Ten-year meteorological record for an upland research catchment near the summit of Snake Pass in the Peak District, UK

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Ten-year meteorological record for an upland research catchment, near the summit of Snake Pass in the Peak District, UK

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Abstract

High elevation meteorological records are sparse in the United Kingdom, due in part to the logistical challenges of setting up and maintaining monitoring stations. These upland regions are also coincident with peatland landscapes, many of which are at the southern limit of the temperate peatland. Given concerns over the long-term stability of these landscapes, which are currently at risk due to shifts in climatic zones, we present a 10-year review of meteorological conditions in an upland peatland catchment in the Peak District, UK which provides baseline data for assessment of change in this area.

Keywords

upland weather records; peatland; Peak District;

Introduction

Although the UK has a dense network of high resolution weather records, the uplands are significantly underrepresented. This is unsurprising since the logistical demands of

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maintaining weather observations at high elevation (>300m; Moorland line) often in extreme weather conditions are severe. Early records such as the work of Gordon Manley at Moor House (Manley, 1942) are particularly impressive in this context, but even with the advent of automated weather stations continuous records from high elevations are sparse.

In this paper we present a 10 year weather record from near to the summit of Snake Pass in the English Pennines. The Snake Pass connects Sheffield and Manchester across the high Pennines with a highest elevation of 510 metres; radio reports of the closure of the pass are an early indication of the onset of the English winter. The Pennine hills of the south Peak District are an iconic landscape, scene of the Kinder Mass trespass, and home to the second most visited National park in the world. The value of a detailed weather record from this location, however, goes beyond the provision of detailed instrumental records for this important English locale, in that these data provide important context for a wide range of environmental science being undertaken in the area.

High elevation records have value, not just because of their rarity, but because they are known to be sensitive to the impacts of climate change, and there is evidence, in some contexts, of elevation dependence of changes in climate (Giori *et al*., 1997). With increasing temperatures, the northward shift of climatic zones may lead to a progressive loss of the southern limit of blanket peat in the UK (Clark *et al*., 2010). In the specific context of the English Pennines, high elevation sites are typically coincident with sensitive and degraded peatland landscapes. Concerns over erosion (Evans and Warburton, 2007), pollutant mobilisation and transport (Rothwell *et al*., 2007), loss of carbon sequestration (Worrall *et al*., 2009) and impacts of restoration (Shuttleworth *et al*., 2015) have made these landscapes a focus of scientific enquiry.

Methods

Study site

The Upper North Grain (UNG) catchment, located on the Bleaklow plateau at the southern end of the Pennines, is a small headwater catchment of the River Ashop, which then feeds into Ladybower reservoir in the Upper Derwent Valley (Figure 1). The catchment is approximately 0.4 km^2 with altitude ranging from 480 – 540 m (Goulsbra *et al*., 2014). The catchment is covered with blanket peat (up to 4 m depth in places) which is dominated by active gully erosion (Bower, 1961). The underlying geology is characterised by interbedded sandstones and shales of the Carboniferous Millstone Grit series (Wolverson-Cope, 1976). The principal vegetation includes: *Eriophorum vaginatum, Calluna vulgaris, Vaccinium myrtillus, Empetrum nigrum* and *Sphagnum spp.*

This site is owned by the National Trust and environmental monitoring infrastructure at this site is maintained by the Department of Geography at the University of Manchester. The catchment was originally instrumented as an outdoor laboratory to study peatland gully erosion (Clay *et al*., 2012; Daniels *et al*., 2008; Goulsbra *et al*., 2014; Pawson *et al*., 2012; Rothwell *et al*., 2007; Yang, 2005) and has been a continued focus of research on the impacts of peatland erosion and restoration on a range of ecosystem services. Meteorological data have played a central role in many of these studies.

Meteorological equipment

The automatic weather station (Figure 2) sits within the UNG catchment at an altitude of 506 m (53° 50’ 24” N 1° 50’ 38” W) and records a range of parameters namely: relative humidity (%); air temperature (°C); soil temperatures at 5 cm and 10 cm depth (°C); solar radiation (W m^{-2}); net radiation (W m^{-2}); wind speed (m s^{-1}); wind direction (°); precipitation (mm). Data were recorded hourly (on the hour) using a Skye instruments Mini Met weather station, and data were downloaded approximately four times a year. Daily and monthly averages were based on the civil day (00-00hUTC). Data were available from 1 April 2003 to 31 December 2013 and this time period was used in the gap-filling approach (see *Data processing and gap filling*). However, due to an incomplete year in 2003, we only present monthly and annual means and totals from 1 January 2004 to 31 December 2013. The instrumentation at the site is summarised in Table 1.

Instrumentation of a high elevation remote site like this requires robust equipment and some inevitable compromises in design. Measuring precipitation in these conditions is particularly challenging because of the effects of wind and snow. The rain gauge at this station is not heated as it was considered that this could result in overcatch from drifting snow. This does however mean that there is potential undercatch and apparent shifts in precipitation timing during snowfall periods. Similarly it was not practicable to install a turf wall at the site so there is potential undercatch due to wind. Relative humidity at the site is measured using a capacitance probe. These instruments suffer reduced accuracy at very high humidity which is relevant at this site because of the prevalence of cloudy and foggy conditions. Despite these limitations the data presented here are the first detailed daily record available in this upland locale and provide a useful meteorological baseline for a landscape which is potentially highly sensitive to future climate change.

Data processing and gap filling

Within the UNG weather record there are a number of missing data in the record (approximately 65 – 90% of daily UNG data were complete), either individual missing data points or larger portions of time. The data gaps relate to periods where there was instrument failure or where conditions prevented timely manual download of the data, both leading to loss of all data for a period of time i.e. all parameters for an entire day. Such situations are to be expected for remote upland sites and therefore a systematic approach to gap filling to create a reliable long term record is required.

The data gaps in this record were filled through benchmarking to nearby meteorological stations, a common approach in gap-filling weather data (e.g. Holden and Rose, 2011). Three nearby stations (Holme Moss, Emley Moor, and Hollowford) were used for infilling different periods of time due to data gaps over different periods of time (Table 2). Up to six core parameters were taken from these sites: air temperature, relative humidity, solar radiation, wind speed, wind direction, and precipitation.

This paper uses the complete overlapping datasets to derive linear least-squares regression curves that can be used to the missing data periods (Box 1). Gap-filling equations were based on daily means rather than hourly data as residuals were much smaller than for hourly data. The regression for precipitation was forced through the origin in order to reduce the likelihood of over/under predicting zero precipitation days; this approach was used for all precipitation gap filling regressions. Box 1 details the various relationships between UNG and nearby stations.

Neighbouring stations

The nearby meteorological station at Holme Moss was used for the majority of the gap filling (Table 2). This site, operated by the School of Earth, Atmospheric and Environmental Sciences, University of Manchester, lies approximately 10 km north from UNG at an altitude of 525m.

Although most of the gaps were infilled using Holme Moss, there were still a number of gaps in the UNG data. Remaining gaps in the precipitation and temperature record between January 2004 and December 2008 inclusive were filled using relationships (Box 1) with the Emley Moor meteorological station selected from the Met Office Integrated Data Archive System at British Atmospheric Data Centre (Table 2). No data were available for solar radiation, wind speed and direction, and relative humidity.

For the gaps in the record between 2010 and 2013 an alternative station was used for gap-filling equations (Box 1). An alternative station at Hollowford Education Centre in Castleton in the Hope Valley, Peak District (Table 2), was used instead where data were available from March 2010 to December 2013 inclusive.

Derived relationships

Soil temperatures (at 5 cm and 10 cm depth) and net radiation are also monitored at UNG but these parameters are not measured at other stations. In the case of soil temperature, it is not appropriate to create correlations to other sites given the local variability of soil thermal properties (e.g. Usowicz *et al.*, 1996) and thus air-soil temperature relationships. Equally for net radiation, local differences in albedo, combined with the scarcity of reliable net radiation data, means that it is often estimated from relationships with incoming solar radiation e.g. Alados *et al.*, 2003). Therefore, in order to fill the gaps in these parameters site-specific relationships were derived from the UNG dataset (Box 1). For net soil temperature (at 5 and 10 cm), relationships were derived from overlapping data in the UNG data *prior* to any gap filling. These site-specific relationships were then applied to the UNG data set *including* any gap-filled data. Equally for net radiation, a relationship between solar radiation and net radiation was calculated on the UNG data before being applied to the overall gap-filled data (Box 1). Between 10 and 18% of the dataset for soil temperatures and net radiation were derived from these relationships (Table 3).

Limitations

The gaps in the original dataset were principally due to technical challenges in this environment; however, the gaps may not be random. To test whether the gaps were non-random, we compared the original data against those values patched into the dataset. Assuming gaps are randomly distributed across all conditions, we should see no significant difference between distributions using a t-test. There were no significant differences found for air temperature or soil temperature at 5cm; however, there were significant differences ($p<0.05$) for all other parameters (%RH, solar and net radiation, wind speed and direction, precipitation and soil temperature at 10 cm). The patched data had higher mean values for solar and net radiation, and soil temperature at 10cm and lower mean values for %RH, wind speed, and precipitation (Table 4). We might infer that stable high pressure systems are overrepresented in the gap-filled portions of the dataset. So there is a caveat that if there are errors in the gap filling they will slightly disproportionately affect these stable high pressure conditions. However, the gap filling correlations are statistically robust and that whilst the t-tests are significant the absolute difference in the means is in most cases very small (Table 4), so that if there is bias it is minor.

After gap filling from Holme Moss, Emley Moor or Hollowford, and derived relationships for soil temperature and net radiation, there were some remaining gaps in the data; however, these constitute a small proportion of the dataset (between 0.1% and 4.7%; Table 3) and as such should have little influence over the decade-long dataset.

Whilst we acknowledge that there are limitations with these approaches e.g. correlation of parameters over a large spatial distance, the challenges of collecting data in remote and hostile environments mean that some gaps in the data are inevitable. Whilst correlation at distance is not a perfect solution, it does offer a reasonable approach to developing multi-annual records in these environments. The gap-filling was applied using daily values and used to derive monthly and annual means. Diurnal variations and timing of synoptic conditions means that extrapolation is likely to be unreliable for sub-daily events and no attempt has been made to do this.

Seasonal comparisons

Comparison to Central England Temperature record

The particular value of upland meteorological records lies in their relative rarity and the potential that upland sites may have enhanced sensitivity to climate change (Giorgi *et al*., 1997). Holden and Rose (2011) reported seasonal variation in the pattern of upland-lowland temperature differentials from sites in the North Pennines. In this context the data from this study were analysed against the Central England Temperature (CET, Parker *et al*., 1992) record to assess any seasonal differences between UNG and CET.

Seasonal differentials

In order to look at seasonal weather variability, the temperature and precipitation data were aggregated into seasonal means where: Spring = March, April, May (MAM); Summer = June, July, August (JJA); Autumn = September, October, November (SON); Winter = December, January, February (DJF). Only complete seasons were included in the analysis e.g. winter 2013-14 was excluded.

Z-scores for both precipitation and temperature were calculated for each season with reference to the mean and standard deviation of that season from the 10-year dataset. For example, summer 2004 precipitation *z*-score is calculated as:

$$z = \frac{Summer\ 2004\ precipitation - Mean\ of\ all\ Summer\ precipitation\ in\ 10\ year\ period}{Standard\ deviation\ of\ all\ summer\ precipitation\ in\ 10\ year\ period}$$

The precipitation and temperature *z*-scores (i.e. normalised seasonal deviations) were then plotted to look at the changes in the seasonal weather patterns.

Results and Discussion

Table 5 presents the summary of the meteorological data (monthly and annual means) from Upper North Grain for the period 1 January 2004 – 31 December 2013. It is worth noting that while there are limitations with the instrumentation and gap-filling process (noted in Methods) this is the first detailed record for this important upland site.

The site has a mean annual temperature of 6.9°C, with a monthly mean temperature range of 1.6 – 13.2 °C (Table 5). The extreme values were 22.2°C on 9 August 2003 and -8.0°C on 20 December 2010. . For the 10 year period daily temperature minima are not extreme given the elevation of the site. This most likely reflects the elevated position of the station which is unlikely to be impacted by cold air drainage. Relative humidity at the site is characteristically high with monthly means close to 90% in all months. Monthly minima are above 50% in all months except February and March. These observations are consistent with a wet peatland site with frequent fog. Price (1992) has observed that in Newfoundland blanket peatlands occult precipitation (e.g. fog drip) can add 10-18% additional inputs to the water balance compared to precipitation measured in a rain gauge.

A simple regression of the UNG and CET datasets showed a significant relationship ($UNG = 0.942\,CET - 2.58$, $r^2 = 0.991$, $n = 129$, $p < 0.001$). The monthly variation in this difference, however, is not constant throughout the year (Figure 3). Spring and summer temperatures are approximately 3.4°C cooler than the CET. However, autumn and winter differences are on average 3.2°C and 2.8°C cooler respectively. A one-way ANOVA shows that the UNG-CET temperature residuals are significantly different between winter and all other seasons ($p < 0.001$), and also between summer and autumn ($p = 0.045$). This shows that differences between CET and UNG temperatures are smaller in autumn and winter compared to spring and summer, implying smaller mean lapse rates. This may be due in part to the increased frequency of inversions in winter months leading to lower temperatures at lower altitudes.

Average measured annual precipitation at UNG is around 1313 mm (Table 5), which is lower than those upland sites further north in the Pennine chain (e.g. Holden and Rose, 2011). Daniels *et al*. (2008) report average precipitation from the UK Meteorological Office site at Featherbed Top, which is close to this site and has a similar elevation, as 1554mm (average for 1964-2004). Featherbed Top site is a monthly read, turf banked gauge so that the ~18% difference may reflect the potential undercatch associated with wind driven rain and snow at Upper North Grain. It should also be noted that precipitation is potentially highly spatially variable so that whilst the gap filling is statistically robust, the detailed of the precipitation record in gap filled areas is subject to some uncertainty.

Average monthly precipitation is between 71 and 149 mm (Table 5) with the spring months (March, April, May) having the lower precipitation totals; around 30% of the annual precipitation falls during the autumn months (September, October, November). Most (54) daily precipitation totals are <1 mm and 76% of all daily totals are less than 5 mm (Figure 4). Large daily precipitation totals (largest daily total 95mm, 25 June 2007) and high hourly precipitation totals (23 mm fell within one hour, 14 July 2010) occur at UNG, often associated with convective summer precipitation events. Further detailed hydro-meteorological analysis of the UNG catchment is required to look at relative importance of intense precipitation events in relation to river discharge and erosion events.

The vector daily mean wind direction was calculated using Oriana 4.02 circular statistics software package, whilst mean wind speeds were calculated as scalar values. Over the period mean daily wind direction was 254° (WSW) and is aligned to the UK prevailing wind direction, though as Lapworth and McGregor (2008) discuss, there is considerable seasonal variation in the prevailing UK wind direction. There is a moderate relationship (circular-linear correlation r = 0.344, p <0.0001) between daily mean wind speed and wind direction, with a tendency for stronger winds from the west and southwest (Figure 5). January 2007 had the highest monthly average wind speed at 8.5 m s^{-1} with a mean wind direction of 275°, whilst the highest daily mean wind speed of 14.7 m s^{-1} had a mean wind direction of 238° (7 January 2012).

By plotting the normalised temperature or precipitation deviations (i.e. seasonal *z*-scores) (Figure 6) it is possible to identify four quadrants of climatic conditions relative to each seasonal norm: ‘cool and wet’; ‘cool and dry’; ‘warm and wet’; ‘warm and dry’. Each quadrant has at least one of the seasons present, except for ‘warm and wet’, where no summer fell into this class. For summers, cool summers tend to be wet, whilst warm summers tend to be dry (Figure 6). Equally in the winter data, warm winters tends to be wet, with cool winters tending to be drier (Figure 6).

Another way of considering the data is to identify extreme seasons within the dataset. If we consider the 2 *z*-score distance to represent a boundary describing approximately 95% of the data, then any season that lies outside ±2 *z*-scores distance from the origin (0, 0) could be considered an extreme event. As each point has an *x* and *y* axis distance, simple trigonometry yields the distance from the origin. Using two as the threshold value, four seasons stand out from the dataset (*z*-score, mean temperature, and total precipitation; condition): summer 2006 (2.2; 14.1°C; 153.0mm; warm and dry); winter 2009-10 (2.0; -0.44°C, 233.4mm; cool and dry); summer 2012 (2.2; 11.6°C; 643.2mm; cool and wet); spring 2013 (2.3; 3.3°C; 225.3mm; cool and dry).

Summary

The data presented in this study give a decade-long insight into meteorological conditions at a well-studied upland research catchment. Whilst acknowledging the limitations with the gap-filing approach, these data, covering the first decade of operation of the weather station, are an important baseline for continuing observation and which adds to the limited stock of high elevation observations across the UK.

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Box 1. Gap filling equations for Upper North Grain

Gap filling from Holme Moss

$UNG_{AirTemp} = 1.0002 \times HolmeMoss_{AirTemp} + 0.4199$ ($r^2 = 0.992$, $p < 0.0001$, $n = 2289$)

$UNG_{RH} = 0.8800 \times HolmeMoss_{RH} + 11.859$ ($r^2 = 0.890$, $p < 0.0001$, $n = 2298$)

$UNG_{Solar} = 0.8644 \times HolmeMoss_{Solar} + 1.4185$ ($r^2 = 0.924$, $p < 0.0001$, $n = 2298$)

$UNG_{WindSpeed} = 0.6301 \times HolmeMoss_{WindSpeed} + 0.4351$ ($r^2 = 0.888$, $p < 0.0001$, $n = 1902$)

$UNG_{WindDir} = 0.7551 \times HolmeMoss_{WindDir} + 55.96$ ($r^2 = 0.452$, $p < 0.0001$, $n = 2015$)

$UNG_{Precipitation} = 0.6537 \times HolmeMoss_{Precipitation}$ ($r^2 = 0.589$, $p < 0.0001$, $n = 1951$)

Gap filling from Emley Moor

$UNG_{AirTemp} = 0.9484 \times Emley\ Moor_{AirTemp} - 1.6423$ ($r^2 = 0.957$, $p < 0.0001$, $n = 1137$)

$UNG_{Precipitation} = 0.9972 \times Emley\ Moor_{Precipitation}$ ($r^2 = 0.514$, $p < 0.0001$, $n = 843$)

Gap filling from Hollowford

$UNG_{AirTemp} = 0.9866 \times Hollowford_{AirTemp} - 2.5356$ ($r^2 = 0.969$, $p < 0.0001$, $n = 1221$)

$UNG_{RH} = 0.8580 \times Hollowford_{RH} + 21.770$ ($r^2 = 0.656$, $p < 0.0001$, $n = 1222$)

$UNG_{Solar} = 0.7683 \times Hollowford_{Solar} - 1.046$ ($r^2 = 0.870$, $p < 0.0001$, $n = 1168$)

$UNG_{WindSpeed} = 0.5247 \times Hollowford_{WindSpeed} + 2.0595$ ($r^2 = 0.726$, $p < 0.0001$, $n = 1222$)

$UNG_{WindDir} = 0.7742 \times Hollowford_{WindDir} + 36.345$ ($r^2 = 0.629$, $p < 0.0001$, $n = 1222$)

$UNG_{Precipitation} = 1.3784 \times Hollowford_{Precipitation}$ ($r^2 = 0.509$, $p < 0.0001$, $n = 1222$)

Derived relationships

$Soil\ temperature_{5cm} = 0.874 \times Air\ Temperature + 1.40$ ($r^2 = 0.887$, $p < 0.0001$, $n = 3728$)

$Soil\ temperature_{10cm} = 0.888 \times Air\ Temperature + 1.33$ ($r^2 = 0.896$, $p < 0.0001$, $n = 2967$)

$Net\ radiation = 0.623 \times Solar\ radiation - 13.3$ ($r^2 = 0.849$, $p < 0.0001$, $n = 3234$)

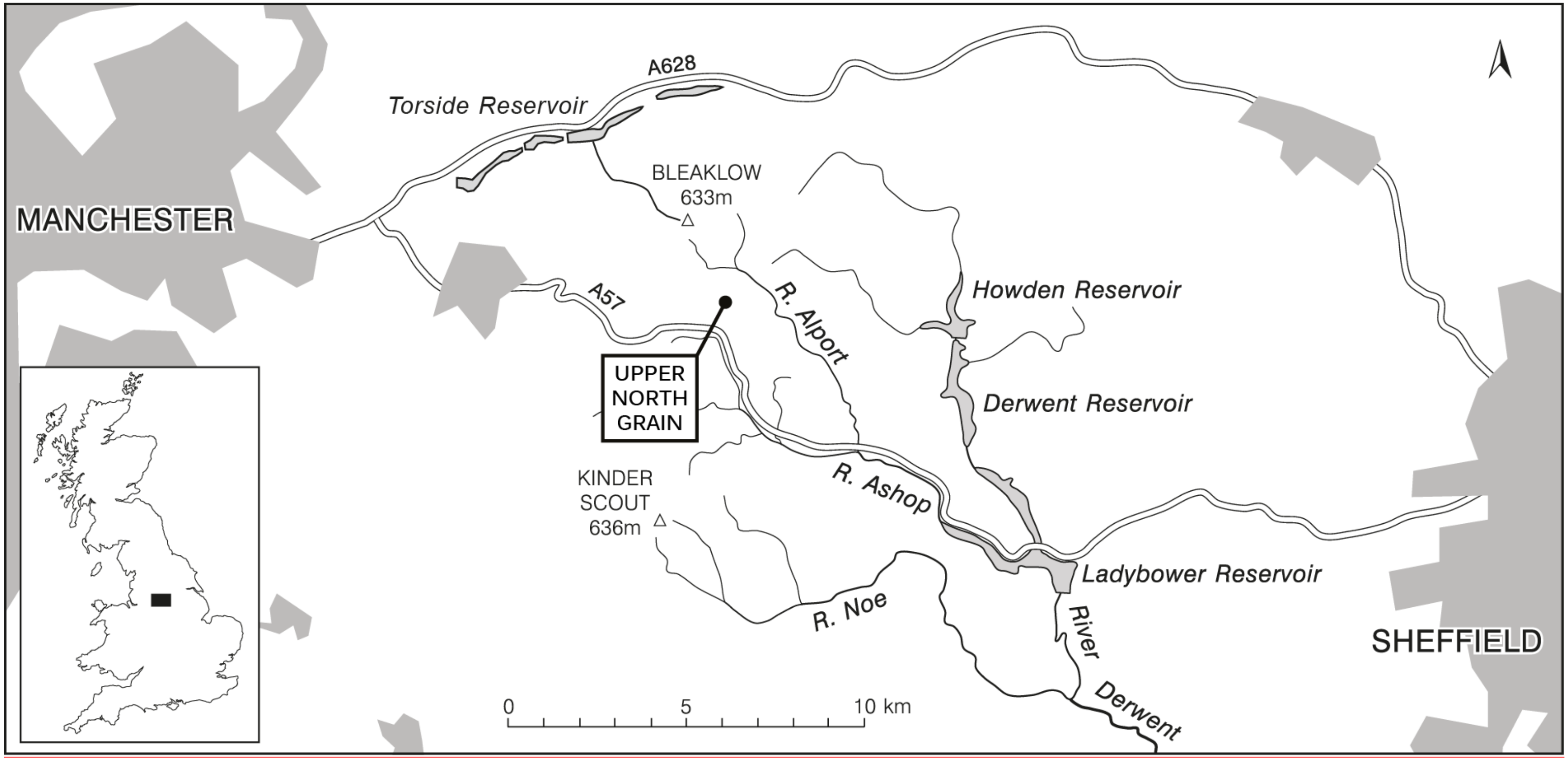

Figure 1. Location of the Upper North Grain catchment in a regional context.

Figure 2. The Upper North Grain weather station.

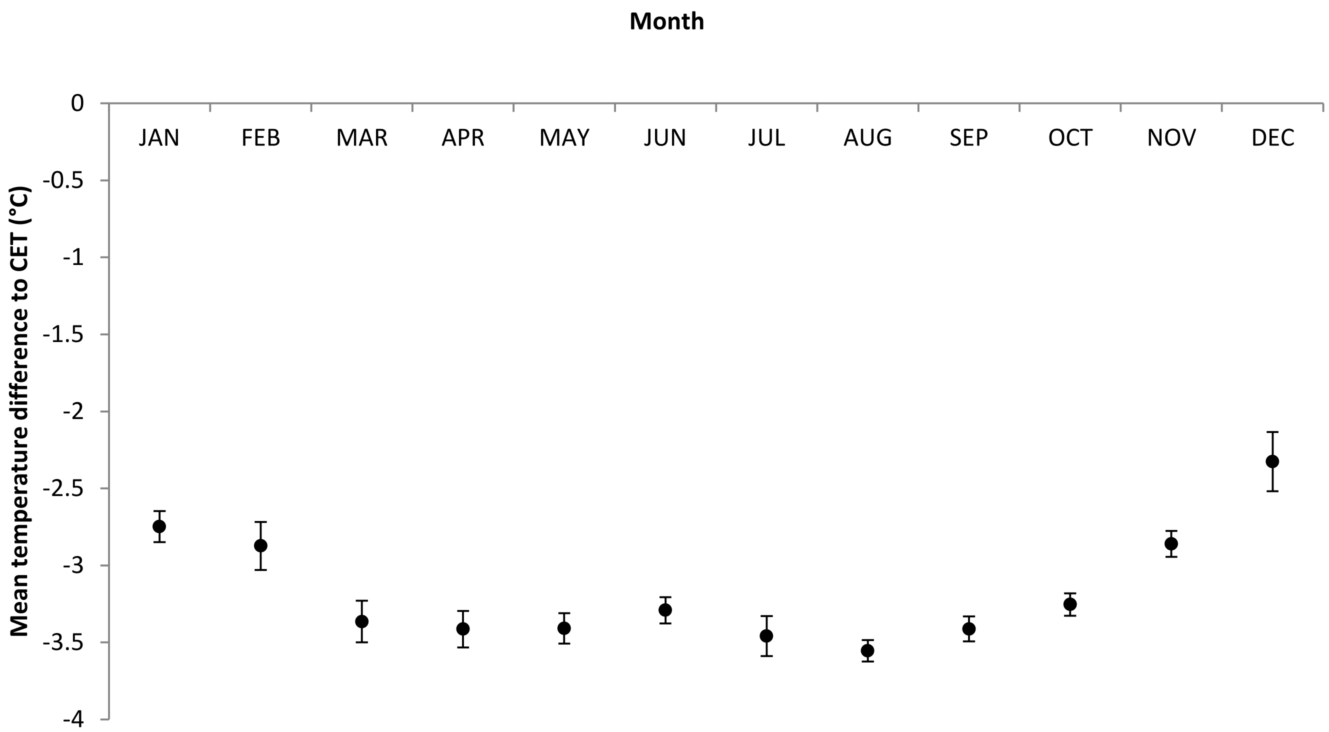

Figure 3. Mean (± standard error) monthly temperature difference to Central England Temperature record for the Upper North Grain catchment.

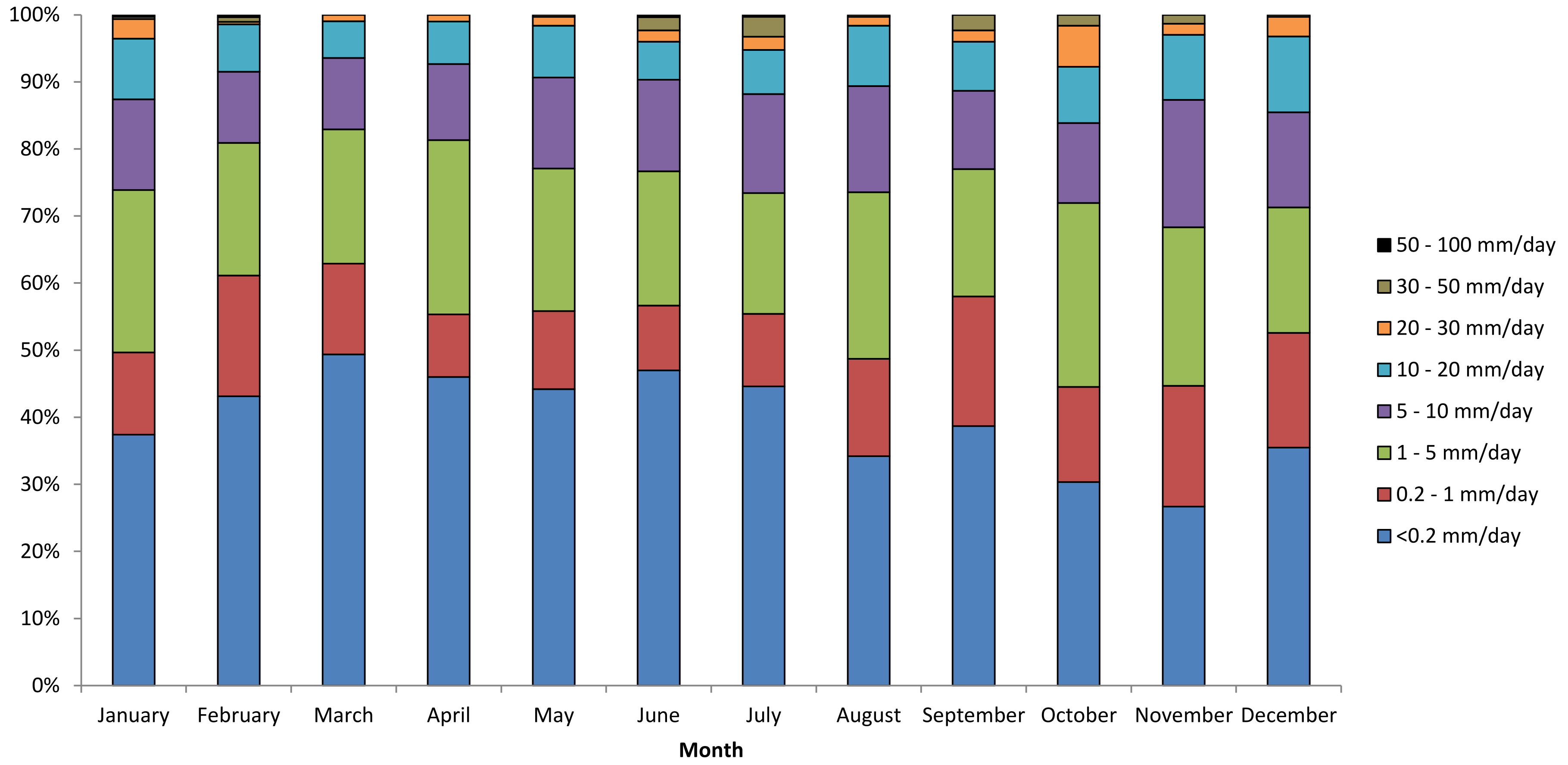

Figure 4. Proportion of daily precipitation totals for each precipitation intensity class for each month.

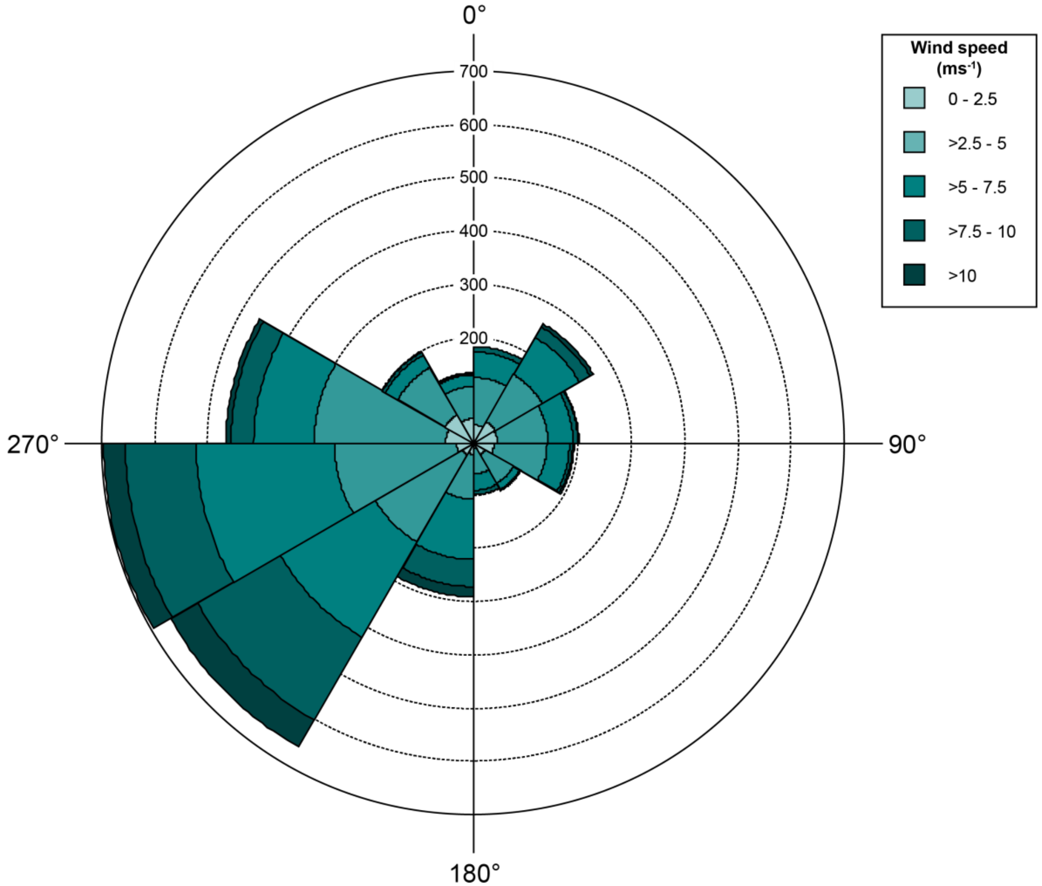

Figure 5. Daily mean 2m wind speed (ms^{-1}) for each 30° sector of wind direction over the period (2004-2013), n = 3468

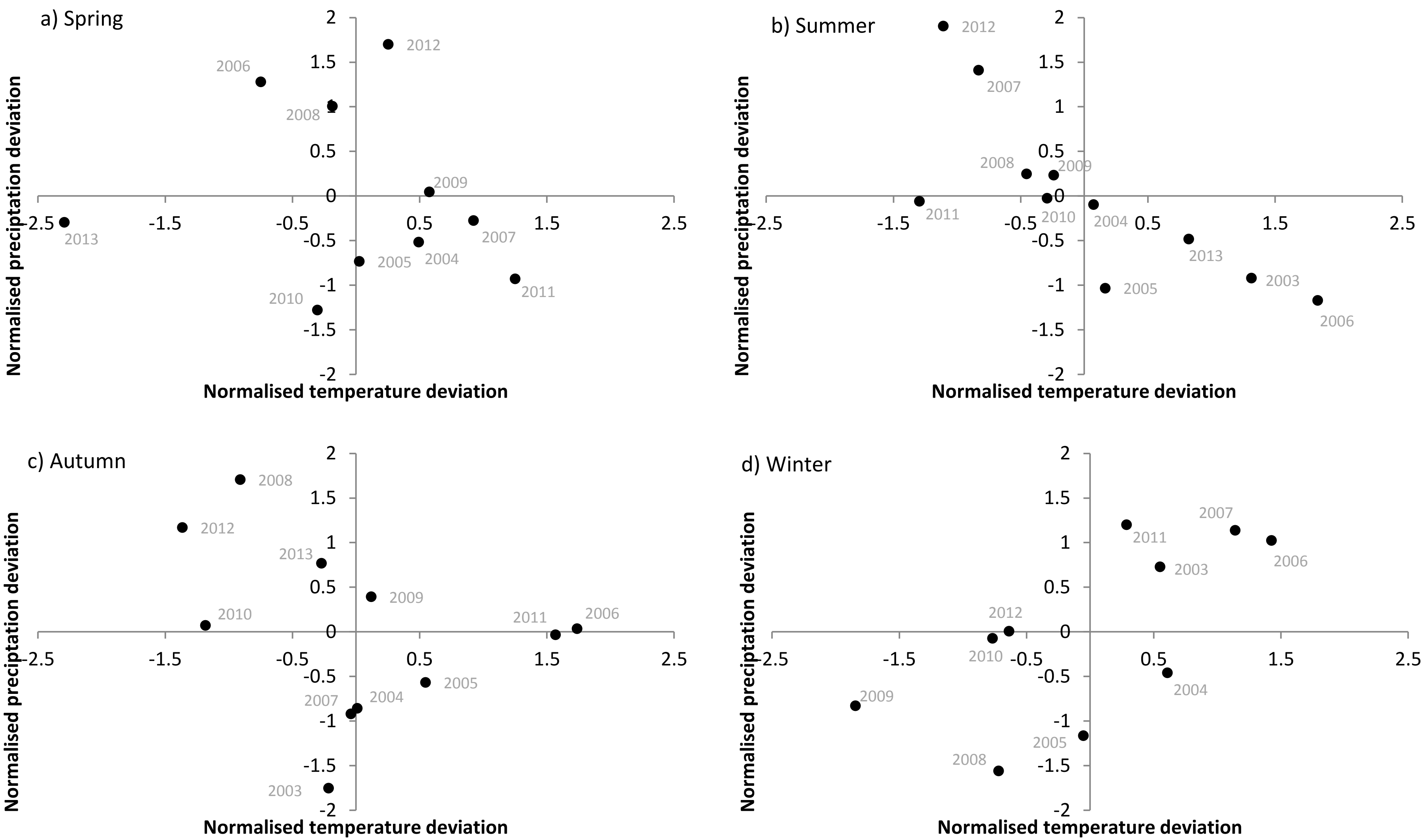

Figure 6. Seasonal temperature and precipitation deviations. Top panel – a) Spring b) Summer; Bottom panel – c) Autumn, d) Winter

Parameter	Instrument	Technology	Accuracy	Specification
Temperature (Measured at 1.2m, also soil temperature measured at 5 and 10 cm depth)	Skye Instruments Temperature Probe	Thermistor	± 0.2°C	Range -40°C - +60°C
Relative Humidity	Skye Instruments RH probe	Capacitance	± 2%	0-100% response time < 10 seconds (10-95%)
Precipitation	ARG 100 Tipping Bucket Raingauge	Tipping bucket	0.2 mm tip	254mm diameter 340mm rim height
Wind Speed (measured at 2m)	Vector Instruments A100R Anenometer	Switching Anenometer	± 0.1 m/s	150mm diameter 3 cup rotor
Wind Direction (measured at 2m)	Vector Instruments W200/P Wind Vane	Potentiometer	± 2°	
Net Radiation	Kipp and Zonen NR Lite radiation sensor	Thermopile	< 10%	0.2-100 µm Sensitivity 10 $\mu vW^{-1}m^{-2}$
Solar radiation	Skye instruments Pyranometer (measuring global solar radiation on a horizontal surface)	Silicon Photocell	< 3%	400-1100 nm response 0-5000 Wm^{-2}

Table 1. Summary of instrumentation at the Upper North Grain Weather Station. Parameters from each instrument are recorded hourly. Wind speed measurements are hourly averages of readings taken every 30 seconds. All other measures are hourly point readings. Instrument parameters as supplied by manufacturers. Instruments were newly calibrated when installed in 2003 and since 2006 calibrated and serviced approximately annually.

Meteorological station	**Latitude/Longitude**	**Altitude (m)**	**Approximate distance from UNG (km)**	**Periods used in gap-filling**	**Parameters used**					
					Temperature	**Precipitation**	**Relative humidity**	**Solar Radiation**	**Wind speed**	**Wind direction**
Holme Moss	N 53.533, W 1.857	525	10	1 April 2003 – 7 March 2012	✓	✓	✓	✓	✓	✓
Emley Moor	N 53.617, W 1.667	267	23	1 January 2004 – 31 December 2008	✓	✓	×	×	×	×
Hollowford	N 53.349, W 1.780	210	10.5	1 March 2010 – 31 December 2013	✓	✓	✓	✓	✓	✓

Table 2. Summary of meteorological stations used in the gap-filling. Much of the data was infilled using Holme Moss but gaps in this data meant that Emley Moor and Hollowford were also used at various points. Those parameters available at each station are noted.

	Meteorological parameter								
	Air temperature	**Precipitation**	**Relative humidity**	**Solar radiation**	**Wind Speed**	**Wind Direction**	**Net radiation**	**Soil temperature (5 cm)**	**Soil Temperature (10 cm)**
UNG data prior to gap-filling	3279 (83.6)	2564 (65.4)	3289 (85.0)	3236 (83.8)	3227 (83.7)	3289 (87.7)	3488 (90.3)	3238 (82.5)	3505 (89.3)
Data from gap-filling	644 (16.4)	1359 (34.6)	582 (15.0)	626 (16.2)	628 (16.3)	462 (12.3)			
Data from derived relationships							374 (9.7)	685 (17.5)	418 (10.7)
Total dataset	3923	3923	3871	3862	3855	3751	3862	3923	3923
Missing data	5 [0.1]	5 [0.1]	57 [1.5]	66 [1.7]	73 [1.9]	177 [4.7]	66 [1.7]	5 [0.1]	5 [0.1]

Table 3. Number of daily observations for core and derived parameters at Upper North Grain (UNG) and for each stage of the gap-filing process. Figures in parentheses are the proportion of the total dataset. Figures in square brackets are represent the percentage of missing data from the overall period (1 April 2003 to 31 December 2013; 3928 days).

Original data only									
	Mean air temperature (°C)	**Mean soil temperature at 5 cm depth (°C)**	**Mean soil temperature at 10 cm depth (°C)**	**Mean daily precipitation (mm)**	**Mean relative humidity (%)**	**Mean solar radiation ($W\ m^{-2}$ / $MJ\ m^{-2}\ day^{-1}$)**	**Mean net radiation ($W\ m^{-2}$ / $MJ\ m^{-2}\ day^{-1}$)**	**Mean wind speed ($m\ s^{-1}$)**	**Mean wind direction (°)**
Mean	6.89	7.38	7.21	3.86	92.48	81.60 / 7.05	38.65 / 3.34	5.19	264.78
Standard deviation	4.98	4.60	4.69	6.60	8.36	69.30 / 5.99	48.07 / 4.15	2.42	82.28
Patched data only									
	Mean air temperature (°C)	**Mean soil temperature at 5 cm depth (°C)**	**Mean soil temperature at 10 cm depth (°C)**	**Mean daily precipitation (mm)**	**Mean relative humidity (%)**	**Mean solar radiation ($W\ m^{-2}$ / $MJ\ m^{-2}\ day^{-1}$)**	**Mean net radiation ($W\ m^{-2}$ / $MJ\ m^{-2}\ day^{-1}$)**	**Mean wind speed ($m\ s^{-1}$)**	**Mean wind direction (°)**
Mean	7.26	7.74	8.28	2.99	90.57	91.08 / 7.87	43.61 / 3.77	4.71	201.35
Standard deviation	5.79	5.06	4.87	5.61	8.82	80.04 / 6.92	49.93 / 4.31	2.48	61.31

Table 4. Mean and standard deviations of original and patched data for each meteorological parameter (2004 – 2013).

Month	Mean air temperature (°C)	Mean soil temperature at 5 cm depth (°C)	Mean soil temperature at 10 cm depth (°C)	Mean total precipitation (mm)	Highest daily precipitation totals (mm)	Mean relative humidity (%)	Lowest daily relative humidity (%)	Mean solar radiation ($W m^{-2}$ / $MJ m^{-2} day^{-1}$)	Mean net radiation ($W m^{-2}$ / $MJ m^{-2} day^{-1}$)	Mean wind speed ($m s^{-1}$)	Mean wind direction (°)
January	1.9	2.5	2.6	120	51	97	65	17 / 1.47	-4 / -0.35	6.1	243
February	1.6	2.3	2.3	81	55	95	28	39 / 3.37	6 / 0.52	5.1	266
March	2.9	3.4	3.4	71	27	92	39	75 / 6.48	29 / 2.51	5.4	254
April	5.7	6.0	6.2	82	29	88	57	117 / 10.11	60 / 5.18	4.9	248
May	8.4	8.9	9.1	95	36	87	54	148 / 12.79	82 / 7.08	4.9	275
June	11.4	11.9	12.2	113	95	87	53	162 / 14.00	96 / 8.29	4.3	260
July	13.2	13.6	13.7	129	55	88	53	152 / 13.13	89 / 7.69	4.2	240
August	12.7	13.3	13.2	111	42	91	60	120 / 10.37	67 / 5.79	4.4	254
September	10.9	11.4	11.3	111	43	92	63	90 / 7.78	45 / 3.89	5.1	252
October	8.1	8.6	8.5	149	47	95	56	46 / 3.97	16 / 1.38	5.3	231
November	4.4	4.9	4.8	128	49	96	70	23 / 1.99	-4 / -0.35	5.7	271
December	2.1	2.5	2.5	122	34	97	63	15 / 1.30	-9 / -0.78	5.7	266
Annual	6.9	7.4	7.5	1313	95	92	28	84 / 7.26	40 / 3.46	5.1	254

Table 5. Monthly and annual means for meteorological data at Upper North Grain, 1 January 2004 – 31 December 2013.