A $\delta^{13}C$ record of late Quaternary climate change from tropical peats in southern India

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STABLE-ISOTOPE ratios of carbon in soils or lake sediments[1–3] and of oxygen and hydrogen in peats[4,5] have been found to reflect past moisture variations and hence to provide valuable palaeoclimate records. Previous applications of the technique to peat have been restricted to temperate regions, largely because tropical climate variations are less pronounced, making them harder to resolve. Here we present a $\delta^{13}C$ record spanning the past 20 kyr from peats in the Nilgiri hills, southern India. Because the site is at high altitude (>2,000 m above sea level), it is possible to resolve a clear climate signal. We observe the key climate shifts that are already known to have occurred during the last glacial maximum (18 kyr ago) and the subsequent deglaciation. In addition, we observe an arid phase from 6 to 3.5 kyr ago, and a short, wet phase about 600 years ago. The latter appears to correspond to the Mediaeval Warm Period, which previously was believed to be confined to Europe and North America[6,7]. Our results therefore suggest that this event may have extended over the entire Northern Hemisphere.

The use of stable carbon isotope ratios as palaeoclimatic indicators is based on the different ecological requirements of the C3 and C4 plant types that have widely differing $^{13}C/^{12}C$ ratios.

C3 and C4 plants, separated on the basis of their photosynthetic pathways of carbon fixation, typically have $\delta^{13}C$ values in the range of −26‰ to −28‰ and −11‰ to −13‰ respectively[8] ($\delta^{13}C$ is defined in the legend of Fig. 2). They also show different ecological preferences, with C4 plants (mainly tropical grasses) favouring conditions of aridity and low soil moisture and C3 plants (most dicotyledonous plants and temperate grasses) dominating areas of higher precipitation and higher soil moisture[9,10]. Although the precise ecological separation of these two plant types in the tropics is not clearly understood, the C4 grasses are known to predominate up to an altitude of 2,500 m above mean sea level (m.s.l.) under conditions of low soil moisture, whereas C3 grasses predominate at greater altitudes, where soil moisture is greater[9]. The balance between C3 and C4 grasses depends on soil moisture and not altitude itself. For this reason, $\delta^{13}C$ values of soil organic matter, calcium carbonate or lake sediments (as they relate to C3 and C4 vegetation) have been used as palaeoclimatic indicators[1-3].

The current vegetation of the high altitude (1,800–2,500 m above m.s.l.) regions of the Nilgiri hills (11°–11° 30′ N, 76° 20′–77° E) in the Western Ghats of southern India is a mixture of stunted evergreen forest and grassland[11,12]. The undulating hills feature an underlying geology of Archaean rocks, chiefly gneisses, charnockites and schists. The western region receives rain mainly from the south-west (summer) monsoon and the eastern region from the north-east (winter) monsoon, with a gradation over the plateau. Present-day rainfall over the plateau varies from about 3,000 mm per year in the west to only 1,200 mm per year in the more sheltered central basins[13]. Mean monthly temperatures typically vary from a maximum of 20 °C in May to 7 °C in January. Frost is however common during the month of January and limits the spread of forest plants[11,12]. A number of climate models have shown a positive correlation between temperature and the strength of the Asian summer monsoon[14-16]. In general, a higher mean temperature would reduce the incidence of frost, increase summer precipitation and promote the spread of forest (C3-type) and C3 grasses in moist soils of grasslands. Conversely, a cooler mean temperature would favour the spread of grassland (C4 grasses in low soil moistures at this altitude). Thus, a strengthening or weakening of the monsoon could be expected to be reflected in a swing towards C3 or C4 vegetation respectively.

The valleys feature peat deposits whose formation can be dated back to at least 40 kyr BP (before present) (refs 17–20, and our unpublished results). The peats derived from the C3 and C4 vegetation of the surrounding area can thus be expected to preserve the vegetational and climatic record of the region, as diagenic alteration usually does not occur[7].

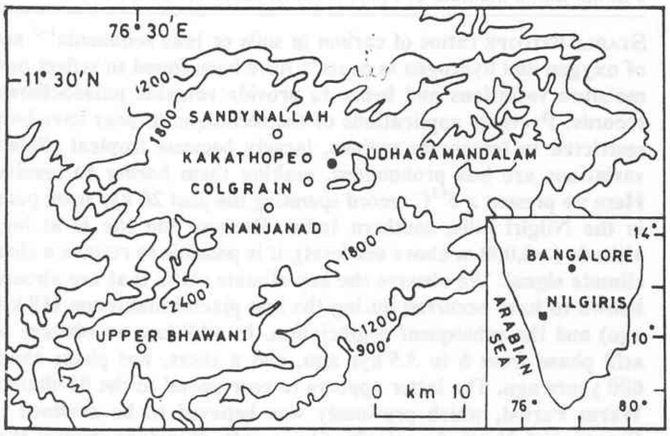

FIG. 1 Map showing the locations of the basins (open circles) in the Nilgiri hills from where peat samples were collected. Contours are given in metres above mean sea level.

TABLE 1 Ages for peat samples from the Nilgiri basins

Basin	Depth (cm)	Lab. sample ref. no.	^{14}C age (±s.d.) (yr BP)	Recalibrated age (yr BP)
Upper Bhawani	0–5	BS-76	290±100	311
	20–40	BS-75	1,980±100	1,935
	130–150	BS-52	5,860±115	6,700
	200–230	BS-53	19,100±300	22,300
Kakathope	70–100	BS-196	5,600±120	6,370
	120–150	BS-187	7,760±140	8,540
	170–200	BS-197	10,620±180	12,280
	220–250	BS-188	14,480±240	17,320
Nanjanad	20–50	BS-106	4,130±100	4,700
	120–150	BS-122	19,890±380	23,000
Colgrain I	20–50	BS-167	7,580±130	8,380
	70–100	BS-168	17,140±290	19,035
Colgrain II	220–250	BS-23	14,920±960	18,000
Sandynallah	5–10	BS-874	Modern	—
	150–155	BS-873	2,230±130	2,315
	160–165	BS-968	2,550±90	2,739
	170–175	BS-871	3,040±80	3,263
	180–185	BS-967	4,050±110	4,500
	190–195	BS-872	4,680±120	5,390
	233–240	BS-869	8,680±140	9,500

Visible plant debris were removed from the samples before processing for radiocarbon counts (ref. 17). Several samples from the upper layers of the Sandynallah basin after removal of visible modern rootlets, did not have sufficient carbon for accurate dating; these have been dated by calculating rates of peat deposition from least-squares regression. The best fit was given by $\log_n y = 0.0165x + 5.207$ ($R^2 = 0.986$), where y is the age in yr and x the depth in cm. Peats between 195 and 227 cm at Sandynallah were lost during collection. One sample at 227–233 cm depth has been dated from the regression. All ^{14}C ages are based on a half-life of 5,730±40 yr. The recalibrated ages are mean ages based largely on dendrochronological data (ref. 21) or U/Th ages of corals (ref. 22) and are approximate for ages greater than 4,000 years. The reference year for BP is AD 1950.

We collected peat samples, each of 5 cm depth, at 10 cm intervals from a 2.4-m-deep pit dug in the Sandynallah basin. Additional samples were obtained from the collections at the Birbal Sahni Institute of Palaeobotany (BSIP)[17-19], which had been made by using a corer (for pollen studies) at Kakathope, Nanjanad, Colgrain and Upper Bhawani (Fig. 1). The general stratigraphy of these basins has been described elsewhere[17-20]. Radiocarbon dating of the samples was carried out at BSIP by methods described in ref. 17. Table 1 shows these ^{14}C ages. In order to correct the radiocarbon ages for past variations in atmospheric ^{14}C, we also indicate recalibrated ages based on tree-ring dates[21] or U/Th dates of corals[22]. In the discussion here, however, we refer to conventional ^{14}C ages in order to facilitate comparison with past studies which report only radiocarbon ages.

For determining $^{13}C/^{12}C$ ratios, samples were combusted in sealed quartz tubes at 800 °C, and the resulting CO_2 analysed (with a resolution of ±0.1‰ (l.s.d.) in a Micromass 602D mass spectrometer at the Physical Research Laboratory. All $\delta^{13}C$ values employ the PDB standard. The fine and coarse fractions (usually vegetal debris) of a number of peat samples were separately analysed to check for consistency: the two values matched closely in all cases. We therefore report the $\delta^{13}C$ values of the fine fraction which is more representative of the carbon contribution of the prevalent vegetation.

Values of $\delta^{13}C$ in present-day dominant vegetation in the Nilgiri basins average −10.9‰ (±1.22, number of samples n = 5) for C4 grasses, −27.8‰. (±2.27, n = 7) for C3 grasses and other herbs, and −28.7‰ (±1.32, n = 8) for C3 trees and shrubs. Modern (sub-surface) peats average −18.1‰ (±1.17, n = 7).

Figure 2 shows the $\delta^{13}C$ values of the peats collected from the Nilgiri basins. The $\delta^{13}C$ values have fluctuated in the past from −12.8‰ to −24.2‰ indicating a dominance of C4 or C3 vegetation respectively. The predominantly C4 signatures during 20–16 kyr BP (Fig. 2*a*) clearly indicate a very arid phase during the last glacial maximum (LGM, believed to be at 18 kyr BP). Evidence from other palaeoclimatic data (including lacustrine pollen deposits in northwestern India[23], oxygen isotope ratios of oceanic sediments and foraminifera[24-27], and climatic simulation models[14-16]) also points to a period of weak (compared to the present) Asian south-west (summer) monsoon during the LGM. This period is accompanied by cooler global temperatures. The north-east (winter) monsoon was perhaps stronger during this period[26,27] but the net precipitation from south-west and north-east monsoons over the Western Ghats of peninsular India could still have been relatively lower then.

From about 16 kyr BP there is a tendency towards a more negative $\delta^{13}C$ signature in the peat, which indicates C3 vegetation dominance, attaining a peak of −24.2‰ at 10.6 kyr BP at Kakathope (Fig. 2*a*). This matches the strengthening of the summer monsoon reported for this period from the following sources; pollen records in lakes of northwestern India[23,28], fluvial deposits in central India[29], oxygen isotope and pollen records from cores in the Arabian Sea[24,25], and simulation models based on increased solar radiation (such as at 9 kyr BP) caused by the earth's orbital variation[16,30]. This evidence indicates that the summer monsoon reached a peak at ~11 kyr BP at 10–15° N latitude, and ~10 kyr BP at more northern latitutes in the sub-continent. The extension of the monsoon over the Indian sub-continent seems to have been a gradual process, following the northward progression of the intertropical convergence zone during the deglaciation[25].

The early Holocene (10–6 kyr BP) is again marked by a shift towards C4 vegetation, indicating a progressively more arid climate. This trend is clearly captured in the closely-sampled Sandynallah basin (Fig. 2*b*), where the $\delta^{13}C$ value of −20.2‰ at 8.7 kyr BP shows a positive excursion to between −14.7‰ and −15‰ during 4.7–3.0 kyr BP. At Nanjanad, a $\delta^{13}C$ value of −14.3‰ at 4 kyr BP (Fig. 2*a*) was found. The weakening of the summer monsoon over the Indian sub-continent has been variously dated at 4.5–2 kyr BP in northern India at latitude 28° N[23,25,28]. A sharp increase in grass pollen, indicating aridity from 3.5 kyr BP onwards, has also been reported from estuarine sediments off the western coast of peninsular India at latitude 15° N (ref. 31). Our data indicate that a weaker monsoon may have established as early as 6 kyr BP in peninsular India at latitude 11° N.

The Sandynallah basin also shows a sudden shift in $\delta^{13}C$ values (beginning ~0.7 kyr BP) to a C3 vegetation (extreme $\delta^{13}C$ of −22.6‰ at 0.6 kyr BP) for a duration of about 200 yr (Fig. 2*b*). After correcting these with dendrochronological ages[21], this period (calendar age AD 1200–1400) roughly corresponds to the Mediaeval Warm Period, dated at AD 1100–1300, characterized by warmer temperatures in Europe and North America[6,7]. Our record seems to be the first evidence of such an event from southern Asia, although its relationship to the better known European event is unclear at this stage.

The broad trends in monsoonal evolution thus seem to be captured in the Nilgiri peats. There could however be pitfalls in the interpretation of peat records. The stratigraphy of two basins on the western fringe of the plateau (that receives torrential rains from the summer monsoon) showed anomalies (through ^{14}C date inversions and contamination with modern carbon) that could have been caused by landslides triggered by a high-energy event (A. K. Singhvi, personal communication). More sheltered basins, such as those investigated in this work, would be better sampling sites. It could also be important to sample peat deposits at altitudes lower than 2,500 m. At higher altitudes a possible predominance of C3 over C4 grasses, due to persistently higher soil moisture, may render the carbon isotope signature ineffective. Natural lag in vegetational response to climatic change should also be taken into account.

Tropical climates are generally more difficult to reconstruct than temperate climates, for a number of reasons. Changes in ocean temperatures in the tropics are very small. Seasonal contrast of climate is also marginal at lower altitudes. For these reasons an elevated region with higher diurnal and seasonal contrast can be expected to give a better record of climate change.

We have demonstrated the potential of using tropical peats as palaeoclimatic indicators. We believe that further extensive studies, using a combination of pollen and stable isotopes of C, O and H may be very useful tools in past reconstruction under the International Geosphere-Biosphere Programme (IGBP). This may allow us to extend the geographic coverage of proxy climatic sets. □

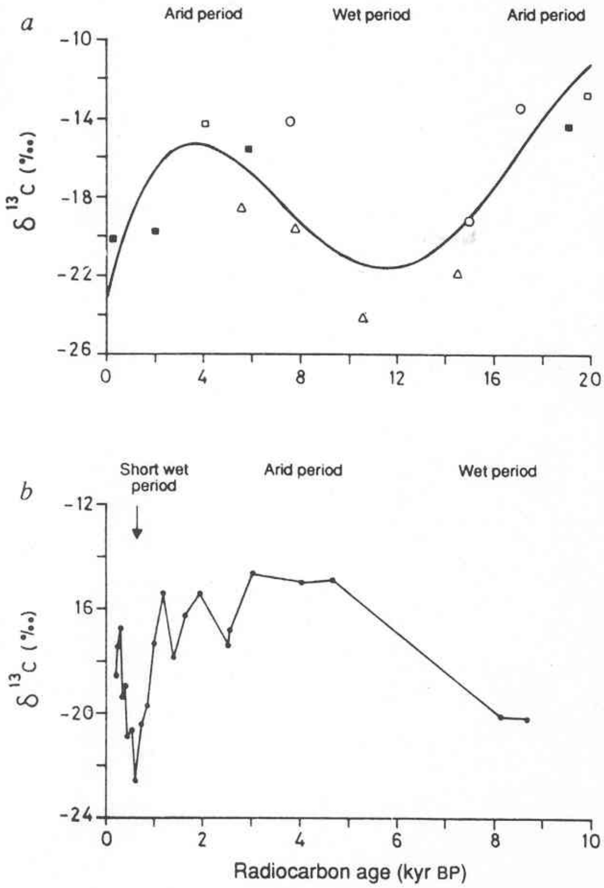

FIG. 2 $\delta^{13}C$ (per mil), relative to PDB standard, versus radiocarbon date (kyr BP) of peats from the Nilgiri basins. *a*, Samples collected by BSIP (refs 17–19) from Nanjanad (open square), Colgrain (open circle), Kakathope (open triangle) and Upper Bhawani (closed square). A fourth-degree polynomial function has been fitted to the data to depict the broad trends in $\delta^{13}C$ since 20 kyr BP. *b*, Samples collected from the Sandynallah basin with ages 9 kyr BP to present. ($\delta^{13}C = [(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{standard}] - 1$).

Received 27 January; accepted 25 June 1993.

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ACKNOWLEDGEMENTS. This work was partially supported by the Ministry of Environment and Forests, Government of India. We thank the Forest Department of Tamilnadu and the Sheep Breeding Centre, Sandynallah, for permission to collect peat samples.. We also thank J. Srinivasan, N. V. Joshi and A. K. Singhvi for suggestions and J. T. Padia, G. Rajagopalan and J. A. Santosh for assistance.