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Montane ecosystem productivity responds more to global circulation patterns than climatic trends

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Abstract

Regional ecosystem productivity is highly sensitive to inter-annual climate variability, both within and outside the primary carbon uptake period. However, Earth system models lack sufficient spatial scales and ecosystem processes to resolve how these processes may change in a warming climate. Here, we show, how for the European Alps, mid-latitude Atlantic ocean winter circulation anomalies drive high-altitude summer forest and grassland productivity, through feedbacks among orographic wind circulation patterns, snowfall, winter and spring temperatures, and vegetation activity. Therefore, to understand future global climate change influence to regional ecosystem productivity, Earth systems models need to focus on improvements towards topographic downscaling of changes in regional atmospheric circulation patterns and to lagged responses in vegetation dynamics to non-growing season climate anomalies.

1. Introduction

In central Europe, a generally warmer (1 °C–6 °C) climate with less precipitation in summer but inconsistent or unchanged conditions in other seasons is projected over the 21st century by regional climate models (Zubler *et al* 2014). Greater change is expected in European mountainous regions, consistent with observed trends in temperature and precipitation in the European Alps. Winter snowfall, which is a significant source of moisture for the early ecosystem carbon uptake period is projected to decline (de Vries *et al* 2014), except possibly at the highest altitudes.

However, these projections primarily reflect large-scale processes that drive mean climate and not variations in topographically induced microclimates, which fall below the spatial resolution of global models. For the mid-latitudes, these local-scale climate variations are often more driven by trends or patterns in general and regional atmospheric circulation (Shepherd 2014). This response is well-known in mountain regions where orographic flow may preferentially form with certain circulation patterns, such North Atlantic tropospheric pressure oscillations that drive the polar jet winter storm track. Consequently, we expect interannual variations in local moisture and thermal conditions experienced by mountain grassland and forest ecosystems in spring to reflect variations in winter large-scale atmospheric processes and how those processes influence orographic flow.

Variations in winter circulation, by modifying snowfall and snowmelt, consequently influence spring soil moisture and temperature. Then, as the growing season progresses, the timing and magnitude of productivity in montane ecosystems would eventually respond to these processes. A complicating factor in predicting this progression is that temperature and precipitation responses from these circulation patterns are exaggerated or sometimes reversed in presence of topography (Berg *et al* 2013, Wagner *et al* 2013). Pressure gradients that set up across topographic barriers can promote preferred direction of orographic ascent and descent. Moist adiabatic ascent promotes precipitation and cooling on the windward side, and subsequent dry isentropic descent leads to accelerating, warm flow that enhances drying.

For the Northern Alps, the south to north flowing Southerly Föhn has long been associated with unseasonable and spirit-dampening weather (von Berg 1950). The Southerly Föhn in the Alps is often compared with the Chinook in the North American Rocky Mountains, and similar topographic winds are found worldwide (e.g., Cape *et al* 2015). These winds bring exceptionally warm and dry air to the downwind areas crossing relevant mountain ranges, sometimes increasing risk of fire (Drechsel and Mayr 2008).

Interestingly, while the mechanics of Southerly Föhn flows are well understood (Drechsel and Mayr 2008, Dürr 2008, Siler and Roe 2014), it is generally seen as a local phenomenon, with primarily local criteria for identification and forecasting. Southerly Föhn has not been previously studied in conjunction with interannual variations in general circulation patterns. We suspect that larger-scale circulation patterns in winter drive this orographic flow and consequently spring montane ecosystem productivity. Thus, we expect regional mountain ecosystem productivity, in particular, to respond more to winter circulation anomalies than to summer (peak carbon uptake period) climate, contrary to what we would expect more generally over Europe, where climate anomalies such as summer drought dominate ecosystem carbon anomalies (Ciais *et al* 2005).

To test this claim, we hypothesized that interannual variability in summer season Alpine ecosystem carbon uptake is significantly related to variability in winter circulation features through impacts on Southerly Föhn flow. We ask the following questions: do changes in circulation modes in the North Atlantic promote shifts in frequency of wintertime Southerly Föhn flows? If so, how do these then influence ensuing ecosystem productivity and phenology? By combining surface meteorological data, climatic pressure indices, eddy covariance flux tower carbon cycle measurements, *in situ* phenology data, satellite-derived vegetation indices, and a numerical ecosystem model, we attempt to demonstrate that the impact on ecosystems from anthropogenic climate changes, at the decadal scale, are subsumed by the impact of highly variable circulation patterns.

2. Methods

Hourly and daily average meteorological surface station observations of wind speed, wind direction, temperature, humidity, pressure, and snow depth for Garmisch-Partenkirchen and Zugspitze, Germany were acquired from the WebWerdis interface of the Deutscher Wetterdienst (DWD). Valley snowfall data were acquired from nearby station at Krün (867 m ASL). For all three stations, hourly and daily observations from 1 November to 31 March were collected for 1979–2014 and quality screened. We determined Southerly Föhn conditions based on the standard criteria (Plavcan *et al* 2014), whereby threshold and minimum hours criteria for wind speed and direction aloft (Zugspitze 2964 m ASL) and potential temperature gradient between Garmisch-Partenkirchen, Germany (718 m ASL) and Zugspitze were used to identify days with Southerly Föhn flow for the Northern Alps. Seasonally averaged observations are shown in supplementary table S1 (available at stacks.iop.org/ERL/11/024013/mmedia).

Climatic observations were derived from long-term observations and reanalyses. Arctic oscillation (AO) and North Atlantic oscillation (NAO) indices were acquired from the National Oceanographic and Atmospheric Administration Climate Prediction Center. NAO and AO are indices derived from principal component analysis of mid-troposphere pressure oscillations in the Northern Hemisphere. Daily time series of these indices were extracted to overlap with the surface station meteorological data. Daily frequency of positive and negative anomalies were derived based on segregating the days that exceeded one positive or negative standard deviation, respectively. Geopotential height analyses were based on 500 hPa height from the NCEP-DOE Reanalysis 2 product. Height anomalies were segregated by quartiles of magnitude of winter Southerly Föhn frequency and tested for significance with F-test at 99% level.

Ecological observations of carbon fluxes and phenology were acquired from two datasets. Phenology observations were retrieved from the European phenology database (PEP725) and subset to include flowering dates for common hazel (*Corylus avellana*) and common snowdrop (*Galanthus nivalis*), two plant species known as phenological indicators during winter/early spring, at Austrian sites in Tyrol (PEP725 Pan European Phenology Data. Data set accessed 28 February 2014).

Eddy covariance flux tower observations of net ecosystem exchange and inferred gross primary

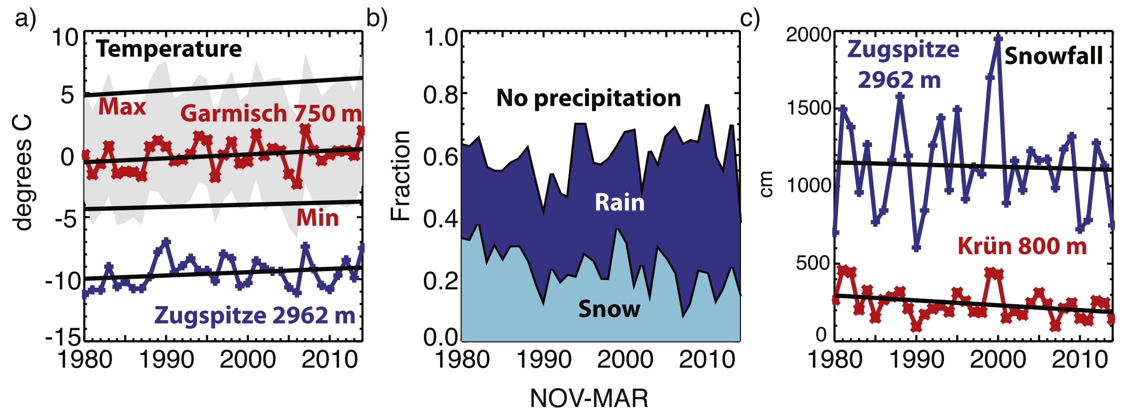

Figure 1. Winter season average (November–March) (a) German Alpine valley hourly temperature (Garmisch, red), valley daily minimum and maximum (gray shadow), mountaintop hourly temperature (Zugspitze, blue), linear trends (black), (b) fraction of snow and rain days in the valley, and (c) seasonal total snowfall (linear trend in black) from 1979–1980 to 2013–2014 all reflect the general pattern of warmer, wetter, but less snowy winters, but with significant interannual variability, especially for snow.

productivity (GPP) (Reichstein *et al* 2005, Papale *et al* 2006) were downloaded from the European Fluxes Database Cluster (http://www.europe-fluxdata.eu/; accessed on 3 November 2014). We used the gap-filled Level 4 products for all flux tower sites in the Alps that had five or more years of data in the database (Marcolla *et al* 2011, Cescatti and Marcolla 2004, Marcolla *et al* 2005, Wohlfahrt *et al* 2008, Amman *et al* 2009, Kutsch *et al* 2010, Etzold *et al* 2011, Zeeman *et al* 2015). Among the sites satisfying these criteria were three grasslands, one cropland, three evergreen needleleaf forests and one deciduous broadleaf forest, as detailed in supplementary table S2. These data were complemented by additional flux data from three grassland sites in the German part of the Alps that were processed separately, but in accordance with the FLUXNET methodology. GPP anomalies and carbon uptake period, based on number of days of positive GPP ($>$0.5 gC m^{-2} d) were compared to site-relative Southerly Föhn anomalies.

Remotely-sensed observations of phenology were derived from NASA Terra and Aqua moderate imaging spectrometer (MODIS) estimates of the eight-day enhanced vegetation index (EVI). Dates of EVI increase and EVI decrease during the snow-free period were provided in the MCD12Q2 MODIS Global Vegetation Phenology product (Ganguly *et al* 2010) for 2002–2009, with quality control filters and smoothing applied to mask anomalous noise from false greening readings caused by changes in snow cover. These data were extracted for the domain from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) MODIS subsetted land products, Collection 5 (http://daac.ornl.gov/MODIS/modis.html, accessed March 2015). Date of spring onset and green period (number of days from green increase to decrease) were linearly regressed to Southerly Föhn frequency, significant slopes ($p < 0.1$) retained, and a 3 km median filter applied to improve figure clarity.

To evaluate mechanisms of observed relationships of wintertime Southerly Föhn and snow on carbon uptake, we applied the multi-layer atmosphere–SOiL–VEGetation model (SOLVEG) (Ota *et al* 2013, Katata *et al* 2014) to a typical pre-alpine grassland site in Germany. Our special interest was the role of Southerly Föhn as a trigger of snowmelt and leaf development via increasing air temperature. SOLVEG is suitable for this objective because it includes schemes of snow, frozen soil, plant growth and frost damage of leaves. Half-hourly observations from Fendt (600 m ASL) were used as input data for SOLVEG to force the initial and boundary conditions of meteorological variables at reference height (atmospheric pressure, downward shortwave and longwave radiation, precipitation, wind speed, air temperature and humidity near the surface) and soil variables at the bottom soil layer (soil temperature and moisture). Further details on calculations and the model are provided in the supplementary methods.

3. Results and discussion

3.1. Global and regional climate and circulation

In the Northern Alps, long-term weather station observations in the valley of Garmisch-Partenkirchen, Germany and the top of Zugspitze mountain reflect significant declining trends in valley snowfall (-3.2 cm yr^{-1}, Kendall $\tau = -0.25$, $p < 0.05$) and days with snow (-0.58 d yr^{-1}, $\tau = -0.38$, $p < 0.001$), but less clear trends in temperature, with only valley maximum winter temperatures showing a slight warming (0.042 C yr^{-1}, $\tau = 0.22$, $p = 0.06$) (figure 1). Trends in other parts of the Alps are regionally inconsistent, though snow trends appear robust (supplementary figure S1).

However, trends are only part of the story. Significant interannual variability is present in the temperature and precipitation time series. Much of this

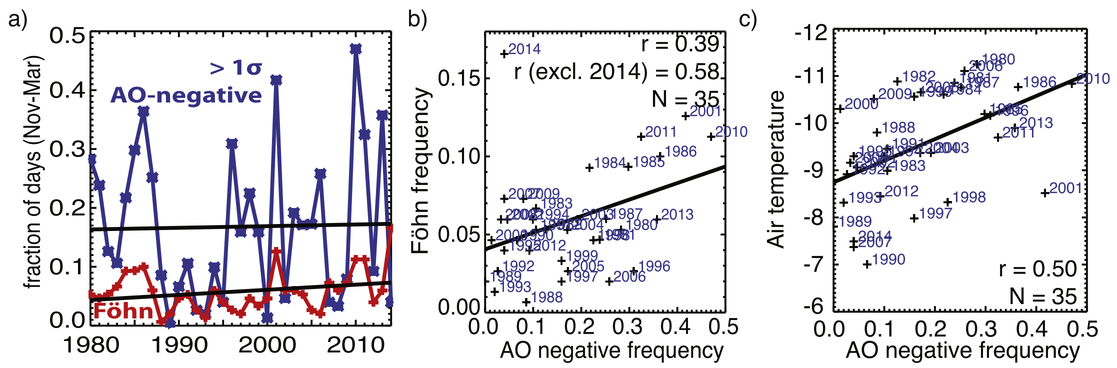

Figure 2. The (a) frequency and linear trend (black lines) of one standard deviation anomalies in Arctic oscillation (AO, blue) and daily occurrence of Southerly Föhn (red) in the northern Alps. The AO has a positive relationship with (b) Föhn frequency ($r = 0.39$, $r = 0.58$ excluding 2014) and (c) temperature (degrees C) ($r = 0.50$).

variability reflects strength and position of quasi-stationary upper-atmosphere pressure patterns that steer the jet stream, such as the NAO and AO (Thompson and Wallace 2001). For Europe, in winter, the NAO and AO, in their negative phases, tend to promote large-scale colder, wetter conditions and extremes in winter weather. Previous research has shown snow day trends in Switzerland to be linked to these oscillations and the frequency of mid-latitude cyclones and anticyclonic flow (Scherrer and Appenzeller 2004, Rudolph and Friedrich 2012).

In the German Alps, the frequency of objectively-determined Southerly Föhn conditions shows no significant trend ($\tau = 0.14$, $p = 0.23$) over the past 35 years, but does have significant interannual variability (figure 2(a)). The AO explains much of the variability in Southerly Föhn frequency ($r = 0.39$, $r = 0.58$ excluding 2014) (figure 2(b)) and winter temperature ($r = 0.50$) (figure 2(b)) except in the most extreme years (e.g., 2014). We found that its occurrence in winter is primarily related to negative anomalies in the AO but less strongly to the negative NAO. Negative AO frequency also positively relates to winter air temperature (figure 2(c)), in contrast to the general pattern over the whole of Europe of cooler conditions during negative AO/NAO anomalies.

Relationships of Southern Föhn flow to the AO are surprisingly stronger, but similar in sign and effect size to that for the related NAO ($r = 0.27$, $r = 0.46$ excluding 2013–2014). This response occurs as the AO and NAO are linked processes (Ambaum *et al* 2001) and both have a clear signal on European winter climate. However, the drivers of the AO and NAO have become a frequent topic of debate, especially on its relationships to ocean or sea ice dynamics. North Atlantic sea surface temperature (SST) warming is associated with weakening mid-latitude westerlies (Kennlyside and Omrani 2014). Poleward shifts in the Atlantic SST front promotes colder conditions in Europe, by developing a thermal gradient from the warm Barents Sea to cooler Eurasia, thereby increasing warm southerly advection (Sato *et al* 2014). Other articles have also posited that sea ice reductions in the Arctic influence the AO (Gerber *et al* 2014, Simmonds and Govekar 2014). Similarly, strengthening European blocking flow patterns have been associated with positive NAO depending on the strength of Atlantic zonal winds (Luo *et al* 2015).

On closer inspection, though, Southerly Föhn frequency is not just an artifact of the AO or NAO. Years with highest frequency of winter Southerly Föhn can occur with either frequent or infrequent negative AO or NAO frequency. Winter of 2013–2014 is a good example as a year with record setting Southerly Föhn frequency despite infrequent AO or NAO negative excursions. Comparing the highest Föhn years relative to the lowest of the last 35 years in reanalysis-based 500 hPa geopotential height significant anomalies (figure 3) reveals a different pressure dipole than the traditional AO or NAO. AO involves the pressure oscillation between the Gulf of Alaska and southern Greenland, while frequent Southerly Föhn is more associated with stationary low pressure over the UK and high pressure over Iceland. This pattern is also related to the intense precipitation received over the UK that winter (Huntingford *et al* 2014). In 2013–2014, a similar anomalous ridge set up in the Pacific, which promoted drought conditions in the western US (Wang *et al* 2014) and the two might have synergistically maintained a persistent flow in the jet position.

This circulation pattern promotes Southerly Föhn flow, which leads to decreased snowfall at Zugspitze (supplemental figure S2). Surprisingly, Southerly Föhn flow frequency doesn't appear to have an impact on winter mean air temperature, which is instead more directly related to the AO. A high frequency Southerly Föhn year on the one side melts existing snow packs in the Alps faster and earlier in the season than under normal conditions, and on the other side may reduce the formation of new snow packs at least in the pre-Alps where the Föhn effect is most pronouced. This may lead to an expansion of snowless surfaces, namely at intermediate elevations, a factor

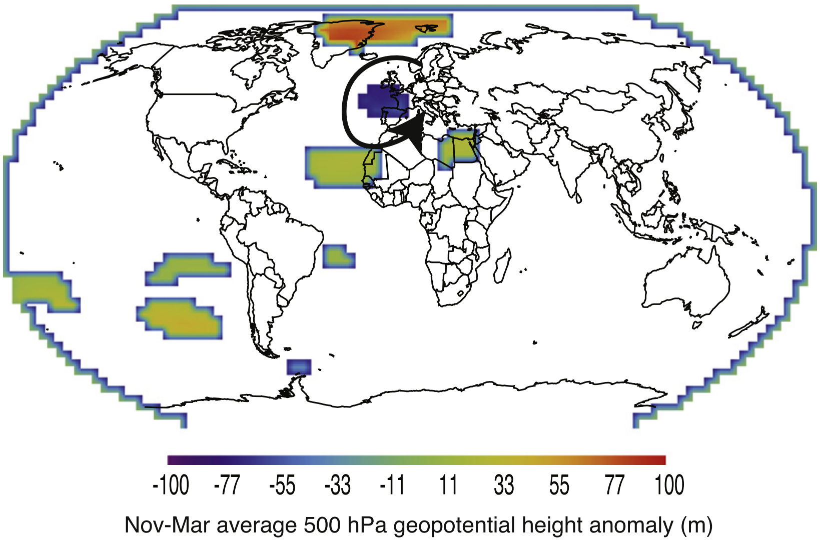

Figure 3. Geopotential 500 hPa height significant anomalies in the top quartile of Southerly Föhn years from 1980 to 2014 depict a pressure gradient from the UK to Northern Greenland, which promotes persistent Southerly Föhn flow in the Alps. The sense of induced circulation anomaly is shown by the black arrow.

that has found little attention in the discussion on climate change effects and has not been investigated in sufficient detail so far.

3.2. Ecosystem responses

The previously described circulation–topography interaction modifies snowfall and snowmelt events that influence consequent ecosystem productivity. Long-term eddy covariance carbon dioxide flux tower inferred interannual variation of spring (March–May) GPP were related to changes in frequency of wintertime Southerly Föhn, though more strongly for sites in the Central and Northern Alps. Across the 11 forested and grassland sites in the Alps, as much as 86% of spring GPP observations were explained by winter Southerly Föhn relative frequency (figure 4(a)). This effect was independent of site altitude or species, but dependent on site location. Northern and Central Alps sites together showed modest increase in spring GPP with increase in winter Southerly Föhn relative frequency, a slope of 14.8 gC m^{-2} per 1% increase in Southerly Föhn frequency ($r^2 = 0.53$, $N = 52$, $P < 0.0001$). Excluding the highest Southerly Föhn years, where the GPP response appears muted, the slope increases to 20.6 gC m^{-2} per 1%. Southern Alps sites, which would expect cooler, snowier conditions during Southerly Föhn, have no significant relationships ($r^2 = 0.03$, $N = 35$, $P = 0.34$), even with outliers removed.

The mechanism that most likely explains this relationship for the Northern and Central Alps is the effect of warming over bare or low snowcover soil during Southerly Föhn events. Southerly Föhn advects a substantial amount of heat and can melt snow packs at rates of ten and more centimeters in 24 h (Siler and Roe 2014). Snowmelt and warm air temperature then promote earlier soil warming and plant development, consistent with what has been observed in long-term phenology monitoring plots in the Austrian Alps (figure 4(b)) (Menzel *et al* 2006). These findings are also consistent with tree ring evidence in the Italian Alps, which shows the greater importance of Alpine tree species response to winter precipitation compared to temperature (Pellizarri *et al* 2014). In contrast, there is an associated increase in snowfall with Southerly Föhn on the southern slopes of the Alps, a phenomenon known as Stau, and this process would be consistent with weaker GPP response to Southerly Föhn we found for the Southern Alps.

Together, shorter snow seasons and earlier start of carbon uptake period are associated with advancement and lengthening of the carbon uptake period (figure 4(c)), which we find most pronounced in the Northern Alps at 3.6 d per 1% increase in Southerly Föhn frequency ($r^2 = 0.26$, $N = 28$, $P = 0.006$), but only 1.6 d per 1% and 0.6 d per 1% in the Central and Southern Alps, respectively. The early growing season effect appears to be the primary driver of increased overall carbon uptake, though reductions in summer peak uptake may occur from vegetation structural changes (Marcolla *et al* 2011, Galvagno *et al* 2013). Very early snow melt periods, such as those seen in 2013–2014, however, are unlikely to significantly influence carbon uptake since eventually, carbon uptake is limited by solar day length (Wohlfahrt *et al* 2013). This supposition provides a clue as to why the carbon uptake relationships fall below the linear regression fit in the highest Southerly Föhn frequency years. Alternative hypotheses for this effect include increased desiccation of evergreen conifer and photoinhibition, particularly at treeline (Montagnani *et al* 2005), which require further investigation.

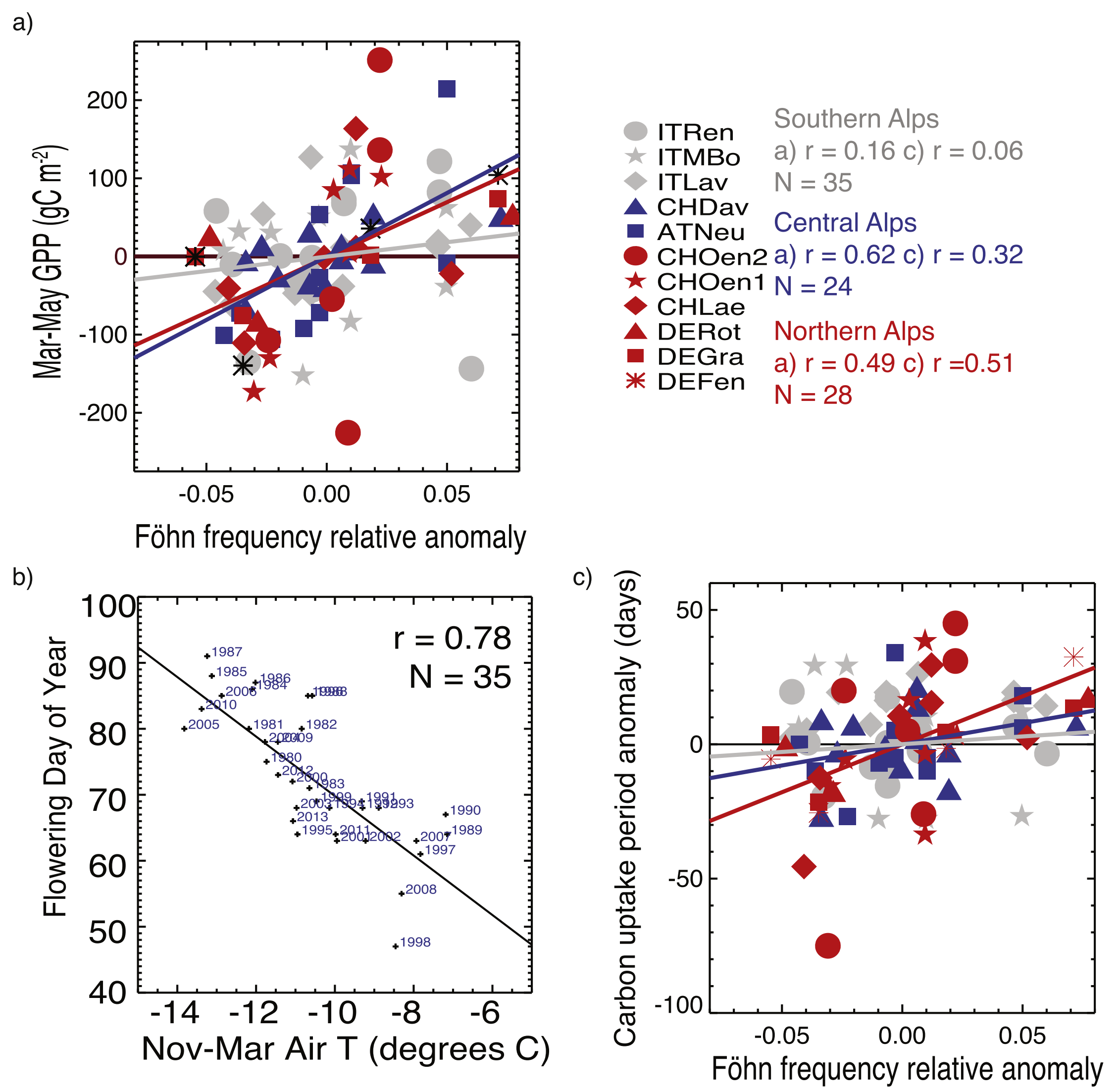

Figure 4. (a) Spring carbon uptake by Alpine forests and grasslands in relationship to local anomalies in Southerly Föhn relative frequency, (b) relationship of spring flowering date of Austrian Tyrolean phenology monitoring sites to winter temperature, and (c) relationship of total growing season carbon uptake period to Southerly Föhn frequency.

Satellite remote sensing further supports the flux tower findings. In the Alps over 2002–2009, satellite indices of start of spring greening advances on average by 4.9 d per 1% increase in winter Southerly Föhn frequency over 84% of the study area (areas where $p < 0.1$, median $p = 0.05$), primarily in the Northern and Central Alps (figure 5(a)). These remotely sensed data are consistent with the previously discussed *in situ* phenology observations in the Austrian (Northern) Alps (figure 4(b)). The relationship of advancing spring in response to increased Southerly Föhn frequency is thus confirmed by remotely sensed estimates of ecosystem greening phenology, which closely tracks vegetation activity, and thus carbon uptake period (Wu *et al* 2012).

However, the advancing spring does not necessarily lead to longer vegetation green period (figure 5(b)). Of the locations where start of spring greening responded to Southerly Föhn with $p < 0.1$, only 40% also had positive response of length of green period, primarily in the Northern Alps, with response of 3.4 d per 1% increase in Southerly Föhn frequency, consistent with the flux tower observations. Opposite responses are seen in the Southern Alps, such that early spring does not necessarily extend growing season length.

Interestingly, the flux tower and satellite observations suggest that the few years with the highest Southerly Föhn frequency anomalies do not follow the general pattern outlined above (e.g., Northern Alps in 2013–2014). It appears that in these cases, earlier season snowmelt does not promote growth owing to light limitation to photosynthesis. When snow melt and warm air temperature does promote early growth, this phenomenon may also lead to the development of false springs, whereby ensuing cold snaps lead to plant tissue damage and reduced productivity. In these cases, soil temperatures can actually decrease from loss of insulating snowpack in mid-winter.

Plant growth simulation using an ecosystem model at one of the pre-Alpine grassland sites in the

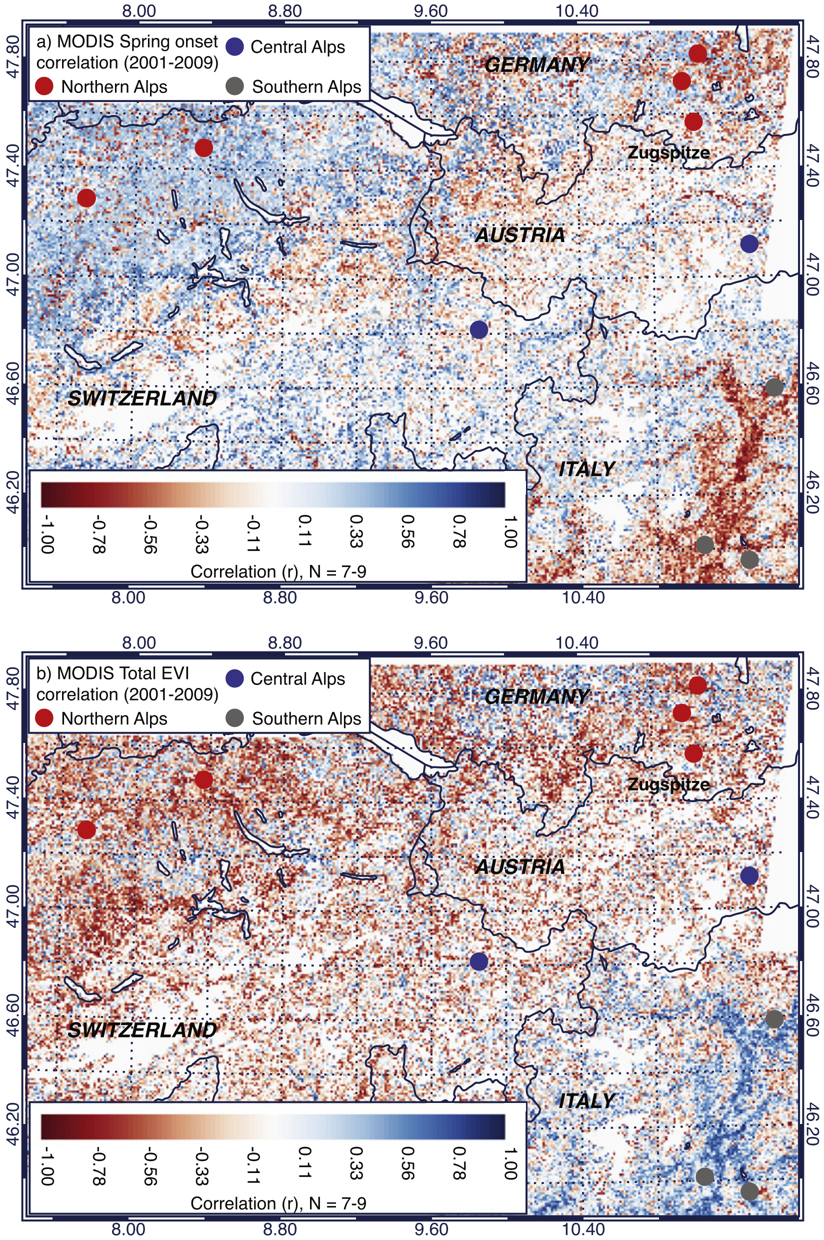

Figure 5. (a) The slope of significant ($p < 0.1$) relationships between 2002 and 2009 Southerly Föhn frequency and remotely-sensed vegetation index date of greening onset is negative across most of the Alps. (b) In contrast, the length of growing season green period shows positive response only in the northern regions and valley locations in the southern valleys.

long snow-free winter of 2013–2014 demonstrates this response. Plant carbon uptake under freezing soil condition was reproduced as shown in time series in CO_2 and latent heat fluxes and liquid and ice water contents (supplementary figure S3). In the simulation, Southerly Föhn conditions led to rapid snowmelt (supplementary figure S4(b)) and caused new leaf development during warm snow-free days (i.e., relatively high air temperature) in the middle of winter (supplementary figure S4(a)). With continued snow-free ground, the model simulated enhanced soil freezing and frost stress leading to leaf loss during cold days before cold acclimation developed in plants. This negative response of grassland ecosystems could affect regional carbon balance under future climate change with large increases in Southerly Föhn frequency.

4. Conclusion

While impacts from decadal temperature and precipitation trends and extremes on ecosystem phenology and biogeochemistry have been documented (Reichstein *et al* 2013), the impacts on plant productivity and nutrient limitation from variability in circulation patterns and its interaction with anthropogenic climate change are not as well quantified (Shepherd 2014). Patterns in atmospheric circulation and their seasonal persistence drive year-to-year variability of temperature and precipitation patterns of the midlatitudes, especially in winter. The frequency and distribution of weather systems in any one location, in turn, is a function of planetary and synoptic circulation features, modified by larger mountain ranges such as the European Alps, which promote features such as the Southerly Föhn. We found that two tropospheric pressure patterns over the North Atlantic interact with European topographic Southerly Föhn flows to influence regional winter weather that contrasts the pattern of the continent as a whole. These effects then significantly influence subsequent spring ecosystem productivity and phenology.

Anthropogenic climate projection assessments suggest a range of scenarios for future 21st century patterns of North Atlantic blocking and jet stream variability (Masato *et al* 2014). Continued Arctic warming appears to drive high amplitude jet stream persistence (Francis and Vavrus 2015), though further warming would diminish pole to equator temperature gradients, weakening the role of large-scale advection in driving within season temperature variation (Screen 2014), except in topographic-driven flow regimes. For example, consider the winter of 2013–2014, which was the warmest for Earth in the instrumental record and associated with a significant retraction of the Arctic cold pool (as indicated by the 850 hPa −5 °C isotherm), leading to poleward displacement of the midlatitude jet (Martin 2015). Increased frequency of winters like these may be expected to significantly increase frequency of Southerly Föhn flows in the Alps. Thus, we suspect that the observed relationships between circulation and productivity will remain robust and possibly increase into the future and drive significant interannual variability in carbon sink capacity of European Alpine ecosystems.

Our results quantitatively verify received wisdom. The word Föhn derives from the Latin *favere*, which means 'to be in favor of', but when referred to plants, translates to 'let grow'. Pliny the Elder in 'Naturalis Historia' noted how these winds promote vegetation growth nearly 2000 years ago. Our findings confirm that mountain ecosystems respond to variability in circulation patterns and topography and that this result has implications for assessment of changes in microclimates suitable for plant growth and for projecting the impact of regional ecosystem response to climate. Current generation coupled climate models are too coarse in spatial resolution to diagnose these effects at the regional scale, have high uncertainty on regional circulation (Shepherd 2014), and downscaling strategies for topography neglect or fail to capture orographic flows (Zubler *et al* 2014). Ecological impact assessments need to account for uncertainty in shifts in circulation features and their links to weather system development, that may positively or negatively interact with mean climate trends.

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