The impact of changes in the weather on the surface temperatures of Windermere (UK) and Lough Feeagh (Ireland)

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Abstract The surface temperatures of Lake Windermere (UK) and Lough Feeagh (Ireland) have been recorded every day since 1960. Here, we examine the factors influencing these measurements and their associated weekly variance. At both sites, there was a progressive increase in the measured temperature but the rate of increase was very much greater in Lake Windermere. The variance of the Lake Windermere temperatures was negatively correlated with the cloud cover but there was no corresponding change in Lough Feeagh. Comparisons with the Lamb system of weather classification showed that the lake temperatures were closely correlated with these synoptic conditions. The highest winter temperatures were recorded during 'westerly' conditions and the highest summer temperatures under 'southerly' conditions. The most striking difference between the lakes was their response to cold winters and windy summers. Such results demonstrate that, lakes that are physically very similar can still 'filter' the climate signal in subtly different ways
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Key words Lake temperatures, weather patterns, climate change, UK, Ireland.

INTRODUCTION

Year-to-year changes in the weather have a major effect on the thermal characteristics of lakes (George, 1989; George *et al*., 2004). Changes in the air temperature and cloud cover regulate the flux of heat across the air-water interface whilst variations in the wind speed influence the vertical dispersion of heat. Lakes thus behave as integrators of the local weather and can even amplify very weak meteorological signals (George & Harris, 1985; George & Taylor, 1995). Very little attention has hitherto been paid to the way in which lakes respond to short-term changes in the weather. Climatologists have devised a number of different ways to quantify these changes. Some, such as the North Atlantic Oscillation Index (Hurrell,1995), are based on regional-scale gradients in the atmospheric pressure. Others, such as those devised Lamb (1972), are based on the detailed analysis of daily weather maps. Here, we use the system devised by Lamb for the British Isles to explore the impact of long-term changes in the weather on the surface temperatures of two deep, thermally stratified lakes.

There are very few long-term records of the day-to-day variations in the surface temperature of a lake. Most long-term studies rely on measurements taken at weekly or fortnightly intervals. Several automatic monitoring stations have recently been established in Europe (Rouen *et al.*, 2000) but these records are too short for systematic analysis. In this paper, we analyze some long-term records of the variations in the surface temperature of Lake Windermere in the UK and Lough Feeagh in Ireland. Both lakes are situated on the Atlantic coast and the measurements cover a 35-40 year period that extends from the early1960's to the late 1990's.

DESCRIPTION OF SITES AND METHODS

Windermere, the largest lake in the English Lake District, covers an area of 8.1 km2 and has a maximum depth of 60 m. It lies in a relatively sheltered valley (54º 22' N; 2º 56' W) and is divided into two basins by a large island. The surface temperatures were measured in a sheltered bay using a mercury thermometer with a resolution of 0.1oC. All measurements were taken in early morning (ca 8.30 hours GMT) to minimise the effects of near-surface heating. Lough Feeagh is a trough-like basin situated on the shores of Clew Bay in the west of Ireland (53o 50'N; 9o35'W). It has a surface area of 3.9 km2 and a maximum depth of 45 m. The surface temperatures were recorded by a Negretti system installed on the shore near the main outflow. The readings used were recorded at 06.00 GMT and the nominal resolution of the chart was 0. 1oC. The raw data from both sites was organised into a days vs years matrix and averages and standard deviations calculated for each week in each year. There were few breaks in the records, but weekend measurements at Lake Windermere were discontinued in the 1990's. Where measurements were not available for the full week, the means and standard deviations were calculated for the remaining 5 days.

The variations in the local weather

At LakeWindermere, meteorological data were acquired from two weather stations in the village of Ambleside (54º 24' N; 2º 57' W). The first station was in operation from 1960 to 1974 and the second from1971 to 2000. Here, we have combined the results to form a harmonised time-series that extends from January 1960 to December 2000. The average air temperature was calculated from the daily minimum and maximum and the cloud cover estimated by visual observation. At Lough Feeagh, meteorological data was acquired from a station located about 50 km away near the town of Belmullet (54º 13' N; 10º 0' W).Here all measurements were taken at hourly intervals by an observer stationed on site.

The variations in the regional weather types

The Lamb classification was originally based on a subjective analysis of daily weather charts but is now based on a multivariate analysis of the pressure gradients around the British Isles (Jones *et al*., 1993). The classification contains eight directional types, two non-directional types and an unclassified category. The directional types (N, NE, E,SE, S, SW, W and NW) are defined according to the general direction of the air flow. The non-directional types (A – anticyclonic and C – cyclonic) occur when high or low pressures systems are dominant. Table 1 shows the seasonal frequencies of the dominant circulation types as listed by Kelly *et al*. (1997).

Table 1 The frequency (%) of the dominant Lamb weather types between 1861 and 1990. From Kelly *et al*. 1997.

Lamb Weather Type	**Winter**	**Spring**	**Summer**	**Autumn**
Westerly (W)	23.0	12.3	17.9	19.7
Anticyclonic (A)	16.1	17.3	18.9	18.9
Cyclonic (C)	10.7	12.0	16.1	12.1
Northerly (N)	3.3	5.6	4.8	4.6

The main circulation types are the westerly, the anticyclonic, the cyclonic and the northerly. There are no major differences in the seasonal distribution of these categories but westerly conditions are more common in winter. Here, we relate the seasonal variations in the lake temperatures and their variability to the changing frequency of westerly and anti-cyclonic conditions. Records of the week-to-week variation in these weather types were abstracted from a web page maintained by the Climate Research Unit (www.cru.uea.ac.uk) and then correlated with the lake measurements. In this way, we could relate both the seasonal variation in the surface temperature of the lakes and their weekly variance to the changing frequency of the dominant weather types.

RESULTS

The seasonal variation in the surface temperature

Fig. 1 shows the average week-to-week variation in the surface temperature of Lake Windermere and Lough Feeagh.

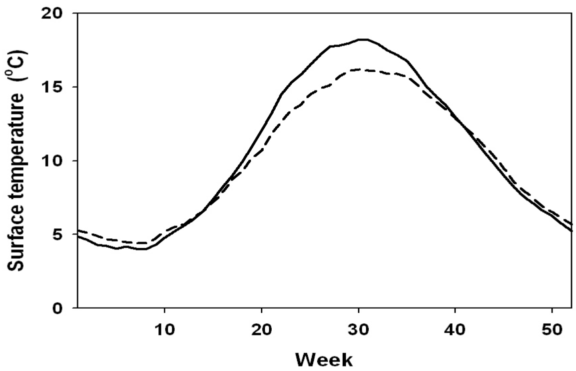

Fig. 1 The seasonal variation in the average surface temperature of Lake Windermere (-) and Lough Feeagh (--).

The seasonal variations recorded at the two sites were very similar but the summer temperatures in Lake Windermere were about 2°C higher than that those in Lough Feeagh. The main factor influencing the surface temperature of a deep lake is the duration and intensity of thermal of stratification. The onset of stratification was practically the same at the two sites but the autumn overturn was a few weeks earlier in Lough Feeagh. The relative exposure of the two sites also has an effect on the stability of the thermocline. The average depth of the thermocline in the two lakes is about 13m but the temperature gradients that develop in Lake Windermere are rather steeper than those reported from Lough Feeagh.

The long-term change in the surface temperature

Figs. 2a and 2b shows the long-term change in the surface temperature of Lake Windermere and Lough Feeagh. The points show the annual means, the lines the three-point running means and the linear regressions the trend. In both lakes, there was a sustained increase in the average temperature but the rate of increase was greater in Lake Windermere than in Lough Feeagh.

At Lake Windermere, the temperature increased by 1.4^{o}C between 1960 and 2000. At Lough Feeagh, the increase was only 0.7^{o}C between 1960 and 1997. The other difference between the lakes was the pattern of change experienced in the 1990's. In Lake Windermere, a rising trend was still evident but the temperature variations in Lough Feeagh were then more irregular. Figs. 2c and 2d shows the long-term change in the variability of the temperature measurements from Windermere and Lough Feeagh. The points show the annual means of the standard deviations and the lines the three-point running means. The range of variation and the pattern of change were strikingly different at the two sites. In Lake Windermere (Fig. 2 c), the standard deviations increased in the 1960's and 70's before declining in the 1980's and 90's. In Lough Feeagh, the standard deviations were lower and remained more or less constant until they increased in the 1990's.

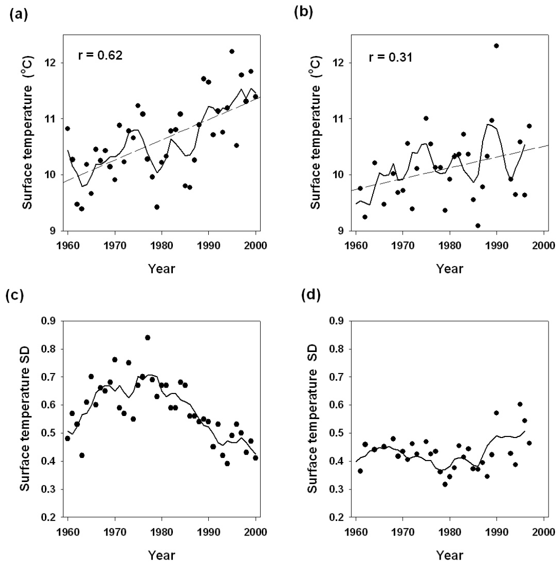

Fig. 2 The long-term trend in the surface temperature of (a) Lake Windermere and (b) Loch Feeagh. The long-term trend in the variability (standard deviation) of the temperature measurements from (c) Lake Windermere and (d) Lough Feeagh. The solid lines are the three-point running means and the broken lines fitted regressions.

Factors influencing the surface temperatures and their variability

In lakes that are free of ice, the surface temperature is closely correlated with the local air temperature. Figs. 3a and 3b show the relationship between the surface temperature and the air temperature at Lake Windermere and Lough Feeagh. At Lake Windermere, there was a very strong positive correlation between the two variables ($r = 0.93$, $p < 0.001$). At Lough Feeagh, the correlation with the Belmullet air temperatures was lower ($r = 0.72$, $p < 0.001$) but this site was 50 km away from the lake. A number of factors can influence the surface temperature of a lake but the most important are the wind speed and the cloud cover. Since there were no wind speed measurements for the sites, our analyses were confined to cloud cover. Fig. 3c and 3b show the relationship between the average standard deviation of the temperature measurements at Lake Windermere and Lough Feeagh and the average cloud cover at the meteorological stations. At Lake Windermere (Fig. 3c), there was a significant negative correlation between the two variables but the variations at Lough Feeagh were not correlated with the cloud cover at Belmullet.

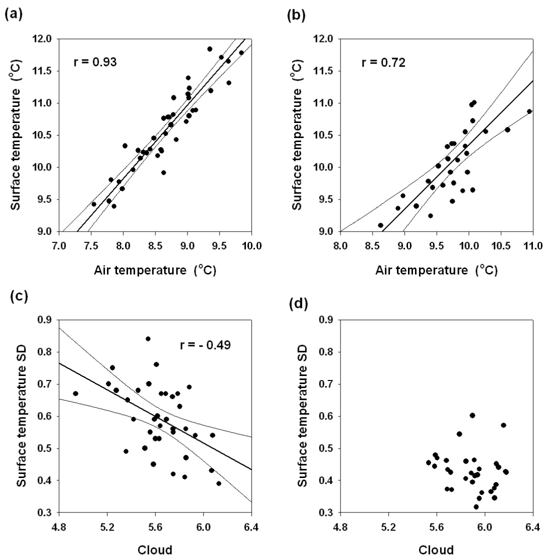

Fig. 3 The relationship between the average temperature of (a) Lake Windermere and (b) Lough Feeagh and the local air temperature. The relationship between the variability (standard deviation) of the temperature measurements in (c) Lake Windermere and (d) Lough Feeagh and the local cloud cover. The heavy lines show the fitted regressions and the light lines the 95% confidence intervals.

The influence of westerly weather on the surface temperature

This weather type is typically associated with higher winds along the western seaboard and milder, wetter conditions during the winter. Fig. 4a and 4b show the effect that this weather type had on the surface temperatures of Lake Windermere and Lough Feeagh. The points show the correlation between the surface temperature in a particular week and the number of westerly days recorded over the same period. The solid line shows the three-point running mean and the broken lines the significance levels for the correlation coefficients. The seasonal variation in these coefficients was very similar at the two sites. At both sites, an increase in the number of westerly days was associated with higher temperatures in the winter and lower temperatures during the summer.

Fig. 4c and 4d show the effect that westerly weather had on the variability of the temperature measurements. In Lake Windermere (Fig. 4c), the correlations were generally low but a few significant negative relationships were recorded during the winter. The pattern in Lough Feeagh (Fig. 4d) was very different. Here, the correlations were more variable and several significant negative relationships were recorded during the summer. The most likely explanations for these differences are the colder winters experienced in Windermere and the windier summers in the west of Ireland.

During the period of study, the average winter air temperatures recorded at Ambleside were 2.7°C lower those recorded at Bellmullet. In contrast, the average summer wind speeds at Belmullet were 2.5 m s^{-1} higher than those recorded at Ambleside.

Cold winters can result in more variable surface temperatures if there are day-to-day variations in the rate of convective cooling. Windy summers can have the same effect by cooling the surface or entraining colder water from deeper layers.

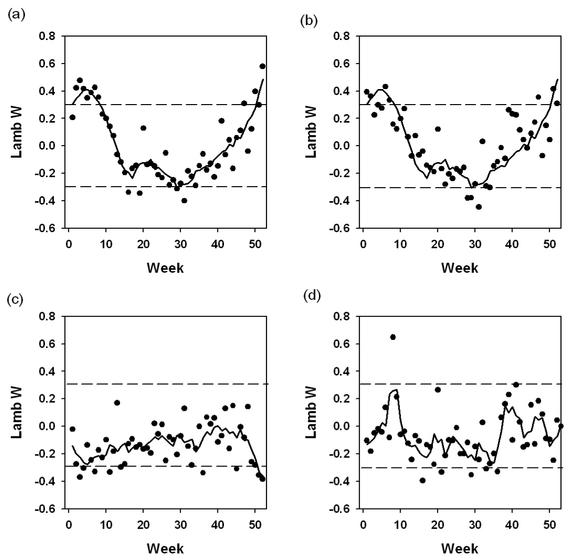

Fig. 4. The correlation between the weekly temperatures of (a) Lake Windermere and (b) Lough Feeagh and the frequency of 'westerly' conditions. The correlation between the variability (standard deviation) of the weekly temperatures in (c) Lake Windermere and (d) Lough Feeagh and the frequency of 'westerly' conditions. The solid lines show the three-point running means and the broken lines the significance levels.

THE INFLUENCE OF ANTICYCLONIC CONDITIONS ON THE SURFACE TEMPERATURE

Anticyclonic conditions are typically associated with cold weather during the winter and warm weather during the summer. Fig. 5a and 5b show the effect that this weather type had on the surface temperatures of Lake Windermere and Lough Feeagh. The points show the correlation between the surface temperature in a particular week and the number of anticyclonic days recorded over the same period. The solid line shows the three-point running mean and the broken lines the significance levels for the correlation coefficients. The seasonal variation in the coefficients was again very similar at the two sites. At both sites, the lowest winter and the highest summer temperatures were recorded when there was an increase in the number of anticyclonic days. Fig. 5c and 4d show the effect that these anticyclonic conditions had on the variability of the temperature measurements. In Lake Windermere (Fig. 5c), the correlations were low but a number of significant positive correlations were recorded during the summer. In Lough Feeagh (Fig. 5d), the correlations were higher and a large number of 'positive' summer relationships were matched by a few 'negative' winter relationships. These differences can again be explained by the relative exposure of the two lakes. Since changes in cloud cover have very little effect on the variability of the Lough Feeagh record, changes in the wind speed must be responsible for most of the variability shown in Fig. 5d.

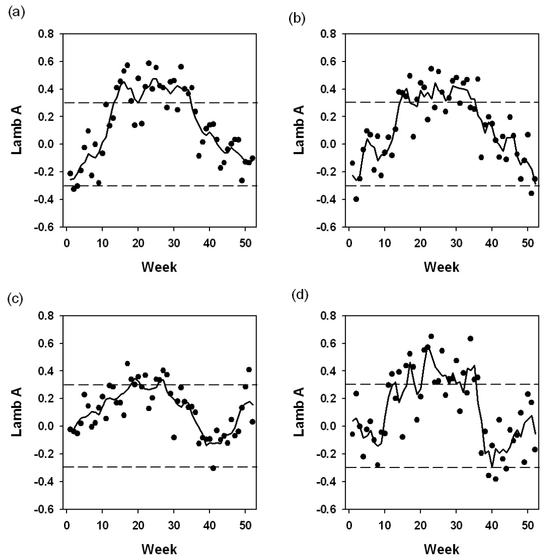

Fig. 5 The correlation between the weekly temperatures of (a) Lake Windermere and (b) Lough Feeagh and the frequency of 'anticyclonic' conditions. The correlation between the variability (standard deviation) of the weekly temperatures from (c) Lake Windermere and (d) Lough Feeagh and the frequency of 'anticyclonic' conditions. The solid lines show the three-point running means and the broken lines the significance levels.

DISCUSSION

In this paper, we have compared the thermal responses of two lakes that are exposed to the same weather systems but are topographically rather different. Lake Windermere is morphometrically complex basin situated in a sheltered valley about 20 km from the sea. Lough Feeagh is a trough-like basin situated in a more open location very close to the sea. The data assembled here showed that the surface temperature of both lakes increased progressively during the period of study but the rate of increase was much greater in Lake Windermere. The most likely explanation for this difference is the more exposed situation of Lough Feeagh and its sensitivity to wind induced mixing. The frequency of severe gales over the British Isles has increased in recent years and there has also been an increase in the wave heights measured in coastal waters (UKCIP, 2002). Our analyses also show that quite subtle changes in the local weather can have a significant effect on the temperature of the lakes. In Lake Windermere, the variability of the temperature measurements has recently declined due to a progressive increase in the cloud cover. No such effect was observed in Lough Feeagh where the variance increased over the same period.

The weather type correlations for the two lakes show that the system of weather classification designed by Lamb for the British Isles works well for the west of Ireland. The weekly correlations between the surface temperatures and these synoptic categories were very similar at the two sites. There were, however, systematic differences in the correlations noted with the weekly variance that may be again be related to the difference in exposure. Such results demonstrate that, lakes that are physically very similar, can 'filter' the imposed climate signal in a different way. At present, we know very little about these filtering effects. The weather pattern approach adopted here has the merit of quantifying these integrating effects using indices that can be directly related to regional-scale changes in the atmospheric circulation.

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