

Past 20,000-year history of Himalayan aridity: Evidence from oxygen isotope records in the Bay of Bengal

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Late Quaternary climate history of the Himalayas is inferred from sea surface salinity (SSS) changes determined from the oxygen isotope in planktonic foraminifers, in a turbidity-free, ^{14}C -dated core from the Bay of Bengal. The heaviest $d^{18}\text{O}$ incursion (-0.9 and -0.44% for *Globigerinoides ruber* and *G. sacculifer* respectively) between 20 and 15 Ka BP reveals that the Himalayas was intensively glaciated with minimum fluvial discharge until 15 Ka BP. During the initial phase of deglaciation between 15 and 12.5 Ka BP, the climate was unstable. The deglaciation intensified after 12.5 Ka BP, and culminated at about 11 Ka BP with a fluvial pulse. The heavier concordant incursions of $d^{18}\text{O}$ in both the species indicate that Himalayan aridity and associated glaciation at 10.5 Ka BP was again enhanced to the magnitude of the Last Glacial Maxima. The beginning of Holocene (~ 9.5 Ka BP) is characterized by excessive lighter $d^{18}\text{O}$ values due to high fluvial discharge attributed to intensified monsoon regime that persisted throughout the Early Holocene. During Mid–Upper Holocene, the Himalayas experienced at least two significant episodes of aridity and intensified glaciation at 5–4.3 and ~ 2 Ka BP.

In recent years, the importance of understanding the history of Himalayan glaciation and its influence on the Asian monsoon has been highlighted^{1,2}. The coupled heating–cooling of the Himalayas and the southern Indian Ocean regulates the strength of the summer monsoon (SW monsoon) in the Indian subcontinent³, and fluvial discharge into the northern Indian Ocean. Compared to the Arabian Sea, the Bay of Bengal (area 2.2 million km^2)^{4,5} receives several-fold higher fluvial discharge, particularly from the Himalayan rivers, which significantly affects the sea surface salinity (SSS) of the bay⁶. The SSS variations in the Bay of Bengal, therefore, can be interpreted in terms of climatic changes in the Himalayas. Being sensitive to SSS and sea surface temperature (SST) variations, the $d^{18}\text{O}$ of the planktonic foraminifers is a reliable proxy of climatic changes. In the bay, such studies are few⁷. In the present study, based upon high resolution $d^{18}\text{O}$ records from a ^{14}C dated core in the middle fan region of bay, the palaeoclimatic variations influenced by the Himalayan climate are reconstructed for the past 20 Ka BP.

The core (5.4 m) was retrieved during the 31st expedition of ORV *Sagar Kanya* at a location from the middle

fan region ($15^{\circ}52'.00''\text{N}$; $91^{\circ}10'.00''\text{E}$, water depth 2713 m; Figure 1), which under modern hydrography is influenced by the SSS changes due to the fluvial influx from the Ganga–Brahmaputra (G–B) system. The upper 100 cm of the core was sub-sampled at 2 cm intervals. Washed, salt-free and oven-dried samples were used for the analyses. $d^{18}\text{O}$ $\{[(^{18}\text{O}/^{16}\text{O})_{\text{sample}}/(^{18}\text{O}/^{16}\text{O})_{\text{standard}} - 1]10^3\}$ was determined in 25–30 shells (size 315–400 μm , ultrasonically cleaned) of *Globigerinoides sacculifer* (without sac), and *Globigerinoides ruber* (s.s. white) versus PDB standard on a VG Micromass Analyser in the Isotope Laboratory of the University of Kiel. The standard deviation of the results is 0.04–0.07%. The core was ^{14}C -dated (bulk sample) at ten levels (Table 1). In the absence of the apparent age of the waters of the bay, ^{14}C -dates are corrected for global sea water age (400 yr) to account for the reservoir effects⁸.

There are marked concordant temporal variations in $d^{18}\text{O}$ in both the species (Figure 2). The heaviest enrichment is observed between 100 and 80 cm (assigned ages 20–15 Ka BP). Heavier incursions also persist at 72 (12.7 Ka BP), 35 (10.5 Ka BP), 18 (4.5 Ka BP) and 8 (~ 2.1 Ka BP) cm levels. These incursions are much more pronounced during the Late Pleistocene compared to those during the Holocene. Significant lighter incursions

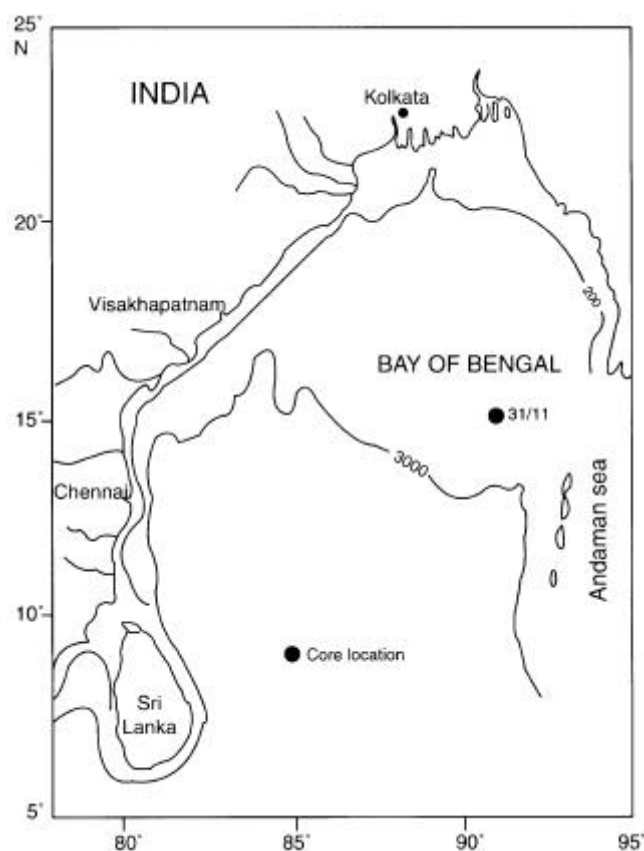


Figure 1. Location of core in the Bay of Bengal.

are also observed at 11.5 and 9.5 Ka BP (55 and 30 cm levels).

The palaeoclimatic variations are inferred from $d^{18}O$ in the planktonic foraminifers species *G. sacculifer* (without sac), and *G. ruber* (*s.s.* white), which mostly sustain in the upper mixed layer, and their shell secretion is influenced by SSS and SST changes⁷. As there are small, localized variations in the SST during the past 20 Ka BP (refs 9, 10), the $d^{18}O$ variations may be linked to SSS variations influenced by fluvial influx, which under modern conditions is regulated by the climate of the Himalayas and the strength of the SW monsoon. In the northern Indian Ocean, 0.3‰ changes in $d^{18}O$ correspond to 1°C change in the SST¹¹. About 0.6‰ change may also be tied to 2‰ change in SSS¹¹. In the present study, the marked concordant temporal variation in $d^{18}O$ in both the species appeared to be closely correlated with stepwise global sea-level rise^{12,13}, and can be used to infer arid and humid climate phases.

Synchronous, heaviest $d^{18}O$ values are observed in both the species during 20–15 Ka BP (–0.9‰ and –0.4‰ for *G. ruber* and *G. sacculifer* respectively; Figure 2). The modern $d^{18}O$ value in the bay is ~ –3.38‰, which is much lighter compared to the Last Glacial Maxima (LGM) and indicates increased SSS (about 8‰) due to much reduced freshwater influx in the bay. During this period, the Himalayas have experienced intense glaciation, particularly in the catchment of the G–B system (Gora Tabela stage) attributed to reduced summer monsoon precipitation¹⁴. Synchronous aridity reported in Greenland¹⁵ and in the North Arabian Sea¹⁶ also corresponds to the LGM event^{17,18}. Persistence of heavier $d^{18}O$ between 100 and 80 cm levels, and interpolated age of 100 cm level (19.7 Ka BP) indicate that the LGM event probably lasted for about 5 Ka in the Himalayas.

The beginning of deglaciation was interpreted shortly after 15 Ka BP from lighter $d^{18}O$ with rather small changes (magnitude of about 0.6‰) until 12.5 Ka. This implies that deglaciation was rather weak and the SW monsoon regime probably was not fully active. The

deglaciation pause observed at 12.7 Ka BP further supports highly unstable climate in the Himalayas. The arid phase of 12.7 Ka BP corresponds to decreased water level in Lake Victoria, possibly due to weak SW monsoon¹⁹, and hence appears to be a regional event.

The lighter incursion of $d^{18}O$ indicates that the Himalayan climate was humid and warm, with enhanced precipitation after 12.7 Ka BP. Due to increased moisture content Tibet was humid²⁰, with intensified deglaciation

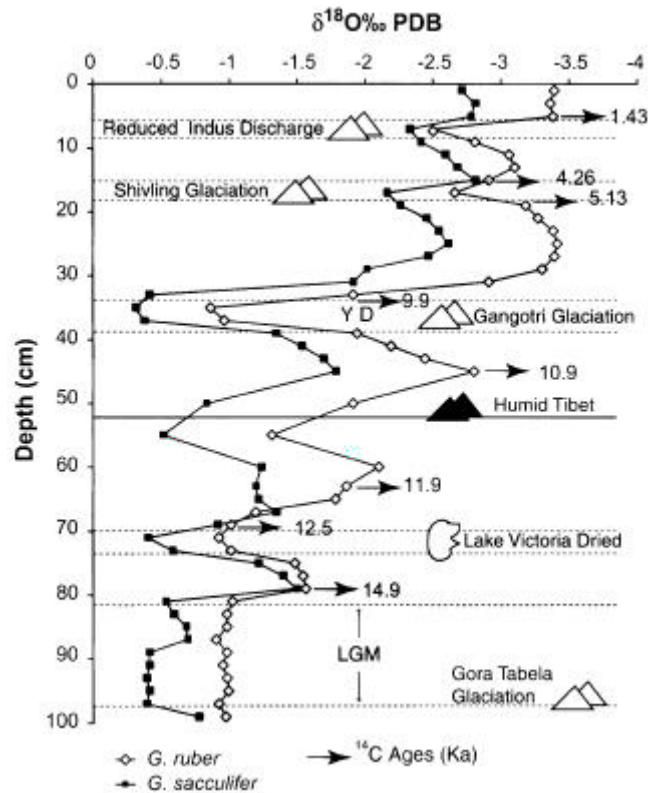


Figure 2. Temporal variations in $d^{18}O$ in *Globigerinoides sacculifer* (without sac) and *Globigerinoides ruber* (*s.s.* white). Corrected ^{14}C ages are shown. Relation between glaciation events of the Himalayas and other global events with that of the present study is schematically shown.

Table 1. Age model for core

S. no.	Sample no.	Source	Sample interval (cm)	^{14}C age in bulk sediments	Corrected ^{14}C age
1	PRL 1686	1	0–5*	1480 ± 120	1080
2	KL 31/11-3	2	4–6	1830 ± 120	1430
3	KL 31/11-8	2	14–16	4660 ± 100	4260
4	KL 31/11-10	2	18–20	5530 ± 160	5130
5	PRL 1687	1	25–30*	8860 ± 120	8460
6	KL 31/11-16	2	32–34	10300 ± 340–330	9900
7	KL 31/11-22	2	44–46	11300 ± 350	10900
8	KL 31/11-28	2	62–64	12300 ± 440–410	11900
9	KL 31/11-30	2	68–70	12900 ± 440–410	12500
10	KL 31/11-35	2	78–80	15300 ± 500–440	14900

1. Kusumgar, S., PRL, Ahmedabad, pers. commun.

2. Elke Vogelsang, University of Kiel, pers. commun.

*Not considered for age model (non-comparable core intervals for ^{18}O data).

in the Himalayas¹⁴. This climate phase correlates reasonably with the European Bolling–Allerod event^{15–17}. The termination of this deglaciation is conspicuous, and is marked with lighter incursions of $d^{18}\text{O}$, of the order of 1.8‰ in *G. ruber*. In world climate models, this event seems to be coeval with the Melt Water Pulse IA (MWP IA), during which the sea level rose by about 24 m (ref. 12). It is therefore deduced that this deglaciation phase in the Himalayas was synchronous with the global warming witnessed by the first major sea-level transgression in the Bay of Bengal.

Aridity appeared to have persisted for ~ 600 years between 10.5 and 9.9 Ka BP. The $d^{18}\text{O}$ excursion during this event approximates the values of the LGM interval. Terrestrial records reveal that around this period the Himalayan glaciers, particularly in the upper reaches of Gangotri, were descended to the lower altitudes²¹. It is therefore inferred that glaciation in the Himalayas during this event was coeval with reduced fluvial flux in the Bay of Bengal. This arid episode coincides with the ‘Younger Dryas’ event which, by and large, is inconspicuous in the marine upwelling records of the Arabian Sea¹⁷.

The beginning of the Holocene is marked with much lighter $d^{18}\text{O}$ compared to LGM (magnitude 2.44‰ for *G. ruber*), which persisted for the entire Holocene, with two pauses at ~ 5–4.3 and ~ 2.0 Ka BP (Figure 2). Between the LGM and the Holocene, the $d^{18}\text{O}$ variations of about 1.2‰ can be assigned to decrease in global ice volume. Other studies have also documented lighter $d^{18}\text{O}$ incursions for the entire Holocene in the other regions of the bay^{20,22}. The observed variation of 2.44‰, however, is too large to be accounted by changes in the global ice volume alone. The excessive lighter values of $d^{18}\text{O}$ could be due to local factors such as changes in SSS by higher fluvial influx from the G–B system, and/or higher SST in the bay. The $d^{18}\text{O}$ variability of 2.44‰ may be accounted either by ~ 8° SST or 7‰ SSS changes. The estimated SST variations are 2°C at these times⁹, and can contribute only to a variability of ~ 0.6‰. Excess lighter $d^{18}\text{O}$ values in both the species, therefore, appear to be a manifestation of enhanced fluvial influx in the bay. After 9.5 Ka BP, the upper reaches of the Himalayas experienced extensive deglaciation²¹. Global climate models also depict a large freshwater influx around this time resulting in global sea-level rise up to 28 m (MWP Ib)¹². It is deduced, therefore, that around the beginning of the Holocene, intensification of the SW monsoon together with extensive deglaciation in the Himalayas might have caused increased freshwater flux and rapid sea-level transgression in the Bay of Bengal^{23,24}.

The arid episodes of 5.0–4.3 and ~ 2.0 Ka BP coincide with similar events of 4.8 Ka and 1.8–2.2 Ka BP respectively, reported from the northern Indian Ocean^{16,18,22}. However, in the continental records, much variability exists about the prevalent climate of the Himalayas dur-

ing Mid Holocene. In the Gangotri area, the Shivling Stage of glaciation has been reported at ~ 5.1 Ka BP (ref. 25). Pollen records from the nearby (Dokini Glacier) periglacial peat, however, indicate prevalence of arid climate during 4000–3500 cal yr BP (ref. 26). In our records this phase terminates at ~ 4.3 Ka BP. Sharma *et al.*²⁷ have reported a humid climate at 4.0 Ka BP from Deoria Tal (2770 m; Uttarkashi), and a drier climate between 3.2 and 1.7 Ka BP.

Other marine records also show aridity at 4.5 cal yr BP (ref. 28) and reduced discharge of Indus during 1.8–2.2 Ka (ref. 16). Around this time, Phadtare²⁶ has also marked a spell of arid climate in Garhwal Higher Himalayas. The arid event of 3.5 Ka BP reported in the upwelling record of the western Arabian Sea²⁹, however, is not conspicuous in the bay. It is summarized, therefore, that the unstable climate of the Himalayas during the Late Pleistocene had induced synchronous century-scale changes in the SSS of the bay, with far-reaching influence on the oceanographic processes, particularly on the dispersal mechanism of fluvial freshwater fluxes of the G–B system, which remains least explored.

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Application of fossil cuticles in determining palaeoatmospheric CO₂ concentration

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During the last decade stomatal index analysis from fossil leaf cuticles has emerged as a powerful tool in estimating palaeo CO₂ (pCO₂) levels. In India, this particular method has yet not been applied on fossil leaves. In order to reconstruct pCO₂ concentration of the time of deposition of the fossil, this technique is applied on a fossil leaf of *Terminalia catappa* Linn., family Combretaceae which has recently been described from the Upper Siwalik sediments of West Kameng District, Arunachal Pradesh and is considered as of Upper Plio-Pleistocene in age.

It is necessary to study the past CO₂ concentration in order to understand the future climatic changes. The amount of CO₂ is rapidly increasing in the atmosphere due to industrial revolution and human activities. The rise in temperature is related to the increase in CO₂ level in atmosphere. Thus, this increase in CO₂ is alarming as it is

expected to increase the earth's mean temperature by 2–5°C at the end of this century¹. The increase in temperature is responsible for the melting of glaciers that are ultimately responsible for the rise in sea level. El Nino, the weather phenomenon which caused havoc, displaced many people from their homes and caused about 30,000 deaths in the last decade is also linked with the increase in CO₂ level. Higher CO₂ level causes plants to develop a more extensive root system which allows the plant to exploit more water and nutrients from the soil and therefore, the good effect of the increase in CO₂ concentration is the increase in the productivity of plants due to stimulation in photosynthesis.

Quantifying palaeo CO₂ (pCO₂) is essential in order to understand climatic changes and their effect on global temperature. The instrumental record of CO₂ concentration is available only for the last six decades. Hence, a number of methods have been evolved to reconstruct pCO₂ in the geologic past, each having its own merits, demerits and limitations. The most reliable method for estimation of pCO₂ concentration during Quaternary is the analysis of air trapped in polar ice. However, this method is only applicable for the past 400 ka because of the absence of ice before this time. Though it is difficult to measure pCO₂ concentration directly with the same accuracy before this period, it is possible to measure it from the proxy signals obtained from carbon isotope analysis of palaeosols, peat or marine organic matter; boron isotope analysis of planktonic foraminifera and by modelling the long-term global carbon budget¹. Recently, stomatal index (SI) analysis from fossil leaf cuticles has emerged as a powerful tool in deducing pCO₂ levels^{1–6}. In India, this particular aspect has not yet been touched and we are applying this method on the Indian Pleistocene fossil leaf to reconstruct pCO₂ concentration.

Recently, Joshi *et al.*⁷ described a fossil of *Terminalia palaeocatappa* Awasthi and Mehrotra⁸ leaf along with its cuticle from the Upper Siwalik sediments of West Kameng District, Arunachal Pradesh. The age of the fossil ranges from the Upper Pliocene to Pleistocene. The fossil was considered similar to the extant species *Terminalia catappa* Linn., family Combretaceae because of the close resemblance in the morphological features of the leaf and cuticle.

Woodward⁹ pointed out, on the basis of the herbarium leaf material collected over the past 200 years, that the stomatal frequency of leaves of woody plants is inversely proportional to atmospheric CO₂ concentration. Stomatal frequency is generally expressed either in terms of stomatal density (no. per mm²) or SI¹⁰ [stomatal density / (stomatal density + epidermal cell density)] × 100. It has been proved through the experiments done by various workers that SI is relatively stable under varying climatic conditions and water supply because changes in the rate of leaf expansion do not affect the ratio between stomata and epidermal cells¹. Herbarium leaf material of *T. catappa*

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