

# Increasing chemical weathering in the Himalayan system since the Last Glacial Maximum

Maarten Lupker, Christian France-Lanord, Valier Galy, Jérôme Lavé,

Hermann Kudrass

## ► To cite this version:

Maarten Lupker, Christian France-Lanord, Valier Galy, Jérôme Lavé, Hermann Kudrass. Increasing chemical weathering in the Himalayan system since the Last Glacial Maximum. Earth and Planetary Science Letters, 2013, 365, pp.243 - 252. 10.1016/j.epsl.2013.01.038 . hal-01763489

# HAL Id: hal-01763489 https://hal.univ-lorraine.fr/hal-01763489

Submitted on 19 Nov 2019  $\,$ 

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Increasing chemical weathering in the Himalayan system since the Last Glacial Maximum

Maarten LUPKER<sup>1</sup>\*, Christian FRANCE-LANORD<sup>1</sup>, Valier GALY<sup>2</sup>, Jérôme LAVÉ<sup>1</sup>,

Hermann KUDRASS<sup>3</sup>

<sup>1</sup> Centre de Recherches Pétrographiques et Géochimiques (CRPG), UMR 7358, CNRS-Université de Lorraine, 15 rue Notre Dame des Pauvres, 54501 Vandoeuvre les Nancy, Cedex, France.

<sup>2</sup> Woods Hole Oceanographic Institution (WHOI) – Department of Marine Chemistry and Geochemistry, 360 Woods Hole Rd., Woods Hole, MA 02543, USA.

<sup>3</sup> MARUM zentrum für Marine Umweltwissenschaften, Bremen, Germany.

\*Corresponding author: Maarten Lupker IGP-ETHZ - NW C 85 - Clausiusstrasse 25, 8092 Zürich - Switzerland

+41 446329383

maarten.lupker@erdw.ethz.ch

**ABSTRACT:** 

2 Continental chemical weathering is central in Earth's surface biogeochemical cycles as it redistributes elements across reservoirs such as the crust and the oceans. 3 4 However the evolution of weathering through time and its response to external forcing 5 such as changes in climate remain poorly constrained. In this work, a composite 6 sediment record from the Bay of Bengal is used to document the evolution of chemical 7 weathering in the Himalayan system (Himalayan range and Indo-Gangetic floodplain), 8 the world largest sediment convevor to the oceans, since the Last Glacial Maximum 9 (LGM). The degree of weathering of the sediments is documented using mobile to 10 immobile ratios such as K/Si and H<sub>2</sub>O<sup>+</sup>/Si as well as detrital calcite abundance. Robust 11 weathering proxies are derived by correcting the chemical composition of sediment for 12 sorting effects that occur during transport and deposition. The Bay of Bengal record is 13 also further compared to the chemical composition of modern river sediments from the 14 Ganga & Brahmaputra basin. Weathering proxies all indicate that the sediments 15 exported by the Ganga & Brahmaputra Rivers became increasingly weathered over the 16 past ~21 kyr, whereas, Sr, Nd and major elements suggest a constant sediment 17 provenance in the system over the last 21 kyr. These changes in the degree of weathering 18 of the sediments show that the weathering flux exported by the system to the Indian 19 Ocean during the LGM was significantly lower than at present and demonstrate that 20 chemical weathering in continental scale basins such as the Ganga & Brahmaputra 21 responds to Late Quaternary climate changes.

23

24	Chemical weathering of continental rocks is the main source of soluble elements to the
25	oceans and therefore exerts a first order control on oceanic bio-geochemical cycles. Over
26	geologic time scales, silicate weathering and subsequent carbonate precipitation also draws
27	down atmospheric CO <sub>2</sub> thereby stabilizing the earth's climate (Walker et al., 1981).
28	Continental weathering fluxes are a function of continent lithology, tectonic activity and
29	climate but the mechanisms and feedbacks linking silicate weathering to the earth's climate
30	remain debated (France-Lanord and Derry, 1997; Willenbring and von Blanckenburg, 2011).
31	A better understanding of these complex climate-weathering couplings can be gained by
32	studying the response of continents to climatic transitions in the past.

33 The role of the Himalayan orogeny in the long-term forcing of oceanic cycles and the 34 global climate has retained much attention (France-Lanord and Derry, 1997; Raymo et al., 1988). However, the temporal variability of and controls on the evolution of weathering 35 36 fluxes exported by large basins remains poorly constrained and is often difficult to reconstruct 37 (Limmer et al., 2012). In particular, direct characterization of the response of chemical 38 weathering to abrupt climate perturbations has heretofore remained a challenge. We present a 39 record of chemical weathering intensity in the Himalayan system since the LGM. The 40 Himalayan system is defined here as the Himalayan range and the downstream Indo-Gangetic 41 floodplain drained by Ganga and Brahmaputra Rivers. No major change in tectonic forcing of 42 the Himalayan orogeny has been documented so far over the last glacial-interglacial period, 43 which enables us to discuss variations in sediment weathering as a response to climate 44 change.

45

#### 46 2. Setting and methods:

The central part of the Himalayan range is drained by two major rivers, the Ganga and 48 49 Brahmaputra (Figure 1). Currently, the Ganga & Brahmaputra transfers ca. 1.10<sup>9</sup> Mt of 50 sediments to the Bay of Bengal, of which 90% is transported during the monsoon (RSP, 51 1996). River sediments were sampled mainly during monsoon seasons, in 2002, 2004, 2005, 52 2007, 2008 and 2010 across the Indo-Gangetic floodplain. Sampling locations mainly 53 included the front of the Himalayan range for the main trans-Himalayan Rivers of the Ganga 54 & Brahmaputra system, the outlet of the Ganga and the Brahmaputra as well as their 55 confluence - the lower Meghna - which integrates the entire sediment load exported from the 56 Ganga & Brahmaputra basin (Figure 1). When possible, sediments were sampled along vertical depth profiles through the water column in order to capture the full variability of the 57 58 sediment load. These profiles were complemented by bedload samples dredged from the 59 active channel of the rivers and freshly exposed bar sediments. Details on the sampling 60 procedure are described in Lupker et al. (2011).

61 Sediment cores were retrieved during RV Sonne cruise SO93 in 1994 from the shelf 62 (105KL and 107KL) and the active channel levee system of the middle fan (117KL, 118KL 63 and 120KL) (Ittekkot et al., 2003). The chronology of the cores is provided by re-calibrated (Reimer et al., 2009) <sup>14</sup>C ages on planktonic foraminifers (Weber et al., 1997) as well as 64 <sup>137</sup>Cs, <sup>210</sup>Pb and <sup>228</sup>Ra gamma spectrometry (Michels et al., 1998). Scarce hemipelagic layers 65 were excluded from the study in order to focus on turbiditic sediments representing the Ganga 66 & Brahmaputra detrital signal (Pierson-Wickmann et al., 2001; Weber et al., 1997). We 67 68 interpret our data by constructing a composite Log from the shelf and levees core following 69 the approach detailed in Galy et al. (2008).

River suspended river sediments were filtered through 0.22 µm PES membrane filters
 within 24 h of sampling and dried in the lab. Major element concentration was determined by

72	ICP-OES after LiBO <sub>2</sub> fusion at SARM, Nancy – France (Carignan et al., 2001). Core samples
73	were repeatedly rinsed with water in order to remove salt contributions. Nevertheless, Na was
74	not considered in this study due to seawater contamination even after these rinsing steps.
75	Carbonate contents were measured manometrically from the CO <sub>2</sub> released after reaction with
76	$H_3PO_4$ and the evolved $CO_2$ was subsequently analyzed for C and O isotopic composition
77	(Galy et al., 1999). Sr and Nd isotopic compositions were measured on the acid leached,
78	silicate fraction of the river and core sediments by TIMS after classical separation and
79	purification by ion exchange resins. Sediment hydration $[H_2O^+]$ and isotopic composition $\delta D$ -
80	SMOW was measured by EA-IRMS after degassing the samples to remove adsorbed free-
81	water (Lupker et al., 2012b). The long-term reproducibility is better than 0.1 $H_2O^+$ wt % and 2
82	‰ δD-SMOW.
83	
84	3. Sediment sorting effects on the chemical composition of detrital sediments:
85	3.1 Hydrodynamic control of sediment sorting
86	
87	The chemical composition of river sediments has to be interpreted carefully. Sediment
88	vertical depth profiles recovered from the water column of large rivers show a strong
89	heterogeneity in terms of concentration and chemical composition. These heterogeneities are
90	the result of the hydrodynamic sorting of sediments, based on grain-size, shape and density,
91	which induce mineralogical and thus chemical differentiation of sediments within the water
92	column (Bouchez et al., 2011a; Bouchez et al., 2011b; Garzanti et al., 2011; Lupker et al.,

2011; Singh and France-Lanord, 2002a). The mineralogy of sediments from the Himalayan
system is dominated by quartz, micas and feldspar, with occurrences of other phyllosilicates,
clay assemblages and hydroxides in the finer fraction (Garzanti et al., 2011; Garzanti et al.,
2010). These minerals are segregated during sediment transport: coarse-grained quartz is

97 enriched in the bedload and at the bottom of the water column while phyllosilicates such as micas and clays are comparatively enriched in the shallow surface waters of the river, leading 98 99 to a strong contrast in chemical composition between samples of a single reach. This is best 100 illustrated using the immobile element ratios Fe/Si and Al/Si (Figure 2). Fe, Al and Si are, to 101 a first order, immobile elements during Himalayan erosion and are thus not notably affected 102 by chemical weathering (Galy and France-Lanord, 2001). The sediments sampled across the 103 Indo-Gangetic plain form a unique mixing trend (to the exception of a few bedload samples 104 that are enriched in Fe due to heavy mineral placer effects) between quartz rich (low Al/Si 105 and Fe/Si) bottom sediments and clay rich (high Al/Si and Fe/Si) surface sediments. Al/Si and 106 Fe/Si are directly correlated to the bulk sediment grain-size and are a proxy of mineral sorting 107 (Bouchez et al., 2011a; Lupker et al., 2011). A single sediment sample from a given river 108 reach can therefore not be considered, a priori, as representative of the whole sediment load, 109 its chemical composition being dependent on river hydrodynamics at the moment of 110 sampling.

111

#### 112 *3.2 Weathering proxies in modern river sediments*

113

114 The degree of chemical weathering experienced by sediments in the Himalayan 115 system can be traced from detrital sediments by using the mobile to immobile elemental ratios 116 of river sediments such as K/Si and H<sub>2</sub>O<sup>+</sup>/Si. The structural hydroxyl content of sediments,  $H_2O^+$ , is a proxy of chemical weathering that traces mineral hydrolysis and secondary neo-117 118 formations (Lupker et al., 2012b). Sediment sorting effects also apply to mobile elements 119 such as K and H<sub>2</sub>O<sup>+</sup>. The K/Si and H<sub>2</sub>O<sup>+</sup>/Si ratios are dominantly controlled by the grain size 120 of the sediments, i.e. clay to quartz mixing (Lupker et al., 2012b) and are, to a first order, 121 linearly correlated to their Al/Si ratio as shown by Figure 3, where these ratios are plotted for sediments from the modern Himalayan system. By using a sediment depth profile sampling approach on modern rivers, we characterize these sorting effects as this method allows sampling a full set of sediments covering a wide range of grain sizes. The degree of chemical weathering can then be assessed based on the trend formed by the chemical composition of the sediments in diagrams such as Figure 3, this trend being representative of the entire sediment load exported by the considered river.

In addition to silicate weathering proxies, we determined the calcite content and the Ca/Si ratio in Bay of Bengal sediments that reflects the carbonate weathering intensity in the Himalayan system. Carbonates, including calcite, account for over 80 % of the bulk Ca and Ca/Si therefore mainly reflects carbonate content. Both carbonates and Ca content are not grain size dependent (Lupker et al., 2011) and are therefore not corrected for sediment sorting.

134

#### 135 *3.3 Accounting for sediment sorting effects in detrital records*

136

137 For detrital records such as the Bay of Bengal cores, changes in sediment transport and 138 deposition patterns induce changes in the grain size of deposited sediments that, in turn, affect 139 the chemical composition of the record. Hence, sediment sorting also has to be taken into 140 account in order to compare the degree of weathering of samples with variable grain-sizes 141 (variable Al/Si ratios). However, unlike for modern rivers, it is not possible for a given age 142 interval of the record to recover a set of sediment samples spanning different grain sizes that 143 would fully describe the sediment weathering trend. By considering that each sample of the 144 Bay of Bengal record is the result of the mixing between a coarse-grained end-member, 145 similar to bedload material and a fine-grained, clay rich sediment, it is nevertheless possible

147

to normalize mobile to immobile ratios (X/Si) to a common Al/Si composition as illustrated in Figure 4 and equation 1:

$$\frac{X}{Si}^* = \frac{\overline{Al}}{Si} \cdot A + B \tag{1}$$

149 where A and B are respectively the slope and intercept of the linear regression through the 150 sample and coarse grained end-member composition (Figure 4). Such normalized ratios allow comparing the chemical composition of sediments that have contrasted grain sizes, while 151 152 properly accounting for sorting effects. Doing so, we assume that a unique coarse-grained 153 end-member composition can be assigned to the low Al/Si mixing end-member and that the 154 weathering signature is mainly carried by the small grain size, clay fraction of the sediment 155 load. This is a reasonable approximation as: 1) contrary to the fine grained suspended load, no 156 systematic evolution of K/Si and H<sub>2</sub>O<sup>+</sup>/Si ratios of modern bedloads in the Ganga basin is detected from up to downstream (Lupker et al., 2012b), suggesting that the effect of chemical 157 158 weathering during transfer in the floodplain is negligible for the coarse fraction of the 159 transported sediments, and 2) the transfer time of bedload material is thought to be an order of magnitude longer than that of fine-grained suspended load (Granet et al., 2010), which makes 160 161 it less sensitive than the suspended load to short-term upstream variations.

162 All corrected ratios presented here were normalized to a common Al/Si value of 0.23. 163 They are referred to as X/Si\* and are listed in the supplementary information along with the 164 composition of the coarse grained end-member used in the calculations. The Al/Si value of 165 0.23 was chosen as the average composition of the sediments exported by the modern Ganga, 166 which was determined by modeling the chemical composition of sediments as a function of 167 the river's hydrological conditions and integrated over a 25-year average hydrograph (Lupker 168 et al., 2011). This composition is also close to the composition of the Himalayan crust eroded 169 in the Ganga basin (Lupker et al., 2011). It should be noted that the choice of the Al/Si ratio 170 used for normalizing K/Si and H<sub>2</sub>O<sup>+</sup>/Si ratios only determines the absolute values of K/Si\*

171 and  $H_2O^+/Si^*$  but has no influence on the general trends observed for Bay of Bengal 172 sediments.

Before normalization, the raw K/Si and  $H_2O^+/Si$  ratios of sediments from the Bay of Bengal cores are correlated to Al/Si (Figure 5), which supports that K/Si and  $H_2O^+/Si$  are dominantly controlled by grain size and sorting effects. However the normalized K/Si\* and  $H_2O^+/Si^*$  ratios show no correlation with Al/Si, which suggests that our normalization properly accounts for sediment sorting.

- 178
- 179

#### *3.4 Comparison with modern river sediments*

180

In order to compare the weathering degree of the Bay of Bengal sediment record to 181 182 modern river sediments we applied a similar normalization to the river sediments. The 183 average compositions of modern river sediments for elements prone to sorting effects (K/Si\*, 184 H<sub>2</sub>O<sup>+</sup>/Si<sup>\*</sup>), reported in Figure 5, were determined by evaluating the regression through all 185 available data of each river reach and a coarse-grained end-member at Al/Si = 0.23. The 186 Himalayan front end-member was reconstructed from the river sediments sampled at the 187 Himalayan front in the Ganga basin and the Brahmaputra basin separately assuming that ca. 188 60% of the total sediment flux exported to the Bay of Bengal come from the Brahmaputra and 189 the remaining 40 % come from the Ganga basin (RSP, 1996). For compositions that are not affected by sorting effects (calcite, Ca/Si,  ${}^{87}$ Sr/ ${}^{86}$ Sr,  $\varepsilon$ Nd,  $\delta^{18}$ O and  $\delta^{13}$ C), a simple average for 190 191 the Ganga, Brahmaputra and lower Meghna and a weighted mean for the Himalayan front 192 were considered (details can be found in supplementary information and Table S2).

193

#### 194 **4. Weathering in the Himalayan system:**

195 *4.1 Weathering in the modern system* 

197	Chemical weathering is marked by a change in the mobile to immobile ratio at
198	constant Al/Si ratio. This mobile element depletion is highest for fine-grained (high Al/Si)
199	sediments (Figure 3). Modern Himalayan rivers sediments, sampled at the front of the range
200	show high K/Si ratios and low $H_2O^+/Si$ ratios compared to the sediments sampled at the outlet
201	of the Ganga & Brahmaputra basins and their confluence, the lower Meghna (Figure 3). The
202	loss of K and gain in hydration during floodplain transfer marks the weathering of the
203	sediments within the floodplain. Even if part of this weathering signal may stem from the
204	sediment contribution of the southern (Ganga) and eastern (Brahmaputra) tributaries, their
205	sediment fluxes remain small compared to that of Himalayan tributaries (Lupker et al., 2012b;
206	Singh and France-Lanord, 2002a). Calcite weathering in the modern floodplain is significant
207	and leads to almost complete dissolution in Brahmaputra sediments in Bangladesh (Singh and
208	France-Lanord, 2002a; Singh et al., 2005) while modern Ganga sediments in Bangladesh
209	display a low calcite content of ca. 3 wt% (Lupker et al., 2012b).
210	It has been shown that in the modern Ganga basin, weathering within the floodplain
211	outweighs weathering within the Himalayan range (Lupker et al., 2012b; West et al., 2002).
212	Significant K depletion and $H_2O^+$ gain is only recorded when sediments transit through the
213	floodplain (Lupker et al., 2012b), which is attributed to the longer residence time of sediments
214	in the floodplain than in the Himalayan range. Overall, these observations emphasize the
215	strong floodplain control on weathering in the Himalayan system.
216	
217	4.2 Weathering record of the Bay of Bengal:
218	
219	The normalized weathering indexes (K/Si* and $\mathrm{H_2O^+\!/Si^*})$ are not biased by sorting
220	effects and can thus be applied to the Bay of Bengal record to reconstruct temporal variations

221 in chemical weathering. Composite logs of K/Si\* and  $H_2O^+/Si^*$  (Figure 6) show a progressive 222 evolution towards lower K/Si\* and higher  $H_2O^+/Si^*$  ratios from the LGM to present. Both 223 weathering proxies suggest that during the LGM, sediments exported to the Bay of Bengal 224 were less weathered than recent Bay of Bengal and modern lower-Meghna sediments. It 225 should also be noted that the chemical composition of sediments from the most recent part of 226 the Bay of Bengal record agrees well with that of the sediments currently exported by the 227 lower Meghna (Figure 6).

228 Calcite content and Ca/Si ratios also decrease from LGM to present (Figure 6). Calcite 229 in sediments from the Bay of Bengal is of detrital origin as demonstrated by their isotopic composition ( $\delta^{18}O_{PDB}$  ranging from -15 to -6 ‰, see electronic appendix), much lower than 230 231 marine biogenic calcite (Hoehndorf et al., 2003) and within the range of composition of 232 detrital Himalayan river calcite (Lupker et al., 2012b). The decrease in calcite concentration and Ca/Si ratios since the last glacial maximum supplement the K/Si\* and H<sub>2</sub>O<sup>+</sup>/Si\* records, 233 234 further reinforcing the conclusion that sediment weathering increased during the studied 235 period.

236 Estuarine and early digenetic reactions such as weathering and reverse weathering 237 may affect the composition of deposited sediments (Jones et al., 2012; Michalopoulos and Aller, 1995; Michalopoulos and Aller, 2004; Wallmann et al., 2008). The close agreement 238 239 between the chemical composition of modern lower Meghna sediments and the recent part of 240 the record, both from the shelf and the levee, suggests that estuarine processes do not alter 241 significantly the composition of river sediments delivered to the Bay of Bengal. The chemical 242 weathering of sediments after deposition cannot explain the trends observed in the Bay of 243 Bengal record either. Indeed, post-depositional weathering would lead to down-core increase 244 in the weathering intensity which is opposite to the observed trend. Reverse weathering leads 245 to an uptake of K and to an overall decrease in structural OH radicals of the sediments

246 (Michalopoulos and Aller, 1995) but cannot explain the observed down-core increase in 247 detrital carbonate content. Furthermore, during reverse weathering reactions, the newly 248 formed minerals will form in equilibrium with seawater so that the D/H isotopic composition 249 of their hydroxyls groups should become heavier as reverse weathering reactions proceed. 250 However no systematic down-core increase in  $\delta D_{H2O+}$  is observed (supplementary 251 information, Figure S1).

- 252
- **5. Sediment provenance since the LGM:**
- 254

255 Potential sediment source effects on the chemical composition of Bay of Bengal 256 sediments since the LGM must be taken into account as changes in precipitation and erosion 257 patterns within and across the Himalayan range may have affected the sedimentary record. 258 The Sr and Nd isotopic signatures of river sediments in the Himalayan range are a first order 259 indicator of the erosion balance between the Lesser Himalaya (LH) and High Himalaya 260 (HHC) (and Transhimalayan formations - THB - for Brahmaputra) as these units have 261 contrasted isotopic compositions (France-Lanord et al., 1993; Singh and France-Lanord, 262 2002a). Sediments from the Ganga and Brahmaputra basins also show distinctive Sr and Nd 263 isotopic compositions so that changes in the balance of sediment supply from both basins 264 would be detected (Figure 7).

Previous studies have shown contrasting changes in the balance between sediments from the LH and HHC in the Indus basin (Clift et al., 2008) and the western part of the Ganga basin (Rahaman et al., 2009; Rahaman et al., 2010; Srivastava and Shukla, 2010) since deglaciation. However, both Sr and Nd isotopic compositions of Bay of Bengal sediments appear constant, implying that there is no evidence for major changes in the distribution of erosion within the Himalayan range at this scale (Figure 7). The Sr and Nd record also

suggests that the balance between the Brahmaputra and Ganga has remained roughly constant over the last 20 kyrs. A significant change in the sediment balance between Ganga and Brahmaputra would furthermore result in a correlated evolution of K/Si\* and  $H_2O^+/Si^*$ , whereas these ratios are actually anti-correlated since the LGM (Figure 6), demonstrating that the weathering signal overprints any potential change in sediment source.

276 An increase in sediments from the Siwalik or from southern tributaries through time is 277 also very unlikely. Siwalik rocks and sediments are characterized by high carbonate content and low  $\delta^{13}$ C compositions (Lupker et al., 2012b; Sanyal et al., 2005). Thus, the concomitant 278 decrease of both carbonate content and  $\delta^{13}$ C values observed in the Bay of Bengal sediments 279 280 is not compatible with an increase of sediment supply from the Siwaliks. In addition, 281 sediments from the Chambal River in the Ganga basin and the Eastern tributaries of the 282 Brahmaputra basin (Lohit and Dibang) have distinctively higher Fe/Si ratios and unradiogenic 283 Sr and Nd signatures (Lupker et al., 2012b; Singh and France-Lanord, 2002a; Singh et al., 284 2008) that are not identified in our record (see supplementary information, Figure S1).

285

Altogether, the observed changes in Bay of Bengal sediment mobile elements composition since the LGM can thus be primarily attributed to changes in the chemical weathering intensity in the Ganga & Brahmaputra basin.

289

#### **6. Discussion:**

291 6.1 Climatic forcing of Himalayan chemical weathering

292

During the last 21 kyrs, climate has been the main external forcing of Himalayan erosion that could have affected the Bay of Bengal weathering signal. Paleo-temperature reconstructions over the Himalayan system are scarce but indicate a ca. 2 °C colder LGM sea 296 surface temperature (SST) in the Bay of Bengal (Kudrass et al., 2001). Hydrological changes 297 were significant with strongly reduced monsoon and therefore a lower continental runoff 298 during the last glacial (Cullen, 1981; Duplessy, 1982; Herzschuh, 2006; Kudrass et al., 2001), 299 which reduced the sediment supply to the Bay of Bengal (Goodbred, 2003; Weber et al., 300 1997). Precipitation and temperature directly control the weathering rate of minerals (White 301 and Blum, 1995), and the conditions during the LGM where therefore less favorable for 302 intense weathering in the floodplain. These changes in floodplain weathering are confirmed 303 by the evolution of clay assemblages in the southern part of the basin that suggests an 304 increase in weathering intensity from at least 10 kyr to present (Heroy et al., 2003).

305 Additional, independent processes should not be excluded (Blum and Tornqvist, 306 2000). The lower base level and a reduced sediment supply during the LGM could have lead 307 to channel incision and a narrower active floodplain (Goodbred, 2003; Heroy et al., 2003), 308 which would reduce channel - floodplain interactions and limit the supply of weathered 309 floodplain sediments to the Bay of Bengal. A complete abandonment of the floodplain during 310 the LGM is nevertheless unlikely as floodplain derived organic material is persistent in the 311 Bay of Bengal cores throughout the deglaciation (Galy et al., 2008) but changes in the 312 sediment locus and volume being mobilized should not be excluded (Dosseto et al., 2010).

313 The weathering degree of sediments does, however, not show any clear change in 314 response to the decrease of monsoon intensity after the Holocene Climatic Optimum (HCO) (Kudrass et al., 2001). The sediment fluxes during the HCO were up to double modern fluxes 315 316 as indicated by sediment volume reconstructions (Goodbred, 2003). These high sediment 317 fluxes may have obliterated the intense weathering conditions prevailing at that time. It can 318 also not be ruled out that modern sediments reflect the export of material weathered during 319 the HCO owing to a long-sediment transfer time so that the post-HCO decrease in 320 precipitation is not yet recorded in the Bay of Bengal. The impact of anthropogenic activity in

321 the Indo-Gangetic floodplain should also be considered as intense land use changes, certainly 322 significant more than 3 centuries ago (Ramankutty and Foley, 1999), may overprint the 323 climatic forcing of the weathering degree in the recent part of the record if already significant 324 thousands of years ago (Bayon et al., 2012).

325

345

326 The sediment transfer time through the Himalayan system has to be considered as 327 well, as a long transfer time would induce a temporal offset between the suggested climatic 328 forcing of weathering in the Ganga & Brahmaputra basin and its recording in the sediment 329 record of the Bay of Bengal. The sediment transfer time in large continental basins remains 330 difficult to constrain. U-series disequilibrium studies on Ganga sediments suggest that the 331 transfer time of coarse sediments may reach several 100 kyrs while fine grained suspended 332 material travel in less than 25 kyrs (Chabaux et al., 2009; Chabaux et al., 2006; Granet et al., 333 2010; Granet et al., 2007). However, simple mass balance considerations based on the volume 334 of the active floodplain and grain size along with modern sediment fluxes suggest shorter 335 transfer time scales of 1 kyrs for fine (<100 µm) sediments along the Ganga floodplain 336 (Lupker et al., 2012a) and most probably even shorter transfer time along the narrower 337 Brahmaputra floodplain. In addition, short term variability of the chemical composition of 338 Ganga sediments observed in Bangladesh and attributed to the variable input of a > 1000 km 339 distant, upstream tributary suggests that for fine-grained suspended sediment the transfer time can be of the order of the season (Lupker et al., 2012b). Finally, a relatively short transfer 340 341 time is also supported by the organic carbon Bay of Bengal record, which shows a change in 342 vegetation photosynthetic type over the Ganga & Brahmaputra basin from the last glacial to 343 present (Galy et al., 2008). This vegetation change follows the model predictions and would not be recorded if the sediment transfer time exceeded glacial – interglacial time scales. 344

Although the transfer time of sediments is probably significant and remains difficult to

quantify, a network of evidences suggests that it is lower than glacial-interglacial time scales
for fine sediments such as those composing the Bay of Bengal record (high Al/Si ratios).
Thus, the observed weathering trends most likely results from the direct or indirect climatic
forcing of weathering in the Ganga & Brahmaputra basin.

350

#### 351 *6.2 Towards a quantitative weathering budget*

352

357

353 Changes in the net weathering flux or dissolved flux ( $\varphi_X$ ) can be estimated by 354 considering that, at steady state, the weathering flux exported as solutes to the oceans is the 355 product of the mobile element depletion of sediments ( $\Delta X$ ) and the sediment flux (F<sub>sed</sub>) 356 (Lupker et al., 2012b):

$$\varphi_X = F_{sed} \cdot \Delta X = F_{sed} \cdot \left( \overline{\frac{X}{Si}}_{Source} \cdot \overline{\left[Si\right]}_{Source} - \overline{\frac{X}{Si}}_{Sink} \cdot \overline{\left[Si\right]}_{Sink} \right)$$
(2)

Where  $\overline{X/Si}$  is the average mobile to immobile ratio of the source and sink sediments and 358 [Si] the average Si concentration of the sediments. A high-resolution reconstruction of 359 360 weathering fluxes is pointless, as the steady state hypothesis is likely not fully satisfied over 361 short time-scales because of late Holocene climatic variations and anthropogenic imprints 362 (possibly acting over timescales shorter than the sediment residence time in the floodplain). A 363 first order estimate can nevertheless be made by comparing the loss of K, and gain in H<sub>2</sub>O<sup>+</sup>, relative to Himalayan front sediments for the LGM (19 – 22 kyr) and the modern (0 – 2 kyr) 364 365 part of the record.

The average  $\overline{K/Si}$  and  $H_2O^+/Si$  ratios of the exported sediment flux can be estimated based on the average Al/Si ratio of the sediments, as Al/Si is relatively insensitive to chemical weathering. The average Al/Si ratio of sediments was estimated to be 0.23 for the Ganga in Bangladesh (Lupker et al., 2011). Hence,  $\overline{K/Si}$  and  $\overline{H_2O^+/Si}$  are well

approximated by  $\overline{K/Si^*}$  and  $\overline{H_2O^*/Si^*}$ , as for these ratios the composition of the sediment 370 is normalized to an Al/Si ratio of 0.23. 371

372 Because the effect of weathering in the Himalayan range is not detected on the K/Si and H<sub>2</sub>O<sup>+</sup>/Si composition of modern river sediments sampled at the front of the Himalayan 373 374 range (Lupker et al., 2012b), we conclude that the composition of these sediments is a good 375 approximation of the average composition of the sediment source. This observation also 376 excludes the possibility of a significantly lower degree of sediment weathering within the 377 Himalayan range during the LGM, as weathering for K and  $H_2O^+$  is already limited at present. We therefore consider that the Himalayan front end-member (as constrained from the mixture 378 379 of 60 % of sediments from the Himalayan front in the Brahmaputra basin and 40 % in the 380 Ganga basin) is a good first order approximation of the sediment source composition, both in 381 the modern day system and during the LGM. The modern dissolved flux of Si is negligible 382 compared to the solid Si fluxes (Galy and France-Lanord, 2001) and this was most likely also 383 the case during the LGM as the chemical weathering intensity was even lower than at present. 384 Furthermore the Si concentration of the exported sediments is only slightly affected by 385 sequestration of Si-rich bedload sediments in the modern floodplain (Lupker et al., 2012b) 386 and we make the assumption that this has been true during the last 21 kyrs. Hence, we consider  $\overline{[Si]}$  constant during the time span of our record. 387

388



$$R\varphi_{X} = \frac{\varphi_{X}|_{Modern} - \varphi_{X}|_{LGM}}{\varphi_{X}|_{Modern}}$$

$$= \frac{F_{Sed}^{Modern} \cdot \left(X_{Si}^{*} * \Big|_{HimalFront}^{Modern} - X_{Si}^{*} * \Big|_{BoB}^{Modern}\right) - F_{Sed}^{LGM} \cdot \left(X_{Si}^{*} * \Big|_{HimalFront}^{LGM} - X_{Si}^{*} * \Big|_{BoB}^{LGM}\right)}{F_{Sed}^{Modern} \cdot \left(X_{Si}^{*} * \Big|_{HimalFront}^{Modern} - X_{Si}^{*} * \Big|_{BoB}^{Modern}\right)}$$

$$(3)$$

391 In order to estimate  $R\phi_X$  from eq. 3, the sediment flux (F<sub>sed</sub>) has to be estimated at present and 392 during the LGM. Based on extensive gauging data the combined modern flux of the Ganga & Brahmaputra in Bangladesh is estimated to be ca. 1.10<sup>9</sup> t.yr<sup>-1</sup> (RSP, 1996). The past sediment 393 394 flux exported by the Ganga & Brahmaputra is largely unknown. However, qualitatively, the 395 sediment flux was most probably lower during the LGM than at present. A weakened 396 monsoon during the LGM (Kudrass et al., 2001; Sharma et al., 2004) may have limited 397 physical erosion in the Himalayan range and lowered the transport capacity of the rivers, 398 leading to a lower sediment flux to the Bay of Bengal (Weber et al., 1997; Goodbred, 2003). 399 A very conservative estimate of the minimum value of  $R\phi_X$  can therefore be made assuming a 400 constant sediment flux over the period. By doing so we also isolate the effect of the change in 401 the chemical composition of sediments only.

 $R\phi$  was computed using eq. 3 for K and  $H_2O^+$  and is summarized in Table 1. 402 403 Uncertainties on the K/Si\* and H2O+/Si\* ratios of individual samples are ca 3% (supplementary information S3). This is of the same order as the variability of K/Si\* and 404 405  $H_2O^+/Si^*$  ratios over the 0 – 2 and 19-22 kyr intervals or of the uncertainties on the regression 406 through the data for the Himalayan front sediments. These uncertainties were propagated 407 through the calculations of  $R\phi_X$  and reported in Table 1. The sensitivity of the weathering 408 budget to the average Al/Si ratio of sediments is lower than the uncertainty propagated from 409 the variability of K/Si\* and H<sub>2</sub>O<sup>+</sup>/Si\* ratios (see supplementary information S3). This first 410 order estimation shows that the weathering flux during the LGM was at least 67 ( $\pm 28$ ) and 89  $(\pm 36)$  % lower (for K and H<sub>2</sub>O<sup>+</sup>, respectively) than for the modern period (0-2 kyrs) for a 411 412 constant sediment flux. The main uncertainty on these estimates comes from the uncertainty 413 on the sediment Ganga and Brahmaputra sediment flux during the LGM. A sediment flux 414 during the LGM of half the present day sediment flux would induce a 83 and 95 % lower 415 weathering flux during the LGM compared to present for K and  $H_2O^+$ , respectively.

417 The loss of K in the Himalayan system is mainly attributed to the weathering of biotite 418 while the gain in hydration also depends on clay secondary mineral formation (Lupker et al., 419 2012). Because the reaction mechanisms in both cases are different, their sensitivity to 420 changes in precipitation and temperature is also most probably different. Despite our 421 estimates for both proxies being similar within uncertainty, it would not be surprising that the 422 relative changes in weathering fluxes recorded by K and H<sub>2</sub>O<sup>+</sup> could be different. It is not 423 possible to estimate the relative change in calcite weathering using a similar approach, 424 because for calcite the Himalayan source composition cannot be reliably estimated. Indeed, 425 significant carbonate dissolution has been documented within the Himalayan range (Galy and 426 France-Lanord, 1999), hence, Himalayan front river sediments cannot accurately represent the 427 eroded source. In addition, no direct estimation of the average calcite content of Himalayan 428 rocks is available.

429 Our quantification of the change in the net weathering flux from LGM to present 430 should only be considered as a rough estimate. In particular, it should be kept in mind that 431 these estimates somewhat depend upon the assumption of a transition between two steady 432 state weathering stages. Nevertheless, our estimates suggest that changes in weathering fluxes 433 exported by the Himalayan system have been significant over short time scales of ca. 20 kyrs. 434 The magnitude of the variations in weathering fluxes reconstructed here exceeds previous 435 estimates (Foster and Vance, 2006). This may be attributed in part to the very high weathering 436 rates of glacial outwash during the very early stage of an interglacial, as proposed earlier 437 (Foster and Vance, 2006; Vance et al., 2009) combined to the short time span of our record. 438 However, for the Himalayan system the weathering intensity in the modern floodplain 439 (Lupker et al., 2012b; West et al., 2002) supports the dominant role of the floodplain in 440 modulating glacial to interglacial weathering fluxes. This study further emphasizes that 441 present day weathering rates are likely higher than long-term averages, which supports the 442 idea that the imbalance of oceanic geochemical cycles may at least partially derive from the 443 over-estimation of Quaternary riverine fluxes to the oceans (Vance et al., 2009).

444

445 **7. Conclusions:** 

446

The geochemistry of detrital sediment records holds valuable information on the weathering regime these sediments have undergone during their transit from sediment producing areas to their deposition in sedimentary basins. The chemical composition of these sediments is primarily controlled by sediment sorting effects that occur during transport and deposition. Nevertheless weathering signals can be extracted from the sediment chemical composition if sorting is properly taken into account by comparing sediment records to modern river systems.

454 The detrital record presented here shows that the degree of chemical weathering 455 experienced by sediments exported by the Himalayan system, drained by the Ganga and 456 Brahmaputra Rivers, has changed significantly since the LGM. An overall decrease in 457 potassium and detrital calcite content along with an increase in sediment hydration all point 458 towards a steady increase in the weathering degree of sediments over the last 21 kyrs, while 459 the sediment provenance has remained unchanged. These changes in the weathering regime are attributed to the direct climatic forcing of chemical weathering in the floodplain, as 460 461 increasing precipitation and temperatures after the deglaciation favored mineral weathering 462 kinetics. Additional hydrological changes in response to increasing runoff and rising base 463 level might also have impacted weathering through enhanced channel-floodplain interactions.

464 A first order estimation of changes in the weathering flux delivered to the oceans can 465 be made using the detrital record and conservatively assuming a steady sediment flux. It

shows that weathering fluxes from the Himalayan system could have been reduced by 90 % during the LGM. This supports previous evidence that current dissolved fluxes are likely higher than average Quaternary estimates. These drastic changes in solute supply to the oceans on glacial-interglacial time scales have to be accounted for to reconstruct global oceanic biogeochemical cycles.

471

#### 472 Acknowledgments:

This work was supported by French INSU program "Relief de la Terre" and ANR Calimero. V.G. was supported by the U.S. National Science Fundation (Grant OCE-0851015, OCE-0928582). We thank C. Guilmette for assistance in the lab. H. Schopka and two anonymous reviewers are also thanked for their constructive comments that helped to improve the manuscript. T.M. Harrison is acknowledged for the very efficient handling of the manuscript.

- 479 **References** :
- 480 Bayon, G., Dennielou, B., Etoubleau, J., Ponzevera, E., Toucanne, S., Bermell, S., 2012.
- Intensifying Weathering and Land Use in Iron Age Central Africa. Science 335, 12191222. 10.1126/science.1215400
- Blum, M.D., Tornqvist, T.E., 2000. Fluvial responses to climate and sea-level change: a
  review and look forward. Sedimentology 47, 2-48.
- 485 Bouchez, J., Gaillardet, J., France-Lanord, C., Maurice, L., Dutra-Maia, P., 2011a.
- 486 Grain size control of river suspended sediment geochemistry: Clues from Amazon River
  487 depth profiles. Geochem. Geophys. Geosyst. 12, Q03008. <u>10.1029/2010gc003380</u>
- Bouchez, J., Lupker, M., Gaillardet, J., France-Lanord, C., Maurice, L., 2011b. How
  important is it to integrate riverine suspended sediment chemical composition with
  depth? Clues from Amazon River depth-profiles. Geochimica Et Cosmochimica Acta 75,
  6955-6970. 10.1016/j.gca.2011.08.038
- 492 Carignan, J., Hild, P., Mevelle, G., Morel, J., Yeghicheyan, D., 2001. Routine analyses of
- 493 trace elements in geological samples using flow injection and low pressure on-line liquid
- 494 chromatography coupled to ICP-MS: A study of geochemical reference materials BR,
   495 DR-N, UB-N, AN-G and GH. Geostandards Newsletter-the Journal of Geostandards
- 496 and Geoanalysis 25, 187-198.
- 497 Chabaux, F., Granet, M., Blaes, E., Dosseto, A., France-Lanord, C., Valier, V., 2009.
- 498 Determination of source and transfer-time of river sediments in alluvial plain from U-499 series nuclides: Evidence from the Ganges River System. Geochimica Et Cosmochimica
- 499 series nuclides: Evidence from th500 Acta 73, A203-A203.
- Chabaux, F., Granet, M., France-Lanord, C., Stille, P., 2006. U-series in Himalayan
   rivers: Timescale of sedimentary transfer. Geochimica Et Cosmochimica Acta 70, A92 A92. 10.1016/j.gca.2006.06.097/ISSN 0016-7037
- 504 Clift, P.D., Giosan, L., Biusztajn, J., Campbell, I.H., Allen, C., Pringle, M., Tabrez, A.R.,
- Danish, M., Rabbani, M.M., Alizai, A., Carter, A., Lueckge, A., 2008. Holocene erosion
  of the Lesser Himalaya triggered by intensified summer monsoon. Geology 36, 79-82.
- 507 **10.1130/g24315a.1**|issn 0091-7613
- Cullen, J.L., 1981. Microfossil evidence for changing salinity patterns in the Bay of
  Bengal over the last 20000 years. Palaeogeography Palaeoclimatology Palaeoecology 35,
  315-356.
- 511 Dosseto, A., Hesse, P.P., Maher, K., Fryirs, K., Turner, S., 2010. Climatic and vegetation
- 512 control on sediment dynamics during the last glacial cycle. Geology 38, 395-398.
   513 <u>10.1130/g30708.1</u>
- 514 Duplessy, J.C., 1982. Glacial to interglacial contrasts in the northern Indian Ocean, .
  515 Nature 295, 494-498.
- 516 Foster, G.L., Vance, D., 2006. Negligible glacial-interglacial variation in continental 517 chemical weathering rates. Nature 444, 918-921. 10.1038/nature05365
- 518 France-Lanord, C., Derry, L., 1997. Organic carbon burial forcing of the carbon cycle 519 from Himalayan erosion. Nature 390, 65-66.
- France-Lanord, C., Derry, L., Michard, A., 1993. Evolution of the Himalaya since
  Miocene time: isotopic and sedimentologic evidence from the Bengal Fan, in: Treloar,
  P.J., Searle, M. (Eds.), Himalayan Tectonics. Geol. Soc. Lond., London, pp. 603-621.
- 523 Galy, A., France-Lanord, C., 2001. Higher erosion rates in the Himalaya: Geochemical 524 constraints on riverine fluxes. Geology 29, 23-26.
- 525 Galy, A., France-Lanord, C., Derry, L.A., 1999. The strontium isotopic budget of
- 526 Himalayan Rivers in Nepal and Bangladesh. Geochimica Et Cosmochimica Acta 63,
- **527 1905-1925.**

- 528 Galy, V., François, L., France-Lanord, C., Faure, P., Kudrass, H., Palhol, F., Singh, S., 529 2008. C4 plants decline in the Himalayan basin since the Last Glacial Maximum. Quaternary Science Reviews 27, 1396-1409. doi:10.1016/j.guascirev.2008.04.005 530
- Garzanti, E., Ando, S., France-Lanord, C., Censi, P., Vignola, P., Galy, V., Lupker, M., 531
- 2011. Mineralogical and chemical variability of fluvial sediments 2. Suspended-load silt 532
- 533 (Ganga-Brahmaputra, Bangladesh). Earth and Planetary Science Letters 302, 107-120. 534 10.1016/j.epsl.2010.11.043
- 535
- Garzanti, E., Ando, S., France-Lanord, C., Vezzoli, G., Censi, P., Galy, V., Najman, Y.,
- 2010. Mineralogical and chemical variability of fluvial sediments 1. Bedload sand 536 537 (Ganga-Brahmaputra, Bangladesh). Earth and Planetary Science Letters 299, 368-381. 10.1016/j.epsl.2010.09.017 538
- 539 Goodbred, S.L., 2003. Response of the Ganges dispersal system to climate change: a source-to-sink view since the last interstade. Sedimentary Geology 162, 83-104. 540
- 541 Granet, M., Chabaux, F., Stille, P., Dosseto, A., France-Lanord, C., Blaes, E., 2010. U-542 series disequilibria in suspended river sediments and implication for sediment transfer time in alluvial plains: The case of the Himalayan rivers. Geochimica Et Cosmochimica 543
- Acta 74, 2851-2865. 10.1016/j.gca.2010.02.016 544
- 545 Granet, M., Chabaux, F., Stille, P., France-Lanord, C., Pelt, E., 2007. Time-scales of
- 546 sedimentary transfer and weathering processes from U-series nuclides: Clues from the 547 Himalayan rivers. Earth and Planetary Science Letters 261. 389-406. 10.1016/j.epsl.2007.07.012|ISSN 0012-821X 548
- 549 Heroy, D., Kuehl, S., Goodbred, S., 2003. Mineralogy of the Ganges and Brahmaputra
- 550 rivers: Implications for river switching and Late Quaternary climate change. Sedimentary Geology 155, 343-359. 551
- Herzschuh, U., 2006. Palaeo-moisture evolution in monsoonal Central Asia during the 552 last 50,000 years. Quaternary Science Reviews 25, 163-178. 553
- Hoehndorf, A., Kudrass, H.R., France-Lanord, C., 2003. Transfer of the Sr isotopic 554 555 signature of the Himalayas to the Bay of Bengal. Deep-Sea Research Part Ii-Topical 556 Studies in Oceanography 50, 951-960. 10.1016/s0967-0645(02)00614-8|issn 0967-0645
- Ittekkot, V., Kudrass, H.R., Quadfasel, D., Unger, D., 2003. The Bay of Bengal--An 557 Introduction. Deep Sea Research Part II: Topical Studies in Oceanography 50, 853-854. 558
- Jones, M.T., Pearce, C.R., Oelkers, E.H., 2012. An experimental study of the interaction 559 of basaltic riverine particulate material and seawater. Geochimica Et Cosmochimica 560 Acta 77, 108-120. 10.1016/j.gca.2011.10.044 561
- Kudrass, H., Hofmann, A., Doose, H., Emeis, K., Erlenkeuser, H., 2001. Modulation and 562
- amplification of climatic changes in the Northern Hemisphere by the Indian summer 563 564 monsoon during the past 80 k.y. Geology 29, 63-66.
- Limmer, D.R., B<sup>ning</sup>, P., Giosan, L., Ponton, C., K<sup>hler</sup>, C.M., Cooper, M.J., Tabrez, 565
- A.R., Clift, P.D., 2012. Geochemical record of Holocene to Recent sedimentation on the 566 Western Indus continental shelf, Arabian Sea. Geochem. Geophys. Geosyst. 13, Q01008. 567 10.1029/2011gc003845 568
- Lupker, M., Blard, P.-H., Lavé, J., France-Lanord, C., Leanni, L., Puchol, N., Charreau, 569
- 570 J., Bourlès, D., 2012a. 10Be-derived Himalayan denudation rates and sediment budgets in the Ganga basin. Earth and Planetary Science Letters 333-334, 146-156. 571 572 10.1016/j.epsl.2012.04.020
- 573 Lupker, M., France-Lanord, C., Galy, V., Lave, J., Gaillardet, J., Gajurel, A.P.,
- Guilmette, C., Rahman, M., Singh, S.K., Sinha, R., 2012b. Predominant floodplain over 574
- 575 mountain weathering of Himalayan sediments (Ganga basin). Geochimica Et
- Cosmochimica Acta 84, 410-432. 10.1016/j.gca.2012.02.001 576

- 577 Lupker, M., France-Lanord, C., LavÈ, J., Bouchez, J., Galy, V., MÈtivier, F., 578 Gaillardet, J., Lartiges, B., Mugnier, J.-L., 2011. A Rouse-based method to integrate the 579 chemical composition of river sediments: Application to the Ganga basin. J. Geophys.
- 580 Res. 116, F04012. 10.1029/2010jf001947
- 581 Michalopoulos, P., Aller, R.C., 1995. Rapid Clay Mineral Formation in Amazon Delta
  582 Sediments: Reverse Weathering and Oceanic Elemental Cycles. Science 270, 614.
- 583 Michalopoulos, P., Aller, R.C., 2004. Early diagenesis of biogenic silica in the Amazon
- 584delta: alteration, authigenic clay formation, and storage. Geochimica Et Cosmochimica585Acta 68, 1061-1085. 10.1016/j.gca.2003.07.018
- 586 Michels, K.H., Kudrass, H.R., H.bscher, C., Suckow, A., Wiedicke, M., 1998. The 587 submarine delta of the Ganges-Brahmaputra: cyclone-dominated sedimentation 588 patterns. Marine Geology 149, 133-154.
- 589 Pierson-Wickmann, A.-C., Reisberg, L., France-Lanord, C., Kudrass, H., 2001. Os-Sr-
- 590 Nd results from sediments in the Bay of Bengal: Implications for sediment transport and
- 591 the marine Os record. Paleoceanography 16, 435-444.
- Rahaman, W., Singh, S.K., Sinha, R., Tandon, S.K., 2009. Climate control on erosion
  distribution over the Himalaya during the past ~100 ka. Geology 37, 559-562.
  10.1130/g25425a.1
- Rahaman, W., Singh, S.K., Sinha, R., Tandon, S.K., 2010. Climate control on erosion
  distribution over the Himalaya during the past similar to 100 ka: REPLY. Geology 38,
  E217-E217. 10.1130/g31119y.1
- 598 Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover:
- 599Croplands from 1700 to 1992. Global Biogeochem. Cycles 13, 997-1027.60010.1029/1999gb900046
- Raymo, M., Ruddiman, W., Froelich, P., 1988. Influence of late Cenozoic mountain
  building on ocean geochemical cycles. Geology 16, 649.
- Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey,
  C.B., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson,
- 604 C.B., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, 605 T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B.,
- 606 McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo,
- 607 S., Turney, C.S.M., van der Plicht, J., Weyhenmeye, C.E., 2009. Intcal09 and Marine09 608 Radiocarbon Age Calibration Curves, 0-50,000 Years Cal Bp. Radiocarbon 51, 1111-
- 609 **1150**.
- RSP, 1996. River Survey Project, Flood Action Plan (FAP) final report. Delft Hydraulics
   and DHI.
- 612 Sanyal, P., Bhattacharya, S.K., Prasad, M., 2005. Chemical diagenesis of Siwalik
- sandstone: Isotopic and mineralogical proxies from Surai Khola section, Nepal.
  Sedimentary Geology 180, 57-74.
- 615 Sharma, S., Joachimski, M., Sharma, M., Tobschall, H.J., Singh, I.B., Sharma, C.,
- 616 Chauhan, M.S., Morgenroth, G., 2004. Lateglacial and Holocene environmental changes
   617 in Ganga plain, Northern India. Quaternary Science Reviews 23, 145-159.
- Singh, S., France-Lanord, C., 2002a. Tracing the distribution of erosion in the
   Brahmaputra watershed from isotopic compositions of stream sediments. Earth and
   Planetary Science Letters 252, 645-662.
- 621 Singh, S.K., France-Lanord, C., 2002b. Erosion distribution in the Eastern Himalaya
- traced by Sr-Nd isotopic compositions of river sediments. Geochimica Et Cosmochimica
   Acta 66, A720-A720.
- 624 Singh, S.K., Rai, S.K., Krishnaswami, S., 2008. Sr and Nd isotopes in river sediments
- 625 from the Ganga Basin: Sediment provenance and spatial variability in physical erosion.
- 626 J. Geophys. Res. 113, F03006. 10.1029/2007jf000909

- Singh, S.K., Sarin, M.M., France-Lanord, C., 2005. Chemical erosion in the eastern
  Himalaya: Major ion composition of the Brahmaputra and delta C-13 of dissolved
  inorganic carbon. Geochimica Et Cosmochimica Acta 69, 3573-3588.
  10.1016/j.gca.2005.02.033/ISSN 0016-7037
- 631 Srivastava, P., Shukla, U.K., 2010. Climate control on erosion distribution over the
  632 Himalaya during past similar to 100 ka: COMMENT. Geology 38, E216-E216.
  633 10.1130/g30838c.1
- 634 Vance, D., Teagle, D.A.H., Foster, G.L., 2009. Variable Quaternary chemical weathering
- 635 fluxes and imbalances in marine geochemical budgets. Nature 458, 493-496. 636 10.1038/nature07828
- Walker, J., Hays, P., Kasting, J., 1981. A negative feedback mechanism for the longterm stabilization of the Earth's surface temperature. Journal of Geophysical Research
  86, 9776-9782.
- 640 Wallmann, K., Aloisi, G., Haeckel, M., Tishchenko, P., Pavlova, G., Greinert, J.,
- Kutterolf, S., Eisenhauer, A., 2008. Silicate weathering in anoxic marine sediments.
   Geochimica Et Cosmochimica Acta 72, 2895-2918.
- 643 Weber, M.E., Wiedicke, M.H., Kudrass, H.R., Hübscher, C., Erlenkeuser, H., 1997.
- Active growth of the bengal Fan during sea-level rise and highstand. Geology 25, 315318.
- West, A.J., Bickle, M.J., Collins, R., Brasington, J., 2002. Small-catchment perspective
  on Himalayan weathering fluxes. Geology 30, 355-358. 10.1130/00917613(2002)030<0355:scpohw>2.0.co;2
- 649 White, A.F., Blum, A.E., 1995. Effects of climate on chemical weathering in watersheds.
  650 Geochimica et Cosmochimica Acta 59.
- Willenbring, J.K., von Blanckenburg, F., 2011. Long-term stability of global erosion
  rates and weathering during late-Cenozoic cooling. Nature 465, 211-214.
  10.1038/nature09044
- 654
- 655

#### 657 Figures:



658

Figure 1: Geographical setting of the Himalayan system. Modern river sediments were sampled in the Ganga & Brahmaputra basin at the Himalayan front (green diamonds), at the outlet of the Ganga basin (red square) and the Brahmaputra basin (blue triangle) and finally after their confluence in the lower Meghna (yellow circle). These sediments were compared to the sediment record of the Bay of Bengal that represents a composite record from proximal shelf sediments (105KL and 107KL) and from the middle fan channel levees (117KL, 118KL and 120KL).



Figure 2: Hydraulic sorting effect on the Si-Al-Fe chemical composition of sediments.
Suspended sediments are the result of the mixing between a low Al/Si and Fe/Si
quartz-rich coarse-grained end-member and a high Al/Si and Fe/Si surface endmember relatively enriched in phylosilicates.



Figure 3: Evolution of K/Si (a) and  $H_2O^+/Si$  (b) in the modern Himalayan system for river suspended load (SL) and bedload or bar sediments (BL). The transfer of sediments from the Himalayan front Rivers (green) to the outlet of the Ganga (red) and Brahmaputra (blue), as well as their confluence the lower-Meghna (yellow) results in a loss of K and an increase in  $H_2O^+$  as weathering proceeds. Envelopes represent 0.95 confidence level on the linear regression.





Figure 4: Normalization of the chemical composition of sediments in of the Bay of Bengal record for hydraulic sorting effects. The K/Si and  $H_2O^+/Si$  ratios of the sample are normalized to a common Al/Si ratio of 0.23 assuming that the sediment sorting line passes through a unique coarse-grained end-member with a composition close to river bedloads (given in the supplementary information, Table S1).



686

Figure 5: K/Si and H<sub>2</sub>O<sup>+</sup>/Si in Bay of Bengal core sediments are strongly correlated to Al/Si, which is a proxy for grain size (Bouchez et al., 2011a; Lupker et al., 2011). Correction for hydraulic mineral sorting yields unbiased weathering indicators (K/Si\* and H<sub>2</sub>O<sup>+</sup>/Si\*).



**Figure 6:** Evolution of K/Si<sup>\*</sup>, H<sub>2</sub>O<sup>+</sup>/Si<sup>\*</sup>, Ca/Si and calcite content of sediments in the composite Bay of Bengal record since the last ca. 21 kyr. The composition of river sediments from the modern Himalayan system (average and 1<sup>st</sup> - 3<sup>rd</sup> quartile range) is also plotted for comparison with the sediment record. The Bay of Bengal sea surface salinity (Kudrass et al., 2001) is shown as a proxy for the Ganga & Brahmaputra continental runoff. The average, 1 $\sigma$  uncertainty on the elemental ratios is indicated by light grey horizontal error bars.



Figure 7: Sr and Nd isotopic composition of the sediments from the Bay of Bengal. 702 703 The modern river sediments of the Ganga in Bangladesh, the Brahmaputra in Bangladesh (along with samples from the Siang, the Brahmaputra in Guwahati and the Teesta, Rivers 704 705 from Singh and France-Lanord, 2002) and the lower Meghna are represented for comparison. 706 The Sr and Nd isotopic data set of the Brahmaputra in Bangladesh has partly been acquired in 707 order to test sediment source effects in the Brahmaputra basin by selecting samples that 708 covered a large span of chemical compositions. This sample choice may have introduced a bias towards samples that recorded a large input from the Teesta upstream right-bank 709 710 tributary. We therefore suspect the average Sr and Nd isotopic composition of the 711 Brahmaputra to be closer to the Brahmaputra in Guwahati and the Siang than our dataset suggests (see supplementary information). The isotopic composition of the Lesser Himalaya 712 713 (LH), Higher Himalaya Cristalines (HHC) and Trans Himalayan Batholith (THB) are from 714 Galy and France-Lanord (2001) and references therein.



715

Figure 8: Sr and Nd isotopic composition of the silicate fraction of Bay of Bengal sediments 716 717 (Pierson-Wickmann et al., 1998; Galy et al., 2008 and this study) along with the 718 modern river sediments composition of the Himalayan front, the Ganga, the Brahmaputra and the lower Meghna (average and 1<sup>st</sup> - 3<sup>rd</sup> quartile range). The isotopic 719 720 composition of sediments from the modern Siang River (Singh and France-Lanord, 2002b) is also plotted. The Siang delivers ca. 50 % of the sediment load of the 721 Brahmaputra (Singh and France-Lanord, 2002b), contributing disproportionally to the 722 723 final isotopic signature of the modern Brahmaputra.

#### 725 Tables

		LGM	Modern		
Sediment flux (t/yr)		1.10 <sup>9</sup>	1.10 <sup>9</sup>		
Himalayan front	$\overline{K / Si^*}$	0.0574 (±0.0025)	0.0574 (±0.0025)		
	$\overline{H_2O^+/Si^*}$	0.1009 (±0.0068)	0.1009 (±0.0068)		
Bay of Bengal	$\overline{K / Si^*}$	0.0553 (±0.0005)	0.0510 (±0.0017)		
	$\overline{H_2O^+/Si^*}$	0.1034 (±0.0075)	0.1236 (±0.0026)		
	Rφĸ	67 (±	28) %		
	<b>Rф</b> н20+	89 (±36) %			

**Table 1:** Relative changes in the weathering flux delivered to the Bay of Bengal as dissolved728load from the LGM to present ( $R\phi_K$  and  $R\phi_{H2O+}$ ) assuming a constant sediment flux729over the period. The weathering flux was estimated using eq. 3 for K and  $H_2O^+$  from730the Himalayan front and Bay of Bengal end-members reported in the table.

#### Supplementary information and data:

- 732
- 733 **S1** Chemical weathering proxies and data:

734 The coarse grained end-members used to normalize the chemical composition of the 735 Bay of Bengal sediments are reported in Table S1. This coarse-grained mixing end-member is 736 determined as the intersection between the linear regression through the composition of 737 Himalayan front sediments and the composition of sediments in Bangladesh (Ganga, 738 Brahmaputra and lower Meghna) for K/Si and H<sub>2</sub>O<sup>+</sup>/Si. For Fe/Si (used in section S2), the 739 common coarse-grained end-member composition is defined by the intersection between the 740 regressions through Himalayan front sediments and southern and eastern tributary sediments 741 (Chambal, Lohit and Dibang) as sediments from these rivers show a very contrasted Fe/Si 742 composition. This method was preferred over averaging all available bedloads as placer 743 effects tend to introduce a very high variability in the chemical composition of the bedloads, 744 which is not found in suspended load samples and therefore does not accurately describe the 745 sediments that are mixed in the water column.

- A summary of the composition of modern river sediments is reported in Table S2 and the composition of Bay of Bengal sediments in Table S3. The full, detailed data set of modern sediments and Bay of Bengal sediments is provided as electronic appendix.
- 749
- 750 S2 Sediment provenance:
- 751 Sr & Nd signature of Brahmaputra sediments:
- 752

It should be noted that the Sr and Nd isotopic data set of the Brahmaputra in Bangladesh has partly been acquired in order to test sediment source effects in the Brahmaputra basin by selecting samples that covered the largest span of chemical compositions. This sample choice introduces a bias towards samples impacted by the influx
from an upstream right-bank tributary, the Teesta, which has high εNd and low <sup>87</sup>Sr/<sup>86</sup>Sr
values (Figure 7). We therefore suspect the average Sr and Nd isotopic composition of the
Brahmaputra to be closer to that of the Brahmaputra in Guwahati (higher for Nd and lower for
Sr) than our whole dataset suggests.

761 The Sr and Nd isotopic composition of Brahmaputra sediments sampled at Guwahati, 762 upstream of the confluence with the Teesta show a homogeneous composition of  $0.7201 \pm$ 763 0.0014  ${}^{87}$ Sr/ ${}^{86}$ Sr and -13.3  $\pm$  0.7  $\epsilon$ Nd (Figure 7, Singh and France-Lanord, 2002). These 764 sediments are mainly derived from the erosion of the Namche Barwa zone by the Siang River 765 that accounts for ca. 50 % of the Brahmaputra sediment load (Singh and France-Lanord, 766 2002). The Teesta River has a contrasted isotopic composition due to the dominant exposure 767 of Lesser Himalayan rocks in the basin (Figure 7, Singh and France-Lanord, 2002) and its 768 confluence with the Brahmaputra mainstream is only ca. 120 km upstream of our sampling 769 station in Bangladesh. These considerations may also explain why the contribution of 770 Brahmaputra sediments to the lower Meghna is overestimated based on a simple Sr and Nd 771 isotopic budget of the Ganga, Brahmaputra and lower Meghna.

772

773 Increase in Southern or Eastern tributaries and Siwalik contribution since the LGM:

774

An increase in Siwalik derived sediments would generate a more weathered signature of the Ganga & Brahmaputra sediment load. Because Siwalik are Neogene floodplain deposits produced by Himalayan erosion and uplifted by the southern propagation of the deformation front, Siwalik sediments have a more weathered silicate signature but similar Sr and Nd isotopic compositions than trans-Himalayan river sediments (Lupker et al., 2012). However, the high carbonate content with lower  $\delta^{13}$ C compositions of Siwalik rocks and

781	sediments (e.g. Sanyal et al., 2005; Lupker et al., 2012) is not compatible with the
782	concomitant decrease of both carbonate content and $\delta^{13}C$ found in the Bay of Bengal
783	sediments (Figure S1).
784	Further changes in erosion patterns involving cratonic tributaries are also unlikely.
785	The Chambal River in the Ganga basin and the Eastern tributaries of the Brahmaputra basin
786	(Lohit and Dibang) have distinctively higher Fe/Si* ratios and unradiogenic Sr and Nd (Singh
787	et al., 2002; Singh et al., 2008; Lupker et al., 2012) signature that are not identified in our
788	record (Figure S1).
789	
790	S3 – Uncertainties and sensitivity of the weathering budget to the average Al/Si ratio:
791	
792	The analytical uncertainty from the major element and $\mathrm{H_2O^+}$ measurements is 2% on
793	the Al/Si and Fe/Si ratios, 3% on the K/Si and $H_2O^+/Si$ ratios (Carignan et al., 2001). The
794	uncertainty on the definition of the coarse grained end-member (Table S1) has only a minor
795	effect on the normalized K/Si* and $H_2O^+/Si^*$ ratios. For an average Bay of Bengal sediment
796	sample with an Al/Si ratio of 0.38, the total uncertainty propagated from the analytical and
797	normalization uncertainty is ca. 3% for the K/Si*, $\rm H_2O^+/Si^*$ and Fe/Si* ratios on a $1\sigma$
798	confidence level.
799	The sensitivity of the weathering budget to the average Al/si ratio of the sediments is
800	assessed by comparing R $\phi$ determined for an Al/Si of 0.23 to R $\phi$ obtained using an Al/Si of
801	0.21 and 0.25 (Table S4). This corresponds to ca. 10% of uncertainty on Al/Si and is higher
802	than the ca. 5% uncertainty estimated by Lupker et al. (2011) for the average Al/Si
803	composition of sediments of the Ganga River but it takes into account the fact that in this case

shows that for the sensitivity of the weathering budget to the average Al/Si is limited for a

804

37

the average Al/Si ratio of Brahmaputra sediments has not been determined directly. Table S4

806 reasonable range of Al/Si ratios.

#### δ<sup>13</sup>C<sub>calcite</sub> (‰ - PDB) Fe/Si\* (mol:mol) δ<sup>18</sup>O<sub>calcite</sub> (‰ - PDB) δD<sub>H2O+</sub> (‰ - SMOW) 0.06 0.05 0.07 0.04 -2.0 -1.5 -1.0 -0.5 0.0 0.5 -20 -15 -10 0 -100 -5 -90 -80 -70 -60 10 1 1 Δ **Yage ky. (cal. BP)** 13 17 ß 5 нсс 9 13 17 21 LGM 21 Shelf ∆ Levees Modern Rivers S & E trib. 🕶 Himal. front 📑 Brahmaputra Ganga Lower Meghna 809

### 808 Supplementary information figures:





# 812 Supplementary information tables:

813

v /c:*	K/Si	$0.029 \pm 0.001$
N/ 31 <sup>-</sup>	Al/Si	0.117 ± 0.005
⊔ ∩+/с:*	H₂O⁺/Si	0.060 ± 0.002
	Al/Si	0.171 ± 0.003
Fa/C:*	Fe/Si	0.020 ± 0.003
re/SI	Al/Si	0.087 ± 0.004

815 Table S1: Coarse-load mixing end-members used for the correction of hydraulic sorting
816 effects on the chemical composition of sediments.

# **Table S2:**

		Ganga Himalayan Front	Brahmaputra Himalayan Front	Himalayan Front Riversª	Ganga	Brahm aputra	L. Meghna	S. and E. tributaries
	Mean <sup>b</sup>	0.063	0.054	0.057	0.052	0.048	0.050	0.036
	sd <sup>b</sup>	0.001	0.004	0.002	0.001	0.001	0.001	0.007
K / C: *	1st Q	0.061	0.051	0.057	0.051	0.048	0.050	0.029
K/SI*	Median	0.062	0.055	0.061	0.054	0.049	0.050	0.039
	3rd Q	0.065	0.057	0.065	0.055	0.051	0.051	0.060
	n	39	14	53	68	106	60	6
	Mean <sup>b</sup>	0.099	0.102	0.101	0.122	0.114	0.122	0.065
	sd <sup>b</sup>	0.003	0.011	0.007	0.005	0.003	0.002	0.004
H <sub>2</sub> O <sup>+</sup> /	1st Q	0.093	0.082	0.090	0.118	0.103	0.117	0.083
Si*	Median	0.099	0.089	0.098	0.127	0.112	0.119	0.118
	3rd Q	0.109	0.104	0.107	0.142	0.115	0.122	0.159
	n	32	12	44	26	26	21	4
	Mean <sup>b</sup>	0.052	0.055	0.054	0.056	0.060	0.059	0.082
	sd <sup>b</sup>	0.001	0.004	0.003	0.001	0.007	0.002	0.012
Fe/Si*	1st Q	0.050	0.052	0.050	0.054	0.059	0.057	0.077
10,01	Median	0.052	0.056	0.053	0.055	0.061	0.058	0.078
	3rd Q	0.054	0.061	0.055	0.058	0.062	0.061	0.096
	n	39	14	53	68	106	60	6
	Mean	6.4	0.9	3.1	3.4	-	0.6	5.1
	sd	6.0	1.1	2.5	1.3	-	0.8	3.1
Calcite	1st Q	0.8	0.0	0.6	2.2	-	0.2	2.8
(wt%)	Median	4.0	0.1	3.1	3.9	-	0.2	4.9
	3rd Q	12.1	2.0	11.1	4.5	-	0.8	6.8
	n	31	5	36	30	-	6	5
	Mean	-1.3	-0.3	-0.7	-1.6	-	-1.2	-0.7
δ <sup>13</sup> C <sub>Calci</sub>	sd	1.2	0.8	0.7	0.4	-	0.1	1.6
te (%)	1st Q	-2.1	-0.6	-2.0	-1.6	-	-1.3	-1.8
- PDB)	Median	-1.2	0.0	-1.2	-1.5	-	-1.2	-1.5
	3rd Q	-0.5	0.1	-0.3	-1.4	-	-1.1	0.2
	<u>n</u>	29	3	32	27	-	3	5
	Mean	-12.3	-9.4	-10.6	-10.0	-	-6.2	-6.8
$\delta^{18}O_{Calc}$	sa 1 et O	1.4	3.8	2.3	2.6	-	6.2	3./
<sub>ite</sub> (%o	Ist Q Madian	-13.2	-11.6	-13.2	-11.6	-	-8.4	-9.8
- PDB)		-12.5	-11.4	-12.4	-10.4	-	-3.5	-4.4
	Sra Q	-12.2	-0.2	-11.7	-10.0	-	-2.0	-4.4
	Mean	0.115	0.027	0.062	0.058	0.042	0.043	0.115
	sd	0.075	0.027	0.002	0.038	0.042	0.045	0.038
	1st O	0.040	0.017	0.028	0.042	0.036	0.032	0.098
Ca/Si	Median	0.104	0.018	0.064	0.063	0.040	0.039	0.108
	3rd O	0.170	0.022	0.153	0.072	0.042	0.050	0.137
	n	39	14	53	68	106	60	6
	Mean	0.7713	0.7660	0.76813	0.77491	0.73562	0.73694	0.70705
	sd	0.0101	0.0439	0.02665	0.01009	0.01271	0.00833	-
<sup>87</sup> Sr/ <sup>86</sup>	1st Q	0.7647	0.7329	0.74925	0.77111	0.72560	0.72547	-
Sr	Median	0.7726	0.7600	0.76440	0.77252	0.72779	0.73790	-
	3rd Q	0.7769	0.7870	0.77921	0.77825	0.74756	0.74157	-
	n	8	11	19	21	13	9	2
	Mean	-18.9	-16.6	-17.5	-18.0	-16.2	-15.8	-9.7
	sd	0.9	3.5	2.3	0.4	1.5	1.1	-
aNd	1st Q	-19.3	-18.9	-19.3	-18.3	-18.0	-16.5	-
ENG	Median	-18.8	-16.0	-18.2	-18.0	-16.0	-15.9	-
	3rd Q	-18.3	-14.4	-16.0	-17.8	-14.7	-15.0	-
	n	10	11	21	22	13	9	2

820 Table S2: Averaged chemical composition of samples from the Himalayan system. The 821 compositions are given separately for samples from the Ganga Himalayan front, the 822 Brahmaputra Himalayan front, the average Himalayan front, the Ganga in Bangladesh, 823 the Brahmaputra in Bangladesh, the lower Meghna (confluence of the Ganga & Brahmaputra) and southern and eastern tributaries. <sup>a</sup>The Himalayan front is 824 825 reconstructed assuming that 60 % of the total sediment flux is generated by front 826 rivers in the Brahmaputra basin and 40 % by the front rivers in the Ganga basin. <sup>b</sup>For element ratios affected by sediment sorting, the average and standard deviation of 827 828 each end-member is constrained by evaluating the linear regression through the entire 829 data set of each reach under consideration along with the coarse-grained end-member at Al/Si=0.23. The 1<sup>st</sup> and 3<sup>rd</sup> quartile, median and number of samples are also 830 831 reported for all reaches. Detail on the chemical composition of samples used can be 832 found in the electronic appendix.

**Table S3:** 

Core	Depth	Age	Al/Si	K/Si*	H2O/Si*	Ca/Si	Fe/Si*		Calcit	e		<sup>87</sup> Sr	eNd
	cm	vr BP	mol	mol	mol	mol	mol	dD	wt%	d13C	d <sup>18</sup> O	Sil	Sil
105	77-86	47	0.346	0.050	0 123	0.032	0.058	-87				-	-
105	129	74	0.270	0.054	0.120	0.002	0.064	-84					
118	7-17	98	0.401	0.052	0.123	0.032	0.060	-82				0.74740	-15.7
105	241	138	0.179	0.049	0.124	0.051	0.048	-85	2.1	-1.3	-12.5	0.73600	-15.9
107	50-60	147	0.391	0.051	0.124	0.034	0.059	-78	1.4	-0.9	-7.5		
105	279-285	161	0.411	0.049	0.119	0.028	0.060	-78					
107	80	213	0.215	0.053	0.121	0.042	0.069	-86	1.4	-1.6	-13.4		
118	29	313	0.405	0.048		0.034	0.063					0.74040	-14.3
105	564-572	325	0.335	0.050	0.124	0.040	0.060	-87					
105	664-670	382	0.398	0.051		0.037	0.060					0.74218	-15.7
105	678-685	390	0.321	0.050	0.123	0.046	0.059	-86					
105	686-690	394	0.192	0.049		0.049	0.059		3.1	-1.3	-11.2	0.73437	-15.9
105	758-765	436	0.392	0.050	0.124	0.032	0.060	-86					
118	70-80	681	0.385	0.052	0.124	0.025	0.060	-80					
120	53	1184	0.447	0.052	0.131	0.024	0.058	-93					
107	145-155	1214	0.389	0.051	0.122	0.032	0.057	-77				0.74255	-15.4
118	134-145	1302	0.393	0.053	0.125	0.032	0.060	-83					
118	165-175	1603	0.400	0.053	0.124	0.035	0.059	-80	1.2	-1.4	-12.8		
120	83	1854	0.412	0.052	0.400	0.027	0.058	75					
107	210-220	2212	0.412	0.051	0.122	0.038	0.057	-75					
118	220-230	2317	0.385	0.053	0.125	0.028	0.060	-79				0 74070	16.1
107	200-270	2799	0.305	0.055	0.124	0.027	0.000	-00				0.74072	-10.1
107	138	2904	0.395	0.051	0.124	0.040	0.057	-//					
120	147-157	3396	0.370	0.052	0.120	0.004	0.050	-80				0 74879	-15.3
107	291-301	3457	0.376	0.053	0.126	0.043	0.001	-77	21	-0.4	-9 1	0.74075	-10.0
118	340-350	3717	0.385	0.053	0.120	0.027	0.060	-84	2.1	0.4	5.1		
107	335-345	4133	0.337	0.053	0.124	0.044	0.057	-82	2.0	-0.7	-3.9		
107	376-385	4748	0.362	0.052	0.127	0.074	0.056	-80				0.74153	-16.1
120	284	6345	0.304	0.056	0.125	0.059	0.057	-87	2.8	-1.0	-16.9		
118	565-575	6496	0.397	0.053	0.121	0.030	0.058	-81					
118	575	6496	0.390	0.054		0.047	0.057						
118	656	6719	0.407	0.051		0.033	0.055						
118	920	7418	0.298	0.055		0.061	0.059					0.75414	-17.3
120	348	7775	0.461	0.050		0.049	0.062					0.74467	-14.5
118	1144	7787	0.340	0.054		0.063	0.060						
120	411	9182	0.422	0.053	0.123	0.030	0.066	-84					
117	242-257	10070	0.372	0.054	0.117	0.082	0.059	-80					
120	452	10098	0.302	0.058	0.115	0.067	0.058	-84					
120	555	11255	0.412	0.053	0.123	0.070	0.061	-83					
120	579	11376	0.306	0.054		0.076	0.060		7.2	-0.7	-6.6	0.74723	-15.3
120	632-642	11668	0.429	0.056	0.121	0.079	0.061	-76		~	11.0		10.0
120	691-701	11940	0.429	0.055	0.119	0.078	0.062	-78	4.5	-0.4	-11.0	0.74899	-16.0
120	701	12200	0.418	0.004	0.119	0.080	0.003	-80					
120	702 787	12290	0.410	0.002	0.119	0.051	0.000	-//				0 7/120	-14.4
120	848	12731	0.322	0.054	0 1 1 8	0.056	0.059	-77				0.74123	- 199,99
120	845-855	12736	0.364	0.054	0.120	0.059	0.059	-81					
120	863	12865	0.423	0.051	0.123	0.055	0.061	-77					
117	722-725	13712	0.401	0.054		0.077	0.061		5.9	-0.4	-8.3	0.74180	-16.0
120	929-939	13744	0.410	0.054	0.121	0.066	0.065	-78					
120	959	14053	0.412	0.053	0.119	0.061	0.061	-77					
117	772-774	14096	0.400	0.054		0.075	0.060		6.4	-0.4	-10.2	0.72754	-15.7

120	965	14127	0.408	0.053	0.114	0.068	0.060	-76					
117	819-822	14457	0.416	0.055		0.071	0.061		4.9	0.0	-8.6	0.74324	-16.1
120	990-1000	14498	0.415	0.053	0.118	0.075	0.060	-78	4.4	-0.6	-14.8		
120	1016	14758	0.388	0.054	0.114	0.076	0.059	-77					
120	1030	14931	0.409	0.054	0.105	0.077	0.060	-80					
117	922-925	15249	0.400	0.055		0.061	0.061		5.3	0.1	-7.4	0.74100	-14.8
117	930-932	15310	0.421	0.055		0.069	0.060		5.4	0.0	-9.2	0.74115	-16.2
117	970-972	15610	0.391	0.054		0.067	0.062		4.5	0.1	-8.1	0.74172	-15.4
117	1025-1029	16048	0.408	0.054		0.057	0.060		4.7	0.0	-8.4		-16.2
117	1027-1029	16056	0.407	0.054		0.059	0.062						
117	1106-1109	16663	0.408	0.055		0.059	0.060						
117	1175	17185	0.402	0.056	0.112	0.065	0.061	-83					-14.7
117	1209-1210	17454	0.391	0.054	0.110	0.065	0.061	-81					
120	1114	18896	0.281	0.055		0.075	0.058		6.4	-0.6	-11.4	0.73811	-14.6
120	1127	19713	0.257	0.055	0.095	0.075	0.050	-84					
120	1104	20775	0.410	0.056	0.108	0.070	0.060	-81					
120	1130-1140	21428	0.383	0.055	0.107	0.074	0.060	-80	3.6	-0.1	-15.5	0.73980	-15.7

**Table S3:** Summary of the chemical composition of Bay of Bengal core samples used in this

work. Details can be found in the electronic appendix.

			LGM	Modern		
	Sediment flux (t/yr)		1.10 <sup>9</sup>	1.10 <sup>9</sup>		
	Himalayan front	$\overline{K / Si^*}$	0.0574 (±0.0025)	0.0574 (±0.0025)		
.23		$\overline{H_2O^+/Si^*}$	0.1009 (±0.0068)	0.1009 (±0.0068)		
= 0.	Bay of Bengal	$\overline{K / Si^*}$	0.0553 (±0.0005)	0.0510 (±0.0017)		
N/Si		$\overline{H_2O^+ / Si^*}$	0.1034 (±0.0075)	0.1236 (±0.0026)		
4		Rφ <sub>κ</sub>	67 (±28) %			
		<b>Rф</b> н20+	89 (±	36) %		
	Himalayan front	$\overline{K / Si^*}$	0.0524 (±0.0020)	0.0524 (±0.0020)		
= 0.21		$\overline{H_2O^+/Si^*}$	0.0871 (±0.0045)	0.0871 (±0.0045)		
	Bay of Bengal	$\overline{K / Si^*}$	0.0499 (±0.0004)	0.0465 (±0.0014)		
ıl∕si		$\overline{H_2O^+ / Si^*}$	0.0865 (±0.0046)	0.0988 (±0.0016)		
4		Rφ <sub>κ</sub>	57 (±	28) %		
		<b>Rф</b> <sub>H2O+</sub>	105 (±	±42) %		
	Himalayan front	$\overline{K / Si^*}$	0.0625 (±0.0029)	0.0625 (±0.0029)		
= 0.25		$\overline{H_2O^+ / Si^*}$	0.1148 (±0.0091)	0.1148 (±0.0091)		
	Bay of Bengal	$\overline{K / Si^*}$	0.0606 (±0.0006)	0.0555 (±0.0021)		
is/Iv		$\overline{H_2O^+}/Si^*$	0.1203 (±0.0104)	0.1484 (±0.0036)		
A		Rφĸ	73 (±	32) %		
		<b>Rф</b> <sub>H2O+</sub>	84 (±	33) %		

**Table S4:** Relative change in weathering fluxes exported as dissolved load to the oceans841obtained for K and  $H_2O^+$  using an average Al/Si ratio of 0.23, 0.21 and 0.25. The end842members used for the calculation are also reported along with their uncertainty.