Statistical Analyses of the Forms of the Glaciers in the Khumbu Himal*

Yoshiyuki Fujii** and Keiji Higuchi***

Abstract

Statistical analyses were performed on the relation between the glacier forms and the topographic conditions of the glacier basins, using an inventory of the glaciers in the Khumbu Himal where climatic conditions can be considered as nearly uniform in the Great Himalayas.

An apparent difference was found between the dimensions of glaciers without debris (C-type glaciers) and those covered with debris (D-type glaciers), the latter being 15 times larger in area and 5 times longer in length on the average.

The correlation between the dimensions of glaciers and their basins is better in the case of glaciers covered with ablation moraine than glaciers without ablation moraine. The large-sized glaciers, having large area, long length, and high upper limit, develop in bigger basins with higher summits, longer basin ridges and wider valleys. However the positions of the lower limits of the glaciers are independent of the dimensions of the glacier basin.

There are good correlations between glacier area and basin area, and between debris covered area and rock face area. Therefore, it would be reasonable to consider that the total precipitation in the area of basin above the firn line controls the size of the glacier, and the debris on the glacier surface were supplied from the rock face of the basin.

After multiple regression analysis by forward selection, elements representing the form of the glaciers were related to elements representing the form of the basins by a regression equation.

1. Introduction

Various types and forms of the glaciers in the Himalayas indicate that multiple conditions of both climates and landforms affect on glacier formation. But, since the climatic conditions can be considered as nearly uniform in a small area, the topographical conditions of glacier basins are predominant factors to decide glacier forms and types in that area.

The Khumbu region in eastern Nepal Himalayas was chosen for a study on the relationship between the forms of the glaciers and those of the glacier basins for several reasons: (a) this test area covers the highest mountain group, including Mt. Sagarmatha (Everest, 8848m), Mt. Lotse

(8510m) and Mt. Cho Oyu (8153m) and is one of the most glacierized areas in the Nepal Himalayas; (b) various field studies were carried out on the glaciers and climates and a large number of photographs were taken during the expedition; (c) maps of different scale are available; (d) a pilot study for an inventory of the glaciers was reported by Müller (1970).

This paper discusses preliminary results of the statistical analyses of the forms of the glaciers in connection with the forms of glacier basins.

2. Inventory of the glaciers and their basins

As a part of the IHD 1965-1974, the International Commission of Snow and Ice (ICSI) of the International Association of Scientific Hydrology (IASH) prepared the report "Perennial ice and snow masses; a guide for compilation and assemblage of data for a world inventory" (Unesco/IASH, 1970), in which an inventory of glaciers in the Mount Sagarmatha (Everest) region was reported by Müller (1970) as one of the pilot studies.

An inventory of glaciers in a small area where

* *Glaciological Expedition of Nepal, Contribution No. 31*

** *Water Research Institute, Nagoya University (present address, National Institute of Polar Research, Kaga 1-9, Itabashi-ku, Tokyo 173)*

*** *Water Research Institute, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464*

Fig. 1. Index map of the glacier inventory of Khumbu Himal. Quoted From Müller (1970).

climatic conditions are nearly uniform can be used for a study of the relation between glacier form and the topographical conditions of the basins in which the glaciers lie.

For such a study, ten elements which seem to represent glacier form and eight elements to represent glacier basins were selected as follows.

a) Elements of glacier form

- G 1 Upper limit (m)
- G 2 Lower limit (m)
- G 3 'Exposed' limit
- G 4 Debris covered area (km²)
- G 5 Total area (km²)
- G 6 Length (m)

- G 7 Debris covered area ratio (G4/G5) (%)
- G 8 Altitudinal range (G1-G2), (m)
- G 9 Gradient (G8/G6)
- G10 Square root of total area (m)

b) Elements of glacier basin

- T 1 Maximum height (m)
- T 2 Length of ridge above 5500m (m)
- T 3 Width of basin at 5500m (m)
- T 4 Area of basin above 5500m (km²)
- T 5 Area of rock face above 5500m (km²)
- T 6 Basin shape index (T2/T3)
- T 7 Rock face area ratio (T5/T4), (%)

Measurements of the above mentioned elements of glaciers and their basins were carried out

	G 1	G 2	G 3	G 4	G 5	G 6	G 7	G 8	G 9	G 10
C 1	4940	4640	4540	0.00	0.16	200	0	300	1.50	400
C 2	5240	4700	4700	0.00	0.20	500	0	540	1.00	529
C 3	5100	4620	4620	0.00	0.25	600	0	480	0.80	500
C 4	5060	5460	5460	0.00	0.23	400	0	500	1.25	479
C 5	5300	4300	4470	1.16	5.31	4000	21	1660	0.41	2304
C 6	5200	4899	4960	0.00	0.15	900	0	300	0.33	387
C 8	6100	5160	5160	0.16	2.04	1400	7	940	0.52	1428
C 9	6100	5119	5119	0.00	0.43	900	0	979	1.00	699
C 10	5360	5040	5040	0.00	0.24	600	0	320	0.54	489
C 11	5400	4809	4899	0.00	1.06	1200	0	580	0.48	1029
C 12	5860	5400	5400	0.00	0.04	200	0	450	2.30	200
C 13	5600	4410	4490	0.52	2.09	3300	24	1190	0.36	1445
C 14	5760	4960	4960	0.00	0.38	1100	0	800	0.72	616
C 15	5840	5100	5100	0.00	0.80	1100	0	740	0.67	894
C 16	5690	5100	5100	0.00	1.00	1400	0	580	0.41	1000
C 17	5800	5259	5259	0.00	1.51	2000	0	540	0.27	1228
C 18	5860	5160	5160	0.00	1.37	5000	0	700	0.23	1170
C 19	5600	5280	5280	0.00	0.82	1500	0	320	0.21	905
C 21	5850	4850	5130	2.35	6.97	7300	33	1000	0.13	2640
C 22	6200	5300	5300	0.00	0.71	1400	0	900	0.64	842
C 23	5630	5410	5410	0.00	0.38	1400	0	270	0.19	616
C 24	5600	5390	5390	0.00	0.18	500	0	210	0.42	424
C 25	5740	5160	5240	0.70	2.61	4500	26	620	0.13	1615
C 27	5760	5369	5390	0.12	0.62	1400	19	390	0.27	787
C 28	6600	5020	5250	3.45	5.65	8500	61	1580	0.18	2376
C 29	5700	5340	5340	0.00	0.19	1000	40	440	0.44	435
C 30	5600	5270	5270	0.00	0.20	600	0	330	0.55	447
C 31	5600	5420	5420	0.00	0.09	400	0	180	0.45	299
C 32	5520	5300	5300	0.00	0.48	900	0	220	0.24	699
C 33	6900	4500	5119	13.40	30.30	19200	44	2400	0.12	5504
C 34	6000	5440	5440	0.00	0.24	600	0	560	0.93	489
C 35	5880	5310	5310	0.00	0.50	1500	0	570	0.43	707
C 36	5680	5259	5259	0.00	0.51	1400	0	420	0.30	714
C 37	6200	5350	5350	0.00	0.24	1000	0	850	0.85	509
C 38	5630	5310	5310	0.00	0.04	500	0	320	0.64	282
C 39	5390	5220	5220	0.00	0.14	700	0	170	0.24	374
C 40	5460	5310	5310	0.00	0.07	500	0	150	0.30	264
C 41	5460	5350	5350	0.00	0.07	500	0	130	0.24	264
C 42	5650	5450	5450	0.00	0.10	600	0	200	0.33	316
C 43	5610	5380	5380	0.00	0.15	400	0	230	0.57	387
C 44	5840	5480	5480	0.00	0.71	1600	0	360	0.22	842
C 45	7200	4840	5210	5.66	14.54	9500	38	2360	0.24	3813
C 46	5580	5230	5230	0.00	0.30	350	0	350	0.24	565
C 47	5380	5119	5119	0.00	0.29	600	0	260	0.43	538
C 48	5650	5390	5390	0.00	0.06	300	0	260	0.86	244
C 49	5950	5240	5240	0.00	0.55	1400	0	710	0.50	741
C 50	5880	5600	5600	0.00	0.09	400	0	280	0.70	299
C 51	5640	5320	5320	0.00	0.31	600	0	320	0.53	556
C 52	5650	5240	5240	0.00	0.15	600	0	400	0.66	587
C 53	5690	5190	5190	0.00	0.12	500	0	290	0.58	346
C 54	5855	5440	5440	0.00	0.17	600	0	415	0.69	412
C 55	5650	5240	5240	0.00	0.14	800	0	410	0.51	400
C 56	5800	5340	5340	0.00	0.22	1000	0	460	0.46	469
C 57	5880	5020	5020	0.00	0.47	1300	0	860	0.66	685
C 58	5700	5360	5360	0.00	0.07	400	0	340	0.85	264
C 59	5450	5100	5100	0.00	0.09	400	0	260	0.65	299
C 60	5600	5210	5210	0.00	0.17	600	0	390	0.65	412
C 61	5380	5200	5200	0.00	0.06	200	0	180	0.90	244
C 62	5700	5350	5350	0.00	0.17	500	0	350	0.70	412
C 63	5560	5340	5340	0.00	0.06	300	0	220	0.73	244
C 64	5520	5100	5100	0.00	0.18	600	0	420	0.70	424
C 65	5540	5270	5270	0.00	0.13	900	0	270	0.30	360
C 66	5800	5380	5380	0.00	0.35	700	0	420	0.60	599
C 67	5880	5350	5350	0.00	1.29	1800	0	530	0.29	1135
C 68	5440	5280	5280	0.00	0.04	400	0	160	0.53	200
D 1	5590	5080	5080	0.00	0.11	500	0	500	1.00	331
D 2	5620	5100	5240	0.03	0.14	800	18	520	0.65	400
D 3	5720	5280	5280	0.00	0.05	500	0	440	0.88	223
D 4	5960	5140	5180	0.24	1.34	2700	20	820	0.30	1174
D 5	5400	5060	5119	0.03	0.09	500	33	340	0.68	299
D 6	5400	4940	4940	0.06	0.15	600	40	460	0.76	387
D 7	5680	5140	5140	0.07	1.03	1500	6	540	0.36	1014
D 8	5520	5300	5300	0.00	0.06	400	0	220	0.55	244
D 9	5620	5180	5180	0.04	0.46	1500	6	440	0.29	678
D 10	5640	5300	5300	0.00	0.90	1500	0	340	0.22	948
D 11	5680	5340	5340	0.00	0.59	1300	0	340	0.26	768
D 12	5720	5420	5420	0.00	0.24	1000	0	500	0.30	489
D 13	5520	5300	5300	0.00	0.10	300	0	220	0.73	316
D 14	5820	5540	5540	0.00	0.06	600	0	280	0.46	844
D 15	5680	5360	5360	0.00	0.11	400	0	320	0.53	331
D 16	5560	5310	5310	0.00	0.94	1800	0	250	0.13	969
D 17	5520	5350	5350	0.00	0.04	400	0	170	0.42	282
D 19	6100	5320	5320	0.00	0.84	1400	0	780	0.55	927
D 20	7200	4690	5009	20.57	63.33	21000	32	2510	0.11	7958
D 21	6059	5330	5330	0.00	0.57	1800	0	730	0.40	754
D 22	5600	5240	5240	0.00	0.59	1000	0	360	0.36	768
D 23	5600	5590	5590	0.00	0.15	500	0	210	0.42	387
D 24	5600	5480	5480	0.00	0.10	700	0	120	0.17	316
D 26	5470	5380	5380	0.00	0.15	800	0	90	0.11	387
D 27	6300	5000	5259	4.51	13.17	10500	34	1300	0.12	3629
D 28	5520	5180	5180	0.00	0.64	1700	0	340	0.20	800
D 29	5800	5390	5390	0.00	0.35	1000	0	410	0.41	591
D 30	6000	5480	5480	0.00	0.15	500	0	520	1.04	387
D 31	5540	5270	5270	0.00	0.07	500	0	270	0.54	264
D 32	5480	5000	5080	0.06	0.37	900	16	480	0.53	608
D 33	5600	5020	5020	0.00	0.54	1000	0	580	0.58	748
D 34	5450	5180	5180	0.00	0.04	300	0	270	0.90	200
D 35	5500	4880	5119	1.04	1.72	3100	60	620	0.20	1311
D 36	5600	4800	5100	1.13	1.37	2400	82	800	0.28	1170
D 37	5320	5090	5090	0.00	0.14	900	0	230	0.25	374

Fig. 2. Inventory of the glaciers in the Khumbu region, Bhote Kosi and Dudh Kosi.

E 1	6542	2000	1100	0.58	0.35	1.81	60
E 2	6542	2000	900	0.48	0.38	2.22	79
E 3	6542	2500	1300	0.64	0.48	1.92	75
E 4	6440	3900	1100	0.93	0.80	3.54	64
E 5	6440	1500	1100	0.35	0.20	1.36	57
E 6	6440	2300	1100	0.25	0.08	2.09	32
E 7	5939	1800	1000	0.25	0.18	1.80	72
E 8	5729	1000	700	0.18	0.13	1.42	72
E 9	5865	1600	800	0.25	0.18	2.00	72
E 10	6169	4000	700	1.18	0.48	5.71	40
E 11	6169	2000	800	0.48	0.18	2.50	37
E 12	6145	1900	700	0.45	0.13	2.71	28
E 13	6145	2600	1400	0.53	0.25	1.85	47
E 14	6119	2100	900	0.43	0.05	2.33	11
E 15	6145	4800	1000	1.20	0.53	4.80	44
E 16	5980	1800	600	0.25	0.18	3.00	72
E 17	6853	13400	2000	6.93	2.85	6.80	58
E 18	6549	3000	1000	0.70	0.55	3.00	78
E 19	7145	9300	1600	6.01	1.38	5.81	22
E 20	6119	2100	900	0.48	0.20	2.33	41
E 21	7145	3800	700	1.05	0.48	5.42	45
E 22	7145	3600	500	0.75	0.08	7.20	10
E 23	8848	26500	3500	32.60	7.48	7.57	22
E 24	5965	3000	1400	0.63	0.35	2.14	55
E 25	5880	4000	1600	0.97	0.40	2.50	40
E 26	5806	1000	600	0.40	0.25	1.66	62
E 27	5820	3800	1700	1.18	0.38	2.23	32
E 28	5796	1500	800	0.30	0.13	1.87	43
E 29	5880	2300	700	0.58	0.40	3.26	68
E 30	7879	8700	1700	4.83	2.95	5.11	61
E 31	6040	2200	700	0.43	0.33	3.14	76
E 32	5860	1500	600	0.28	0.13	2.50	46
E 33	7800	6000	2500	3.49	1.43	5.20	40
E 34	5775	1900	1100	0.16	0.03	1.72	18
E 35	6280	2400	500	0.58	0.13	4.40	17
E 36	8501	11100	2300	7.93	3.01	4.82	37
E 37	6149	3500	1800	1.48	0.43	1.94	29
E 38	6169	3000	2300	2.20	1.30	1.30	59
E 39	8383	21900	3400	16.21	5.75	6.44	35
E 40	6466	3600	2100	1.40	0.50	1.71	35
E 41	6835	9700	1600	3.38	1.60	4.12	47
E 42	6205	1200	300	0.20	0.10	4.00	50
E 43	6238	2000	1500	0.48	0.18	1.33	37
E 44	6430	6600	3000	2.93	0.13	2.20	4
E 45	6856	6000	1800	1.70	0.73	3.33	42
E 46	6856	3100	2000	0.68	0.20	1.55	29
E 47	6040	600	700	0.11	0.07	0.85	63
E 48	6856	3200	1600	0.95	0.33	2.00	34
E 49	6856	2600	800	0.88	0.63	4.25	71
E 50	6856	7100	2200	3.63	0.83	3.22	22
E 51	6571	8000	2500	3.93	0.85	3.20	21
E 52	6000	2500	1700	0.25	0.13	1.47	52
E 53	6077	2200	900	0.43	0.35	2.44	81
E 54	6077	1700	1100	0.15	0.15	1.57	45
E 55	6080	2000	500	0.35	0.25	4.00	71
E 56	6040	2100	1000	0.40	0.25	2.10	62
E 57	6440	1400	700	0.30	0.05	2.00	16
E 58	6440	2000	700	0.23	0.08	2.85	34
E 59	6865	5200	1900	1.38	0.50	2.73	16
E 60	6608	2400	1000	0.58	0.10	2.40	17
E 61	6346	2000	1300	0.33	0.08	1.53	24

Fig. 3. Inventory of the glaciers in the Khumbu region, Imja Khola.

carefully on maps of the drainage basin of the individual glacier shown in the map of Khumbu Himal (1: 50,000; Schneider, 1965).

The numbering system of the glaciers in the area studied is the same as Unesco/Iash (1970) by the use of the index map with glacier number by Müller (1970) which is shown in Fig. 1.

The 'inactive' ice aprons, frequent above the bergschrund, are included in the glacierized area in the guide for the glacier inventory of Unesco/Iash (1970), however, such inactive ice aprons as fluted walls are considered to be separate from the glacier in this paper. The upper limit of a glacier (G1) was considered to be the highest position of the boundary between the active glacier and inactive ice aprons or snow walls, using aerial or terrestrial photographs and maps (Schneider, 1957 and 1965).

Length of glacier (G6) was measured on the map from the terminus to the upper limits along the center lines of the glacier.

G7 to G10 were calculated by computer using compiled data G1~G6.

Since the smaller areas are more frequent, square root of glacier area (G10) is used as an index of glacier size as well as the procedure by Nogami (1968).

On the other hand, the elements of the glacier basin are measured on the map of the area above 5500m, which corresponds nearly to the lower limit of precipitation in the form of snow during the warmest season, and is often about 1 ~200m below the firn line and the boundary between the steep wall and gentle slope. Therefore, the area of the basin above 5500m seems to be suitable when considering a glacier basin from a view point of accumulation in this study.

The length of the 5500m contour line (T3) is assumed to approximate the width of the basin at that altitude. The rock face area (T5) is considered in order to examine its effect on the covering of the glacier by debris, and the basin shape index (T6;=T2/T3) is chosen as an index of the effect of the basin shape on the gathering and concentrating of snow to feed the glacier.

The computer print-out sheets of inventory

	T 1	T 2	T 3	T 4	T 5	T 6	T 7
C 1	5400	0	0	0.00	0.00	0.00	0
C 2	6187	3000	2100	0.00	0.18	1.42	20
C 3	6119	1600	1100	0.30	0.05	1.45	16
C 4	6500	3600	2700	1.23	0.83	1.33	67
C 5	6718	10200	4500	4.40	0.83	2.26	18
C 6	5673	400	150	0.03	0.00	2.66	0
C 8	6940	7900	2100	3.63	0.93	3.71	25
C 9	6179	2100	1000	0.45	0.03	2.10	6
C 10	6059	1600	800	0.28	0.05	2.00	17
C 11	6650	4500	2100	1.30	0.40	2.14	30
C 12	6010	1000	600	0.18	0.13	1.66	72
C 13	6940	6500	2000	3.13	1.00	3.25	31
C 14	6640	3100	700	0.66	0.23	4.42	34
C 15	6362	3500	1100	0.90	0.35	3.18	38
C 16	6362	4600	1100	1.00	0.95	4.18	59
C 17	6293	4700	1600	1.93	0.97	2.93	50
C 18	6293	4500	1000	0.95	0.18	4.50	18
C 19	5967	3500	1600	0.73	0.50	2.18	68
C 21	6801	14800	2900	6.50	2.99	5.10	45
C 22	6320	3000	1000	0.95	0.33	3.00	34
C 23	6000	4000	1000	0.65	0.18	4.00	27
C 24	5800	2200	600	0.35	0.25	3.66	71
C 25	6716	7900	1100	3.30	1.53	7.18	46
C 27	6716	4500	1400	1.08	0.80	3.21	74
C 28	6846	9000	1500	3.90	1.75	6.00	46
C 29	5855	1200	500	0.18	0.12	2.40	66
C 30	5777	1000	300	0.08	0.00	3.33	0
C 31	5777	1800	500	0.13	0.00	3.60	61
C 32	5666	1200	1200	0.10	0.03	1.00	30
C 33	7352	27000	6600	27.15	7.29	4.09	26
C 34	6777	2600	1300	0.95	0.50	2.00	52
C 35	6797	4600	1400	1.20	0.65	3.28	54
C 36	6236	3400	900	0.70	0.50	3.77	71
C 37	6296	2500	800	0.40	0.10	3.12	25
C 38	5680	1700	500	0.18	0.13	3.40	72
C 39	6790	15500	600	0.18	0.18	2.50	100
C 40	5790	1600	700	0.15	0.15	2.28	100
C 41	5680	1500	700	0.10	0.10	2.14	100
C 42	5820	2600	1100	0.63	0.53	2.36	84
C 43	6296	3100	1000	0.75	0.50	3.10	66
C 44	6800	6300	1900	1.98	0.96	3.31	48
C 45	7352	10800	4000	10.38	2.28	2.65	21
C 46	5720	2100	900	0.18	0.13	2.33	72
C 47	5845	1400	1400	0.10	0.10	1.28	100
C 48	5927	1000	500	0.13	0.05	2.00	38
C 49	5977	2700	1400	0.45	0.10	1.92	22
C 50	5977	1600	800	0.25	0.20	2.00	80
C 51	5860	900	800	0.20	0.10	1.12	50
C 52	5740	1000	600	0.10	0.03	1.66	30
C 53	5855	900	1200	0.13	0.10	0.75	76
C 54	5947	1500	900	0.28	0.13	1.66	46
C 55	5905	1900	800	0.33	0.18	2.37	54
C 56	5949	3600	1200	0.45	0.28	2.50	62
C 57	6185	2500	1400	0.30	0.20	1.78	40
C 58	6185	1500	500	0.18	0.08	3.00	44
C 59	5970	1500	700	0.23	0.23	2.14	100
C 60	5880	2000	800	0.20	0.08	2.50	40
C 61	5845	1000	500	0.10	0.03	2.00	30
C 62	5845	2000	1600	0.45	0.23	1.25	51
C 63	5960	500	400	0.03	0.01	1.25	33
C 64	5590	400	400	0.08	0.01	1.00	12
C 65	5673	800	500	0.03	0.02	1.60	66
C 66	5880	2000	700	0.58	0.20	2.85	34
C 67	5185	4400	1000	1.58	0.53	4.40	33
C 68	5590	700	400	0.05	0.03	1.75	60
D 1	5726	600	900	0.05	0.03	0.66	60
D 2	6185	2100	900	0.25	0.18	2.33	64
D 3	6185	1600	300	0.40	0.23	5.33	76
D 4	6073	5800	1800	1.60	0.78	3.22	48
D 5	6073	1800	700	0.23	0.15	2.57	65
D 6	5977	2000	1200	0.45	0.30	1.66	86
D 7	5977	2100	2000	0.34	0.30	1.05	76
D 8	5678	400	200	0.02	0.02	2.00	100
D 9	5947	1900	1500	0.38	0.13	1.26	34
D 10	5977	4000	1600	0.85	0.33	2.50	38
D 11	5815	2800	1200	0.55	0.20	2.33	36
D 12	5815	2100	1000	0.40	0.10	2.10	25
D 13	5613	1000	900	0.13	0.12	1.11	92
D 14	5977	1500	700	0.23	0.08	2.14	34
D 15	5845	1000	600	0.30	0.20	3.16	96
D 16	5845	3800	1500	0.63	0.43	2.53	68
D 17	5600	600	300	0.05	0.00	2.00	0
D 19	6500	3400	1400	1.38	0.40	2.42	28
D 20	6153	27000	7900	50.75	11.44	4.53	22
D 21	6086	2900	1200	0.60	0.20	2.41	33
D 22	5913	3100	1500	0.60	0.10	2.06	16
D 23	5913	2800	300	0.31	0.15	9.33	50
D 24	5957	2600	300	0.50	0.20	8.66	36
D 26	5947	1500	700	0.24	0.13	2.14	78
D 27	7020	19500	3800	11.40	4.25	5.13	35
D 28	5845	3700	1700	0.58	0.23	2.17	39
D 29	6013	2800	700	0.55	0.20	4.00	36
D 30	6049	2600	1400	0.53	0.24	1.85	52
D 31	6049	1400	900	0.25	0.22	1.55	88
D 32	5737	1100	900	0.45	0.28	1.22	84
D 33	6440	3800	1300	0.85	0.13	2.92	15
D 34	5706	700	600	0.05	0.03	1.16	60
D 35	6367	5500	1700	1.18	0.33	3.23	27
D 36	6542	4500	1700	1.60	0.60	2.64	60
D 37	5600	600	500	0.02	0.02	1.20	100

Fig. 4. Inventory of the glacier basins in the Khumbu region, Bhote Kosi and Dudh Kosi.

E 1	5500	5280	5280	0.00	0.05	400	0.00	220	0.55	223
E 2	5400	5100	5100	0.00	0.33	900	0.00	300	0.33	574
E 3	5200	4880	4880	0.89	1.27	2400	70.07	620	0.22	1126
E 4	5600	5020	5020	0.00	0.24	800	0.00	580	0.72	529
E 5	5600	5040	5040	0.00	0.05	500	0.00	360	0.72	223
E 6	5300	4740	4840	0.20	0.32	1200	62.50	620	0.51	565
E 7	5620	5100	5100	0.00	0.17	800	0.00	520	0.65	412
E 8	5560	5160	5160	0.00	0.10	500	0.00	400	0.80	316
E 9	5560	5280	5280	0.00	0.41	1400	0.00	280	0.20	640
E 10	5670	5180	5180	0.00	0.95	2000	0.00	480	0.24	974
E 11	5600	5300	5300	0.00	0.19	700	0.00	300	0.42	435
E 12	5600	5160	5160	0.00	0.20	800	0.00	440	0.73	447
E 13	5400	5140	5140	0.00	0.27	500	0.00	260	0.52	519
E 14	5840	5140	5140	0.00	0.39	1000	0.00	700	0.70	624
E 15	5840	4980	5119	0.70	1.40	2100	50.00	860	0.40	1183
E 16	5880	5540	5540	0.00	0.07	400	0.00	340	0.85	264
E 17	6040	5220	5280	2.98	8.28	7000	35.99	820	0.11	2877
E 18	5280	5300	5440	0.51	0.92	2200	55.43	380	0.17	959
E 19	6200	5119	5290	2.54	5.96	4600	42.44	1080	0.23	2441
E 20	5840	5440	5440	0.00	0.22	800	0.00	400	0.50	469
E 21	6000	5320	5440	0.85	1.24	2000	68.54	680	0.34	1113
E 22	6000	5520	5520	0.00	0.25	600	0.00	480	0.80	500
E 23	7400	4920	5270	8.27	19.01	16500	43.50	2480	0.15	4360
E 24	5900	5270	5270	0.00	0.42	900	0.00	630	0.70	648
E 25	5800	5100	5100	0.00	0.69	2100	0.00	700	0.33	830
E 26	5800	5360	5360	0.00	0.13	400	0.00	440	1.10	360
E 27	5720	5540	5540	0.00	0.17	800	0.00	180	0.22	412
E 28	5640	5380	5380	0.00	0.13	500	0.00	260	0.52	360
E 29	5840	5580	5580	0.00	0.11	400	0.00	260	0.65	331
E 30	5800	4970	5480	3.50	4.82	6400	72.61	830	0.12	2195
E 31	5650	5420	5420	0.00	0.20	500	0.00	230	0.46	447
E 32	5750	5380	5380	0.00	0.13	400	0.00	370	0.61	360
E 33	5800	4980	5180	2.57	3.32	4500	71.38	920	0.18	1822
E 34	5440	5250	5250	0.07	0.17	500	41.17	230	0.46	412
E 35	6000	5400	5400	0.00	0.15	700	0.00	600	0.85	387
E 36	5850	4920	5200	5.55	7.22	6400	76.86	880	0.12	2687
E 37	6179	5259	5259	0.00	0.95	1000	0.00	920	0.92	974
E 38	6179	5560	5560	0.00	0.24	700	0.00	620	0.88	489
E 39	6010	5020	5280	7.09	16.90	11200	41.95	2980	0.26	4110
E 40	6300	5259	5259	0.00	0.80	1000	0.00	1040	1.04	894
E 41	5600	5100	5259	1.01	3.04	3500	32.79	500	0.14	1754
E 42	5700	5380	5380	0.00	0.09	600	0.00	520	0.53	299
E 43	5400	5020	5020	0.00	0.09	500	0.00	380	0.76	299
E 44	6050	5020	5020	0.00	4.73	2300	0.00	1030	0.44	2174
E 45	5600	4820	5100	2.58	3.20	4500	80.62	780	0.17	1768
E 46	5400	4920	4920	1.19	1.51	2400	78.80	620	0.22	1228
E 47	5300	4520	4740	0.42	0.73	2200	57.53	780	0.35	854
E 48	5800	5100	5100	0.00	0.74	1400	0.00	700	0.50	860
E 49	5800	5100	5100	0.30	0.41	1600	73.17	500	0.31	640
E 50	5880	5020	5340	7.34	4.34	3400	53.91	860	0.22	2083
E 51	5919	5020	5140	0.35	3.67	2200	9.53	900	0.40	1915
E 52	5600	4620	4960	1.17	1.63	400	71.77	979	1.63	1276
E 53	5500	4580	5000	0.20	0.34	800	58.82	920	1.15	583
E 54	5259	4780	4820	0.04	0.15	600	26.66	480	0.80	387
E 55	5259	4740	4780	0.03	0.14	900	16.66	520	0.57	424
E 56	5300	4620	5000	0.28	0.47	500	59.57	680	1.36	685
E 57	5400	4840	4840	0.00	0.14	900	0.00	580	0.62	400
E 58	5400	4860	4860	0.00	0.14	1000	0.00	540	0.54	424
E 59	5300	4220	4520	0.18	1.17	1400	15.38	1080	0.67	1081
E 60	5900	5320	5320	0.00	0.31	400	0.00	580	0.72	556
E 61	5240	4420	4820	0.76	0.29	900	20.68	460	0.51	538

Fig. 5. Inventory of the glacier basins in the Khumbu region, Imja Khola.

data of the glaciers and their basins in the Khumbu region are shown in Figs. 2~5.

3. Statistical analysis of glacier forms and their relation to basin morphology.

1) Preliminary statistics of glacier inventory.

Two classifications of the glaciers in the Nepal Himalayas were proposed by Tanaka (1971) and Moribayashi (1973) based on their field observations in Khumbu Himal. Tanaka classified them into the Lower Himalayan type developed below 6000m and the Higher Himalayan type formed in the altitudinal range 5000~7000m. Moribayashi proposed to call the debris-covered glaciers "Dirty type (D-type) glaciers" and the debris-free glaciers "Clean type (C-type) glaciers".

Table 1. shows the results of a statistical analysis of the glacier inventory in the Khumbu region. As seen in this table, C-type glaciers develop in the altitudinal range between 5250m and 5700m and have an area of 0.4 km² on the average. On the other hand, D-type glaciers develop from 4890m to 5960m, more than double

the altitudinal range of C-type glaciers, and have an area of 6.6 km² on the average, more than fifteen times the C-type glaciers area. The mean length of D-type glaciers, 5.2 km, is more than five times as long as that of C-type glaciers, 1.0 km.

It is, therefore, clear that there is an apparent difference in the dimensions of C- and D-type glaciers in the Khumbu Himal.

Each element of basins containing D-type glaciers, especially length of basin ridge and basin area, is bigger than the corresponding element for C-type glaciers, and so is like to be more effective for glacierization.

The total area of glaciers and the total number of glaciers in the Khumbu region are 287 km² and 167 respectively.

2) Correlation coefficients between the dimensions of glaciers and their basins.

Correlation coefficients between the dimensions of glaciers and their basins were computed and the results are shown in Tables 2 and 3.

In general, the correlation is better in the case

Table 1. Elements representative of the forms of glaciers and glacier basins in the Khumbu region.

Elements of glacier and its basin above 5500 m		C-type glacier with G5 above 0.1km ² (89)		D-type glacier with G4 above 0.1km ² (37)	
		MEAN	ST. DEVIATION	MEAN	ST. DEVIATION
U. LIMIT (m)	G1	5706	237	5963	639
L. LIMIT (m)	G2	5247	187	4886	289
EXP. LIMIT (m)	G3			5114	255
DEBRIS AREA (km ²)	G4			2.72	4.10
TOTAL AREA (km ²)	G5	0.43	0.55	6.55	11.50
LENGTH (km)	G6	0.96	0.49	5117	4.99
MAX. HEIGHT (m)	T1	6090	325	6937	700
RIDGE LENGTH (m)	T2	2555	1232	8816	7223
VALLEY WIDTH (m)	T3	1080	529	2222	1544
BASIN AREA (km ²)	T4	0.62	0.52	6.17	10.31
ROCK F. AREA (km ²)	T5	0.26	0.24	1.88	2.47
BASIN S. INDEX	T6	2.60	1.43	3.85	1.71
ROCK F.A. RATIO (%)	T7	45	24	43	18

Table 2. Correlation Coefficients between the dimensions of the debris-free glaciers and their basins.

		MAX. HEIGHT T1	RIDGE LENGTH T2	VALLEY WIDTH T3	BASIN AREA T4	ROCK F. AREA T5	BASIN S. INDEX T6	ROCK F.A. RATIO T7
U. LIMIT	G1		0.40	0.30	0.50	0.31	0.16	-0.29
L. LIMIT	G2		0.06	0.08	0.06	0.25	0.27	0.23
T. AREA	G5	0.28	0.65	0.56	0.71	0.17	0.03	-0.30
LENGTH	G6	0.23	0.64	0.33	0.49	0.22	0.15	-0.25
AL. RANGE	G8	0.52	0.39	0.40	0.49	0.12	-0.06	-0.51
GRADIENT	G9	0.24	-0.17	0.14	0.03	-0.01	-0.23	-0.20
ROOT T. AREA	G10	0.37	0.74	0.60	0.73	0.28	0.04	-0.36

(on 89 glaciers with an area above 0.1 km²)**Table 3.** Correlation Coefficients between the dimensions of the debris-covered glaciers and their basins.

		MAX. HEIGHT T1	RIDGE LENGTH T2	VALLEY WIDTH T3	BASIN AREA T4	ROCK F. AREA T5	BASIN S. INDEX T6	ROCK F.A. RATIO T7
U. LIMIT	G1		0.82	0.66	0.75	0.77	0.51	-0.45
L. LIMIT	G2		-0.02	-0.29	-0.10	-0.04	0.51	0.15
EXP. LIMIT	G3		0.15	-0.12	0.06	0.15	0.53	0.19
DEBRIS AREA	G4	0.65	0.85	0.87	0.95	0.94	0.25	-0.39
TOTAL AREA	G5	0.56	0.82	0.89	0.96	0.93	0.21	-0.40
LENGTH	G6	0.70	0.94	0.85	0.93	0.95	0.44	-0.43
DEBRIS A. RATIO	G7	0.01	-0.31	-0.31	-0.21	-0.19	-0.21	0.36
AL. RANGE	G8	0.06	0.81	0.78	0.78	0.77	0.28	-0.51
GRADIENT	G9	-0.48	-0.41	-0.29	-0.29	-0.35	-0.46	0.26
ROOT T. AREA	G10	0.67	0.93	0.94	0.94	0.95	0.38	-0.53

(on 37 glaciers with a debris covered area above 0.1 km²)

Table 4. Multiple regression equation of the debris-covered and debris-free glaciers, using the elements representing the forms of the glacier basins.

a) C-type glacier with an area above 0.1 km ² (89 glaciers)	
G1 (m)=5135+190×T ₄ −1.04×T ₇ +0.08×T ₁	0.52
G2 (m)=5018+39.70×T ₆ +1.98×T ₇ +131×T ₅	0.44
G5 (km ²)=−0.25+1.56×T ₄ −2.19×T ₅ +0.0062×T ₇	0.70
G6 (m)=2.25+0.0003×T ₂ −0.50×T ₅ −0.0003×T ₁	0.88
b) D-type glacier with a debris covered area above 0.1 km ² (37 glaciers)	
G1 (m)=4249+0.06×T ₂ +0.16×T ₁ +21.68×T ₆	0.83
G2 (m)=4574+134.71×T ₆ −0.03×T ₂ +45.38×T ₅	0.64
G3 (m)=4237+81.81×T ₆ +5.31×T ₇ +0.05×T ₁	0.63
G4 (km ²)=−0.72+0.15×T ₄ +0.0005×T ₃ +0.63×T ₅	0.96
G5 (km ²)=−1.27+1.05×T ₄ +0.0024×T ₃ −0.0004×T ₂	0.98
G6 (m)=0.29+1.14×T ₅ +0.0002×T ₂ +0.0003×T ₃	0.97

of D-type glaciers than in that of C-type glaciers. The reason will be discussed in the next section.

The large-sized glaciers, having a large area, long length, and high upper limit, develop in bigger basins with higher summits, longer ridges and wider valleys.

The correlations between glacier area and basin area; glacier length and ridge length; and debris covered area and rock face area are especially good.

Therefore, it would be reasonable to consider that the total precipitation in the basin above the firn line controls the size of the glacier, and the debris on the glacier surface was supplied from the rock face of the basin.

The position of the lower limit of the glacier is independent the dimensions of the glacier basin, as in the case of the Cordillera Real, Bolivia (Nogami, 1968).

3) Multiple regression analysis of glacier forms

A multiple regression analysis of glacier forms was performed as a pilot study to relate glacier form to some basin factors by a regression equation.

The program of this analysis is for a single dependent and a maximum of 49 explaining variables. The technique used is the so-called forward selection method. Explaining variables are added to the regression equation one at a time. At each step, the program selects that remaining variable which makes the greatest improvement in 'goodness of fit', that is the greatest reduction in the residual sum of squares.

The results are shown in Table 4. Each regression equation is shown with three explaining variables and the multiple correlation coefficients are greater in the case of D-type glaciers than

in the case of C-type glaciers. This may indicate that the forms of D-type glaciers which have dead ice in terminal part are close to the forms attained during the maximum stage in the last advance. On the other hand, the forms of C-type glaciers are different in each glacier which is in response to present or past climatic conditions, after separation from debris covered dead ice body by melting (Fushimi, 1977) depending on the individual size of the glacier, so that the coefficient is smaller than in that of D-type glaciers.

References

- Fushimi, H. (1977): Structural studies on glaciers in the Khumbu Region, in this issue.
- Moribayashi, S. (1973): Nepal Himalaya no Hyôga ni tsuite sono tokusei to saikin no hendô (On the Characteristics of Nepal Himalayan Glaciers and Their Recent Variation). *Seppyo*, 36, 1, 11-21.
- Müller, F. (1970): Inventory of glaciers in the Mount Everest region. In *Technical Papers in Hydrology 1-Perennial ice and snow masses*, UNESCO/IASH, 47-59.
- Nogami, M. (1968): Cordillera Real (Bolivia) no hyôga (Statistical Analysis of the altitudinal Distribution of Glaciation in the Cordillera Real, Bolivia). *Journal of Geography*, 77, 125-140.
- Schneider, E. (1957): Mahalangur Himal (1: 25,000), Kartographische Anstalt Freytag-Berndt und Artaris, Wien.
- Schneider, E. (1965): Khumbu Himal (1: 50,000), Kartographische Anstalt Freytag-Berndt und Artaris, Wien.
- Tanaka, H. (1971): On Preferred Orientation of Glacier and Experimentally Deformed Ice. A thesis for a master's degree of Faculty of Science, Hokkaido University.
- UNESCO/IASH, (1970): *Technical papers in hydrology 1.- Perennial ice and snow masses*, 59.