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Mild winter and spring 2007 over western Europe led to a widespread early vegetation onset

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[1] Europe has experienced a wide scale warming over the past decades and climate simulations predict further warming and changes in precipitation patterns during the 21st century. The winter of 2006–2007 has been exceptionally mild with averaged temperatures that may become the norm during the second half of the 21st century. Here we report on satellite observations of the vegetation greening that occurred at the subcontinent scale almost 10 days earlier than the average over the past three decades. Even at the relatively coarse resolution of the satellite data, which mixes several vegetation types, there is a strong negative temporal correlation between the February–April mean temperature and the start of growth date. The western Europe mean vegetation onset sensitivity is −3.9 days per degree of temperature, and is mainly driven by crops and grasslands, with a biome-specific sensitivity of −4.7 days/°C. For forested biomes, onset anomalies are better correlated to the March–May mean temperature, with a sensitivity of −3.6 days/°C. Based upon the satellite data, there is no consistent indication that a lack of cold days in the winter 2006–2007 had any effect in delaying the vegetation onset.
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1. Introduction

[2] Western Europe has experienced extreme and persistent warm conditions during autumn 2006 and winter 2007 [*Schiermeier*, 2006; *Luterbacher et al.*, 2007]. Several monthly mean temperature records have been broken, but the exceptional nature of the meteorological event lies in the duration of the warm anomaly. As a consequence of warming, the greening of vegetation has occurred earlier than usual in spring 2007. In situ observations of the vegetation onset has shown anomalies of more than 30 days for specific species widespread over Germany [*Luterbacher et al.*, 2007]. Satellite observations can complement in-situ observations and provide a more homogeneous and spatially extensive description of the phenology anomaly. Indeed, several satellite-derived phenology products have recently been produced at continental or global scale and a 1 or 8-km resolution [*Delbart et al.*, 2006; *Zhang et al.*, 2006; *Maignan et al.*, 2008]. These products are derived from near daily observations, cloud cover permitting, of the surface spectral reflectances.

[3] We analyzed long-term satellite observations of the vegetation greenness over temperate western Europe (40°N–60°N, 10°W–20°E) in relation to air temperature. The objective is to quantify the advance of vegetation growth as a result of increasing temperature. We also searched for evidences of a delayed onset in the spring in the absence of frost during the previous winter.

2. Data and Method

[4] The MODIS land surface reflectance team provides a global daily data set at a lat/lon resolution of 0.05 degree, including reflectances in channel 1 (visible; R1: 620–670 nm) and channel 2 (near IR; R2: 841–876 nm) together with the acquisition geometry. These surface reflectances have been corrected for atmospheric absorption and scattering following the procedure described by *Vermote et al.* [2002]. The data set used here is based on collection 5 data when available (2000, 2001 and 2007), and collection 4 data for the period 2002–2006. The surface reflectances were corrected for directional effects, as by *Bacour et al.* [2006], using predefined directional signatures that depend on the biome [*Bacour and Bréon*, 2005]. To enlarge the time range, we also use the AVHRR 1982–1999 PAL daily data set at a resolution of 8km. Although the AVHRR data is of lesser quality than MODIS, it can be used to extract a reliable onset date. The data processing, atmospheric correction and directional effect correction was described by *Bacour et al.* [2006]. For both data sets, the onset date was derived from the Difference Vegetation Index (DVI = R2–R1), following a method described by *Maignan et al.* [2008]. The measurement time series are interpolated and filtered to derive a smooth curve, which is the sum of a trend and a seasonal cycle with zero mean. We determined each year the date of vegetation onset as the point when the seasonal cycle crosses the zero-axe upward. This implies that the estimated onset date is generally later than observed with in situ methods (there is a systematic bias). Our method has shown better robustness than several others that were tested in the sense that it better retrieves the interannual variations of in situ observations. Onset dates and their median were computed at a 0.1° spatial resolution for both satellite periods. When the number of measurements was too low or when multiple dates within a year were detected, the onset date was not estimated (grey pixels in Figure 1). Anomalies were computed as the difference from the median separately for the two satellite data sets.

[5] Surface air temperature data were acquired from NCEP reanalysis [*Kalnay et al.*, 1996] and interpolated at the satellite data spatial resolution from an original 1.9°. We

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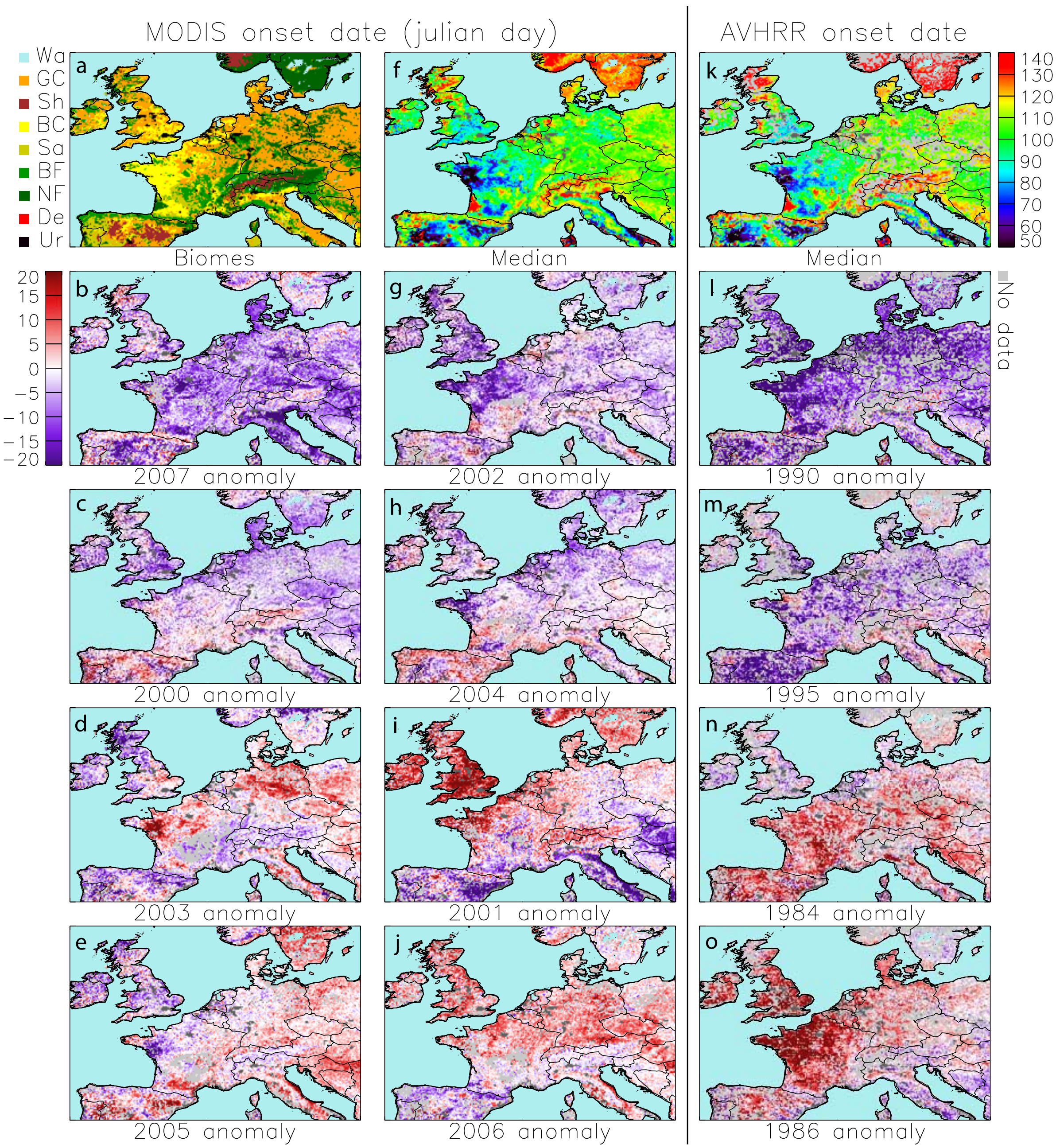

Figure 1. Anomaly of the start of the vegetation growth over western Europe. The data are from the MODIS or AVHRR instruments and processed as by *Maignan et al.* [2008]. When an onset date could not be retrieved with the method, the corresponding pixel is colored in grey (labeled 'No data'). (a) The vegetation types according to the *Knyazikhin et al.* [1999] classification: Water (Wa), Grasses and cereal Crops (GC), Shrublands (Sh), Broadleaf Crops (BC), Savannas (Sa), Broadleaf Forests (BF), Needleleaf Forests (NF), Deserts (De), and Urban areas (Ur). (left) and (middle) The other panels are related to MODIS: (f) the vegetation onset date median value computed over the 2000–2007 period and (b)–(e) and (g)–(j) the anomaly patterns of the onset date for each year of the MODIS period and are ordered from the year with the largest negative mean anomaly (early onsets) to the year with the largest positive one (late onsets). (right) Related to the AVHRR period: (k) the vegetation onset date median value computed over the 1982–1999 period, (l) and (m) then the 2 years within this period with the largest negative mean anomaly of the onset date, and (n) and (o) finally, the 2 years with the largest positive mean anomaly.

used the daily mean temperature and computed monthly and seasonal averages. The various monthly and seasonal averages were compared against the onset date anomalies.

[6] For the biome classification we used the 2001 version 4 MODIS Land Cover Product Binary Data from Boston University, based on the LAI/fPAR Class Scheme of *Knyazikhin et al.* [1999]. It includes seven land cover types

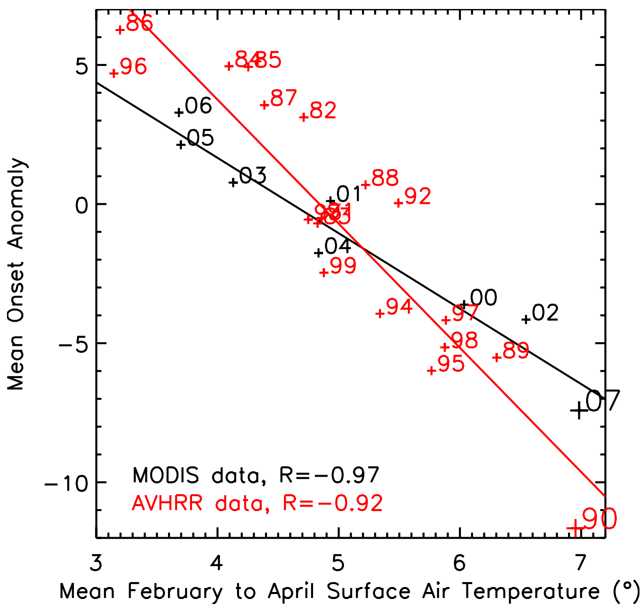

Figure 2. Scatterplot of the vegetation onset date anomaly against the February–April mean temperature. Both parameters have been averaged at the subcontinent scale. The phenology parameters have been derived from the MODIS data for the 2000–2007 period and AVHRR data for the 1982–1999 period. The temperatures are 2m air temperatures from the NCEP reanalysis [*Kalnay et al.*, 1996].

(see Figure 1). The 1km original grid was aggregated at the 0.1° spatial scale, using a majority vote algorithm.

3. Results and Discussion

[7] Figure 1 (left) and 1 (middle) show (a) the surface type classification, following *Knyazikhin et al.* [1999], (b)–(e) and (g)–(j) together with the vegetation onset results derived from MODIS over the 2000–2007 period, i.e., (f) the median date and the anomalies with respect to the median date for the 8 years of the MODIS archive. The earlier vegetation onsets are observed in Spain and western France (Loire river basin), while the latest onset dates are mainly found in Scandinavia and mountainous regions. The interannual anomalies range within ± 20 days around the median, which is far lower than the onset spatial variability and enables a better representation of the interannual variability. Anomaly maps exhibit generally large coherent regional patterns. Since the processing is done independently on a pixel basis, it provides some indication of the estimate validity. The anomalies are rather small in 2003 and 2004, indicating a normal onset pattern, while other years show large deviations. 2001 presents the strongest positive anomaly (onset delay) over England, whereas large negative anomalies are found over Italy and Hungaria (see Figure 1). However, the year 2007 appears as the most exceptional, not so much for the maximum anomaly values, but rather considering the geographic coverage of the strong negative anomaly. It produces the largest averaged value over the study area, with a mean advance of −7.7 days relatively to the MODIS period average, and a standard deviation of 9 days. For the four main biomes, the 2007 onset advance is 9 days (Broadleaf Crops), 9 days (Grasses and Cereal Crops), 5 days (Broadleaf Forests) and 2 days (Needleleaf Forests).

[8] This result indicates that grasses and crops have responded more strongly to the exceptional 2006–2007 warmth than forests have. The lesser sensitivity of forests is in agreement with the findings of *Root et al.* [2003] that show a general advance of onset dates of 3 days/decade for the forests of the Northern hemisphere versus 5 days/decade for non-tree biomes.

[9] Using AVHRR data in complement with the MODIS archive allows a longer perspective, back to 1982 (third column of Figure 1). The median onset date is earlier for MODIS than for the AVHRR data set (−2.6 days), perhaps as a result of the relatively small sample, but most probably because of the positive temperature trend during the full period. Indeed, during the MODIS era, the mean February–April temperatures are, on average, 0.76 degree larger than during the AVHRR period. The analysis of AVHRR data together with MODIS suggests that 1990 is maybe even more exceptional than 2007 for the onset anomaly over western Europe, with no larger negative anomaly over the 26 year period. 1990 shows a mean advance of 11.3 days, with respect to the AVHRR period median, which is larger than the 2007 value. There is some spatial bias in the pixel selection however. Indeed, if we take into account pixels only if their onset dates could be estimated for at least half of the AVHRR period and half of the MODIS period, the anomaly averaged over the study area is −10.4 days for 1990 and −9.2 days for 2007. We will now evaluate three models relating the onset date to temperature-related parameters.

3.1. Correlation With Temperature Variations

[10] It is known since *De Réaumur et al.* [1735] that spring budburst dates are closely linked to air temperature of the previous months. *Menzel et al.* [2006] shows that most phenophases of in situ data in Europe correlate significantly with mean temperatures of the month of onset and the two preceding months. We searched for the best correlation between the mean onset anomaly over the study area and various monthly or seasonal temperature averages. The best score (with no biome distinction) was obtained for the February–April mean temperature with a correlation of −0.97 for MODIS data and −0.92 for AVHRR data (Figure 2). A leave-one-out cross-validation gives respectively correlation coefficients of 0.96 and 0.89. When the two data sets are put together, the correlation decreases to −0.87, which is still highly significant (the associated risk p is lower than 0.001). The slopes are respectively of −2.7 days/°C (MODIS only), −4.5 (AVHRR only) and −3.9 (AVHRR and MODIS). A change of temperature sensitivity has already been reported over Eurasia around year 1992 [e.g., *Slayback et al.*, 2003]. Indeed, a slope of −4.8 days/°C (R = 0.95) is found for the (1982–1992) AVHRR period while it is only −3.6 days/°C (R = 0.98) during (1993–1999). The MODIS period suggests that the onset sensitivity to temperature has continued to decrease over western Europe.

[11] Such correlation coefficients and slopes confirm the analysis of in situ observations. For instance, *Chmielewski et al.* [2004] found a correlation of 0.89 between the beginning of growing season in Germany and the average

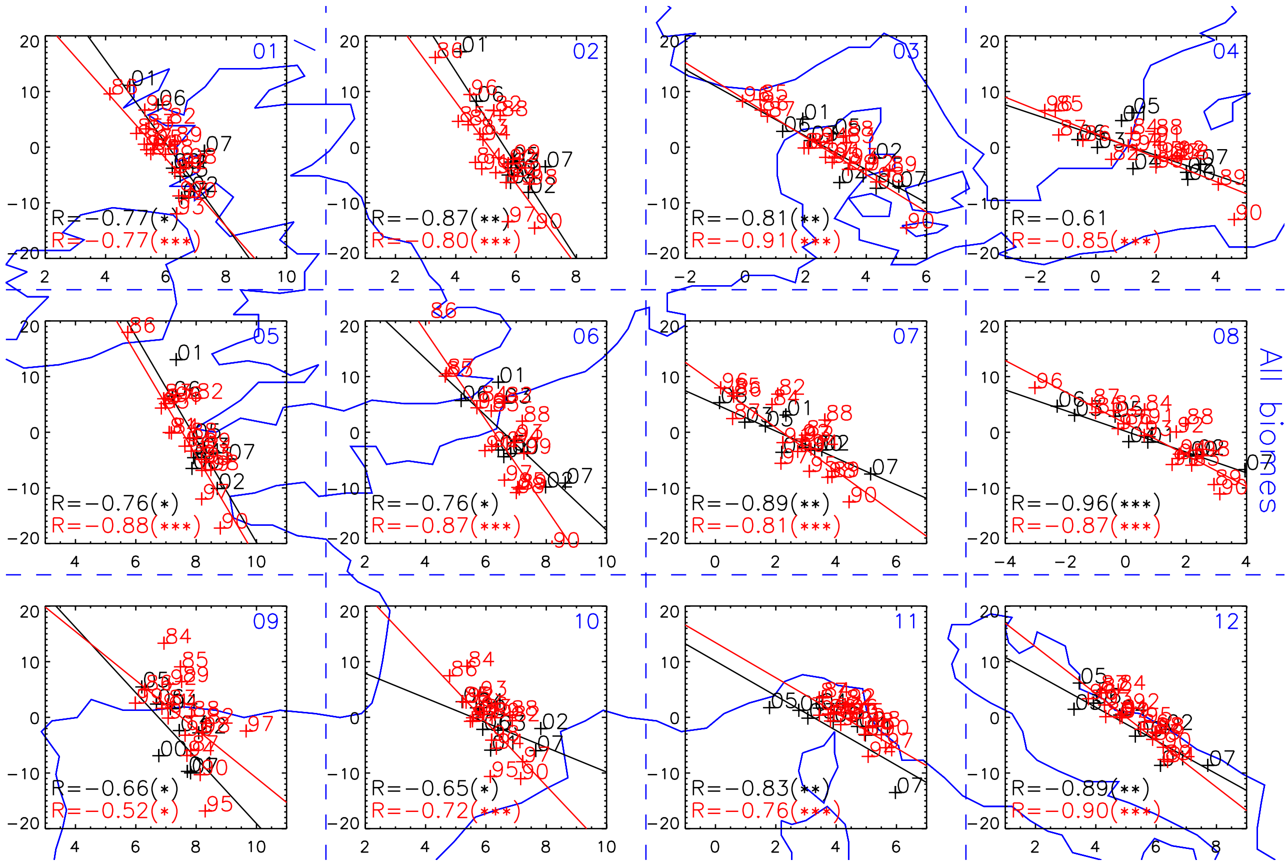

Figure 3. Same as Figure 2 but for twelve regions: scatterplot of the vegetation onset date anomaly against the February–April mean temperature. MODIS data are printed in black, and AVHRR data are printed in red. The regions are numbered from West to East and North to South (the region number is indicated in the top-right corner). The correlation coefficient R of each data set is given in each region. A single asterisk following R value indicates it is significant with a risk p lower than 0.05, double asterisks indicate $p < 0.01$ and triple asterisks indicate $p < 0.001$. Note that while the y-axis is fixed, the x-axis (temperature) varies but with a fixed range amplitude, so that the slopes are directly comparables.

air temperature from February to April, for the 1961–2000 period with a response of 4.7 days/°C for fruit trees and crops. Note that the in situ data show that 1990 had an exceptional early onset, in agreement with our satellite-based analysis.

[12] Figure 3 shows the result of a similar analysis as for Figure 2 but for twelve regions of Europe. The strong negative correlation between onset date anomalies and the mean February to April temperature holds for a large majority of the regions: 11 out of 12 exhibit correlations (both with MODIS and AVHRR) significant with a risk p lower than 0.05 (identified by a single star) and 75% of the regressions have $p < 0.01$ (identified by a double star). For both satellite data sets, the sensitivity of onset to temperature (linear regression slope) decreases eastwards, i.e. towards lower mean temperatures. Such a stronger sensitivity to temperature in the warmer western regions was also noticed by *Menzel et al.* [2006] based on in situ observations: for 7 of the 8 studied species (including trees and non-trees), the phenology spring phases sensitivity to temperature is found to be larger in warmer than in colder countries.

[13] We also performed this analysis with a distinction between pixels dominated by grasses or crops, broadleaf forested pixels and needleleaf forested pixels. Grasses and crops dominate every region except North-Eastern most region (n° 4) where the needleleaf forest biome coverage is 60%. This last biome represents more than 16% only in the North-Eastern regions (n° 3, 4, 7 and 8, corresponding mainly to Norway, Sweden, Germany and Poland) whereas the broadleaf forest coverage is significant in Germany, Southern France and Italy (n°7, 10, 11 and 12). When considering each biome separately, the best correlation with various temperature averages is found for the February–April period for grasses and crops, but the March–May period is selected for forested pixels. On the other hand the onset sensitivity to temperature is generally larger, and the regression are generally more significant for grasses and crops (median slope of −4.5/°C, median R of −0.84) than they are for broadleaf forests (median slope of −3.7/°C, median R of −0.78) and needleleaf forests (median slope of −3.0/°C, median R of −0.72).

3.2. Growing Degree Days (GDD) Model

[14] Phenological models for temperate trees are reviewed by *Chuine et al.* [1998] and *Hänninen and Kramer* [2007]. The simplest models predict that the onset occurs when the sum of daily-mean temperature above a

temperature threshold reaches a cutoff point (GDD cutoff). Based on such simple models, and using the satellite-derived onset date together with the daily NCEP temperature fields, we computed a GDD cutoff for each year. Following widely used parameterizations, we selected a temperature threshold of 0°C and the 1st of January as the starting date. There is a significant variability in the annual GDD cutoff (from 1000°C to 1340°C), which indicates that the simple models are over-simplistic. This conclusion holds whatever the region and biome distinction we considered.

3.3. Chilling Requirement

[15] It has been shown that some species need a "dormancy" period, triggered by cold temperatures, for an early onset [e.g., *Orlandi et al.*, 2004]. Models that account for such a chilling requirement make the GDD cutoff point a function of the number of winter days with a mean temperature below a threshold (NCD: Number of Chilling Days). Because the winter of 2006–2007 was exceptionally mild over western Europe, we searched for evidences of delayed onset due to the absence of cold periods. The NCD is computed for each pixel using the 1st of October as starting date and a chilling temperature of 0°C.

[16] For the various regions of Figure 3, we fitted the mean GDD as a negative exponential of the mean NCD, over the 1982–2007 period. The correlation coefficients range around 0.55 for the warmer regions and around 0.79 for the colder ones. This suggests indeed an influence of chilling on the GDD cutoff point. However, one must be careful as NCD and winter mean temperatures are highly correlated ("warm" winters tend to have fewer "cold" days; $R = -0.83$). We therefore searched for a partial correlation between the onset date anomaly and the NCD, i.e. a correlation not explained by the February–April temperature. The result indicates that, averaged over the region of interest, the NCD has little or no influence on the onset date anomaly ($R = -0.06$) if the NCD-temperature correlation is accounted for. When studying this partial correlation with regional and biome distinctions, it becomes significant only in regions 3 and 4 (Denmark, Southern Norway and Sweden, $p<0.05$) for the needleleaf biome during the MODIS period. In these regions, 2007 and 2001 have the warmest autumn-winter (October of previous year to February) temperature anomalies of respectively 2.6° and 1.8° while the spring (March–May) temperature is close to average. The relatively late onset may therefore be interpreted as the result of a lack of chilling requirement. For the other regions and biomes, no such effect is observed. Although the winter of 2007 was very mild, the chilling requirements were still fulfilled or, at least, the positive effect of high temperatures on heat unit accumulation counterbalanced the negative effect on chilling requirements.

3.4. Last Freeze Injuries

[17] Late freeze may have damaging impacts on vegetation, in particular for the production of fruits. In the context of global warming and trends towards earlier vegetation onset, it is therefore natural to fear a higher occurrence of late freezes, after vegetation onset. From the NCEP analyzed temperatures, we derived the last freeze date over our study zone for each of the 26 years and temporally correlated it against the mean February to April air surface temperature ($R = -0.89$). The slope of the linear regression is −8.7 days/°C. Therefore, the slope of the last freeze date is larger than that of the onset date (−8.7 days/°C versus −3.9 days/°C). This result indicates that, over the region of interest, late freeze damages on vegetation may become less frequent than they have been. Using a phenological model, *Schwartz et al.* [2006] draws the same conclusion over western Europe, but an opposite one for Northern and Eastern Europe.

4. Conclusions

[18] Satellite observation of the vegetation dynamic can be used to detect the vegetation onset and therefore spatially extend in situ observations made at phenological gardens. The satellite data shows a mean sensitivity of roughly 4 days of earlier onset per degree of temperature averaged over the February–April period, with some variations with biome type and mean winter temperature. Meteorological observations have shown that the winter and early spring of 2006–2007 was exceptionally mild. Not surprisingly, vegetation responded to this anomalous warm temperature with a very early onset, widespread over western Europe. A similar anomaly had occurred during the spring of 1990. On the satellite data, there is no consistent indication that a lack of cold days had any adverse effect on the vegetation onset. However, the temperature models used to predict budburst are based on in situ data related to specific species, and may not be adequate to the pixel scale, which integrates different information from different species. For coarse, global scale studies, a model based on satellite observations such as those presented in this paper may be better suited.

[19] **Acknowledgments.** NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/.

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