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Estimating the Loss of Himalayan Glaciers under Global Warming Using the δ^{18}O−Salinity Relation in the Bay of Bengal

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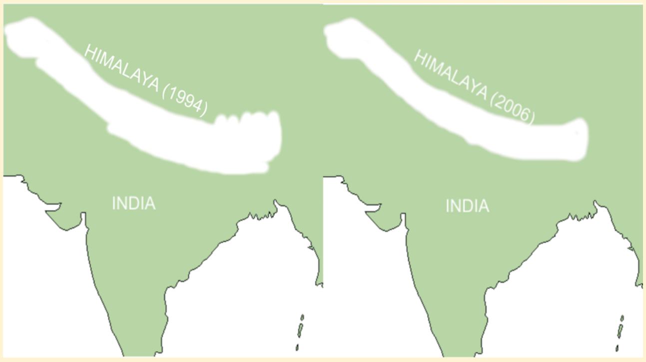
Supporting Information

ABSTRACT: Quantifying the water loss of Himalayan glaciers due to global warming from direct measurement is difficult, as some glaciers are advancing or stable in spite of an overall retreat. We use a novel approach to provide an alternative estimate of the amount of Himalayan ice melt. Because a major part of this melted ice debouches into the Bay of Bengal through the Ganga−Brahmaputra basin, it causes significant variations in the oxygen isotopic composition (δ^{18}O) and salinity (S) of the sea surface water and their mutual linear relationship. We document the temporal change in the δ^{18}O−S relation for the bay at three different times during the period from 1994 to 2006, and using a model, we infer that 2.4×10^{11} m^3 water was lost by melting from the Ganga−Brahmaputra basin during this period.



■ INTRODUCTION

The Himalaya, meaning the "abode of snow" in Sanskrit, also known as the "third pole", affects climate profoundly by influencing the monsoon.[1] Reduced water availability from Himalayan glaciers in the future is a serious threat to the food security of Asians.[2] The impending water loss of Himalayan glaciers has attracted global attention;[3] however, the impact of climate change on the Himalaya is yet to be quantified. The prediction of the Intergovernmental Panel on Climate Change (IPCC) on glacier melting in the Himalaya raised much debate leading to its eventual withdrawal.[3,4] The difference between winter snow accumulation and summer ice melting is the annual change of glacier mass. Field measurements of glacier loss are difficult in the Himalayas,[5] and moreover, from the field observations, it is difficult to generalize, as some glaciers are retreating and some others are advancing and those too with different rates.[6−9] Tibetan glaciers and the Gangotri glacier have rapidly retreated, and the Siachen glacier retreated moderately, whereas other glaciers in the Karakoram are either stable or advancing.[10,11] Satellite observations suggest a large variation in the rates of retreat and advance of glaciers from −80 to +40 m yr^{-1} during 2000−2008.[8] Such space-based observations might have been hampered by bad weather, and therefore, offer only a rough estimate of the glaciated area.[9,12]

The contribution of glaciers to sea level rise is uncertain. Sea level rise depends on thermal expansion due to warming, fresh water inputs from glacial ice melt, and changes in terrestrial water storage.[13] Decoupling of the causes of sea level rise is difficult, and once the water enters the ocean, it is not possible to ascertain which glacierized region it came from. Here, we present a new approach that is based on the linear relation between oxygen isotopic composition (δ^{18}O) and salinity (S) of the surface seawater, which can detect and quantify the amount of ice melt from glaciers located in the hinterland. This relation for the Bay of Bengal surface water is applied here for the detection of Himalaya melting.

■ METHODS

Surface water samples were collected in the Bay of Bengal during November 2006. All samples were kept tightly closed for δ^{18}O analysis, which was completed within a month of collection. δ^{18}O was measured by the CO_2 equilibration method[14,15] using a dual-inlet stable isotope mass spectrometer with a reproducibility of ±0.13‰ (1σ). Salt correction of δ^{18}O values was not needed as the molalities of major ions were less than the values that require significant correction.[15] Salinity was measured using Autosal with a reproducibility of 0.001 (see Singh et al.[16] for a more detailed methodology of δ^{18}O and salinity measurements, and inter-laboratory comparisons).

δ^{18}O is defined as the deviation of the sample $^{18}O/^{16}O$ from that of the Vienna Standard Mean Oceanic Water (VSMOW): $\delta^{18}O = (R_{sam}/R_{VSMOW} - 1) \times 1000$ in ‰, with $R = {}^{18}O/{}^{16}O$ being the ratio of the abundances of the heavier to lighter

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isotopes in water. $\delta^{18}O$ and S covary in the surface ocean, and their linear relation depends on various physical processes.[17] Melted ice from the Himalaya is depleted in ^{18}O relative to monsoon rain[18] that debouches into the Bay of Bengal through the Ganga−Brahmaputra river system (Figure 1). This modifies

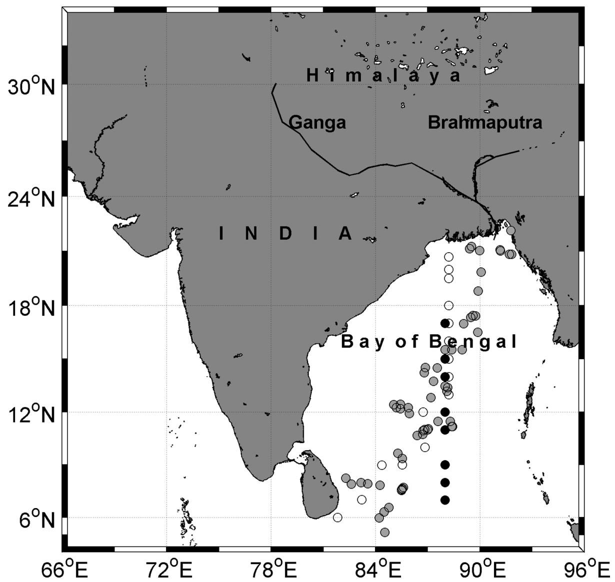

Figure 1. Sampling locations for different cruises in the Bay of Bengal. Gray circles: January−February 1994 (Delaygue et al.[26]). Black circles: September−October 2002 (Singh et al.[16]). Open circles: This study (November 2006).

the slope and intercept of the $\delta^{18}O-S$ relationship for the Bay of Bengal. It is inferred from this mixing model that either a decrease in the quantity of runoff or its ^{18}O content increases the slope and decreases the intercept of the $\delta^{18}O-S$ relation. We attempt to quantify the amount of ice melted during the study period using such observed changes.

Error Analysis. Best fit lines (linear regression using the method of least-squares) are drawn for the $\delta^{18}O$ and S data obtained from this and earlier studies in the Bay of Bengal

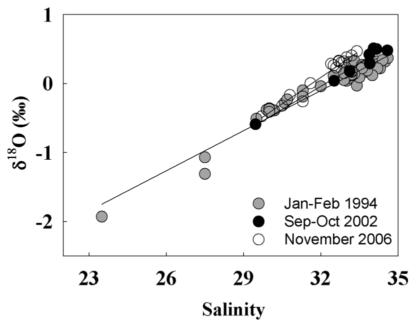

Figure 2. Temporal variation of the $\delta^{18}O-S$ relation in the Bay of Bengal.

(Figure 2). Uncertainty in the slope (m) of this linear relation is given by[19]

$$\sigma_m = \pm\sqrt{\left(\frac{n}{n-2}\right)\frac{\sum d^2}{[n(\sum S^2) - (\sum S)^2]}} \quad (1)$$

where n is the number of observations, and d is the residual. Uncertainty in the intercept (c) is given by

$$\sigma_c = \pm\sigma_m\sqrt{\frac{\sum S^2}{n}} \quad (2)$$

$\delta^{18}O$ and S in all the data sets were strongly correlated ($p \ll 0.05$) with a coefficient of linear correlation (r^2) close to one (Table 1). The regression parameters obtained from these observations (e.g., slopes and intercepts) were significantly different from each other.

■ RESULTS AND DISCUSSION

The Model. The oxygen isotope ratio R of a water body (with an initial oxygen isotopic ratio R_0) evolves as two competing processes take place, i.e., evaporation (E) and addition of fresh water (of oxygen isotopic ratio R_m, assumed to be constant for simplicity) by surface runoff (Q)/precipitation (P), as given by (see for details, Ramesh and Singh[20])

$$R = R_0 f^{\rho} + [\beta R_m/(\alpha + \beta - 1)][1 - f^{\rho}] \quad (3)$$

Here, f is the fraction of the water left in the reservoir relative to its initial amount; $\rho = \alpha/(1 - \beta) - 1$, where α is the effective fractionation factor that includes kinetic effects;[17] and β is the ratio of the rates of gain by runoff plus precipitation to loss by evaporation. When $\beta = 0$, i.e., when there is only loss of water by evaporation and no runoff, eq 3 reduces to $R = R_0 f^{\alpha-1}$, the classical Rayleigh fractionation equation.[21] In δ notation (eq 3) becomes

$$\delta = \delta_0 f^{\rho} + [1 - f^{\rho}](\beta\delta_m - \varepsilon)/(\alpha + \beta - 1) \quad (4)$$

Here δ, δ_0, and δ_m are R, R_0, and R_m, respectively, expressed in ‰ relative to a common standard, and ε (isotopic fractionation factor between vapor and liquid for oxygen expressed in ‰) is $(\alpha - 1) \times 1000$, also expressed in ‰. Evaporating water leaves the salt behind, and addition of runoff/precipitation does not add salt. Thus, the salinity changes only as a function of the net amount of water removed and, therefore, is a function of f only (vertical mixing does not occur significantly because of stratification and lateral advection in the Bay, e.g., the Indonesian throughflow is significant only south of the equator)[22]

$$S = S_0/f \quad (5)$$

Using eqs 4 and 5, the $\delta^{18}O-S$ relation is obtained as

$$\delta = \delta_0(S_0/S)^{\rho} + [1 - (S_0/S)^{\rho}](\beta\delta_m - \varepsilon)/(\alpha + \beta - 1) \quad (6)$$

We may assume the initial isotopic composition of the ocean δ_0 to be zero. For relatively small changes in salinity, i.e., $|(S - S_0)/S_0| \ll 1$, the above equation could be linearized as

$$\delta = [(\varepsilon - \beta\delta_m)/(1 - \beta)] + [(\beta\delta_m - \varepsilon)/(1 - \beta)](S/S_0) \quad (7)$$

Equation 7 describes the $\delta^{18}O-S$ relation in the surface ocean, where $[(\varepsilon - \beta\delta_m)/(1 - \beta)]$ is the intercept and $[(\beta\delta_m - \varepsilon)/(1 - \beta)]/S_0$ is the slope. This equation is valid for all non-negative values of β except unity. When it is unity, the amount lost by evaporation is exactly balanced by runoff, meaning that salinity remains constant and only the isotopic composition changes. This seldom occurs in nature.

Isotopic fractionation during evaporation is a non-equilibrium process. The vapor is always 2−5‰ more enriched than

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Table 1. $\delta^{18}O$−S Relationship in the Bay of Bengal

sampling period	number of observations	slope ± σ	intercept ± σ	correlation coefficient (r^2)	refs
January−February 1994	57	0.19 ± 0.01	−6.3 ± 0.2	0.95	Delaygue et al.[26,a]
September−October 2002	8[b]	0.22 ± 0.02	−7.2 ± 0.5	0.97	Singh et al.[16]
November 2006	16	0.26 ± 0.02	−8.1 ± 0.7	0.92	this study

[a]Data of sample locations south of 5°N are excluded. [b]Only data points that match with the samples collected during January−February 1994 and November 2006 are considered.

expected from equilibrium fractionation.[17,23−25] We have adopted ε to be −4‰.[17,25] S_0 = 34.6, the mean salinity of the deep oceanic reservoir,[21,26] is considered as initial salinity (S_0). This model implies that a decrease in the quantity of runoff or its ^{18}O content increases the slope and, likewise, decreases the intercept of the $\delta^{18}O$−S relation.

The rate of variation of the intercept with respect to β for constant values of ε and δ_m is given by $[(\varepsilon - \delta_m)/(1-\beta)^2]$. As ε is negative (∼ −4‰) and δ_m is more negative (∼ −6‰), this derivative is positive as long as $|\delta_m| > |\varepsilon|$, indicating that the intercept increases with increasing proportion of runoff. Likewise, the rate of variation of the slope with respect to β for constant values of ε and δ_m is given by $(\delta_m - \varepsilon)/\{S_0(1-\beta)^2\}$, which is positive as long as $|\delta_m| > |\varepsilon|$. Therefore, higher runoff results in a lower slope. We also note that the intercept is more sensitive than the slope to changes in the runoff. The sensitivity is high when β is close to unity.

Observed Changes in the $\delta^{18}O$−S Relationship in the Bay of Bengal. Results from the present and previous studies (with similar sampling locations; Figure 1) are presented in Table 1. A strong relationship between $\delta^{18}O$ and S in the surface waters of the Bay of Bengal has been reported in the literature.[16,26] We also observed a strong linear correlation (r^2 = 0.92) in the $\delta^{18}O$−S relation in the Bay of Bengal that has a significantly higher slope and smaller intercept ($\delta^{18}O = 0.26 \pm 0.02S - 8.1 \pm 0.7$) than the previous estimates (Table 1). We observed a temporal change in this relationship, with a significant increase in the slope and decrease in the intercept.

Attempts were made previously to explain the observed variation in the $\delta^{18}O$−S relation in the northern Indian Ocean using the multi-box and general circulation models.[26] Prior studies have also noted the importance of rainfall over India for the $\delta^{18}O$−S relation.[16] Variability in the rainfall can change the relationship in the coastal bay.[16] We may note that there is no significant variation (no secular trends) in the annual rainfall over India during the study period,[27] which is also verified independently from the annual rainfall data over India (Figure S1, Supporting Information). The Bay of Bengal is a well stratified basin as reported in several physical oceanographic studies.[22] In addition, subsurface water in the Bay has a different relationship ($\delta^{18}O = 0.42 \pm 0.15S - 14.4 \pm 5.1$)[16] than that observed at the surface waters (Table 1), suggesting stratification and no mixing. Here, we present a model updating the isotopic mass balance equations of Ramesh and Singh[20] for describing the alteration of the $\delta^{18}O$−S relation due to the mixing of ^{18}O-depleted river water and simultaneous evaporation of ocean water.

Estimating Melted Ice. Prior studies that have noted the importance of various physical oceanographic features reported that averages of E = 135 cm yr^{-1} and P = 220 cm yr^{-1} in the Bay of Bengal.[28] We estimated river discharge (Q) to be 88 cm yr^{-1} from several years of data from 35 rivers debouching into the Bay of Bengal (2.59×10^{12} m^3 yr^{-1} river discharge spread over the area of the Bay of Bengal, 2.93×10^{12} m^2) (data available at River Discharge Database, http://www.sage.wisc.edu/riverdata/index.php?qual=32, last accessed on October 11, 2011). δ_m is calculated as the weighted mean of the oxygen isotopic compositions of precipitation (δ_p) and river runoff (δ_q), i.e., $(P\delta_p + Q\delta_q)/(P + Q)$. δ_p is −5‰ in the Bay of Bengal from the data obtained by the Global Network for Isotopes in Precipitation (GNIP).[29,30] We estimated δ_q to be −7.4 ± 2.5‰ from the various data sources presented by Breitenbach et al.[31] Taking all the above data into account, we estimated δ_m (hereafter, δ_m is referred as $\delta^{18}O_m$ that represents the oxygen isotopic composition of the external source) to be −5.7‰ and $\beta = (P + Q)/E = 2.3$.

Using all the above estimates in eq 7, we have determined that $\delta^{18}O = 0.20S - 7.0$, similar to what was observed in 1994.[26] Equation 7, using different combinations of β and $\delta^{18}O_m$, could be used to interpret the observed changes in the $\delta^{18}O$−S in the Bay of Bengal. We have observed the temporal change in this relation from the three different studies, including the present one (Table 1). In the following, we explain this relation for the most recent data, i.e., $\delta^{18}O = 0.26 \pm 0.02S - 8.1 \pm 0.7$.

Because of the geographical setting of India, most of the annual precipitation on the Ganga−Brahmaputra basin runs off into the Bay of Bengal. Long-term records show that there are annual fluctuations (∼10%) and spatial and seasonal variability in the rainfall over India.[27,32] Heavy rainfall events have become more frequent in recent years;[33] however, no secular trends have been observed in the annual rainfall during the study period. There is no record that E, P, and Q over the Bay of Bengal have significantly changed over the past decade. This suggests that β may be taken as constant, leaving δ_m as the only variable. When δ_m decreases, the slope increases and the intercept decreases. The observed relationship for 2006 can be reproduced using eq 7 if β = 2.3 and $\delta^{18}O_m$ = −6.6 ± 0.4% (this is an average of the two values, i.e., −6.8‰ and −6.3‰, that are required to reproduce slope and intercept, respectively).

Our data as well those from the previous studies are from the season (September−February) when ice melt might show its complete effect on the $\delta^{18}O$−S relation. Hence, the observational period (September−February) may broadly be considered as one season. Because we have not observed any variation in the rainfall and its isotopic composition over the ocean and land, it appears that $\delta^{18}O_m$ is affected mostly by the glacial melt and changes to $\delta^{18}O_m^*$. Glacial meltwater is quite depleted in ^{18}O.[18] From the two end member mixing, the isotopic composition of a mixture of two end members can be defined as[31]

$$\delta^{18}O_m^* = f_g \delta^{18}O_g + (1 - f_g)\delta^{18}O_m \quad (8)$$

where $\delta^{18}O_m^*$ is the isotopic composition of rivers after being altered by a mixing of the glacier component of fraction f_g having an isotopic $\delta^{18}O_g$. We can reproduce the estimated $\delta^{18}O_m^*$ value (−6.6‰) if the glacier contribution (f_g) has

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increased to 9.4 ± 0.2% more than it was in 1994, with its oxygen isotopic composition ($\delta^{18}O_g$) of −15.3 ± 2.1‰ (average oxygen isotopic composition of Himalayan glaciers reported by many authors and summarized by Rai et al.[18]). Using 9.4% glacial melt, we estimated that 2.43 ± 0.05 × 10^{11} m^3 of Himalayan ice has melted during these 12 years (1994−2006). Our estimated rate (~20 km^3 yr^{-1}) is generally higher than that reported earlier[9,34] but consistent with a recent estimate of 26 ± 12 km^3 yr^{-1}.[35]

Recent estimates suggest that an ice mass of 4000−8000 km^3 was present late in the last century in the Himalaya−Karakoram region.[36] Taking all of the above calculations into account, our estimate suggests that if glaciers continue to melt at the estimated rate then Himalayan ice will disappear in 200−400 years. We have not accounted for the change in the $\delta^{18}O-S$ relationship in the Arabian Sea, and this time of disappearance is somewhat higher because it is based on the change in the $\delta^{18}O-S$ relationship in the Bay of Bengal that occurs only due to a major fraction of ice melting from the Himalaya. However, we emphasize that our prediction is a statistical extrapolation. This prediction does not account for potential non-linear changes in the climate system (e.g., abrupt change).

In conclusion, a significant change in the $\delta^{18}O-S$ relationship of the surface waters of the Bay of Bengal has been observed during 1994−2006. This change is mainly caused by river discharge containing glacier melt with highly depleted ^{18}O that mixes with the surface water of the Bay of Bengal. We estimate that 2.43 × 10^{11} m^3 of Himalayan ice is likely to have melted during 1994−2006. This is a conservative estimate because it is based on an increase in the fresh water contribution from Himalayan glaciers only to the Bay of Bengal. If Himalayan glaciers continue to melt at this rate, then their ice will disappear in 200−400 years.

■ ASSOCIATED CONTENT

Supporting Information

Figure S1 showing rainfall variation over India. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Bamzai, A. S.; Shukla, J. Relation between Eurasian snow cover, snow depth, and the Indian summer monsoon: An observational study. *J. Climate* **1999**, *12* (10), 3117−3132.

(2) Immerzeel, W. W.; Beek, L. P. H.; Bierkens, M. F. P. Climate change will affect the Asian water towers. *Science* **2010**, *328* (5984), 1382−1385.

(3) Cruz, R. V.; Harasawa, H.; Lal, M.; Wu, S.; Anokhin, Y.; Punsalmaa, B.; Honda, Y.; Jafari, M.; Li, C.; Huu Ninh, N. Asia. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ; Parry, M. L. et al., Eds.; Cambridge University Press: Cambridge, U.K., 2007; pp 469−506.

(4) IPCC Statement on the Melting of Himalayan Glaciers, 2010. IPCC. http://www.ipcc.ch/pdf/presentations/himalaya-statement-20january2010.pdf.

(5) Cogley, J. G. Climate science: Himalayan glaciers in the balance. *Nature* **2012**, *488*, 468−469.

(6) Ganjoo, R. K.; Koul, M. N. Is the Siachen glacier melting? *Curr. Sci.* **2009**, *97* (3), 309−310.

(7) Raina, V. K. Himalayan Glaciers. A State-of-Art Review of Glacial Studies, Glacial Retreat and Climate Change, 2009. Ministry of Environment and Forests, Government of India. http://go.nature.com/pLgJ6D.

(8) Scherler, D.; Bookhagen, B.; Strecker, M. R. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geosci.* **2011**, *4* (3), 156−159.

(9) Kääb, A.; Berthier, E.; Nuth, C.; Gardelle, J.; Arnaud, Y. Contrasting patterns of early twenty−first−century glacier mass change in the Himalayas. *Nature* **2012**, *488* (7412), 495−498.

(10) Bolch, T.; Kulkarni, A.; Kääb, A.; Huggel, C.; Paul, F.; Cogley, J. G.; Frey, H.; Kargel, J. S.; Fujita, K.; Scheel, M.; Bajracharya, S.; Stoffel, M. The state and fate of Himalayan glaciers. *Science* **2012**, *336* (6069), 310−314, DOI: 10.1126/science.1215828.

(11) Gardelle, J.; Berthier, E.; Arnaud, Y. Slight mass gain of Karakoram glaciers in the early twenty−first century. *Nat. Geosci.* **2012**, *5* (5), 322−325.

(12) Fujita, K.; Nuimura, T. Spatially heterogeneous wastage of Himalayan glaciers. *Proc. Natl. Acad. Sci. U.S.A.* **2011**, *108* (34), 14011−14014.

(13) Bindoff, N. L.; Willebrand, J.; Artale, V.; Cazenave, A.; Gregory, J.; Gulev, S.; Hanawa, K.; Le Quéré, C.; Levitus, S.; Nojiri, Y.; Shum, C. K.; Talley, L. D.; Unnikrishnan, A. Observations: Oceanic Climate Change and Sea Level. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L., Eds.; Cambridge University Press: Cambridge, U.K., 2007.

(14) Epstein, S.; Mayeda, T. Variation of ^{18}O content of water from natural sources. *Geochim. Cosmochim. Acta* **1953**, *4* (5), 213−224.

(15) Gonfiantini, R. The δ-Notation and the Mass-Spectrometric Measurement Techniques. In *Stable Isotope Hydrology: Deuterium and Oxygen-18 in the Water Cycle*; Technical Report Series 210; Gat, J. R., Gonfiantini, R., Eds.; International Atomic Energy Agency: Vienna, Austria, 1981.

(16) Singh, A.; Jani, R. A.; Ramesh, R. Spatiotemporal variations of the $\delta^{18}O$−salinity relation in the northern Indian Ocean. *Deep Sea Res. I* **2010**, *57* (11), 1422−1431, DOI: 10.1016/j.dsr.2010.08.002.

(17) Craig, H.; Gordon. L. I. Deuterium and Oxygen 18 Variations in the Ocean and the Marine Atmosphere. In *Stable Isotopes in Oceanographic Studies and Paleotemperatures*; Tongiorgi, E., Ed.; Lab. Di Geol. Nucl., Cons. Naz. Delle Ric.: Pisa, Italy, 1965; pp 9−130.

(18) Rai, S. P.; Kumar, B.; Singh, P. Estimation of contribution of southwest monsoon rain to Bhagirathi River near Gaumukh, western Himalayas, India, using oxygen-18 isotope. *Curr. Sci.* **2009**, *97* (2), 240−245.

(19) Topping, J. *Errors of Observation and Their Treatment*. Reinhold Publishing Corporation: New York, 1962.

(20) Ramesh, R.; Singh, A. Isotopic fractionation in open systems: Application to organic matter decomposition in ocean and land. *Curr. Sci.* **2010**, *98* (3), 406−411.

(21) Clark, I.; Fritz, P. *Environmental Isotopes in Hydrology*; Lewis Publishers: Boca Raton, FL, 1997.

(22) Shetye, S. R.; Gouveia, A. D.; Shankar, D.; Shenoi, S. S. C.; Vinayachandran, P. N.; Sundar, D.; Nampoothiri, G. Hydrography and circulation in the western Bay of Bengal during the northeast monsoon. *J. Geophy. Res.* **1996**, *101* (C6), 14011−14025.

(23) Merlivat, L.; Jouzel, J. Global climatic interpretation of the deuterium−oxygen 18 relationship for precipitation. *J. Geophys. Res.* **1979**, *84* (C8), 5029−5033, DOI: 10.1029/JC084iC08p05029.

(24) Jouzel, J.; Koster, R. D. A reconsideration of the initial conditions used for stable water isotope models. *J. Geophys. Res.* **1996**, *101* (D17), 22933−22938, DOI: 10.1029/96JD02362.

(25) Cappa, C. D.; Hendricks, M. B.; DePaolo, D. J.; Cohen, R. C. Isotopic fractionation of water during evaporation. *J. Geophys. Res.* **2003**, *108* (D16), 4525 DOI: 10.1029/2003JD003597.

(26) Delaygue, G.; Bard, E.; Roollion, C.; Jouzel, J.; Stievenard, M.; Duplessy, J. C.; Ganssen, G. Oxygen isotope/salinity relation in the northern Indian Ocean. *J. Geophys. Res.* **2001**, *106* (C3), 4565−4574.

(27) Guhathakurta, P.; Rajeevan, M. Trends in the rainfall pattern over India. *Int. J. Climatol.* **2007**, *28* (11), 1453−1469, DOI: 10.1002/joc.1640.

(28) Prasad, T. G. Annual and seasonal mean buoyancy fluxes for the tropical Indian Ocean. *Curr. Sci.* **1997**, *73* (8), 667−674.

(29) Araguas−Araguas, L.; Froehlich, K.; Rozanski, K. Stable isotope composition of precipitation over southeast Asia. *J. Geophys. Res.* **1998**, *103* (D22), 28721−28742.

(30) Global Network of Isotopes in Precipitation. The GNIP Database, 2006. IAEA/WMO. http://isohis.iaea.org.

(31) Breitenbach, S. F. M.; Adkins, J. F.; Meyer, H.; Marwan, N.; Krishna Kumar, K.; Haug, G. H. Strong influence of water vapor source dynamics on stable isotopes in precipitation observed in Southern Meghalaya NE India. *Earth Planet. Sci. Lett.* **2010**, *292* (1), 212−220.

(32) Krishnamurthy, V.; Shukla, J. Intraseasonal and interannual variability of rainfall over India. *J. Climate* **2000**, *13* (24), 4366−4377.

(33) Goswami, B. N.; Venugopal, V.; Sengupta, D.; Madhusoodanan, M. S.; Xavier, P. K. Increasing trend of extreme rain events over India in a warming environment. *Science* **2006**, *314* (5804), 1442−1445.

(34) Jacob, T.; Wahr, J.; Pfeffer, W. T.; Swenson, S. Recent contributions of glaciers and ice caps to sea level rise. *Nature* **2012**, *482* (7386), 514−518.

(35) Gardner, A. S.; Moholdt, G.; Cogley, J. G.; Wouters, B.; Arendt, A. A.; Wahr, J.; et al. A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science* **2013**, *340* (6134), 852−857.

(36) Cogley, J. G. Present and future states of Himalaya and Karakoram glaciers. *Ann. Glaciol.* **2011**, *52* (59), 69−73.