JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, D03109, doi:10.1029/2005JD005894, 2006

Thirty-year history of glacier melting in the Nepal Himalayas

Koji Fujita,[1] Lonnie G. Thompson,[2] Yutaka Ageta,[1] Tetsuzo Yasunari,[3]
Yoshiyuki Kajikawa,[4] Akiko Sakai,[1] and Nozomu Takeuchi[5]

Received 17 February 2005; revised 24 October 2005; accepted 17 November 2005; published 15 February 2006.

[1] Two net balance records of neighboring glaciers under different conditions are analyzed to extract temporal variations in glacier melting in the Himalayas. Significant melt was observed every year at one site (wet site), whereas no melt occurred at the second site because of its high elevation (dry site). Accumulation at the wet site of a glacier is estimated from the dry site neighboring another glacier through a measured precipitation record for a short time period. The difference between the estimated accumulation and the net balances at the wet site is obtained as the "melt index," which represents the glacier melting conditions. The melt index with an interannual timescale is significant as a climatic proxy at high elevation since no relationship between stable isotopes and temperature is established and few long-term temperature records are available at high elevations in the Himalayas. The melt index showed a decadal fluctuation with a major amplitude never reported in previous studies with respect to temperature and ice cores analyses in the Himalayas. Ice cores from a site where significant melt occurs every year have not been considered available in reconstructing past climates since climatic signals in ice were disturbed by meltwater infiltration. However, we suggest a new approach to glean temperature information by a combination of wet and dry cores, not obtainable from a good-quality ice core alone.

Citation: Fujita, K., L. G. Thompson, Y. Ageta, T. Yasunari, Y. Kajikawa, A. Sakai, and N. Takeuchi (2006), Thirty-year history of glacier melting in the Nepal Himalayas, *J. Geophys. Res.*, *111*, D03109, doi:10.1029/2005JD005894.

1. Introduction

[2] Rapid shrinkage of glaciers in the Nepal Himalayas has been observed during recent decades [e.g., *Yamada et al.*, 1992; *Kadota et al.*, 1997; *Fujita et al.*, 1997a, 1998, 2001a, 2001b]. *Shrestha et al.* [1999], by analyzing air temperature records, reported a drastic warming over the last 24 years in Nepal. However, it is still not known how global warming affects the Himalayan mountains, since long-term meteorological records for high elevations (more than 4000 m asl) are few.

[3] Although a few ice cores have been extracted from northern slopes of the Himalayas [*Hou et al.*, 1999; *Kang et al.*, 2000; *Qin et al.*, 2000; *Thompson et al.*, 2000], there are various interpretations of stable isotopes in ice cores, which are used as a temperature index in polar regions. *Yao et al.* [1996] and *Thompson et al.* [2000] concluded that the stable isotopes could be used as a temperature index on a multi-decadal scale, whereas *Kang et al.* [2000] and *Qin et al.* [2000] suggested that the stable isotopes indicated monsoon fluctuation in the Himalayas. It is well known that seasonal changes in stable isotopes in precipitation and temperature show an inverse relationship in the southern part of the Tibetan Plateau, including the Himalayas [*Wushiki*, 1977; *Tian et al.*, 2001; *Zhang et al.*, 2001]. Strong monsoon activity in the southern Tibetan Plateau results in high precipitation rates and more depleted heavy isotopes, which is described as a precipitation "amount effect." This effect causes a poor δ^{18}O-T relationship on both seasonal and annual scales [*Tian et al.*, 2003]. Therefore it remains difficult to extract annual changes in air temperature from stable isotope records in ice cores of the Himalayas.

[4] In ice core studies, it is recognized that good environmental proxy data can be obtained in the higher-accumulation zone where minimal melting does not disturb the climatic signals initially deposited. The accumulation history can be better revealed from an elevation higher than the percolation zone, where no mass loss is expected. Nevertheless, appropriate sites are considerably limited on the southern side of the Himalayas because of its difficult accessibility as well as transportation and safety problems [*Fujita et al.*, 2002]. In addition, it has been pointed out that significant melts occurred even at 6000 m asl because of the strong solar radiation at low latitudes [*Fujita et al.*, 2001a, 2002]. Because of the melting at higher elevations and the poor relationship between stable isotope and temperature above mentioned, it is still difficult to obtain temperature records, another source of significant information expected in ice core study, from the Himalayan ice

[1] Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan.
[2] Byrd Polar Research Center and Department of Geological Sciences, Ohio State University, Columbus, Ohio, USA.
[3] Hydrospheric Atmospheric Research Center, Nagoya University, Nagoya, Japan.
[4] International Pacific Research Center, University of Hawaii, Honolulu, Hawaii, USA.
[5] Research Institute for Humanity and Nature, Kyoto, Japan.

0148-0227/06/2005JD005894$09.00

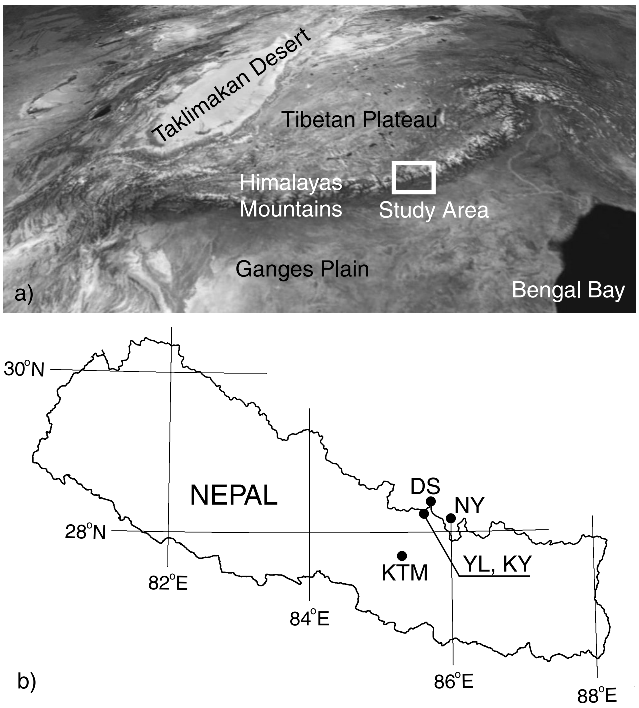

Figure 1. (a) Topographical image of the Asian highland by World Wind, NASA, and (b) map of Nepal. KTM, KY, and NY denote Kathmandu (capital of Nepal), Kyangjin, and Nyalam meteorological stations, where instrumental records are available. YL and DS denote Yala and Dasuopu glaciers, where net balance records were analyzed in this study.

core on an interannual timescale. In general, it is thought to be difficult to reconstruct a paleoenvironment from a "wet ice core." In this study, however, we attempt to extract interannual change in glacier melting conditions using net balance records from different sites of the two neighboring glaciers, one exposed to melting and the other not. Since the net balance of the "wet site" consists of accumulation (solid precipitation) and ablation (melting and evaporation), the ablation record could be extracted if the accumulation record was obtained somehow. We attempt, therefore, to evaluate the glacier melting history of a "wet site," which is thought to be unsuitable for paleoclimatology, by estimating the accumulation of the site from the "dry site" of the neighboring glacier.

2. Data Used

2.1. Net Balance of Yala Glacier

[5] The Yala Glacier in the Langtang Valley is located in the central Nepal Himalayas (28°14′N, 85°37′E; YL in Figure 1). Several glaciological investigations have been carried out on this glacier since the 1980s. *Ageta et al.* [1984] and *Steinegger et al.* [1993] have analyzed photographs of crevasse walls at different altitudes. Since 1985, successive pit observations were carried out at 5350 m asl in the accumulation zone of the glacier [*Iida et al.*, 1987; *Ozawa*, 1991]. Shallow ice cores (several meters in depth) have been extracted at a neighboring altitude in 1991 [*Shiraiwa*, 1993], 1994 [*Yoshimura et al.*, 2000] and 1996 (this study). Distinct dirt layers formed during a dry season [*Iida et al.*, 1987; *Kohshima*, 1987; *Yoshimura et al.*, 2000] are utilized as clearly discernable annual markers in pits and ice cores of this glacier. Dirt layers on crevasse walls appeared more clearly than those in pit/ice cores, because the concentration of dirt materials and algal cells growing on them occurred wherever meltwater and abundant light were available [*Yoshimura et al.*, 2000]. Dirt layer spacing of crevasse walls is converted to a net balance (mm water equivalent, w.e.; Figure 2) by use of a density-depth relation of firn [*Iida et al.*, 1984]. Since ±10% scattering was found in densities at the same depth from all pit observations, the error bar due to the density assumption (±10%) is also drawn for the data from crevasse walls in the figure. The depth (22 m) at which the tritium peak of 1963 was found in the ice core drilled in 1982 [*Watanabe et al.*, 1984] coincided with the depth of the layer counted as 1963 (21.7 m) in the crevasse wall analysis by *Ageta et al.* [1984]. This implies, therefore, that the crevasse wall could be used as an alternative for an ice core as long as its dirt layer spacing can be measured precisely. Net balance in the water equivalent of the other observations (pits and ice cores) was measured in each observation. Although the deepest ice core (60 m to the bed rock) was extracted in 1982 [*Watanabe et al.*, 1984], only the density-depth relationship was used for this study since no annual layers had been detected. Depth of pits, height of crevasse walls, length of ice cores, estimated age, observed altitudes and data sources are summarized in Table 1.

[6] These net balances were obtained during different years and at different altitudes. Because deeper layers came from a higher altitude where the net balance was more positive because of less melting, corrections had to be made to take account of the glacier flow and mass balance gradient. The effects of those variables are calculated by the following equation:

$$b_c(t) = b_i(t) + \frac{\partial b}{\partial z} \times (v \times (t - t_o) \times \tan\beta - (z_o - z_c)). \quad (1)$$

Here,

$b_c(t)$ corrected net balance in a given year (mm w.e.);
$b_i(t)$ original net balance in a given year (mm w.e.);

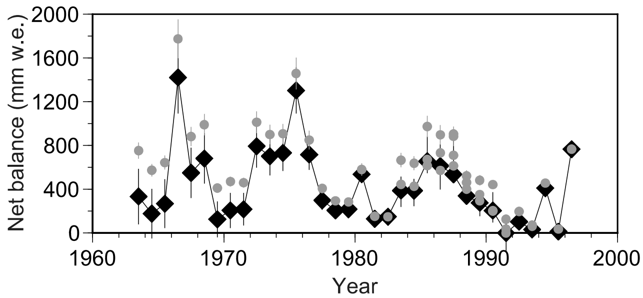

Figure 2. Temporal variations in net balance obtained by several observations (gray circles) and in corrected net balance at 5380 m asl (solid rhombuses) of Yala Glacier, Langtang Valley, Nepal Himalayas. Gray error bars are attributed to assumption of density-depth relation (±10% difference), adopted for crevasse wall observations. Black error bars show possible range of net balance attributed to assumptions with respect to glacier movement (see text).

Table 1. Data Sources for Net Balance of Yala Glacier

Year Observed	Objective	Altitude, m asl	Depth, m	Estimated Year at the Bottom of Each Observation	References
1982	ice core	5400	60.0	1912[a]	*Watanabe et al.* [1984]
1982	crevasse	5370	21.7	1963	*Ageta et al.* [1984]
1985	pit	5350	5.3	1983	*Iida et al.* [1987]
1987	pit	5350	4.5	1985	*Ozawa* [1991]
1989	crevasse	5580	12.8	1983	*Steinegger et al.* [1993]
1991	ice core	5350	6.0	1986	*Shiraiwa* [1993]
1994	ice core	5350	6.7	1987	*Yoshimura et al.* [2000]
1996	ice core	5385	10.0	1990	present study
1996	ice core	5430	10.0	1991	present study

[a]Annual layers were not detected.

$\partial b/\partial z$ net balance gradient (5 ± 1 mm w.e. m^{-1});
β slope angle above the study site ($18 \pm 2°$);
v horizontal surface flow speed above the study site (13 ± 3 m a^{-1});
t a given year;
t_o observed year for each net balance data set (year of surface layer);
z_o altitude where a net balance data set was observed (see Table 1);
z_c altitude (5380 m asl) where net balance was corrected.

[7] The net balance gradient (5 ± 1 mm w.e. m^{-1}) in the accumulation zone was obtained by mass balance measurement in 1996 [*Fujita et al.*, 1998] and the difference between the two ice cores extracted at 5385 m and 5430 m asl, respectively, in 1996. The slope angle ($18 \pm 2°$) above the site and the horizontal surface flow speed (13 ± 3 m a^{-1}) were obtained from survey observation data in 1982 and 1996 [*Yokoyama*, 1984; *Ageta et al.*, 1984; *Fujita et al.*, 1998]. Vertical strain was neglected since the depths were shallow enough (<10 m) against the glacier thickness (60 m). Temporal variations in the corrected net balance at 5380 m asl were finally calculated as shown in Figure 2, which also shows a possible range of the net balance due to the above assumptions and overlapping data. The net balance of the Yala Glacier has decreased during the last few decades (−76.8 mm w.e. per decade), showing large periodical fluctuations.

2.2. Ice Core of Dasuopu Glacier

[8] Two ice cores were extracted in 1997 at 7200 m asl from the Dasuopu Glacier located 19 km north of the Yala Glacier (28°23′N, 85°43′E; DS in Figure 1). The net balance of the Dasuopu core (C3) was obtained by counting the annual cycles of stable isotopes, dust and ions, which were well preserved under the high annual accumulation (∼1000 mm w.e.) [*Thompson et al.*, 2000]. The annual layer counting was verified at 42.2 m by the location of a 1963 beta radioactivity horizon. Few errors in the annual layer counting are expected since the present study covers only the history after the 1960s. Since no melt feature was found in the core and borehole temperatures were cold enough (−16°C at 10 m depth), the net balance record from ice cores is considered to be that of the total accumulation at the site (Figure 3). Any effect of glacier flow can be ignored since the coring site was located at the top of the glacier [*Thompson et al.*, 2000]. The accumulation at Dasuopu Glacier has decreased since the 1960s (−50.8 mm w.e. per decade). Another ice core from Mount Qomolangma (Everest) also showed the same decreasing trend in accumulation in recent years [*Hou et al.*, 1999], while no obvious long-term trend was found in measured precipitation records in Nepal [*Shrestha et al.*, 2000].

2.3. Precipitation and Air Temperature Records

[9] Meteorological data for 5 years are available at Kyangjin (28°13′N, 85°37′E, 3880 m asl; KY in Figure 1), a village at the foot of the Yala Glacier. In order to estimate the precipitation on the Yala Glacier, annual precipitation at Kyangjin is analyzed in a later chapter (circles in Figure 3). Since long-term meteorological records at high altitudes near glaciers in Nepal are few, we selected the capital city of Nepal, Kathmandu (27°42′N, 85°18′E, 1336 m asl; KTM in Figure 1), located about 70 km south of the Yala Glacier, where records of air temperature have been kept since the 1950s (Figure 4). However, it should be noted that the air temperature of Kathmandu shows a strong urban effect, which is enhanced by its location at the bottom of a basin surrounded by mountains [*Shrestha et al.*, 1999]. Therefore the grid air temperature at 500 hPa from the NCEP/NCAR reanalysis project [*Kalnay et al.*, 1996] was also used. In particular, we selected the grid point at 27.5°N, 85.0°E which includes Yala Glacier (hereafter T_{500}). In order to compare glacier melt and air temperature, boreal summer mean air temperatures (June to August, JJA) were calculated for all data (Figure 4). Data for Kyangjin are cited from *Department of Hydrology and Meteorology, Ministry of Water Resources*, HMG of Nepal [1993, 1995a], *Takahashi et al.* [1987a, 1987b], and *Fujita et al.* [1997b]. Data on air temperature at Kathmandu are

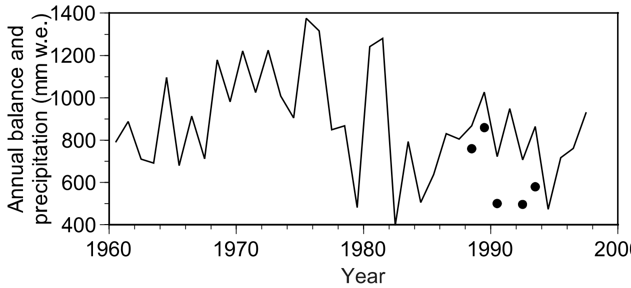

Figure 3. Temporal variations in annual balance at 7200 m asl of Dasuopu Glacier, Mount Xixabangma, Tibet (solid line), and annual precipitation at Kyangjin (3880 m asl), a village at the foot of Yala Glacier for 5 years (solid circles).

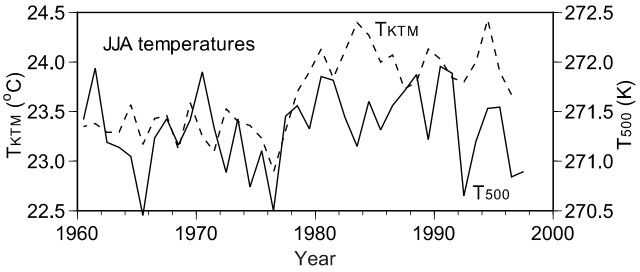

Figure 4. Temporal variations of summer mean air temperatures (June to August, JJA) at Kathmandu (T_{KTM}, dashed line) and grid air temperature (T_{500}, solid line).

cited from *Department of Irrigation, Hydrology and Meteorology, Ministry of Food, Agriculture and Irrigation*, HMG of Nepal [1977, 1982, 1984, 1986] and *Department of Hydrology and Meteorology, Ministry of Water Resources*, HMG of Nepal [1988, 1992, 1995b, 1997].

3. Accumulation on Yala Glacier

[10] The net balance consists of total accumulation (precipitation as snow) and total ablation (melt and evaporation) in the glacier mass balance. At the study site of the Yala Glacier (5380 m asl), a certain amount of melt was found during previous observations, while no melt feature was found in the ice core from the Dasuopu Glacier. The net balance record of the Yala Glacier, therefore, is most likely affected by variations in both melting condition and precipitation. In contrast, the record of the Dasuopu Glacier is thought to reflect variations only in precipitation [*Thompson et al.*, 2000; *Duan and Yao*, 2003].

[11] It is necessary to evaluate annual accumulation at the Yala Glacier in order to reconstruct a record of the melting conditions of the glacier. Although it is only a 5-year record, a relation between the precipitation at Kyangjin and the net balance of the Dasuopu Glacier shows a good linear correlation (r = 0.92 with a 95% significance level; Figure 5). Since the steep and complex topography of the Himalayas would strongly affect local precipitation, this kind of comparison should be carefully made even between short distances. *Tian et al.* [2003] compared the Dasuopu accumulation with recorded precipitation at Nyalam (28°11′N, 85°58′E, 3810 m asl; 33 km southeast from the

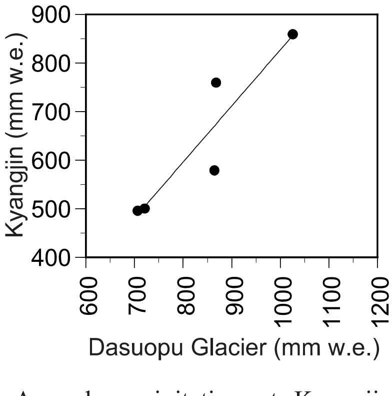

Figure 5. Annual precipitation at Kyangjin, Langtang Valley, Nepal Himalayas, versus annual accumulation obtained from ice core at 7200 m asl of Dasuopu Glacier, Tibet. The line is a linear regression line.

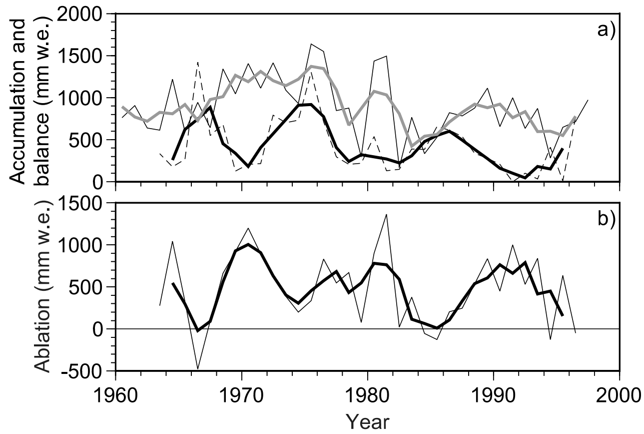

Figure 6. Temporal changes in (a) accumulation (thin solid line) and net balance (thin dashed line) and (b) ablation (thin solid line) of Yala Glacier. Three-year running means are drawn for each data with thick lines (gray for accumulation and black for net balance and ablation).

Dasuopu Glacier, NY in Figure 1) for 11 years. The correlation coefficient between them was sufficiently high (r = 0.78 with a 99% significance level). The linear relationship between the accumulation at Dasuopu Glacier and the precipitation at Kyangjin, therefore, seems to be plausible since another independent analysis also showed a linear relationship among precipitations.

[12] Since it had been found that the amount of precipitation at the Yala Glacier, which was measured by tipping bucket during the melting seasons of 1985 and 1996, was about 1.3 times more than that of Kyangjin [*Seko*, 1987; *Fujita et al.*, 1997b], we finally derived the annual amount of precipitation on Yala Glacier as $P_{YL} = 1.50\ P_{DS} - 425$. Here, P_{YL} and P_{DS} denote the annual amount of precipitation or accumulation at Yala and Dasuopu Glaciers, respectively. Temporal variations in the annual precipitation (accumulation) at Yala Glacier are obtained as shown in Figure 6a (thin solid line). According to the obtained regression lines, the accumulation at Yala Glacier has decreased since the 1960s (−76.2 mm w.e. per decade). The decreasing trends of accumulation at both glaciers suggest that the drastic shrinkage of the Yala Glacier in recent years [*Fujita et al.*, 1998] is attributable not only to warming, but also to decreasing accumulation.

4. Melt Index

[13] Since the net balance of Yala Glacier consists of accumulation (solid precipitation) and ablation (melt and evaporation), the effect of any fluctuation in accumulation has to be subtracted from the glacier net balance record in order to extract information with respect to the glacier melting condition only. Meltwater should leave the glacier since firn temperature was confirmed as 0°C even at 5380 m asl [*Watanabe et al.*, 1984], whereas it would be refrozen in a cold glacier body if the firn temperature was less than 0°C. In addition, an ice layer was formed at the boundary of the summer surface because of autumn cooling [*Iida et al.*, 1987; *Kohshima*, 1987], and meltwater could be assumed not to infiltrate into the layers formed in the previous years. Even if meltwater had infiltrated through ice layers, the

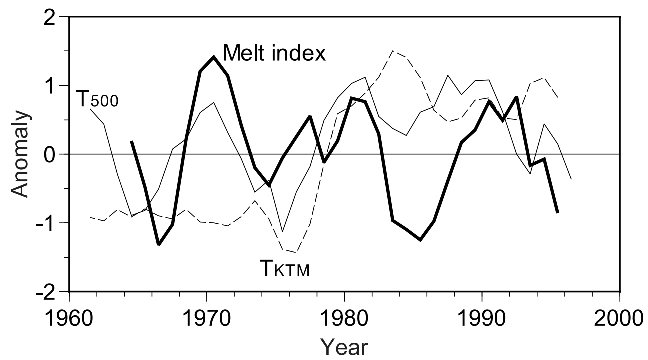

Figure 7. Three-year running mean of normalized anomalies of ablation of Yala Glacier (melt index, thick solid line), and JJA temperatures at Kathmandu (T_{KTM}, thin dashed line) and T_{500} (thin solid line).

effect would be negligible because the water content of snow has not exceeded 5% in the snow pit observations [*Iida et al.*, 1987; *Ozawa*, 1991; *Fujita et al.*, 1998]. The difference between the accumulation and net balance of Yala Glacier, therefore, is considered to be the ablation in every year (Figure 6b). In the figure, interannual fluctuations in the glacier ablation exhibit a decadal cycle with a much greater amplitude (standard deviation is 302 mm w.e.) than in the multidecadal trend (−54.7 mm w.e. per decade).

[14] This ablation, however, includes many potential errors derived from dating of annual layers, depth-density relationship, glacier flow correction, and accumulation estimation from the neighboring glacier. The amount of estimated accumulation, in particular, could be controversial because of local topographic effect on precipitation. Nevertheless, if we accept a linear relationship of precipitations between the two sites, Dasuopu and Yala Glaciers, a normalized ablation (the deviation from the mean scaled with its standard deviation) will work as a "melt index." Figure 7 shows the 3-year running mean of the melt index and anomalies of JJA air temperatures at Kathmandu (T_{KTM}) and T_{500}. Correlation coefficients of air temperatures at T_{KTM} (−0.20) and T_{500} (+0.19) against the melt index showed less relationship between the melt index and air temperatures. We note a drastic warming in the late 1970s at both T_{KTM} and T_{500}. At T_{KTM}, however, high-temperature conditions continued into the 1980s while T_{500} did not show such conditions after the 1980s. Although the record of T_{KTM} is the longest one in Nepal, this figure suggests that the temperature could well be influenced by the urban effect [*Shrestha et al.*, 1999]. In case of T_{500}, on the other hand, cooling phases appearing in the previous half-period of each decade, however, seem to coincide with the decreasing phase of the melt index. Since glacier melting conditions would be affected not only by air temperature but also by incoming solar radiation, cloud amount and surface albedo, the fluctuation of glacier melting does not always correspond to that of the air temperature on the glacier. In addition, use of reanalysis data in this region, where few observed data contributes to reanalysis, is thought to be somewhat limited [*Wu et al.*, 2005]. Considering these uncertainties in temperatures, therefore, the melt index should provide significant climatic information from a high elevation in the Himalayas, albeit there is less correlation with temperatures. Figure 7 shows that the melt index has some decadal cycles rather than any long-term trend. This implies that the shrinkage of Yala Glacier since the 1980s could be more affected by the decrease of accumulation.

5. Conclusion

[15] Using the two net balances under different conditions (one exposed to melting and the other not), the melt condition of a glacier, namely the "melt index," is extracted with the interannual timescale in the Nepal Himalayas where no long-term meteorological data are available. Although some problems would remain in the accumulation estimation and thus the estimated ablation level would not be without some degree of uncertainty, the melt index should work as a climatic index of glacier melting condition if a linear relationship exists in precipitation between a base site (such as dry ice core, meteorological station and tree ring) and an estimated site. For instance, the melt index should provide more precise information if two ice cores, one from a sufficiently higher elevation and another from a somewhat melting elevation (but higher than equilibrium line altitude), were obtained on one glacier. The melt index established for Yala Glacier showed a decadal fluctuation of great amplitude, a phenomenon that had never been detected in ice core studies in this region to date [e.g., *Yao et al.*, 1996; *Thompson et al.*, 2000]. This periodic fluctuation is also difficult to confirm from instrumental records from the lower elevation sites in Nepal [*Shrestha et al.*, 1999].

[16] Deriving climatic information from ice cores at melting sites in the Arctic region has been attempted, even though the melt could introduce time gaps and remove good seasonal signals [*Koerner*, 1997]. The distribution of melt layers and the variation of ice texture in ice cores, in particular, have been used as summer temperature proxies. However, no study in the Himalayan ice core has succeeded in reconstructing melting conditions with an interannual timescale. In particular, extracting melt information from two different sites such as performed in this study has never been attempted. Although the accumulation and ablation have been readily distinguished as winter and summer balances in European glaciology, this is not the case in glaciers in a summer monsoon climate, where both accumulation and ablation occur simultaneously during the summer melting season. Separation of accumulation and ablation from the net balance record is thus difficult for Himalayan glaciers. This new method of combining wet and dry core data is a promising approach to obtain temperature information no provided by a good-quality ice core alone in the Himalayas.

[17] **Acknowledgments.** We express our sincere thanks to the staff of the Department of Hydrology and Meteorology, Ministry of Science and Technology, HMG of Nepal. We are very indebted to the people who assisted us in this field observation in Nepal. The critical comments from anonymous reviewers significantly improved this paper. The field research was funded by a Grant-in-Aid for Scientific Research (project 13373006) from the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT). The analysis was supported by Dynamics of the Sun-Earth-Life Interactive System G-4, the 21st Century COE Program from MEXT.

References

Ageta, Y., H. Iida, and O. Watanabe (1984), Glaciological studies on Yala Glacier in Langtang Himal, in *Glacial Studies in Langtang Valley, Report of the Boring Project 1981–82 in the Nepal Himalaya*, *Publ. 2*, pp. 41–47, Data Cent. for Glacier Res., Jpn. Soc. of Snow and Ice, Tokyo.

Department of Hydrology and Meteorology, Ministry of Water Resources, HMG of Nepal (1988), *Climatological Records of Nepal, 1985–1986*, 232 pp., Kathmandu.
Department of Hydrology and Meteorology, Ministry of Water Resources, HMG of Nepal (1992), *Precipitation Records of Nepal, 1987–1990*, 253 pp., Kathmandu.
Department of Hydrology and Meteorology, Ministry of Water Resources, HMG of Nepal (1993), *Snow and Glacier Hydrology Yearbook 1987–1992*, 167 pp., Kathmandu.
Department of Hydrology and Meteorology, Ministry of Water Resources, HMG of Nepal (1995a), *Snow and Glacier Hydrology Yearbook 1993*, 55 pp., Kathmandu.
Department of Hydrology and Meteorology, Ministry of Water Resources, HMG of Nepal (1995b), *Climatological Records of Nepal, 1987–1990*, 519 pp., Kathmandu.
Department of Hydrology and Meteorology, Ministry of Water Resources, HMG of Nepal (1997), *Precipitation Records of Nepal, 1991–1994*, 272 pp., Kathmandu.
Department of Irrigation, Hydrology and Meteorology, Ministry of Food, Agriculture and Irrigation, HMG of Nepal (1977), *Climatological Records of Nepal, 1921–1975*, 129 pp., Kathmandu.
Department of Irrigation, Hydrology and Meteorology, Ministry of Water Resources, HMG of Nepal (1982), *Climatological Records of Nepal, 1976–1980*, 410 pp., Kathmandu.
Department of Irrigation, Hydrology and Meteorology, Ministry of Water Resources, HMG of Nepal (1984), *Climatological Records of Nepal, 1981–1982*, 174 pp., Kathmandu.
Department of Irrigation, Hydrology and Meteorology, Ministry of Water Resources, HMG of Nepal (1986), *Climatological Records of Nepal, 1983–1984*, 187 pp., Kathmandu.
Duan, K., and T. Yao (2003), Monsoon variability in the Himalayas under the condition of global warming, *J. Meteorol. Soc. Jpn.*, *81*, 251–257.
Fujita, K., M. Nakawo, Y. Fujii, and P. Paudyal (1997a), Changes in glaciers in Hidden Valley, Mukut Himal, Nepal Himalayas, from 1974 to 1994, *J. Glaciol.*, *42*, 583–588.
Fujita, K., A. Sakai, and T. B. Chhetri (1997b), Meteorological observation in Langtang Valley, 1996, *Bull. Glacier Res.*, *15*, 71–78.
Fujita, K., N. Takeuchi, and K. Seko (1998), Glaciological observations of Yala Glacier in Langtang Valley, Nepal Himalayas, 1994 and 1996, *Bull. Glacier Res.*, *16*, 75–81.
Fujita, K., F. Nakazawa, and B. Rana (2001a), Glaciological observations on Rikha Samba Glacier in Hidden Valley, Nepal Himalayas, 1998 and 1999, *Bull. Glaciol. Res.*, *18*, 31–35.
Fujita, K., T. Kadota, B. Rana, R. B. Kayastha, and Y. Ageta (2001b), Shrinkage of Glacier AX010 in Shorong region, Nepal Himalayas in the 1990s, *Bull. Glaciol. Res.*, *18*, 51–54.
Fujita, K., F. Nakazawa, N. Takeuchi, M. Nakawo, B. Rana, N. Azuma, and Y. Fujii (2002), Ice core drilling on the southern slope of Nepal Himalayas, *Mem. Natl. Inst. Polar Res.*, *56*, 59–66.
Hou, S., D. Qin, C. P. Wake, and P. A. Mayewski (1999), Abrupt decrease in recent snow accumulation at Mount Qomolangma (Everest), Himalaya, *J. Glaciol.*, *45*, 585–586.
Iida, H., O. Watanabe, and M. Takikawa (1984), First results from Himalayan Glacier Boring Project in 1982–1982: Part II, Studies on internal structure and transformation process from snow to ice of Yala Glacier, Langtang Himal, Nepal, in *Glacial Studies in Langtang Valley, Report of the Boring Project 1981–82 in the Nepal Himalaya*, *Publ. 2*, pp. 25–33, Data Cent. for Glacier Res., Jpn. Soc. of Snow and Ice, Tokyo.
Iida, H., Y. Endo, S. Kohshima, H. Motoyama, and O. Watanabe (1987), Characteristics of snowcover and formation process of dirt layer in the accumulation area of Yala Glacier, Langtang Himal, Nepal, *Bull. Glacier Res.*, *5*, 55–62.
Kadota, T., K. Fujita, K. Seko, R. B. Kayastha, and Y. Ageta (1997), Monitoring and prediction of shrinkage of a small glacier in the Nepal Himalaya, *Ann. Glaciol.*, *24*, 90–94.
Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.
Kang, S., C. P. Wake, D. Qin, P. A. Mayewski, and T. Yao (2000), Monsoon and dust signals recorded in the Dasuopu Glacier, Tibetan Plateau, *J. Glaciol.*, *46*, 222–226.
Koerner, R. M. (1997), Some comments on climatic reconstructions from ice cores drilled in areas of high melt, *J. Glaciol.*, *43*, 90–97.
Kohshima, S. (1987), Formation of dirt layers and surface dust by microplant growth in Yala (Dakpatsen) Glacier, Nepal Himalayas, *Bull. Glacier Res.*, *5*, 63–68.
Ozawa, H. (1991), Thermal regime of a glacier in relation to glacier ice formation, Doctoral thesis, 51 pp., Hokkaido Univ., Sapporo, Japan.
Qin, D., P. A. Mayewski, C. P. Wake, S. Kang, J. Ren, S. Hou, T. Yao, Q. Yang, Z. Jin, and D. Mi (2000), Evidence for recent climate change from ice cores in the central Himalaya, *Ann. Glaciol.*, *31*, 153–158.
Seko, K. (1987), Seasonal variation of altitudinal dependence of precipitation in Langtang Valley, Nepal Himalayas, *Bull. Glacier Res.*, *5*, 41–47.
Shiraiwa, T. (1993), Glacial fluctuations and cryogenic environments in the Langtang Valley, Nepal Himalaya, Doctoral thesis, 227 pp., Hokkaido Univ., Sapporo, Japan.
Shrestha, A. B., C. P. Wake, P. A. Mayewski, and J. E. Dibb (1999), Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971–94, *J. Clim.*, *12*, 2775–2786.
Shrestha, A. B., C. P. Wake, J. E. Dibb, and P. A. Mayewski (2000), Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters, *Int. J. Climatol.*, *21*, 317–327.
Steinegger, U., L. N. Braun, G. Kappenberger, and G. Tratari (1993), Assessment of annual snow accumulation over the past 10 years at high elevations in the Langtang region, *IAHS Publ.*, *218*, 155–165.
Takahashi, S., H. Motoyama, K. Kawashima, Y. Morinaga, K. Seko, H. Iida, H. Kubota, and N. R. Turadahr (1987a), Meteorological features in Langtang Valley, Nepal Himalayas, 1985–1986, *Bull. Glacier Res.*, *5*, 35–40.
Takahashi, S., H. Motoyama, K. Kawashima, Y. Morinaga, K. Seko, H. Iida, H. Kubota, and N. R. Turadahr (1987b), Summary of meteorological data at Kyangchen in Langtang Valley, Nepal Himalayas, *Bull. Glacier Res.*, *5*, 121–128.
Thompson, L. G., T. Yao, E. Mosley-Thompson, M. E. Davis, K. A. Henderson, and P.-N. Lin (2000), A high-resolution millennial record of the South Asian Monsoon from Himalayan ice cores, *Science*, *289*, 1916–1919.
Tian, L. D., T. D. Yao, A. Numaguti, and W. Z. Sun (2001), Stable isotope variations in monsoon precipitation on the Tibetan Plateau, *J. Meteorol. Soc. Jpn.*, *79*, 959–966.
Tian, L. D., T. D. Yao, P. F. Schuster, J. W. C. White, K. Ichiyanagi, E. Pendall, J. Pu, and Y. Wu (2003), Oxygen-18 concentrations in recent precipitation and ice cores on the Tibetan Plateau, *J. Geophys. Res.*, *108*(D9), 4293, doi:10.1029/2002JD002173.
Yamada, T., T. Shiraiwa, H. Iida, T. Kadota, O. Watanabe, B. Rana, Y. Ageta, and H. Fushimi (1992), Fluctuations of the glaciers from the 1970s to 1989 in the Khumbu, Shorong and Langtang regions, Nepal Himalayas, *Bull. Glacier Res.*, *10*, 11–19.
Yao, T., L. G. Thompson, E. Mosley-Thompson, Z. Yang, X. Zhang, and P.-N. Lin (1996), Climatological significance of δ^{18}O in north Tibetan ice cores, *J. Geophys. Res.*, *101*(D23), 29,531–29,537.
Yokoyama, K. (1984), Ground photogrammetry of Yala Glacier, Langtang Himal, Nepal Himalaya, in *Glacial Studies in Langtang Valley, Report of the Boring Project 1981–82 in the Nepal Himalaya*, *Publ. 2*, pp. 99–105, Data Cent. for Glacier Res., Jpn. Soc. of Snow and Ice, Tokyo.
Yoshimura, Y., S. Kohshima, N. Takeuchi, K. Seko, and K. Fujita (2000), Himalayan ice core dating with snow algae, *J. Glaciol.*, *46*(153), 335–340.
Watanabe, O., S. Takenaka, H. Iida, K. Kamiyama, K. B. Thapa, and D. Mulmi (1984), First results from Himalayan Glacier Boring Project in 1982–1982: Part I. Stratigraphical analyses of full-depth cores from Yala Glacier, Langtang Himal, Nepal, in *Glacial Studies in Langtang Valley, Report of the Boring Project 1981–82 in the Nepal Himalaya*, *Publ. 2*, pp. 7–23, Data Cent. for Glacier Res., Jpn. Soc. of Snow and Ice, Tokyo.
Wu, R. G., J. L. Kinter III, and B. P. Kirtman (2005), Discrepancy of interdecadal changes in the Asian region among the NCEP-NCAR reanalysis, objective analysis, and observations, *J. Clim.*, *18*, 3048–3067.
Wushiki, H. (1977), Deuterium content in the Himalayan precipitation at Khumbu district, observed in 1974/1975, *J. Jpn. Soc. Snow Ice*, *39*, 50–56.
Zhang, X., M. Nakawo, K. Fujita, T. Yao, and J. Han (2001), Variation of precipitation δ^{18}O in Langtang Valley, Himalayas, *Sci. China D*, *44*, 769–778.

Y. Ageta, K. Fujita, and A. Sakai, Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan. (cozy@nagoya-u.jp)

Y. Kajikawa, International Pacific Research Center, Pacific Ocean Science and Technology Building, Room 401, University of Hawaii, 1680 East-West Road, Honolulu, HI 96822, USA.

N. Takeuchi, Research Institute for Humanity and Nature, 457-4 Kamigamo-motoyama, Kita-ku, Kyoto 603-0878, Japan.

L. G. Thompson, Byrd Polar Research Center, Ohio State University, Scott Hall Room 108, 1090 Carmack Road, Columbus, OH 43210-1002, USA.

T. Yasunari, Hydrospheric Atmospheric Research Center, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan.