The North Atlantic Oscillation and regional phenology prediction over Europe

BENJAMIN I. COOK, THOMAS M. SMITH and MICHAEL E. MANN
Department of Environmental Sciences, University of Virginia, 291 McCormick Road, Charlottesville, VA 22904, USA

Abstract

We present an integrated modeling study designed to investigate changes in ecosystem level phenology over Europe associated with changes in climate pattern, by the North Atlantic Oscillation (NAO). We derived onset dates from processed NDVI data sets and used growing degree day (GDD) summations from the NCEP re-analysis to calibrate and validate a phenology model to predict the onset of the growing season over Europe. In a cross-validation hindcast, the model (PHENOM) is able to explain 63% of the variance in onset date for grid cells containing at least 50% mixed and boreal forest. Using a model developed from previous work we performed climate change scenarios, generating synthetic temperature and GDD distributions under a hypothetically increasing NAO. These new distributions were used to drive PHENOM and project changes in the timing of onset for forested cells over Europe. Results from the climate change scenarios indicate that, if the current trend in the NAO continues, there is the potential for a continued advance to the start of the growing season by as much as 13 days in some areas.

Keywords: climate change, ecosystem/climate interactions, North Atlantic Oscillation, phenology modeling

Received 17 March 2004; revised version received 9 August 2004 and accepted 11 November 2004

Introduction

Climate change over the globe, anthropogenic or otherwise, probably will not be uniformly distributed throughout the world, but will very likely be expressed as changes in regional climate patterns. The North Atlantic Oscillation (NAO) and its' circum-hemispheric analogue, the Arctic Oscillation (AO), is one such pattern and, along with the El Nino Southern Oscillation, represents one of the primary large-scale recurrent modes of climate variability in the Northern Hemisphere (Hurrell, 1995, 1996; Thompson & Wallace, 1998, 2001; Wallace & Thompson, 2001; Wanner *et al.*, 2001). The NAO represents a meridional displacement of atmospheric mass between the low and high pressure cells centered near Iceland and the Azores, respectively. The strength of this pressure gradient changes at annual, seasonal, and monthly time scales. A steeper gradient (the high or positive NAO phase), indicating an intensified Icelandic low and Azores high, is associated with stronger westerly winds, greater

Correspondence: Benjamin I. Cook, fax + 1 434 983 2137, e-mail: bc9z@virginia.edu

advection of moist air off the Atlantic and onto mainland Europe, and warmer winter temperatures in Northern Europe and Eastern North America. The reverse holds true when this gradient is shallower (the low or negative NAO phase): storm tracks are much more zonal, the maritime air moves into the Mediterranean and North Africa, and Northern Europe and Eastern North America are cooler than normal. The strength of this pressure gradient, reflecting the magnitude and phase of the NAO, is expressed as the NAO index, the normalized difference in sea level pressure between these two pressure cells, using data from Southwest Iceland and Gibraltar or Ponta Delgada, Azores (Hurrell, 1995; Jones *et al.*, 1997). This NAO index alone resolves 31% of the variance in Northern Hemisphere winter temperatures (December–March) above 20°N (Hurrell, 1996). Since the mid-1960s, there has been a positive trend towards higher NAO index values and concomitant winter-time warming over Europe and much of the Northern Hemisphere extratropics (Hurrell, 1996; IPCC WG I, 2001), a trend that may be related to anthropogenic forcing (Shindell *et al.*, 1999; Ulbrich & Christoph, 1999; Wallace & Thompson, 2001).

Alongside these atmospheric changes is increasing evidence for shifts toward an earlier onset and increased length of the growing season. Chmielewski & Roetzer (2001), using records from four tree species, found an earlier start to the growing season in Europe by 8 days. The first flowering dates for 60 plant species in Britain have advanced 15 days in the last decade alone (Fitter & Fitter, 2002). And, perhaps even more significant, Zhou *et al.* (2001) observed an 18 and 12 day increase in growing season length at the ecosystem level over extratropical Eurasia and North America, respectively, based on satellite-derived vegetation indices. Numerous other studies using phenological records have documented phenological changes throughout the Northern Hemisphere (including Europe) and support the same general conclusion: the growing season is beginning earlier (Sparks & Carey, 1995; Menzel & Fabian, 1999; Post & Stenseth, 1999; Beaubian & Freeland, 2000; Schwartz & Reiter, 2000; Menzel, 2000; Roetzer *et al.*, 2000; Defila & Clot, 2001; Ottersen *et al.*, 2001; D'Odorico *et al.*, 2002; Penuelas & Filella, 2002; Walther *et al.*, 2002).

Because changes in the NAO may represent a distinctly separate impact of anthropogenic climate change (*i.e.*, aside from secular warming), the impact that changes in this climate pattern may have on phenology warrants investigation. To that end, the primary purpose of this paper is to apply a new, novel modeling approach to investigate covariability between the NAO and ecosystem level phenology. We develop an ecosystem level phenology model for forested areas over Europe, and drive the phenology model using an ensemble of climate change scenarios from a previously developed model (Cook *et al.*, 2004). We validate the model using a cross-validation hindcast and then drive the model into the future to investigate ecosystem level phenology changes under a hypothetically increasing NAO. This paper concludes with a discussion of the strengths and limitations of this modeling approach and possible future directions.

Materials and methods

The normalized difference vegetation index (NDVI) is a metric derived from satellite measurements, defined as (Carlson & Ripley, 1997)

$$\text{NDVI} = \frac{(Ch2 - Ch1)}{(Ch1 + Ch2)},$$

where $Ch1$ and $Ch2$ are visible (0.58–0.68 μm) and near infrared (0.73–1.1 μm) reflectance, respectively. The theoretical limits for NDVI are -1 to $+1$ but, practically, NDVI rarely drops below -0.2 or rises above 0.8. NDVI is a good proxy indicator for vegetation activity and correlates well with leaf area, leaf biomass, and potential photosynthesis (Myneni *et al.*, 1995; Carlson & Ripley, 1997; Zhou *et al.*, 2001). It is also quite sensitive to atmospheric interference, background soil color (Liu & Huete, 1995), and tends to saturate at high leaf areas (Carlson *et al.*, 1990), making the raw data product quite noisy. Still, its' value for the study of ecosystem processes in boreal and temperate forests has been well established, including for use in ecosystem level phenology studies (Moulin *et al.*, 1997; Botta *et al.*, 2000; Zhou *et al.*, 2001; Jenkins *et al.*, 2002; White *et al.*, 2002).

By examining the temporal NDVI profile over the course of a year, we can investigate the length of the growing season and the timing of phenological events at the ecosystem level (Moulin *et al.*, 1997). These phenological dates can then be used, in conjunction with meteorological data, to develop a model to predict the occurrence of the ecosystem level phenological event 'onset'. Onset is defined as a rapid increase in NDVI associated with the start of photosynthetic activity, essentially the beginning of the growing season. The term onset is intentionally vague, as it reflects behavior at the ecosystem level, rather than any ground-based phenological events (e.g., budburst, first flowering, etc.) that cannot be discerned from satellite images. We used the 10-day composite NDVI data extracted from the NOAA/NASA Pathfinder AVHRR Land (PAL) Global Data Product (Agbu & James, 1994). Spatial resolution is $1° \times 1°$ and covers every longitude and latitude over the world from 1981 to 2000. In this analysis we used data from years 1982 to 1998.

The 10-day compositing removes some cloud and atmospheric interference, but further processing is required. To remove any residual contamination left after the 10-day compositing, we used the Best Index Slope Extraction (BISE) technique developed by Viovy & Arino (1992) and used in several studies related to regional phenology (Moulin *et al.*, 1997; White *et al.*, 1997; Ebata & Tateishi, 2001). BISE-filtered values were then interpolated to the daily time step using a piecewise cubic Hermite spline interpolation.

Because there is a spatial mismatch between the temperature data from the NCEP re-analysis (used in the development of the phenology model and the growing degree day (GDD) model described later) and the AVHRR NDVI data, the data sets must be scaled to the same resolution in order to be compared and analyzed together. Scaling, in this case, is simply the interpolation of data at one spatial resolution to another (finer or coarser) resolution using statistical or empirical techniques. We chose to upscale the NDVI data from a $1° \times 1°$ resolution to $2.5° \times 2.5°$, the same resolution as the NCEP data. We had two reasons. First, it is much

simpler and more straightforward to upscale, rather than downscale. Upscaling required simply a spatial averaging of the NDVI data; downscaling climate data is a much debated and controversial topic with a wealth of literature describing the weakness and merits of various statistical and empirical techniques (for a thorough discussion, please see IPCC WG I, 2001). Additionally, there are several regional/global ecosystem models available at a coarse $2.5° \times 2.5°$ resolution (Gerber *et al.*, 2002; Lucht *et al.*, 2002), allowing for a reasonably simple coupling of the completed phenology model for future research. To eliminate the signal from agriculture, we used a $1° \times 1°$ land cover dataset to remove any agricultural cells prior to the upscaling (Defries & Townshend, 1994). From these processed, upscaled NDVI values, we derived dates of onset for every gridcell for every year using the methodology of White *et al.* (1997). For more detailed discussions of the BISE algorithm and the methodology for deriving the onset dates, the reader is referred to Viovy & Arino (1992) and White *et al.* (1997).

It should be noted that the purpose of this project is to try to isolate and model the influence of the NAO on ecosystem level phenology over Europe. We are not necessarily attempting to create the most 'accurate' phenology model, so much as we want to see how much variability in the onset of the growing season can be tied to changes in the NAO. With that in mind, our analysis over Europe is limited in two respects. First, the only meteorological variable considered is temperature. It is conceivable, and even likely, that phenology in Europe is also sensitive to insolation, daylength, moisture, or even internal processes (e.g., plant hormones). However, the influence of the NAO manifests itself primarily through changes in winter-time day-to-day temperature variability, and so we have chosen temperature as our focus. Second, because we are only considering temperature, our analysis will be confined to phenological events in ecosystems considered to be most temperature sensitive. Over Europe, this encompasses boreal and mixed forest types, as defined by Defries & Townsend (1994). These ecosystems also display strong seasonal cycles in their NDVI profiles, making it relatively easy to derive the date of onset. To this end, model development and analysis were confined to grid cells containing at least 50% forest cover (boreal and mixed), determined during the upscaling with the land cover map (Fig. 1). The NDVI signal and subsequent timing of the onset event may still be influenced by other ecosystems in these cells included in the upscaling (e.g., grassland), but a 50% threshold ensures that at least half of the signal originates from forest cover. As mentioned previously, all agricultural cells have been removed from the
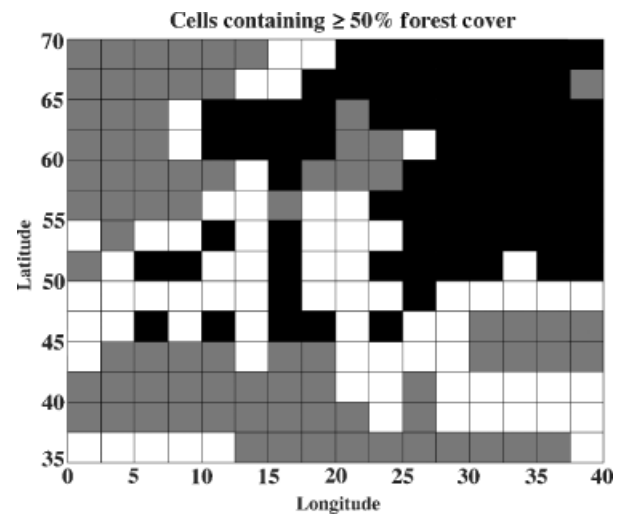

Fig. 1 Cells (in black) containing at least 50% boreal or mixed forest, used for calibration, validation, and prediction in PHENOM.

upscaling and subsequent analysis. We tried to obtain ground data from the POSITIVE Project, the European Phenological Network (EPN), and the International Phenological Gardens (IPG) to validate the satellite-derived onset dates. However, representatives and participants from these organizations informed us that, since we were not directly involved in these projects, we were not allowed access to this data. Annette Menzel did provide us with the IPG European Phenology Anomaly time series, a singular, nonspatial index derived from various species across the IPG network. We used this series to validate the efficacy of our climate conditioning model (Spatial Autoregressive Modelling Framework (SPARM), described below) for phenological modeling, an in depth discussion of which is in Cook *et al.* (2004).

Models used to predict the timing and occurrence of phenological events (e.g., budburst, leaf-out, first flowering, onset, etc.) often use GDD approaches (Hunter & Lechowicz, 1992; White *et al.*, 1997, 1999; Kramer *et al.*, 2000). In a typical GDD model, mean daily temperatures above a certain threshold ('GDD') are summed each day ('GDD summations') until a critical sum is reached, triggering the phenological event of interest. The threshold at which a day qualifies as a GDD usually represents some temperature that will elicit a biochemical response from the plants that will stimulate the occurrence of the phenological event of interest. Our threshold is $0°C$, the same used in White *et al.* (1997). Phenology models may also incorporate moisture or radiation summations (White *et al.*, 1997, 1999), although these variables will not be dealt with here for reasons already discussed. Some

models may also incorporate chilling requirements, although this is by no means universal. Indeed, many studies have shown that more sophisticated models do not necessarily produce better results (Hunter & Lechowicz, 1992; Botta *et al.*, 2000). For each year, our model begins summing GDD on January 1. As such, we have not implemented any chilling requirement in the model and implicitly assumed that, in the data used for model calibration, any chilling requirement would have been met prior to this date.

For any given grid cell, the timing of onset is a function of the GDD summation and the critical growing degree summation (i.e. the GDD summation required to trigger onset). The assumption is that the critical summation will be constant from year to year, but climate variability will affect the actual GDD summations. Through this mechanism, the timing of phenological events will covary from year to year with the climate. It is possible that plants may evolve and adapt to changing climate conditions, becoming more or less sensitive to temperature or other factors: under this scenario the assumption of a constant critical summation is erroneous. However, because of the short time scale of our analysis (17 years), we feel this assumption is appropriate. Additionally, our climate change scenarios (described below) take place over a time scale (~ 50 years) shorter than the time it takes most forests to evolve and mature.

To expand the model from one grid cell to a larger regional area, we needed to determine some driver for predicting the critical GDD summation across the landscape. We used climatological annual mean temperature for the different grid cells for the period of available phenology data (1982–1998) to predict critical summations, similar to the method used by White *et al.* (1997). Climatological temperature allows us to account for differential temperature sensitivities in forests in different climatic regimes. For example, ecosystem processes in high latitude forests with lower annual average air temperatures can be expected to respond to lower temperature summations than more southerly, naturally warmer forests. We used daily surface temperature data from the NCEP/NCAR reanalysis (Kalnay *et al.*, 1996) to calculate GDD summations and average annual mean temperatures for all grid cells for the same period as our satellite phenology data (1982–1998). A linear regression shows a strong relationship between the critical GDD summations and average annual temperature (Fig. 2).

Using the relationship in Fig. 2 to determine critical GDD summations for every grid cell, we used data from the NCEP re-analysis to hindcast onset dates for 1982–1998. The hindcasts were conducted using a cross-validation procedure, where data from the current year
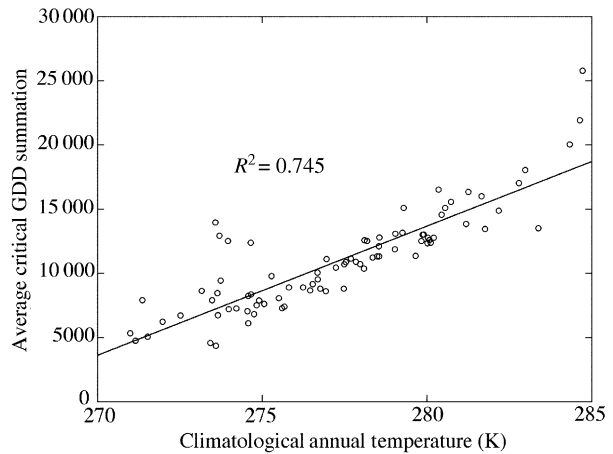

Fig. 2 Climatological annual temperature vs. average critical growing degree days (GDD) summation. Climatological annual temperature acts as a proxy for geographical location, allowing for spatial heterogeneity in the response of ecosystems to meteorological forcing.

in which onset was being predicted were not used in the GDD/climatology regression. A comparison between the onset dates from the model and onset dates derived from the satellite data (Fig. 3) shows good agreement between predicted and real dates, with the model accounting for about 63% of the variance in actual onset dates. The diagonal line represents the 1 : 1 line between observed and predicted dates. There is some increase in variability at the extreme ends of the regression, suggesting alternative factors besides GDD summations may influence phenology in the more southerly sites and northerly sites. Southern sites, with earlier onset dates, can be expected to be warmer, normally. Thus, systems in these areas may be less sensitive to temperature changes. The naturally higher temperatures, in turn, may also make moisture a limiting factor for plant processes. Northern sites, in addition to a strong annual cycle in temperature, also have a stronger seasonal cycle in insolation than more southern sites. Thus, insolation may be an increasingly important factor as one goes north. Additionally, work by Botta *et al.* (2000) suggests that boreal and arctic systems may be limited by soil frost or may require a more explicit implementation of chilling requirements to accurately predict onset. Despite these weaknesses, however, this model, using GDD summations as the driving parameter, accounts for a greater proportion of the variation in onset dates than either the NAO alone or seasonal/monthly/annual average temperatures.

To simulate the influence of the NAO on daily temperature and GDD distributions, we used the
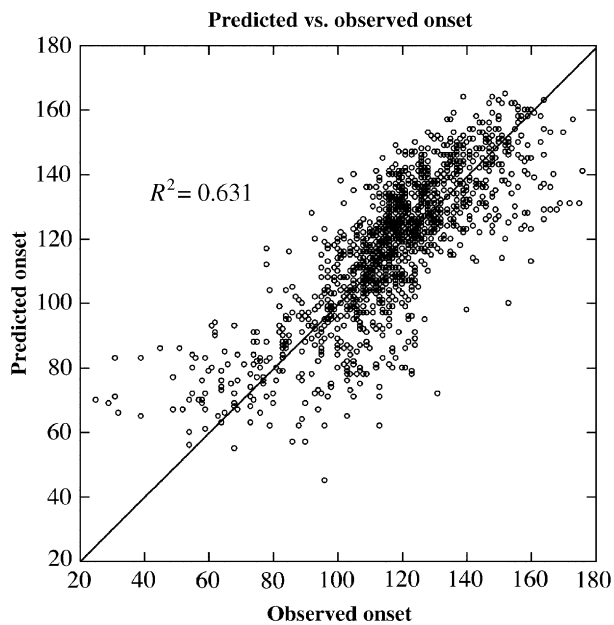
Predicted vs. observed onset

$R^2 = 0.631$

Fig. 3 Observed onset dates (derived from normalized difference vegetation index data and relative greenness profiles) and predicted onset dates (from PHENOM) over forested cells for years 1982–1998.

SPARM. SPARM is detailed elsewhere (Cook *et al.*, 2004), but here we provide a brief overview. SPARM is an empirical/statistical model derived from, initially, a principal component analysis of daily surface temperatures for the winter season (December–March) over Europe for years 1949–1996 from the NCEP/NCAR re-analysis. The results from the principal component analysis (the eigenvectors and principal components) are then used to generate synthetic temperature and GDD distributions. The eigenvectors are retained as is and are used to define the spatial, synoptic scale structure of the temperature fields. The principal components are used to represent the temporal variability of the daily temperatures and are generated synthetically by resampling from the original principal components as lag-1 autoregressive processes. For those principal components that are significantly correlated with the NAO (at the seasonal level), the parameters for the AR(1) models are calibrated for different temperature distributions associated with the phases of the NAO: low, neutral, or high. This allows for a priori selection of the phase of the NAO and the generation of synthetic daily temperatures and GDD with distributions consistent with the prescribed phase of the NAO. We demonstrated in our previous paper (Cook *et al.*, 2004) that our framework adequately reproduced the temperature and GDD distributions (spatially and temporally) associated with the different phases of the NAO and had more skill at predicting

several phenological indices than the NAO alone. Our previous work indicates that SPARM is appropriate for investigating phenology under moderate climate scenarios.

Results

Recent modeling evidence suggests the distinct possibility that the trend towards increasing prevalence of the positive phase of the NAO during the Northern Hemisphere winter may indeed represent a signature of anthropogenic climate change (Osborn *et al.*, 1999; Shindell *et al.*, 1999). We might speculate, in this scenario, that the recent trend in the NAO will continue, e.g., into the mid-21st century and beyond. For the climate change scenarios, we used a hypothetical NAO series, from 1949 to 2051 (Fig. 4). From 1949 to 2002, the actual Hurrell NAO index is used (Hurrell, 1996). From 2003 to 2051 we generated a stochastic NAO series by resampling as a Gaussian white noise process from the original Hurrell NAO series, and superimposing on it the trend in the NAO from 1960 to 2000. We note that, while some of the values in the hypothetical NAO series may seem too large to be realistic, the model itself is only set up for three phases: low, neutral, and high. Therefore, for example, a winter diagnosed with an NAO index of 3 would generate daily temperatures based on the same distributions as a winter with an NAO index of 6 (both qualify as the 'high' index case).

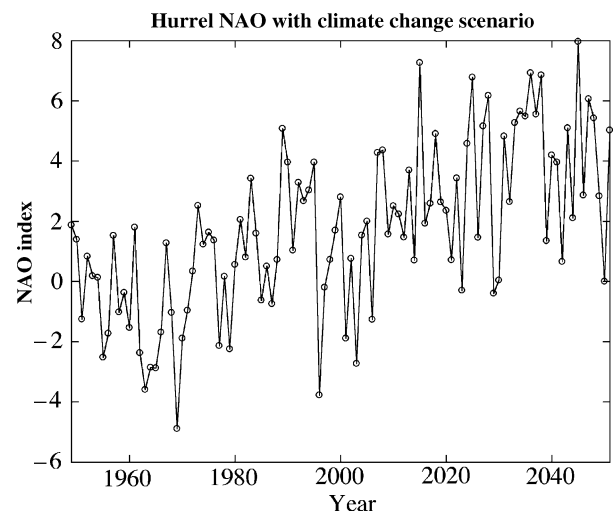**Hurrel NAO with climate change scenario**

Fig. 4 North Atlantic Oscillations (NAO) series used to drive the climate change scenario. From 1949 to 2002, the Hurrel NAO series is used (Hurrell, 1996); for projections 50 years into the future (2003–2052) we stochastically generated a synthetic NAO series, superimposed over the same linear trend of the Hurrell series from 1960 to 2002.

Using SPARM to generate winter temperature distributions using the NAO series in Fig. 4, we conducted climate change scenarios into the future under a stochastically increasing NAO, generating 400 realizations of the model. For each year in the model simulation, January–March temperatures are diagnosed using SPARM. For every day afterward, mean temperature for that day (calculated from 1982 to 1998) is used. Again, we are trying to isolate the influence of the NAO (through daily surface temperatures): in this case, by only allowing the NAO to affect winter season temperatures and confining any interannual variability in temperatures to these months (January–March).

Figure 5 shows the composite onset anomaly time series, calculated by removing the mean onset date (for the period 1960–2002) for each forested grid cell and averaging the anomalies across all forested grid cells for an ensemble of 400 realizations. This is designed to give a general indication of the overall trend in the forested cells. The gray shaded area represents ± 1 standard deviation and the dashed lines represent the average ± 1 standard deviations for the period from 1960 to 1970. The overall trend in the graph (in both the mean state and confidence intervals) is toward negative anomaly values, indicating a general shift toward earlier onset for forested areas as a whole.

A more cohesive spatial picture is shown in Figs 6 and 7, where mean trends (averaged across all simulations) in GDD summations and onset date (during the period of 2002–2053; trend in actual date, not anomaly)

Fig. 6 Mean trends (Kelvins per year) in growing degree days across simulations from climate change simulations, from 2002 to 2051. Nonforest grid cells are in white and water cells are in gray (for contrast).

Fig. 7 Mean trends (days per year) in onset date across simulations from climate change simulations, from 2002 to 2051. Nonforest grid cells are in white and water cells are in gray (for contrast).
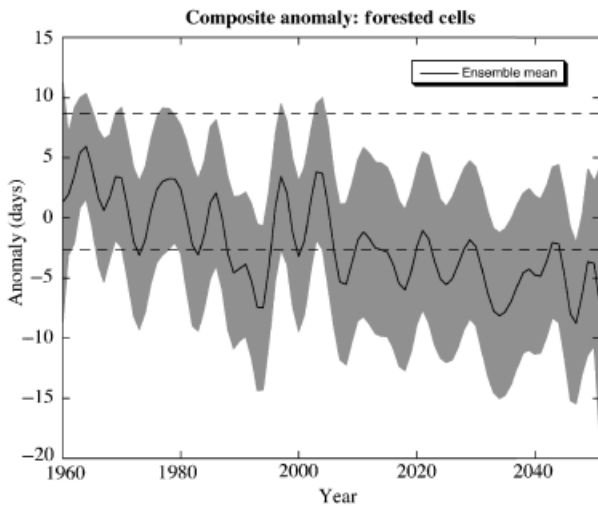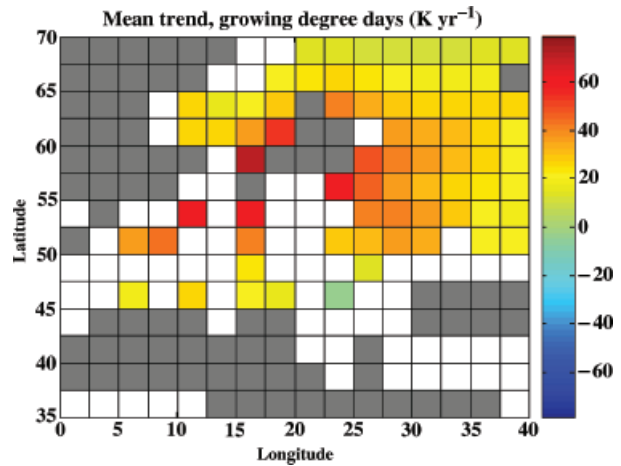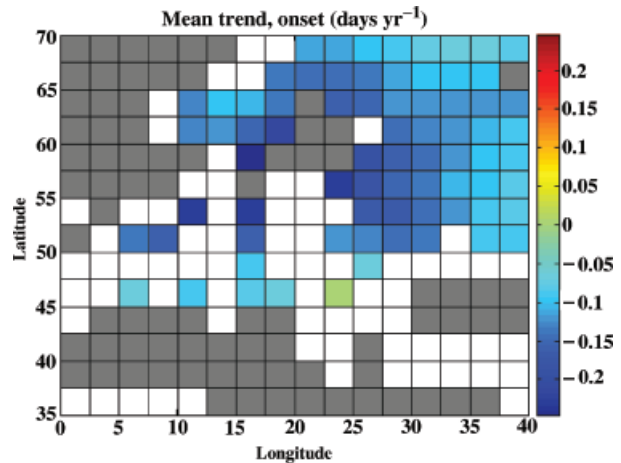

Fig. 5 Composite onset anomaly from climate change scenarios across forested cells. Anomalies are calculated relative to the mean over the period of 1960–2002. The gray shaded area represents ± 1 standard deviation and all curves are 5 year lowpass butterworth filters. Dashed red lines represent the average ± 1 standard deviations for the period from 1960 to 1970.

for each grid cell are shown. Non-forest grid cells (outside the scope of the model) are in white and water cells are colored in gray for contrast. The model predicts the largest warming trend in the areas surrounding the Baltic Sea (Fig. 6), driving the largest trends in onset (Fig. 7). Trends in both GDD, and onset gradually become weaker towards the more inland and southerly sites. Across forested cells, predicted trends in onset date range from + 0.0061 to −0.2604 days per year, similar in magnitude to ranges for the entire (1960–2051) modeled time period (ranging from −0.0064 to −0.2405 days per year).

Discussion

Our phenology model (PHENOM), driven into the future under a stochastically increasing NAO (via SPARM), suggests the potential for a continued trend toward earlier onset of the growing season in many forested areas over Europe. The areas of strongest trend indicate the potential for an advance in onset by, on average, 13 days (−.26 days per year) over the next 50 years.

The framework developed here has several limitations. SPARM implicitly assumes a stationarity in the relationship between the NAO and daily winter surface temperatures. Similarly, PHENOM assumes that the sensitivity of the vegetation to temperatures will remain the same. These are limitations imposed by the statistical/empirical nature of the models. The models, therefore, are only useful for moderate climate change scenarios, either into the recent past or near future under boundary conditions similar to the current state. A limitation in PHENOM, imposed by the limited availability of satellite data, is that the NDVI data used to develop the model cover a limited period of time and only include one low NAO index year. Similarly, the temperature data only cover the latter part of the 20th century, although in the development of SPARM they encompass both positive and negative trends in the NAO. It should also be noted that the SPARM model only coarsely resolves the effects of the NAO by only diagnosing three phases; low, neutral, and high. This allows for some uncertainty in our understanding of the relationship between daily temperatures and the NAO.

Despite these weaknesses, SPARM and PHENOM are both useful tools. SPARM reliably reproduces daily temperature and GDD distributions consistent with the phase of the NAO. PHENOM possesses considerable skill in predicting ecosystem level onset over Europe based on GDD summations, reinforcing the importance of considering daily (rather than seasonal, monthly, etc.) environmental influences in phenological modeling. Use of both models has facilitated the investigation of covariability in the NAO and ecosystem level phenology in a new, and novel, way.

If the current trend in the NAO continues for the next 50 years, this model suggests the potential for a continued trend toward earlier onset for mixed and boreal forests over much of Europe. This could have significant ramifications for the terrestrial carbon budget, as a longer growing season will change the annual balance of respiration and production in the biosphere. The next logical step will be to couple these results to an ecosystem model (e.g., the LPJ-DGVM) to investigate connections between the NAO, phenology, and more dynamical ecosystem processes (e.g., production and respiration). These aspects of ecosystem modeling are, however, beyond the scope of this paper.

References

Agbu PA, James ME (1994) *The NOAA/NASA Pathfinder AVHRR Land data set user's manual.* Goddard Distributed Active Archive Center, NASA Goddard Space Flight Center, Greenbelt, MD.

Beaubian EG, Freeland HJ (2000) Spring phenology trends in Alberta, Canada: links to ocean temperature. *International Journal of Biometeorology*, **44**, 53–59.

Botta A, Viovy N, Ciais P *et al.* (2000) A global prognostic scheme of leaf onset using satellite data. *Global Change Biology*, **6**, 709–725.

Carlson TN, Perry EM, Schmugge TJ (1990) Remote estimation of soil moisrure availability and fractional vegetation cover for agricultural fields. *Agricultural and Forest Meteorology*, **52**, 45–69.

Carlson TN, Ripley DA (1997) On the relation between NDVI, fractional vegetation cover, and leaf area index. *Remote Sensing of Environment*, **62**, 241–252.

Chmielewski FM, Roetzer T (2001) Response of tree phenology to climate change across Europe. *Agricultural and Forest Meteorology*, **108**, 101–112.

Cook BI, Mann ME, D'Odorico P *et al.* (2004) Statistical simulation of the NAO on European winter surface temperatures: applications to phenological modeling. *Journal of Geophysical Research-Atmospheres*, **109**, D16106, doi: 10.1029/2003JD004305.

Defila C, Clot B (2001) Phytophenological trends in Switzerland. *International Journal of Biometeorology*, **45**, 203–207.

Defries RS, Townshend JRG (1994) NDVI-derived land cover classification at a global scale. *International Journal of Remote Sensing*, **15**, 3567–3586.

D'Odorico P, Yoo J, Jaeger S (2002) Changing seasons: an effect of the North Atlantic oscillation? *Journal of Climate*, **15**, 435–445.

Ebata M, Tateishi R (2001) Phenological stage monitoring in Siberia by using NOAA/AVHRR data. *Paper presented at the 22nd Asian Conference on Remote Sensing, 5–9 November 2001, Singapore.*

Fitter AH, Fitter RSR (2002) Rapid changes in flowering time in British plants. *Science*, **296**, 1689–1691.

Hunter AF, Lechowicz MJ (1992) Predicting the timing of budburst in temperate trees. *Journal of Applied Ecology*, **29**, 597–604.

Hurrell JW (1995) Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. *Science*, **269**, 676–679.

Hurrell JW (1996) Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. *Geophysical Research Letters*, **23**, 665–668.

IPCC WG I (2001) *Climate Change 2001. The Scientific Basis.* Cambridge University Press, Cambridge.

Gerber S, Joos F, Brugger PP *et al.* (2002) Constraining temperature variations over the last millenium by comparing simulated and observed atmospheric CO_2. *Climate Dynamics*, **20**, 281–299.

Jenkins JP, Braswell BH, Frolking SE *et al.* (2002) Detecting and predicting spatial and interannual patterns of temperate forest springtime phenology in the eastern U.S. *Geophysical Research Letters*, **29** doi: 10.1029/2001GL014008.

Jones PD, Jónsson T, Wheeler D (1997) Extension of the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. *International Journal of Climatology*, **17**, 1433–1450.

Kalnay E, Kanamitsu M, Kistler R *et al.* (1996) The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, **77**, 437–471.

Kramer K, Leinonen I, Loustau D (2000) The importance of phenology for the evaluation of climate change on growth of boreal, temperate and Mediterranean forests ecosystems: an overview. *International Journal of Biometeorology*, **44**, 67–75.

Liu Q, Huete A (1995) A feedback based modification of the NDVI to minimize canopy background and atmospheric noise. *IEEE Transactions in Geoscience and Remote Sensing*, **33**, 457–465.

Lucht W, Prentice IC, Myneni RB *et al.* (2002) Climate control of the high-latitude vegetation greening trend and Pinatubo effect. *Science*, **296**, 1687–1689.

Menzel A (2000) Trends in phenological phases in Europe between 1951 and 1996. *International Journal of Biometeorology*, **44**, 76–81.

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

Moulin S, Kergoat L, Viovy N *et al.* (1997) Global scale assessment of vegetation phenology using NOAA/AVHRR satellite measurements. *Journal of Climate*, **10** (6), 1154–1170.

Myneni RB, Hall FG, Sellers PJ *et al.* (1995) The interpretation of spectral vegetation indices. *IEEE Transactions in Geoscience and Remote Sensing*, **33**, 481–486.

Osborn TJ, Briffa KR, Tett SFB *et al.* (1999) Evaluation of the North Atlantic Oscillation as simulated by a coupled climate model. *Climate Dynamics*, **15**, 685–702.

Ottersen G, Planque B, Belgrano A *et al.* (2001) Ecological effects of the North Atlantic Oscillation. *Oecologia*, **128**, 1–14.

Penuelas J, Filella I (2002) Responses to a warming world. *Science*, **294**, 793–795.

Post E, Stenseth NC (1999) Climatic variability, plant phenology, and northern ungulates. *Ecology*, **80**, 1322–1339.

Roetzer T, Wittenzeller M, Haeckel H *et al.* (2000) Phenology in central Europe-differences and trends in spring phenophases in urban and rural areas. *International Journal of Biometeorology*, **44**, 50–66.

Schwartz MD, Reiter BE (2000) Changes in North American spring. *International Journal of Climatology*, **20**, 929–932.

Shindell DT, Miller RL, Schmidt GA *et al.* (1999) Simulation of recent northern winter climate trends by greenhouse-gas forcing. *Nature*, **399**, 452–455.

Sparks TH, Carey PD (1995) The responses of species to climate over two centuries: and analysis of the Marsham phenological record, 1936–1947. *Journal of Ecology*, **83**, 321–329.

Thompson DWJ, Wallace JM (1998) The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters*, **25**, 1297–1300.

Thompson DWJ, Wallace JM (2001) Regional climate impacts of the Northern Hemisphere annular mode. *Science*, **293**, 85–89.

Ulbrich U, Christoph M (1999) A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. *Climate Dynamics*, **15**, 551–559.

Viovy N, Arino O (1992) The best index slope extraction (BISE): a method for reducing noise in NDVI time-series. *International Journal of Remote Sensing*, **13**, 1585–1590.

Wallace JM, Thompson DWJ (2001) Annular modes and climate prediction. *Physics Today*, **55**, 28–33.

Walther GR, Post E, Convey P *et al.* (2002) Ecological responses to recent climate change. *Nature*, **416**, 389–395.

Wanner H, Bronnimann S, Casty C *et al.* (2001) North Atlantic oscillation – concepts and studies. *Surveys in Geophysics*, **22**, 321–382.

White MA, Nemani RR, Thornton PE *et al.* (2002) Satellite evidence of phenological differences between urbanized and rural areas of the Eastern United States deciduous broadleaf forest. *Ecosystems*, **5**, 260–277.

White MA, Running SW, Thornton PE (1999) The impact of growing season length variability on carbon assimilation and evapotranspiration over 88 years in the eastern US deciduous forest. *International Journal of Biometeorology*, **42**, 139–145.

White MA, Thornton PE, Running SW (1997) A continental phenology model for monitoring vegetation responses to interannual climatic variability. *Global Biogeochemical Cycles*, **11**, 217–234.

Zhou L, Tucker CJ, Kaufmann RK *et al.* (2001) Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. *Journal of Geophysical Research-Atmospheres*, **106**, 20069–20083.