of spring is found for early spring events, such as flowering of hazel, snowdrop, coltsfoot, elder, and willows [E. Bruns, DWD, personal communication, 2007]. Further research on possible lack of winter chilling to break winter dormancy or photoperiodic constraints in which plants are able to react to warmer conditions is needed. As SAT anomalies are expected to increase up to 5 (3) SD from 1961–1990 in autumn (winter) at the end of the 21st century [*Scherrer et al.*, 2007], the AU06 and WI07 warmth discussed in this study may be seen as typical representation of upcoming climate change at continental scale. It is also likely, that these changes will be accompanied by changes in variability and extremes with further impacts for terrestrial ecosystems. The latter is particularly relevant for climate risk assessment and the adaptation to climate change in various societal and economic sectors.

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