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Earth and Planetary Science Letters 165 (1999) 157–162

EPSL

Express letter

Stalagmite luminescence and peat humification records of palaeomoisture for the last 2500 years

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Received 17 July 1998; revised version received 30 September 1998; accepted 5 November 1998

Abstract

Recent research has suggested that both raised and blanket bogs can provide proxy climate signals from variations in peat humification. In particular, oceanic margin sites have provided sensitive records that demonstrate century scale variations in humification. However, previous research has not compared records of peat humification with other terrestrial palaeoclimate proxies. Here, two records of climate change from an oceanic marginal site in NW Scotland are analysed. One, from a blanket bog, is derived from peat humification and covers the period 2100–100 BP. A second, from two stalagmites in a cave overlain by the bog, is derived from stalagmite luminescence wavelength variations for the samples deposited over 2500–0 BP. Both peat humification and stalagmite luminescence records demonstrate 90–100 year oscillations in bog wetness, that are attributed to variations in rainfall intensity or totals over this time period. It is argued that this is probably generated by a southward shift of the path of northern hemisphere depression tracks, possibly linked to variations in solar output. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: climate; peat bogs; humification; stalagmites; luminescence; Holocene; Highland region Scotland

1. Introduction

Raised peat bogs have been argued to be a good palaeoclimate archive, especially of rainfall variations [1–4], with proxies including plant macrofossils [2] and humification [3]. Oscillations in humification have been observed in duplicate blanket bogs accumulated over the last 1000 years, with decreased humification caused by decreases in temperature or increased moisture supply, with a frequently observed correlation between increased mire surface wetness and the Little Ice Age/Maunder Minimum [3,4]. Longer humification records from blanket and raised bogs also suggest that 200–800 year variability occurred over most of the Holocene [3,5], with both solar and ocean-driven causes postulated. Other palaeoclimate records that demonstrate decadal to millennial scale climate oscillations are those of glacier advance and retreat [6], where correlation

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PII: S0012-821X(98)00258-1

with the 2500 year solar variability is proposed, and varves [7–9], where 80 and 200 year cycles have been observed and correlated to solar output variations. In addition, variations in atmospheric ^{14}C production have suggested the presence of a 127 year solar cyclicity within the last two millennia [10], and analysis of the historical record of sunspot numbers has revealed the presence of both 11 and 100 years cyclicities [11]. Although peat humification records demonstrate a good correlation with solar output variations, comparison with other terrestrial palaeoclimate proxies would be beneficial in order to confirm the precise timing and nature of the palaeoclimate proxy that is being recorded. Below are presented results from mass spectrometrically dated peat and speleothem deposits covering overlapping time periods between 0–2500 BP from NW Scotland, a climatically sensitive location, being highly maritime in climate and close to the northern hemisphere mid-latitude depression path.

2. Site description

The blanket bog in the Traligill Basin, NW Scotland (58º15′N, 4º57′W), is located in a maritime climate with annual precipitation >1900 mm, 250–270 rain days, 4–6 snow days and an average 77% cloud cover. The site was chosen for peat sampling as it overlies Cambro-Ordovician dolomites which contain cave systems, and there is thus the potential for deriving independent records of climate change from both peat cores and cave stalagmites [12]. The relatively permeable dolomite bedrock also makes it unlikely that groundwater supply to the bog occurs, and indeed would drain the bog rapidly in periods of drier climate, thus making the site of particular sensitivity to moisture variations. A core was taken for analysis from an 80 cm deep peat directly overlying the cave system Uamh an Tartair, from which two stalagmite samples, one 160 mm high (SU-2) and a second 32 mm high (SU-96-7) were collected.

3. Analytical methods

Humification of the peat was analysed at 0.5-cm intervals and the results normalised using standard techniques [3]. The stalagmites were analysed for variations in luminescence using an Elmer-Perkin LS-50B Luminescence Spectrophotometer with fibre-optic extension (1-mm beam width) and at 2 nm resolution in excitation wavelength and 0.5 nm resolution in emission wavelength. The stalagmite luminescence derives from organic acids trapped within the stalagmite calcite and originating from the overlying bog [12], and the maximum luminescence was recorded in terms of its emission and excitation wavelengths. Increases in the emission wavelength of the maximum luminescence intensity of organic acids are due to greater proportion of high molecular mass fractions, which have increased aromacity, a high content of carboxylic groups and polycondensed aromatic and conjugated structures [13,14]. Increased proportions of high molecular mass humic substances have been demonstrated to correlate with increasing mean annual rainfall in temperate climates [15,16]. Increases in speleothem luminescence wavelength have been demonstrated to correlate with increased rainfall over the last 100 years [17], with a typical lag of 5–10 years soil carbon residence time between soil organic matter production and transport onto speleothems [18]. Therefore, increases in speleothem luminescence emission wavelength, correlating with a 5–10 year lag with humification directly recorded from the bog profile, would demonstrate increasing bog surface wetness.

The peat profile was dated by five AMS ^{14}C analyses on the fine fraction of 1-cm slices of peat that were corrected using CALIB3.0.3c [19]. Stalagmite SU-2 was dated by five TIMS U–Th analyses using standard techniques [20] (Tables 1 and 2); sample SU-96-7 exhibited annual luminescent laminae throughout the period of its formation and a chronology was constructed from laminae counting. Dating results demonstrate that the dated section of peat profile UAM4 (12–64 cm) accumulated over the period 2000–∼100 BP, with a slowly increasing growth rate over that time period and a mean of 48 yr cm^{-1}, a resolution level for the humification (samples at 0.5 cm) varying between 39 and 17 years. Sample SU-2, which commenced at 2500 BP, was deposited at an increasing growth rate (mean of 80–140 $\mu m\ yr^{-1}$) until 1200 BP. With luminescence analysis at 2 mm intervals, this provided a mean sampling resolution of ∼20 years. Sample SU-96-7 commenced at 1050

Table 1
AMS ^{14}C analyses for peat samples from Assynt, NW Scotland

Lab code	Sample code	Depth (cm)	^{13}C (per mil)	^{14}C age BP	Corrected age BP (2σ error)
aa-26319	uam4-12	12	−29.4	25 ± 50	
aa-26320	uam4-20	20	−29.3	135 ± 50	140 ± 130
aa-26321	uam4-34	34	−29.0	630 ± 50	601 ± 61
aa-26322	uam4-47	47	−28.9	1210 ± 45	1107 ± 135
aa-26323	uam4-62	62	−29.4	2165 ± 50	2155 ± 154

Table 2
TIMS U–Th analyses for stalagmite samples from Assynt, NW Scotland

Sample Code	Distance from base (cm)	^{238}U (ppm)	$^{234}U/^{238}U$ [act]	$^{230}Th/^{234}U$ [act]	$^{230}Th/^{232}Th$ [act]	Corrected age BP (2σ error)
su2-bas	0.2	0.55724 ± 0.00066	1.1464 ± 0.0215	0.02334 ± 0.00054	29.99 ± 0.28	2567 ± 120
su2-bas(r)	0.2	0.56018 ± 0.00146	1.1615 ± 0.0228	0.02230 ± 0.00050	59.20 ± 0.64	2451 ± 114
su2-mid1	4.1	0.56010 ± 0.00072	1.1351 ± 0.0213	0.01741 ± 0.00038	28.29 ± 0.17	1909 ± 84
su2-mid2	9.0	0.44391 ± 0.00077	1.1618 ± 0.0225	0.01212 ± 0.00029	18.83 ± 0.18	1326 ± 64
su2-top	14.3	0.47516 ± 0.00052	1.1352 ± 0.0213	0.01101 ± 0.00055	9.61 ± 0.43	1204 ± 120

BP and deposited at a slowly increasing growth rate of 30 $\mu m\ yr^{-1}$ until the date of sampling in 1996. With luminescence analysis of at 1 mm (top 20 mm) and 0.5 mm (basal 12 mm) intervals, this provided a comparable mean sampling resolution of ~33 years.

4. Results

Comparison of the climate proxies contained in UAM4, SU-96-7 and SU-2, as well as the locations of radiometrically dated samples, are presented in Fig. 1. Data for UAM4 is presented as normalised to remove the humification trend observed at the acrotelm/catotelm boundary (~18 cm from top); raw humification values for the peat (as light transmitted at 540 nm) equalled 35.1 ± 7.8% ($n = 110$). The emission wavelength of maximum luminescence for the stalagmite samples equalled 441.4 ± 15.5 nm ($n = 69$) and 437.7 ± 2.1 nm ($n = 30$) for SU-2 and SU-96-7 respectively, comparable to those obtained from stalagmites overlain by peat elsewhere [17]. Results for each stalagmite were also normalised to enable better comparison between the two samples that were of differing variability of luminescence wavelength.

Fig. 1 demonstrates that UAM4 and SU-96-7 correlate well both with each other and with historical climate events. Wetter conditions at 150–400 BP and 500–600 BP correlate with Maunder and Spörer sunspot minima and climate deterioration recognised in other peat records [3,4]. Over the whole of the period 2600–0 BP, peat humification demonstrates a reasonable correlation with changes in stalagmite luminescence wavelength. The errors of approximately ±100 years on both the AMS ^{14}C and TIMS U–Th results prevent precise correlation between the records, or any assessment of potential lags between soil carbon residence and incorporation of organic acids in the stalagmites at this site.

Spectral analysis was performed using SPECTRUM 2.1 [21], a package that utilises a Lomb–Scargle Fourier Transform for unevenly spaced time-series. Two different spectral windows (Rectangular, Hanning) were used on both adjacent averaged and unsmoothed, detrended, records of stalagmites SU-2 and SU-96-7 (stacked) and peat profile UAM4, using a ×4 oversampling factor and $\alpha = 90\%$. Results using a rectangular spectral window on the smoothed time-series are presented in Fig. 1. Although the short length (~100 data points) of both time-series are near the limit of that which can be applied to

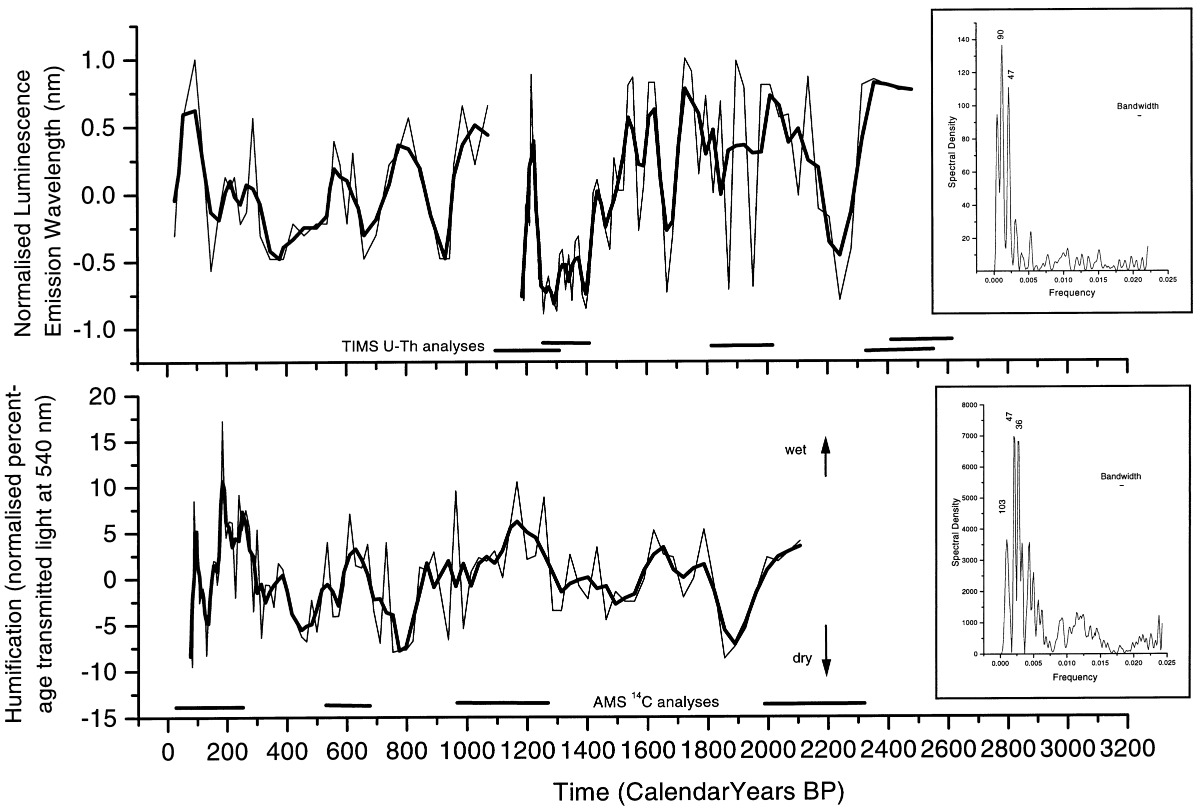

Fig. 1. Comparison of palaeoclimate proxies for the period 0–2600 BP: (top) normalised luminescence emission wavelength data for stalagmites SU-96-7 and SU-2, together with 3-point smoothing and timing of TIMS U–Th analyses for SU-2; (base) humification, expressed as normalised percentage transmission of light at 540 nm, for peat core UAM-4 together with 3-point smoothing and timing of AMS ^{14}C analyses. All dates are expressed as calendar years from 1997, with calibrated ^{14}C years increased by 47 years. Inserts: spectral analysis of the detrended, smoothed time series, using a rectangular window. Reliable f range is from 125 to 5 years.

spectral analysis, all analyses exhibited statistically significant spectral peaks at 80–125 years (which accounted for 11% of the variance in UAM4 and 25% in the composite stalagmite records). In addition harmonics of this peak are visible at 47–55 years and 33–36 years. The similarity of the spectral analyses on both the peat and stalagmite records, as well as the visible correlation observed in Fig. 1, suggest that both deposits reflect a soil-derived palaeomoisture signal.

5. Conclusions

Two complementary records demonstrate variability in wetness in NW Scotland over the period 2500–100 BP. Oscillations with a clear periodicity of 80–125 years are visible in both the stalagmite and peat climate proxies. These may correlate with solar output variations as measured by ^{14}C and in historical sunspot records, which have a period of 100–127 years over this time period [10,11], and can be ascribed to the 80–100 year Gleissberg cycle [11]. Precise correlation between surface wetness and the residual ^{14}C record as a measure of solar variability [10], are hampered due to the age uncertainties of the AMS ^{14}C and TIMS U–Th analyses being the same as the periodicity of the residual ^{14}C. The increased recognition of possible sun–climate relationships at the decadal to millennial time scale has led to a series of General Circulation Model simulations [22–24]. Models have suggested that a decrease in solar irradiance of 0.1–0.25%, such as experienced during the Maunder minimum, would lead to a $\sim$10 W m^{-2} decrease in incoming radiation and a decrease in global mean temperature of <0.5ºC [22,23], although with significant regional variations due to land–ocean interactions. More recent models have recognised the importance of solar output variations on ozone concentration [24], which would enhance any climate effects. In particular, modelling of solar output variations over an 11 year cycle suggested a southward shift in the track of N Atlantic depressions of ca. 70 km and a 3–4% decrease in depression number (measured by model transient eddy frequency) at periods of solar output minima due to the decreased equator–pole energy gradient [24].

Comparison of both our data and previous studies of bog humification [2–4] with global temperature for the last 600 years [25] suggests little correlation, with mean Northern Hemisphere changes of less than ±0.4ºC over this period. Together with GCM predictions of the impact of solar output variations of <0.5ºC over the decadal to centennial time scales, it seems likely that the decrease in bog humification, and its impact on the deposition of organic acids in the underlying speleothem must be due to increased water availability. Whether this is solely due to a more southern track of the polar front due to solar output variations, or in addition due to the internal variability of the ocean–climate system, remains the focus of future research.

Acknowledgements

We thank the Royal Society for an equipment grant, and the NERC for research and radiocarbon grants. Scottish Natural Heritage and the Assynt Estate provided access to the sampling sites. Richard Foster and Mark Roberts provided field assistance and Darrel Maddy advice on spectral analysis. ***[AC]***

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