Modelling the impact of climate change on the phenological development of forest trees in the Upper Danube Basin

Tobias Hank & Wolfram Mauser

Abstract

The BMB+F funded cooperative project GLOWA-DANUBE investigates climate change induced variances of water cycle components on the catchment scale. The surface water balance is sensitively affected by the length of the vegetation period. In order to map future trends of active growth phases, a temperature based modelling approach for the modelling of forest phenology was implemented into the DANUBIA land surface core model PROMET. A 45-year test model run (1961–2006) was able to reproduce observed values at a satisfying level, while the evaluation of a climate scenario (2007–2057) returned continued but increased trends towards earlier leaf growth and a prolonged vegetation period.

Keywords: climate change, GLOWA-DANUBE, IPCC scenario, forest phenology

1 Introduction

Over the past years, climate change and its impact on environmental processes has been one of the most intensely discussed topics. The vegetation cover is a component that is likely to react most sensitively to a changing climate, as it connects processes in soil and atmosphere through its multiple functionality as erosion inhibitor, carbon dioxide sink and transpiration source. The BMB+F funded cooperative project GLOWA-DANUBE investigates climate change induced variances of water cycle components on the catchment scale. Shading the soil and thus inhibiting soil evaporation, the living vegetation has a major influence on these components. On the other hand, it contributes enormously to the atmospheric water content through transpiration processes. As forests represent land use categories with large acreages and relatively long vegetation periods, they sensitively affect the water balance of the land surface. The transpiration capacity of trees again is strongly correlated with the phenological stage of the forest (Menzel 1997). The most crucial growth stages are those determining the absolute length of the vegetation period, i.e. the time the forest can contribute to the overall evapotranspiration. The model that is applied for this study uses a simple temperature related approach to simulate the leaf emergence as well as the defoliation of deciduous trees. For coniferous trees the date of the first mayshoot in spring is determined dynamically. The other, less determinant growth stages are implemented as a static function of the day of year (DOY) for both of the forest categories. The model returned spatially distributed maps for the incidence of the major phenological phases. A model run for the past 45 years (from 1961 to 2006) was able to reproduce a significant trend towards earlier leaf growth and a prolonged vegetation period, like it is observed throughout the current publications of different sciences as could be summarised by Menzel et al. (2006). Since large areas (45.2%) of the Upper Danube Basin belong to the "mountainous" altitudinal vegetation belt exceeding 600 m a.s.l., they are investigated separately. The results indicate that the Alps and the alpine foreland are regions that already are affected by climate change and are likely to experience continuing and increased trends towards prolonged phases of active vegetation growth.

2 The study area

The area of this study is limited to the watershed boundaries of the Upper Danube catchment. It covers more than 76 x 10^3 km^2 and has a geographic extension from roughly 8.5° E to 14° E and from 46° N to 50° N (figure 1, right). The geographic information system (GIS) forming the basis of the model calculations is screened in a resolution of 1 km x 1 km. From the resulting 76.212 x 10^3 proxels, a number of 5.81 x 10^3 is classified as deciduous forest, representing 7.45% of the total area, while a greater count of 25.013 x 10^3 raster elements, or 32.82% of the catchment area respectively, are mapped as coniferous forest (figure 1, left).

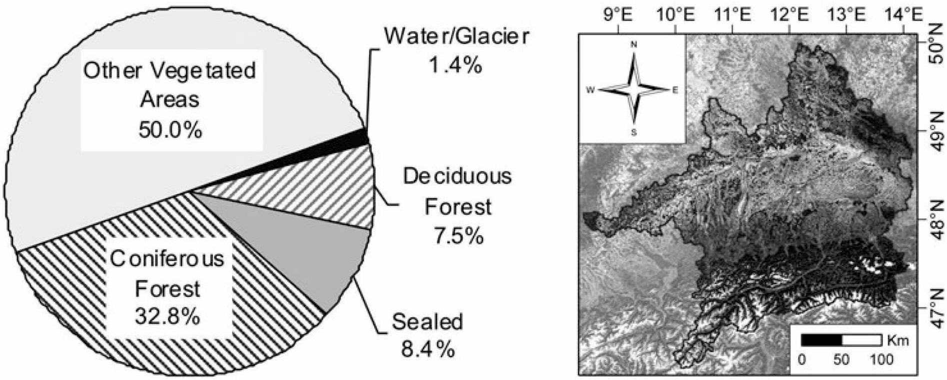

Figure 1: Landuse percentages used for the model runs (left). Watershed of the Upper Danube catchment area. Backdrop: ESA ENVISAT/MERIS image, recorded the 20th of September 2003 at 09:53h UTC (right).

3 Methods

3.1 The Landsurface Process Model PROMET

The process of radiation mass and energy transfer model PROMET (Mauser & Schädlich 1998) is a physically based process model that simulates a wide variety of land surface parameters. It is designed for worldwide application and can be operated on different scales. PROMET has been adapted to fit within the DANUBIA modelling framework (Mauser & Ludwig 2002) and is used as land surface core model of the climate change decision support system DANUBIA (Ludwig et al. 2005). The main task of the model is the solution of the energy balance at the land surface, while all determinant energy fluxes are taken into account. PROMET requires input data in form of a raster based GIS. Also parameter sets characterising soil and vegetation properties as well as meteorological inputs are needed.

3.2 Modelling forest phenology

In PROMET, a temperature-based approach simulates both, the spring activation that signalises the beginning of the growing season and the autumnal defoliation that ends the vegetation period. A simplified version of the EXP55 model by Cannel and Smith (1983) LN55, modified and parameterised by Menzel (1997), was used for the reproduction of the start of "leaf emergence" for deciduous trees, as well as for the incidence of "mayshoot" in case of the coniferous trees. For the deciduous trees, the loss of the leaves in autumn is modelled in dependence of frost occurrence.

3.2.1 Deciduous phenology

The model implicitly divides the winterly dormancy of trees into two phases. First, the endogenous dormancy determined by inner restrictions has to be neutralised by a winterly chill impulse. If the inner dormancy is resolved, the start of growth is secondarily inhibited by external conditions, resulting in an exogenously determined dormancy. The chill impulse that is essential for the neutralisation of the endogenous dormancy is calculated by accumulating the chill days (CD) that occur when the daily mean temperature (DMT) falls below a plant specific temperature threshold (t_bCD, equation 1).

$$CD = \min \left(\sum_{d_1}^{d} 1; CD_{min} \right) \qquad (1)$$

if DMT is below t_bCD. The term d_1 is marking the start day of the accumulation while d represents the currently modelled day. The accumulation of chill days starts on the first of November (d_1) and continues until the necessary amount of chill days (CD_{min}) is accumulated. Since *Fagus sylvatica* (beech) nearly represents 40% of the deciduous trees in the alpine foreland (LWF 2004) and features more or less average phenological characteristics compared to other regional tree types (see figure 2, left), the phenological response of the regional deciduous forest was assumed to be largely represented by that tree type. Therefore, the threshold value (t_bCD) of 9°C that applies to beech trees (table 1) was chosen for the calculation of the chill days. The actual amount of temperature below the threshold is unessential, since each chill day is weighted equally. For beech trees, a sum of 83 chill days is considered to be the critical threshold that ends the endogenous dormancy. From the day, when the inner dormancy is overcome, the daily mean temperature is accumulated in form of thermal degree days (TDD, equation 2).

$$\mathrm{TDD} = \sum_{i=1}^{n} \left(\overline{\mathrm{T}}_{a,i} - \mathrm{T}_{b} \right) \quad (2)$$

In equation 2, the term $T_{a,i}$ holds the daily mean air temperature on day I, while T_b represents the plant specific base temperature assumed with 6°C for beech trees. At the same time, the chill days are further accumulated until they either reach an assumed maximum amount of chill days (CD_{max}) or the critical temperature sum (TT_{crit}) is surmounted by the thermal degree days (equation 3).

$$\mathrm{CD} = \min \left(\sum_{d_1}^{d} 1; \mathrm{CD}_{max} \right) \quad (3)$$

if DMT is below t_bCD.

If the accumulated thermal degree days exceed the calculated critical emergence temperature, the growing season is activated. The TDDs necessary to overcome the exogenous dormancy, decrease with an increasing number of accumulated chill days (equation 4), so that the threshold will become lower, the longer it takes for the forest to reach the critical temperature sum and the more chill days occur in that time (figure 2, left).

$$\mathrm{TT}_{crit} = a + b \cdot \ln(\mathrm{CD}) \quad (4)$$

The parameters a and b are plant specific and are assumed for beech trees with a = 1708.4645 and b = −312.0680 (table 1). If the temperature threshold has definitely not been reached, the leaf emergence is enforced after a maximum amount of chill days has been accumulated (CD_{max}).

The reduction of the critical temperature threshold depends on the tree type, but the parameterisation for beech trees seems to represent an average course of the function compared to other regional trees (figure 2, left). An exemplary model run for a deciduous forest is shown in figure 2 (right). The accumulation of the chill days starts at the beginning of November. At the 22nd of January, the minimum sum of chill days is already surpassed and the endogenous dormancy is replaced by the

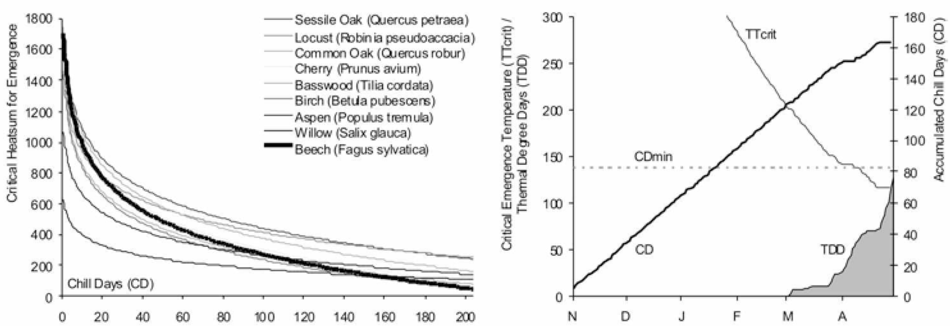

Figure 2: Critical temperature sum for leaf emergence (TTcrit) of different deciduous tree types (left). Example of modelled leaf emergence for a deciduous forest in the East of the Upper Danube Basin, indicating the variables involved (model year 1998, 467 m a.s.l.) (right).

Table 1: Parameters used for the description of the phenological behaviour of deciduous and coniferous trees (Menzel 1997).

	Deciduous (*Fagus sylvatica*)	**Coniferous** (*Picea abies*)
d_1 (DOY)	305	305
$t_b CD$ (°C)	009	009
t_b (°C)	006	005
a (-)	1708.4645	1615.5578
b (-)	-0312.0680	-0247.0063
CD_{min} (d)	083	076
CD_{max} (d)	204	244

exogenous dormancy. While the critical emergence temperature decreases with the further accumulating chill days, the temperature starts to sum up from the 3rd of March onwards, when the average air temperature surpasses the base temperature of 6°C for the first time in the year. The graphs finally meet at the 30th of April, causing the leaf emergence to be initiated.

The defoliation at the end of the growing season is modelled using an approach that depends on the occurrence of consecutive frost events (Schneider 1999). From the 1st of September on, the minimum day temperatures are logged. If the minimum day temperature falls below zero on consecutive days and accumulates to a frost sum of −3.0 °C, the defoliation is initialised, resulting in a rapid decrease of the leaf biomass. If a warmer day with no frost interrupts the accumulation of the frost sum, the frost sum is reset to zero. The latest possible day for the defoliation is the day of year 334, i.e. the 30th of November (Menzel 1997). Figure 3 shows an exemplary course for the accumulation of frost temperatures. Short frost events at the beginning and middle of October do not lead to a defoliation of the trees, as long as they do not penetrate the critical frost sum of −3.0 °C. Two days, with consecutive

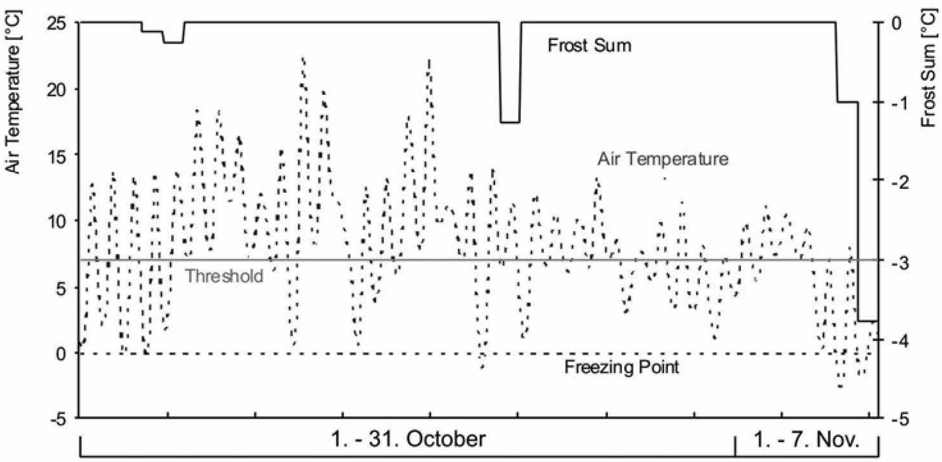

Figure 3: Example of modelled defoliation for a deciduous forest in the East of the Upper Danube Basin (model year 1987, 467 m a.s.l.), showing hourly values of air temperature and the resulting frost sum as well as the critical boundaries of 0°C for the air temperature (dashed) and –3.0°C for the frost sum (solid).

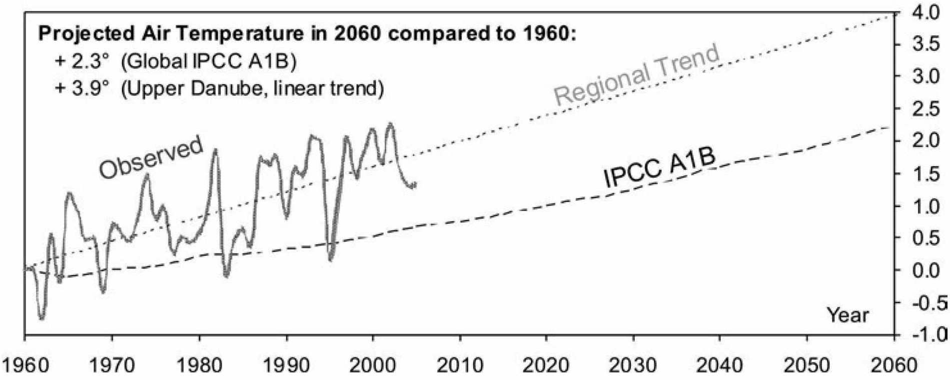

Figure 4: Observed local increase of air temperature, relative to the average annual temperature of 1960 for the Upper Danube catchment, compared to the global temperature increase predicted by the IPCC A1B scenario (IPCC 2002).

frost events falling well below the freezing point, finally cause the forest to discard its leaves on the 7th of November (figure 3).

3.2.2 Coniferous phenology

Coniferous trees in the model are parameterised like *Picea abies* (spruce). With a percentage of more than 65% (LWF 2004) they represent the predominant coniferous tree type in the Upper Danube Basin.

Spruce trees are an all season vegetation type that does not discard needles during wintertime. The start of the growth activity in spring is characterised by a sudden increase of leaf area, if the external conditions are favourable. The incidence of this phenological shift is modelled analogously to the leaf emergence of deciduous trees, but applies a parameter set that meets the requirements of the spruce tree type (table 1, Menzel 1997).

3.3 Scenario generation

The climate change scenario used for this study was generated using a stochastic approach based on the analysis of historic meteorological data (1960–2006, Mauser et al. 2008, this issue).

The scenario characteristics emulate the moderate IPCC A1B scenario (IPCC 2002), but are adjusted by a regional impact factor of 1.7. This elevated temperature increase of approximately 4°C from 1960 to the year 2060 follows the already mapped course of the regional development and is supposed to be more applicable to the Upper Danube Basin compared to the global trend (figure 4).

4 Results and discussion

The model reproduced the spatially distributed incidence of the phenological stages "leaf emergence", "defoliation" and "mayshoot" for the years 1960 to 2057 (fig-

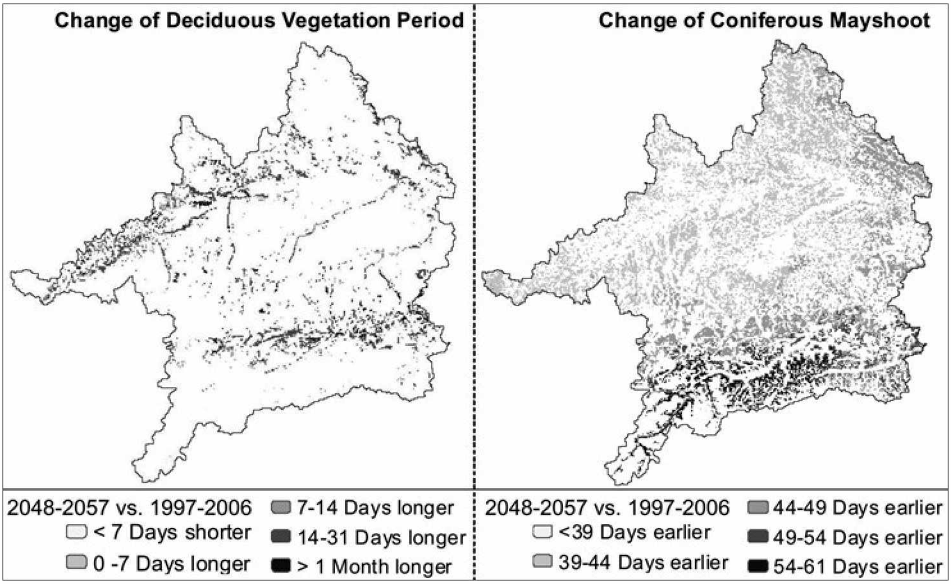

Figure 5: Difference of the modelled 10-year averages "1997–2006" vs. "2048–2057" indicating the prolongation of the vegetation period of deciduous forests (left) and the earlier incidence of mayshoot of coniferous forests (right).

Table 2: 10–year averages and extreme values (DOY) of modelled incidences of phenological stages for the Upper Danube Basin and observed long–term values for Southern Germany (Menzel 1997).*

	Leaf Emergence	Defoliation	Mayshoot
	min – mean – max	**min – mean – max**	**min – mean – max**
Obs. (1959–1997)*	073 – 125 – 201	196 – 302 – 336	092 – 139 – 163
Mod. (1961-1970)	086 – 125 – 139	246 – 292 – 334	118 – 146 – 181
Mod. (1997-2006)	085 – 123 – 134	245 – 297 – 334	117 – 139 – 181
Mod. (2048-2057)	053 – 078 – 097	245 – 274 – 307	074 – 093 – 126

ure 5). While for the reference period from 1960 to 2006 measured meteorological data was applied, the scenario period from 2007 to 2057 was calculated using the stochastically generated scenario meteorology. Compared to observed phenological data, the modelled reference 10-year average (1997–2006) very closely matches the measurements (table 2).

Throughout the modelled period, the leaf emergence in the "plain" regions occurs five days earlier compared to the "mountainous" regions, while the defoliation is initiated 8 days later (figure 6, left).

For the reference period both, the plain and the mountainous leaf emergence show weak trends towards earlier leaf growth. This results in a modelled average prolongation of the vegetation period by 7 days, closely matching the change observed by Chmielewski & Rötzer (2001) for Central Europe. During the scenario period, the trends are far more stable and their gradient is stronger. The defoliation

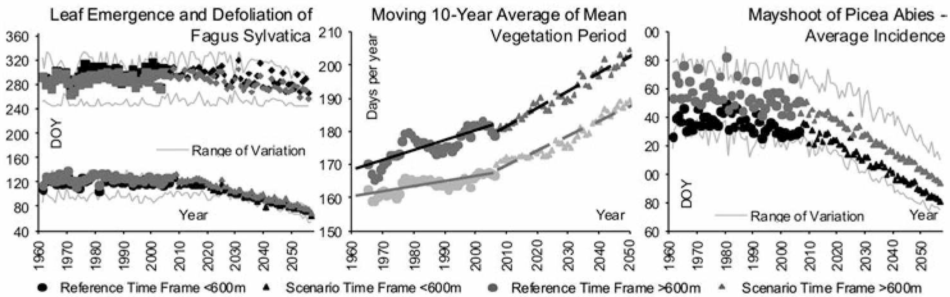

Figure 6: Average model results for the Upper Danube Basin, discerned into the altitudinal zones "plain" (below 600 m) and "mountainous" (above 600 m).

for the reference period shows a very weak trend towards later days of the year, while during the scenario it slowly develops towards an earlier discard of leaves. This may be due to the scenario generator selecting more extreme autumnal months. Although both phenological phases develop towards an earlier incidence, the stronger gradient of earlier leaf growth in spring dominates the development and leads to an overall extension of the vegetation period (figure 6, middle) so that in the ten-year average for 2048–2057, the vegetation period, averaged for the whole Upper Danube Basin, appears 22 days longer compared to contemporary conditions. A parallel development can be observed for the mayshoot that also accelerates its trend towards earlier incidence (figure 6, right).

The model results indicate that the impacts of a warming climate are already affecting the phenological behaviour of alpine forests. The future projections show that these trends are likely to continue and yet are accelerating their course. The vegetation period for the years 2048–2057 is modelled three weeks longer compared to the years 1997–2006, while the incidence of mayshoot is mapped even 45 days earlier than it is observed at present.

The elevated temperature increase and the direct response of the phenological phases to the temperature change indicate that the changes mapped for the Upper Danube basin are likely to manifest more extremely compared to changes that may be expected for a larger scale. Nonetheless, the general trend towards a prolonged vegetation period and the accompanying extension of phases of transpiration activity can be expected to result in a higher strain of the soil water supply, which again may have an effect on the summerly low-flow rates of rivers. The extent and intensity of the effects that these changes will have on the water balance of the Upper Danube Basin will be the substantial interest of future work.

Acknowledgments

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