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Survey of stable isotope values in Irish surface waters

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Abstract

We present a study of the spatial distribution of $\delta^{18}O$ and δD values of lake and river waters from 144 locations in Ireland. Before we can gain a better understanding of paleoclimate records derived from lacustrine carbonate minerals we must understand mechanisms that produce variation in isotope values of modern surface waters. The focus of this study is to provide insight into the behavior of lakes and rivers in Ireland, including source, recycling and loss through evapotranspiration. The short duration of sampling in this project provides a snapshot of modern isotope variability to be applied towards long-term climate change in Ireland and provides a basis of comparison for other proxy records.

Introduction

Recent studies of Northern Hemisphere Holocene climate reveal that the Holocene is dominated by several climate regimes punctuated by periods of rapid climatic change (e.g., Dansgaard et al. 1993; Alley et al. 1997; Anderson et al. 1997; Fisher et al. 2002). During the summer of 2003, Europe experienced some of the highest temperatures recorded since the development of meteorological instruments. France experienced the warmest summer on record, leading to as many as 14,000 heat-related deaths (NCDC 2004). Furthermore, climate models predict that wetter winters will be five times more likely to occur in central and northern Europe (Palmer and Raisanen 2002) suggesting an increased climate impact on Europeans. Many of these recent increases in northern hemispheric surface temperatures may be partly explained by changes in the North Atlantic Oscillation on decadal time scales that are associated with increasing or decreasing strength of the westerlies (Hurrell 1995; Hurrell et al. 2001). To better understand and help predict future climate change requires development of more long-term paleoclimate records in order to facilitate construction of a baseline of climate change for climate models. This necessitates a modern spatial reference with which to interface modern analogs with paleoclimate archives (Bowen and Wilkinson 2002) such as speleothems, ice cores, lacustrine calcite records, lake sediment cellulose, trees rings, and many other isotope proxies (e.g., Kirby et al. 2001; McDermott et al. 2001; Sauer et al. 2001; Anderson et al. 2002; McFadden et al. 2004; Leng and Marshall 2004).

Lacustrine carbonate records derived from lake sediment cores can provide a diverse suite of information that includes temperature, humidity, precipitation, lake productivity and terrestrial vegetation (e.g., Kirby et al. 2002; McFadden et al. 2004; Leng and Marshall 2004). However, $\delta^{18}O$ records derived from lakes are often dominantly controlled by changes in precipitation that alter $\delta^{18}O$ values of lake water. $\delta^{18}O$ values of precipitation at mid- to high-latitudes correlate somewhat

with mean annual surface temperatures such that higher temperatures are reflected by higher $\delta^{18}O$ values (Fricke and O'Neil 1999). The influence of changing storm tracks and complicated weather patterns is only beginning to be understood (e.g., Burnett et al. 2004). Continental isotope records frequently display large variation in $\delta^{18}O$ values and are thus likely controlled by changes in the water vapor and temperature of the ocean source area. This large variation may also be caused by changes in temperatures at the precipitation site that may require source area corrections before interpretations are made of isotope proxy records (Grootes 1993). Little research has focused on the distribution of isotopes across a geographic area, but has rather generally focused on climate and $\delta^{18}O$ values of precipitation (Bowen and Wilkinson 2002). $\delta^{18}O$ in precipitation in mid- and high-latitudes correlates well with mean annual surface temperatures (Rozanski et al. 1993). Ultimately, this suggests that changes in climate that alter temperature gradients will alter the resulting isotope value (Fricke and O'Neil 1999). If changes in climate through time alter temperature patterns, then it is not possible to use well-known mean annual temperature models (e.g., Dansgaard 1964) to calculate temperature or $\delta^{18}O$ values in precipitation through the geologic time (Fricke 1999) because these relationships may be incorrect (Bowen and Wilkinson 2002). Detailed analysis of local study areas are needed if the longer geological records are to be realistically interpreted.

Analyses of lacustrine proxy records require detailed local studies of the spatial distribution of isotope values of precipitation and meteoric waters to determine whether lacustrine isotope records are reflective of local or regional climate. Evaluation of modern surface waters is also important in characterizing the degree of isotopic variability across a geographic area. Spatial variations in modern meteoric waters can also be evaluated to determine such climatic parameters as sources of precipitation, transport, recycling of water, and residence times of water bodies. If there are large variations in isotope values across a generally small region, this suggests that climate may be controlled by multiple parameters such as different air masses. Changes in behavior of air masses can play a large role in altering isotope values of precipitation at high latitudes (Fricke 1999). Furthermore, this would suggest that multiple lake cores across this region are required to best characterize regional climate. The record stored in individual lakes will vary depending on differences in depth, area, catchment size, and many other intrinsic and extrinsic factors.

In an ongoing climatological study of Ireland, we relate variation in sediment isotope values to the circumpolar vortex, the Atlantic Ocean, changes in the Gulf Stream and reduced continentality (Diefendorf and Patterson, unpublished data). A $\delta^{18}O$ calcite record from the late Pleistocene through the Holocene at Lough Inchiquin in western Ireland requires significant variability in $\delta^{18}O$ values of lake water to explain changes in $\delta^{18}O_{calcite}$ values. It is important to determine whether this variability in $\delta^{18}O$ values exists in modern surface waters across the region. If so, this would suggest strong site-specific controls on isotope values of surface waters where low variations in climate exist. With this information in hand, we will have a basis to compare paleolacustrine sediment records and to determine if the lakes of interest are unique or generally representative of regional lakes.

Study area

Ireland has a temperate maritime climate where annual changes in temperature are moderated by the proximity of the Atlantic Ocean (Jordan 1997) resulting in low seasonal variation. The influence of the Gulf Stream provides an additional moderating effect on Ireland's climate (Kiely et al. 1998). The mean annual temperature of Ireland is 9.0 °C, with average summer maximum temperatures of 19.0 °C and average winter minimum temperatures of 2.5 °C. Average monthly temperatures at Valentia (Global network for Isotopes in Precipitation), western Ireland vary from 6.9 °C in January to 15.1 °C in August (IAEA 2001). Average annual rainfall varies from 800 to 2800 mm across Ireland with 1 mm or more of rain falling 150 days each year, with proportionately more during the summer. The majority of rain is in the southwest, west, and the northwest portions of Ireland (MET 2004) with as much as 1400–1600 mm per year (Jordan 1997). The probability of days with rain in western Ireland during summer months can be up to 50% and during winter months as high as 80% (Kiely et al.

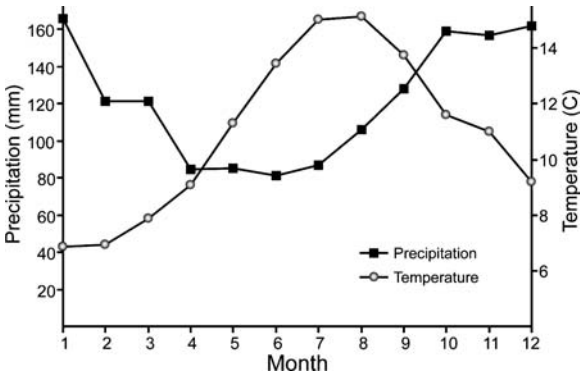

Figure 1. Valentia, Ireland GNIP monthly averaged precipitation and temperature data from the years 1957 to 2001. The summer is characterized by highest temperatures and lowest rainfall.

1998). Relative humidity in Ireland is generally high, averaging between 70% and 90% (MET 2004). In the more central western part of Ireland, climate is very similar to the Valentia IAEA site with higher annual rainfall than the rest of Ireland.

Rainfall data has been tracked at Valentia since 1957 as part of the IAEA project on collecting isotopes in precipitation. Meteorological data were grouped monthly with arithmetic mean, minima, and maxima calculated each month (Figure 1). Mean monthly precipitation at this site varies from 166 mm in January to 81 mm in June. Winter months contribute a major component of total annual precipitation, occasionally twice that of summer. Temperature is highest in July and August averaging 15.0 °C. A gradual decrease occurs to the coolest temperatures in January of ~7.0 °C. This rather small variability in temperatures for such high latitudes is due to proximity of the Atlantic Ocean, which moderates Ireland's climate.

Methods

Samples were collected in Ireland during June and July of 2003 (Figure 2, see supplemental information). Water was collected using 30 or 60 ml Nalgene® bottles. Sample locations were established using a Magellan® GPS and Ireland Ordnance Survey topographic maps at a scale of 1:50,000. Sample names were recorded using the original Gaeilge (Irish Gaelic).

δD and δ^{18}O values were determined using a continuous flow pyrolysis technique. Aliquots of 1 μl of water are injected via septa into a Finnigan MAT TC/EA via a GC PAL® auto-sampler using a 10 μl syringe. Water is vaporized in a ceramic column lined with glassy carbon and packed with glassy carbon fragments at 1450 °C and reduced to CO and H_2 gases. These gases are passed through the system using ultra-high purity helium as the carrier gas. Gases exiting the column are separated in a 5 Å molecular sieve gas chromatograph at 90 °C followed by a Conflo III interface/open split for helium dilution. Gas is measured on a Finnigan MAT Delta Plus XL mass spectrometer relative to reference gases from the dual inlet port. Samples are analyzed using four internal standards (characterized by VSMOW, VSLAP, and GISP). Multiple injections are employed to minimize any memory effect associated with needle contamination or with the glassy carbon reactor. Data reduction is conducted using a two-point calibration with two of the internal standards, corrected for drift using a third internal standard (normally less than 1‰ on δ^{18}O and 2‰ on δD throughout a run), and the fourth internal standard is used as a check to determine run reproducibility. Sample precision is determined to be ± 0.3‰ for δ^{18}O and ± 3.0‰ for δD (1σ, $n = 45$) using an internal standard and all values are reported relative to VSMOW.

Results and discussion

IAEA/GNIP precipitation at Valentia

Data were obtained from the IAEA station in Valentia to determine long-term changes in precipitation in Ireland and as a general comparison to regional water sampling at lower temporal resolutions (IAEA 2001). The IAEA site measured temperature, precipitation, tritium, δD, and δ^{18}O values from most months encompassing the years between 1957 and 2002. Although these data are only available for the Valentia station in the southwestern part of Ireland, they provide a framework for initial investigations into precipitation isotope data and ultimately surface water in Ireland.

A total of 339 monthly averaged samples for both δD and δ^{18}O were taken during this period by the IAEA and a local meteoric water line (LMWL) was calculated from the δD and δ^{18}O

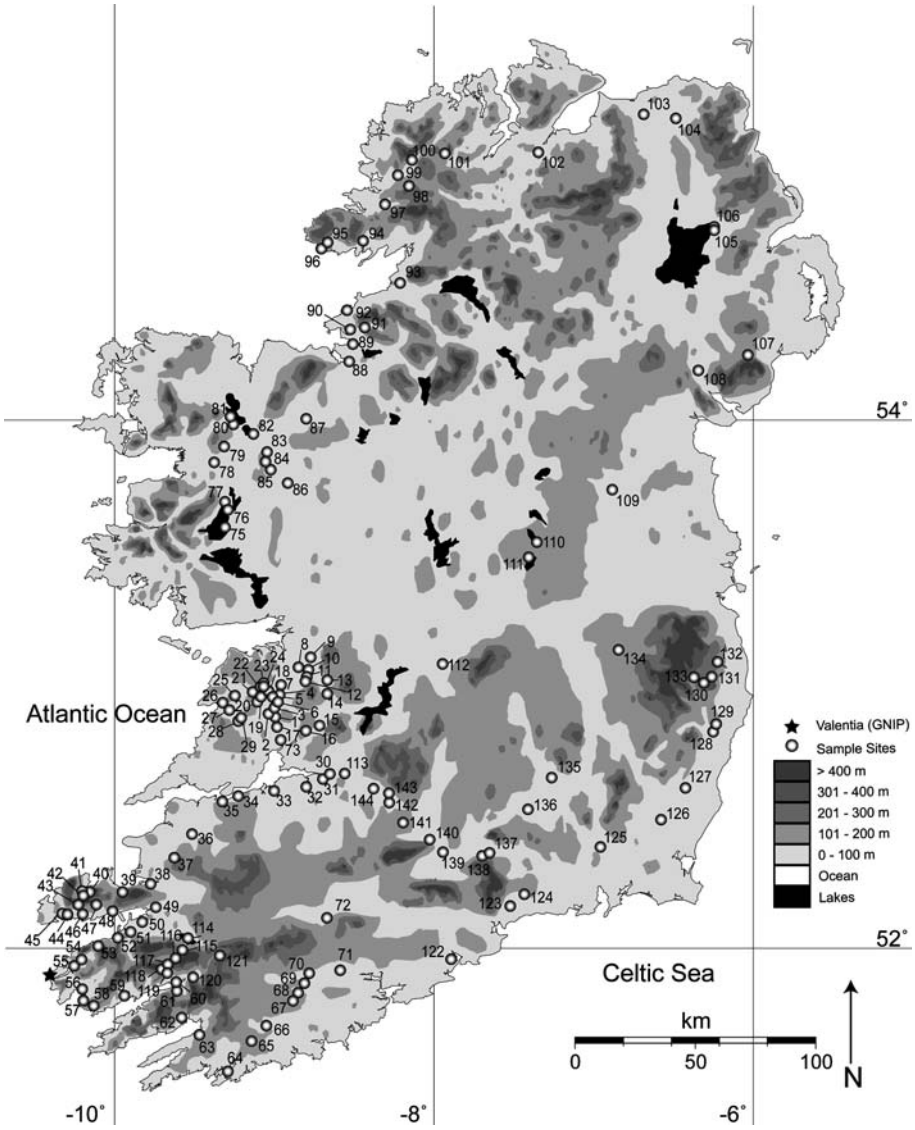

Figure 2. Locations and respective numbers of surface water sample sites in Ireland. The Ireland GNIP collection site at Valentia is marked with a star. Elevation contours are shown as well for comparison.

values (Craig 1961; Dansgaard 1964) and is reported in Figure 3. The best-fit regression line (least squares assuming low standard error) for the data is described by an equation for the LMWL of $\delta D = 6.86\ (\pm 0.13) \bullet \delta^{18}O + 1.97\ (\pm 0.71)$ ($r = 0.94$, $n = 339$). Long-term monthly averages were also calculated, as well as the minimum and maximum value for each month (Figure 4), with precipitation varying by 3.6–15.5‰ in $\delta^{18}O$ and δD, respectively. However, variations between minimum and maximum values for each month can be significant. This range in values is most extreme in January with a difference of −7.8‰ in $\delta^{18}O$ and −55‰ in δD. This can be attributed to an increased frequency of storms, decreased temperatures, and increased snow during winter months. Winter values are lower than summer values due to lower condensation temperatures. As a result, greater fractionation of isotopes occurs as proposed by Dansgaard (1964) and Rozanski et al. (1993).

The deuterium excess ($d = \delta D - 8 \bullet \delta^{18}O$; Dansgaard 1964) has been previously studied by Rozanski et al. (1993) for Valentia. Monthly

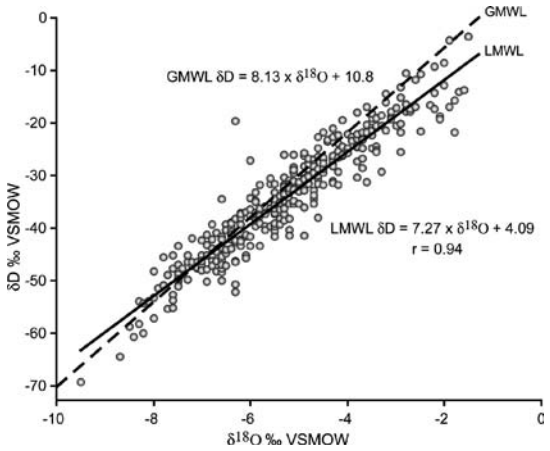

Figure 3. Isotopes in precipitation at the GNIP site in Valentia. Samples are averaged monthly. A LMWL (solid line) and a GMWL (dashed line) are for comparison.

d-excess values have been calculated from the IAEA data set at Valentia (Figure 5): mean values range from 4.5 to 10.5‰ with the highest values occurring in the winter and the lowest values occurring in the summer. The largest variability in monthly *d*-excess values occurs during the winter months. Differences in *d*-excess values between summer and winter months are caused by two main factors: lower relative humidity in the source region (Atlantic Ocean) during evaporation of the source waters imparting a kinetic fractionation of the vapor during the winter months and lower relative humidity in summer months causing partial evaporation of raindrops during precipitation events (Rozanski et al. 1993). This causes the LMWL to have a slope less than 8 due to this bimodal distribution of isotope values (Rozanski et al. 1993).

Surface water data results and discussion

Samples were collected during a three-week period in June and July, thus reflecting low temporal resolution, but may be considered as a snapshot of stable isotope values of surface waters for one season. A few samples were taken at sites that appeared in the field to have a tidal influence and therefore may have an isotopic signal influenced by seawater (samples 38, 102, and 122 not used in data analysis).

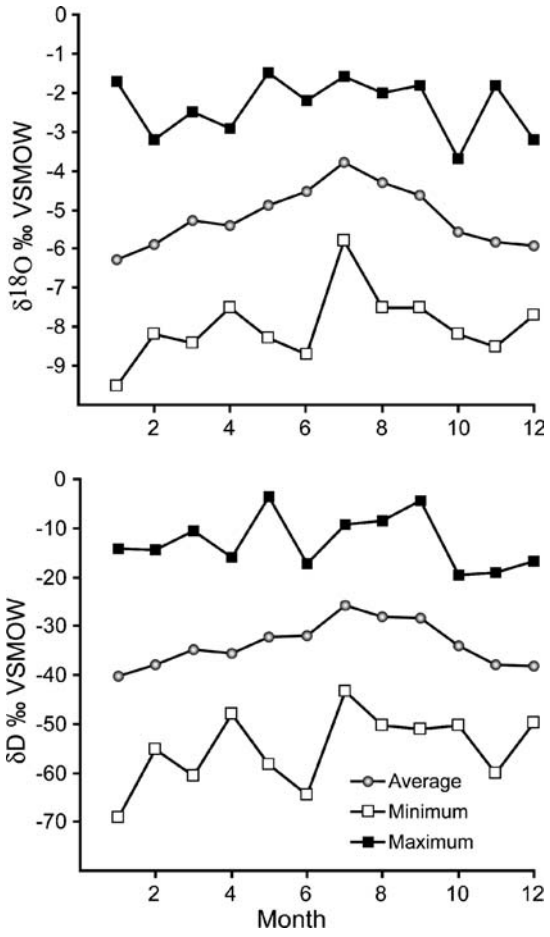

Figure 4. Monthly averaged isotopes in precipitation at the GNIP site in Valentia for δ^{18}O and δD.

Surface water δ^{18}O values range from -7.4 to -2.4‰, averaging -5.4‰, and δD values ranging from -53 to -17‰, averaging -37‰. Sample values were separated into lakes, rivers unrelated to lakes (not downstream), rivers downstream of lakes, and reservoirs. Linear regressions (least squares assuming low standard error) were calculated for each group of data (except reservoirs) and equations are shown on Figure 6. The slopes all have equations that are lower than the GMWL and a majority of the data plot below the GMWL. A study of fresh waters in the British Isles also records similar results, although the number of surface waters is low (Darling et al. 2003). The slopes are all lower than the GMWL because surface waters are affected by evaporation that results in values plotting with lower slopes than the

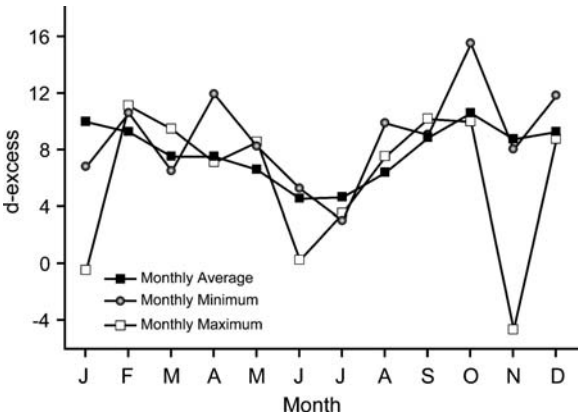

Figure 5. Monthly averaged *d*-excess values from in precipitation at the GNIP Valentia.

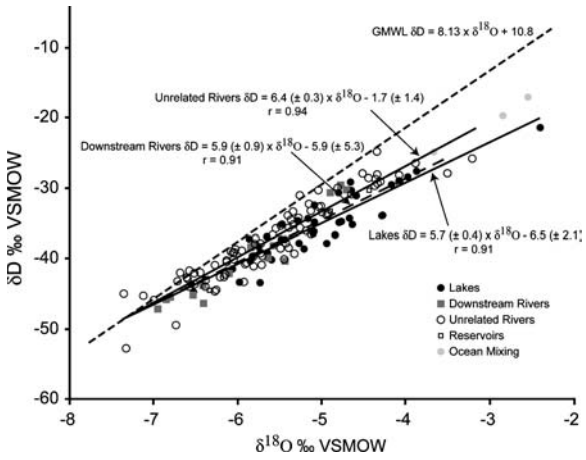

Figure 6. $\delta^{18}O$ and δD values of types of surface waters in Ireland and their respective best fit equations and are compared to the GMWL.

GMWL. As expected, lakes have the lowest slope of all the surface waters. Lakes have lower slopes than rivers in part due to increased residence time (Gibson et al. 2002) resulting in greater evaporation, thus causing values to be higher due to preferential evaporation of $H_2{}^{16}O$. Initially, we were surprised that downstream rivers had a slope higher than lakes (7.6 ± 0.6) because downstream rivers should have characteristics more in common with lakes. However, after closer examination of the data, these differences are caused by the 3 highest samples (41, 42, and 52), which are the only downstream rivers located in the southwest of Ireland (Kerry Peninsula). These three sites affect the slope because of the higher humidity and higher rainfall due to the proximity of the Atlantic Ocean. After removing these three values, the downstream rivers have an equation that is the same as the lakes (within tolerances) and is shown on Figure 6.

Samples were also plotted geographically with ranges outlined for $\delta^{18}O$, δD, and *d*-excess values (Figures 7, 8, 9). δD and $\delta^{18}O$ have similar contours as expected due to the same processes controlling both isotopes. However, there is a larger effect on δD values due to increased kinetic fractionation. Contour lines are closest along the west coast and become further apart inland. Surface water values across Ireland exhibit several general trends. δD and $\delta^{18}O$ values are significantly higher in western Ireland decreasing to the east. This correlates to general precipitation trends with prevailing winds coming from the southwest (Kiely et al. 1998). Isotope values decrease to the east due to progressive distillation of air masses as rain tracks west to east.

There does appear to be a correlation between altitude and isotope values of surface waters. However, integral stream head altitude was not factored into this study and therefore a more rigorous comparison was not attempted at this time. Altitude isotope effects are generated by adiabatic cooling and resultant isotopic fractionation during rainout of precipitation. Thus, higher altitude regions of Ireland generally correlate with lower isotope values. Some general altitude effects may be seen in the Kerry Peninsula where $\delta^{18}O$ values range from -3.9 along the coast to $-5.5‰$ further inland on the peninsula. This corresponds to a change in altitude of about 600 m or $0.27‰$ per meter, within the general altitude effect of -0.15 to $-0.5‰$ per meter (Clark and Fritz 1997). Because few mountains in Ireland are higher than 1000 m, altitude effects are mostly localized.

The Burren watershed

The Burren region of County Clare in western Ireland is of considerable interest due to its unique ecological, archaeological, and climatological setting (Drew and Magee 1994). Although the region covers less than one percent of the land surface of Ireland, more than half of the country's native species of flora are found there (Drew 1994). Geology is dominated by Lower Carboniferous

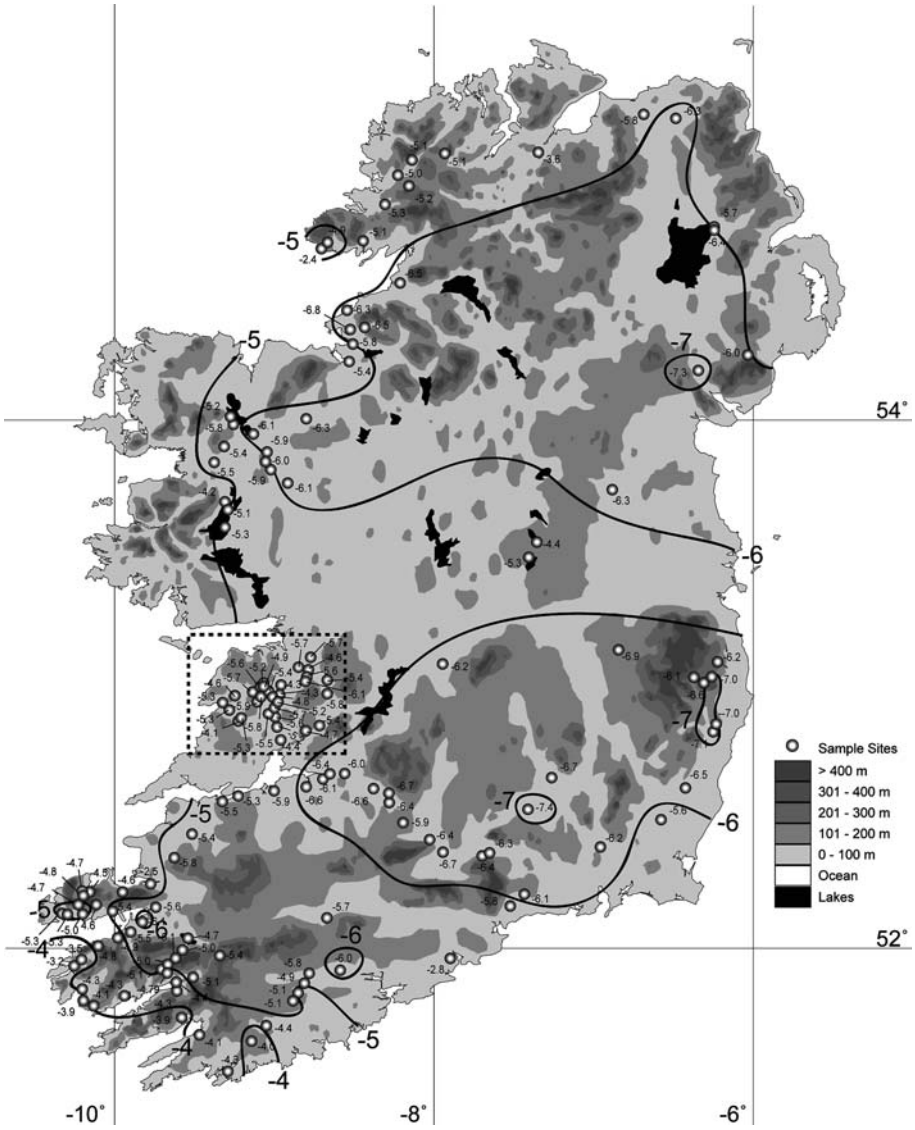

Figure 7. Contour line of $\delta^{18}O$ in Irish surface waters with sample values next to positions. All values are in ‰ VSMOW. Detailed map of surface waters of The Burren, dashed box, are shown in Figure 9.

limestone deposited in shallow equatorial seas (Moles and Moles 2002). Since the last glacial maximum, ~17,400 cal. yr B.P. in Ireland (Bowen et al. 2002), many areas of this region have remained non-vegetated due to the lack of soil formation in the higher areas and only moderate soil formation in the valleys. Moles and Moles (2002) have undertaken detailed studies of the Burren's soils to determine soil processes, accounting for the loss of the region's soils and to develop future management practices for The Burren National Park. Burren hydrology is not well understood due to the complicated karstic nature of the region (Drew 1990) Furthermore, few studies have examined the numerous lakes in a regional context. To date, studies have been confined to temperature, dissolved oxygen, and heat budgets of only a few of the numerous lakes (Allott 1986). Additionally, this region has numerous seasonal lakes called turloughs that are found in regions underlain by limestone that generally flood in the autumn and drain through swallow holes by spring (Coxon 1987). Lakes of the Burren contain superb high-resolution records of climate change.

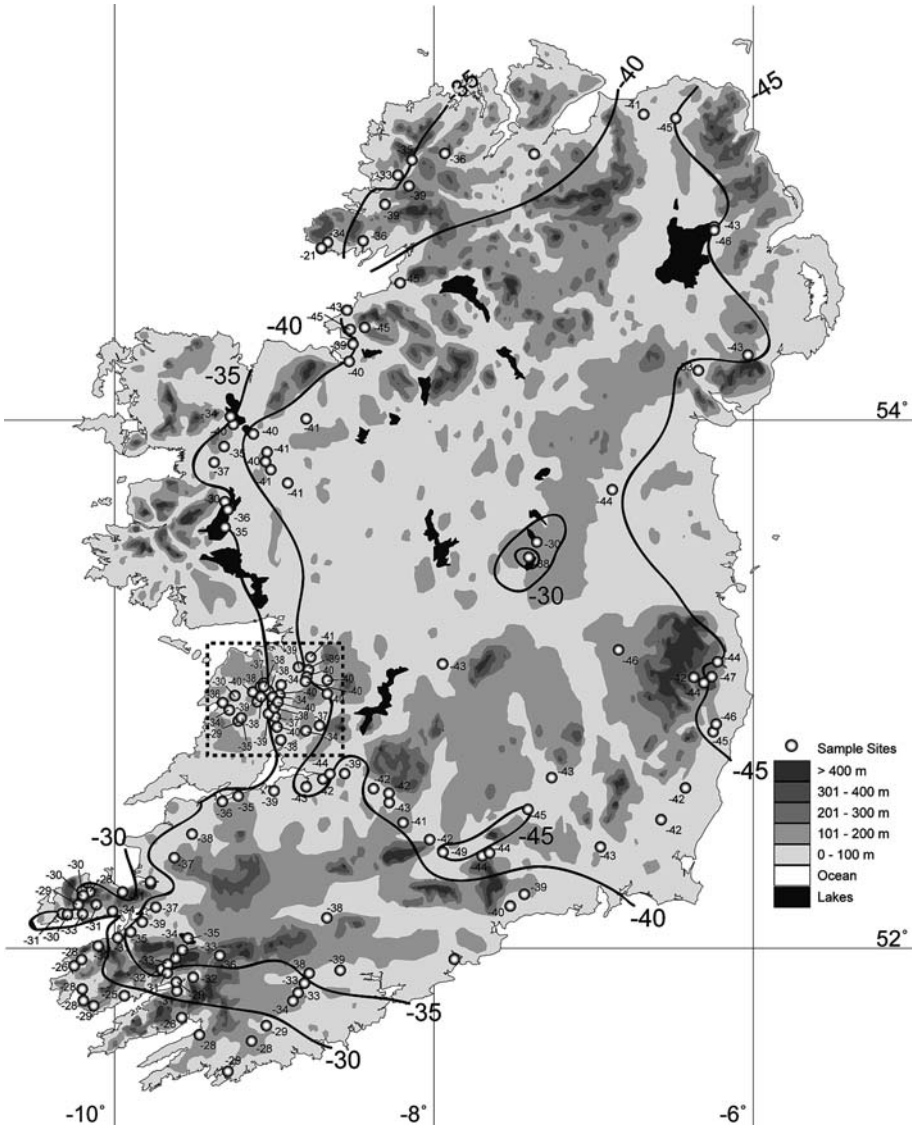

Figure 8. Contour line of δD in Irish surface waters with sample values next to positions. All values are in ‰ VSMOW. Detailed map of surface waters of The Burren, dashed box, are shown in Figure 9.

However, to better understand the meaning of carbonate sediment isotope values requires a better understanding of regional hydrology and the intricacies displayed by individual lakes. To our knowledge, stable isotope values of surface waters in this region have not been previously determined.

We sampled 31 lakes and rivers within this region (Figure 9) to determine a general distribution and variation of isotope values. Turloughs were not sampled because they are generally dry during the summer. Of the 31 lakes and rivers sampled, the overall variation was between 1.8‰ in δ^{18}O and 7‰ in δD. These variations do not seem to follow a general pattern or trend. This may be in part due to variations in the residence time of these lakes and the extent/orientation of the catchment regions. Altitude variation in this region is limited to ~300 m therefore contributing very little to isotope variability. Along the largest and longest rivers in this region, the Fergus, isotope values are essentially invariant. The upstream value to the north has an initial δ^{18}O value of -5.7‰ with only a slight increase to -5.4‰ along the flowpath, corresponding to input from a tributary with

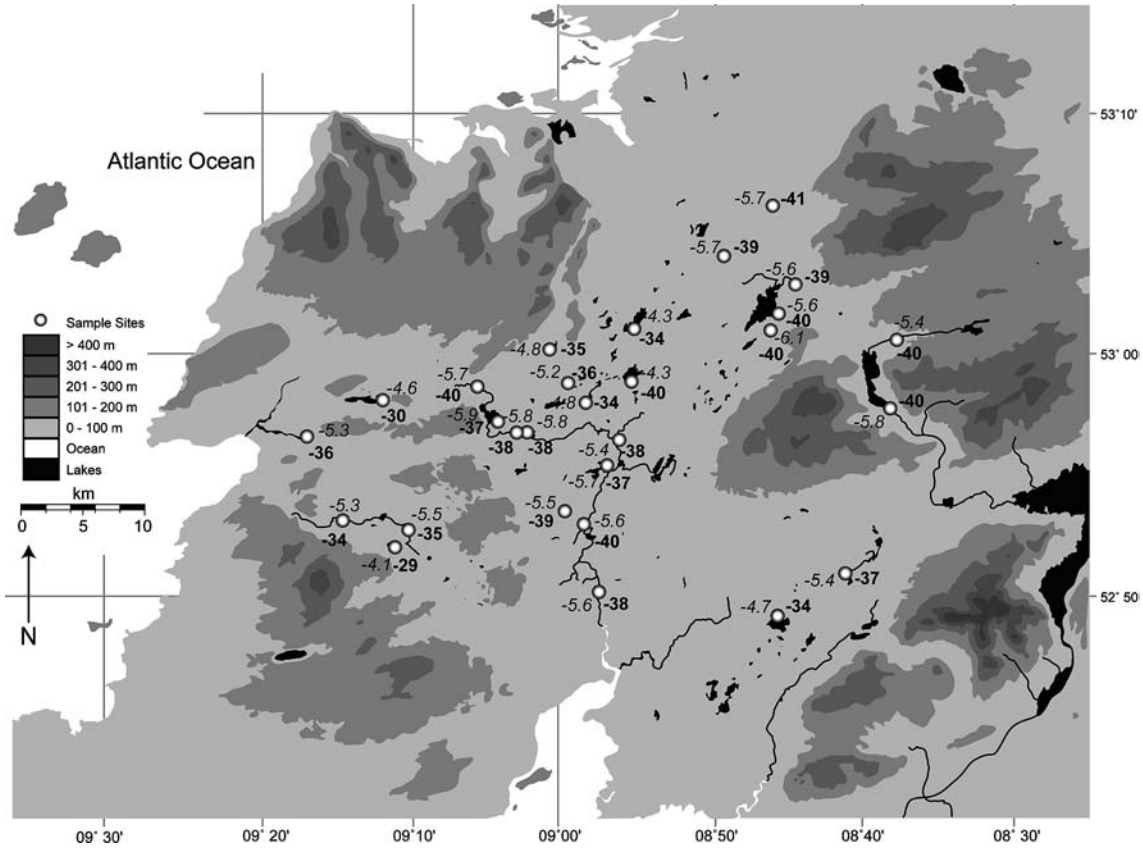

Figure 9. Map of $\delta^{18}O$ and δD values of The Burren region in ‰ VSMOW. $\delta^{18}O$ values are in italics and δD values in bold.

higher values. This tributary derives its source water from a different area that we interpret to have increased evaporation effects and/or longer residence time. This is the most reasonable scenario because some of the highest values in this region are just north of this tributary. Values decrease slightly towards the south end of the Fergus River before draining into the Shannon River.

Evapotranspiration

To best understand the regional distribution of isotopes in surface waters, it is important to be aware of the origin of the source water. The two main sources of water for precipitation, other than oceans, are continental sources in the form of transpiration from plants and evaporation from large lakes (Ziegler et al. 1989). Surface waters dominantly come from precipitation and a significant percentage of this may come from evapotranspiration. Evapotranspiration has been demonstrated in other parts of the world that such processes are significant and sources sometimes include lake effect snow (Burnett et al. 2003). One method to quantify the amount of evapotranspiration is to use the *d*-excess (Dansgaard 1964). The *d*-excess is defined by the amount of "extra" deuterium from relating the $\delta^{18}O$ and δD. It is controlled by kinetic fractionation during evaporation of surface waters because average humidity is always lower than 100%. As humidity decreases, kinetic fractionation increases. As surface water evaporates, an increase in δD and $\delta^{18}O$ values results. However, this occurs to a greater degree for deuterium because of the greater mass difference between H and D compared to ^{16}O and ^{18}O (Clark and Fritz 1997). As vapor is recycled, the *d*-excess increases in response to greater proportions of evaporate content (Fröhlich et al. 2002). When water is lost by evaporation, the *d*-excess will decrease. Other factors that may contribute to differences in *d*-excess include changes in physical conditions such as humidity, air temperature,

and sea surface temperature of the source area (Fröhlich et al. 2002).

Surface water *d*-excess values for Ireland were determined from the data. The average *d*-excess value for Ireland is 6.6‰, below the world average of 10‰. However, the LMWL for Ireland falls below a slope of eight suggesting that *d*-excess should be slightly lower. A contour map of *d*-excess values was generated for Ireland that shows highest values in the southwestern portion of Ireland, including the Wicklow Mountains and in southeastern Ireland with values around 10‰ (Figure 10). Values in the north are somewhat lower than in the south. It is also important to keep in mind the standard deviation imparted by this sampling method results in *d*-excess values having a standard deviation of ±3.1‰.

Evapotranspiration has previously been modeled in Ireland by Mills (2000) using meteorological variables that include precipitation, temperature and sunshine hours employing a dataset from 1961 to 1990. From six sites in Ireland where potential evapotranspiration was actually measured, it appears that it is the highest in the summer months ranging from approximately 60 to 95 mm. Values in the winter were significantly lower with quantities around 5 to 15 mm. Mills' model estimated actual evapotranspiration as a percentage of the annual precipitation across Ireland using a 5×5 km grid and then generated a contour map. The contour lines show that the entire west coast of Ireland has nearly half the evapotranspiration of eastern Ireland. Our *d*-excess contour lines compare favorably to those of Mills, except in the southwest. More interestingly, our data demonstrate that much of the southwest and southeast regions have similar *d*-excess values. This is surprising because we expected that the southeastern portion of Ireland to have lower *d*-excess values due to the increase in evapotranspiration (assuming a significant portion of this is evaporation). This could be explained by a larger proportion of the evapotranspiration in southeast Ireland being derived from transpiration, resulting in *d*-excess values that are not much different than the southwest (transpiration does not result in a significant fractionation of water isotopes). However, a more likely scenario for the lack of variation in the south of Ireland may be due to significant input from cyclones that form over the Atlantic Ocean and then travel across Ireland. If recycling of waters occurs, it is likely mixing with these large cyclonic systems during advection. This could moderate or overwhelm isotope recycling signatures. Furthermore, if evaporation has any effect on *d*-excess values, it is likely small due to the high humidity year round (usually greater than 85%) causing a small amount of kinetic fractionation.

Implications for sediment based research

The spatial variation of surface waters in the modern is defined by atmospheric circulation, which controls the atmospheric temperature, source of moisture, humidity, and moisture trajectory. Moisture trajectory of air masses is important in regions where orographic effects, moisture recycling, and additional sources of moisture modify isotope values. Changes in atmospheric circulation through time will alter the spatial variation of surface waters. This is significant when studying the long-term variation in isotope values of lacustrine sediment records. For example, variations in isotope values of surface waters in Ireland are more frequent in the southwest where isotope contour lines are closer together indicating a higher isotope gradient (e.g., Figure 7). If atmospheric circulation was shifted so that air masses are predominantly derived from the southeast, then the isotope gradient would be greater in the southeast than the southwest. This would result in higher isotope values in the southeast reflecting closer proximity to the source of moisture. This is significant over the Holocene where atmospheric circulation has deviated from the present such as during the 8.2 ka event where the jet stream was shifted south resulting in less precipitation in Ireland (Magny et al. 2004).

Spatial variations of isotopes are important in interpreting lake sediments at Lough Inchiquin (sample location 20, Figure 2) in western Ireland. The distribution of surface waters (Figure 7) suggests that $\delta^{18}O$ values in this region are similar with values averaging 5‰ with prevailing storm tracks from the southwest. If atmospheric circulation changes such that the prevailing storm tracks are from the west, $\delta^{18}O$ values would be more similar to coastal values such as modern values are in the southwest. The extreme case would be if storm tracks alter to come from the

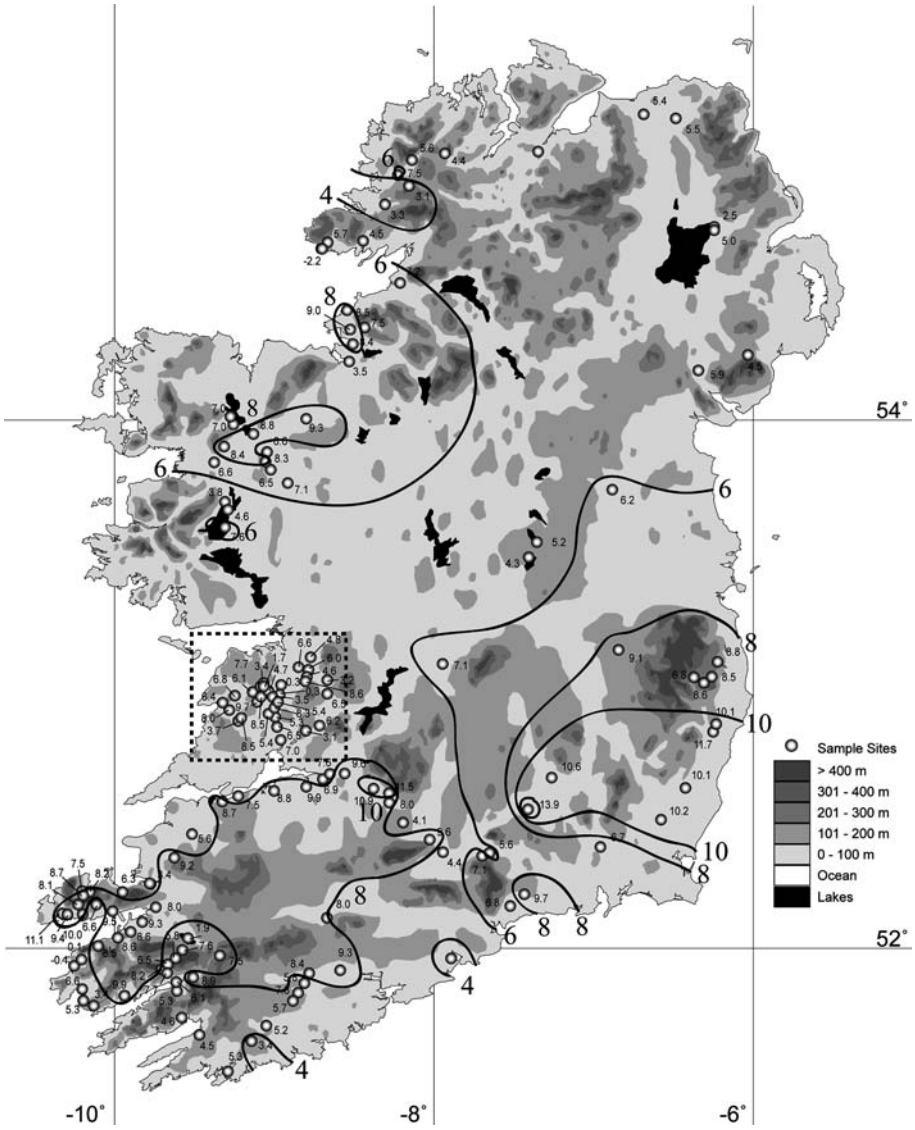

Figure 10. Contour line of *d*-excess in Irish surface waters with sample values next to positions. Burren region (denoted in dashed box) was not included in determination of positions of contour lines due to the complexity of the region.

east which would significantly modified $\delta^{18}O$ values such that values in western Ireland would be more similar to modern values in the east of ~6‰. This spatial variation urges caution in using simplified models for the interpretation of lake marl isotope data.

For example, comparison of sediment isotope records between east and west would suggest that temperatures in the east would be 4.2 °C warmer than in the west because the water values are 1‰ lower in the east. This study encourages generation of surface water data sets for use in the interpretation of lake sediment data in all areas. Differences in contemporaneously precipitated carbonate in geographically spaced locations can generate records of changes in spatial variations through time, which can be used to produce paleo-circulation maps through the Holocene.

Conclusion

This study provides a first regional survey of surface water isotope values for Ireland that are

useful for characterizing modern meteorological behavior and providing a template for comparison with lake sediment-based paleoclimate records. Significant variation in isotope values suggest that climate records derived from sediment isotope values need to be evaluated in a regional context if applications to global models are to be realistic. In the Burren region of County Clare, variation in lake values suggest that factors in addition to precipitation are significant in determining the values of individual lakes. These factors likely include differences in residence times, catchment size, evaporation, and many other factors. Therefore, future studies of climate change would provide the most comprehensive record by using several different types of lakes, each of which shows differential sensitivity to different meteorological parameters.

Supplementary information available

Supplementary information to this article can be found in the online version of this article at www.springerlink.com

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