Human Contribution to the Lengthening of the Growing Season during 1950–99

NIKOLAOS CHRISTIDIS, PETER A. STOTT, AND SIMON BROWN
Met Office, Hadley Centre for Climate Prediction and Research, Exeter, United Kingdom

DAVID J. KAROLY
School of Meteorology, University of Oklahoma, Norman, Oklahoma

JOHN CAESAR
Met Office, Hadley Centre for Climate Prediction and Research, Exeter, United Kingdom

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ABSTRACT
Increasing surface temperatures are expected to result in longer growing seasons. An optimal detection analysis is carried out to assess the significance of increases in the growing season length during 1950–99, and to measure the anthropogenic component of the change. The signal is found to be detectable, both on global and continental scales, and human influence needs to be accounted for if it is to be fully explained. The change in the growing season length is found to be asymmetric and largely due to the earlier onset of spring, rather than the later ending of autumn. The growing season length, based on exceedence of local temperature thresholds, has a rate of increase of about 1.5 days decade⁻¹ over the observation area. Local variations also allow for negative trends in parts of North America. The analysis suggests that the signal can be attributed to the anthropogenic forcings that have acted on the climate system and no other forcings are necessary to describe the change. Model projections predict that under future climate change the later ending of autumn will also contribute significantly to the lengthening of the growing season, which will increase in the twenty-first century by more than a month. Such major changes in seasonality will affect physical and biological systems in several ways, leading to important environmental and socioeconomic consequences and adaptation challenges.

1. Introduction
Climate change detection and attribution to external influences have involved considerable scientific effort. As a result, sophisticated statistical methods have been developed that combine information from observations and climate models and have been used to investigate the role of human activity in climate change (Hegerl et al. 1997; Tett et al. 2002; Karoly et al. 2003; Stott et al. 2006). Evidence continues to accumulate of the major role played by human-induced greenhouse gas emissions in causing warming observed near the surface of the earth over the recent decades (Allen et al. 2006; Stott 2003; Zwiers and Zhang 2003). The growing confidence in this attribution statement is evident in the reports of the Intergovernmental Panel on Climate Change (IPCC). The most recent Third Assessment Report (TAR; Houghton et al. 2001) concludes that greenhouse gas emissions are the main contributors to the recent observed warming, whereas earlier reports would only indicate human influence as an agent of climate change with, at best, a “discernible” impact. The International ad hoc Detection and Attribution Group (IDAG) summarized the latest developments in a paper that supports and strengthens the TAR conclusion (IDAG 2005).

While changes in the mean temperature are very important, several temperature-dependent indices have also been defined and used to investigate some particular implications of warming. For example, such indices have enabled the study of changes in temperature extremes (Hegerl et al. 2004; Christidis et al. 2005) in the diurnal temperature range (Braganza et al. 2004a), in the hemispheric and the land-ocean contrast, and the meridional temperature gradient (Braganza et al.
Along the same line, this work focuses on the growing season length, another important temperature index, expected to increase in a warming climate. This is the first attempt to detect any significant change in climatological seasons on a global scale and measure the contribution of the human influence using formal statistical detection and attribution methodology. The two ends of the growing season are also examined separately, to infer whether any observed change is asymmetric and dominated by spring or autumn warming.

The lengthening of the growing season affects both physical and biological systems in an array of ways. A comprehensive understanding of all its facets is a multidisciplinary task and beyond the scope of this work. A brief mention to some key aspects is given here to set the context. As the growing season is commonly linked to agriculture, the most obvious impacts are related to changes in crop phenology. Advances in production due to earlier springs have been documented for several types of crops (e.g., Chmielewski et al. 2004), while benefits in viticulture due to longer growing seasons have also been established (Nemani et al. 2001; G. V. Jones et al. 2005). Adverse impacts include reduced yields of certain crops like rice (Peng et al. 2004) and also increases in insect and pest diseases (Patterson et al. 1999). In addition to crops, there are numerous studies that report regional phenological changes in various other plant species and also forestry (Cayan et al. 2001; Matsumoto et al. 2003; Zhou et al. 2001). Seasonal activities of animals are also affected by changes in the growing season. Examples include changes in the return dates of migrant birds (Cotton 2003), in egg laying and breeding dates (Crick and Sparks 1999), and the spring appearance of butterflies and other invertebrates (Roy and Sparks 2000). Studies based on meta-analyses (Parmesan and Yohe 2003; Root et al. 2003) argue that wild plants and animals are better indicators of changes in the growing season than crops, as the latter can be affected by changes in management practice. Finally, changes in marine and lake ecosystems constitute another important strand of impacts (Edwards and Richardson 2004; Winder and Schindler 2004).

Longer growing seasons, and especially earlier springs, also lead to changes in the hydrological cycle with serious implications. Earlier snowmelt results in earlier peak river flows, which have been observed in various locations (Peterson et al. 2002; Groisman et al. 2004; Yang et al. 2002). Barnett et al. (2005) pointed out that a sixth of the world’s population inhabits areas where the river runoff is dominated by snowmelt. Although much of the water supply in these areas relies on rivers, there is little water storage infrastructure. Consequently an earlier shift in the maximum river flow would lead to water shortage in the summer, when the demand is greater. On a different note, earlier snowmelt would also adversely impact tourism in ski areas (Beniston 2003; Nicholls 2005).

In contrast with previous studies that examined changes in seasonality based on its impacts on ecosystems, this work examines the climatological changes that underline all the impacts. This is the first investigation to employ a standard optimal fingerprinting methodology to this end, which not only aims to discriminate between the human and natural influences on seasonality, but also to directly determine the contribution from each component. The threefold aim of the study concentrates on 1) establishing the significance of the lengthening in the growing season, 2) tracing its origins, and 3) examining both the beginning and end of the growing season to investigate whether the change is symmetrical.

In the remainder of the paper, the analysis method is outlined and the main findings are presented and discussed. Section 2 lists various indices that have been proposed to define the growing season length and introduces the indices employed in this work. Details on the observational and the model data used in the analysis are given in section 3, where index trends computed from these data are also shown. Section 4 describes the statistical modeling approach and how it is applied here. Results from the detection and the attribution analysis are found in sections 5 and 6, respectively. Future projections into the twenty-first century are shown in section 7. Finally, section 8 presents a discussion and summarizes the main points of the study.

2. Index definitions

The wide range of impacts associated with changes in the growing season length has led to a great wealth of indices in literature, used to investigate different outcomes. The more straightforward climatological definitions of season indicators with reference to temperature are often abandoned for various other impact-related definitions, based, for example, on phenological events, the carbon cycle, or river runoff. Before introducing the indices employed in this work, a brief summary of some alternative definitions will be given.

In the earlier studies of changes in the growing season, the human influence on the climate had not yet emerged as an important issue, though such changes were already acknowledged as an indicator of climatic variations. Climatological day-count indices were most commonly employed, measuring the days of the year when the temperature exceeds certain thresholds. A threshold of 0°C, pertinent to agriculture, marks the frost-free season and has featured as a popular choice
for several decades (Wang 1963; Brinkmann 1979; Cooter and LeDuc 1995; Kunkel et al. 2004). However, the actual “killing temperatures” for vegetation vary with plant species and the damage also depends on the frost duration and severity. Therefore, a host of threshold temperatures from −4.4° to 5.6°C has also been utilized to define the growing season (Moran and Morgan 1977; Brinkmann 1979; Robeson 2002). If the focus is on vegetation growth rather than resilience, higher temperature thresholds need to be considered. For this purpose, Davis (1972) defined the onset of spring and the end of autumn using temperatures of 10° and 6.1°C, respectively. In an attempt to provide a common benchmark to investigators, Frich et al. (2002) selected the 5°C threshold to standardize the definition of the growing season, while they also included a frost-related index based on the 0°C threshold in their list of indicators of climatic extremes.

Another stream of studies has tried to infer changes in the growing season from trends in phenological data (Schwartz 1992; Menzel and Fabian 1999; Cayan et al. 2001; D’Odorico et al. 2002). Such studies examine annual phases of plant development like leafing (unfolding, coloring, and fall) and flowering (first bloom), in order to determine the beginning of spring and/or the end of autumn. This approach is of course spatially limited to regions of common vegetation. It should be noted that seasonal plant phases are not dependent only on temperature, but also on other parameters like rainfall, light, biotic factors, and CO₂ fertilization, which can also be altered by anthropogenic climate change, and so it could be argued that this provides a holistic climate change index. The major disadvantage, however, is that the definition of the growing season then becomes subject to particular plant species, while different species, even in the same region, could yield very different season lengths.

There are other indices related to vegetation, though not directly to its characteristics, which measure the growing season from changes in the phase of the carbon cycle (Keeling et al. 1996; Myneni et al. 1997). The advantage in this case is that the index is independent of plant types and the analysis can therefore be extended to larger scales. Myneni et al. (1997) studied changes in the growing season with a carbon cycle–based index and with satellite-based measurements of changes in photosynthetic activity and found good agreement between the two different approaches.

Finally, there are studies that are concerned more with impacts of climatic changes on water availability that resort to hydrological season definitions. In this case, the growing season can be computed from changes in the ice breakup and freeze dates in lakes or rivers (Magnuson et al. 2000; Yoo and D’Odorico 2002), or from snowmelt pulses in rivers (Cayan et al. 2001). This gives valuable information, which is again peculiar to the region of the analysis.

Given the plethora of indices in literature, all the recent investigations come to agree that, in the second half of the twentieth century, there has been a noticeable lengthening of the growing season and an earlier onset of spring. In an effort to demonstrate and quantify the change on global scale and attribute it to possible causes, three climatologically based indices are employed here, namely the growing season length (GSL), the spring onset (SPR), and the autumn ending (AUT). In contrast with previous studies, the aim is to establish the climate change that underpins all phenological or hydrological impacts, rather than narrow the scope to a singular aspect of local interest only. To make this a global analysis, local (rather than fixed) temperature thresholds have been employed, defined as the observed annual mean temperature at each grid point, averaged over the period 1950–99 (Fig. 1a). Index values from both observations and model data are computed with the same thresholds. With this definition, emphasis is placed on the locally relevant temperature threshold, which is deemed preferable to a fixed threshold like 0°C, as the latter would not be meaningful in the warmer regions. In this way, regionally unbiased indices can be computed at all grid points where a seasonal cycle exists, a fact that also enables the most efficient use of the available observed and model data. Defining seasonality as a function of temperature alone would not be appropriate in the Tropics where the interseasonal temperature variations are relatively small. In those regions phenology is more closely linked to the duration of the rainy season. Analyses with emphasis on the Tropics would therefore require indices that describe changes in the water availability.

Figure 1b provides a schematic illustration of the three indices for a specific year and location. It is a known problem that day-to-day variability may lead to misleading index calculations, as, for example, in the case of an odd, unusually warm winter day when the threshold is exceeded before spring actually arrives. The most common solution is to ensure consistency with the previous (for spring), or subsequent (for autumn) 5-day periods (i.e., Frich et al. 2002). Here, however, we simply smooth the seasonal cycle by applying a third-degree polynomial to the data and compute the indices from the points where the temperature threshold intersects the smoothed cycle, as shown in Fig. 1b. For grid points in the Southern Hemisphere, the seasonal cycle is shifted half a year forward, in order to retain the same shape as in the Northern Hemisphere.
Points where interseasonal temperature variations are below 1.5°C are assumed to have no seasonal cycle and are omitted.

3. Observed and modeled trends

Observations are taken from the Caesar et al. (2006) gridded dataset of maximum and minimum daily temperatures. Daily mean values are computed simply as the average of the respective maximum and minimum and only data for the period 1950–99 are considered in the analysis. The data coverage includes only land areas, mainly in the Northern Hemisphere and Australia. This is the first comprehensive dataset that enables analyses of quasi-global daily data. Model data are taken from experiments with the Third Hadley Centre Coupled Ocean–Atmosphere General Circulation Model (HadCM3; Gordon et al. 2000; Pope et al. 2000). The experiments are four member ensembles, forced with different forcings, or forcing combinations (Johns et al. 2003; Tett et al. 2002). The following four ensembles are considered: (a) GHG, forced with historical changes in well-mixed greenhouse gases; (b) ANTHRO, forced well-mixed greenhouse gases (like GHG) and also changes in sulfate aerosols (with their effect on cloud albedo included) and ozone (both tropospheric and stratospheric); (c) NAT, forced with volcanic aerosols and changes in the solar output; and (d) ALL, forced with all the forcings in the previous ensembles (both anthropogenic and natural). Internal climate variability is estimated from 1800 yr of a HadCM3 control run. Whether the model provides a good representation of the variability will be discussed in the next section.

The three indices (GSL, SPR, and AUT) were calculated for each year in the analysis period and time series of 5-yr mean index anomalies (relative to the period mean), averaged over the observation area and also over Europe and North America are shown in Fig. 2. Model results correspond to the ensemble mean of the four members for each experiment. The time series indicate that, irrespective of the overall trends, there appear to be decades with both warming and cooling in the analysis period. The observations and model experiments that include anthropogenic forcings show in all cases an increase in GSL, a decrease in SPR, and little change in AUT, indicating a lengthening of the growing season, primarily due to an earlier onset of spring. The NAT experiment yields more moderate trends, mostly of the opposite sign to the observations. A summary of the area-averaged trends is given in Table 1 for the observations and the ALL experiment. Values significant at the 90% level are in bold. Both model and observational trends in GSL and SPR are significant even at a continental scale. There are no regional variations in the increase of GSL, with trends of about 2-days decade$^{-1}$ in Europe and over the whole observations area, but only about 1-day decade$^{-1}$ in North America. The model tends to underestimate the trends in GSL and SPR. This can be attributed to limitations of the model, though internal climate variability (present in the observations and reduced in the model ensemble means) and missing forcings in the ALL experiment may also account for some
of the discrepancy. The significance of the difference between the observations and the model was assessed with a $t$ test using data from the control experiment. The differences were found to lie within the 5%–95% uncertainty range, implying that they are indeed much determined by internal climate variability. Optimal detection will provide a more thorough investigation of the level of agreement between model and observations, taking into account the effect of internal variability. Patterns of the index change that illustrate the local characteristics of the response will be shown in section 6.

The trends presented here are in accord with the general consensus in literature, while they manifest the

Table 1. Index trends (days decade$^{-1}$) from the observations and the ALL experiment over the observations area, Europe and North America. Model values are the average of the four trends for each ensemble member. Significance was assessed with a $t$ test and values tabulated in bold lie outside the 5%–95% range of the distribution of trends from segments of the control experiment. Thirty nonoverlapping control segments were used in total. For the significance testing of the model trends (ensemble mean), the control trends were first grouped in 20 sets of 4 and the distribution of the set means was used in the test.

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global nature of the change. The few studies that have quantified the change in the frost-free season for the whole United States (Easterling 2002; Kunkel et al. 2004) found increases of the same order as the GSL increases shown here for North America. Kunkel et al. (2004) also pointed out that the change is mainly an outcome of the earlier occurrence of spring rather than the later arrival of autumn, which is now found to be the case on a much larger scale too.

4. Optimal detection

This section describes the statistical model employed to analyze the data and assesses one of its major assumptions. The bulk of the effort in detecting and attributing external influences that act on the climate system has been centered on multiple regression models, generally referred to as optimal detection. The method is termed “optimal,” because it aims to optimize detection by looking at directions in the variability space that maximize the signal to noise ratio. The method has been formalized for climate change applications (Hasselmann 1979; Allen and Tett 1999) and provides a powerful statistical tool that addresses the need for an objective assessment of the human contribution to the recent changes. Given the response patterns to external forcings from the observations, y, and from m model experiments (ensemble means) that include different forcings, x, and also a noise estimate of the internally generated variability, u0, optimal detection can be expressed using the simple linear relationship

\[ y = \sum_{i=1}^{m} (x_i - u_i)\beta_i + u_0. \]  

The algorithm used in this work is based on the Total Least Squares (TLS) regression (Allen and Stott 2003), which also includes sampling noise, denoted as ui, in (1). This noise term accounts for the small ensemble size and corrects the bias of the scaling factors, βi, toward zero, a well-known problem with Optimal Least Squares regression, used in earlier versions of the code (Allen and Tett 1999). The scaling factor for each model experiment indicates the level of agreement with the observations and its 5%–95% uncertainty range helps assess whether the signal is detectable. A range consistent with zero implies no detection. The same methodology has already been used in several studies that have established its credentials (Tett et al. 1999, 2002; Stott 2003; G. S. Jones et al. 2005; Christidis et al. 2005; Nozawa et al. 2005; Stone and Allen 2005).

Spatiotemporal patterns for the 3 indices introduced in section 3 are used here to construct the signals. The patterns comprise 5-yr mean index anomalies for the ten intervals in segment 1950–1999. The anomalies are relative to the segment mean. In contrast to spatial response patterns (e.g., trend fields), spatiotemporal patterns represent the evolution of the climate response to external forcings in more detail and add quality to the analysis (Christidis et al. 2005). As they provide more information, they help optimal detection discriminate between forcing components, and problems of signal degeneracy may thus be avoided.

Internal climate variability is approximated by the control simulation, which, however, is not long enough to provide the full inverse of the noise covariance matrix. For this reason, the analysis is restricted to the subspace of the noise covariance, defined by the k leading EOFs. The present analysis uses 39 control segments (20 nonoverlapping) and the scaling factors are computed with 30 EOFs. The adequacy of this EOF truncation is confirmed, when assessed against prescribed criteria (Allen and Tett 1999), while the results are found not to vary considerably in the spectral vicinity of the chosen truncation. To alleviate the bias with respect to the chosen control segments and compute the uncertainty in the scaling factors, a second set of 19 extra control segments (10 nonoverlapping) is used. The sampling noise (ui) is calculated as a scaled version of the noise in the observations (u0).

The assumption that climate model representations of internal variability are realistic has been subject to criticism and its validity has often been tested in power spectra analyses (Stouffer et al. 2000; Gillett et al. 2000a; Stott et al. 2000). Such analyses of temperature time series show no evidence of serious inconsistency between modeled and observed variability, at least at time scales relevant to optimal detection. The same approach is used here for GSL, SPR, and AUT. Power spectra for time series of 5-yr mean index values are plotted in Fig. 3. The indices are time meaned, as in the detection patterns, to concentrate on time scales between 10 and 50 yr. To remove the climate change signal from the observations, the data are either detrended, or have an independent estimate given by the ALL ensemble mean subtracted from them. The latter was suggested by Stott et al. (2000) as a way of treating the negative bias that may be introduced when detrending the time series. The shaded area in Fig. 3 marks the 5%–95% range from the control spectra. The observations are found to be within the model range in most cases, while small departures toward lower values may suggest that the model overestimates variability at certain scales for GSL and SPR. If this is the case, the enhanced model variability would provide a more strin-
gent measure of signal detectability, and would increase confidence if significant index changes are found.

The following two sections present two applications of optimal detection. First, a single fingerprint analysis is carried out with fingerprints from different model experiments. The aim is to establish whether significant changes have risen above noise and can therefore be detected in the observations. Second, a two-fingerprint analysis takes a step further and aims to separate the anthropogenic and natural forcing components and hence attribute the change to possible causes.

5. Detection of changes in GSL, SPR, and AUT

The response patterns from each HadCM3 experiment are compared separately against the observations in the framework of optimal detection, and the resulting scaling factors with their uncertainty range are depicted in Fig. 4. The analysis is carried out over the whole observation area, but also over Europe and North America. It is common practice to project the response patterns on spherical harmonics and retain only the larger spatial scales, but in order to facilitate continental-scale analyses, spatial smoothing is omitted in this section and both global and continental signals are constructed with the actual gridpoint data. It should be noted, however, that, as this is not a formal regional analysis (as it would be with higher resolution, regional model data and probably more dense observations), continental-scale results are only rough guides of the regional changes.
In all cases, the GSL scaling factors (Fig. 4a) are inconsistent with zero, implying that the model fingerprints represent detectable changes. Exclusion of all the anthropogenic forcings, however, generates a response opposite to that observed (negative scaling factors for NAT). Over the whole observations area, ALL yields the best agreement between model and observations, while the absence of the natural forcings in ANTHRO and, additionally, of the aerosol forcing in GHG, leads to an overestimate of the modeled change (scaling factors less than unity). Despite larger internal variability over smaller regions, GSL changes in Europe and North America are also clearly detected in experiments that include the forcing of well-mixed greenhouse gases.

Looking at the beginning and the end of the growing season, the earlier onset of spring is also detectable in all experiments with anthropogenic forcings (Fig. 4b), whereas in most cases no significant change in the end of autumn is detected (Fig. 4c). Regression generates open-ended intervals for natural forcing SPR scaling factors and also for some regional AUT scaling factors. This is a well-known feature of TLS regression that can arise in the case of small response patterns with finite amplitude in the observations (Allen and Stott 2003). The SPR scaling factors are generally consistent with unity and the biggest discrepancies arise in North America, where the model underestimates the change. Changes in AUT are too small to be detected in the observations with the exception of Europe, where the signal is more pronounced for experiment ALL, though the uncertainty range is large. In conclusion, when anthropogenic forcings are taken into account, a lengthening of the growing season is clearly detected at continental or larger scales, and this arises mainly from an also detectable earlier onset of spring.

The analysis was also carried out with the indices computed based on the Frich et al. (2002) definition, which looks at threshold exceedences in 5-day periods. This, however, did not improve the analysis compared to the smoothed cycle approach. A negative aspect of smoothing the annual cycle is that some of the benefit of using daily data is lost. It was indeed confirmed that computing the indices with monthly data instead has generally a small impact on the analysis. On the other hand, this can also become an advantage, as there are more monthly data available that can be utilized in the future and the analysis can therefore be extended over most land areas where seasons exist. Finally, an analysis was also carried out for a simple day-count index that gives the total number of days when the temperature exceeds the threshold, but this also gave a detriment compared to GSL, despite the better utilization of the daily data. The contrast between analyses with and without smoothing of the seasonal cycle suggests that it is the change in the overall shape of the cycle rather than in daily temperature variations that maximize the signal-to-noise ratio. In the following, only the index definitions in Fig. 1b will be considered.

6. Attribution to possible causes

Although the work presented so far suggests that there have been significant changes in GSL and SPR during 1950–99 that cannot be explained by natural influences alone, the relative importance of external forcings can only be quantified in multifingerprint analyses. Assuming no significant contribution from other missing forcings, a two-fingerprint investigation is carried out next, in order to partition the response between the ANTHRO and NAT components. Ideally, the response could be further decomposed by including fingerprints from more experiments, but as linear combinations of signals can be quite similar, degeneracy is likely to hinder such an undertaking.

The analysis is now carried out on a global scale only and the signals are projected on spherical harmonics beforehand, allowing only spatial scales greater than about 2500 km (total wavenumber truncation T8). The scaling factors for the three indices are plotted in Fig. 5a. For the GSL and SPR indices the anthropogenic effect is clearly detected and is sufficient to explain the whole observed signal. In contrast, NAT scaling factors, centered close to zero, indicate that the effect of natural forcings is unlikely to rise above the internal climate variability and to make a significant contribution to the observed change. As probably expected, the AUT signal is too small to be distinguished from model noise and attributed to any external forcings.

The next step is to scale the model fingerprints using the optimal detection results and construct the components of the climate response. Figure 5b illustrates how the observed global mean trend is partitioned between the anthropogenic and natural forcings. The uncertainty range in the observations reflects the effect of internal variability, whereas in ANTHRO and NAT it represents the range of the scaling factors. Small discrepancies with the values in Table 1 for the observations arise because of spatial smoothing and signal reconstruction with a limited number of EOFs. The results suggest that significant changes in GSL and SPR trends are the outcome of human activity. Smaller uncertainty in SPR implies higher confidence in that statement. The large uncertainty in AUT prevents a definitive conclusion, though it can be argued that also for
this case the small index trends are likely to be linked to anthropogenic forcings.

Local patterns of the change in GSL and SPR between the second and the first half of the 1950–99 period are shown in Fig. 6 for the observations and the scaled fingerprint components. GSL increases in the latter part of the period by about 4 days in the global mean. In the United States (US), however, the signal is mixed, with reductions in the east and increases in the west. This longitudinal contrast in the US was also found in other studies (Easterling 2002; Kunkel et al. 2004). Mixed local response in North America, as opposed to the uniform European signal, is consistent with the higher European GSL trends already mentioned (Fig. 2, Table 1). The observed changes in SPR show an earlier arrival of spring for the second half of the period by about 3 days in the global mean. The ANTHRO component is highly correlated with the observed signal (the correlation coefficient is above 0.8 for GSL and above 0.9 for SPR) and can therefore account for the whole change. NAT, on the other hand, yields a response of the opposite sign. In the global mean (over the observations area), the ANTHRO component gives a similar change in GSL and SPR with the observations, whereas the NAT component gives smaller changes (a decrease in GSL of about one day and an increase in SPR by about half a day).

7. Future projections

Detectable signals associated with changes in the length of the growing season and the onset of spring are found to have emerged as early as in the second half of the twentieth century. Rising temperatures in a changing climate (Cubasch et al. 2001; Stott et al. 2006) are expected to intensify the signal in the future. Twenty-first century projections for GSL, SPR, and AUT are presented here, with anthropogenic greenhouse gas and sulfur emissions following the Special Report on Emissions Scenarios (SRES) A1B, A2, and B2 (Nakicenovic and Swart 2000). These scenarios represent a range of possible storylines, describing a world of rapid economic growth and regional convergence relying on the balance of all energy sources (A1B), a heterogeneous world with economic development being mainly regional (A2), and a world with emphasis on local solutions to economic, social, and environmental sustainability (B2). Time series of annual mean index anomaly values relative to the 1950s and averaged over the observations area are plotted in Fig. 7. The earlier part of the time series shows the observed trends to the end of the twentieth century, together with model estimates from the ALL and the NAT ensembles. Again, as in the 5-yr mean time series (Fig. 2), the increase in the GSL and the decrease in SPR are captured in ALL but not in NAT, which actually shows a small trend of the opposite sign. HadCM3 indicates substantial changes for all the indices in the future under the three SRES scenarios and intensification of the signal well above internal climate variations. There are no large discrepancies between the three projections up until the middle of the 21st century, but the signals begin to separate after that, reflecting the peculiarities of each scenario. Late arrival in autumn, which has not yet been detected in the observations, is postulated to become a major contributor in modifying GSL. The synergy between
SPR and AUT changes will enhance the lengthening of the growing season. Within the span of the twenty-first century, the highest model predicted increase in GSL with the A2 scenario is about 50 days, 30 days because of the earlier arrival of spring and 20 days because of the later ending of autumn. The change remains high even under the lower emissions B2 scenario, in which case the growing season is extended by a month during the century with similar contributions from SPR and AUT. The projections shown in Fig. 7 are indicative of a major shift of the annual cycle toward higher temperatures, which, if materialized, will alter the current perception of a typical season. In all the calculations presented here the indices are defined using locally dependent, but time-independent thresholds. These are good descriptors of the local growing seasons at present, but in a warmer climate they will be too low to describe the changed regime and will therefore need to be redefined according to the new seasonal characteristics.

8. Discussion and conclusions

Phenological changes in a warming climate have been the subject of thousands of articles, looking at traits of thousands of species (e.g., McCarthy et al. 2001). The bulk of the available information compiles an impressive catalogue of species with different biological complexity, including zooplankton as well as mammals, grasses as well as trees. Studies like Parmesan and Yohe (2003) and Root et al. (2003) attempted to collate the reported changes in the context of meta-analyses and look for a coherent fingerprint of global warming across the spectrum of species. Both show a shift toward earlier spring events and measure advances of a phenologically defined spring by 2.3 and 5.1 days decade$^{-1}$, respectively. Of course, the above estimates depend on several factors, such as the number and the range of species included in the study, the geographical spread and homogeneity of the data, and competing explanations. Although evidence from meta-analyses alludes to global warming as the key factor to the recent changes in animal and plant behavior, such investigations do not decompose the response between individual climate forcing components. Root et al. (2005) were the first to employ a climate model in order to measure the contributions by natural and anthropogenic components. They compared multispecies phenological data with temperature changes from climate model experiments with and without anthropogenic forcings and came up with attribution statements by looking at the correlations. The diversity in the response of very different species to climatic changes challenges the versatility of phenological measures of

Fig. 6. Patterns of the index difference between the mean of 1975–99 and the mean of 1950–74 for (top row) GSL and (bottom row) SPR for the observations and also for the ANTHRO and NAT fingerprints scaled with factors from the attribution analysis (Fig. 5a). All fields are reconstructed with a number of spherical harmonics and leading EOFs from the control determined by the specified truncation. The area weighted correlations between the individual components and the observation patterns are noted on the title of each component frame. Index differences are in units of days.
Fig. 7. Index anomalies relative to the 1950s for (a) GSL, (b) SPR, and (c) AUT over the observations area. The time series to the end of the twentieth century come from the observations (thick black line) and the ensemble members of experiments ALL (red lines) and NAT (blue lines). The time series to 2100 come from HadCM3 runs with anthropogenic forcings, which follow the SRES A1B (orange line), A2 (purple line), and B2 (green line) scenarios after year 2000.
seasonality. In this work the change in seasonality is measured on a climatological basis (i.e., is a cause rather than effect entity), which in turn can measure all the resulting impacts. Hence, advances of the climatological spring become the benchmark to quantify a wide range of by-products, such as advances in phenological events, as well as in snow melting and peak river flows, agricultural impacts, changes in water storage requirements, and decreases in tourism profit.

Optimal detection shows that increases in GSL cannot be explained by internal climate variability or by natural external forcings alone. The anthropogenic influence is essential in order to account for the emerging signal, both globally and on the continental scales of Europe and North America during 1950–99. Another important finding is that the lengthening of GSL is primarily an outcome of earlier springs rather than later winters. The relative effect of natural and anthropogenic influences is also examined in the context of a two fingerprint analysis. It is found that the observed global-scale trends in GSL and SPR can be elucidated by the anthropogenic emissions of greenhouse gases and sulfur.

Although one might expect that warming of the climate system would shift the whole seasonal cycle toward higher temperatures, it appears it is mainly its first half that has warmed significantly to date. Groisman et al. (1994) and Cayan et al. (2001) suggested that this seasonal asymmetry may be linked to the snow feedback. The earlier melting of snow feeds back to enhance the warming. As the snow comes later in autumn, the feedback does not affect the later part of the growing season, which may explain the observed asymmetry. As model projections reveal, the situation is expected to change in the future, as rising temperatures will markedly increase the delay in the ending of autumn and will so lead to an even longer GSL.

It could be argued that changes in the large-scale circulation, not explicitly investigated here, could impact the analysis. Cayan et al. (2001) tested the hypothesis that earlier springs in the western US are associated with shifts to one of the phases of the Pacific decadal oscillation (Gershunov et al. 1999). They looked at the correlation between the principal component of their phenological spring index (for EOF1) and the 700-mb height anomalies, and it was clear that their results did not support the hypothesis. In another study, Gillett et al. (2000b) found that changes in the Northern Hemisphere circulation, when accounted for, hardly changed the results from an optimal detection analysis applied to warming patterns (which underline the changes in GSL). Finally, the use of a long control simulation (1800 yr of it in the present analysis) should ensure that internal climate variability is represented adequately to disentangle the signal from climatic oscillations. It is therefore safe to assume that external forcings are the key factors that drive the significant index departures from their climatological mean.

The lengthening of the growing season attributable to human activity is detected in its early stages and is expected to become more prominent as greenhouse gas emissions continue to warm the climate system. HadCM3 twenty-first century projections indicate increases over the whole observation area of a month or more by 2100. Although predictions are influenced by uncertainties in future emissions, internal variability, missing forcings, and modeling limitations, the scale of the change is so large that even if only some of its impact was felt, it would still be considerable. So far it is mainly the earlier onset of spring that has made the growing season longer, but it is shown that in the future both ends will tend to increase its length. The new season regime in the near future will bring about important environmental and socioeconomic impacts.

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