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 (1–6°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 et al 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 (Dreschel and Mayr 2008).

Interestingly, while the mechanics of Southerly Föhn flows are well understood (Dreschel 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 (867m ASL). For all three stations, hourly and daily observations from Nov 1 to March 31 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, 2964m ASL) and potential temperature gradient between Garmisch-Partenkirchen, Germany (718m 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.

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 (NOAA) 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 2014-02-28).

Eddy covariance flux tower observations of net ecosystem exchange (NEE) and inferred gross primary productivity (GPP) (Papale *et al* 2006, Reichstein *et al* 2005) were downloaded from the European Fluxes Database Cluster ([http://www.europe-fluxdata.eu/](http://www.europe-fluxdata.eu/); accessed on November 3rd 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* 2001, 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\(^{-2}\) day) 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 8-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 (600m 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 days 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\(^{-1}\), \(\tau = 0.22\), \(p = 0.06\)) (Fig. 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 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 anti-cyclonic 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 (Fig. 2a). The AO explains much of the variability in Southerly Föhn frequency ($r = 0.39$, $r=0.58$ excluding 2014) (Fig. 2b) and winter temperature ($r = 0.50$) (Fig. 2b) 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 (Fig. 2c), 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 (Fig. 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 U.S. (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 Fig. 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 pronounced. This may lead to an expansion of snowless surfaces, namely at intermediate elevations, a factor 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 (Mar-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
(Fig. 4a). 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 hours (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 (Fig. 4b) (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 (Fig. 4c), which we find most pronounced in the Northern Alps at 3.6 days per 1% increase in Southerly Föhn frequency ($r^2=0.26, N=28, P=0.006$), but only 1.6 days per 1% and 0.6 days 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 limits (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.

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 days 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 (Fig. 5a). These remotely sensed data are consistent with the previously discussed in situ phenology observations in the Austrian (Northern) Alps (Fig. 4b). 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 (Fig. 5b). 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 days 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 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 Fig. S3). In the simulation, Southerly Föhn conditions led to rapid snowmelt (Supplementary Fig. S4b) and caused new leaf development during warm snow-free days (i.e., relatively high air temperature) in the middle of winter (Supplementary Fig. S4a). 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 mid-latitudes, 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 2,000 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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**Figure Legends**

**Figure 1.** Winter season average (Nov-Mar) 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.

**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 ($r = 0.50$).

**Figure 3.** Geopotential 500 hPa height significant anomalies in the top quartile of Southerly Föhn years from 1980-2014 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.

**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.

**Figure 5.** a) The slope of significant ($p<0.1$) relationships between 2002-2009 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.
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Supplementary Information For

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S1 Supplementary Materials and Methods

S1.1 Föhn calculation

Föhn diagnosis was derived using objective criteria for wind direction, wind speed, relative humidity and potential temperature (Plavcan et al 2014) applied to hourly data collected between 1988 and 2014 for Zugspitze and Garmisch-Partenkirchen by the Deutscher Wetterdienst (DWD). Föhn conditions at the Zugspitze (2984 m a.m.s.l.) were assumed to be limited to a south wind sector (105 to 225 degrees) with substantial wind speed (exceeding the median, 6.4 m s\(^{-1}\)). Not all Föhn wind breaks through to the downwind valleys. Therefore, dry air conditions in the valley (relative humidity less than the median, 90%) and small differences in potential temperature between the summit and valley (less than the 25% quartile, 7.2 K) were prescribed for Garmisch-Partenkirchen. When all the above criteria were true for at least two consecutive hours, a day was classified as Föhn day. Annual periods were defined from November and December of the previous year and January to October of the analysis year, in order not to split winter between two calendar years.

S1.2 Ecosystem model description

SOLVEG is a one-dimensional multi-layer model that consists of four modules for the atmosphere near the surface, and for soil, vegetation, and radiation within the vegetation canopy. The atmosphere module calculates the variables in each atmospheric layer by numerically solving one-dimensional diffusion equations for horizontal wind speed components, potential temperature, specific humidity, liquid water content of the fog, turbulent kinetic energy and length scale, and gas and aerosol concentrations by the second-order turbulence closure model (Yamada 1982). The soil module calculates soil temperature, volumetric soil water content, and specific humidity of the air in the soil pores using equations for heat conduction, mass balance in
liquid water, and water vapor diffusion, respectively (Katata et al 2007). The module has been updated to simulate the organic matter decomposition and dissolved organic carbon (DOC) leaching in the aboveground litter layer, the belowground input of carbon from roots, and soil organic carbon (SOC) turnover and DOC transport along water flows throughout the soil profile for three SOC pools (active, slow, and passive, characterized by a turnover time of years, decades, and millennia, respectively) (Ota et al 2013). The vegetation module calculates the leaf temperature, the water on the surface of the leaves (leaf surface water) for each canopy layer and the vertical liquid water flux through the entire canopy. In this module, photosynthesis is also incorporated to calculate the CO₂ assimilation rate based on the relationship between stomatal resistance and the net CO₂ assimilation rate (Nagai 2005). The radiation module separately calculates direct and diffuse downward and upward fluxes of solar and long-wave radiation in the canopy and provides the radiation energy input for the heat budget calculations at the soil surface and canopy layers (Nagai 2003). The basic equations related to gas exchange processes are described in (Katata et al 2011, Katata et al 2013). Schemes for the deposition of gaseous and particulate matters (including fog droplets) at each canopy layer were incorporated into the model and verified with flux data measured by gradient and eddy covariance methods over semi-arid deserts (Katata et al 2007, Katata et al 2010), croplands (Nagai 2003, Katata et al 2007, Nagai 2002), rice paddy field (Katata et al 2013), temperate grasslands (Nagai 2005, Ota et al 2013), and forests (Nagai 2003, Katata et al 2008, Katata et al 2014).

Our special interest is the role of Föhn as a trigger of snowmelt and leaf development via increasing air temperature. To simulate this situation, new schemes for snow, soil frozen, plant growth, and frost damage of leaves were implemented in SOLVEG. The snow module has a multi-layer structure based on selected schemes of available literature summarized in Essery et al
The module has a multi-layer structure based on processes of snow albedos for four-radiation components (Wiscombe and Warren 1980), gravitational and capillary water flows in unsaturated snow based on van Genuchten’s model (Hirashima et al 2010), snow grain growth and compaction (Jordan 1991), and melting and freezing in snow. When snow covers grasses, no photosynthesis is assumed due to low light availability and only soil respiration is considered. In the soil module, frozen process in the soil is modeled based on the concept of freezing point depression (Zhang et al 2007). After the above modification, SOLVEG can predict temporal changes in ice and liquid water content, temperature, and grain size at each snow layer, and ice water content in each soil layer.

The original SOLVEG did not predict phenological processes such as leaf development and senescence. In this study, we coupled SOLVEG with the existing grass growth model LINtul GRAssland, LINGRA (Schapendonk et al 1998, Höglind et al 2001) to simulate these processes. LINGRA is based on plant morphological key processes and light interception and has separated algorithms for source- and sink-related processes and a mechanistic, though simple, approach of grass morphological development, simulating the natural sequence of events in grasslands as regular defoliation due to grazing or cutting. Natural turnover of leaves and roots are modeled using typical life spans in years (Arora and Boer 2005). The fraction of roots in soil layers and rooting depth are modeled as a function of root biomass (Arora and Boer 2003). In coupling simulations, net assimilation rate calculated in SOLVEG is used for source-limited plant growth calculation. Dead leaf biomass is used as input to the aboveground litter layer in soil module.

To simulate leaf damage due to freezing and frost effects in the snow-free period, the damaged leaf area at the leaf temperature and the level of cold hardening (Leinonen 1996) is incorporated into SOLVEG. Plants adapt to winter conditions by reallocating assimilates from
growth to storage organs and by undergoing a number of physiological changes aimed at
avoiding or mitigating cellular injuries caused by sub-zero temperatures, so-called “cold
hardening”. This cold acclimation process to temperature is considered via decreasing the
maximum catalytic capacity of Rubisco ($V_{cmax}$) by simply multiplying the factors of annual
change of photosynthesis (Mäkelä et al 2004) and short-term frost impacts, $f_{cA}$ (King and Ball
1998). Both factors vary from 0 to 1 depending on seasonal air temperature variations.

Key parameters used in SOLVEG simulation are summarized in Supplementary Table
S3. Simulations were carried out from the beginning of wintertime (1 November 2013) to just
after the first cut of grasses (26 May 2014). The date of the first grass cut at Fendt was recorded
22 May 2014.

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Supplemental Figure S1. Similar analysis to Figure 1 for Davos, Switzerland showing a) mountain (blue) and valley (red) mean (line) and daily maximum and minimum (pink and blue shading) average winter temperature and trend (black line), b) fraction of rain (blue), snow (light blue), and clear days (white), and c) total snowfall at high (blue) and low (red) altitude site.

Linear trends are shown as black lines.
Supplementary Figure S2. Relationships of a) Southerly Föhn to Zugspitze mountaintop winter air temperature is weak, but b) strong for snowfall.
Supplementary Figure S3. Temporal changes in calculated (blue and red lines) and observed (open circles) a) CO₂ flux, b) latent heat flux, c) relative soil liquid and ice water content, and d) live leaf biomass at Fendt pre-alpine grassland site in Germany from 1 November 2013 to 26 May 2014. Observed fluxes were measured by eddy covariance technique. Freezing soil conditions were reproduced as shown in decreases in liquid and increases in ice water contents. The above-ground biomass in d) was sampled on 22 May 2014, several days later than the first grass cut in the field on 18 May 2014 (red arrow).
Supplementary Figure S4. Time series of a) calculated leaf area index (LAI; red line) by SOLVEG and observed daily mean air temperature ($T_a$: blue line), b) Southerly Föhn frequency (yellow triangles), and snow depth (blue lines) at Fendt pre-alpine grassland site in Germany from 1 November 2013 to 8 February 2014. Föhn frequency is represented as cumulative hours in a day. In a), leaf development and freezing damage of leaves were simulated on relatively warm day (Day 8, red arrow) and cold day (Day 27, black arrow), respectively. b) shows that snow often disappeared just after Föhn days (Days 80 and 97).
**Supplementary Table S1.** Nov.-Mar. Föhn frequency, climate oscillation frequency, and weather station averages.

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<th>NAO Negative Frequency (%)</th>
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<th>Krün snowfall (cm)</th>
<th>Zugspitze Air Temperature (°C)</th>
<th>Garmisch Air Temperature (°C)</th>
<th>Mean Daily Temperature (°C)</th>
<th>Days with Snowfall (Krün)</th>
<th>Average Daily Sunshine (Hours)</th>
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Supplementary Table S2. Fluxnet study site characterization.

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<th>Longitude</th>
<th>Elevation (m)</th>
<th>MAT (°C)</th>
<th>MAP (mm)</th>
<th>Vegetation type</th>
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<td>47° 43’ 12” N</td>
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<td>11° 01’ 48” E</td>
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<td>11° 03’ 36” E</td>
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<td>Lavarone</td>
<td>IT-Lav</td>
<td>45° 57’ 23” N</td>
<td>11° 16’ 52” E</td>
<td>1349</td>
<td>7.8</td>
<td>1150</td>
<td>Evergreen mixed silver fir-beech-spruce forest</td>
<td>2000-2012</td>
<td>Cescatti and Marcolla 2004</td>
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<td>Monte Bondone</td>
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<td>46° 00’ 53” N</td>
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<td>Marcolla et al 2011</td>
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<td>Renon</td>
<td>IT-Ren</td>
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<td>11° 26’ 05” E</td>
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<td>Evergreen Norway spruce forest</td>
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<td>Marcolla et al 2005</td>
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**Supplementary Table S3.** Key parameters for SOLVEG simulations at Fendt grassland site in Germany during the wintertime.

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
<th>Key reference</th>
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<td>Time step</td>
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<td>Initial volumetric soil water content</td>
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<td>Bottom soil temperature</td>
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<td>Bottom volumetric soil water content</td>
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<td>Saturated hydraulic conductivity</td>
<td>m s⁻¹</td>
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<td>Initial carbohydrate storage</td>
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<td>Schapendonk et al 1998</td>
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<td>Maximum catalytic capacity of Rubisco at 25 °C</td>
<td>µmol m⁻² s⁻¹</td>
<td>60</td>
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<td>Initial tiller density</td>
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<td>Full hardened temperature</td>
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<td>Dark respiration rate of leaves at 25 °C</td>
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<td>Activation energy for dark respiration</td>
<td>J mol⁻¹</td>
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<td>Minimum stomatal conductance</td>
<td>mol m⁻² s⁻¹</td>
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<td>Initial leaf area index (LAI)</td>
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<td>Initial root biomass</td>
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<td>Slope of stomatal conductivity in response to assimilation</td>
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<td>Phyllochron (interval between leaf appearance)</td>
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<td>Leaf life span</td>
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<td>Root life span</td>
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<td>Maximum drought leaf loss rate</td>
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<td>Shape parameter for leaf loss due to drought</td>
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<td>Maximum storage carbohydrate fraction</td>
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<td>Time constant for storage carbohydrate</td>
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<td>Specific leaf area (SLA)</td>
<td>m&lt;sup&gt;2&lt;/sup&gt; kgDW&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>10 Tjoelker et al 2005</td>
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<td>Maximum LAI-induced leaf loss rate</td>
<td>day&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>0.06 Van Oijen et al 2005</td>
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<td>Minimum threshold temperature for leaf appearance and tillering</td>
<td>°C</td>
<td>5 Schapendonk et al 1998</td>
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<tr>
<td>Maximum threshold temperature for leaf appearance and tillering</td>
<td>°C</td>
<td>10 Schapendonk et al 1998</td>
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<td>LAI after the grass cut</td>
<td>m&lt;sup&gt;2&lt;/sup&gt; m&lt;sup&gt;-2&lt;/sup&gt;</td>
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<td>Parameters for soil microbiological module</td>
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<tr>
<td>Snow layer thickness</td>
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<td>Parameter for the effect of soil specific surface on matric potential due to the presence of ice</td>
<td>–</td>
<td>8 Zhang et al 2007</td>
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<tr>
<td>Irreducible liquid water content in snow</td>
<td>m&lt;sup&gt;3&lt;/sup&gt; m&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>0.03 Hirashima et al 2010</td>
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*DM: dry matter, DW: dry weight

720 Other parameters for snow and soil frozen modules