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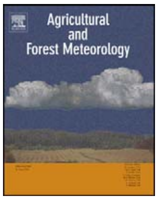

Characterising inter-annual variation in the spatial pattern of thermal microclimate in a UK upland using a combined empirical–physical model

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ABSTRACT

Temperature exerts a fundamental control on ecosystem function, species' distributions and ecological processes across a range of spatial scales. At the landscape scale, near-surface air temperature may vary spatially over short distances, particularly in mountainous regions. Both the magnitude and spatial pattern of surface temperature may vary on diurnal, seasonal and inter-annual timescales. Furthermore, temperatures measured at the surface of vegetation, influenced by the energy balance of the surface, can differ considerably from air temperature. In order to explore spatial patterns in temperature across the Moor House sector of the Moor House—Upper Teesdale National Nature Reserve (NNR), Northern Pennines, UK, we derived an empirical linear regression model to predict air temperature at 1 m height as a function of landscape metrics derived from a digital elevation model (DTM), and coupled this to an existing physical land-surface model (JULES) in order to predict and map thermal climate at the vegetation surface across the study area. Spatial patterns in temperature associated with altitudinal lapse rate, katabatic flow and a local föhn effect were incorporated into the regression model. JULES was driven using spatially distributed air temperatures from the empirical model, along with distributed solar and long-wave radiation flux estimates adjusted for surface slope and aspect, and sky-view in order to model the surface energy balance and predict thermal climate at the vegetation surface (skin temperature). Aggregate properties such as annual degree days above 5 °C (GDD5), number of "frost days" when the temperature fell below 0 °C (FD0) and number of "severe frost days" when the minimum temperature fell below −5 °C (FD−5) were mapped across the reserve for the years 1994–2006. Spatial mapping of surface temperature revealed differences in the 12-year average spatial pattern between GDD5, FD0 and FD−5, and differences in the spatial patterns of FD0 and FD−5 between different years, depending on the relative strength of lapse rates, temperature inversions and the föhn effect. The location of "warm" and "cool" microclimates within the study area varies depending on the dominant atmospheric conditions in a given year and on the thermal property of interest. While GDD5 tended to decrease and FD0 increased with increasing altitude in all years, following the gradients in average temperature, the magnitude of these relationships varied considerably between years. FD−5 increased in some years and decreased in others, due to the influence of temperature inversions during extreme cold temperature events. We conclude, that in order to predict the landscape-scale response of species and communities to climatic change in upland areas accurately, it will be necessary to take into account changes in the frequency and magnitude of different synoptic atmospheric conditions under future climate scenarios.

1. Introduction

Surface microclimate exerts a fundamental control on ecosystem function, species' distributions and ecological processes across a range of spatial scales (Chen et al., 1999). In order to predict and manage the effects of changes in global climate on ecological systems it is essential to understand the spatial and temporal distribution of climate at the landscape scale. This will often require "downscaling" of climatic data from the coarse spatial resolution of global or regional climate models to a finer spatial resolution, or interpolating data from sparse meteorological stations across spatial domains. Spatial patterns in climate differ depending on the process and timescale involved. For example, average surface temperatures at screen height tend to decrease

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with elevation (Barry, 1992), near-surface temperatures are influenced by slope and aspect under periods of high solar radiation (Rorison et al., 1986), and temperature inversions may form under certain atmospheric conditions (Pepin et al., 1996). These different processes give rise to different spatial patterns in surface temperature and the relative strength of each process will define the dominant spatial pattern in temperature. Both the magnitude and the spatial pattern of surface temperature across complex topography have been shown to change depending on the synoptic climatic conditions (Lundquist and Cayan, 2007; Rolland, 2003). Therefore under conditions of changing climate, spatial patterns of microclimate, as well as the average climatic conditions, are likely to change; such changes may lead to different rates of climatic change in mountainous regions and lowlands (Diaz and Bradley, 1997) or even lead to a localised reversal of regional trends, for example a net cooling at high altitudes during a period of regional warming (Pepin and Losleben, 2002).

Microclimate plays an important role in the distribution of many species, particularly towards the edge of their range and in marginally suitable climates (Pigott, 1970; Thomas et al., 1999). Moreover, the fine-scale distribution of species may reflect the distribution of aspects of microclimate that are not represented by broad climatic averages. The climate of the British uplands is characterised by relatively windy and overcast conditions throughout the year. However, both extreme low temperatures (which typically occur at night at high elevations and/or in "frost hollows" of restricted cold-air drainage) and extreme high temperatures (typically occurring on short vegetation or bare rock on south-west-facing slopes in mid afternoon) tend to occur on atypically still, clear days and nights during anticyclonic conditions when radiation terms dominate the energy balance. Seasonal mean climate and smooth climatic surfaces are unlikely to be able to predict ecological processes driven by these microclimatic factors in a mechanistic way. To quantify adequately such factors, predictive studies must incorporate the effects of both spatial landscape structure at the scale of interest and synoptic and diurnal climatic variability at a relevant temporal scale.

Landscape-scale climatic models are frequently used to model vegetation and/or species distributions (Ashcroft, 2006; Dymond and Johnson, 2002; Gottfried et al., 1999; Trivedi et al., 2008). Three approaches to extrapolating climatic variables across gridded landscapes have been widely used. Smoothing algorithms, designed to interpolate between observations, e.g. partial thin plate splines (Hulme et al., 1995; Hutchinson, 1987), are most suitable for data at a coarse temporal (monthly/annual) resolution and on regional/continental scales at which climatic data are relatively smooth. These are typically unsatisfactory for mountainous regions, where surface climates vary over relatively small distances and observations are sparse. An alternative approach is to use empirical or semi-empirical regressions on topographic predictors, such as elevation, or slope and aspect. These methods require validation by a network of observations and, because of their empirical or semi-empirical nature, relationships typically are specific to the sites in which they were developed. Physically based surface exchange models that explicitly resolve the surface energy balance require large quantities of input data. Such models have been developed for hydrological or climatological purposes. They therefore have an emphasis on accurately estimating fluxes (e.g. evapotranspiration, sensible and latent heat, trace gases).

We developed a spatial model of surface climate for the Moor House sector of the Moor House—Upper Teesdale National Nature Reserve (NNR), a region of moderately complex upland terrain in the northern Pennines, in the United Kingdom, and of considerable conservation interest as a result of its sub-Arctic plant and animal communities, including a unique flora encompassing pre-Alpine, Alpine, Arctic-Alpine and sub-Arctic species (Pigott, 1956) and sub-Arctic soil faunal assemblages (Cragg, 1961). The region is considered to be a climatically marginal location for such communities that are restricted to much higher altitudes or latitudes elsewhere in Europe. Under future climatic change, it is uncertain whether these sub-Arctic species and communities will persist in their current locations, shift to other locations in the landscape as local microclimate becomes suitable, or become locally extinct. The spatial pattern of microclimate across the region, and the extent to which global climatic change will affect the upland microclimate, are therefore of considerable interest.

The objective of this study was to determine whether modelled spatial patterns of thermal microclimate at the study site (specifically growing season heat sums and the frequency of low-temperature events) vary between years and/or between thermal properties. Surface climate was modelled in two stages. First, an empirical regression model of air temperature anomalies at 1 m across the site was developed using spatial variables derived from a digital terrain model and tested against data collected from mobile automatic weather stations (AWSs). The second stage was to use time series of modelled air temperature, along with other regional climatic variables, to drive a distributed run of an existing land-surface model, JULES (Cox et al., 1999), in order to predict spatio-temporal patterns of surface temperature at a scale relevant to ecological processes.

2. Study area and methods

2.1. Study area

The study site, which contains the Moor House sector of the Moor House—Upper Teesdale National Nature Reserve, lies in the northern Pennines at approximately 54.7°N 2.4°W between the Vale of Eden to the west and Teesdale to the east (Fig. 1). Elevation within the study site ranges between 340 m and 893 m, and the reserve includes part of the largest area of land over 400 m in England. Climatic investigations at two localities within the area, Moor House and Great Dun Fell, date back to the 1930s (Manley, 1942). The region is considered to be a climatically marginal location for the pre-Alpine, Alpine, Arctic-Alpine and sub-Arctic plant and animal communities which led to the establishment of the reserve (Cragg, 1961; Pigott, 1956). Elsewhere, species have been shown to adapt to recently warming climatic conditions by establishing at higher altitudes, for example in the Alps (Grabherr et al., 1994), or at higher latitudes (Parmesan et al., 1999). Since the North Pennines rise to only 893 m at Cross Fell, and are geographically remote from high altitude or latitude regions, it is unlikely that cold-adapted species will be able to disperse to colder sites. Moreover, many of the rarer plant species are restricted to limestone outcrops or calcareous flushes, and are unlikely to be able to colonise the deep acidic peats that cover much of the higher altitude parts of the area. The site is part of the United Kingdom Environmental Change Network (ECN); a range of organisms and ecosystems are being monitored in order to detect any impacts upon them of climatic change. The sensitivity of the plant communities of the North Pennines to temperature has been shown by recent vegetation changes attributed to the construction of a water storage reservoir at Cow Green, located approximately 1 km to the east to the study area, which appears to have moderated extremes of temperature and, in particular, reduced the frequency and intensity of frost events directly adjacent to the reservoir (Huntley et al., 1998).

A digital terrain model (DTM) of the site was available as a raster matrix of elevation at a 50 m spatial resolution.