Divergent vegetation growth responses to the 2003 heat wave in the Swiss Alps

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[1] In 2003, Europe experienced its hottest summer in >500 years. Satellite-derived photosynthetic activity estimates across the Alps revealed a pattern of high elevation growth enhancement and low elevation growth suppression in response to these extreme summer temperatures. Surface weather-derived effective growing season lengths were shorter in 2003 by an average of 9% and 5% for colline and montane areas respectively and were 2%, 12% and 64% longer for subalpine, alpine and nival areas respectively. In situ forest growth measurements of 244 trees at 15 sites across Switzerland verified this pattern and revealed that this divergent response was consistent between species. We suggest that warmer summer temperatures lengthened the snow-free growing season at high elevations while they increased summertime evaporative demand at lower elevations. Our investigation demonstrates that climatic changes are affecting plants beyond simply shifting the elevation belts upwards.

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1. Introduction

[2] In 2003, Europe experienced its warmest summer in over 500 years [*Luterbacher et al.*, 2004]. This heat wave significantly impacted the European economy, particularly the agriculture and forestry sectors [*Committee of Professional Agricultural Organisations in the European Union—General Confederation of Agricultural Co-operatives in the European Union* (*COPA-COGECA*), 2003]. In the future, such extreme events may become more frequent and more variable [*Meehl and Tebaldi*, 2004; *Schär et al.*, 2004]. Temperatures strongly affect the growing season of plants in mid- and high-latitudes and temperature changes like this heatwave may differentially impact vegetation depending on their growing environment. Plants growing at higher elevations may benefit from warmer summer temperatures because their growth is primarily temperature-limited [*Körner and Paulsen*, 2004] whereas those growing at lower elevations may experience more droughty conditions than normal [*Barr et al.*, 2002]. Therefore, we must evaluate climatic changes and seasonal extremes in a biological context if we are to understand how these variations may affect photosynthesis, carbon sequestration and growth of natural vegetation.

2. Methods and Conclusions

2.1. Remotely Sensed Photosynthetic Activity Changes

[3] We used a multidisciplinary approach combining satellite-remote sensing data from multiple platforms, surface weather observations and forest growth measurements to analyze the impacts of this extreme event on natural vegetation. First, we acquired satellite-derived fraction of absorbed photosynthetically active radiation (FPAR) estimates that fell within a rectangular box bounding the entire European Alps (43.5°–48° Latitude, 5°–16° Longitude). These data are processed regularly throughout the year using Terra/MODIS satellite data and the method is well-documented [*Myneni et al.*, 2002]. We screened the data according to the quality control information provided with the data to avoid atmospheric contamination and calculated the mean Jul–Aug–Sept FPAR for the full range of available data (2000–2004). The July–September period encompasses the peak of the heatwave. We expressed 2003 summer FPAR as a percentage of the five year mean (Figure 1).

[4] *Theurillat and Guisan* [2001] define the elevation limits of five distinct vegetation zones in the Alps: colline (<700m), montane (700m–1400m), subalpine (>1400m–2100m), alpine (>2100m–2800m) and nival (>2800m). We calculated mean FPAR changes over these five zones using a moderate resolution elevation map, GTOPO30 (Figure 2a). This analysis showed three distinct responses to this extreme warming event: FPAR was approximately 5% lower in 2003 in the colline zone, was roughly average for montane and subalpine zones, and was above average for alpine and nival zones by 5% and 28% respectively. This pattern was verified with Normalized Difference Vegetation Index (NDVI) data from the Global Inventory Modeling and Mapping Studies (GIMMS) dataset (see auxiliary material[1]). GIMMS data showed that summer NDVI in colline areas was 5% below the long-term average, montane and subalpine areas were within 1% of average and both alpine and nival regions again showed above average photosynthetic activity (4% and 8% respectively). Spatial patterns of this high elevation photosynthetic enhancement and low elevation photosynthetic suppression in 2003 were consistent across most of the Alps

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[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL023252.

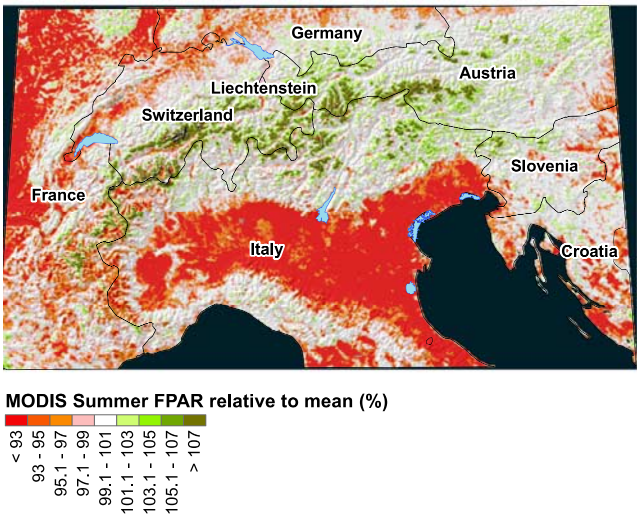

Figure 1. MODIS summer 2003 fraction of absorbed photosynthetically active radiation (FPAR) expressed as a proportion of the five year mean. Red areas show where FPAR was less in 2003 as compared to the mean, green areas show where FPAR was higher in 2003 and white areas show places where values were little changed compared to the five year mean.

except in southeastern France where summer temperatures were much higher than in the rest of the European Alps [*Luterbacher et al.*, 2004; *Schär et al.*, 2004]. We observed fewer FPAR increases at high elevations in those areas (Figure 1). These higher temperatures could have created water stress even at higher elevations.

[5] Decreases in colline FPAR are consistent with reported wide-spread decreases in agricultural crop production as a result of severe temperature and water stress [*COPA-COGECA*, 2003]. Our analysis is also consistent with a study of deciduous broadleaf trees in a colline area near Basel, Switzerland that showed large reductions in 2003 summer maximum net photosynthesis and stem basal area growth in response to the heatwave [*Leuzinger et al.*, 2005]. Increased photosynthetic activity in alpine regions is important because small increases in FPAR in vegetation with leaf area indices below $\sim$3 m^2 m^{-2} can result in large increases in productivity [*Jolly et al.*, 2004]. Increased FPAR in nival areas, where only a few specialist plants survive, are likely a result of depleted summer snowpack in 2003 rather than a large increase in photosynthetic activity. However, these changes could be significant if sustained warming enhances growing conditions and fosters subsequent plant dispersal into areas that were previously inhospitable for even the heartiest of alpine plants.

2.2. Weather-Driven Effective Growing Season Length Estimates

[6] We expanded the analysis with weather data from 150 World Meteorological Organization (WMO) weather stations located throughout the Alps. We retrieved all daily surface weather data for stations that fell within our study region (<= 3576 meters elevation) that had no more than five missing days of data annually. We used these data to estimate the "effective" growing season length (EGSL) for each year over the period of record (1995–2004). EGSL is calculated by annually summing daily growth indicators that are the product of low temperature and high evaporative demand limits. These indicators describe the relative daily constraints of temperature and evaporative demand on plant physiological processes [*Jolly et al.*, 2005]. EGSL can be reduced as a result of colder temperatures or drought.

[7] We expressed the 2003 EGSL at all 150 weather stations as a percentage of the ten year mean EGSL and calculated the mean departure for each of the aforementioned five vegetation zones in the Alps. The individual weather station values, zonal means and standard errors are shown in Figure 2b. Without exception, effective growing season lengths in the colline zone were shorter in 2003 compared to the mean and 91% of the stations in the

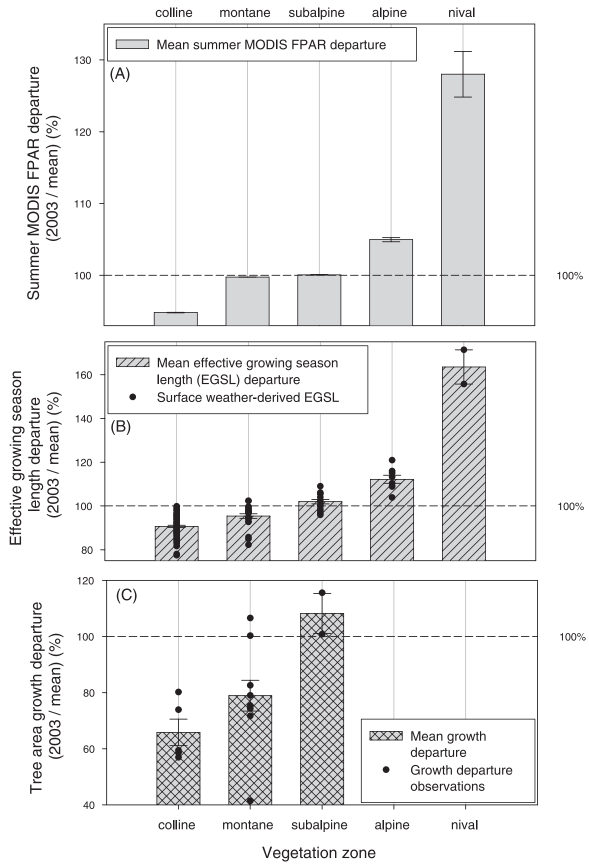

Figure 2. (a) Changes in 2003 FPAR relative to the mean for the five vegetation zones in the Alps [*Theurillat and Guisan*, 2001]. These values were calculated using a moderate resolution elevation map and the data shown in Figure 1. (b) Changes in 2003 effective growing season lengths (EGSL) relative to mean estimated at 150 weather stations. Individual data values are plotted as closed circles along with the mean and standard error. (c) Changes in 2003 stem circumference growth relative to the mean for each of the fifteen forest monitoring sites. Site values are plotted as closed circles along with the mean and standard error. For all panels, values below 100% show areas where that quantity was reduced in 2003 relative to the mean, values near 100% signifies quantities where 2003 values were very close to the long-term mean and values above 100% indicates areas where those quantities were higher in 2003 relative to the mean.

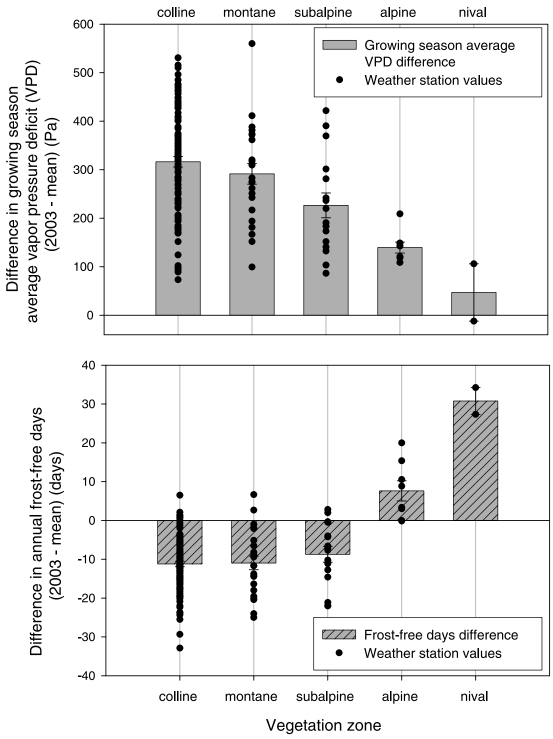

Figure 3. Zonal mean of differences in frost free days and growing season average VPD between 2003 and the ten year mean for weather stations. Individual data values for each of the 150 stations are plotted as closed circles along with the zonal mean and standard error. On average, there were more frost-free days in 2003 in alpine and nival regions and fewer frost-free days in colline, montane and subalpine areas. Growing season average vapor pressure deficit decreased consistently with each increasing vegetation zone.

montane zone showed shorter effective growth periods in 2003. In the subalpine zone, 63% of the stations showed longer growth periods in 2003 and all stations in both alpine and nival regions showed longer 2003 EGSL. Consistent with the FPAR analysis, the largest reductions in growing season lengths occurred in the colline zone and the largest increases occurred in the nival zone. EGSL decreased by 9% and 5% for colline and montane areas respectively and increased by 2%, 12% and 64% for subalpine, alpine and nival areas respectively.

[8] A detailed investigation of the daily meteorological conditions at each weather station reveals differences in the duration and quality of the growing season at different elevations. First, differences between 2003 growing season average vapor pressure deficit and their ten year mean were highest at low elevations suggesting a much larger evaporative demand at lower elevations and this effect decreased with increasing elevations (Figure 3, top). Furthermore, the number of frost-free days in 2003 relative to their ten year mean increased with increasing elevation (Figure 3, bottom). There were fewer frost-free days in the colline, montane and subalpine zones in 2003 and there were more days without frost in the alpine and nival regions. Most of the increases in frost frequency at lower elevations occurred in spring, fall and winter, thus reducing the effective length of the growing season. In contrast, the decreases in the number of days with frost at higher elevations occurred during the growing season, lengthening the frost-free period.

2.3. In Situ Radial Stem Growth Differences

[9] Furthermore, we attempted to verify these patterns with radial stem growth data collected at fifteen long-term forest ecosystem research sites (LWF) throughout Switzerland. We used girth bands that measure the annual change in stem circumference to within 1/10 mm to collect growth data from those species representing >10% of the stem basal area at each site while stratifying to cover the entire range of size classes (n = 9 to 31 per site, depending on the number of dominant species at each site). Altogether, we analyzed the growth of 244 trees at 15 sites spanning a large range in elevations (480–1850 m). Three species comprised approximately two thirds of the data: Norway spruce (*Picea abies Karst L.*), Common beech (*Fagus sylvatica* L.) and Silver fir (*Abies alba L.*); this percentage is consistent with their stem counts in the Swiss National Forest Inventory. We calculated a tree growth index by comparing annual circumference growth increments of all individual trees at each of the fifteen sites in 2003 to the mean increment for 1996–1999, 2002–2004 for the same individuals (see auxiliary material). This index expresses the stem growth of a given site relative to the long-term mean where 100% indicates that stem growth was equal to the mean, values less than 100% indicate that stem growth was reduced in 2003 and values above 100% indicate a growth enhancement in 2003. We regressed the tree growth index for a given site against that site's elevation and we found that this index depicting growth differences between 2003 and the mean was significantly related to elevation (r^2 = 0.49, t = 3.51, n = 15, p < 0.01, see auxiliary material). Again, these data confirm our original findings. Growth in colline areas was significantly reduced in 2003, while growth in montane areas showed less growth reductions and subalpine areas show more circumference growth in 2003 (Figure 2c). This response was similar across the three main species (see auxiliary material, Figure S5). Our results agree with results found in southern Germany where *Meining et al.* [2004] reported reduced stem diameter growth rates in 2003 for all 10 *Picea abies* monitoring forests in Baden-Württemberg at sites ranging in elevation from 510 m to 1020 m. In Bavaria, all *Picea abies* at sites over a range of elevations from 415 m to 1110 m showed reduced 2003 radial growth, while growth in a mixed, montane forest showed no growth reductions and a larch forest at 1500 m showed a 50% growth increase in 2003 as compared to previous years [*Bavarian State Institute of Forestry*, 2004].

2.4. Leaf Duration Changes

[10] We also examined the leaf duration period of 90 deciduous broadleaf (*Fagus sylvatica*) and deciduous needleleaf (*Larix decidua* Mill.) trees at 54 sites throughout Switzerland because leaf duration has been equated to growing season length in Europe [*Menzel and Fabian*, 1999]. Phenology sites cover the same range of elevations as the long term forest monitoring sites where growth observations were taken (305–1800 m). We calculated the leaf duration for each site and regressed differences in leaf duration between the long-term average and 2003 against

elevation and found that the pattern did not differ between high and low elevations ($r^2 = 0.011$, $t = 1.0$, $n = 90$, N.S.). This supports the idea that canopy duration and growth are sometimes poorly correlated [*Kaufmann et al.*, 2004; *White and Nemani*, 2003]. Furthermore, *Leuzinger et al.* [2005] also showed that leaf duration was longer in 2003 while stem growth decreased significantly. We stress the important distinction between an ''effective'' growing season (quality) and one defined by the period when leaves are present (quantity).

3. Summary

[11] The 2003 heatwave posed serious climatic limitations to low elevation vegetation growth while promoting better growing conditions at higher elevations. Water stress at low elevations was associated with increased evaporative demand (VPD) that likely contributed to a significant growth decrease while the evaporative demand during the growing season at higher elevations was similar to other years (Figure 3, top). There were also more frost-free days during the growing season at higher elevations, possibly promoting a lengthening of the snow-free period which is highly correlated to the number of days below freezing in Europe [*Bednorz*, 2004]. In the Alps, a 1° C temperature increase can reduce the presence of snow by up to six weeks [*Hantel et al.*, 2002]. Above treeline, alpine plants would benefit from warmer temperatures and a longer snow-free period if their photoperiod requirements were already met [*Keller and Körner*, 2003]. Both changes in frost frequency and more pronounced summer droughts are important because they may promote the decline of some tree species and the restructuring of European forest ecosystems [*Rebetz and Dobbertin*, 2004; *Thomas et al.*, 2002]. Only 20% of our study area lay in areas where plants benefited from the heat wave, suggesting that the areas that suffered reduced growth in 2003 associated with increased evaporative demand far outweighed areas that benefited from increased summer warmth.

[12] In the future, Europe may oscillate more frequently between normal and extreme climatic conditions, making it worthwhile to critically evaluate how extreme weather conditions constrain biological processes seasonally. Specifically, we feel there is merit in defining how evaporative demand, frost, and drought interact to affect the performance of plants during their growing season.

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