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Seasonal changes in dissolved chemical composition and flux of meltwater draining from Lirung Glacier in the Nepal Himalayas

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Abstract Glacier meltwaters were sampled at approximately weekly intervals at the outlet of the debris-covered glacier, Lirung Glacier (28°12.9'N, 86°39.9'E; 4000 m a.m.s.l.), in the Nepal Himalayas from 16 May (pre-monsoon) to 26 October (post-monsoon) 1996. The average water discharge during the monsoon period (19 June–13 September) was 2.85±0.35 times higher than that during the pre- and post-monsoon periods. During the monsoon period the average TDS concentration was lower (0.57 times) and the average daily TDS flux was higher (1.63±0.23 times) than during the pre- and post-monsoon periods. The major cation and anion compositions in equivalent l^{-1} were $Ca^{2+} >> Mg^{2+} \geq Na^+ \geq K^+ >> NH_4^+$ and $Alk > SO_4^{2-} >> NO_3^- > Cl^-$, respectively. The composition of the major species was, however, quite constant throughout the observed period. The dominance of Ca^{2+}, Alk and SO_4^{2-} indicates that sulphide oxidation coupled with carbonate dissolution is the dominant chemical weathering processes occurring within the subglacial drainage system of this glacier as widely observed in other alpine glacierized basins. The monsoon season affected the weathering fluxes of solutes through the enhanced meltwater mass but not the weathering mechanism(s) within the subglacial drainage system of the glacier.

INTRODUCTION

Meltwaters from mountain glaciers of the Himalayas are one of the dominant water resources for Nepal. Understanding the associated geochemical processes for the development of their chemical composition is important. Glaciological and meteorological observations on glaciers and climate in the Nepal Himalayas have been carried out since 1973, and the Langtang Valley has been under observation since 1980 through the Glaciological Expedition of Nepal (Higuchi *et al.*, 1982). However, there are only limited data on the chemical composition of glacier meltwaters, pond waters and ice cores in the Nepal Himalayas (Watanabe *et al.*, 1984; Kamiyama, 1984; Reynolds *et al.*, 1995). There have been no measurements of seasonal changes in glacier meltwaters in the Nepal Himalayas although these data have been reported for other Himalayan areas (Hasnain & Thayyen, 1999; Collins, 1999). This study was undertaken to observe seasonal changes and fluxes of major chemical constituents in

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glacier meltwaters from the debris-covered glacier, Lirung Glacier. Data acquired through the pre- to post-monsoon season indicate that the principal weathering processes controlling the chemical composition of the glacier meltwaters is sulphide oxidation coupled with carbonate dissolution as widely observed in other alpine glacierized basins. The effect of surface debris cover on the chemical composition of discharge waters seems to be not significant.

STUDY AREA

Lirung Glacier (28°12.9′N, 86°39.9′E) is located 60 km north of Kathmandu in the Langtang Valley and is the headwater area of the Langtang–Narayani River system. Figure 1 shows a topographical map of Lirung Glacier basin (Sakai *et al.*, 1997). The
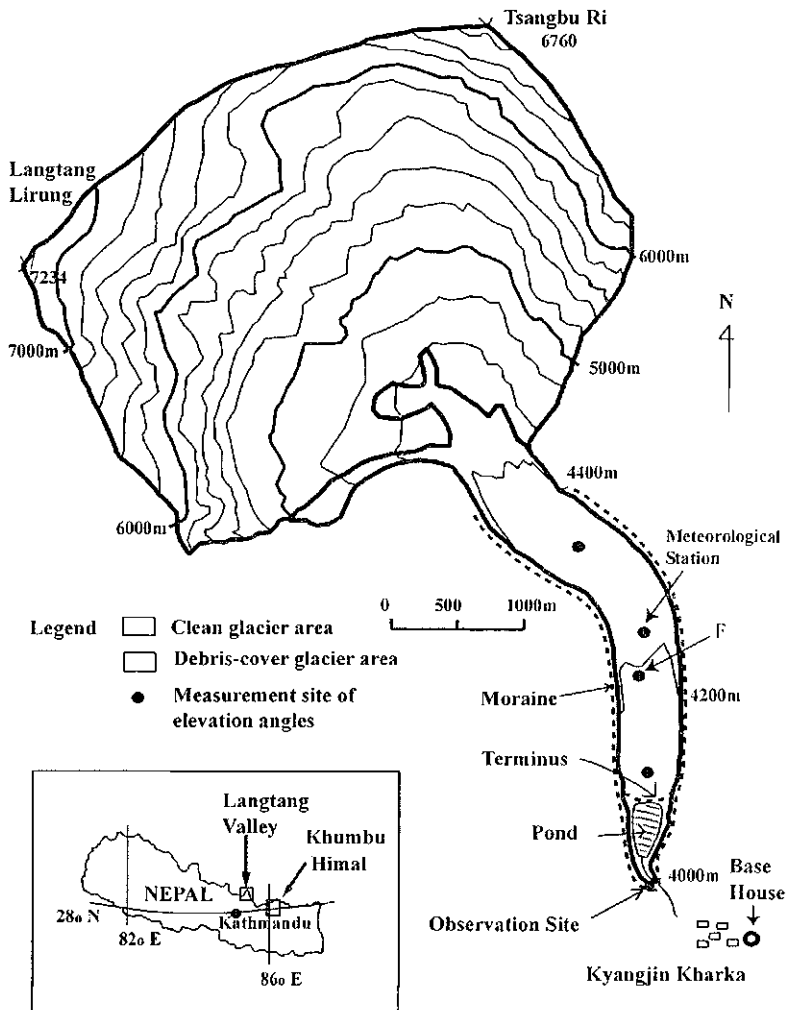

Fig. 1 Topographic map of Lirung Glacier basin in the Nepal Himalayas (after Sakai *et al.*, 1997).

altitude of the Lirung Himal is 7234 m and the lowest point of the basin, the outlet, is 4000 m a.m.s.l. The total area of the drainage basin is 13.8 km^2, of which 33% is steep bedrock walls, 16% debris-covered glacier and the remaining 51% debris-free ice (Fukushima *et al.*, 1987). Geologically, the Langtang Lirung area lies in a complex transition zone between the High Himalayan metasediments (south) and the Tethyan sedimentary series (north). The lithology mainly consists of high-grade metamorphic rocks with traces of igneous rocks including migmatites, gneisses, schists, phyllites and granites (Inger & Harris, 1992).

MATERIALS AND METHODS

Discharge waters were sampled at approximately weekly intervals from 16 May to 26 October 1996 at the outlet of Lirung Glacier (Fig. 1), as a part of the Cryosphere Research Expedition in the Himalayas in 1996 (Nakawo *et al.*, 1997; Fujita *et al.*, 1997; Sakai *et al.*, 1997). Hourly measurements of physical variables and tri-hourly sampling for chemical analyses were carried out for 30 h on 30–31 May and 29–30 September 1996 at the outlet to examine diurnal changes. Discharge at the outlet was observed from 8 May to 25 October 1996 except for a period from 29 June to 5 July (Sakai *et al.*, 1997). Daily precipitation was observed at the debris-covered area of Lirung Glacier (P_{LR}; 4190 m a.m.s.l.) and at Kyanjing Base House (P_{BH}; 3880 m a.m.s.l.; Fig. 1). Meteorological variables were measured during the same calendar interval in 1996 (Fujita *et al.*, 1997).

Each water sample was filtered with a pre-weighed 25-mm or 47-mm GELMAN Supor polyethersulfone filter with a 0.2-μm pore size by using a hand vacuum pump or a syringe just after sampling. The filter with the residue was stored in a petrislide. The filtrate was stored in a pre-washed Milli-Q-water-filled 50-ml polyethylene (PE) bottle for major species analyses (non-acidified) and a pre-washed 50-ml PE bottle filled with ultra-pure water prepared by sub-boiling distillation and added 0.5 ml of 6M HCl for PO$_4$-P and trace element analyses (acidified). The non-acidified samples were stored in a refrigerator and the acidified samples at room temperature until chemically analysed. Air temperature, water temperature, electrical conductivity (EC; Horiba B-173) and pH (Horiba B-212) of discharge waters were measured at the time of sampling.

Analytical methods used for the water samples were as follows: Suspended sediment (SS) was weighed with the filter after drying in a vacuum oven at 60°C for 48 h. Major cations (Na$^+$, K$^+$, Mg^{2+}, Ca^{2+} and NH$_4^+$) and anions (Cl$^-$, NO$_2^-$, NO$_3^-$ and SO$_4^{2-}$) were determined by cation (DIONEX DX-100) and anion (DIONEX QIC) chromatography, respectively, relative to IAPSO international standard seawater as well as to standard solutions prepared from analytical reagents. Alkalinity (Alk) was determined by acid titration, and dissolved silica (SiO$_2$) and PO$_4$-P spectrophotometrically (Hitachi 124) by the standard molybdenum blue methods. Detection limits for SS and Alk were 1 mg l^{-1} and 1 μequivalent (μeq) l^{-1}, respectively, and analytical errors were <2% for Cl$^-$, NO$_3^-$, SO$_4^{2-}$, Na$^+$, K$^+$, Mg^{2+}, Ca^{2+} and SiO$_2$, <4% for NH$_4^+$ and <5% for PO$_4$-P. The analysis of a few blank solutions kept in washed PE bottles, which were carried to Nepal and then back to Japan, indicated that

contamination of these chemical species was negligibly small during the processes of storage and transportation.

RESULTS AND DISCUSSION

Physical variables and chemical composition of the discharge waters are listed in Table 1 and shown in Figs 2 and 3. The monsoon season in 1996 was from 19 June (Julian day 170) to 13 September (Julian day 257) according to the precipitation data (Fujita *et al.*, 1997).

Two 30-h periods of hourly observations, one in May and one in September 1996, showed that discharge maxima occurred in the evening and minima in the morning. The ratios of maximum to minimum discharge were 1.38 and 2.13, respectively. Tri-hourly variations in concentrations and relative proportions of major dissolved species were, however, small compared with the large variation in discharge.

The concentrations of all measured dissolved species were lower during the monsoon period than those in the pre- and post-monsoon periods (Fig. 3). Conversely, daily discharge fluxes of these species were higher during the monsoon period than those in the pre- and post-monsoon periods (Fig. 4). The major cation and anion compositions in eq l^{-1} (Fig. 3) are $Ca^{2+} >> Mg^{2+} \geq Na^{+} \geq K^{+} >> NH_4^{+}$ and $Alk > SO_4^{2-} >> NO_3^{-} > Cl^{-}$, respectively, and Ca^{2+}, Alk, most of which is as HCO_3^{-}, and SO_4^{2-} are the dominant ions.

For discussion below, the observation period is divided into three periods, pre- (9 May to 18 June; 41 days), actual (87 days) and post- (14 September to 25 October; 42 days) monsoon. Averages calculated and discussed below refer to these intervals.

Precipitation over Lirung Glacier basin (P_{LG}) is estimated based on altitude dependency of precipitation and area fractions for altitude zones (Rana *et al.*, 1997) as a function of P_{BH} (Fujita *et al.*, 1997). The P_{LG} value is separated into precipitation as snow (P_{SN}) and that as rain (P_{RA}) based on an air temperature of 2°C (Ageta *et al.*, 1980) set at an altitude estimated from the daily air temperature observed at Kyanjing Base House (Fujita *et al.*, 1997) and a laps rate of –0.6°C per 100 m. Cumulative P_{LG}, P_{SN} and P_{RA} values for the pre-, actual and post-monsoon periods in 1996 are given in Table 2. The estimated average percentages of P_{SN} relative to P_{LG} are 89, 69 and 89% for the pre-, actual and post-monsoon periods, respectively. Cumulative precipitation through the observed period (170 days) was 852 mm and accounts for 36% of cumulative discharge (2344 mm; Table 2). Since most of the annual precipitation and melting occur during this period, this suggests a strongly negative mass balance for Lirung Glacier similar to observations at Glacier AX010 in the east Nepal Himalayas (Kadota *et al.*, 1997).

Discharge (V_D) is given by the sum of meltwater (V_M) and rain (V_{RA}). Evaporation can be neglected due to very low temperature (Fukushima *et al.*, 1987). Changes in water storage are unknown, but are assumed to be negligible. Average concentration of species *i* in meltwater as a result of chemical weathering within the glacier system (C_{Mi}) is estimated by using a mass balance equation:

$$C_{Mi} = (V_D\,C_{Di} - V_{RA}\,C_{RAi})/V_M \tag{1}$$

Table 1 Seasonal changes in discharge, air temperature (T_a), water temperature (T_w), pH, electrical conductivity (EC), suspended sediment (SS) and chemical compositions of discharge waters at the outlet of Lirung Glacier from 16 May to 26 October 1996.

| Name	Date	Time	Julian day	Discharge* (10^3 m^3 day^{-1})	T_a (°C)	T_w (°C)	pH	EC (µS cm^{-1})	SS (mg l^{-1})	Na (µmol l^{-1})	NH_4 (µmol l^{-1})	K (µmol l^{-1})	Mg (µmol l^{-1})	Ca (µmol l^{-1})	Cl (µmol l^{-1})	NO_3 (µmol l^{-1})	SO_4 (µmol l^{-1})	Alk (µeq l^{-1})	PO_4 (µmol l^{-1})	SiO_2 (µmol l^{-1})	ΣAnion (µeq l^{-1})	ΣCation (µeq l^{-1})
LO-1	16/5/96	14:55	137	74.8	11.7	7.1	-	38	-	40.1	0.5	27.2	21.3	160.5	5.0	24.6	71.0	217	0.02	47.4	388	431
LO-2	17/5/96	11:00	138	66.4	9.4	5.1	7.2	28	-	37.8	0.4	27.7	20.4	154.3	4.5	24.1	67.4	213	0.02	46.0	376	415
LO-3	17/5/96	16:00	138	66.4	6.9	5.0	7.1	28	-	38.6	0.0	27.1	20.8	158.8	4.2	25.1	69.0	245	0.05	47.6	413	425
LO-4	18/5/96	08:00	139	75.2	5.4	0.7	-	34	-	36.9	0.0	27.1	20.3	152.9	4.1	24.5	65.8	201	0.01	45.6	362	410
LO-5	22/5/96	08:35	143	70.3	-	1.7	7.9	47	148	38.2	0.4	26.5	20.9	152.6	5.4	25.8	68.0	192	0.01	46.8	359	412
LO-6	22/5/96	15:10	143	70.3	-	5.6	8.1	50	42	40.3	1.9	26.7	21.2	154.7	7.2	25.6	68.2	204	0.07	47.3	374	421
LO-7	23/5/96	17:30	144	62.3	-	-	7.3	43	97	35.5	4.8	24.9	19.6	145.2	4.4	25.2	64.1	192	0.02	45.0	350	395
LO-8	26/5/96	09:30	147	120.9	-	2.9	6.4	30	375	28.2	2.2	23.2	14.1	107.1	7.6	21.9	42.1	145	0.02	32.5	259	296
LO-9	29/5/96	08:05	150	91.0	-	-	7.3	33	308	34.3	5.6	23.0	14.5	112.2	12.0	21.6	44.0	151	0.07	32.2	273	316
LO-10	30/5/96	09:00	151	76.4	-	3.6	7.1	34	158	28.8	1.0	22.1	15.7	120.1	5.0	24.5	50.0	160	0.05	36.7	290	324
LO-18	31/5/96	09:00	152	67.0	-	1.3	7.8	37	93	30.8	0.3	22.7	17.3	129.6	4.6	25.2	55.8	158	0.09	40.0	299	348
LO-21	02/6/96	09:35	154	62.6	-	-	7.6	42	93	35.3	0.4	23.2	18.9	140.9	4.2	26.5	61.3	178	0.00	44.9	331	379
LO-22	04/6/96	09:00	156	61.9	-	1.6	8.2	47	48	44.5	0.6	26.3	22.0	160.3	7.0	26.2	71.9	204	0.00	49.9	381	436
LO-23	06/6/96	13:30	158	70.8	-	-	7.6	52	218	51.7	0.4	28.8	23.8	174.1	8.3	24.8	80.6	235	0.00	56.6	429	477
LO-24	12/6/96	08:15	164	105.4	11.6	2.5	-	27	101	26.9	0.0	20.4	15.3	114.2	4.9	20.2	46.8	146	0.20	34.9	265	306
LO-25	16/6/96	-	168	126.5	-	-	-	-	122	20.7	0.0	17.7	12.6	97.6	3.0	21.0	36.2	124	0.00	29.4	221	259
LO-26	19/6/96	09:00	171	253.3	-	-	7.5	23	321	16.2	1.8	17.4	10.4	86.1	3.1	18.7	30.0	109	0.00	26.9	191	228
LO-27	29/6/96	11:00	181	-	8.3	2.3	8.5	25	115	14.4	0.8	14.0	9.0	74.7	2.2	12.5	26.7	92	0.00	23.1	161	196
LO-28	05/7/96	08:00	187	-	7.6	1.0	8.4	17	84	19.6	1.8	15.4	11.4	90.9	2.6	13.1	35.2	114	0.00	28.4	200	241
LO-29	13/7/96	07:50	195	299.1	8.2	0.8	8.6	20	140	14.0	1.3	14.3	8.9	72.7	1.8	8.8	24.7	94	0.00	23.3	153	193
LO-30	20/7/96	07:50	202	282.5	10.2	1.1	8.9	15	112	14.5	0.2	13.7	8.9	74.1	1.8	7.5	26.0	95	0.00	23.8	156	194
LO-31	28/7/96	10:05	210	365.3	11.8	2.2	8.4	20	86	14.8	1.1	13.2	8.9	74.2	1.8	6.9	26.2	97	0.00	23.1	158	195
LO-32	06/8/96	08:10	219	318.1	9.9	1.0	-	20	81	15.5	0.4	13.0	9.7	79.7	1.7	6.7	27.5	104	0.00	24.0	167	208
LO-33	13/8/96	08:50	226	386.0	10.7	1.0	-	14	436	12.9	0.0	14.2	8.4	70.9	1.5	5.6	26.8	96	0.00	21.1	157	186
LO-34	20/8/96	08:10	233	244.6	10.6	1.1	-	26	74	20.4	1.0	15.2	11.9	95.9	1.8	7.1	38.4	139	0.00	31.3	225	252
LO-35	26/8/96	09:30	239	199.0	-	-	-	31	71	24.8	0.5	17.5	13.9	108.1	2.0	7.6	46.8	151	0.00	35.9	254	287
LO-36	02/9/96	08:20	246	271.1	7.3	1.1	-	26	66	20.2	0.4	15.8	12.0	95.0	2.2	6.9	39.0	129	0.00	30.3	216	250
LO-37	09/9/96	11:20	253	212.1	9.8	5.2	-	28	60	24.1	0.0	17.3	13.9	108.2	2.3	7.5	46.8	144	0.00	35.3	247	286
LO-38	15/9/96	10:25	259	137.9	13.7	4.5	-	33	69	28.4	1.3	19.0	16.3	121.9	2.3	8.5	53.7	168	0.00	40.1	286	325
LO-39	22/9/96	07:30	266	140.1	7.4	1.2	-	33	64	30.3	1.3	20.0	16.4	121.8	2.9	10.2	53.4	168	0.00	40.2	288	328
LO-40	28/9/96	16:15	272	205.6	7.9	0.5	7.9	35	120	22.1	0.0	16.5	13.0	104.2	3.0	11.8	43.9	141	0.00	29.6	243	273
LO-41	29/9/96	09:00	273	182.3	11.7	2.8	7.8	27	63	23.5	0.2	16.8	13.4	106.5	2.9	11.5	43.4	142	0.00	28.2	244	280
LO-49	30/9/96	09:00	274	122.4	8.4	−0.6	7.8	46	39	32.8	0.4	20.2	16.0	124.6	5.1	12.8	53.9	177	0.02	41.6	302	335
LO-53	04/10/96	11:45	278	73.3	5.6	−0.3	7.5	57	29	41.6	0.0	24.5	21.7	157.1	5.8	13.5	74.0	227	0.00	53.7	394	424
LO-54	06/10/96	13:30	280	96.4	5.7	3.1	7.8	53	41	37.5	0.0	24.0	19.9	149.1	3.9	12.0	66.4	223	0.00	50.8	372	400
LO-55	06/10/96	14:30	280	96.4	6.1	1.4	8.3	53	67	44.1	1.5	25.4	20.3	151.2	10.1	12.8	67.4	224	0.01	51.4	382	414
LO-56	13/10/96	08:40	287	73.0	7.4	1.5	8.4	42	11	42.9	0.5	25.4	22.8	162.0	3.7	11.3	76.4	228	0.01	52.7	396	438
LO-57	19/10/96	14:30	293	87.4	9.7	5.3	9.6	42	15	47.2	0.5	26.6	24.1	172.8	4.1	8.8	82.5	231	0.09	54.4	409	468
LO-58	26/10/96	09:10	300	64.2	1.2	0.7	10.4	31	52	55.1	0.4	30.0	26.8	192.9	5.1	13.3	93.8	286	0.01	61.9	492	525

* Sakai *et al.* (1997).
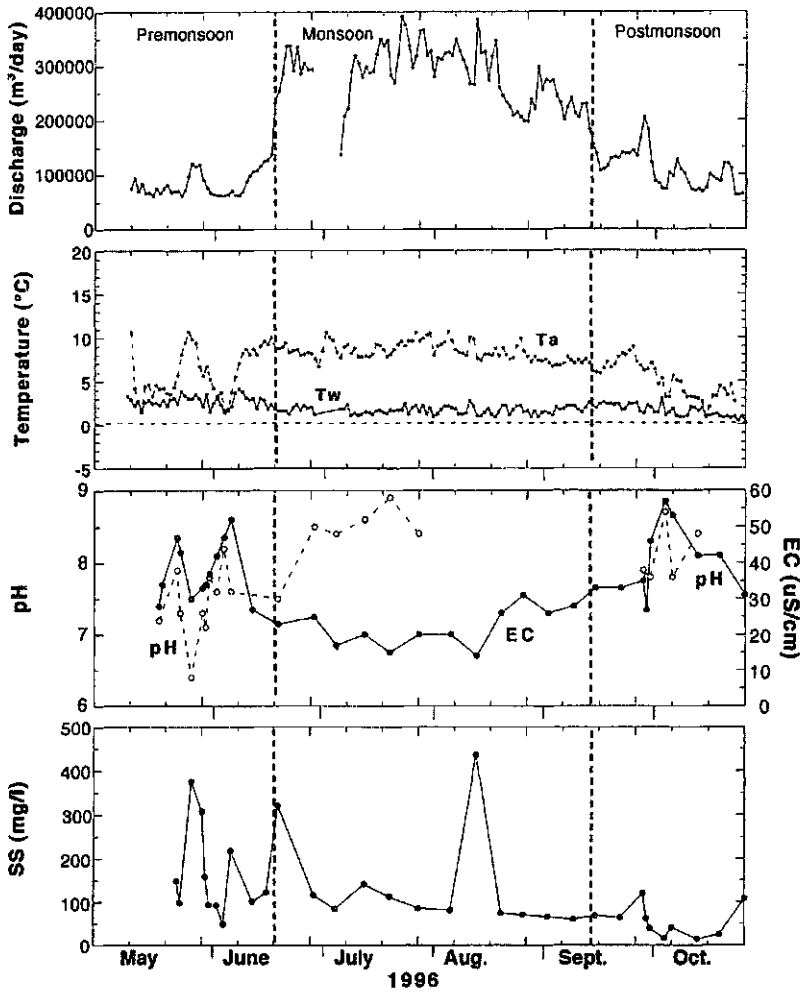
Fig. 2 Seasonal variations of discharge (Sakai *et al.*, 1997), water and air temperature, pH, electrical conductivity (EC) and concentration of suspended sediment (SS) of discharge waters at the outlet of Lirung Glacier in the Nepal Himalayas from May to October 1996.

where C_{Di} and C_{RAi} are average concentrations of species i in discharge water and rainwater, respectively. The C_{RAi} values as well as those of snow (C_{SNi}) for the pre-, actual and post-monsoon periods are assumed to be equal to average concentrations of snow pit samples collected at Yala Glacier (5450 m a.m.s.l.) on 20 May (245 cm deep), 3 August (158 cm deep) and 9 October (200 cm deep) 1996, respectively (Bhatt *et al.*, unpublished data). The C_{Di} (observed), C_{SNi} and C_{RAi} (assumed) and C_{Mi} (estimated) values for the three periods in 1996 are listed in Table 2. Average daily fluxes of dissolved species in discharge, rain and melt waters are estimated by multiplying the average concentrations with cumulative volumes of discharge, rain and melt waters, respectively, for the three periods, and are also shown in Table 2.

The average daily water discharge during the monsoon period was 3.2 and 2.5 times higher than those of pre- and post-monsoon periods, respectively (Table 2). The average

TDS concentration during the monsoon period was lower (0.57 times) than those during the pre- and post-monsoon periods. The average daily TDS flux during the monsoon period was 1.86 and 1.46 times higher than those during the pre- and post-monsoon periods. The total discharge of TDS through the observed period (170 days) was 597 t, and that during the monsoon period (87 days) was 63% of the total discharge (Table 2). The contributions of dissolved species from rain to discharge water were less than 1% by mass except for NH_4^+ (25%) and Cl^- (2.3%). This indicates that dissolved species in the discharge waters were derived from chemical weathering within the subglacial drainage system (Tranter *et al.*, 1993). During the monsoon period, the concentrations
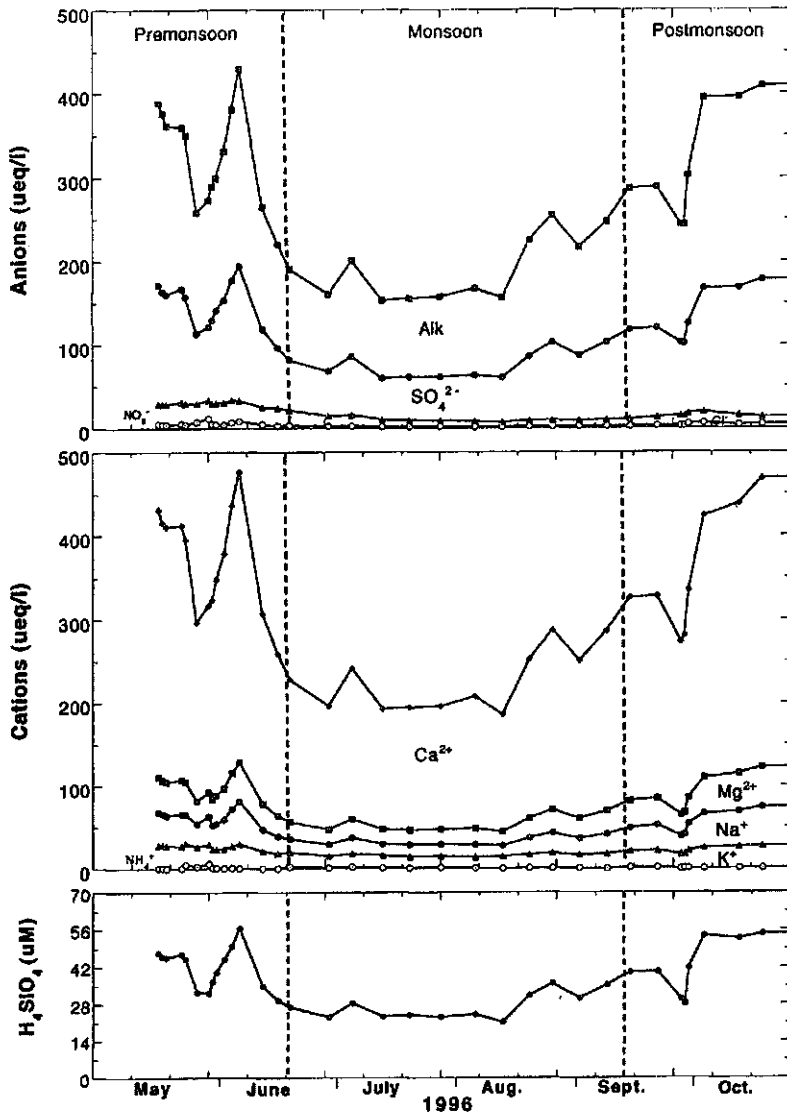

Fig. 3 Seasonal variations of concentrations of major anions (μeq l^{-1}), major cations (μeq l^{-1}) and dissolved silica (μmol l^{-1}) in discharge waters at the outlet of Lirung Glacier in the Nepal Himalayas from May to October 1996.
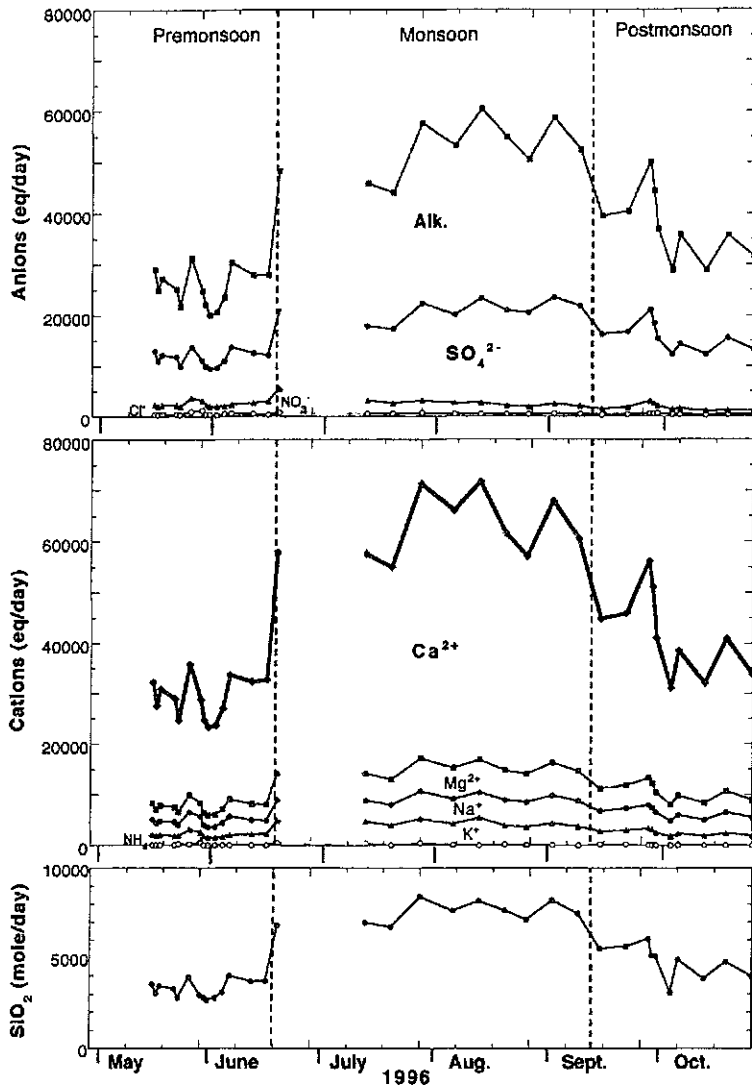
Fig. 4 Seasonal variations of discharge fluxes of anions, cations (eq day^{-1}) and dissolved silica (moles day^{-1}) at the outlet of Lirung Glacier in the Nepal Himalayas from May to October 1996.

were lower than those of the pre- and post-monsoon periods mainly by dilution from enhanced melting and rainfall (Fukushima *et al.*, 1987; Rana *et al.*, 1997). However, weathering activity was much higher during the monsoon period due to the larger melting water mass.

The dominance of Ca^{2+}, Alk and SO_4^{2-} in glacier meltwaters has been widely observed and considered to be due to sulphide oxidation (SO) coupled with calcium carbonate dissolution (CD) within the subglacial drainage system (Tranter & Raiswell, 1991; Tranter *et al.*, 1993; Hasnain & Thayyen, 1999). Linear relationships of cation and anion concentrations *vs* sulphate concentration (Tranter & Raiswell, 1991) are also observed at the outlet of Lirung Glacier.

Table 2 Water fluxes, average concentrations, daily average fluxes and sum of daily fluxes of eleven chemical species at the outlet of Lirung Glacier during the pre-monsoon (9 May to 18 June), monsoon (19 June to 13 September) and post-monsoon (14 September to 25 October) periods in 1996.

Season	Period (day)	Water flux (10^3 m^3 day^{-1})	Water flux (mm day^{-1})	Na	NH$_4$	K	Mg	Ca	Cl	NO$_3$	SO$_4$	Alk (eq)	PO$_4$	SiO$_2$	ΣAnion (eq)	ΣCation (eq)	TDS (kg)
Concentrations (μmol l^{-1} or μeq l^{-1})																	
Discharge																	
Pre-monsoon	41	87.0	6.31	35.5	1.1	24.7	18.7	139.7	5.7	24.2	60.1	185.3	0.04	42.7	335.5	378.1	
Monsoon	87	277.8	20.13	17.6	0.8	15.1	10.6	85.9	2.1	9.1	32.8	113.6	0.00	27.2	190.4	226.4	
Post-monsoon	42	109.6	7.94	38.2	0.6	23.1	19.7	145.8	4.6	11.5	66.5	207.3	0.01	47.6	356.5	392.9	
*Snow**																	
Pre-monsoon	41	14.4	1.35	0.55	4.08	0.27	0.16	2.47	1.03	2.12	0.67	0.00	0.02	0.14	4.5	10.2	
Monsoon	87	74.5	5.42	0.72	2.11	0.24	0.04	0.43	0.68	0.17	0.04	0.00	0.00	0.07	0.9	4.0	
Post-monsoon	42	34.5	2.32	0.07	0.07	0.06	0.02	0.04	0.40	0.72	0.10	0.00	0.00	0.05	1.3	0.3	
*Rain**																	
Pre-monsoon	41	1.8	0.18	0.55	4.08	0.27	0.16	2.47	1.03	2.12	0.67	0.00	0.02	0.14	4.54	10.16	
Monsoon	87	32.7	2.43	0.72	2.11	0.24	0.04	0.43	0.68	0.17	0.04	0.00	0.00	0.07	0.94	4.01	
Post-monsoon	42	4.3	0.20	0.07	0.07	0.06	0.02	0.04	0.40	0.72	0.10	0.00	0.00	0.05	1.32	0.33	
Meltwater																	
Pre-monsoon	41	85.2	6.12	36.3	1.1	25.2	19.0	142.6	5.8	24.6	61.4	189.1	0.0	43.6	342.4	385.7	
Monsoon	87	245.1	17.69	19.9	0.6	17.0	12.0	97.3	2.3	10.3	37.2	128.7	0.0	30.8	215.6	256.0	
Post-monsoon	42	105.3	7.74	39.8	0.6	24.1	20.5	151.7	4.8	11.9	69.3	215.8	0.0	49.6	371.0	408.9	
Daily fluxes (mol day^{-1} or eq day^{-1})																	
Discharge																	
Pre-monsoon	41	87.0	6.31	3 093	100	2 146	1 624	12 156	496	2 103	5 233	16 120	3.4	3 713	29 193	32 899	2 541
Monsoon	87	277.8	20.13	4 890	213	4 185	2 944	23 851	575	2 523	9 121	31 545	0.0	7 560	52 884	62 877	4 739
Post-monsoon	42	109.6	7.94	4 189	66	2 538	2 164	15 980	503	1 261	7 296	22 731	1.6	5 224	39 090	43 081	3 388
Sum	170	32 339	2 344	728 164	25 377	558 728	413 567	3 244 575	91 511	358 685	1 314 523	4 360 017	208	1 029 372	7 439 674	8 628 552	658 794
Rain																	
Pre-monsoon	41	1.8	0.18	1.0	7.2	0.5	0.3	4.4	1.8	3.7	1.2	0.0	0.0	0.2	8.0	18.0	1.13
Monsoon	87	32.7	2.43	23.4	69.0	7.8	1.3	14.2	22.2	5.5	1.4	0.0	0.0	2.2	30.6	131.1	4.20
Post-monsoon	42	4.3	0.20	0.3	0.3	0.3	0.1	0.2	1.7	3.1	0.4	0.0	0.0	0.2	5.7	1.4	0.22
Sum	170	3 096	228	2 086	6 31	711	126	1 418	2 080	765	192	0.0	1.3	215	3 233	12 198	421
Meltwater																	
Pre-monsoon	41	85.2	6.12	3 092	93	2 146	1 624	12 152	494	2 100	5 232	16 120	3.4	3 713	29 185	32 881	2 540
Monsoon	87	245.1	17.69	4 866	144	4 178	2 942	23 837	553	2 517	9 120	31 545	0.0	7 558	52 854	62 746	4 735
Post-monsoon	42	105.3	7.74	4 189	65	2 538	2 164	15 980	502	1 258	7 295	22 731	1.6	5 224	39 085	43 079	3 387
Sum	170	29 243	2 116	726 078	19 062	558 017	413 441	3 243 157	89 431	357 919	1 314 330	4 360 017	206	1 029 158	7 436 441	8 616 353	658 374

* Average concentrations of snow and rain are assumed to be equal to those of pit work snow samples from Yala Glacier (5450 m a.s.l) sampled at respective seasons in 1996 as shown in the text.

Figure 5 shows seasonal variations of relative proportions of anions to the sum of anions, those of cations to the sum of cations, and SiO_2/Alk ratio. They were quite constant throughout the pre- to post-monsoon period in 1996. For example, average relative proportions (+1 SD) of Alk, SO_4^{2-}, NO_3^- and Cl^- were 57.4 ± 2.5%, 35.6 ± 2.1%, 5.5 ± 2.2% and 1.43 ± 0.67%, respectively, and those of Ca^{2+}, Mg^{2+}, Na^+, K^+ and NH_4^+ were 74.6 ± 1.2%, 9.7 ± 0.4%, 8.9 ± 1.0%, 6.5 ± 0.6% and 0.29 ± 0.37%, respectively. The constancy of chemical composition of meltwaters throughout the pre- to post-monsoon period suggests that the principal chemical weathering processes are not changed by the enhanced melting during the monsoon period.
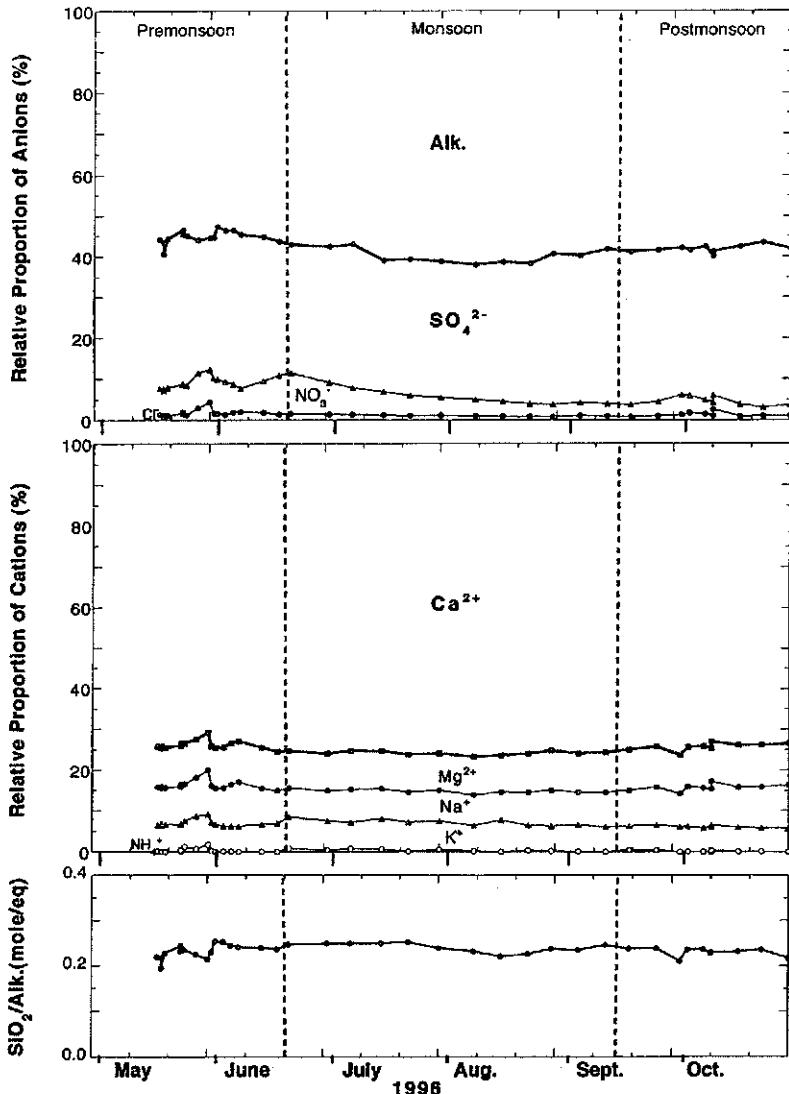
Fig. 5 Seasonal variations of relative proportions of anions (%), those of cations (%) and SiO_2/Alk ratio in discharge waters at the outlet of Lirung Glacier in the Nepal Himalayas from May to October 1996.

Impurities in pond waters on the debris-covered surface of Lirung Glacier showed that most of them were much more dilute than in the discharge waters (Masuzawa *et al.*, paper in preparation). Weathering of the surface debris may be relatively slow compared to the fresh rock flower introduced into the water at the base of the glacier. Furthermore, Rana *et al.* (1997) suggested the melting within the debris-covered area was about 10% of total melting of Lirung Glacier. So the effect of surface debris cover on the chemical composition of discharge water of Lirung Glacier seems to be not significant.

The cationic denudation rate (CDR) of the Lirung Glacier basin is estimated to be 740 meq m^{-2} year^{-1} based on assumptions that the water discharge from November to April is 12% of the annual discharge (Fukushima *et al*, 1987) and that average concentrations of dissolved species in discharge waters from November to April are equal to the average values for the pre- and post-monsoon periods in 1996 (Table 2). The estimated CDR for Lirung Glacier is about 1/6 of CDR found for Dokriani Glacier, Garhwal Himalayas, India, but is similar to CDR for European and North American glaciers (Hasnain & Thayyen, 1999).

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