The onset of the growing season in northwestern Europe, mapped using MODIS NDVI and calibrated using phenological ground observations

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Abstract – Using Moderate Resolution Imaging Spectroradiometer (MODIS) normalized difference vegetation index (NDVI) data, we mapped the onset of spring in the years 2000-2004 in Fennoscandia. First, NDVI maximum value composite (MVC) time series were filtered and smoothed to remove noise. Next, pixel specific NDVI thresholds were calibrated using field observations of budburst in *Betula pubescens* Ehrh. (n = 81). This method achieves modest agreement between the predicted and observed dates (RMSE = 13 days). The resulting maps show that the arrival of spring varies by more than two months within the study area and by more than a month between years. We illustrate how MODIS NDVI images track phenological patterns in great detail and can be used to monitor the effects of ongoing climate change.

Keywords: phenology, downy birch, maximum value composites, MODIS, Fennoscandia

1. INTRODUCTION

Current climate models predict pronounced environmental changes to occur in the nearby future, especially at high latitudes (Cubasch et al., 2001). These changes will affect vegetation growth and productivity, and the distribution of biomes. Potential scenarios include a northward displacement of the area suitable for boreal forest by 150–550 km over the next century (Kirschbaum et al., 1996). Alterations in the timing of annual or phenological events are among the earliest detectable effects of climate change on vegetation. These events, such as spring foliation and flowering, appear to represent the response of plants to the recent local climate (Lieth, 1974). Therefore, monitoring vegetation phenology is fundamental to understanding the consequences of a changing climate for the biosphere. Among these consequences are changes in species distribution, plant herbivore interactions, carbon storage, and the flow of minerals and gases within the biosphere.

Satellite sensors make it possible to register vegetation phenology for large areas. By using time series of satellite images, and calculating vegetation indices, such as the normalized difference vegetation index (NDVI), the temporal and spatial variation in vegetation growth and activity can be quantified (Myneni et al., 1997). The NDVI provides an estimate of the amount of live green vegetation in an area (Goward et al., 1985). It relies on the fact that chlorophyll and other pigments in plants absorb radiation in the red spectrum whilst reflecting near-infrared radiation.

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \quad (1)$$

where ρ_{red} = reflectance in the red spectrum
ρ_{nir} = reflectance in the infrared spectrum

NDVI time series for phenological studies need to be of sufficiently high temporal resolution, in order to detect variations in NDVI during a single year. Such time series can be acquired from sensors aboard satellites with short revisit periods. In the past, the NOAA Advanced Very High Resolution Radiometer (AVHRR) in particular has been much used to map phenological events (Goward 1995). In 1999 and 2002, respectively, the TERRA and AQUA satellites were launched, both with a Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard. Compared to AVHRR sensors, MODIS offers improved calibration and atmospheric correction when compared. Furthermore, MODIS NDVI products exist at spatial resolutions as high as 250 and 500 m for the entire globe (compared to 1.1 km for the NOAA AVHRR), which allows for studies of regional vegetation dynamics.

Here we present maps of the onset of spring for the years 2000 to 2004 in Fennoscandia and neighbouring parts of northwestern Russia, derived from MODIS NDVI data. The area is characterized by a high climatic diversity comprising both highly oceanic sections in the west and highly continental sections in the east. Vegetation zones change from nemoral in the south through boreal to arctic in the north.

2. METHODS

2.1 Sensor and data set

We used the 16 day maximum value composite (MVC) MODIS NDVI dataset at a 250 m resolution spanning the period from 2000 to 2004 (Huete et al., 2002). It is produced from surface reflectance data which is corrected for molecular scattering, ozone absorption, and aerosols (Vermote et al., 2002). The MVC procedure selects for each pixel the highest observation from a 16 day interval to represent this period. Prior to compositing the NDVI data, a filter selects cloud free near-nadir observations. Because vegetation indices (VI) often increase when they are measured more obliquely, the compositing algorithm used for the MODIS VI constrains the variation in viewing angle in the data. It compares the two

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highest NDVI values after filtering and selects the observation closest to nadir view to represent the 16 day composite cycle.

The MVC dataset contains 23 NDVI observations per pixel per year. These observations are accompanied by auxiliary information on different parameters such as aerosol quantity and likelihood of snow cover, as well as an overall indication of the quality of each data point (scaled from 15 to 0, with 0 indicating 'perfect quality', Didan and Yuan, 2002).

2.2 Data processing

During a single year, the NDVI of most vegetation types displays a unimodal response whereby the NDVI increases during spring, stays more or less level during summer, and decreases during autumn. We followed a three step process to map the start of spring. First we estimated the *winter NDVI* per pixel. This is the minimum NDVI value a pixel displays throughout the year when it is free from snow. Such an estimate is necessary because coniferous trees maintain their foliage during winter. Unfortunately, snow and the polar night limit the opportunities to measure NDVI during winter at high latitudes. We estimated the *winter NDVI* as half the logarithmic mean of the maximum NDVI recordings during the intervals October 18th to October 31st and November 1st to November 16th, over the five year period. For this calculation we excluded observations with a usefulness index of 7 or higher, corresponding to less than average quality. The two time intervals are situated before the earliest onset of the polar night in most of the study area and have a lower probability of snow in the landscape than the first months of each year. At the same time they are situated after the growing season, as ground observations indicate that leaf fall in Norway initiates no later than mid October (NML, 2005). For each pixel, we substituted all NDVI values lower than the winter NDVI with the winter NDVI, assuming that values were influenced by snow cover.

As a second step, we eliminated the low quality NDVI recordings and noise present in the data. We excluded all NDVI observations with a usefulness index higher than 6, corresponding to average quality or worse. For each year, pixels where less than 8 NDVI recordings exceeded the winter NDVI were eliminated from further calculation. To the remainder of the time series, we applied a median smoothing filter (with a window size of 3) in order to retain only the most significant temporal changes in NDVI. These changes are believed to reflect spring green up and autumn canopy senescence.

The third step consisted of determining the onset of spring for each pixel *i* and year *j*. It was set to the date when the smoothed NDVI values (mNDVI) first exceeded a pixel-specific threshold, termed *spring NDVI*:

$$springNDVI_{ij} = wNDVI_i + (mNDVI_{MAX,ij} - wNDVI_i) \times P \qquad (2)$$

where $mNDVI_{MAX}$ = maximum smoothed NDVI
wNDVI = winter NDVI

P was calibrated so that it produced the minimal root mean square error (RMSE) between the predicted onset of spring and observed budbreak in downy birch (*Betula pubescens* Ehrh.), which is the dominant deciduous tree species in Fennoscandia. These observations (n = 81) were made by pupils of a network of secondary schools throughout Norway (NML 2005). Finally, the onset of spring was estimated throughout Fennoscandia for the period 2000-2004.

3. RESULTS AND DISCUSSION

The best correspondence (RMSE = 13 days) between the predicted onset of spring and observed budbreak in downy birch was achieved at P = 0.17 (Fig. 1).

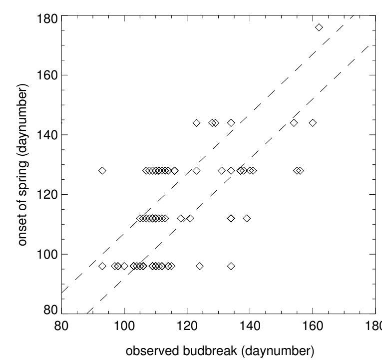

Figure 1. Result of the calibration of a threshold P to estimate the onset of spring from yearly NDVI curves. The best correspondence obtained between the onset of spring and observed budbreak is shown (RMSE = 13 days at P = 0.17). The broken lines delimit the boundaries of the NDVI compositing periods.

Few studies that map the onset of spring in natural vegetation using NDVI time series have evaluated or calibrated their method using ground observations (Høgda et al., 2002, Schwartz and Reed, 1999, White et al., 1999). They achieved only a low to moderate correlation between estimates derived from remote sensing and ground observations. The lack of good agreement in our study is due to several factors. The ground observations were made at single locations rather than plots comparable in size to the pixel size of the MODIS NDVI product. Although downy birch occurs throughout Fennoscandia, it is not dominant at all sites where ground observations were made. Phenological recordings on a set of plant species, rather than a single one, might thus be preferable. Finally, the timing of each NDVI recording has an uncertainty of 16 days. This is an artefact of the MODIS MVC algorithm. More precisely, it does not register the exact date of the NDVI recording that was selected by the algorithm to represent the 16 day composite cycle.

Nevertheless, the maps depicting the onset of spring show large differences throughout the study area and between years. The amplitude of the variation in the estimates exceeds the 16 day uncertainty in the NDVI data. Within a single year, the onset of spring in northwestern Europe varies by more than 2 months, form mid April to mid June (Fig. 2). Latitude and elevation gradients, as well as the distance to the sea appear determining factors. Local differences between years amounted to more than 4 weeks with spring starting late in 2000 and exceptionally early in 2002 and 2004 (Fig. 3). The largest variation is observed in mountainous and oceanic areas. This might be related to interannual variations in spring temperature and the timing of snowmelt. Note, however, that areas with an average onset of spring prior April to 23 were excluded from the comparison. These areas are mostly continental and at lower altitudes. Interestingly, opposite trends are observed during a single year. In 2001 for example, spring started relatively late in Southern Norway, but early on Kola peninsula, Russia. When analyzing trends in the length of the growing season in a 16 year AVHRR NDVI data set, Høgda et al. (2001) reported that northern Fennoscandia displays an opposite trend compared to the rest of Fennoscandia. The growing time series of MODIS NDVI data makes it possible to investigate such regional differences in phenology in greater detail than hitherto possible.

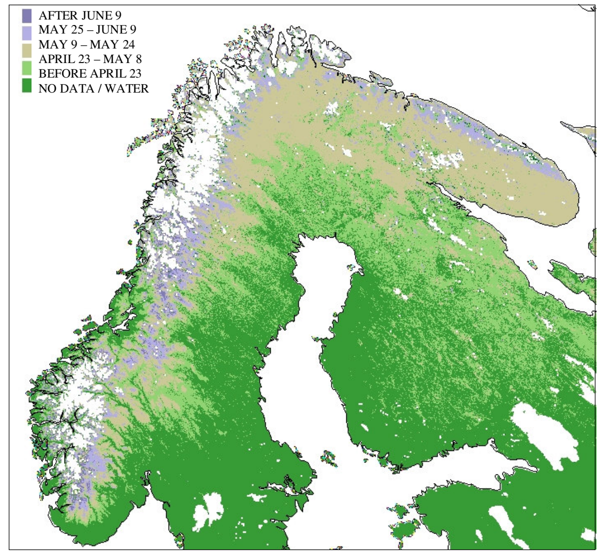

Figure 2. Onset of spring in Fennoscandia. The dates represent average modelled values for the years 2000-2004.

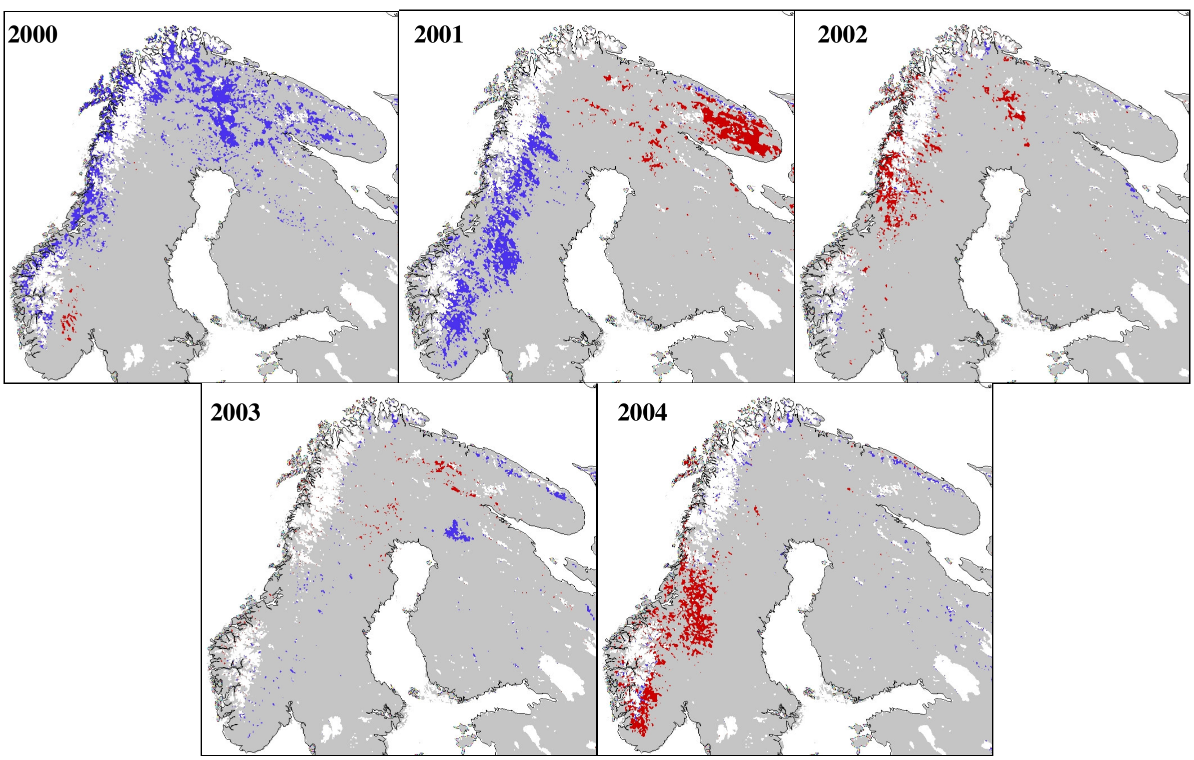

Figure 3. Yearly variation in the onset of spring. Red and blue areas, respectively, indicate where the onset of spring was more than 16 days earlier and later than the 2000-2004 average. The maps were resampled to 2300 m pixels after and a 3 × 3 median filter was applied. Pixels with an average predicted onset of spring prior to April 23 were excluded from the comparison.

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