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Response of vegetation to the 2003 European drought was mitigated by height

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Abstract

The effects on climate of land-cover change, predominantly from forests to crops or grassland, are reasonably well understood for low and high latitudes but are largely unknown for temperate latitudes. The main reason for this gap in our knowledge is that there are compensating effects on the energy and water balance when land cover changes. To obtain a better understanding of the direction of this response, we analyse the differential response of tall and short vegetation to the 2003 European drought. We analyse precipitation, temperature and normalized difference vegetation index data and compare these with direct measurements of vegetation height. At the height of the 2003 drought we find for tall vegetation a significantly smaller decrease in vegetation index and a smaller diurnal temperature range, indicating less water stress on tall vegetation, which can be explained by access of tall vegetation to deeper soil water. Based on these results we question the current parameterizations of short and tall vegetation in some land-surface models.

1 Introduction

Summer (June, July, August) 2003 temperatures over Europe were probably the warmest since 1500 (Luterbacher et al., 2004; García-Herrera et al., 2010), with periods of exceptional heat occurring in June and early August (Schär et al., 2004; García-Herrera et al., 2010). Over large areas JJA temperatures exceeded the 1961–1990 average by 3 °C, a value equivalent to 5 standard deviations above the 30 yr JJA average (Schär et al., 2004). It is estimated that the heatwave contributed to the global atmospheric CO_2 growth rate (Ciais et al., 2005), led to a reduction in crop growth and caused an estimated 40 000 extra deaths (García-Herrera et al., 2010). A key component in the amplification and persistence of the heatwave was a spring precipitation deficit (Loew et al., 2009) followed by low spring soil water content resulting in reduced evapotranspiration, reduced latent cooling, and increased sensible heat fluxes (Fischer et al., 2007).

The extreme conditions of 2003 had a significant impact on biomass productivity over much of Europe with dependencies on geographic location, topographic elevation, and vegetation type as revealed in a variety of modelling and observational studies (Gobron et al., 2005; Coret et al., 2005; Jolly et al., 2005; Lobo and Maisongrande, 2006). Vegetation was affected as early as March in northern France, Belgium, the Netherlands, Luxembourg and Germany, and the impact spread east and south through the summer (Gobron et al., 2005). In south-western France different vegetation types were shown to respond differently to the drought, with forests being less affected than either meadows, spring wheat or maize (Coret et al., 2005). Zaitchik et al. (2006) also found that in France the vegetation response to the drought and heatwave was clearly a function of land-cover type, with the impact showing earlier, and becoming more severe, for crops and pastures than for forests. The difference was greatest at the height of the heatwave in mid-August. Water stress, as measured by the difference between precipitation and potential evapotranspiration, was shown to be a major factor in the geographic distribution of vegetation response to the north and south of the Pyrenees (Lobo and Maisongrande, 2006). However, at high altitudes, in the Swiss Alps for example, the reduced snow cover meant that photosynthetic activity actually increased (Jolly et al., 2005).

Tall and short vegetation had a different response to the 2003 drought. An analysis of European flux-tower sites (Teuling et al., 2010) showed that, at the beginning of the 2003 heatwave, grassland and herbaceous vegetation dampened local increases in temperature associated with increased radiation and with reduced precipitation via enhanced (evapo)transpiration. As soil water was depleted by the evaporative demand, temperatures started to increase. Tall vegetation on the other hand showed an initial larger increase in temperature but this was subsequently dampened because tall vegetation has access to deeper soil water. In addition, the closed canopy shelters the soil from solar radiation and this reduces soil evaporation and forms a barrier for water vapour flux from the canopy layer to the atmosphere (Teuling et al., 2010).

The importance for climate in understanding the vegetation response to drought lies in the potential feedbacks between vegetation and the atmosphere. Changes in evapotranspiration, albedo and aerodynamic roughness associated with changes in vegetation (e.g. canopy cover, stomatal closure, leaf angle, number of leaves and vegetation height) affect the transfer of energy and water between the land surface and atmosphere. Various studies find that vegetation plays a role in recycling water from the land to the atmosphere through evapotranspiration which is then returned in the form of precipitation (Dirmeyer, 1994; van den Hurk et al., 2003). Fischer et al. (2007) established that soil moisture depletion propagated the severity of the 2003 drought. Vegetation, in regulating the transfer of soil moisture to the atmosphere is therefore potentially an important factor in mitigating or enhancing the effects of a drought.

The differential effects of tall vs. short vegetation on climate through changes in albedo, photosynthesis, evapotranspiration, and surface roughness are reasonably well understood for the tropics and high latitudes (Bonan, 2008). These effects are less clear in temperate regions however and this is largely caused by uncertainties in the magnitude of compensating effects. For example, higher leaf area associated with tall vegetation tends to increase transpiration but at the same time reduces soil evaporation by shading (Bonan, 2008). Moreover, the studies by Teuling et al. (2010) and Zaitchik et al. (2006) show potentially a different response in short vegetation at the onset of the 2003 drought; the flux-tower study (Teuling et al., 2010) shows an initial cooling effect for short vegetation compared with tall vegetation, whereas the remote sensing study Zaitchik et al. (2006) shows short vegetation to be negatively affected throughout the drought, including the beginning. A recent comparison of seven land-surface models highlights the uncertainty in the effects of tall vs. short vegetation on the energy and water balance in temperate latitudes. Five models showed a cooling during summer as a result of land-cover change and one model a warming (Pitman et al., 2009). The reason for the different response of the models was attributed to differences in the description of processes such as shading effects and albedo effects as well as differences in estimates of land-cover change.

The aim of the present research is to investigate the vulnerability of short and tall vegetation to the 2003 drought across Europe. We use a range of data sets: vegetation height data from the ICESat GLAS instrument, MODIS Normalized Difference Vegetation Index (NDVI) data – a measure linked to the amount of solar radiation absorbed for photosynthesis and net primary productivity of vegetation, MODIS day and night surface temperature data, precipitation data, reanalysis temperature data and land-cover type from the CORINE data base. We analyse how the response of vegetation to the 2003 drought as manifested in the NDVI and the diurnal temperature range (DTR) is affected by land-cover type and vegetation height. We find that during the drought tall vegetation has smaller anomalies in NDVI and a smaller DTR than short vegetation. This result allows correct quantification of the response of vegetation to drought in models and will improve predictions of the impacts of land-cover change on climate.

2 Data

We investigate the impact of the 2003 heatwave and drought on European vegetation using remotely sensed NDVI and surface temperature data, re-analysis temperature data and combined remotely sensed and gauge precipitation data. We also use vegetation heights and land-cover class to test the hypothesis that taller vegetation is more resilient to drought.

ECMWF ERA-Interim monthly means of daily 2 m air temperature at a spatial resolution of 1.5° were obtained from the ECMWF Data Server. The data were projected to the MODIS Sinusoidal projection, and were scaled spatially to 1 km resolution using B-spline smoothing, and scaled in time by averaging to produce fields of mean temperature for the 32 day period prior to each 16 day NDVI composite. Anomalies for the resulting 32 day means were computed relative to the 2000–2010 mean (Berrisford et al., 2011).

Global Precipitation Climatology Project (GPCP) One Degree Daily Precipitation Data Sets (Huffman et al., 2001, 2009, 2011), were used to generate fields of precipitation anomalies relative to their 2000–2010 mean. The data were projected to the MODIS Sinusoidal projection and were spatially scaled using the same B-spline method as applied to the temperature data. The daily data were accumulated for the same 32 day periods as the temperature data, i.e. each period ends on the starting date of the next NDVI composite.

We use remotely sensed NDVI data to indicate the vegetation's response to the drought. Nine tile mosaics of MODIS Terra NDVI (MOD13A2) Collection 5 were downloaded for the period 2000 to 2012. The NDVI is expressed as the difference between reflected solar radiation in the infra-red (ρ_2) and red (ρ_1) wavelengths normalized by their sum: $\text{NDVI} = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$. Temporal changes in NDVI are proportional to temporal changes in fAPAR (Sellers, 1985; Myneni and Williams, 1994), and vegetation net primary productivity. The NDVI fields are at a spatial resolution of 1000 m and cover the area shown in Fig. 1. The data were screened using the quality flags to remove pixels having an overall usefulness of 11, this excludes pixels with high aerosols, clouds or adjacent clouds, and possible cloud shadows (Samanta et al., 2010). The MODIS NDVI 16 day composites were linearly interpolated in time to fill gaps in the data that resulted from the quality screening. Anomalies for all 16 day periods were computed relative to their 2000 to 2010 average.

The DTRs were calculated by subtracting night-time from day-time MODIS Aqua land surface temperatures (MYD11A2). These data are 8 day averages and have the same coverage and spatial resolution as the NDVI product. The day-time overpass was between 13:40 and 13:50 LT for the region analysed, no quality control was applied.

Vegetation heights were based on 2003–2009 data from the Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud and land Elevation Satellite (ICESat) (Rosette et al., 2008; Los et al., 2012). Heights are estimated from each GLAS measurement which has an along-track sampling rate of 172 m, and filtered to eliminate spurious observations, e.g. data that are affected by clouds, atmosphere and steep terrain (Los et al., 2012).

In order to investigate the effect of vegetation class on the response to drought in 2003 we use the Version 16 Corine Land Cover 2000 (CLC2000) 250 m raster data (EEA, EEA data service). The legend and the grouping into tall and short vegetation types is summarised in Table 1.

3 Results

Similar to previous research (e.g. Zaitchik et al., 2006; Reichstein et al., 2007), our analysis starts by investigating the evolution and distribution of the vegetation response to the meteorological conditions of summer 2003. Figure 1 shows the NDVI anomalies, deviations from the multi-year mean significant at the 95 % level, for the 16 day composite periods beginning on 23 April, 26 June and 29 August 2003. April 2003 shows positive NDVI anomalies for central and eastern France, west Germany, the Alps, north-west Spain and Portugal and northern Scotland associated with the warm early spring (Fig. 1a) (Zaitchik et al., 2006). Large negative NDVI anomalies appear first in central France in mid June and advance to the north, south and east during the summer eventually including north-west France, parts of Germany and the eastern UK (Fig. 1b). The most intensive and widespread anomalies are apparent from mid August. (Fig. 1c). By this date, significant negative anomalies are observed over much of central Europe, excluding the Iberian Peninsula and the western parts of the UK. Areas less affected by the drought are southern Italy, Scandinavia and the high-elevation regions of the Alps. The large negative anomalies in central Portugal have been attributed to forest fires (Reichstein et al., 2007).

Research has suggested that overall, reductions in European gross primary productivity (GPP) during the summer of 2003 correlate better with decreased rainfall than with increased temperature (Ciais et al., 2005; Reichstein et al., 2007), although decreased rainfall and increased temperatures are clearly linked. To investigate the contribution of each parameter we calculate the Pearson's correlation coefficient (R) between NDVI anomaly and temperature anomaly, and between NDVI anomaly and precipitation anomaly for the summer months of June, July, August and September over the period 2000 to 2010. The precipitation and temperature anomalies are based on the 32 day periods described earlier, and summer correlation values are highest when considering the month immediately prior to the NDVI observation compared with other time lags. Figure 2a and b shows the results (where significant at 95 %) for the 1 month lag and indicate that, for much of Europe, summer (JJAS) NDVI is positively correlated with precipitation and negatively correlated with temperature.

We confirm higher absolute correlations between summer precipitation and summer NDVI than absolute correlations between summer temperature and NDVI by inspecting histograms and quantile–quantile (Q–Q) plots of the squares of the correlation coefficients. The differences are small, but statistically significant (Fig. 3). The positive correlations of NDVI with precipitation and negative correlations with temperature confirm the findings by Lobo and Maisongrande (2006), based on data from 1999 to 2003, that much of the geographic structure in NDVI anomaly for 2003 is governed by atmospheric water stress as measured by the difference between precipitation and potential evapotranspiration.

The results of our analyses of temporal anomalies and correlations of vegetation with precipitation and temperature are similar to those of previous studies. It is explored below how vegetation stress, expressed as an increased DTR or decreased NDVI, depends on vegetation height.

Vegetation height estimates based on GLAS data are retrieved at intervals along the ICESat tracks as shown in Fig. 4; typical sampling rates within a 50 km in Germany are shown in Fig. 5. For every vegetation height data point we extract the corresponding NDVI anomaly for 29 August 2003. This method means that, as can be seen for example in Fig. 5a, the same NDVI anomaly may be matched to more than one vegetation height point. Then, for every 50 km square throughout the study region we calculate the correlation coefficient (Pearson's R) between vegetation height and NDVI anomaly, as, for example, shown in Fig. 5b. These correlations are mapped in Fig. 6. For eastern France, and most of Germany, the Netherlands, Belgium and areas to the north and south of the Alps there is a small but significant and regionally coherent positive correlation between vegetation height and NDVI anomaly. A positive correlation indicates where short vegetation experiences a greater degree of browning, and inferred reduction in GPP, than taller vegetation.

Our working hypothesis is that tall vegetation has deeper roots and therefore has access to a larger amount of soil moisture at greater depths. The greater availability of water would lead to a larger heat capacity of the canopy and a smaller DTR (Collatz et al., 2000). The DTR, obtained from MODIS data, is correlated with vegetation height similar to the approach adopted for the NDVI. We find a negative correlation between vegetation height and DTR (Fig. 9), thus taller vegetation is associated with a smaller anomaly in leaf area index, a smaller DTR and likely a larger canopy heat capacity and moisture availability.

As an alternative test of the relationship between vegetation height and response to drought we make use of the Corine Land Cover classes. For each vegetation height point we also extract the CLC2000 class and separate the associated NDVI anomalies into two groups according to CLC2000 class. Group 1 includes land cover classes 10 to 22 which are sub classes of "Artificial, non-agricultural vegetated areas", "Arable land", "Permanent crops", "Pastures", "Heterogeneous agricultural areas", and 26 to 29, "Scrub and/or herbaceous vegetation associations", Group 2 includes classes 23 to 25, "Forests"". Within each 50 km square we use a t test to decide if the mean NDVI anomaly is significantly lower (i.e. more negative) for Group 1 than for Group 2. The differences in mean NDVI anomaly between Group 1 and Group 2 are shown in Fig. 7. A comparison of Figs. 6 and 7 shows that the distributions and relative strengths of the relationships between NDVI anomaly and either vegetation height or vegetation class are very similar.

The magnitude of the correlation between vegetation height and NDVI anomaly over Europe, for the period under consideration, increases with precipitation deficit and with temperature anomaly. Figure 8 shows the correlation as a function of precipitation deficit under regions experiencing temperature anomalies of +1 °C, +2 °C and +3 °C.

4 Discussion

Land cover in western Europe has changed significantly over the past two millennia; original vegetation cover, for a substantial part consisting of trees, has to a large extent been replaced by short vegetation, predominantly pasture and crops. Land-cover change continued during the 20th century as agriculture became more mechanised and efficient and small parcels of land were merged into large parcels. During the past decades the declining trends in forest cover have reversed with a proportion of agricultural land taken out of production and converted to natural land (Klein Goldewijk and Ramankutty, 2004). For some time there has been intense speculation on the effect of land-cover change on climate, e.g., Sagan et al. (1979) suggest that the conversion of land was accompanied by changes in albedo and that these likely affected the regional climate. Conversion of land may have an impact on the atmosphere and several regions have been identified where feedbacks between vegetation and precipitation are likely to occur. One such region is the Sahel, the region south of the Sahara, where both models and observations indicate a positive feedback between vegetation greenness and precipitation (Charney et al., 1977; Los et al., 2006; Xue et al., 2010). Another region where similar feedbacks have been identified in model simulations is the Amazon, e.g. (Costa and Foley, 2000), whereas in high latitude boreal forests a positive feedback between temperature and tree cover is likely (Betts et al., 2001a, b; Thomas and Rowntree, 1992; Bonan et al., 1992), see Bonan (2008) for an overview.

Much larger uncertainties exist when it comes to assessing the effect of land cover change in temperate regions. A recent comparison of 7 climate simulations showed that some land-surface models showed an increase in evapotranspiration when land cover changes from tall to short, whereas one simulation showed a decrease (Pitman et al., 2009). The reason for this discrepancy is that the interactions of vegetation with the energy budget are complex. Tall vegetation is in general darker than short vegetation and will absorb more solar radiation; tall vegetation has also access to more water from deeper parts of the soil and can maintain transpiration during a drought (increase in evapotranspiration) for longer periods than short vegetation. Tall vegetation is likely to increase shading of the soil and this reduces evaporation.

5 Conclusions

The 2003 drought provides an opportunity to explore differences in the response of short and tall vegetation to an extended period of water stress. For short vegetation we find larger negative anomalies in NDVI and higher values for the DTR than for tall vegetation. The association between tall vegetation, resistance of the NDVI to drought and a smaller diurnal temperature range points towards the importance of soil water availability and perhaps a closed canopy that resist exchange of water vapour from the canopy air space into the atmosphere. Albedo, expected to be lower for tall than for short vegetation, has been suggested as an alternative mechanism controlling local climate. However our results suggest evaporative cooling by tall vegetation, with contrasting impact to albedo, is much more significant than albedo during drought. The results support the conclusions of Zaitchik et al. (2006) and Teuling and Seneviratne (2008), who suggest contrasting drought radiative impacts at different wavelengths may reduce net impact on total albedo.

Based on the results of our present analysis we would expect warmer conditions for the summer for a land-cover change simulation where tall vegetation is converted to short vegetation with an important caveat that the comparison of land-surface models by Pitman et al. (2009) did not pertain to a drought. A simulation of the 2003 drought with the investigated models would likely reveal if the response of tall vs. short vegetation is correctly represented within the models.

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Table 1. Corine Land-cover Classes 2000 (EEA, EEA data service) contributing to the short and tall vegetation groupings discussed in the text.

Group	Corine Level 2 class	Corine CLC_CODE
Short	Artificial, non-agricultural	141, 142
	Arable land	211–213
	Permanent crops	221–223
	Pastures	231
	Heterogeneous agricultural areas	241–244
	Scrub and/or herbaceous vegetation associations	321–324
Tall	Forests	311–313

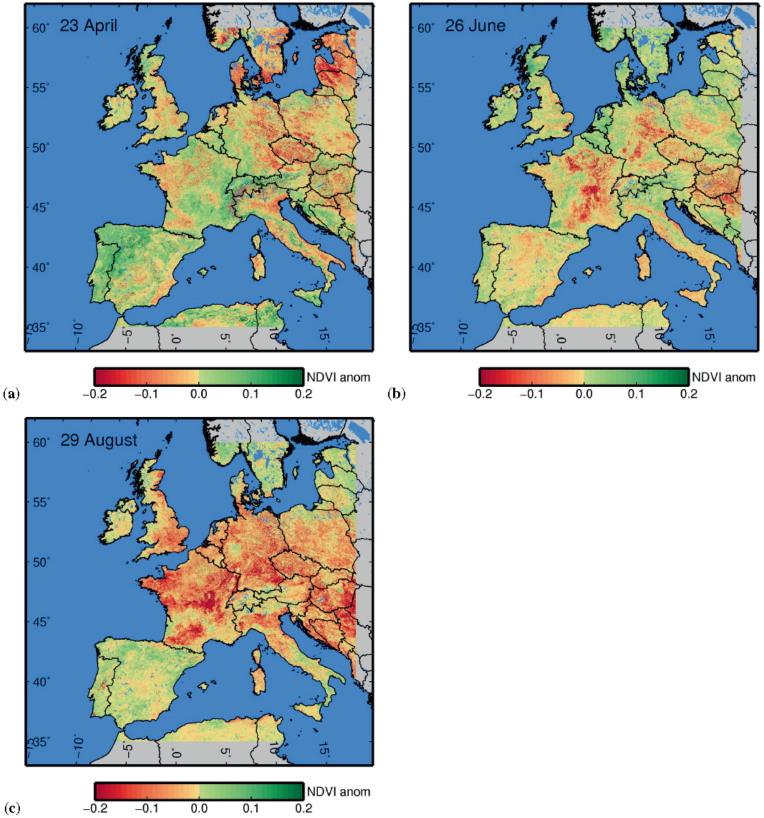

Fig. 1. Anomalies in MODIS NDVI for **(a)** 23 April 2003, **(b)** 26 June 2003, **(c)** 29 August 2003. The anomalies are relative to the mean for that date over the period 2000–2010.

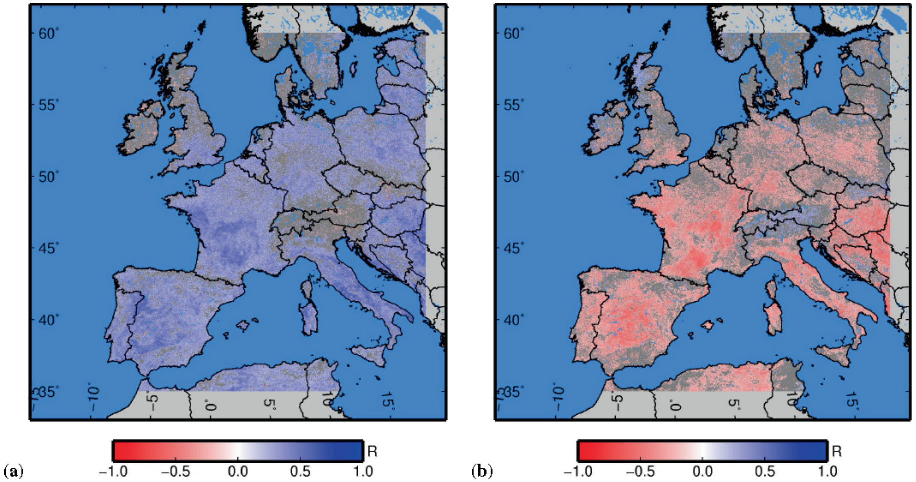

Fig. 2. **(a)** Correlation coefficient (Pearson's *R*, where significant at 95 %) between the anomaly in GPCP precipitation accumulated for the preceding 32 days and the anomaly in MODIS NDVI for all June, July, August and September NDVI, over the period 2000 to 2010. All anomalies are relative to the mean for 2000–2010. **(b)** The same as for **(a)** except the correlation is between ERA-Interim 2 m air temperature and MODIS NDVI.

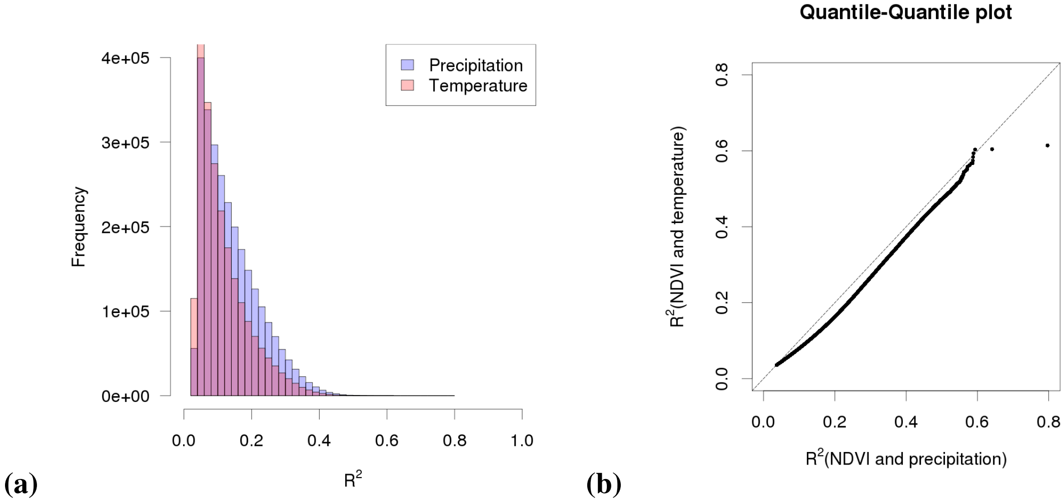

Fig. 3. (a) Histogram of the squares of the correlation coefficients in Fig. 2. **(b)** Quantile–quantile plot of the squares of the correlation coefficients in Fig. 2.

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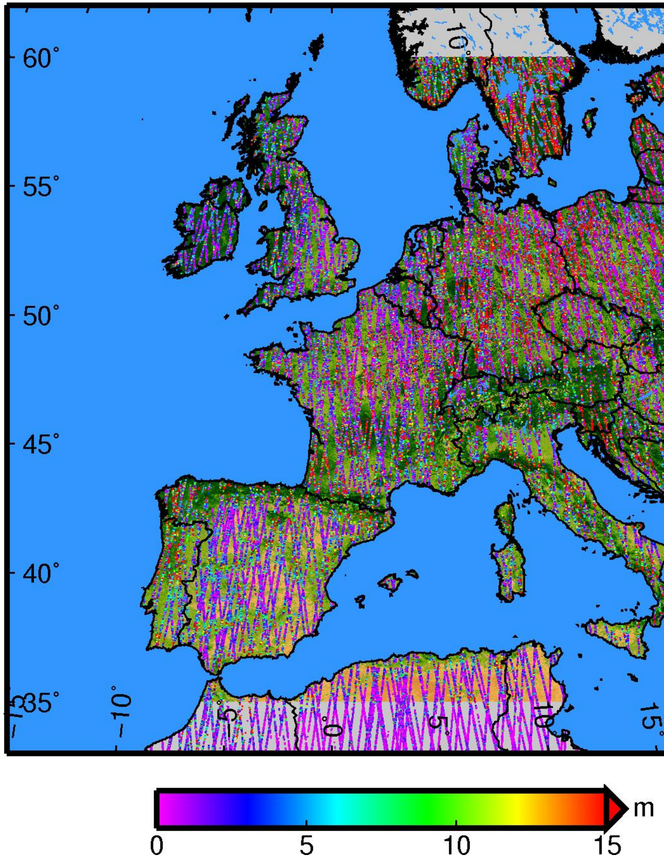

Fig. 4. ICESat GLAS derived vegetation heights. The underlying image is NDVI for 29 August 2003. Heights greater than 15 m are in red.

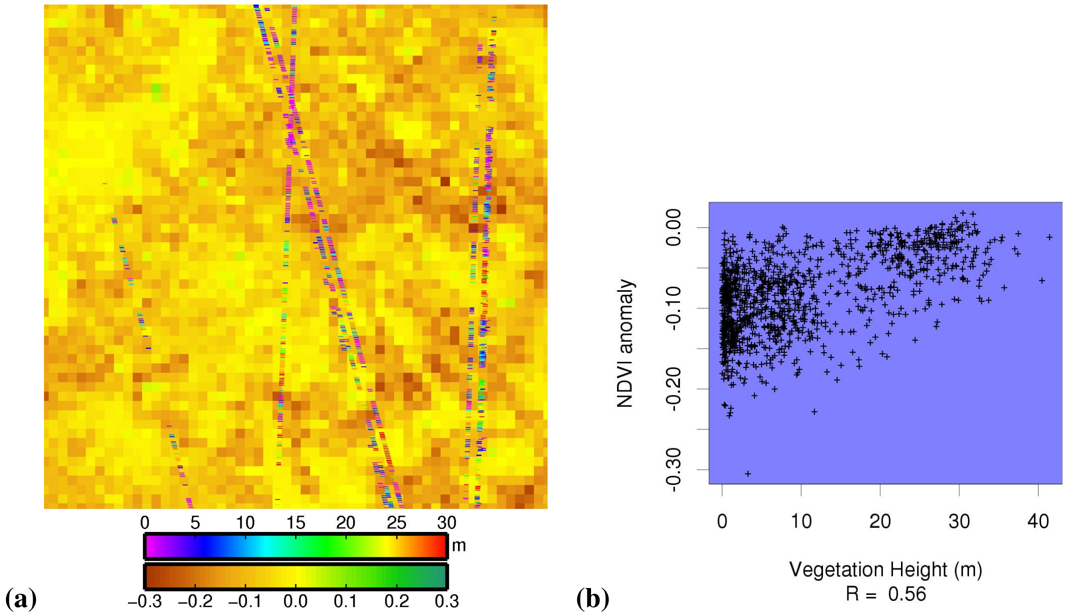

Fig. 5. (a) An example of the distribution of vegetation height data points within a 50 km square. The square corresponds to the one indicated in Fig. 6 and the underlying image is the NDVI anomaly for 29 August 2003. **(b)** Scatter plot of the data in **(a)**. The correlation coefficient (Pearson's *R*) for this square is 0.56.

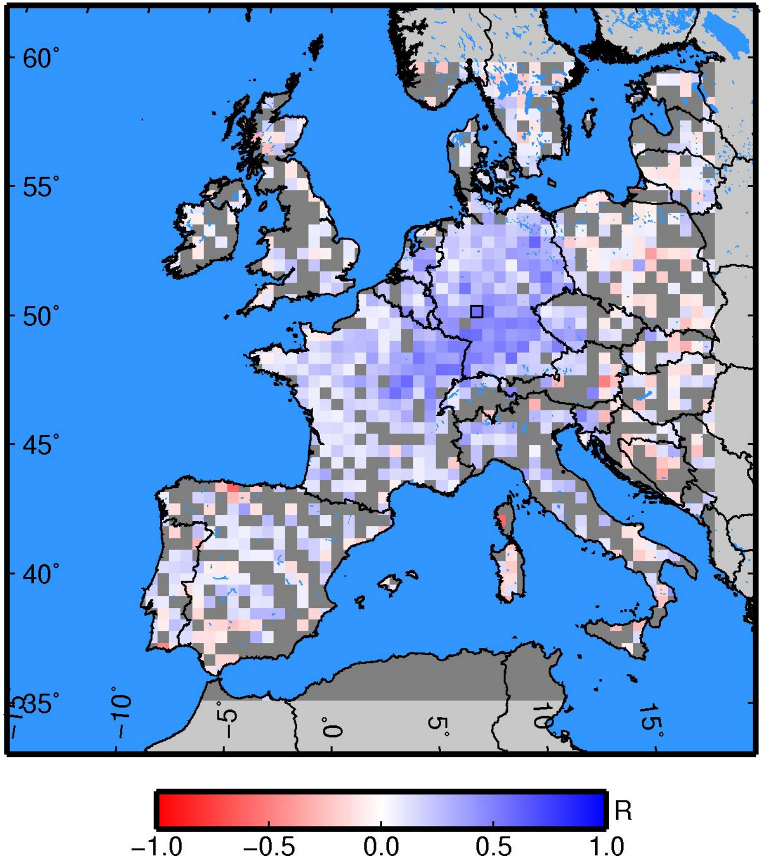

Fig. 6. Correlation coefficient (Pearson's R, where significant at 95 %) between vegetation height and NDVI anomaly for 29 August 2003, within 50 km squares. The square outlined in black in Germany corresponds to that used in Fig. 5a and b.

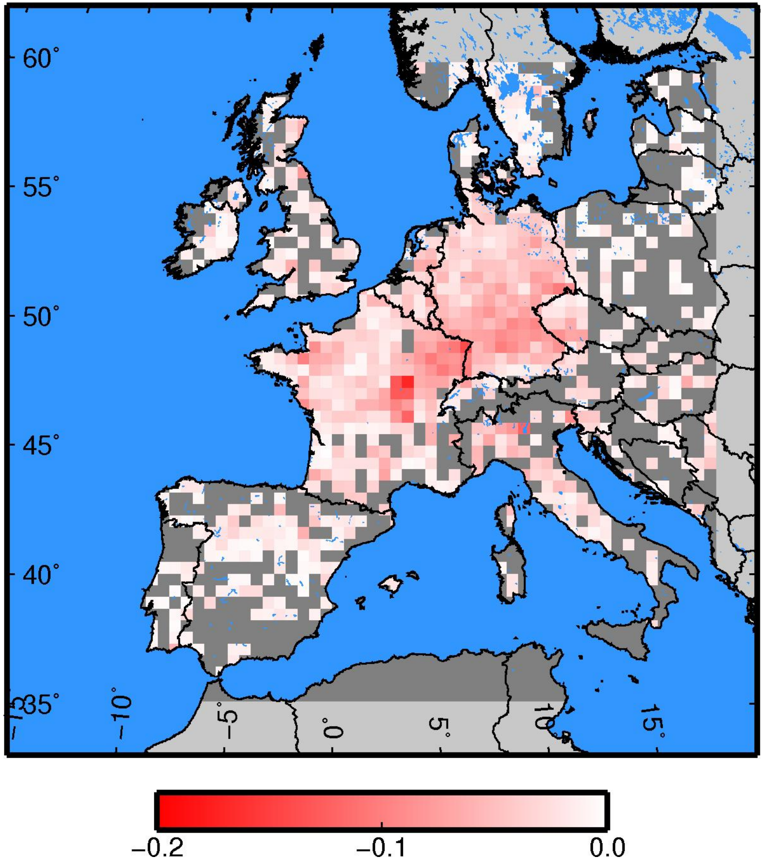

Fig. 7. Mean NDVI anomalies for data points in Corine Land Cover (CLC) group 1 minus mean NDVI anomalies for data points in CLC group 2, where the mean difference is significant at the 95 % level. See text and Table 1 for a description of groups 1 and 2.

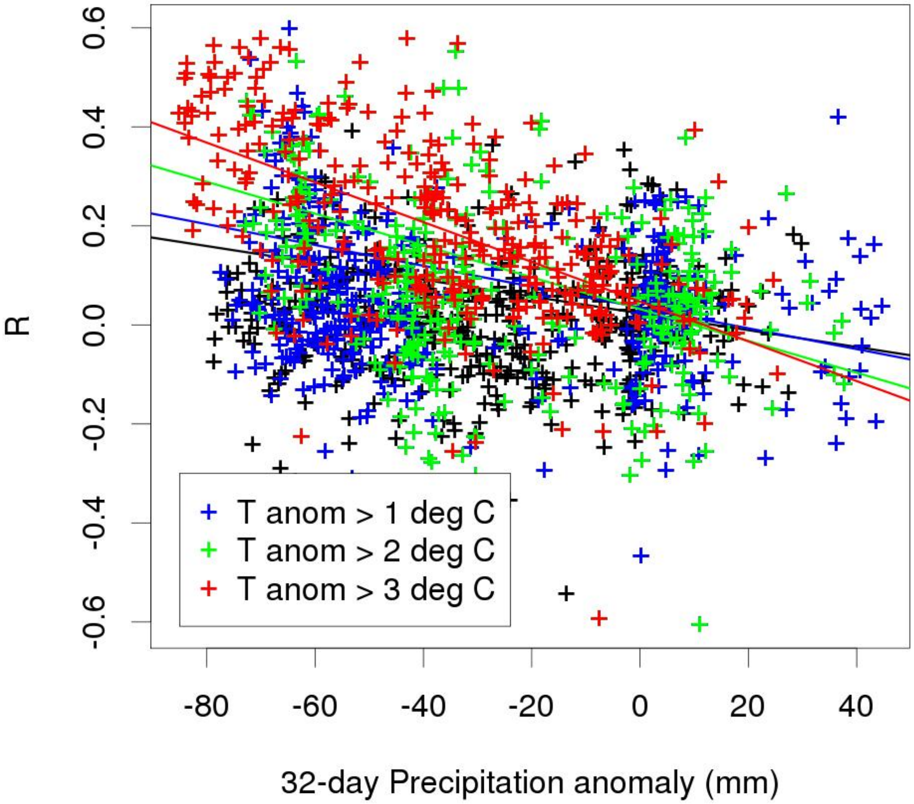

Fig. 8. The correlations between vegetation height and NDVI anomaly (*R*) as mapped in Fig. 6 against the precipitation anomaly over the preceding 32 day period. Coloured data points represent *R* values under varying magnitudes of temperature anomaly.

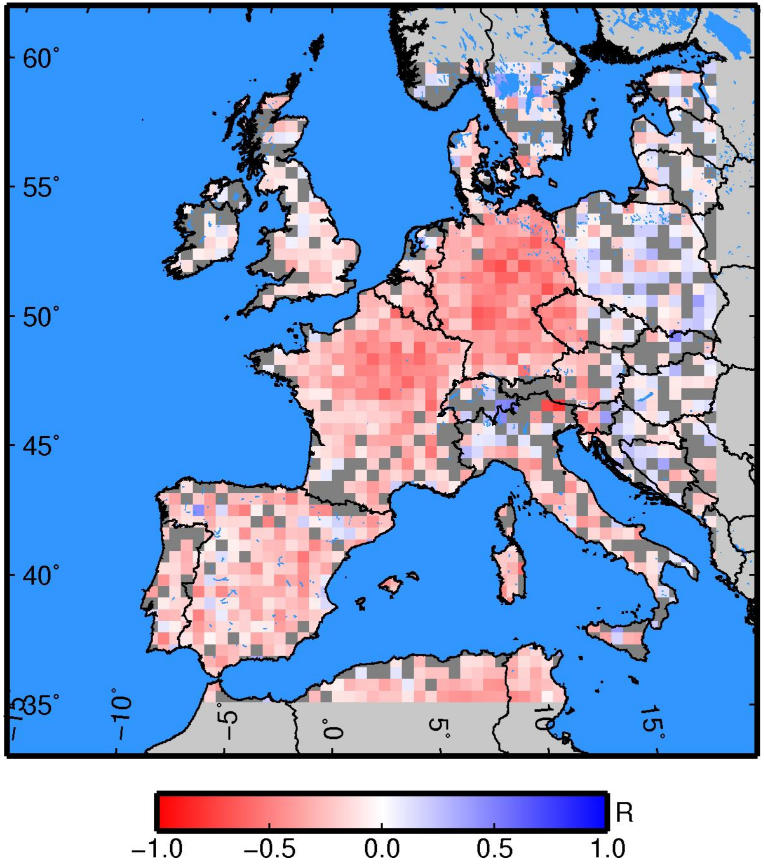

Fig. 9. Correlation coefficient (Pearson's *R*, where significant at 95 %) between vegetation height and diurnal temperature range for day 25 August 2003, within 50 km squares.

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