Supplementary online material

Variability of Indian monsoonal rainfall over the past 100 ka and its implication for C_3-C_4 vegetational change

Table S1 Carbon isotope ratio of modern C_3 plants.

Location	Name of plant	Sample number	$\delta^{13}C$ values of C_3 plants (‰, VPDB)
	Alysicarpus vaginalis	SR-1	−31.3
	Phyla nodiflora	SR- 3	−29.5
	NI	SR- 8	−31.4
	NI	SR-10	−31.6
	Phyla no diflora	SR-11	−30.2
	Cyperus difformis	SR-15	−28.8
Out side of the IIT	*NI*	KG-3	−29.0
Kharagpur campus	*Dismodium Triflorum*	KG-6	−30.9
	NI	KG-8	−29.8
	NI	KG-9	−30.3
	Alysicarpus morilifer	KG-10	−30.7
	NI	KG-11	−28.9
	NI	VG-06	−30.7
	NI	VG-03	−30.0
	Sida Cordifolia	C	−30.5
	Boerhaavia repens	D	−30.7
Inside of the IIT	*NI*	E	−31.9
Kharagpur campus	*Compositae*	F	−31.2
	Euphorbia Hirta - Euphorbiaceae	J	−28.3

	Momosa Pudica	K	−32.6
	Tridax Procumbens	L	−29.9
	Justicea procumbus	N	−28.7
	NI	2	−32.1
	NI	6	−29.8
	NI	I/GG/17	−30.8
	Tephrosia purpurea	I/GG/13	−30.1
	NI	VG/08	−28.9
	Marshila sp.	KR/07	−27.0
	NI	KP-1	−28.7
	Phylanodiflora nadiflora	KP-2	−30.8
	NI	KP-3	−25.1
	NI	KP-4	−29.3
	NI	KP-7	−26.2
	Heliotropium ovaliflolium	KP-8	−27.8
	Mollugo oppositifolia	BTP-2	−27.9
	Polygonum barbatum	BTP-3	−30.3
South-central	*NI*	BTP-5	−19.2
Ganga Plain	*Ammania baccifera*	BTP-6	−29.8
	Eclipta alba	BTP-8	−31.4
	Sida cordifolia	GP-1	−27.7
	NI	GP-2	−30.7
	Parthenium histoflorum	GP-5	−30.8
	NI	GP-6	−29.6
	NI	GP-8	−29.4
	Croton bonplandiaum	GP-10	−26.8
	Oxalise corniculata	GP-11	−32.0

NI	GP-12	−28.5

Note: NI - Not identified till date; SR-Swarn Rekha River; KG-Kaleghai; Alphabet, numbers and VG series-IIT Kharagpur campus; KP- Kalpi Cliff; BTP-Hamirpur, Betwa River; GP-Bithur near Kanpur

Table S2 Carbon isotope ratio of modern C_4 plants.

Location	Name of plant	Sample number	$\delta^{13}C$ values of C_4 plants (‰, VPDB)
Out side of the IIT Kharagpur campus	*NI*	SR-2	−12.3
	Fimbristylis Sp.	SR-4	−12.0
	Cynodon dactylon	SR-5	−14.1
	NI	SR-6	−12.0
	NI	SR- 7	−12.2
	NI	SR-9	−12.6
	Cyprus exaltatus	SR-12	−12.2
	NI	SR-13	−11.4
	NI	SR-14	−13.3
	Chryopogon Aciculatus	KG-1	−11.7
	Cynodon dactylon	KG-2	−13.0
	NI	KG-4	−11.1
	NI	KG-5	−12.2
	NI	KG-7	−10.5
	NI	VG/18	−11.8
Inside of the IIT Kharagpur campus	*NI*	A	−11.4
	NI	B	−13.5
	NI	G	−12.6
	Fimbristylis Sp.	H	−11.1
	Sporobolus diander	I	−13.0
	NI	M	−12.4
	Cynodon Dactylon- Poaceae	O	−14.8
	NI	1	−14.6

	Cynodon dactylon	3	−15.3
	NI	5	−13.5
	Anternanther sessilis	KP-5	−14.1
	NI	KP-6	−14.2
	NI	KP-9	−14.4
	NI	BTP-1	−14.5
South-central Ganga	*NI*	BTP-4	−12.2
Plain	*NI*	BTP-7	−12.6
	NI	GP-4	−14.8
	NI	GP-7	−16.6
	NI	GP-13	−13.1
	NI	GP-15	−14.7

Note: NI - Not identified till date; SR-Swarn Rekha River; KG- Kaleghai; Alphabet, numbers and VG series-IIT Kharagpur campus; KP- Kalpi Cliff; BTP- Hamirpur, Betwa River; GP-Bithur near Kanpur

Table S3 Stable isotope data of soil carbonate and SOM from the Kalpi, IITK and Firozpur cores.

Core location	Sample number	Depth (m)	Age (ka)	$\delta^{18}O_{SC}$ (‰, VPDB)	$\delta^{13}C_{SC}$ (‰, VPDB)	$\delta^{13}C_{SOM}$ (‰, VPDB)
Kalpi core Lat 26° 07.80'N Long 79°45.60'E	S-1 LC	8.9	18.6	−5.0	−2.9	−21.1
	S-2 LC	9.4	19.1	−4.8	0.9	−21.8
	S-3 LC	9.9	19.5	−5.0	−1.7	−21.4
	S-4 LC	10.2	20.0	−5.3	−2.8	−19.7
	S-5 LC	10.5	20.4	−5.2	−0.8	−21.2
	S-6 LC A	10.6	20.6	NA	NA	−22.1
	S-6 LC B	10.9	20.9	−5.3	−2.1	−20.3
	S-7 LC A	11.2	21.2	−5.3	−4.2	−19.7
	S-7 LC B	11.5	21.6	NA	NA	−20.6
	S-8 LC A	11.7	21.9	−6.6	−6.3	−19.4
	S-8 LC B	12.0	22.2	NA	NA	−20.8
	S-9 LC A	12.3	22.6	NA	NA	−20.8
	S-9 LC B	12.5	22.9	−6.1	−3.0	−20.9
	S-10 LC A	12.7	23.1	−5.7	−4.0	−22.4
	S-10 LC B	12.9	23.4	NA	NA	−20.0
	S-11 LC A	13.2	23.7	NA	NA	−21.7
	S-11 LC B	13.4	24.1	−5.3	−3.1	−21.4
	S-12 LC A	13.7	24.6	NA	NA	−22.4

S-12 LC B	14.0	24.9	−5.9	−5.5	−22.1
S-13 LC A	14.3	25.2	−6.2	−5.9	−20.7
S-13 LC B	14.5	25.4	−5.8	−3.9	−25.3
S-14 LC	14.6	25.6	−5.6	−2.4	−22.7
S-15 LC	15.0	26.1	NA	NA	−21.5
S-16 LC	15.3	26.5	−5.2	−1.3	−24.0
S-17 LC	16.4	27.8	NA	NA	−22.5
S-18 LC	17.2	28.9	−4.8	−0.9	−21.5
S-19 LC	18.3	30.4	−5.0	−4.1	−22.3
S-20 LC	19.2	31.5	NA	NA	−23.5
S-21 LC A	19.8	32.2	−5.7	−3.6	−21.0
S-22 LC*	21.0	33.8	−4.9	−0.8	−20.8
S-23 LC*	21.7	34.7	−5.6	−1.0	−24.9
S-24 LC A*	22.5	35.7	−5.4	0.9	−23.4
S-24 LC B*	22.6	35.9	−4.8	−0.7	−23.8
S-25 LC	24.2	37.9	−4.8	−0.7	−23.2
S-26 LC	24.8	38.8	−6.5	−1.1	−23.4
S-27 LC	25.6	39.7	NA	NA	−22.5
S-28 LC	26.2	40.5	−6.0	−0.7	−22.5
S-28 LC (R)	26.2	40.5	−5.6	−0.8	NA
S-29 LC	26.9	41.3	−6.1	−1.4	−21.9
S-29 LC (R)	26.9	41.3	−5.5	0.9	NA
S-30 LC	27.1	41.6	−5.9	0.4	−22.3

S-30 LC (R)	27.1	41.6	−5.7	0.9	NA
S-31 LC	27.7	42.3	−5.8	0.4	−23.3
S-31 LC (R)	27.7	42.3	−5.7	0.6	NA
S-32 LC	28.5	43.5	−5.6	−1.0	−23.9
S-32 LC (R)	28.5	43.5	−5.7	0.0	NA
S-33 LC*	30.5	46.0	−5.6	−1.0	−26.7
S-34 LC*	30.7	46.3	−5.1	−0.6	−25.3
S-35 LC	31.8	48.6	NA	NA	−25.9
S-36 LC	33.0	50.7	NA	NA	−26.9
S-37 LC	33.0	50.9	−6.4	−2.0	−25.9
S-38 LC	34.3	53.4	−5.9	−4.9	−26.4
S-39 LC A	35.3	55.2	NA	NA	−26.5
S-39 LC B	35.8	56.1	−5.8	−0.1	−26.9
S-40 LC	36.3	57.2	NA	NA	−27.5
S-41 LC	37.5	59.5	−5.5	−0.9	−27.1
S-42 LC A	37.9	60.3	NA	NA	−26.5
S-42 LC B	38.4	61.3	−6.0	−4.9	−26.3
S-43 LC A	38.9	62.1	−6.3	−4.4	−27.6
S-43 LC B	39.3	62.9	−6.2	−3.3	−27.3
S-44 LC	39.8	63.9	NA	NA	−28.1
S-45 LC	41.2	66.7	−6.4	−4.5	−27.5
S-46 LC	41.4	67.1	−6.5	−5.8	−28.9
S-47 LC	43.4	70.9	−6.8	−3.3	−27.4

	S-48 LC	44.2	72.4	−6.5	−3.4	−27.8
	S-49 LC	45.3	74.6	−6.5	−1.1	−24.9
	S-50 LC A	47.5	78.8	−7.5	−3.7	−24.9
	S-50 LC B	48.0	79.3	NA	NA	−26.5
	S-51 LC	48.3	79.8	−7.1	−4.5	−24.9
	S-52 LC	49.0	82.0	NA	NA	−25.7
	S-53 LC	50.0	84.0	−6.9	−4.8	−26.6
IITK core Lat 26° 28.80’N Long 80°15.60’E	IITK 4	1.8	18.8	−6.9	−2.6	−19.4
	IITK 5	3.3	19.1	−5.4	−1.1	−24.2
	IITK 6	4.2	20.4	−8.1	−5.3	−24.5
	IITK 7	4.4	20.6	−6.6	−2.2	−24.2
	IITK 8	4.9	21.2	−8.2	−5.4	−23.7
	IITK 9	5.0	21.3	−6.9	−2.7	−24.3
	IITK 10	5.1	21.5	−6.8	−2.9	−24.2
	IITK 11	5.4	21.9	−6.6	−2.8	−24.8
	IITK 12	5.5	22.0	−6.7	−3.7	−24.7
	IITK 14	10.5	28.4	−5.6	0.5	−22.4
	IITK 15	13.2	31.3	−6.6	−3.5	NA
	IITK 16*****	14.3	32.3	−6.3	1.7	−23.2
	IITK 17	15.1	33.0	−6.8	−3.4	NA
	IITK 18	16.1	33.9	−5.1	−0.6	−23.9
	IITK 19	17.5	35.2	−5.1	−1.0	−25.2
	IITK 20	18.1	35.6	−4.1	−1.4	−26.8

	IITK 23	25.0	60.3	−7.2	−4.8	NA
	IITK 29	39.0	79.1	−6.7	0.6	−24.4
	IITK 30	39.2	79.5	−6.7	0.4	−25.2
	IITK 31	40.0	81.4	−6.7	−0.5	−24.1
	IITK 32	40.3	82.0	−6.6	−0.3	−26.3
	IITK 33	40.5	82.5	−6.7	0.0	−25.2
	IITK 34	41.0	83.6	−6.9	−0.3	−24.9
	IITK 35	41.5	84.8	−6.5	0.0	−25.0
	IITK 36	43.0	87.8	−7.1	−1.9	−24.4
	IITK 37	44.9	89.5	−5.9	−3.0	−24.9
	IITK 38	44.5	90.4	−6.8	−2.0	−25.0
	IITK 39	45.7	92.5	−7.0	−2.9	−24.8
	IITK 40	47	94.8	NA	NA	−27.2
	IITK 41	51.0	101.8	−7.8	−2.0	−26.9
Firozpur core Lat 26°39.90’N Long 80°26.64’E	FP 1	11.0	19.2	−6.2	1.5	−21.1
	FP 2	11.7	20.1	NA	NA	−24.0
	FP 3	12.9	21.6	NA	NA	−24.0
	FP 4	13.5	22.3	−7.2	−0.6	−26.6
	FP 5	13.9	22.8	−7.3	0.2	−26.0
	FP 6	14.4	23.4	−7.7	1.6	−25.9
	FP 7-1	14.9	24.0	−7.2	0.0	−26.2
	FP 7-2	15.0	24.1	−7.5	0.2	−25.4
	FP 8	15.1	24.2	−7.8	−0.6	−23.7

FP 10	16.0	25.5	−6.9	−3.2	−26.7
FP 15	17.0	25.9	−7.1	−4.3	NA
FP 16	17.9	27.6	−6.8	−3.5	−26.6
FP 17	17.9	27.7	−7.3	−2.9	−27.3
FP 18	18.0	27.8	−7.4	−3.9	−27.2
FP 19	18.5	28.4	−7.1	−3.8	−26.9
FP 20*	18.7	28.7	−7.1	−1.2	−27.1
FP 21	19.0	29.0	−7.0	−4.5	−26.8
FP 22	19.3	29.4	−7.1	−3.9	−27.4
FP 23*	20.0	30.3	−6.9	−2.0	−27.6
FP 24-1*	20.3	30.6	−7.0	−3.6	−28.2
FP 25*	23.1	34.1	−7.8	−4.1	−27.4
FP 26	23.8	34.9	NA	NA	−27.4

*Ground-water carbonate; NA- not available; (R) - replicate sample

Table S4 Correlation of continental proxies (i.e. pollen, magnetic susceptibility and geochemical data) with monsoon reconstructed from the Ganga Plain.

	Goting Lake, higher central Himalaya	**Thar Desert**	**Central Asia**	**Sutlaj Valley, Greater Himalaya**
Monsoon variations from the Ganga Plain (this study)	*Magnetic susceptibility and geochemical data*	*Calcrete*	*Paleo-moisture*	*Lake*
	Juyal et al., 2009	*Andrews et al., 1998*	*Herzschuh, 2006*	*Bookhagen et al., 2005*
~18 ka (weak monsoon)	22 ka, LGM	-	21.3 to 19.8 dry to moderate dry climate	-
~25 ka (monsoon intensification)	25 ka, moderate to strong monsoon	22 to 26 ka, weak monsoon		29 to 24 ka high monsoon
~35 ka (weak monsoon)	-	-	Between 40 and 30 ka, high moisture, wet	-
~40 ka (monsoon intensification)	-	43 to 55 ka, strong monsoon		-

			condition	
~60 ka (weak monsoon)	-		-	-
~84 ka (monsoon intensification)	-	-	-	-

Table S5 Correlation of monsoonal rainfall with sedimentary sequences of the Indian subcontinent. The high monsoon phases during 84, 40 and 25 ka are well correlated with the phase of aggradation and incision.

Monsoon variations from the Ganga Plain (this study)	**Ganga Plain**			**Thar Desert**	**Thar Desert margin**			**Narmada Valley**
	Bithur	**Son and Belan Valley**	**Regional geomorphic surface**	**Luni River basin**	**Mahi basin**	**Sabarmati basin**	**Orsang basin**	**Narmada River**
	Gibling et al., 2005; Sinha et al., 2007	*Williams et al., 2006; Gibling et al., 2008*	*Srivastava et al., 2003*	*Jain and Tandon, 2003*	*Juyal et al., 2000; Jain and Tandon, 2003*	*Wasson et al., 1983; Tandon et al., 1997; Srivastava et al., 2001*	*Juyal, et al., 2006*	*Kale et al., 2003*
~18 ka (weak monsoon)	-	Progressively weakening of monsoon during 39 to 16 ka causes the aggradation	-	Fluvial and Aeolian process ceased	Aeolian activity	Aeolian activity	20 to 11 ka, dry climate sedimentary sequence change from fluvial to aeolian	-
~25 ka (monsoon intensification)	~30 to 23 ka, floodplain detachment and valley aggradation at Firozpur		26 to 22 ka humid climate	-	Two aggradation phases 52 to 44 ka and 37 to 30 ka	~58 to 30 ka, floodplain aggradation (silty sand) influence by the enhance	~ 60 to 30 ka, enhanced monsoon	Just before LGM humid condition

~35 ka (weak monsoon)	-			Progressive aridity causes ephemeral sand and sheet flood event		SW monsoon		-
~40 ka (monsoon intensification)		58 and 45 ka reduced monsoon followed by increasing monsoon	50 to 40 ka humid climate					-
~60 ka (weak monsoon)	-							-
~84 ka (monsoon intensification)							~100 to 70 ka, enhanced monsoon floodplain aggradation	
	-	85 to 72 ka sustained fluvial activity	-	MIS 5a sustained climate	MIS 5a sustained climate	MIS 5a sustained climate		-

Table S6 Relationship between monsoon and atmospheric CO_2 with vegetation. The higher abundance of C_4 plants in low monsoon condition and vise verse suggest monsoonal rainfall intensity controlled the relative abundance of C_3-C_4 plants.

Time (ka)	**Monsoon**	**Atmospheric CO_2 concentration (*ppmV; Barnola et al., 1987*)**	**Abundance of C_4 plants Based on $\delta^{13}C_{SC}$ values**
18 ka	Low Rainfall	Low	Increase in abundance of C_4 plants
25 ka	High Rainfall	low	Increase in abundance of C_3 plants
60 ka	Low Rainfall	High	Increase in abundance of C_4 plants
84 ka	High Rainfall	High	Increase in abundance of C_3 plants

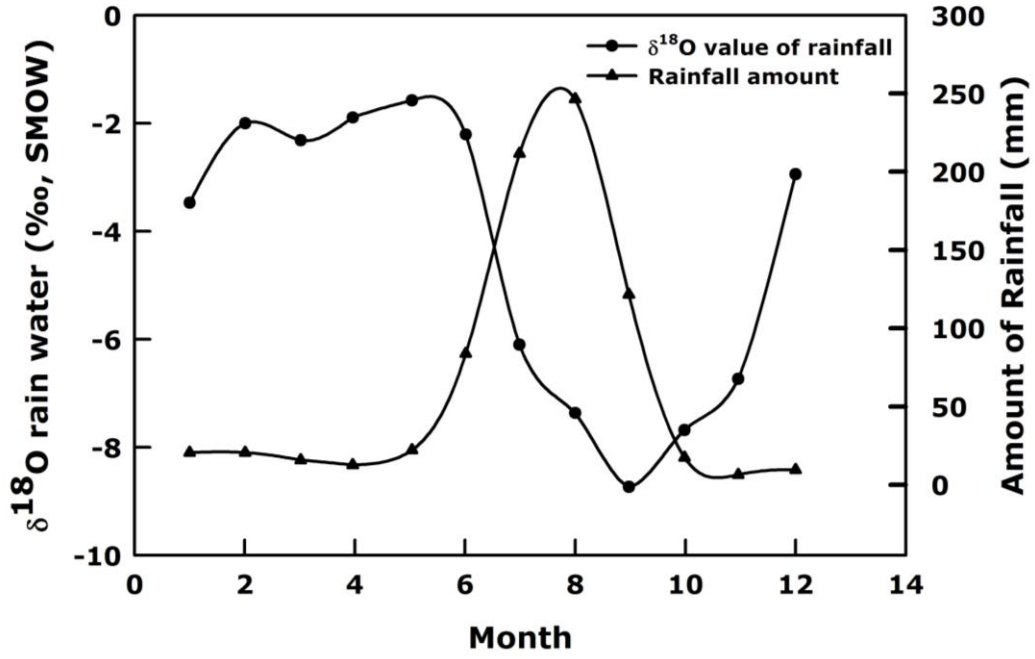

Figure S1. The relation between $\delta^{18}O$ of rainwater and amount of rainfall. The plot shows lowering of $\delta^{18}O$ values with increase in amount of rain during monsoon month (month: 6 to 9; June to September; Bhattacharya et al., 2003).