A 200-year precipitation index for the central English Lake District

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Abstract The geographical context and hydroclimatology of the English Lake District means that the region is an important monitor of changes to nationally significant environmental assets. Using monthly rainfall series for sites in and around the central Lake District, a continuous ~200-year precipitation index was constructed for a representative station close to Grasmere. The bridged series shows a significant decline in summer rainfall since the 1960s, offset by increases in winter and spring that are strongly linked to North Atlantic forcing. Over longer time periods, the index exhibits several notable dry (1850s, 1880s, 1890s, 1930s, 1970s) and wet (1820s, 1870s, 1920s, 1940s, 1990s) decades. These patterns are strongly reflected by reservoir inflow series and by indicators of the biological status of the region's freshwater lakes. It is argued that long-term climate indices will become increasingly important as managers seek to evaluate recent and project environmental changes within the context of long-term natural variability.

Key words precipitation; reconstruction; natural variability; climate change; historical records; English Lake District

Un indice de précipitation de 200 ans pour la Région des Lacs en Angleterre

Résumé Le contexte géographique et hydro-climatologique de la Région des Lacs en Angleterre en fait un témoin significatif des problèmes environnementaux nationaux. En utilisant des chroniques mensuelles de pluie obtenues en des sites de la Région des Lacs ou alentour, un indice de précipitation continu sur environ 200 ans a été construit pour une station représentative proche de Grasmere. Les séries croisées montrent une diminution significative des pluies d'été depuis les années 1960, compensée par une augmentation des pluies d'hiver et de printemps qui sont fortement corrélées au forçage Nord-Atlantique. Sur de plus longues périodes, l'indice met en évidence des décennies particulièrement sèches (1850–59, 1880–89, 1890–99, 1930–39, 1970–79) et humides (1820–29, 1870–79, 1920–29, 1940–49, 1990–99). Ces tendances se reflètent clairement dans les chroniques des apports en eau aux réservoirs, et dans les indicateurs de l'état biologique des lacs d'eau douce de la région. Il en est déduit que les indices climatiques à long terme seront de plus en plus importants pour les gestionnaires qui cherchent à évaluer l'impact des changements environnementaux récents et prévus dans un contexte de variabilité naturelle à long-terme.

Mots clefs précipitation; reconstruction; variabilité naturelle; changement climatique; chroniques historiques; Région des Lacs, Angleterre

INTRODUCTION

The enthusiasm of early meteorologists served the English Lake District well, and has led to a large number of precipitation records of at least monthly frequency, that offer an important resource to contemporary studies of climate variability. For example, Kendal, Lancaster and Carlisle, towns at the edge of the Lake District, have rainfall

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series beginning in the 1780s that are essentially continuous to the present day (Craddock, 1976; Thompson, 1999; Tufnell, 1997). In the central Lake District, one of the best known early records is for Keswick, where a time series has been published for 1840–1926 (Craddock, 1979), but other important long records have received less attention. Such data provide rare opportunities to identify interannual variability, precipitation trends and seasonality changes within this ecologically and economically important region.

Changes in the Lake District's precipitation climatology are of importance for several reasons. First, there has been a well-documented steepening of the present-day rainfall gradient between the northwest and southeast of Britain (Mayes, 2000) and the Lake District lies just to the north of the fulcrum. Secondly, the westerly, maritime location of the Lake District means that the region's precipitation is sensitive to multi-year variations in North Atlantic sea-surface temperatures and atmospheric circulation changes linked to the North Atlantic Oscillation (Wilby *et al.*, 2002, 1997). Thirdly, seasonal and interannual rainfall variability affects nationally significant water resources and natural assets (including landscapes and biodiversity) within the National Park.

Having outlined the most salient features of the regional precipitation, long records for the central Lake District are evaluated and a ~200-year bridged series of precipitation totals with monthly resolution is constructed. Periodicity in the record, changes in seasonality and possible links to large-scale climate indices are examined. The overall aim is to construct a homogeneous index that will assist environmental scientists and managers to better understand precipitation trends and forcing across the region.

LAKE DISTRICT PRECIPITATION AND ENVIRONMENTAL RESPONSES

The Lake District climate has two distinctive features: the highest annual rainfall in England, and extreme spatial heterogeneity in its distribution. Annual totals vary from over 3000 mm year^{-1} at Seathwaite (Manley, 1946) to 1300 mm year^{-1} at Kendal (Tufnell, 1997). Montane topography and associated orographic rainfall processes and rain shadow effects challenge the sensibility of homogenous rainfall series for the whole of northwest England (Jones & Conway, 1997). This is especially pertinent when comparing the Lake District with the relatively drier lowlands of south Lancashire (Tufnell, 1997), and even the Eden Valley to the east which lies within the shadow created by the Lake District mountains (Mayes, 1996).

Rainfall in the Lake District is strongly related to westerly air flows from the Atlantic, and oceanic conditions influence the seasonal and annual totals of precipitation (Mayes, 1996). Enhanced sea-surface temperature gradients between 30ºN and 60ºN have been linked to more vigorous westerly airflows and hence wetter winters (Rodwell & Folland, 2002; Rodwell *et al.*, 1999). These westerly flows and mild wet winters occur during positive phases of the North Atlantic Oscillation Index (NAOI) (Hurrell, 1995; Hurrell *et al.*, 2001). Conversely, a negative NAOI indicates reduced pressure gradients and on average milder, drier winters for the UK. An analysis of monthly variability in UK-wide rainfall has revealed higher winter rainfall in western areas in the standard period 1961–1990 than in 1941–1970, linked to increased westerly airflows since the 1970s (Mayes, 1996, 2000).

It has become increasingly apparent that the Lakes and their catchments are tightly coupled to climate forcing and particularly hydrological flushing, with some biotic changes correlated with conditions in the North Atlantic. It is suspected that the northward movement of the Gulf Stream generates a lower frequency of cyclones in the North Atlantic and reduced pressure over the central Atlantic area. However, direct relationships between changes in the Gulf Stream and Lake District weather patterns are not statistically significant (Taylor, 1996). Nonetheless, spatially separated and/or very different aquatic ecosystems show coherence at the interannual scale due to mutual climate forcing. For example, the long-term population dynamics of Daphnia in Esthwaite Water and Windermere are correlated with the latitudinal position of the Gulf Stream in the western Atlantic (George & Taylor, 1995). Stable atmospheric conditions in spring and summer promote early summer lake stratification, resulting in the production of eggs by Daphnia ahead of the major phytoplankton blooms that provide their food source, leading to high mortality (George, 2000; George & Hewitt, 1999; George & Taylor, 1995). Furthermore, surface water temperatures of lakes and winter ice cover in the Windermere catchment are highly correlated with the NAOI ($r \sim 0.8$, $p < 0.01$) (George, 1999; George *et al.*, 2000).

In Grasmere, enhanced flushing of nutrients through the system during wet winters has, in part, mitigated the sewage loads that have augmented trophic levels since the 1960s (Reynolds & Lund, 1988). Landscape processes are also controlled by positive precipitation anomalies as demonstrated by destructive flood episodes identified from geomorphological investigations near Grisedale tarn in the central Lake District (Johnson & Warburton, 2002). The functioning and management of these lake-catchment ecosystems is therefore closely related to the region's precipitation regime. Probably the most important control is the seasonality of precipitation, since this determines nutrient and sediment fluxes from catchments, as well as the residence time of water in the lakes themselves. The development of a continuous 200-year precipitation index provides the basis for understanding contemporary process responses, and to speculation about future climate change impacts for the region.

CONSTRUCTION OF A CENTRAL LAKE DISTRICT (CLD) PRECIPITATION INDEX

In addition to the important series for Kendal and Keswick, numerous other rainfall records were collected in the Lake District during the 19th century. A total of 92 recorders in the old counties of Cumberland and Westmoreland were submitting data to *British Rainfall* by 1883 (Symons, 1883), with 37 of these recording daily amounts. The monthly data used herein were digitized from Met Office 10-year sheets with station records selected on the basis of continuity, longevity and proximity to Grasmere and Rydal Water (Tables 1 and 2). To extend the record to the beginning of the 19th century, data were bridged from Kendal and Keswick to Grasmere. Monthly precipitation totals were employed to reduce the problem of heterogeneity of daily rainfall patterns and to better address seasonal variability. The location and site histories of individual records are listed in Table 1. The data were not further corrected for changes in site or location, as these should have already been incorporated in the records. Moreover, the CLD is presented as an index in order to overcome local collection errors. Note that the long-running record for Seathwaite (1867–) was excluded from the present

Table 1 Location and site details of the rainfall records. Location data are derived from the record sheets if present and verified against the Ordnance Survey 1:25 000 maps. Altitude is converted from imperial units. Notes appearing on the sheets, include gauge diameters (in inches) and heights or possible sources of error are listed without alteration.

Town/ village	Gauge location	Latitude (N)	Longitude (W)	Grid ref.	Alt. (m)	Dates of records	Observer	Notes
Kendal	Kirbie Kendal School	54°19′01″	2°44′31″	SD (34) 518915	41	1951–1982	N. Whitton	A 5-inch gauge.
*Kendal	St Georges Church -Kent Terrace	54°19′45″	2°44′12″	SD (34) 521928	44	1788–1789 (a), 1790 –1792 (a), 1802 (b), 1806–1899 (c) & (d)	(a) Sir John Dalton FRS (b) Brother of Sir J. Dalton FRS (c) Samuel Marshall from 1822 (d) R. J. Nelson from 1870	Gauge moved from school in 1851(?); gauge moved ~100 m in 1884. Gauge size 8 in., 4ft 6 in. above ground. NB the grid reference added to the 10-year sheets at a later date is 1 km west of St Georges church.
Ambleside	Wansfell	54°24′57″	2°57′20″	NY (35) 385025	46	1920–1940	Miss Wrigley	
Ambleside	Skelwith Bridge	54°25′00″	3°0′27″	NY (35) 347028	58	1891–1923 (a–c)	(a) A. J. Adams (b) Miss Adams, J. Gaskill from 1910, (c) Miss C. Marshall from 1918	A 5-in. homemade gauge "Snowdon design", 1 ft 8 inches above ground. Inspector notes an open slit which "must inevitably give too high a reading. Glass very roughly graduated."
Ambleside	The Lakes U.D.C.	54°25′41″	2°58′07″	NY (35) 372040	46	1931–1970	Clerk to the council	A 5-in. gauge, 1 ft above ground.
Ambleside	Lesketh How,	54°26′15″	2°58′09″	NY (35) 375055	53	1850–1867 (a), 1870–1903 (b) & (c), 1905–1907, 1909–1923	(a) J. Davy MD (b) F. M. T. Jones (c) Miss M. Benson from 1900	Davy records altitude of gauge as 130 ft and 6-in. gauge 2 ft 6 in. above ground, thereafter 150 ft and 5-in. gauge.
Ambleside	Nook Cottage	54°26′10″	2°57′47″	NY (35) 376049	70	1860–1868 (a), 1875–1893 (b)	(a) J. C. Wilson (b) E. Hird	Gauge moved from Low Nook to Ambleside Nurseries in 1868. Gauge was 5 in., and 1 ft above ground.
*Grasmere - Rydal	High Close	54°26′18″	3°1′17″	NY (35) 338052	167	1870–1909 (a) & (b) 1920–1950 (c)	(a) E. B. W. Balme (b) F. M. T. Jones-Balme from 1900 (c) F. E. T. Balme-Jones from 1920	An 8-in. gauge, 9 in. above ground.
*Rydal	The Stepping Stones	54°26′29″	2°58′49″	NY (35) 365056	58	1901–1944 (a) & (b)	(a) Gordon Wordsworth (b) Mrs Dorothy Dickson from 1935	A 5-in. homemade gauge "Snowdon design", 1 ft 3 in. above ground.
*Rydal	Rydal Hall	54°26′58″	2°58′37″	NY (35) 367064	108	1921–2000	R. E. Porter	A 5-in. gauge, 6 in. above ground.
Grasmere	Pavement End	54°27′26″	3°01′24″	NY (35) 337073	66	1884–1902	J. A. Green	A 5-in. gauge, 4 ft 8 in. above the ground.

Grasmere	The Wray	54°27′24″	3°1′30″	NY (35) 336073	67	1903–1944	Miss G. M. Simpson	A 5-in. gauge, 1 ft above ground.
Keswick	The Mirehouse	54°38′36″	3°11′18″	NY (35) 234282	85	1931–1950	Miss Spedding	A 5-in. gauge, 1 ft 6 in. above ground.
Keswick	Deer Close	54°35′09″	3°07′32″	NY (35) 273217	91	1870–1889 (a–b) 1910–1919 (c)	(a) H. G. Marshall (b) John Marshall from 1870 (c) Miss C. Marshall	A 7-in. gauge, 1 ft 9 in. above ground. Gauge moved in 1914.
Keswick	Derwent Island	54°35′29″	3°08′41″	NY(35) 261224	85	1865–1965 (a–f)	(a) H. G. Marshall (b) John Marshall from 1890 (c) C. E. Marshall from 1923 (d) D. Marshall from 1941 (e) National Trust from 1951–1965	H.C. Marshall notes totals affected by tree growth when winds from west. Poor data quality in 1951–1954.
*Keswick	Post Office	54°36′03″	3°08′18″	NY (35) 265234	75	1790–1802 (a), 1841–1879 (b) & (c)	(a) P. Crosthwaite (b) J. Otley from1841 (c) J. F. Crosthwaite from 1850	8-in. gauge, 6ft above ground.

* sites included in the homogenous series.

Table 2 The number of months of data (*N*), mean (mm), and standard deviation (mm) of monthly rainfall amounts at each site. Statistics for Seathwaite are provided for comparative purposes only.

Site	Code	*N*	Mean	SD
Kendal, Kirbie Kendal School	KKS	384	108	59
Kendal, St Georges Church	KSG	1201	110	61
Ambleside, Wansfell	AWF	252	160	96
Ambleside, Skelwith Bridge	ASB	396	194	110
Ambleside, The Lakes UDC	ATL	480	155	91
Ambleside, Lesketh How	ALH	840	171	99
Ambleside, Nook Cottage	ANC	336	161	92
Grasmere, High Close	GHC	849	179	103
Rydal The Stepping Stones	RSS	516	176	104
Rydal, Rydal Hall	RRH	953	180	107
Grasmere, Pavement End	GPE	228	182	111
Keswick, The Mirehouse	KMH	239	113	63
Keswick Deer Close	KDC	451	128	75
Keswick Derwent Island	KDI	1200	123	73
Keswick Post Office	KPO	549	127	78
Seathwaite	-	1587	273	155

analysis because this more westerly site is a clear outlier compared to others in the series (Table 1), and is acknowledged as being the wettest inhabited place in England (Tufnell, 1997).

Figure 1 shows the names and dates of the overlapping precipitation records available for the central Lake District; Fig. 2 shows their geographical distribution. Grasmere High Close (GHC) was selected as the primary station for bridging because the record overlaps with both the earliest (Kendal and Keswick series) and ongoing contemporary observations (at Rydal Hall). Second, Grasmere is located within the central highlands of the Lake District and is representative of precipitation affecting

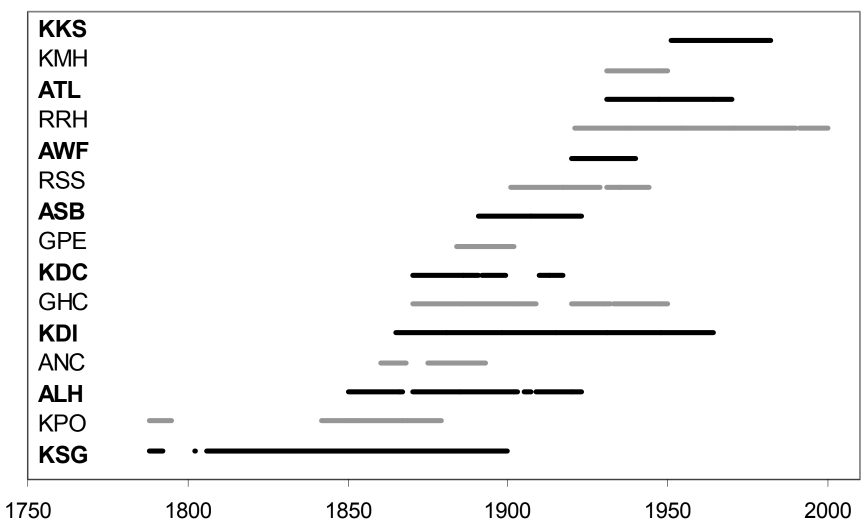

Fig. 1 Overlapping monthly precipitation records for the central English Lake District.

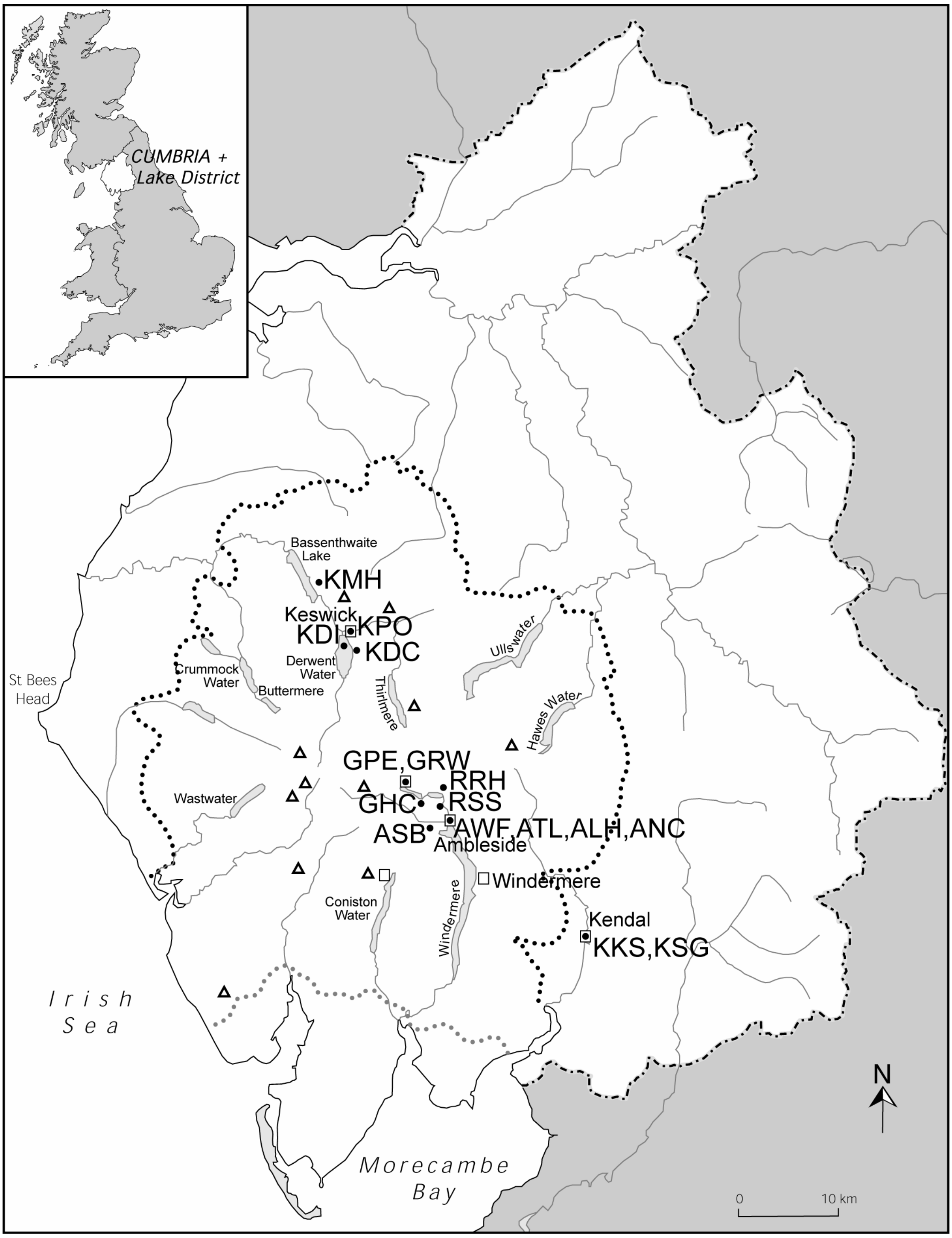

Fig. 2 Location of the central English Lake District and distribution of precipitation stations.

nearby sites with long-running biological records (e.g. Windermere and Esthwaite Water) used for monitoring environmental change in the UK (George & Hewitt, 1999; Maberly *et al*., 1994). Third, the series for GHC is broadly representative of other meteorological records in the region in terms of the mean and standard deviation of monthly precipitation totals despite the fact that the site has the highest elevation (Table 2).

Table 3 Correlation of overlapping time series, where (*N*) is the number of months in common between pairs of stations. All correlations shown are significant at the 0.01 level (2-tailed).

Sites	KKS	KSG	AWF	ASB	ATL	ALH	ANC	GHC	RSS	RRH	GPE	KMH	KDC	KDI	KPO
KKS	1														
KSG		1													
AWF			1												
ASB		0.901 (109)	0.970 (48)	1											
ATL	0.913 (240)		0.940 (120)		1										
ALH		0.861 (577)	0.987 (48)	0.961 (372)		1									
ANC		0.901 (336)		0.994 (36)		0.958 (324)	1								
GHC		0.896 (361)	0.987 (249)	0.973 (276)	0.960 (237)	0.960 (504)	0.946 (228)	1							
RSS			0.978 (240)	0.970 (276)	0.950 (168)	0.972 (252)		0.979 (393)	1						
RRH	0.921 (384)		0.984 (240)	0.978 (36)	0.958 (480)	0.991 (36)		0.986 (357)	0.981 (276)	1					
GPE		0.891 (193)		0.967 (144)		0.969 (228)	0.971 (120)	0.984 (228)	0.971 (24)		1				
KMH			0.949 (120)		0.912 (239)			0.949 (236)	0.937 (168)	0.942 (239)		1			
KDC		0.860 (355)		0.947 (199)		0.931 (451)	0.888 (223)	0.932 (355)	0.944 (96)		0.941 (187)		1		
KDI	0.801 (168)	0.846 (421)	0.948 (252)	0.924 (396)	0.866 (408)	0.897 (660)	0.871 (276)	0.936 (849)	0.937 (516)	0.917 (528)	0.928 (228)	0.970 (239)	0.951 (451)	1	
KPO		0.861 (513)				0.834 (336)	0.924 (168)	0.938 (120)					0.956 (120)	0.947 (180)	1

Finally, time series of monthly totals at GHC are also significantly correlated with all other overlapping records in the region except Kirbie Kendal School (Table 3).

A continuous index of monthly precipitation amounts was constructed for the central Lake District (CLD) by bridging overlapping series from Keswick Post Office (KPO), Kendal St Georges Church (KSG), Rydal Stepping Stones (RSS) and Rydal Hall (RRH) with GHC. Correction factors were estimated for each climatological season by regressing monthly totals at these sites against available data for GHC. In each case, the intercept of the regression line was constrained to pass through the zero point. The weakest relationship and largest correction factor was returned for KSG—the most distant and lowest elevation site chosen. Even so, monthly totals at all four bridging sites explain a significant portion (>80%) of the variance in monthly totals at GHC (Fig. 3). Although data at KSG exhibit some heteroscedacity, paired relationships at remaining sites were strikingly linear with only a handful of outliers. Table 4 provides a summary of the periods of bridging and the correction factors, by season.

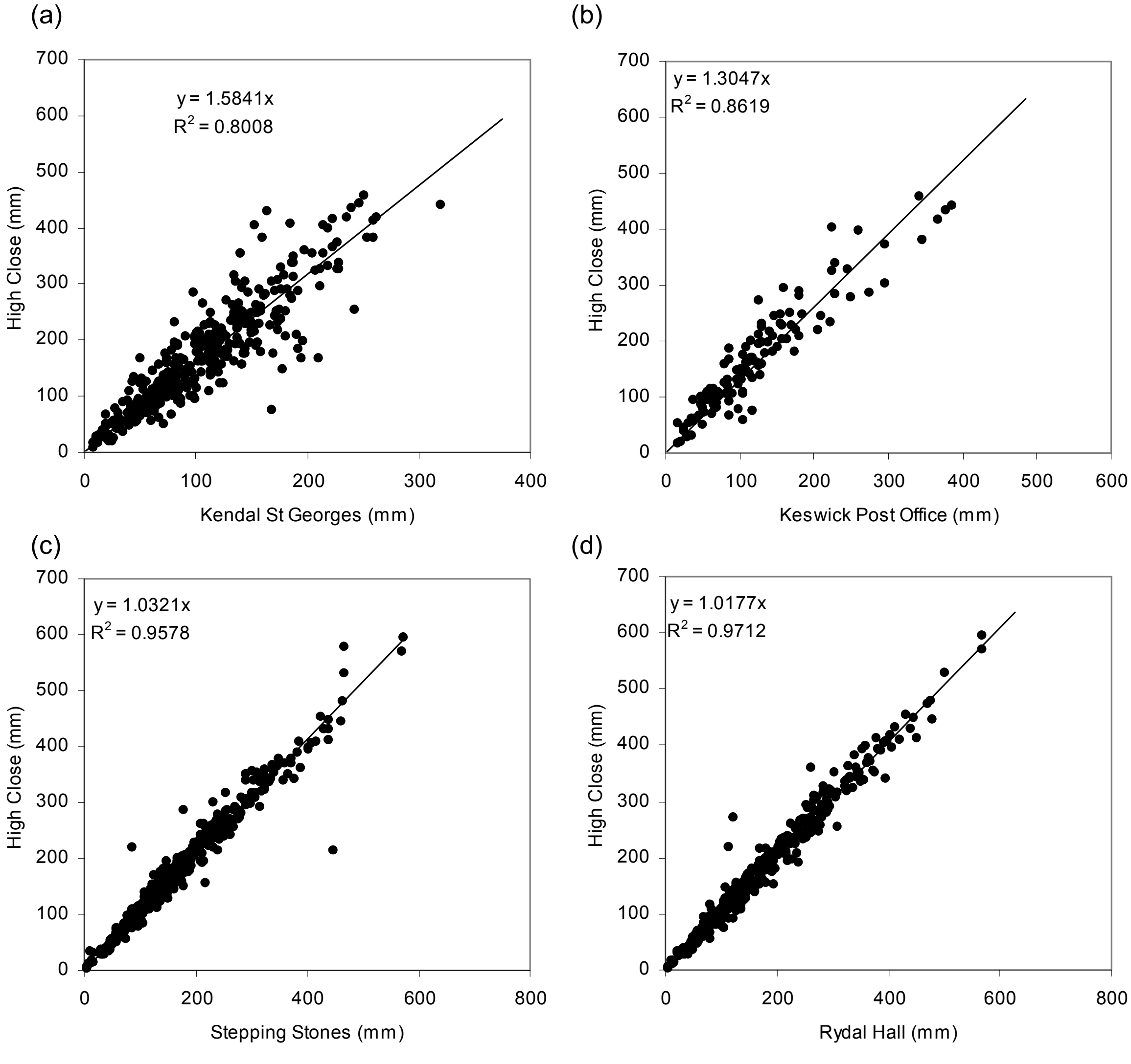

Fig. 3 Relationship between overlapping monthly precipitation totals at (a) Kendal (KSG), (b) Keswick (KPO), (c) and (d) Rydal (RSS, RRA) and Grasmere High Close. The correction factor and percentage of explained variance are shown in each case.

Table 4 Years of data and correction factors used to construct the bridged series for Grasmere High Close (GHC).

Site	Years	Factors: DJF	MAM	JJA	SON	Annual
Keswick, Post Office	1788–1795	1.3591	1.3321	1.0622	1.2205	1.3047
Kendal, St Georges Church	1796–1841	1.7354	1.5089	1.3514	1.6339	1.5841
Keswick, Post Office	1842–1869	1.3591	1.3321	1.0622	1.2205	1.3047
Grasmere, High Close	1870–1909	1.0000	1.0000	1.0000	1.0000	1.0000
Rydal, The Stepping Stones	1910–1919	1.0322	0.9855	1.0225	1.0546	1.0321
Grasmere, High Close	1920–1950	1.0000	1.0000	1.0000	1.0000	1.0000
Rydal, Rydal Hall	1951–2000	0.9978	1.0213	0.9896	1.0193	1.0177

Note: DJF = December, January, February, etc.

Analysis of the CLD index

The consistency of the CLD index was assessed through comparison with the homogeneous regional rainfall series for northwest England (1873–2000) and southern Scotland (1931–2000) (Alexander & Jones, 2001; Jones & Conway, 1997), along with reconstructed inflow series for Thirlmere (Lake District) and Stocks (N. Lancashire) reservoirs (supplied by the Environment Agency). Annual totals of the CLD index are significantly correlated with both regional rainfall series for the available records (Fig. 4(a) and (b)). This suggests that the CLD index reflects the wider precipitation signature of northwest England and southern Scotland. Furthermore, CLD is highly correlated with annual precipitation totals at Seathwaite ($r = 0.88$, $p > 0.001$), indicating that the index is representative of even the wettest site in the Lake District.

The CLD index is also strongly correlated with the two inflow series (Fig. 4(c) and (d)), although data for Thirlmere indicate five outliers at the very beginning of the flow series (1920–1924). The same years appear as anomalies when annual inflows are plotted against the annual precipitation totals for northwest England (Fig. 4(e)), suggesting that the outliers are probably due to the reconstructed inflows rather than the CLD index (Stanley, personal communication). This example illustrates the value of long climate series for detecting non-homogeneity in derived hydrometeorological records or, at least, signalling the need for more detailed investigations of suspect data.

The robustness of the CLD index was further assessed by comparing observed and bridged monthly totals at GHC for data that were not employed in the final index (Fig. 5). From visual inspection, it is evident that the series bridged from KSG and KPO faithfully reproduce observed precipitation totals at GHC, but below average amounts are better represented than wet months, suggesting that (for earlier periods) the CLD index is a more reliable guide of the long-term "drought" history of the region. For example, noteworthy "droughts" in the late 1880s and early 1930s were replicated in the bridged series (see plots for KSG and RRH). Therefore, the remainder of the discussion focuses upon the occurrence and severity of relative droughts within the record.

Annual series of the seasonal CLD index reveal increases in winter, spring and autumn precipitation, offset by marked declines in summer totals since the 1960s (Fig. 6) that are consistent with analyses of national precipitation data (Alexander & Jones, 2001; Jones & Conway, 1997; Osborn *et al.*, 2000). Relative to the dry 1880s,

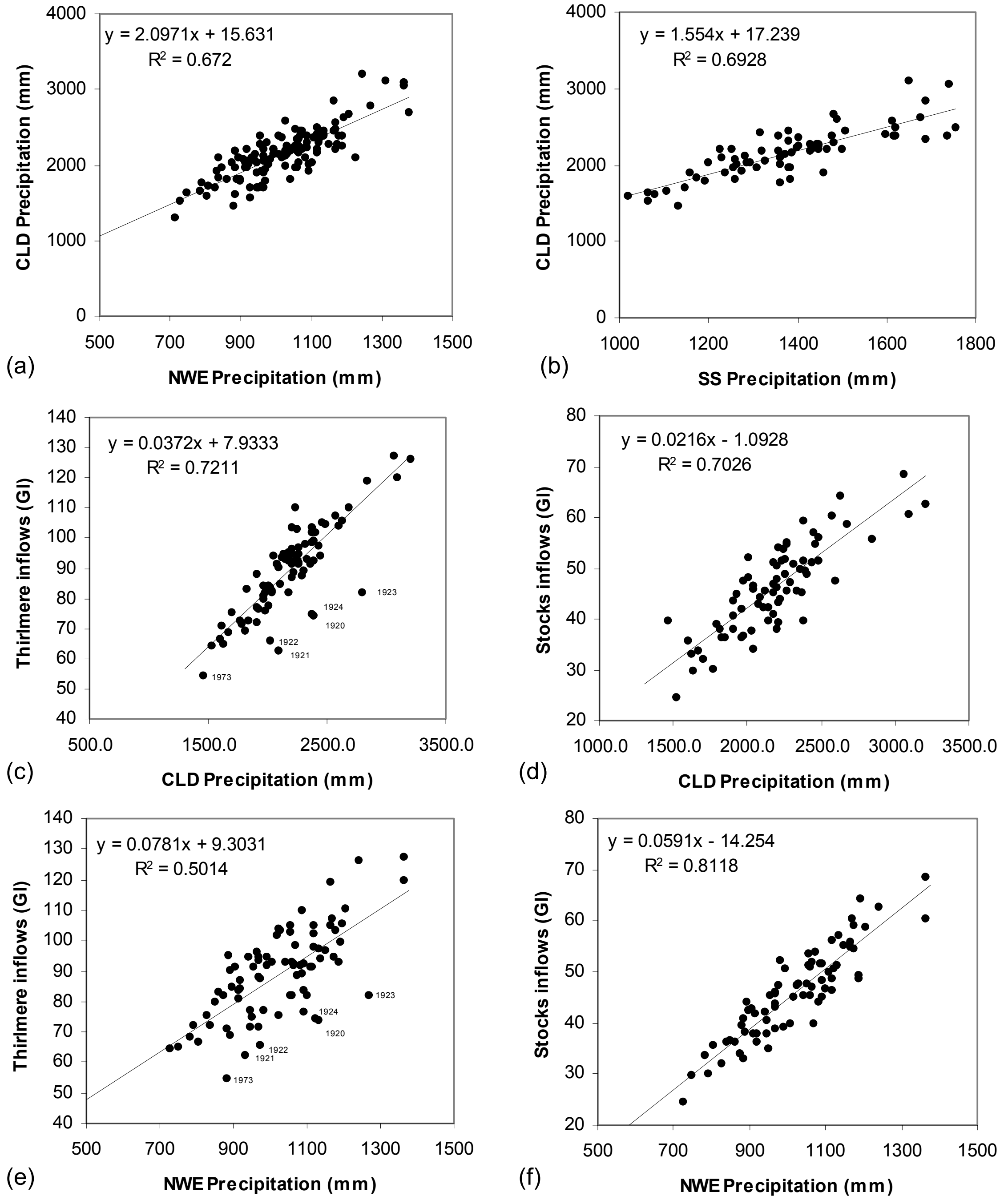

Fig. 4 Relationship between the annual central Lake District (CLD) precipitation index and (a) northwest England (NWE) (1920–2000), (b) southern Scotland (SS) (1931–2000) annual precipitation totals; annual inflows for (c) Thirlmere (1920–2000) and (d) Stocks (1927–2000) reservoirs. For comparative purposes, the relationship between annual NWE and annual inflows for (e) Thirlmere and (f) Stocks reservoirs are also shown.

seasonal precipitation totals in the wet 1990s were +37% in winter, +24% in spring, –9% in summer, and +11% in autumn; yielding a net difference of +17% in annual totals between the two contrasting decades. Changes in the partitioning of seasonal amounts are further reflected by the increasing winter-to-summer ratio, particularly

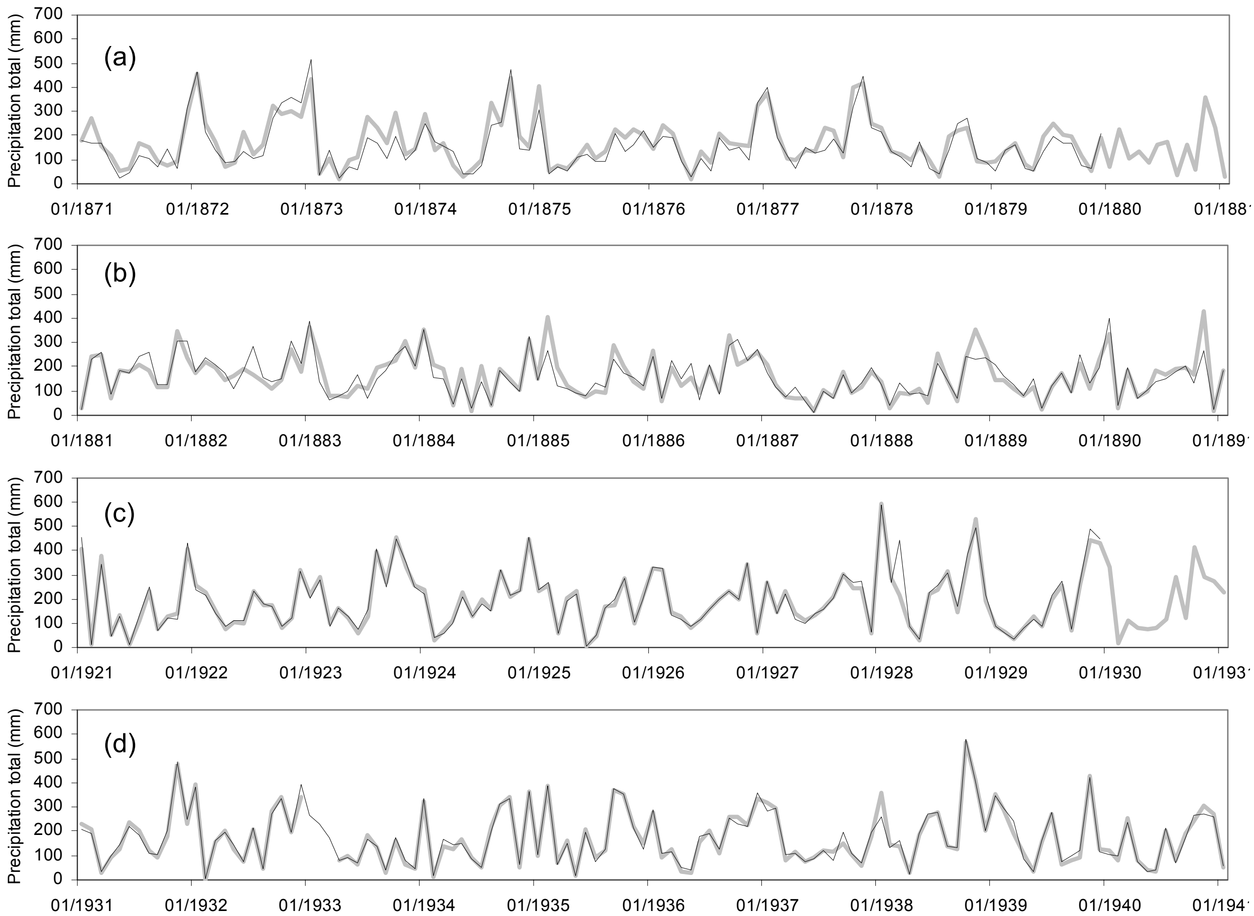

Fig. 5 Comparison of observed monthly precipitation totals (grey lines) at Grasmere High Close and bridged series (black lines) from (a) Keswick Post Office (1871–1879), (b) Kendal St Georges (1881–1890), (c) Rydal Stepping Stones (1921–1929), and (d) Rydal Hall (1931–1940).

since the 1960s. For example, the seasonal contrast for 1994/95 was the second greatest on record (Fig. 6) due to the combination of the sixth driest summer (Table 5(a)) and the fourth wettest winter (Table 5(b)) since 1788.

Overall, there was a marked preponderance of dry summers in the second half of the nineteenth century (see Brugge, 1993) that coincided with the onset of reservoir construction in the Lake District (Ritvo, 2003). Well-documented UK summer droughts of the late 20th century, such as 1976, 1984 and 1995 (Marsh & Monkhouse, 1993; Marsh & Turton, 1996), also figure prominently being ranked second, eighth and sixth, respectively. However, the terminating dates of the very driest 3-, 6-, 12- and 24-month totals (and their precipitation anomalies compared to 1961–1990) were respectively March 1829 (–81%), August 1984 (–68%), June 1855 (–48%) and July 1856 (–41%). The 1850s was the driest decade with –17% of the 1961–1990 average, and the 1920s the wettest decade with 111% average precipitation. The two wettest winters were 1833/34 (242% average rainfall) and 1999/2000 (188% average). The three-month period October–December 2000 was the second wettest such period in the CLD record with 180% average precipitation, again consistent with the national picture of widespread flooding at this time (DEFRA, 2001; Marsh, 2001a).

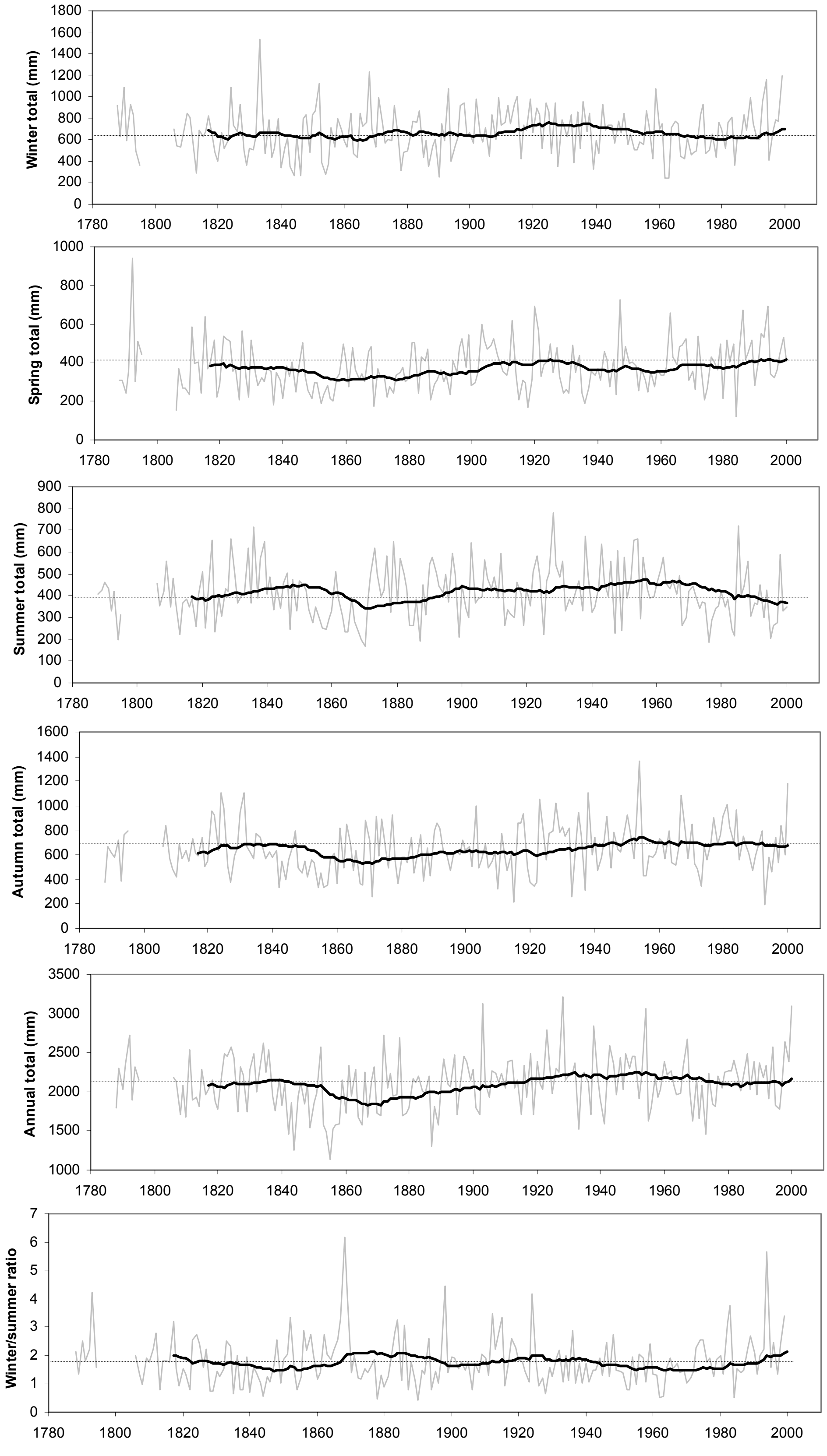

Fig. 6 Seasonal totals of the CLD index, including the winter/summer ratio for 1788–2000. The smooth line denotes the 30-year running average; the dashed horizontal line shows the 1961–1990 average.

Table 5 Seasonal totals (mm) since 1788 and year of occurrence. The climatological means for the period 1961–1990 are also shown.

Rank	DJF	MAM	JJA	SON	Annual
(a) *Lowest seasonal totals*:					
1	238 (1963)	123 (1984)	168 (1870)	195 (1993)	1139 (1855)
2	239 (1962)	153 (1806)	185 (1976)	219 (1915)	1256 (1844)
3	250 (1890)	169 (1918)	193 (1887)	254 (1933)	1307 (1887)
4	260 (1844)	176 (1869)	198 (1794)	262 (1871)	1453 (1842)
5	267 (1846)	184 (1837)	200 (1869)	312 (1937)	1462 (1973)
(b) *Highest seasonal totals*:					
1	1530 (1833)	941 (1792)	780 (1928)	1365 (1954)	3209 (1928)
2	1235 (1868)	724 (1947)	720 (1985)	1179 (2000)	3127 (1903)
3	1192 (1999)	695 (1994)	714 (1836)	1111 (1831)	3095 (2000)
4	1158 (1994)	694 (1920)	674 (1938)	1106 (1824)	3059 (1954)
5	1119 (1852)	668 (1986)	658 (1954)	1103 (1938)	2842 (1938)
Mean	**622**	**406**	**395**	**692**	**2115**

FORCING FACTORS

Long-term hydrometeorological series are invaluable sources of information for monitoring environmental change and attribution of forcing factors (Marsh, 2001b). One approach involves searching for periodicities that can be linked to contemporaneous quasi-cyclic phenomena, such as solar variability or ocean temperatures. Wavelet analysis provides one means of exploring the power spectrum of a time series and the robustness of any periodicity in the record. The interactive wavelet software of Torrence & Compo (1998) detected no periodicities at the 5% significance level that persisted throughout any seasonal record. However, strong signals were found in the 16–32 year wave-band of the spring CLD between the 1850s and 1880s and again between the 1940s and 1960s.

As noted previously, inter-decadal variations in seasonal rainfall and temperature across northwest Europe (Hurrell, 1995) and, more specifically, the British Isles (Wilby *et al.*, 1997) are linked to the NAOI. Other studies point to the weak forcing of European winter and spring precipitation by teleconnections to Pacific sea-surface temperatures (Lloyd-Hughes & Saunders, 2002; Wilby, 1993). Figure 7 indicates that CLD precipitation totals in winter (and to a lesser extent spring and autumn) are indeed strongly correlated with the NAOI. This also accounts for the weak association between the annual CLD and central England temperatures ($r = +0.36$, $p > 0.001$), i.e. wetter winters tend to be warmer winters because of strong zonal airflows from the North Atlantic. Similarly, higher values of the NAOI in recent decades have coincided with fewer days with ice cover on Lake Windermere (George, 1999).

There is an increasing expectation that human-induced global change will affect the future regional climatology of the UK. Recent summer drying and winter wetness in the central Lake District (Fig. 6) are consistent with the latest UKCIP02 climate change scenarios (Hulme *et al.*, 2002). For example, under the Medium-High emissions scenario, winter precipitation is projected to increase by 10–15% and summer totals to fall by 20–30% by the 2050s. Such changes are expected to have major ramifications for the region's river flows, amplified by natural multi-decadal variability (Arnell, 2003). In particular, projected decreases in summer river flows

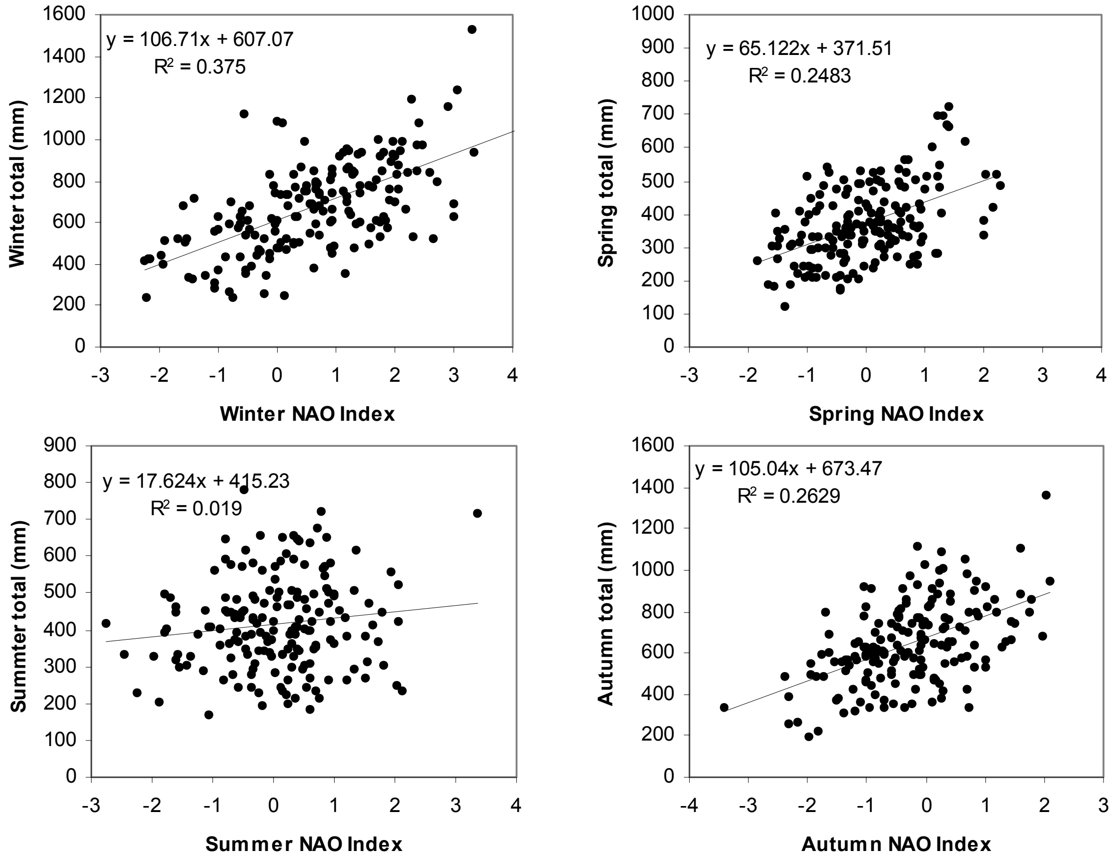

Fig. 7 Relationship between the North Atlantic Oscillation Index and seasonal precipitation totals of the CLD index, 1821–2000.

coupled with increased air temperatures could have significant consequences for the thermal regimes, inflows and ecohydrology of the Lakes.

DISCUSSION

The geographical context and hydroclimatology of the English Lake District means that the region provides an important barometer of nationally significant environmental assets. Using monthly precipitation series for stations in and around the central Lake District, a ~200-year index was constructed for the representative site at Grasmere. This bridged series shows a significant decline in summer rainfall since the 1960s, offset by increased precipitation in winter and spring that is strongly linked to North Atlantic forcing. As a consequence, one of the most striking features of the record is the marked increase in the ratio between winter and summer rainfall (as observed previously by Mayes, 1996). Over longer time periods, the record exhibits several notable dry (e.g. 1850s, 1880s, 1890s, 1930s, 1970s) and wet (e.g. 1820s, 1870s, 1920s, 1940s, 1990s) phases enabling recent decades to be placed within the context of long-term natural variability. Other work has suggested that there may be an elevation component to the changes, with higher altitude sites showing increases in winter precipitation unseen at lower elevations (Orr, 2000).

The strong link between CLD precipitation and the North Atlantic forcing may provide some scope for the development of a seasonal forecasting capability. For instance, the winter phase of the NAOI has predictive skill for a range of summer variables including temperature, precipitation, river flow and even crop yields (Kettlewell *et al.*, 2003; Wedgbrow *et al.*, 2002; Wilby, 2001, Wilby *et al.*, 2004). Preliminary analyses suggest a relatively weak association between the winter NAOI and summer CLD index (r = –0.17) compared with northwest England generally (r = –0.33) (Kettlewell *et al.*, 2003). However, further work is needed to ascertain the temporal robustness of such relationships and the extent to which other lagged predictors might provide useful outlooks for the Lake District's water and tourist industries.

Finally, the CLD index could provide a valuable reference series when implementing the EU Water Framework Directive to raise the quality of inland waters to "benchmarked" standards by 2015 (European Union, 2000). Given the fundamental control exerted by climate on Lake District ecosystems, and the variability inherent to these long time series data, climate variability and change will increasingly figure in the National Park's management plans.

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