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CLIMATE RESEARCH
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Deviation between projected and observed precipitation trends greater with altitude

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ABSTRACT: Variation in the amount and intensity of precipitation is one of the most important factors determining how biological systems respond to anthropogenic climate change. Moreover, given the importance of climate projections for influencing (inter)national policy, there is a pressing need to contextualise contemporary projections with observed trends to better inform environmental strategy and planning. In this study, we examine trends from one of the longest paired time series of upland (>300 m a.s.l.) and lowland precipitation records (1879–2012), and shorter-term observations (1961–2015) from multiple upland locations in southwestern (SW) England (Dartmoor National Park). In the period 1879–2012, total precipitation at the upland site increased by more than 10 % for spring, autumn, winter and annually; at the lowland site, only spring experienced a significant increase (8 %) in precipitation. Increases in autumn, winter and annual precipitation were recorded at upland sites since the 1960s. We compare observed precipitation trends with the latest UK climate projections (UKCP18) for the region across 2 timeframes (60 and 90 yr). Changes in the 30 yr average between reference (1981–2010) and observed and projected precipitation totals were compared and deviations calculated. Comparisons between model projections and observed trends show large deviations for spring, summer and autumn precipitation in the mid- to late 21st century, with the deviation greatest in upland localities. However, winter projections were broadly consistent with observed trends. Our results suggest that uncertainties in future precipitation change are greatest in the uplands, where the impacts on ecosystem services are the largest.

KEY WORDS: Upland ecosystems · UKCP18 · Precipitation trends · Ecosystem Services · Global change biology · Western Europe

1. INTRODUCTION

Upland areas (>300 m a.s.l.) cover around one-third of the UKs land area, and are considered of national and international importance due to their biodiversity and cultural heritage (Reed et al. 2009). In southwestern (SW) England, regionally (i.e. NW Europe) important habitats such as upland heathland, Atlantic oak woodland and blanket bog are associated with the upland granite plateaus of Dartmoor and Exmoor National Parks (JNCC 2019). These areas are vital for important ground-nesting birds such as the ring ouzel *Turdus torquatus*, dunlin *Calidris alpina* and golden plover *Pluvialis apricaria* (Mercer 2009, DNPA 2019) and the conservation of globally significant lichen and bryophyte communities (Lamacraft et al. 2018).

Understanding precipitation change in the UK uplands is particularly important. These areas are integral for the delivery of multiple provisioning, regulating and cultural services (Holden et al. 2007, Curtis et al. 2014), being the source of 68 % of the UK's freshwater (Van der Wal et al. 2011) and an estimated 40 % of UK soil carbon stocks (Bradley et al. 2005). UK upland landscapes may provide significant future carbon farming opportunities (Brockett et al. 2019, Lunt et al. 2019).

Levels of precipitation in the SW uplands are over twice the average for UK lowland sites (Burt & Hol-

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den 2010, Perry 2014). Changes in precipitation patterns and distribution are significant because rainfall, more than any other climatic variable, has the greatest effects on below-ground carbon storage and plant species growth and composition (Collins et al. 2018, Lunt et al. 2019). This is particularly critical for SW England, where blanket bogs are considered climatically marginal (Clark et al. 2010).

Changes in precipitation can change the distribution of semi-natural plant communities via soil moisture (Morecroft et al. 2009, Cowles et al. 2018), particularly vital during the 'growing season', between spring and autumn for northern European blanket mire (March–October) and Atlantic oak woodland habitats (April–September). Reduced precipitation is associated with lower viability of sphagnum and bryophyte communities (Ellis 2015) and is a contributing factor for oak (*Quercus* spp.) decline (Thomas 2008, Sohar et al. 2014).

Increases in precipitation are associated with surface run off and considerable downstream infrastructure damage and crop losses via flooding (Collaku & Harrison 2002, Schaller et al. 2016). The economic and social costs are significant; the UK summer floods of 2007 for example, incurred an estimated £3.2 billion (€3.7 billion) in economic losses (Chatterton et al. 2010), and the wet winter of 2013/2014 between £1 and 1.5 billion (Chatterton et al. 2016). Impacts are likely to be greatest in higher-elevation areas, where total precipitation is higher, soils are poorer, and agricultural productivity is marginal (Reed et al. 2009, Burt & Holden 2010, Short & Dwyer 2012). The exceptionally wet summer of 2012 was associated with high economic costs to UK upland agriculture; severe rumen fluke outbreak was reported in livestock for the first time (Gordon et al. 2012). As a result, total productivity fell by 3.2%, the largest single year fall since records began in 1973 (Morison & Matthews 2016).

In the UK, the frequency of precipitation is largely determined by the position of the jet stream, pressure patterns in the NE Atlantic and the movement of extra-tropical cyclones over the North Atlantic (Lavers et al. 2013). The jet stream helps determine the position of atmospheric rivers (ARs), which are narrow ribbons (300 km) of atmospheric vapour, transporting moisture from the tropics to mid latitudes. ARs are responsible for the majority of rainfall events in Western Europe and are connected with extreme winter precipitation and flood events in the UK (Lavers et al. 2011).

In the summer months, the position of the jet stream over the UK can be predicted by spring North Atlantic sea surface temperatures (SSTs), with warm spring SSTs associated with a higher probability of wet summer weather (Ossó et al. 2018). De-trended averaged North Atlantic SSTs, known as the Atlantic Multi-decadal Oscillation index (AMO), naturally oscillate from positive to negative states at a periodicity of 60 yr (Knudsen et al. 2011). A positive AMO is associated with more storms tracking across the Atlantic to the UK and into northwestern Europe, leading to wet summers in these regions (Dong et al. 2013).

Rising temperatures are projected to result in increased precipitation during existing rainfall events due to increased water-holding capacity of the atmosphere, as predicted by the Clausius-Clapeyron equation (Held & Soden 2006, Rajczak & Schär 2017). On current projections, parts of SW England are expected to experience some of the greatest climate changes within the UK. SW England is set to be the first UK region to experience extreme winter rainfall associated with anthropogenic climate change (Fowler & Wilby 2010). Winter projections suggest median increases in winter precipitation of 10–20% in areas of the region under all climate change scenarios (RCP2.6, 4.5, 6.0, 8.5) by 2040–2059, according to the latest UK Met Office (UKCP18) probabilistic projections (Murphy et al. 2018). Projections are linked to expected changes in the North Atlantic winter storm track (Zappa et al. 2013) and to a greater magnitude and frequency of winter storms along Atlantic European coasts, leading to higher rainfall totals and greater winter flooding (Lavers et al. 2011, 2013, Ramos et al. 2016).

Summer projections suggest median reductions of 20–30% in parts of the region under all climate change scenarios by 2040–2059 (Murphy et al. 2018), linked to positive summer North Atlantic Oscillation (NAO) (Belleflamme et al. 2015) and associated with increased prevalence of anti-cyclonic pressure systems and below-average precipitation. High-resolution (convection permitting) modelling also suggests that heavier rainfall events are likely in the summer (Kendon et al. 2014). The lowest confidence projections are for summer precipitation (Rowell 2006, Murphy et al. 2018), particularly in 'upland' regions (>300 m a.s.l.) where seasonal variation in rainfall gradients and lapse rates challenge upland climate projections. Moreover, although upland areas cover around one-third of the UK land area, they contain less than 10% of UK climate recording stations (Burt & Holden 2010).

Considering the recent release of UKCP18 land projections (Murphy et al. 2018), the importance of changes in upland precipitation and the likely use of projections in conservation and land management decisions, there is a pressing need to contextualise projected changes in seasonal precipitation with observed trends. The aim of this study was to scrutinise one of the longest running (1879–2012) ‘upland’ (Cowsic River, Dartmoor National Park) and ‘lowland’ (Plymouth) precipitation records in Western Europe, alongside shorter-term records from multiple upland sites. We evaluated long-term records for SW England in the context of recent model projections (Murphy et al. 2018) across 2 timeframes (2040–2069, 2070–2099), whilst assessing the nature and drivers of precipitation trends in this region. Results are likely to be important at a local scale within SW England, but also for upland coastal sites throughout the NE Atlantic.

2. METHODS

2.1. Climate data and quality control

Monthly precipitation totals were obtained from the UK Meteorological Office's (UKMO) Integrated Data Archive System database via the British Atmospheric Data Centre using the web processing service of the Centre for Environmental Data Analysis (Met Office 2012). Climate data were also obtained directly from the UK Environment Agency's Hydrometric Archive (Environment Agency 2018) (quality-controlled by the UKMO) and the UKMO National Meteorological Archive (Met Office 2018).

Due to the long-term nature of precipitation records, stations have experienced instrumentation and locational changes over the observation periods (Table A1 in the Appendix), with Plymouth and Princetown records subject to homogenization (Table 1), a potential source of inaccuracy (Zhang et al. 2014). To mitigate potential errors, all data were subject to rigorous UKMO onsite and off-site quality control procedures, which include: (1) basic point of observation checks; (2) input checks, ensuring values do not lie outside long-term climate extremes for the locality and time period; (3) checks against neighbouring stations for consistency; (4) flagged manual quality control correction; (5) final quality control sweep to eliminate remaining gross errors (Met Office 2018). Small gaps (<2%) in Plymouth and Princetown records were infilled using the UKMO gridded (5 km) observation datasets (Hollis & McCarthy 2017)

Seasons were divided as follows: spring (March, April, May), summer (June, July, August), autumn (September, October, November), winter (December, January, February; note that the winter season for the year includes December and the immediately following January and February of the following year). Annual change represents the 12 mo period from March (start of spring) to February (end of winter).

2.2. Study location

Climate records come from stations located in the SW peninsula of England (approximately 50° N) in Western Europe, an area characterised by its proximity to the North Atlantic Ocean and its temperate, largely mild, maritime oceanic climate (Perry 2014) (Fig. 1). Mean temperatures typically fall between 20 and 13°C in summer and between 8 and 4°C in winter. Annual precipitation totals are typically close to 1000 mm in lowland coastal areas of the region, but doubling in upland moorland areas such as Dartmoor National Park (DNP). Six upland precipitation records come from within DNP, an area dominated by a granite plateau, which forms the highest point (621 m a.s.l.) and largest open access area (953 km^2) in southern England (Mercer 2009). One lowland record (Plymouth) is located just outside DNP on the windward southwestern coast. UKCP18 25 km grid cells covering stations used in the observed vs. projected trend analysis were centred over latitude (° N), longi-

Table 1. Location of weather stations used in precipitation trend analysis with time period covered in the analysis. Data source: climate records as monthly precipitation totals from the UK Meteorological Office (Met Office 2012, 2018) and Environment Agency (2018)

Location (abbreviation)	Latitude (° N), Longitude (° W)	Elevation (m)	Period
Plymouth Mountbatten (PLY)[a]	50.3548, 4.1211	50	1879–2015
Cowsic Valley (COW)	50.5735, 3.9861	445	1879–2012
Deancombe Farm (DCF)	50.5015, 4.0058	309	1920–2012
Princetown (PRT)[a]	50.5485, 4.0014	433	1961–2015
Hurston Ridge (HRR)	50.6296, 3.8832	418	1961–2015
White Ridge (WHR)	50.6256, 3.9099	488	1961–2015
Double Waters (DBW)	50.5330, 4.0106	355	1961–2015

[a] Denotes use of multiple stations within same locality, use of correction factor (averaged divergence between stations) for overlapping periods to minimise specific locational differences by creating an homogenized record following standardised methodology (Burt & Holden 2010)

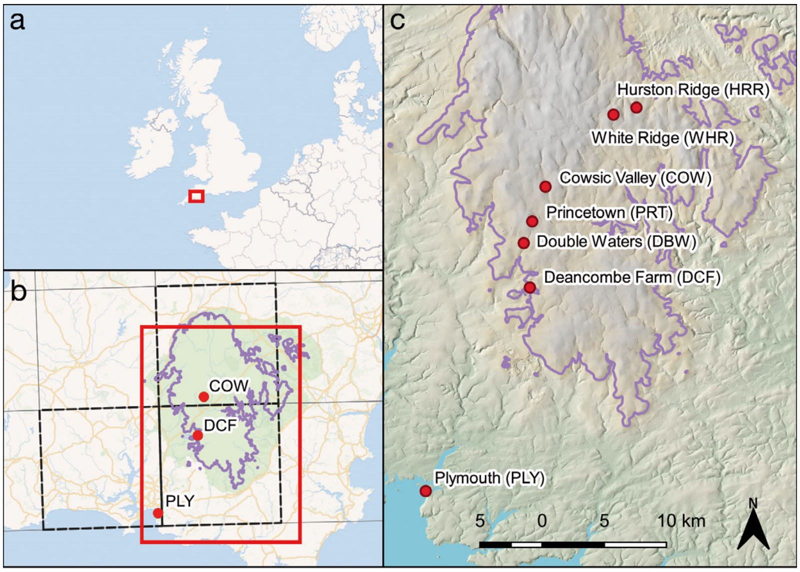

Fig. 1. (a) Location of study area (SW England) within NW Europe. (b) Locations of climate observation sites and UKCP18 25 km grid cells (black dashed lines) used in observed vs. projected trend analysis, with 300 m a.s.l. 'upland' isoline, and Dartmoor National Park denoted in green. (c) Locations of climate observation sites in reference to the 'upland' isoline

tude (°W) positions (climate stations): 50.439794, 4.2897746 (Plymouth), 50.670882, 3.9471840 (Cowsic Valley), 50.446188, 3.9379437 (Deancombe Farm).

2.3. Model projections

UKMO 25 km, horizontal resolution probabilistic climate projections (UKCP18) (Murphy et al. 2018) were accessed via the 'user interface' (Lowe et al. 2018). These projections are intended to represent a useful starting point for risk assessments, aimed to represent the uncertainty consistent in existing climate models combined with internal climate variability effects (Murphy et al. 2018). Probabilistic 'strand one' projections combine 3 Pertubed Parameter Ensembles (PPEs) (HadCM3) and 12 earth system multi-models (CMIP5) to produce broad ranges using a Bayesian statistical framework, and range wider than those derived from multi-model information in isolation (Sexton & Murphy 2012, Sexton et al. 2012, Harris et al. 2013). The 3-stage process (1) integrates HadCM3 PPEs and earth system models, (2) timescales model outputs (Sexton & Harris 2015) and (3) downscales projections (Murphy et al. 2018). Our analysis makes use of a 3000 member sub-sample taken from the 10^6 members produced in Stage 1. This subsample was accessed for each 25 km grid cell covering climate stations used in the analysis, and median change (%) for these grid cells was then calculated. These projections represent 'emissions–driven' projections and account for uncertainties under a range of climate change scenarios (Murphy et al. 2018).

Projections show expected change (%) in monthly precipitation totals (mm) between the reference 30 yr mean (1981–2010), and future 30 yr means for a range of future climate change scenarios represented by representative concentration pathways (RCPs). Probabilistic projections are available for a range of RCPs: 2.6, 4.5, 6.0 and 8.5, which represent median levels of radiative forcing (W m^{-2}) under a range of climate change scenarios resulting from different CO_2 emission pathways and associated temperature changes by 2100 (Moss et al. 2010, Van Vuuren et al. 2011). RCP 2.6, 4.5, 6.0 and 8.5 scenarios are equivalent to mean increases of respectively 1, 1.8, 2.2 and 3.7°C in global mean surface temperature by 2081–2100, compared to the 1986–2005 reference period (Stocker et al. 2013). RCP 2.6 is an emission pathway that assumes very low greenhouse gas concentration levels and represents a peak in CO_2 concentration of 490 ppm before declining by 2100 (Van Vuuren et al. 2007). RCP 4.5 represents a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing target level; this pathway represents a peak of 650 ppm CO_2 before stabilizing after 2100 (Smith & Wigley 2006, Wise et al. 2009). RCP 6.0 represents an emissions stabilization scenario with a peak of 850 ppm CO_2 before stabilizing after 2100 by using a combination of technology fixes (Fujino et al. 2006, Hijioka et al. 2008). RCP 8.5 represents a scenario of high greenhouse gas concentrations with a rising radiative forcing pathway and 1370 ppm CO_2 by 2100 (Riahi et al. 2007).

2.4. Trend tables and statistical analysis

The trend of local, observed climate records was determined using linear least squares fit, a standard method for analysing climate trends (Burt & Holden 2010). Whilst the linear least squares fit method is more vulnerable to outliers than other methods in climate analysis, it is often difficult to distinguish variability from trend (Santer et al. 2000). The magnitude of any changes over the period were calculated by subtracting the period mean from the trend value for the last recorded year. Significance was determined using a Mann Kendall trend test, commonly employed to detect monotonic trends in environmental and climate series data (Yue et al. 2002, Dixon et al. 2006, Pohlert 2018), due to its robustness with outliers (Kundzewicz & Robson 2004). The strength of time series trends was determined by Kendall- or *T*-statistic (tau value). Least squares fit linear regressions were used to represent trends, and LOESS smoothing curves were fitted. This is a non-parametric method of local regression, suitable for data sets with outliers (Cleveland 1979) and used to measure environmental variability at multi-decadal scales (Hannaford 2013). Statistics were performed using R studio (R Core Team 2017), trend analysis and the graph-production packages 'kendall' (McLeod 2011) and 'ggplot2' (Wickham 2009).

2.5. Deviation tables (observed vs. projected trends)

Observed trends represent the difference between reference (1981–2010) and past 30 yr averages as a proportion of the current total (% change) and use climate station data (Table 1). Model projections use UKCP18 probabilistic projections which define changes in precipitation (%) between reference and future 30 yr averages. Observed and projected trends are compared over equivalent time-periods, e.g. 60 yr before and beyond the 'reference' (1981–2010) 30 yr period. Examining the difference between the 'Trend' and 'Model projections' forms the basis of the analysis (Fig. 2), and is termed the 'deviation'.

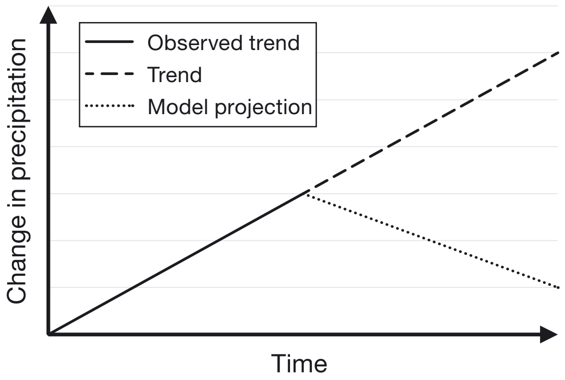

Fig. 2. Example schematic representation of the approach for comparing trends in observed data with median model projections. This example shows a positive deviation between 'Trend' and 'Model projection' as depicted by the upwards arrow symbols (▲) in the deviation tables. Trends could be higher (positive deviation) or lower (negative deviation) than model projections

3. RESULTS

3.1. Observed trends

While there was a significant ($p \le 0.05$) positive trend (1879–2012) in total annual precipitation at the Cowsic Valley station (upland) (+226 mm, +11%), there was no concomitant significant change at the Plymouth station (lowland) (Fig. 3, Table 2). Spring precipitation increased in both lowland (16 mm, +8%) and upland (49 mm, +13%) stations over the period, with greater increases at the upland station (Table 2). Although there was no significant change in summer precipitation (1879–2012), the lowland station showed a 3% decrease and the upland station a 4% increase (Table 2). Autumn and winter records match annual precipitation, i.e. significant precipitation increases at the upland station (autumn +12%, winter +14%), but no significant change (1879–2012) at the lowland station (Table 2).

Examination of multiple upland Dartmoor stations (1961–2015) shows significant increases in annual precipitation at 3 of the 4 stations (Fig. 4, Table 3), with only White Ridge (+167 mm) marginally non-significant ($p = 0.072$). The most westerly stations, Double Waters and Princetown, experienced the steepest annual increases of 331 mm (+18%) and 289.7 mm (+15%), respectively. There was no change in annual precipitation over the same period (1961–2015) at the lowland station (Plymouth; +5%, $p = 0.360$) (Table 3).

Examination of seasonal changes at upland and lowland sites (1961–2015) (Table 3) showed no significant changes in spring precipitation. While marginally non-significant, summer precipitation increased, with the most western upland Dartmoor station (Double Waters) experiencing a significant increase (+83 mm, +23%, $p = 0.009$). While all sites had increasing precipitation in autumn and winter seasons, Double Waters and the other western upland station (Princetown) experienced significant increases ($p \le 0.05$) in autumn (20 and 15%) and winter precipitation (21 and 17%).

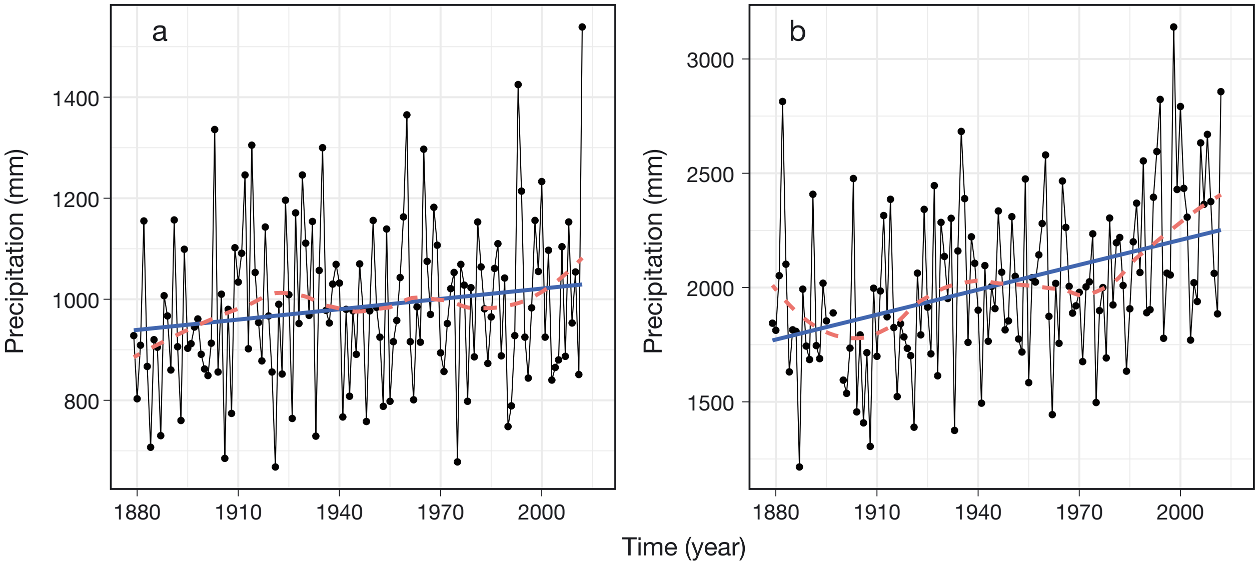

Fig. 3. Total annual precipitation recorded in (a) Plymouth and (b) Cowsic Valley between 1879 and 2012. Black dots represent total annual precipitation recorded. The blue line is the least squares fit linear trend. The red dashed line is a LOESS (local regression) smoothing curve (span = 0.5)

Table 2. Annual and seasonal trends in monthly precipitation totals at lowland (Plymouth) and upland (Cowsic Valley) sites in Dartmoor, UK, for the period 1879–2012. Values show observed change (mm and %) from the mean, calculated by subtracting the mean for 1879–2012 from the 2012 trend line (linear least squares fit). Statistically significant ($p \leq 0.05$) linear trends using the seasonal Mann Kendall test are denoted in **bold** (*$p \leq 0.001$)

Season	Lowland		Upland	
	mm	%	mm	%
Spring	**16**	**8**	**49***	**13***
Summer	–6	–3	16	4
Autumn	14	5	**68**	**12**
Winter	18	6	**89**	**14**
Annual	46	5	**226***	**11***

3.2. Observed vs. projected trends

The interquartile range (IQR) of UKCP18 25 km projections for the 2040–2069 period (Table 4) suggests that the season with the greatest variability around the median is summer, with reductions in mean total precipitation of between 34 and 11 % and between 32 and 10 % for grids covering lowland and upland stations, respectively. Spring, autumn and winter seasons had a much lower variability, suggesting higher confidence than summer projections, with moderate decreases in spring and increases in autumn precipitation by 2040–2069. Winter projections suggest increases of between 2 and 18 % in rainfall across locations and climate change scenarios.

Deviation tables for 2040–2069 (Table 5) show that spring and summer yield the highest deviation between observed and median projected precipitation under both RCP 2.6 and 4.5 climate change scenarios, especially for upland locations (circa 24 % for both seasons at Cowsic Valley). Autumn and winter projections, whilst not completely consistent, suggest increases but with lower anomalies. Projections for lowland Plymouth in autumn are most consistent with observations.

In common with 2040–2069 projections, the IQR of projections for 2070–2099 scenarios (Table 6) suggest that the season with the greatest variability is summer. Reductions in total mean precipitation of 10–42 % and 10–39 % are projected in lowland and upland areas, respectively, between 2070 and 2099 under RCP 2.6 and 4.5 climate change scenarios. There is lower variability for spring, autumn and winter seasons, with moderate decreases projected for spring and moderate increases for autumn precipitation totals. The range of projections for winter suggests increases in total precipitation of between 3 and 26 % across locations and emissions scenarios.

Deviation tables for 2070–2099 projections (Table 7) suggest that spring, summer and autumn are the seasons with the greatest divergence between observations and latest UKCP18 projections, with divergence higher at the upland (Cowsic Valley) than the lowland site (Plymouth). Deviation is as high as 30, 33 and 31 % for spring, summer and autumn, respectively, under RCP 4.5 for 2070–2099 at upland sites compared to 15, 18

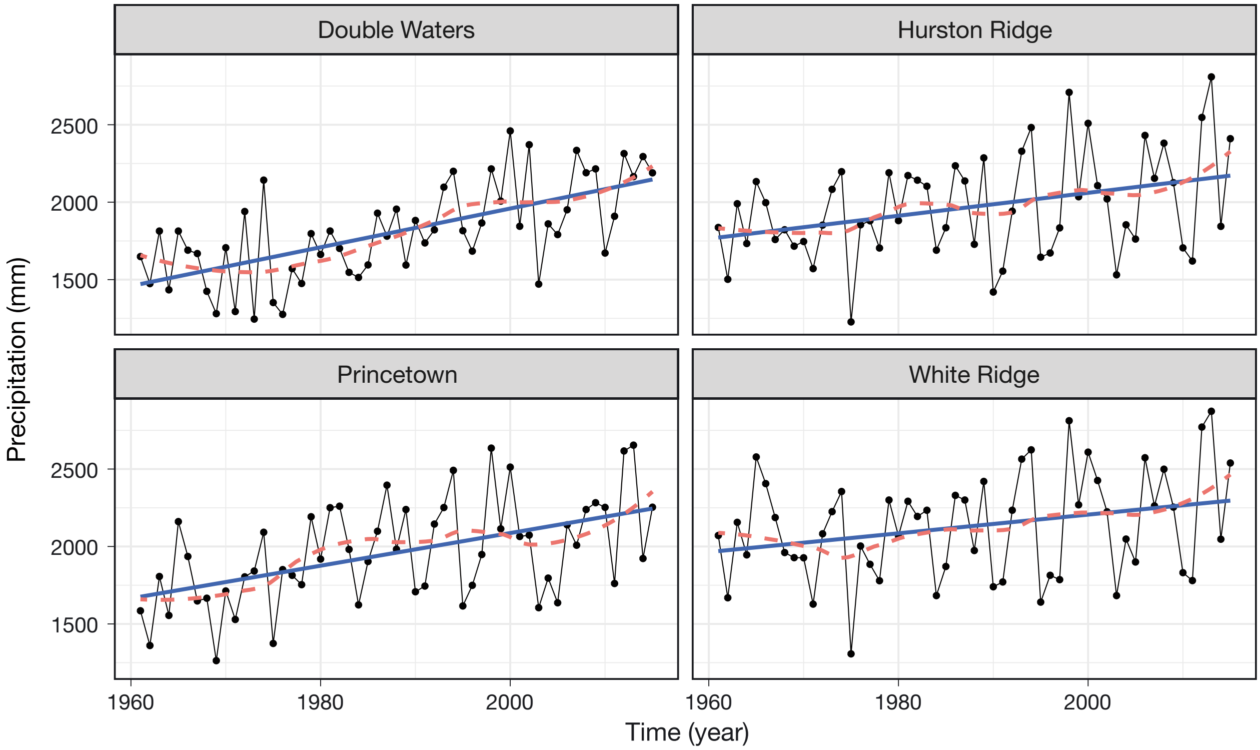

Fig. 4. Total annual precipitation recorded on upland Dartmoor stations (Double Waters, Hurston Ridge, Princetown and White Ridge) between 1961 and 2015. Black dots represent total annual precipitation recorded. The blue line is the least squares fit linear trend. The red dashed line is a LOESS (local regression) smoothing curve (span = 0.5)

Table 3. Annual and seasonal trends in monthly precipitation totals in lowland (Plymouth) and upland Dartmoor stations (site abbreviations as in Table 1) between 1961 and 2015. Values show observed change (mm and %) from the mean, calculated by subtracting the mean for 1961–2015 from the 2012 trend (linear least squares fit). Statistically significant ($p \leq 0.05$) linear trends using the seasonal Mann Kendall test are denoted in **bold** (*p ≤ 0.001)

Season	Lowland		Upland							
	PLY		DBW		HRR		PRT		WHR	
	mm	%	mm	%	mm	%	mm	%	mm	%
Spring	–11	–5	21	6	–6	–2	26	7	–15	–4
Summer	26	14	**83**	**23**	40	13	75	19	47	13
Autumn	22	8	**106***	**20***	56	10	**81**	**15**	49	8
Winter	18	6	**121***	**21***	98	14	**106**	**17**	85	11
Annual	52	5	**331***	**18***	**208**	**11**	**290***	**15***	167	8

Table 4. Interquartile ranges (IQRs) of projected changes (UKCP18, 25 km resolution) in average seasonal precipitation totals (%) by 2040–2069 for 1 lowland (Plymouth: PLY) and 2 upland locations (Cowsic Valley: COW, Deabcombe Farm: DCF). The IQR shows the middle 50 % of projected changes between reference 30 yr average (1981–2010) and future average 60 yr ahead or by 2040–2069 under RCP 2.6 and 4.5 climate change scenarios. Projected data cover 3 grid cells (25 km) covering each station (coordinates provided in Table 1). ▲ denotes an increase, ▼ a decrease in precipitation totals

Season	Lowland		Upland			
	PLY		COW		DCF	
	RCP 2.6	RCP 4.5	RCP 2.6	RCP 4.5	RCP 2.6	RCP 4.5
Spring	▼12 – 0	▼11–▲1	▼11 –▲1	▼11 –▼2	▼11 –▼1	▼11 –▲1
Summer	▼31–▼9	▼34 –▼11	▼28 –▼8	▼32 –▼10	▼29 –▼8	▼32 –▼10
Autumn	▼2 –▲8	▼1 –▲9	▼2 –▲8	▼1–▲9	▼2 –▲9	▼1 –▲9
Winter	▲2 –▲15	▲2 –▲16	▲1 –▲12	▲2 –▲13	▲2 –▲16	▲3 –▲18
Annual	▼2 –▲3	▼2 –▲3	▼2 –▲1	▼2 –▲1	▼1 –▲3	▼1 –▲4

Table 5. Deviation between 'observed' and median 'projected' (UKCP18, 25 km resolution) changes (%) in average annual and seasonal precipitation totals by the 2050s for lowland and upland locations (observed change % – projected change %). Observed changes use climate records from 1 'lowland' (Plymouth: PLY) and 2 'upland' stations (Cowsic Valley: COW, Deabcombe Farm: DCF) and refer to recorded changes in mean total seasonal precipitation between the reference 30 yr average (1981–2010) and the 30 yr average 60 yr previously (1920–1949) (reference – past). Projected changes represent median difference between reference 30 yr average (1981–2010) and future average 60 yr ahead or by 2040–2069 under RCP 2.6 and 4.5 climate change scenarios. ▲ denotes a positive, ▼ a negative anomaly between observed and projected changes

Season	Lowland		Upland			
	PLY		COW		DCF	
	RCP 2.6	RCP 4.5	RCP 2.6	RCP 4.5	RCP 2.6	RCP 4.5
Spring	▲ 17	▲ 17	▲ 24	▲ 24	▲ 23	▲ 23
Summer	▲ 19	▲ 21	▲ 22	▲ 24	▲ 20	▲ 22
Autumn	0	▼ 1	▲ 12	▲ 11	▲ 8	▲ 7
Winter	▼ 7	▼ 8	▲ 9	▲ 8	▼ 3	▼ 4
Annual	▲ 3	▲ 3	▲ 14	▲ 13	▲ 8	▲ 8

Table 6. Interquartile range of projected changes (UKCP18, 25 km resolution) in average seasonal precipitation totals (%) by 2070–2099 for lowland and upland locations. Details as for Table 4, but refers to 2070–2099

Season	Lowland		Upland	
	PLY		COW	
	RCP 2.6	RCP 4.5	RCP 2.6	RCP 4.5
Spring	▼9 – ▲2	▼9 – ▲ 2	▼9 – ▲ 1	▼9 – ▲ 1
Summer	▼36 – ▼10	▼42 – ▼14	▼33 – ▼10	▼39 – ▼14
Autumn	▼1 – ▲8	0 – ▲10	▼1 – ▲7	▼1 – ▲8
Winter	▲5 – ▲8	▲9 – ▲26	▲3 – ▲14	▲6 – ▲20
Annual	0 – ▲4	0 – ▲5	▼2 – ▲3	▼2 – ▲3

Table 7. Deviation between 'observed' and median 'projected' (UKCP18, 25 km resolution) changes (%) in average annual and seasonal precipitation totals by 2070–2099 for lowland and upland locations (observed change % – projected change %). Details as for Table 5, but refers to 2070–2099

Season	Lowland		Upland	
	PLY		COW	
	RCP 2.6	RCP 4.5	RCP 2.6	RCP 4.5
Spring	▲15	▲15	▲30	▲30
Summer	▲14	▲18	▲30	▲33
Autumn	▲9	▲9	▲32	▲31
Winter	▼12	▼18	▲15	▲10
Annual	▲1	▲1	▲24	▲24

and 9% in the lowlands. Median projections for winter precipitation change are more consistent with observations than other seasons, but while observations are above projected trajectories for the upland location, they fall below them for the lowland site. The seasonal difference between the upland and lowland sites means that although annual precipitation deviation between observations and projections is negligible for the lowland site (+1%) under both emissions scenarios, it is considerable for upland Cowsic Valley (+24%).

4. DISCUSSION

Long term (>130 yr) precipitation records from SW England evidence significant anthropogenic forcing, which is more pronounced at upland sites (Fig. 2, Table 2). Our study is fortunate to use one of the longest pair of upland and lowland precipitation records in Western Europe, and the dependence of seasonal trends on the time-period analysed (Tables 2 & 3) highlights the importance of long-term climate observations (Burt & Holden 2010). The differences between time periods underscore the difficulty of linking shorter-term (<50 yr) climate records to anthropogenic climate change, as trends may be confounded by natural multi-decadal atmospheric and/or oceanic cycles (Parker et al. 2007, Bindoff et al. 2013).

Elevated autumn, winter and annual precipitation trends in the UK uplands (Fig. 3, Tables 2 & 3) have previously been linked to a 'double orographic enhancement', associated with positive NAO (+NAO), linked to stronger maritime airflow and high atmospheric moisture content (Burt & Holden 2010, Burt & Howden 2013). Upland sites experience enhanced precipitation via susceptibility to the 'seeder-feeder' process, which involves raindrops in upper-level clouds washing out droplets within lower-level 'feeder' clouds, which form over hills, producing higher rainfall intensities (Bergeron 1965, Lee et al. 2000). Other mechanisms can occur through primary (sea salt and other organics) and secondary (ocean released dimethyl-sulphide) marine aerosols, which can drive cloud formation and increase cloud condensation nuclei (CCN) (Hudson et al. 2011, Sanchez et al. 2018). Therefore, while 'double orographic enhancement' has been linked to +NAO associated with periods of maritime weather and south-westerly winds (Burt & Howden 2013, Burningham & French 2013), it is perhaps the interaction between the seeder-feeder process and oceanic-derived CCN that underpins the mechanism of increased upland precipitation change. This interaction would become stronger during +NAO and could explain enhanced precipitation noted for west coast UK upland sites (Burt & Howden 2013). Observed precipitation trends in upland, windward stations (Fig. 4, Table 3) may reflect this process, and explain recorded amplification of the rain-shadow effect by +NAO (Burt & Howden 2013).

A better understanding of the interaction between oceanic–atmospheric processes and upland climate mechanisms is therefore important for accurately modelling future climate changes for upland sites in the NE Atlantic and other ocean-influenced upland regions. The sensitivity of upland precipitation to atmospheric and oceanic cycles may additionally have important implications for understanding the ecological dynamics and conservation priorities, and planning for effective climate mitigation in these areas (Morecroft et al. 2009, Lunt et al. 2019).

Records of seasonal precipitation from upland SW England suggest significant divergence between observed trends and recently released UKMO climate projections. Although increases in winter precipitation are broadly consistent with a range of climate model scenarios, records for spring, summer and autumn precipitation show no signs of projected drying (Murphy et al. 2018), with deviation greatest in upland locations.

Using observed changes in precipitation to infer confidence in projected changes has its limitations, namely the uncertainty of future emissions pathways (many of which are non-linear); our methods did not explicitly seek to determine model validity, as climate models consider many and varied processes when generated. There are considerable limitations in downscaling projections to the scale used in this study; however, projections for grid cells used reflect their intended application as a useful starting point for risk assessments and to represent the uncertainty present in existing climate models (Murphy et al. 2018). We felt it was vital to contextualise projected trends (Fig. 2), considering the likely applicability of these projections in land management decisions, particularly when projected changes in future precipitation are so variable and the range of outcomes is high (Murphy et al. 2018). Our timeframes for comparison (60 and 90 yr) were chosen to avoid being confounded by natural cycles such as AMO and NAO, but this restricted the number of suitable stations. We used RCP 2.6 and RCP 4.5 climate change scenarios in our analysis, as these are the most conservative RCPs, which we judged more suitable for comparison. Probabilistic projections for RCP 6.0 and 8.5 climate change scenarios show similar deviation to observed trends seen for RCP 2.6 and 4.5 (Tables A2 & A3 in the Appendix), but with elevated magnitude in these more extreme climate change scenarios.

Considerable interest is presently focussed on understanding ecological patterns and processes within the context of climate projection data (Parmesan & Hanley 2015, Smith et al. 2018). Our results highlight the need for caution when examining the future response of upland organisms and ecosystems to projected changes in growing season precipitation totals and that ecologists must actively explore uncertainty in all aspects of climate data before making inferences about biological responses (Suggitt et al. 2017).

This uncertainty is greatest in summer (Murphy et al. 2018), as drying is predicated on large-scale changes in the placement of anti-cyclonic pressure systems (Belleflamme et al. 2015), linked to a natural downturn of the Atlantic SSTs, yet confidence levels for these large-scale changes are relatively low (Rowell & Jones 2006). The emergence of an Atlantic SST tri-pole pattern and an enhanced meridional SST gradient could lead to increased storminess in the Atlantic, associated with intensifying atmospheric baroclinicity (Frajka-Williams et al. 2017). It is interesting to note that without a changed position of anti-cyclonic systems in the North Atlantic, blocking flow from the Atlantic Ocean, some models (HadAM3PEur) project a net increase in rainfall in the UK and Scandinavia due to the enhanced moisture content of the warmer atmosphere (Rowell & Jones 2006).

Other uncertainties in summer precipitation rest on the uncertain influence of variations in local SSTs on evaporation behaviour (Long & Xie 2015), the downscaling of regional and global models (Rowell 2006) and the large observed seasonal variation in lapse rates (Holden & Rose 2011, Burt & Howden 2013). Consequently, changes in short-duration (sub-daily) summer events are unclear, as projections are less reliable at these scales (Fowler et al. 2007). Improvements in the accuracy of summer projections may be available with the use of 'convection permitting' models, run at high resolution (<5 km) to project more localised high-impact rainfall events (Kendon et al. 2014, Kendon et al. 2017).

Recent increases in summer precipitation (Table 3) coincide with a move from the negative to the positive phase of the AMO and are supported by long-term UK river flow monitoring data, which show no reduction in summer flow rates (Hannaford 2013). Given the evidenced influence of SSTs on summer precipitation (Dong et al. 2013, Ossō et al. 2018) and pressure patterns (Belleflamme et al. 2015), future interaction between natural AMO and background anthropogenic SST warming is likely to prove important. This interaction could be influential in determining the temporal and spatial pattern of future precipitation trends in SW England and more widely for NW European upland coastal sites.

Winter projections are more robust, associated with enhanced atmospheric water vapour content and increased precipitation (Held & Soden 2006, Schaller et al. 2016). ARs are expected to increase in strength and frequency in the UK and Europe-wide under multiple global climate model simulations, resulting in heavier precipitation and greater flood risk (Lavers et al. 2013, Ramos et al. 2016). Precipitation observations support other records from paired upland and lowland sites and highlight that upland locations are particularly sensitive to recent changes in climate (Burt & Holden 2010, Burt & Ferranti 2012). Our study provides support for local winter projections (Murphy et al. 2018), underlines the significant potential for future winter flood risk and suggests that the damaging floods experienced in the UK between 2007 and 2015 may have set a precedent for future changes.

Our results signpost significant increases in spring, autumn, winter and annual precipitation for upland SW England between 1879 and 2012. Moderate increases in summer precipitation represent a deviation from the drier summers predicted with current and previous climate models. Deviation between observed and projected precipitation trends were greatest in upland locations. Taken together, our results highlight the uncertainty between predicted and observed climate trends, particularly for summer precipitation totals, and evidence the need for caution when making assumptions about climate impacts based solely on predictive models (Parmesan et al. 2018). We also highlight the value of long-term upland climate monitoring and the importance of model projections at appropriate spatial scales (Watts et al. 2015) to better enable policy makers and practitioners to deliver ‘future proofed’ decisions for the delivery of multiple ecosystem services in the uplands of NW Europe (Reed et al. 2013, Brown & Everard 2015).

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Appendix. Supplementary data

Table A1. Changes in the location and instrumentation of weather stations used in trend analysis (abbreviations as in Table 1). Details of weather stations were obtained from the National Meteorological Archive (Met Office 2018)

Station	Change	Date
PLY	Location and instrumentation	1940
COW	Instrumentation	1991
DCF	Instrumentation	1961
PRT	Location and instrumentation	2009
HRR	No change	–
WHR	No change	–
DBW	No change	–

Table A2. Deviation between 'observed' and median 'projected' (UKCP18, 25 km resolution) changes (%) in average annual and seasonal precipitation totals by 2040–2069 for lowland and upland locations (observed change % – projected change %). Details as for Table 5, but refers to 2070–2099 and RCP 6.0 and RCP 8.5 climate change scenarios

Season	Lowland		Upland			
	PLY		COW		DCF	
	RCP 6.0	RCP 8.5	RCP 6.0	RCP 8.5	RCP 6.0	RCP 8.5
Spring	▲17	▲17	▲24	▲24	▲23	▲23
Summer	▲21	▲26	▲24	▲29	▲21	▲27
Autumn	▼1	▼1	▲11	▲11	▲7	▲6
Winter	▼7	▼11	▲8	▲5	▼4	▼7
Annual	▲3	▲3	▲13	▲13	▲8	▲8

Table A3. Deviation between 'observed' and median 'projected' (UKCP18, 25 km resolution) changes (%) in average annual and seasonal precipitation totals by 2070–2099 for lowland and upland locations (observed change % – projected change %). Details as for Table 7, but refers to RCP 6.0 and RCP 8.5 climate change scenarios

Season	Lowland		Upland	
	PLY		COW	
	RCP 6.0	RCP 8.5	RCP 6.0	RCP 8.5
Spring	▲15	▲15	▲30	▲30
Summer	▲22	▲32	▲37	▲46
Autumn	▲8	▲8	▲31	▲31
Winter	▼20	▼27	▲9	▲3
Annual	▲1	▲1	▲24	▲23

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