GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L22503, doi:10.1029/2008GL035556, 2008

Mass loss on Himalayan glacier endangers water resources

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Received 1 August 2008; revised 24 September 2008; accepted 21 October 2008; published 22 November 2008.

[1] Ice cores drilled from glaciers around the world generally contain horizons with elevated levels of beta radioactivity including ^{36}Cl and ^{3}H associated with atmospheric thermonuclear bomb testing in the 1950s and 1960s. Ice cores collected in 2006 from Naimona'nyi Glacier in the Himalaya (Tibet) lack these distinctive marker horizons suggesting no net accumulation of mass (ice) since at least 1950. Naimona'nyi is the highest glacier (6050 masl) documented to be losing mass annually suggesting the possibility of similar mass loss on other high-elevation glaciers in low and mid-latitudes under a warmer Earth scenario. If climatic conditions dominating the mass balance of Naimona'nyi extend to other glaciers in the region, the implications for water resources could be serious as these glaciers feed the headwaters of the Indus, Ganges, and Brahmaputra Rivers that sustain one of the world's most populous regions. **Citation:** Kehrwald, N. M., L. G. Thompson, Y. Tandong, E. Mosley-Thompson, U. Schotterer, V. Alfimov, J. Beer, J. Eikenberg, and M. E. Davis (2008), Mass loss on Himalayan glacier endangers water resources, *Geophys. Res. Lett.*, *35*, L22503, doi:10.1029/2008GL035556.

1. Introduction

[2] Recent retreat of Tibetan Plateau (TP) glaciers affects at least half a billion people. The Chinese Glacier Inventory catalogued 46,377 glaciers in western China, with approximately 15,000 glaciers in the Himalayas storing an estimated 12,000 km^3 of freshwater [*Ding et al.*, 2006; *Cruz et al.*, 2007]. These glaciers seasonally release meltwater into tributaries of the Indus, Ganges, and Brahmaputra Rivers with glacial melt contributing up to ~45% of the total river flow [*World Resources Institute*, 2003]. Approximately 500 million people depend upon water from these three rivers to support agricultural and economic practices [*Cruz et al.*, 2007]. Regions where water supply is dominated by melting snow and/or ice are predicted to suffer hydrologic disruptions as a result of recent warming [*Barnett et al.*, 2005]. Thus the mass balance of Himalayan glaciers is of broad societal concern.

[3] In 2006 four ice cores, including three to bedrock, were drilled on or near the summit of the Naimona'nyi ice field (30°27.06′ N, 81°91.94′ E, 6050 masl) located in a region with sparse climate records. The Naimona'nyi climate record complements four existing high-resolution Tibetan ice cores (Figure 1), each drilled to bedrock. These include Guliya (35°17′N, 81°29′E, 6200 masl), Dasuopu (28°23′N, 85°43′E, 7200 masl), Puruogangri (34°30′N, 89°10′E, 6500 masl), and Dunde (38°06′N, 96°24′E, 5325 masl) [*Thompson et al.*, 1989, 1997, 2000, 2006a]. Snowfall on Dasuopu and Puruogangri arrives with the South Asian monsoon while snowfall over Guliya and Dunde is dominated by continental westerly flow. These four glaciers representing two different climatic zones were all actively accumulating mass at the time they were drilled (Table 1) and provide a regional and temporal context for the observations on Naimona'nyi.

2. Methods

[4] The 2006 Naimona'nyi ice core drilling project was a collaboration between the Institute for Tibetan Plateau Research, Chinese Academy of Sciences (ITPR-CAS) and The Ohio State University's Byrd Polar Research Center (BPRC). Naimona'nyi is a subcontinental ice field in the central Himalaya consisting of fifty-eight glaciers, many originating from a shallowly-sloping ice divide at 6050 masl. The joint BPRC and ITPR-CAS team drilled three cores to bedrock on or near the ice divide: Core 1 (C1) 113.74 m, Core 2 (C2) 137.79 m, and Core 3 (C3) 157.48 m. One shallow 10.94 m core (C4) was drilled parallel to C3 to assist in dating modern post-bomb accumulation. The cores were obtained using a portable diesel-powered electro-mechanical drill system and all cores were returned frozen. Due to their proximity, the upper sections of the cores are assumed to be recording similar conditions and C2, C3, and C4 were used for different analysis depending on ice core mass and the ice needed for the techniques.

[5] Beta radioactivity was measured at BPRC on 15 continuous samples from C2 and 11 continuous samples from C4 using BPRC's Tennelec LB 1000 series alpha/beta counter. Eawag and ETH analyzed 12 ^{36}Cl samples from C4 using the AMS facility of ETH/PSI. Tritium analyses were conducted at the Division of Climate and Environmental Physics, Physics Institute, University of Bern using large volume liquid scintillation counting (LSC) and proportional gas counting (GC) to examine 20 samples from C4. Lead-210 was measured on 17 samples repre-

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0094-8276/08/2008GL035556$05.00

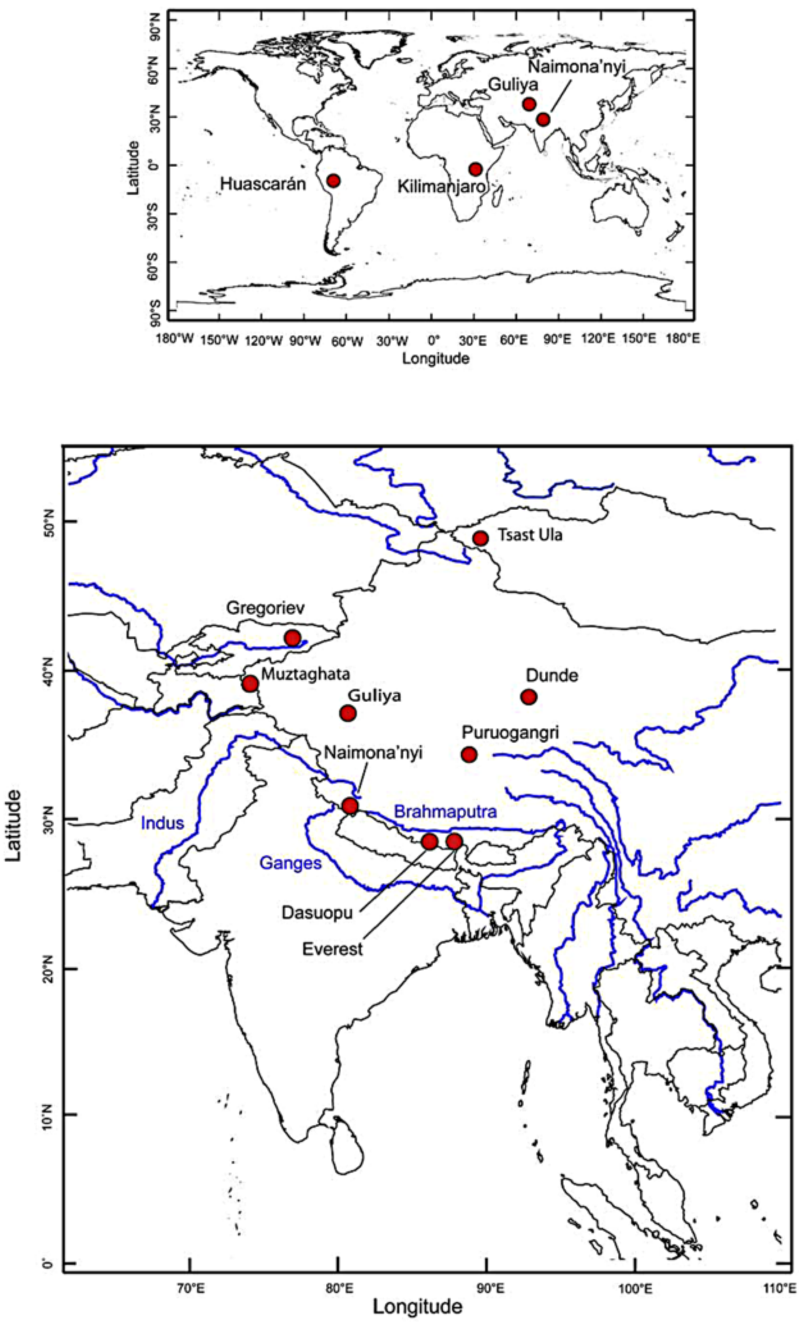

Figure 1. (top) Global and (bottom) Tibetan Plateau ice core locations and proximity to regional rivers.

senting the upper 5.5 meters of C3 at Paul Scherrer Institute (PSI).

3. Results and Discussion

[6] The Tibetan Plateau is characterized by a southeast to northwest precipitation gradient [*Anders et al.*, 2006]. The South Asian monsoon brings abundant precipitation to southeastern Tibet while extreme continental conditions in the northwest result in lower precipitation rates (Figure S1 of the auxiliary material[1]). Tibetan ice cores reflect these precipitation trends such that Dasuopu annually receives an

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL035556.

Table 1. Tritium Concentrations in Tibetan Plateau Ice Cores[a]

Ice Core	Year (AD)	Tritium (TU)	Method
Naimona'nyi	unknown	2.65 ± 0.49	LSC
Puruogangri	2000	29.51 ± 0.91	GC
Puruogangri	1999	23.55 ± 1.68	LSC
Dasuopu	1997	12.63 ± 0.90	GC
Dasuopu	1996	14.91 ± 1.49	LSC
Guliya	1990	46.40 ± 2.10	LSC
TsastUla	1990	55.00 ± 3.00	GC

[a]Tritium (TU) levels in the most recent year for each core demonstrating the presence of modern accumulation that contrasts sharply with the absence of tritium in the Naimona'nyi core. Tritium is measured by gas chromatography (GC) and liquid scintillation counting (LSC). Years are determined by annual layer counting.

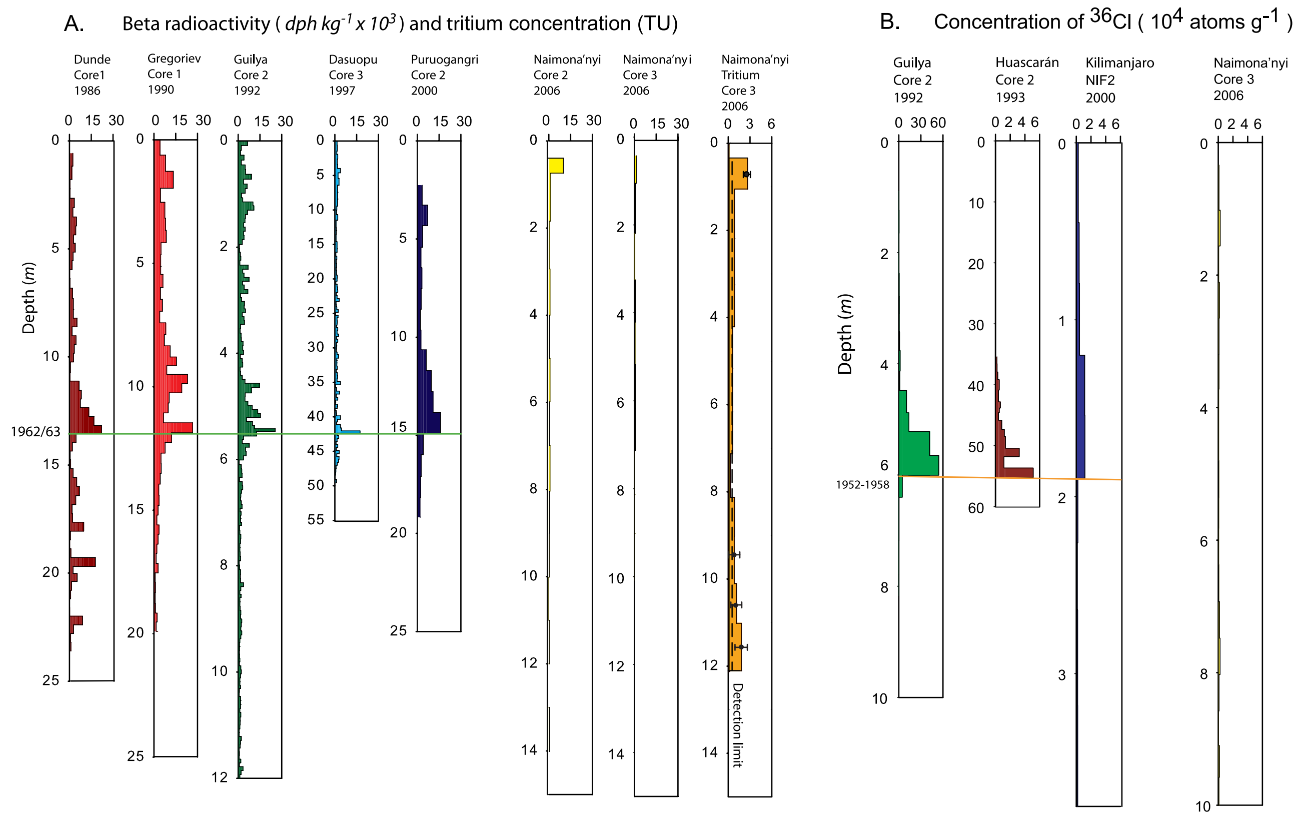

Figure 2. (a) Beta radioactivity (*dph kg*$^{-1}$) measured in Tibetan ice cores compared to the negligible amounts of both beta radioactivity and tritium concentration (TU) measured in the Naimona'nyi core (also see Table 1). (b) ^{36}Cl (*10*^{4} *atoms g*$^{-1}$) measured in three Tibetan ice cores compared to a virtual absence of ^{36}Cl measured in the Naimona'nyi core.

average of ~1000 mm of water equivalent (w.e.) while Guliya receives ~200 mm w.e. Orographic precipitation in complex terrain can vary on the scale of ~10s of kms [*Anders et al.*, 2006], yet general regional trends suggest that Naimona'nyi should receive a net annual accumulation ranging between that of Dasuopu and Guliya. However, the snowfall received annually on Naimonan'nyi is not accumulating as evidenced by stake measurements, the lack of radiogenic bomb horizons, and ^{210}Pb dates discussed in detail throughout this section.

[7] The measurement of accumulation stakes revealed that the surface had lowered 0.675 m a^{-1} at the summit and 1.425 m a^{-1} at 4800 masl between 2004 and 2006 [*Yao et al.*, 2007a]. This ablation was unexpected as Naimona'nyi (6050 masl) is of similar or higher elevation than two of the four Tibetan glaciers drilled by BPRC that all contained prominent beta radioactivity peaks or horizons indicating a net positive accumulation when drilled [*Thompson et al.*, 1989, 1997, 2000, 2006b].

[8] Radioactive horizons have been identified in all Tibetan ice cores as well as in nearly all high elevation and polar cores. The Dunde, Dasuopu, Guliya, Puruogangri, and Gregoriev (41°N, 78° E, 4660 masl) cores [*Thompson et al.*, 1993, 2006b] all contained prominent beta radioactivity associated with the 1962–1963 Soviet Arctic thermonuclear tests (Figure 2a). In addition, Puruogangri, Dasuopu, Guliya, and TsastUla (46°32′N; 93°32′E; 4200 masl) all contain tritium (^{3}H) produced by the Arctic nuclear tests (Table 1). Tritium is deposited as meteoric precipitation, and tritium concentration is dependent on latitude in the northern hemisphere [*Schotterer et al.*, 1997]. Although this latitudinal effect is evident in previously drilled TP and Mongolian glaciers between 30°N and 46°N, the most recent year in each core (except Naimona'nyi) contains tritium concentrations exceeding 8 TU depending on the proportions of contributing monsoonal and continental moisture sources (Table 1).

[9] Most glaciers worldwide preserve a radioisotopic signal that is a remnant of a global pulse of ^{36}Cl injected to the atmosphere by the 1952–1958 marine nuclear weapons tests in the South Pacific [*Elmore et al.*, 1982]. The ^{36}Cl horizon is present in ice cores from both hemispheres (Figure 2b), including Huascarán, Perú (9°S, 77°30′W, col elevation 6050 m), and Kilimanjaro, Tanzania (3°04.6′S, 37°21.2′E, 5893 masl) [*Thompson et al.*, 2002]. The high accumulation rate of 1.4 m w.e. a^{-1} on Huascarán [*Thompson et al.*, 1995] is not sufficient to dilute the ^{36}Cl signal and a peak significantly above the cosmic ray induced background (0.03 10^{4} ^{36}Cl g^{-1}) is apparent (Figure 2b).

[10] Naimona'nyi is very anomalous as its ice cores do not contain horizons with elevated beta radioactivity, ^{36}Cl or ^{3}H (Figures 2a and 2b). Only one beta sample is elevated (995.3 dph kg^{-1}) compared to the average activity for the upper 14.01 meters of the core (92.1 dph kg^{-1}). This sample is from a near-surface (0.4 to 0.74 m depth) layer of superimposed ice which comprises the firn-ice transition and physically differs from the ice below as it contains a prominent dust layer. This layer contains very little tritium (2.65 TU) suggesting that it was deposited before 1963. The virtual absence on Naimona'nyi of any ice or snow strata

Table 2. The ^{210}Pb Activity Ratios in the Naimona'nyi and Dasuopu Ice Cores[a]

Ice Core	A_i/A_o Activity Ratio	Sample Age (years)	Deposition Year (AD)	Profile Depth (m)	Precipitation Rate (mm w.e. a^{-1})
Dasuopu	1.000	0.5	1995	0.0–2.6	~1000
Naimona'nyi	0.223	48.3	1947	0.5–1.1	17
Naimona'nyi	0.026	117.6	1877	1.1–2.4	14
Naimona'nyi	0.004	>130	before 1860	2.4–3.4	<22
Naimona'nyi	0.004	>130	before 1860	3.4–4.5	<30
Naimona'nyi	0.008	>130	before 1860	4.5–5.5	<38

[a]Lead-210 activity ratios in the Naimona'nyi and Dasuopu ice cores. Dasuopu retains contemporary snowfall while the low ^{210}Pb radioactivity in ice from Naimona'nyi indicates ablation of the glacier surface (6050 masl).

containing beta radioactivity including ^{3}H and ^{36}Cl from post-1950 thermonuclear tests provides strong evidence for a net negative mass balance from 1950 to the present.

[11] The absence of modern accumulation on the Naimona'nyi ice field is supported by ^{210}Pb dates on the upper 5.5 meters of C3 (Tables 2 and 3). Lead-210 is a naturally occurring radiogenic isotope that is removed from the atmosphere mainly by wet deposition and decays with a half-life of 22.6 years [*Picciotto et al.*, 1967]. The ^{210}Pb A_i/A_o (A_o being the modern value) activity ratio for a Naimona'nyi sample (depth: 0.5 to 1.1 m) is 0.223, suggesting an approximate deposition year of 1947. At 2.4 meters the A_i/A_o activity ratio of 0.004 suggests the ice was deposited more than 130 years ago. The A_{iB}/A_o activity ratios in the top 5.5 meters of Naimona'nyi contrast sharply with the activity ratio for Dasoupu (A_{iB}/A_o of 1), that provides a reference for the ^{210}Pb radioactivity in modern (1994–1997 AD) TP snow. The upper 2.5 m of Naimona'nyi C2 were remeasured with Guliya as a reference to test the repeatability and precision of the dates (Table 3). The ^{210}Pb dates complement the ^{3}H and ^{36}Cl results that virtually confirm a lack of net modern accumulation on the Naimona'nyi ice field and suggest the glacier is thinning at all elevations.

4. Glacier Thinning

[12] Himalayan glacier retreat is well documented through remote sensing techniques including Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), China-Brazil Earth Resources Satellite (CBERS), Landsat Thematic Mapper, and aerial photographs [*Ding et al.*, 2006]. Over 80% of the glaciers in western China have retreated in the past 50 years, with the greatest percentage of retreat occurring on the north slope of the Himalaya [*Ding et al.*, 2006]. Not only are the majority of Tibetan glaciers retreating, but this retreat is accelerating across much of the plateau [*Yao et al.*, 2007b]. ASTER and Landsat satellite imagery in the Naimona'nyi region reveal average annual decreases in glacier surface area of 0.17, 0.19 and 0.77 km^2 a^{-1} for the time periods 1976–90, 1990–1999, and 1999–2003, respectively [*Yao et al.*, 2007b]. While satellite imagery is valuable in providing changes in glacier surface area across remote locations, it cannot measure glacier thinning. However, the Naimona'nyi cores provide ground truth which complements and expands inferences derived from satellite imagery.

[13] Himalayan glaciers have been retreating more rapidly than glaciers elsewhere in the world [*Cruz et al.*, 2007]. The Tibetan Plateau has been warming at an annual rate of 0.16°C per decade with winter temperatures rising 0.32°C per decade [*Liu and Chen*, 2000]. The length of the snow-cover season has decreased by 23 days at elevations between 4000 to 6000 masl across the Tibetan Plateau and earlier snow melt has been observed at elevations up to 5500 masl [*Rikiishi and Nakasato*, 2006]. Declining snow cover and earlier melt seasons decrease the regional albedo and may enhance the rapidity and spatial scale of Himalayan glacier retreat.

[14] While recent warming of the TP is well documented, precipitation changes are less well known. Most regional weather stations are located below 4000 m and/or on the southern slopes of the Himalaya and therefore may not provide an applicable comparison to the Naimona'nyi ice field. Although weather station data are sparse, the Global Precipitation Climatology Project (GPCP) in-situ rain gauge networks can be used in conjunction with infrared (GOES, GMS, Meteosat) and microwave (DMSP)

Table 3. The ^{210}Pb Activity Ratios in the Naimona'nyi and Guliya Ice Cores[a]

Ice Core	A_i/A_o Activity Ratio	Sample Age (years)	Deposition Year (AD)	Profile Depth (m)	Precipitation Rate (mm w.e. a^{-1})
Guliya	1.000	0.5	1987	0.5–2.0	200
Naimona'nyi	1.158	−4.7	Firn (N/A)	0.0–0.4	N/A
Naimona'nyi	0.416	28.2	1959	0.4–0.6	18
Naimona'nyi	0.240	45.9	1941	0.6–0.8	15
Naimona'nyi	0.138	63.8	1923	0.8–1.0	13
Naimona'nyi	0.159	59.1	1928	1.0–1.2	19
Naimona'nyi	0.075	83.3	1904	1.2–1.4	16
Naimona'nyi	0.124	67.2	1920	1.4–1.6	22
Naimona'nyi	0.100	73.9	1913	1.6–1.8	23
Naimona'nyi	0.054	93.9	1893	1.8–2.0	20
Naimona'nyi	0.053	94.6	1892	2.0–2.2	22
Naimona'nyi	0.065	87.9	1899	2.2–2.4	26
Naimona'nyi	0.041	103.0	1884	2.4–2.6	24

[a]Lead-210 activity ratios in the Naimona'nyi and Guliya ice cores sampled at 20 cm resolution to provide more precise dates and accumulation rates.

satellite estimates of precipitation to extract monthly rainfall measurements for a 2.5° × 2.5° global grid from 1979 to 2007 (Figure S2). These combined ground and satellite data show decreased precipitation near Naimona'nyi in the early 1990s, but an increase in mean annual precipitation over the last decade (Figure S2). This observed precipitation record is too short to determine significant long-term trends, but tree-ring records suggest an increase in twentieth century precipitation in the Karakoram [*Treydte et al.*, 2006] while ice core data [*Duan et al.*, 2004] suggest a decrease in monsoon strength in the eastern and central Himalaya over at least the past 80 years. Naimona'nyi is located between these two regions and thus existing paleoclimate data are inconclusive regarding decadal to centennial precipitation trends.

[15] The observed thinning of the Naimona'nyi ice field at 6050 masl is the highest documented occurrence of surface mass loss. The regular depletion in ^{210}Pb between 0.4 and 2.6 m demonstrates that the processes responsible for net accumulation remained relatively constant between ~1880 to 1950. While wind scour and sublimation occur on Naimona'nyi, there is no evidence that these factors have increased since 1950. If the ablation were primarily controlled by sublimation, particulate matter would remain on the glacier surface and the dust layer at 0.47 m would be expected to contain a beta radioactivity horizon comparable to that recorded in Puruogangri (2658 dph kg^{-1}), Guliya (2559 dph kg^{-1}), Dasuopu(1732 dph kg^{-1}) and Dunde (2202 dph k g^{-1}) instead of only 995 dph kg^{-1} [*Thompson et al.*, 1989, 1997, 2000, 2006b]. There is no evidence for redistribution of wind-blown snow to lower glacier elevations and/or near the ablation stakes. The majority of evidence suggests melt as the principal factor. Melt is apparent on the glacier surface in the form of cryocanite holes and surface runoff. The visible stratigraphy of the upper 3 meters of C2 and C3 show repeated melt layers as well as narrow pipes and vertical elongated bubbles. This melt and thinning may be due to the statistically significant TP warming since 1950 with an increased temperature trend at higher elevations [*Liu and Chen*, 2000].

5. Global Scope

[16] Glaciers located at lower elevations would be expected to experience more ablation than those at higher elevations. The ice cores from Dasuopu (7200 masl) and Puruogangri (6500 masl), located at elevations higher than Naimona'nyi (6050 masl), contain prominent beta peaks indicating a net positive accumulation [*Thompson et al.*, 2000, 2006a]. Naimona'nyi is higher than Dunde (5325 masl) and nearly as high as Guliya (6200 masl) which both contained beta horizons when drilled [*Thompson et al.*, 1989, 1997]. Tritium concentrations in the uppermost firn and ice layers of Guliya, Dasuopu, Puruogangri as well as TsastUla, Mongolia were re-measured in 2008 and validate previous results indicating elevated modern radioactivity [*Schotterer et al.*, 1997; *Thompson et al.*, 1997, 2000, 2006b] in sharp contrast to that in Naimona'nyi (Table 1).

[17] Ablation above 6000 masl is rare, even when many parameters such as accumulation rate, aspect, average annual temperature, and latitude are considered. Kilimanjaro is the only other ice field at a similar elevation (5893 masl) with documented summit ice loss. Ice cores drilled from the Northern Ice Field (NIF) on Kilimanjaro in 2000 contained the early 1950s ^{36}Cl peak at 1.8 m below the surface. Since then the ice surface of the NIF has lowered 2.5 meters, removing the surface present in 2000. The fact that ablation is occurring at these high elevation sites in both East Africa and on the Tibetan Plateau suggests that high elevation surface ablation warrants further examination to determine if it is spatially expansive. Surface wasting may become more common, even for Earth's highest ice fields, creating critical water shortages for people who depend on glacier fed streams.

6. Implications for Water Resources

[18] Geographic regions where water supply is dominated by melting snow or ice are predicted to suffer severe consequences as a result of recent warming [*Barnett et al.*, 2005]. Negative impacts including seasonal shifts in water supply, flood risks, and increased precipitation variability will eventually offset benefits incurred by short-term increases in runoff from glacier melt [*Cruz et al.*, 2007]. TP ice fields are a critical resource for one sixth of the world's population because they provide dry season runoff for major rivers [*Cruz et al.*, 2007]. More specifically, Naimona'nyi and other glaciers in the region form the headwaters of the Indus, Ganges, and Brahmaputra Rivers in the southwestern Himalaya (Figure 1). The Indus and Ganges Rivers currently have little outflow to the sea during the dry season and are in danger of becoming seasonal rivers due to climate change and increased water demand [*Cruz et al.*, 2007]. The surface area of glaciers across the TP is projected to decrease from 500,000 km^2 measured in 1995 to 100,000 km^2 in 2030 [*Cruz et al.*, 2007], thereby threatening regional rivers and water resources. Estimates of the impact of Himalayan glacier retreat on water resources have not accounted for mass loss through high elevation thinning such as is currently occurring on the Naimona'nyi ice field. If Naimona'nyi is characteristic of other glaciers in the region, alpine glacier meltwater surpluses are likely to shrink much faster than currently predicted with substantial consequences for approximately half a billion people.

[19] **Acknowledgments.** We thank V. Zagorodnov and V. Mikhalenko for recovery of the ice cores, P.-N. and S. Lin for stable isotopic analysis. The authors acknowledge the members of the Naimona'nyi 2006 field season. The images and data used in this study (Figures S1 and S2) were acquired using the GES-DISC Interactive Online Visualization ANd aNalysis Infrastructure (Giovanni) as part of the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC). The fieldwork was funded by the NSF Award ATM 0502476, and support for laboratory analyses and tuition and fees for NMK was provided in part by the Gary Comer Foundation. This is Byrd Polar Research Center Publication 1372.

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