8 Glaciers in South America

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8.1 INTRODUCTION

The presently glacierized area in South America is estimated at some 26,000 km² (IAHS(ICSI)/UNEP/UNESCO, 1989), with the bulk of this ice mass being found in the Patagonian Ice Fields and Tierra del Fuego. A great number of mountain glaciers exist in the Andes of Argentina, Bolivia, Chile, Colombia, Ecuador, Peru and Venezuela. The following text illustrates mainly the situation in Argentina, Bolivia, Chile and Peru.

8.2 DISTRIBUTION AND CHARACTERISTICS

Glaciers in South America occur along the high Andes. More than half of the Andean range is located in Chile and Argentina (Fig. 8.1). In northern Chile and Argentina (17°–27°S), the highest summits rise above 6,000 m a.s.l., with a high plateau (Altiplano) extending several tens of kilometres to the east. To the south, the Andes are concentrated along a narrower belt only a few tens of kilometres wide. Aconcagua, located in Argentina at 33°S, is the highest summit not only of South America but of the entire western hemisphere. South of 34°, the elevation of the highest summits decreases rapidly (Table 8.1).

In their northern part, the Chilean Andes start at latitude 17°S and straddle Bolivia to 23°S. The climate here is dominated by the subtropical high pressure of the Pacific with associated arid conditions. The main precipitation source comes from the Atlantic and occurs during the summer months,

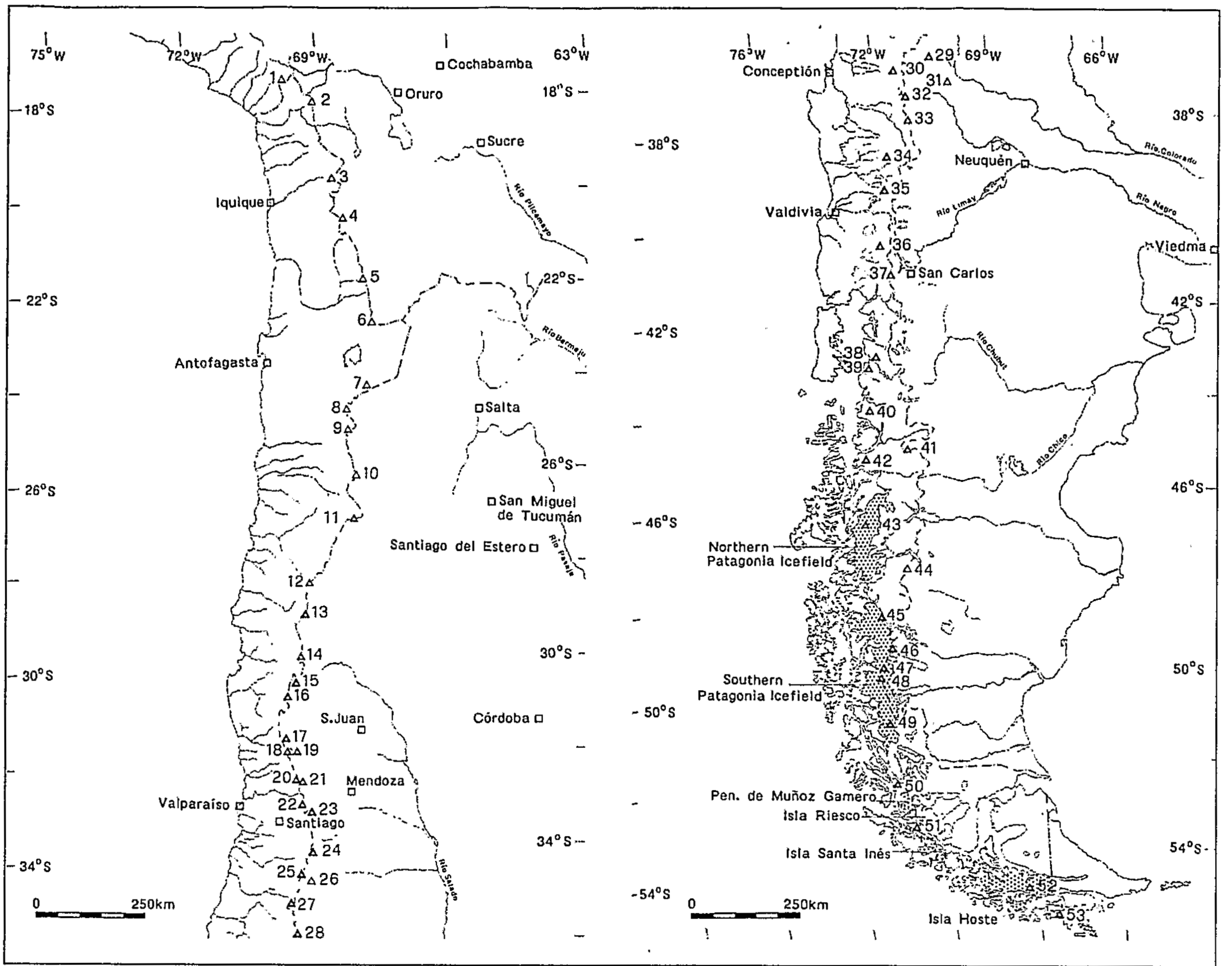


Figure 8.1 Map of Chile and Argentina. (left) – northern part; (right) – southern part. Numbers represent the high mountains of the Andes as shown in Table 8.1.

amounting to only a few tens of mm/ year in the mountain areas. The orographic effect on precipitation results here in an east-west gradient of the equilibrium line altitude (ELA, Fig. 8.2), the precipitation being higher in the east. The precipitation decreases southward as the distance from the humidity source in the Atlantic increases. Only very few mountain glaciers with areas generally smaller than 15 km² occur on high volcanoes in this area (e.g., Parinacota and Pomerape).

Of all the tropical regions (i.e., areas between the tropic of Capricorn and the tropic of Cancer), the mountains of Peru have the largest number of glaciers. At the same time, the Andes of Peru are densely populated. On the one hand, the local population benefits from continuous and reliable meltwa-

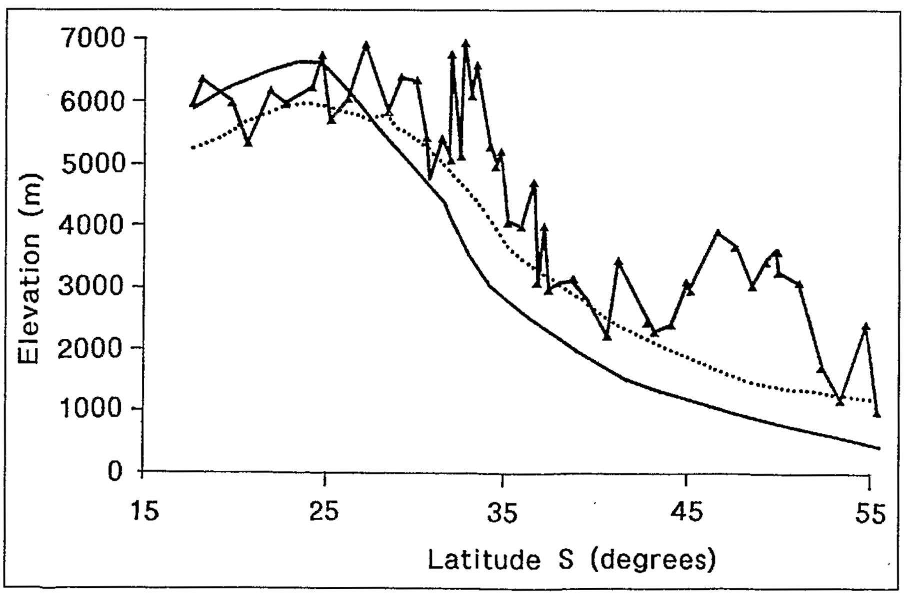


Figure 8.2 North-south variation of the regional snow-line on the western margin of the Andes (continuous line) and on the eastern side (dotted line), and highest elevation of peaks (line joining triangles). The snow-lines are adapted from Nogami (1972).

ter runoff but, on the other hand, is frequently affected by glacier catastrophes of various kinds. Catastrophic events caused by ice avalanches and proglacial lake outflows happen from time to time in all Cordilleras (high mountain ranges) of the Peruvian Andes. They have caused serious damage in the lower valleys, destroying towns, villages, roads, bridges, paths, etc. In many cases, people were killed. Since the catastrophes usually occurred unexpectedly and suddenly, there was little chance for people to escape. For example, during a particularly tragic event in 1941, at least 4,000 people drowned in the town of Huaraz as a result of the outflow from two small proglacial lakes in the Cordillera Blanca. This event led to the realization that it was necessary to (a) make an inventory of dangerous proglacial lakes and (b) lower or to strengthen the outlet of the most dangerous lakes if settlements were endangered and if this was technically at all possible. For this purpose, the Comisión de Control de Lagunas de la Cordillera Blanca was set up. The development of hydroelectric power further increased interest in glaciers, particularly in the Cordillera Blanca. At first, four glaciers were chosen for a pilot study on mass balance measurements. Two more glaciers were added to this network later on. Understanding glacier fluctuations in the Peruvian Andes is also of great importance in connection with the formation of new lakes as a result of rapid tongue retreat. In parallel with this work, cooperation with the Temporary Technical Secretariat for the World Glacier Inventory was initiated. The inventory was made possible by the availability of various sets of aerial photographs, some of which were taken in the aftermath of the biggest glacier catastrophe to occur in Peru in recent centuries, the gigantic rock and ice avalanche from Nevado Huascarán in 1970.

From 23°S to 51°S, the Andes are shared by Argentina and Chile. Climatic conditions from 23° to 30°S range from arid to semi-arid, with precipitation increasing slightly south of 25°S as the region affected by the westerlies is approached. The precipitation increase results in an ELA decrease to the west from 6,600 m at 24°S to 4,700 m at 30°S (Fig. 8.2). The transition from an eastern precipitation source to a western source appears in Fig. 8.2 as the intersection of the ELA on the western side of the Andes and the ELA on the eastern side at 27°S. Glacierization is limited in this area to very few small mountain glaciers (in general less than 1 km^2) occurring on the highest summits (e.g., Cerros Colorados, Tres Cruces, Los Tronquitos). At 30°S, a clear influence of the westerly circulation occurs, with pronounced seasonality in precipitation during the winter months associated with low pressure systems from the Pacific. By contrast, summer conditions are dry owing to the presence of the subtropical high-pressure system. A marked precipitation increase explains the existence of important mountain and valley glaciers from 32°S to 35°S, where many summits exceed 5,000 m a.s.l. and a few even 6,000 m

TABLE 8.1 Highest Andean summits along a north-south transect from the Bolivian-Chilian border to the very south of the American continent.

	Mountain	*Latitude S* (°)	(′)	*Elevation* (*m*)
1	Volcán Tacora	17	43	5,988
2	Volcán Parinacota	18	10	6,330
3	Cerro Sillajhuay	19	45	5,995
4	Cerro Copa	20	37	5,320
5	Volcán San Pedro	21	54	6,154
6	Sairecábur	22	42	5,970
7	Pular	23	11	6,225
8	Llullaillaco	24	42	6,723
9	Volcán Lastarria	25	11	5,700
10	Cerros Colorados	26	11	6,049
11	Ojos del Salado	27	07	6,880
12	Cerro del Potro	28	23	5,830
13	Cerro del Toro	29	07	6,380
14	Cerro de la Tórtolas	29	57	6,332
15	Cerro Alto	30	34	5,430
16	Cerro Maruez	30	42	4,750
17	Chanchones	31	56	5,370
18	Cerro Ojotas	31	57	5,070
19	Mercedario	31	28	6,770
20	Cerro Volcán	32	32	6,130
21	Cerro Aconcagua	32	39	6,959
22	Nevado Juncal	33	04	6,110
23	Volcán Tupungato	33	22	6,550
24	Maipo	34	11	5,290
25	Alto los Arrieros	34	37	4,986
26	Sosneado	34	45	5,159
27	Volcán Peteroa	35	15	4,090
28	Campanarío	35	56	4,002
29	Volcán Domuyo	36	37	4,709
30	Chillán	36	50	3,122
31	Volcán Tromen	37	08	3,979
32	Volcán Antuco	37	25	2,985
33	Volcán Callaqui	37	55	3,080
34	Volcán Llaima	38	42	3,124
35	Volcán Villarrica	39	25	2,840
36	Volcán Puyehue	40	35	2,240
37	Monte Tronador	41	10	3,460
38	Nevado Minchinmávida	42	52	2,470
39	Volcán Corcovado	43	12	2,300
40	Cerro Melimoyu	44	05	2,400
41	Cerro Catedral	44	56	3,060
42	Cerro Macá	45	06	2,960
43	San Valentín	46	37	3,910
44	Cerro San Lorenzo	47	37	3,700
45	Cerro Mellizo Sur	48	33	3,050
46	Cerro Fitz Roy	49	17	3,441
47	Murallón	49	48	3,600
48	Cerro Bertrand	49	57	3,270
49	Cerro Paine Grande	51	02	3,100
50	Monte Burney	52	20	1,750
51	Monte Córdova	53	19	1,219
52	Monte Darwin	54	44	2,438
53	Monte Hardy	55	24	1,036

a.s.l. (e.g., Mercedario, Aconcagua, Juncal Tupungato, Marmolejo). South of 35°S, the highest summits rarely exceed 4,000 m, which restricts the development of glaciers to mainly volcanic cones (e.g., Peteroa, Domuyo, Antuco, Callaqui, Llaima, Lanín, Osorno) to 42°S. Precipitation increases from about 200 mm/year at 30°S to 2,000 mm at 40°S. There is a strong orographic effect on circulation, with an important reduction in precipitation on the eastern side of the Andes. South of 42°S, in the region known as Patagonia, the climate is wet temperate, being completely dominated by the westerly circulation, with high precipitation and reduced seasonality. This results in a larger glacierized area. Three small ice caps from 40 to 100 km^2 exist on the Chilean side from 42°S to 44°S: Minchinmávida, Yanteles and Melimoyu. The Patagonian Andes have been carved extensively by Pleistocene glaciers, resulting in a complex pattern of fjords both in the Pacific and in large pedemontane lakes to the east. The orographic effect on circulation in Patagonia is highly pronounced, with precipitation amounts in excess of 5,000 mm/year in certain areas to the west and as little as 200 mm/year or less on the Pampa to the east. South of 46°S, the two largest ice bodies of the southern hemisphere outside Antarctica are to be found: the Northern Patagonia Ice Field, with an area of about 4,200 km^2 (Aniya, 1988), and the larger Southern Patagonia Ice Field covering about 13,000 km^2 (Aniya *et al.*, 1992). Glacier Upsala, a 60 km-long outlet on the eastern margin of the Southern Patagonia Icefield, is the largest glacier in South America.

From 51°S to 55°S, the Andes lie completely in Chile, changing from a north-south to an east-west orientation. In this area, the third-largest glacier body in South America is found: Cordillera Darwin in Tierra del Fuego, with an estimated area of 2,000 km^2. Smaller ice caps exist in Peninsula Muñoz Gamero, Isla Santa Inés and Isla Hoste. At 55°S, near Ushuaia in Tierra del Fuego, a subdued portion of the Andes with reduced glacierization is again shared with Argentina.

Glaciers in Bolivia, Colombia, Ecuador, Peru and Venezuela are mostly mountain glaciers existing under tropical climatic conditions. Recent studies carried out in the Central Andes (Thompson, 1992; cf. also Hastenrath and Kruss, 1992, for Kenya) suggest that the effects of global warming could be more pronounced in the short term for tropical glaciers like these than for glaciers of high and medium latitudes. Other studies also indicate that tropical glaciers are excellent indicators of short-term climatic variations, as seen in the Andes by their response to anomalies of short duration and of variable intensity resulting from the El Niño phenomena (ENSO) (Thompson *et al.*, 1984; Francou *et al.*, 1995; Ribstein *et al.*, 1995). The sensitivity of tropical glaciers to climatic variability is still inadequately explained, mostly due to the lack of data available on net mass balances and on the climatic variables that control these glaciers. This sensitivity could be due, at least in part, to a particular condition affecting the mass balance which is that, on these glaciers, the accumulation period stretches throughout the summer and is therefore synchronous to the period in which ablation is at its maximum. Thus, a deficit in precipitation during this season translates directly into strong ablation tied to the increase in direct radiation. It could also be suggested that, with the summer rainfall, an increase in the temperature would shift the snow-rain boundary to higher altitudes, causing a significant contribution in sensible heat over the majority of the glacier (Lliboutry *et al.*, 1977*a*).

8.3 EXISTING INVENTORIES

Early glacier inventories of Chile and Argentina have been summarized by Mercer (1967). The distribution of glaciers in Chile has been described by Lliboutry (1956), who was the first to conduct detailed glaciological work in Chile. In the late 1970s, the Dirección General de Aguas of the Ministry of Public Works started a detailed glacier inventory programme. As part of this programme, glaciers have been inventoried in the Río Maipo basin (33° to 34°S; Maragunic, 1979), in the Río Cachapoal basin (34°S; Caviedes, 1979), in the Río Aconcagua catchment (32°S; Valdivia, 1984), in the Río Mataquito basin (35°S; Noveroy, 1987), in the north of Chile (18° to 32°; Garín, 1986) and in the Lake District (37° to 41°30'S; Rivera, 1989). In addition, a preliminary glacier inventory based on 1:250,000 maps has been compiled for the Northern Patagonia Ice Field by Valdivia (1979*a*, 1979*b*). A more precise and complete glacier inventory for the Northern Patagonia Ice Field based on 1:50,000 cartography has been compiled by Aniya (1988). Table 8.2 summarizes the glacier inventory in Chile. The total area covered by detailed glacier inventories is 5,515 km^2, representing approximately only one-fourth of the total glacier area in Chile (cf. Table 8.3).

In Argentina, Helbling and Reichter explored the high Cordillera between Mt. Aconcagua and Mt. Tupungato from 1907 to 1912 (Reichter, 1929; 1967). Helbling (1919; 1935; 1940) published an accurate map of the Río del Plomo valley (33°S) on a scale of 1:25,000, describing the glaciers and fluctuations of the glaciers' termini since 1909–1934; Groeber (1947*a*; 1947*b*; 1951; 1955) studied the geology and described the glaciers in the Central Andes; Lliboutry (1956) published maps and measured the englaciated area between 32°30'S and 35°S and the glaciers in Patagonia. Feruglio (1957) described the glaciers in the Cordillera Argentina between 21°S and 51°S. An inventory of Patagonian glaciers was first undertaken by Lliboutry (1956) and Bertone (1960). In the provinces of Mendoza (33°S) and San Juan (31°S), the Instituto Argentino de Nivología y Glaciología (IANIGLA-CONICET) has compiled glacier inventories (IAHS(ICSI)/UNEP/UNESCO, 1989) in the following basins: Río Mendoza: Corte and Espizua (1978; 1981) identified 1,025 ice bodies bigger than 0.02 km^2 that

TABLE 8.2 Inventoried glaciers in Chile

Region	*Basin*	*No. of Glaciers*	*Area (km²)*	*References*
I	*		29.70	
II	*	14	12.13	
III	*	49	66.83	
IV	*	11	7.02	
V	Aconcagua	267	151.25	Valdivia 1984
Metropolitán	Maipo	647	421.90	Marangunic 1979
VI	Cachapoal	146	222.42	Caviedes 1979
VI	Tinguiririca	261	106.46	Valdivia 1984
VII	Mataquito	81	81.91	Noveroy 1987
VIII-IX	Bío Bío	29	52.37	Rivera 1989
IX	Imperial	13	18.72	Rivera 1989
IX-X	Toltén	14	68.48	Rivera 1989
IX-X	Valdivia	6	42.33	Rivera 1989
X	Bueno	11	19.35	Rivera 1989
X	Maullín	1	2.84	Rivera 1989
X	Chamiza	1	1.05	Rivera 1989
X	Petrohué	12	60.57	Rivera 1989
XI	Northern Patagonia Icefield	**28	4,200.00	Aniya 1988
Total		***1,600	5,515.33	

* Only a few glaciers in the North of Chile drain into distinct rivers and they have not been classified into basins.
** This number reflects the outlet glaciers of the Northern Patagonia Icefield. Contiguous mountain glaciers, although included in the total area, are not counted individually (Aniya 1988).
*** Five glaciers in Regions VIII, IX and X drain into two different basins. This is accounted for in the total.

TABLE 8.3 Uninventoried glaciers in Chile

Latitude	*Region*	*Description*	*Estimated Area (km²)*
35° to 37° S	VII & VIII	Río Maule and Rio Itata basins, glaciers limited to a few high peaks (e.g., Volcán San Pedro, 3,499 m)	50
41° 30′ to 45° 30′ S	X & XI	Continental Chiloé and northern Aisén, three main ice caps on Mt. Minchinmávida (2,470 m), Mt. Yanteles (2,042 m), and Mt. Melimoyu (2,400 m) (Lliboutry 1956), plus many smaller mountain glaciers	*250
45° 30′ to 49° S	XI	North, East and South-east of Northern Patagonia Icefield, and North-east of Southern Patagonia Icefield. Many mountain glaciers, e.g., Volcán Hudson, Cerro San Lorenzo	400
48° 15′ to 52° S	XI & XII	Southern Patagonia Icefield, total area 13,000 km² (Aniya *et al.*, 1992), of which 90% is claimed by Chile (Martinic 1982)	11,700
51° 45′ to 52° S	XII	Cordillera Sarmiento, ice caps and mountain glaciers, first explored by Miller	100
52° 40′ to 53° S	XII	Península Muñoz Gamero, icefield on south-western part of peninsula	*200
52° 50′ to 53° 20′ S	XII	Isla Riesco mountain glaciers	100
53° 45′ to 54° S	XII	Isla Santa Inés, icefield on eastern part of island	*250
54° 20′ to 54° 50′ S	XII	Cordillera Darwin, 150 km-long icefield, 25 km wide in central part	2,000
55° 10′ S	XII	Isla Hoste, ice cap located on Península Cloue, western part of the island, plus smaller glaciers to the East	150
Total			15,200

Note: * indicates areas estimated by Lliboutry (1956). Otherwise, area estimations are made in this study by inspection of 1:500,000 scale maps.

covered 304 km^2 of bare ice and 344 km^2 of debris-covered ice. Río Tunuyán: eastern slopes of Cordón del Plata and Cordón del Portillo (the glacierized area is 144 km^2, 40% of which corresponds to uncovered ice and 60% to covered ice) (Espizua, 1983*a*; 1983*b*). In the Río Atuel: Cobos (1979, unpublished IANIGLA report) revealed a glacierized area of 186 km^2 consisting of 80% of uncovered ice and 20% of covered ice. Río Malargüe: in this basin, the englaciated area covered 12 km^2, 2% of bare ice and 9.5% of ice covered by debris (Cobos, 1987). The Río San Juan catchment, with Ríos de los Patos, Blanco, Calingasta, Ansilta and Castaño (Aguado, 1983; 1986 (unpublished IANIGLA report); Espizua and Aguado; 1984) has a total glacierized area of 556 km^2 (42% of uncovered ice and 58% of ice covered by debris). Glacier inventories from the Patagonian Andes, Argentina, have been published by Rabassa *et al.*, 1975; Rabassa *et al.*, 1978*a*; 1978*b*; 1978*c*; Rabassa, 1980; 1981; Rabassa *et al.*, 1981; Rabassa, 1983. At 55°S, Lendaro and Iturraspe studied the Martial Glacier and Roig (1990) studied the geomorphology and hydrology of de cirque glaciers in the Tierra del Fuego Andes. Rabassa *et al.* (1981; 1982) compiled a glacier inventory of the James Ross and Vega Islands in the Antarctic Peninsula.

Detailed glacier inventories (cf. IAHS(ICSI)/UNEP/UNESCO, 1989) were also compiled in Bolivia (Cordillera Occidental and Cordillera Oriental, Jordan, 1991), Peru (Northern and Southern Cordilleras, Ames *et al.*, 1988) and partially in Ecuador, Colombia (Sierra Nevada de Santa Marta and various volcanoes) and Venezuela (Sierra Nevada de Mérida). In Peru, the Glaciology Division of Electroperú in Huaraz completed an inventory which is mainly based on aerial photogrammetric flights conducted between 1955 and 1970. The flights in 1970 were undertaken by NASA and the Servicio Aerofotográfico Nacional (SAN) after the catastrophic earthquake on May 31. These photographs were recorded on infrared film and were used for the inventory of the Cordillera Blanca. The 1955 material was used for Cordillera Ampato and some zones of the Cordilleras Chila and Huanzo (cf. Fig. 8.3). The rest of the inventory is based mainly on 1962 pictures. The bulk of the Peruvian ice masses are located in the Cordilleras Blanca, Vilcanota, Ampato and Central (Ames *et al.*, 1988; cf. Table 8.4). The total glacier area (excluding the insignificant amounts in the Cordilleras Barroso and Volcanica) is 2,042 km^2. Altogether, 3,044 glaciers were recorded. Fig. 8.4 shows some interest-

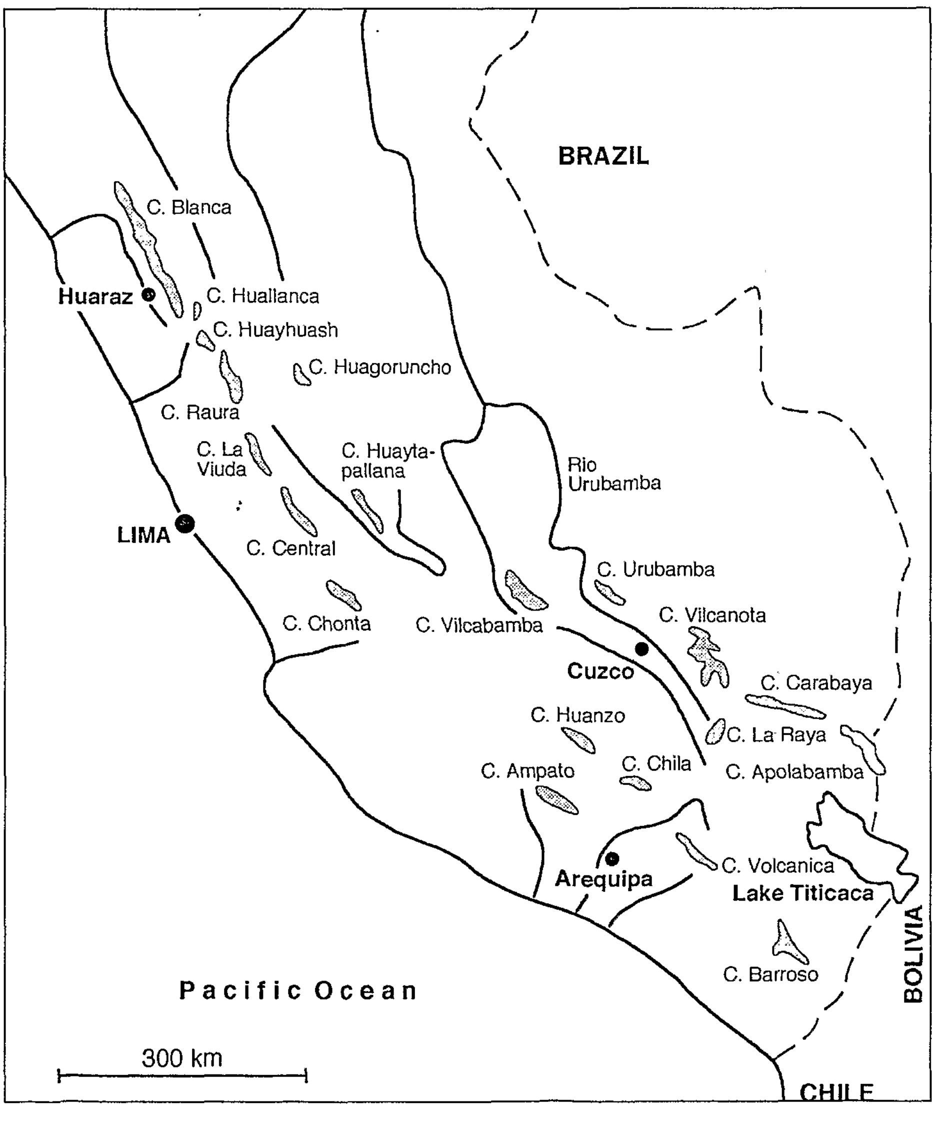


Figure 8.3 Distribution of glaciated Cordilleras (high mountain ranges) in north, central and southern Peru. The true extent of glaciated areas cannot be shown on this scale.

TABLE 8.4 Number, total area and estimated total ice volume in the Peruvian Cordilleras according to the Peruvian Glacier Inventory

	Cordillera	*Number of glaciers*	*Total area (km²)*	*Total volume (km³)*
1	Blanca	722	723	22.60
2	Huallanca	56	21	0.43
3	Huayhuash	117	85	2.99
4	Raura	92	55	1.33
5	La Viuda	129	29	0.43
6	Central	236	117	2.54
7	Huagoruncho	80	23	0.40
8	Huaytapallana	152	59	1.15
9	Chonta	95	18	0.26
10	Ampato	93	147	5.12
11	Vilcabamba	98	38	0.72
12	Urubamba	90	41	0.78
13	Huanzo	115	37	0.60
14	Chila	87	34	0.58
15	La Raya	48	11	0.16
16	Vilcanota	469	418	12.00
17	Carabaya	256	104	1.96
18	Apolobamba	109	81	2.11
19	Volcanica	-	-	-
20	Barroso	-	-	-
	Total	3,044	2,042	56.15

ing statistical results from the Cordillera Blanca. Although this mountain range appears most spectacular to any visitor to the Santa Valley, no glacier is larger in surface area than 16.5 km² (Jankapampa). The longest glacier is Copap (7.0 km). Of particular interest is the distribution of average glacier altitudes (Fig. 8.4b). On the eastern side, average altitudes are sometimes lower than 4,800 m a.s.l. and typically around 5,000 m. On the western side of the Cordillera, they are significantly higher. Here, average equilibrium lines are usually above 5,100 m and sometimes even above 5,400 m. This can be interpreted as an effect of precipitation distribution since the main advection of moisture is from the Amazon basin in the east. Nevertheless, quite a large part of the glacier surfaces are oriented towards the southwest (cf. Fig. 8.4c) because the high valleys on this side of the Cordillera Blanca are somewhat less steep than on the other, thus providing relatively extensive accumulation areas at high altitudes. Similarly interesting relationships can also be found when comparing the Cordilleras La Viuda, Central, Huaytapallana and Chonta (IAHS (ICSI)/UNEP/UNESCO, 1989). It is to be expected that a general glacier retreat as a result of continued climatic warming will soon lead to a total loss of glaciers in the Cordilleras Chonta, Huallanca or La Raya, where only a few small glacierlets can be found.

8.4 EXISTING LONG-TERM OBSERVATIONS (LENGTH CHANGE, MASS BALANCE, MAPS)

In Chile and Argentina, there are several cases of surging glaciers near Mendoza (Glaciar Horcones Inferior and Glaciar Grande del Nevado del Plomo) and Santiago (Juncal Sur, Museo and Colina). A few glaciers in the Southern Patagonia Ice Field are presently advancing and Moreno Glacier is largely stable. In contrast to the above glaciers, most glaciers in Chile and Argentina are presently retreating, as indicated by recent moraines and their present behaviour. The only glacier in Chile presently monitored for mass balance is Echaurren Norte Glacier at 33°S. Monitoring has been done by the Dirección General de Aguas routinely in spring, summer and autumn since 1975. Results have been published for the periods 1975–1983 (Peña *et al.*, 1984) and 1975–1994 (Escobar *et al.,*, in press) and the programme still continues today. With respect to frontal variations, the only systematic studies based on aerial photographs and satellite imagery are on glaciers of the Northern Patagonia Ice Field (Aniya, 1988; 1992; Aniya and Enomoto, 1986; Warren, 1993) and the Southern Patagonia Ice Field (Aniya *et al.*, 1992; Warren and Sugden, 1993). Sporadic observations of glacier variations elsewhere in Chile are described in Lliboutry (1956), Mercer (1962; 1967) and Marangunic (1964*a*; 1964*b*).

In Argentina, some glaciers are presently monitored by IANIGLA for mass balance in the Río Mendoza basin. Mass-balance measurements in the Cajón del Rubio area began in 1979. Balances were calculated continually up to 1987 but no measurements were taken in 1986, 1988 and 1990. Balance measurements re-started in 1991. The authors reconstructed the accumulation data at Piloto Glacier for the missing years and analysed the mass balance behavior of Piloto and Alma Blanca Glaciers (Leiva *et*

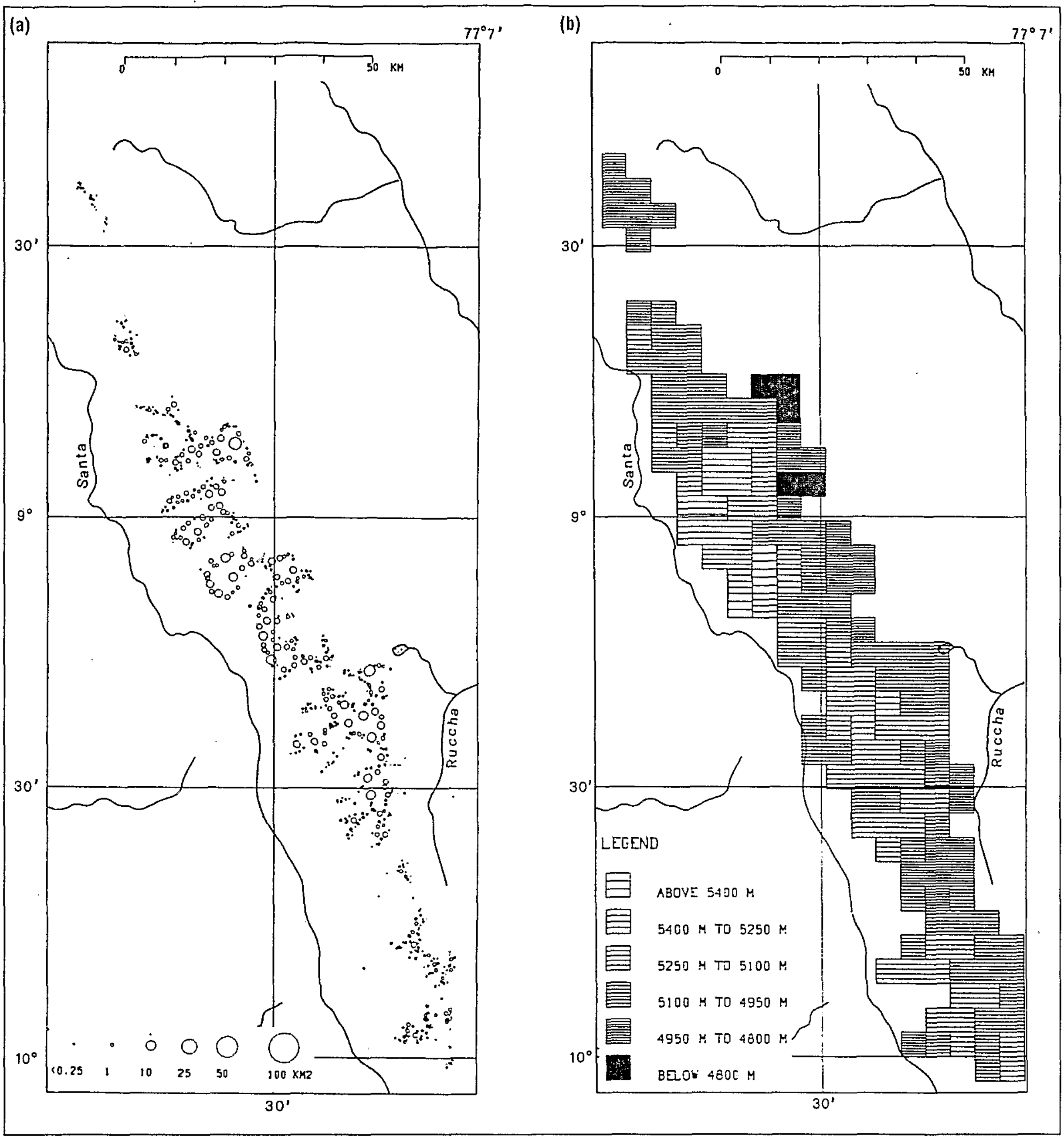
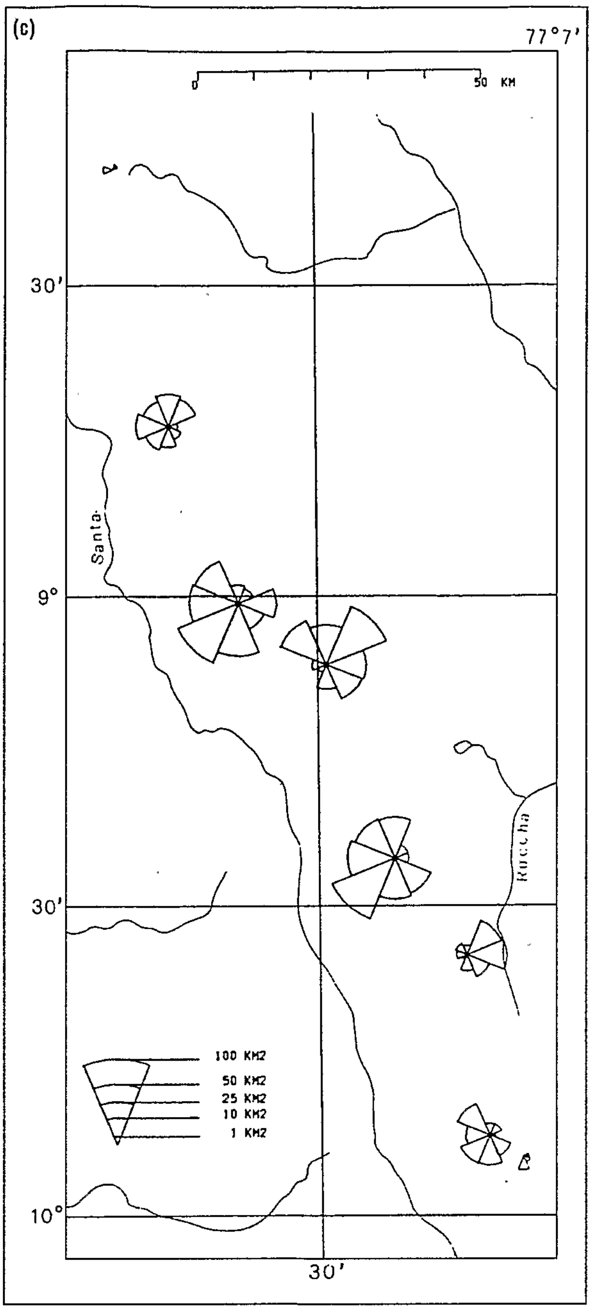


Figure 8.4 (a) Glaciers in the Cordillera Blanca according to surface area; (b) mean glacier elevations in the Cordillera Blanca (notice that the mean elevation is somewhat lower on the eastern side compared with the western side of this mountain range);

al., 1986; Leiva and Cabrera, in press). Regarding glaciers' frontal variations, studies have been made in the following basins: Río del Plomo basin (33°S) (Espizua, 1986; 1987; Espizua and Bengochea, 1990; Leiva *et al.*, 1989; Llorens and Leiva, in press); Río Tunuyán basin (33°15'S) (Llorens and Leiva, 1994); Rio Atuel basin (34°S) (Cobos and Boninsegna, 1983); Río Frías basin (41°S) (Villalba *et al.*, 1990). Mercer (1965; 1968) studied the fluctuations of ice margins in Patagonia. Fluctuations on Castaño Overo Glacier, Mount Tronador, in Northern Patagonia have been studied by Bertani *et al.*, 1985; 1986; Brandani *et al.*, 1986 and on Martial Glacier in Ushuaia (55°S) by Lendaro and Iturraspe. A Glacier Research Project in Patagonia that included *Characteristics of Recent Glacier Variations in Patagonia, Southern Andes* was carried out during the summer of 1993–94 at and around the Upsala, Ameghino and Moreno Glaciers (Skvarca *et al.*, 1995; Naruse *et al.*, 1995; Takeuchi *et al.*, 1995; Aniya and Sato, 1995).

Until recently, there were very few mass balance studies available for the Central Andes comparable to those undertaken for tropical African glaciers, notably Lewis Glacier (Hastenrath, 1984). This lack of work is all the more regrettable in that the Central Andes represent more than 95% of the surface area of glaciers found in the Tropics. Over the last fifteen years or so, only the Cordillera Blanca (Peru) has provided data on the balances of ablation areas of two glaciers, Uruashraju and Yanamarey (Ames, 1985; Kaser *et al.*, 1990), in addition to data over several decades concerning the oscillations of the gla-



(c) summarized surface areas and aspects of glaciers according to catchment basins. After IAHS(ICSI)UNEP/UNESCO, 1989.

cier's termini. From ice cores taken from the Quelccaya Ice Cap (Peru), we know that the Little Ice Age commenced in the Central Andes around 1480 A.D. and ended around 1880 A. D. (Thompson *et al.*, 1986). According to photographic documentation analysed by Broggi (1945) in the Peruvian Andes, the retreat at the end of the 19th and beginning of the 20th centuries is interrupted by a phase of advance between 1909 and 1932. This advance is itself followed by a significant retreat in the period 1932–1945.

In Peru, systematic length measurements of glacier tongues and mass balance measurements began in 1968 in the Cordillera Blanca. The aim was to estimate the contribution of meltwater runoff to the water available for hydroelectric power production. Since 1940, a general tendency towards glacier retreat has been documented by aerial photographs taken in 1948 and 1962 and by topographic surveys carried out every year since 1968 at the terminus of about half a dozen glaciers of the Cordillera Blanca (Ames, 1985; Kaser *et al.*, 1990). In the early 1970s, an ablation stake network was installed and monitored on the tongues of Uruashraju and Yanamarey. Since 1980–81, the stakes have been measured at the end of both the wet and dry seasons (Kaser and Ames, 1990). Owing to the problems associated with very high altitudes, stakes could only be maintained up to 4,900 m a.s.l. It is noteworthy that accumulation mainly takes place during the rainy season, which usually lasts from October until March or April. There is hardly any seasonal temperature variation. Therefore, ablation takes place at any time of year. The longest record of length fluctuations is detained by the Broggi (located north of Nevado Huascarán, 1.1 km long), Uruashraju (2.5 km) and Yanamarey (1.7 km) Glaciers. The latter two are located in the southern part of Cordillera Blanca. Later on, the Gajap, Huarapasca and Pastoruri Glaciers completed the observational programme. The selection of regularly visited glaciers had to be done mainly from the point of view of accessibility. Additional glacier snout positions could be reconstructed using aerial photographs (1948 and 1962). The cumulative length changes as recorded by field measurements (Fig. 8.5) indicate a relatively modest retreat from 1948 until the end of the 1970s. Uruashraju and Yanamarey even recorded a very slight readvance around 1975. Between 1948 and 1980, Broggi Glacier retreated, on average, 11 m per year. Nevertheless, the total length loss of 366 m during this period amounted to one-third of the glacier's length in 1970! From 1980 to 1991, the retreat accelerated. Broggi lost an average of 26.2 m per year. In 1991, it retreated by 53.2 m, the biggest single-year retreat ever recorded. The glacier was then 654 m shorter than in 1948. The other glaciers, including the newly-measured ones, retreated, on average, between 17.2–21.1 m per year. Clearly, this pronounced ice loss is a general phenomenon in the Cordillera Blanca: maps and terrestrial photogrammetric pictures produced by German-Austrian expeditions in the 1930s (Kinzl, 1940*b*; 1942; Kinzl and Schneider, 1950) show various small glaciers which have since disappeared. Until now, it has been difficult to relate the observed glacier retreat to local climatic data, although a simple meteorological station has been maintained at Querococha, a site 3,980 m a.s.l. and 8.5 km below Yanamarey. Precipitation measurements commenced in 1954 and temperature recordings in 1964. During this interval, the recordings do not show a clear, systematic increase in temperature. However, at least the small readvance of Yanamarey and Uruashraju, as well as the decelerated retreat of Broggi around 1975, correlates with slightly lower temperatures and somewhat increased precipitation in the early 1970s. Given that the analysed glaciers were very short, their length varying between

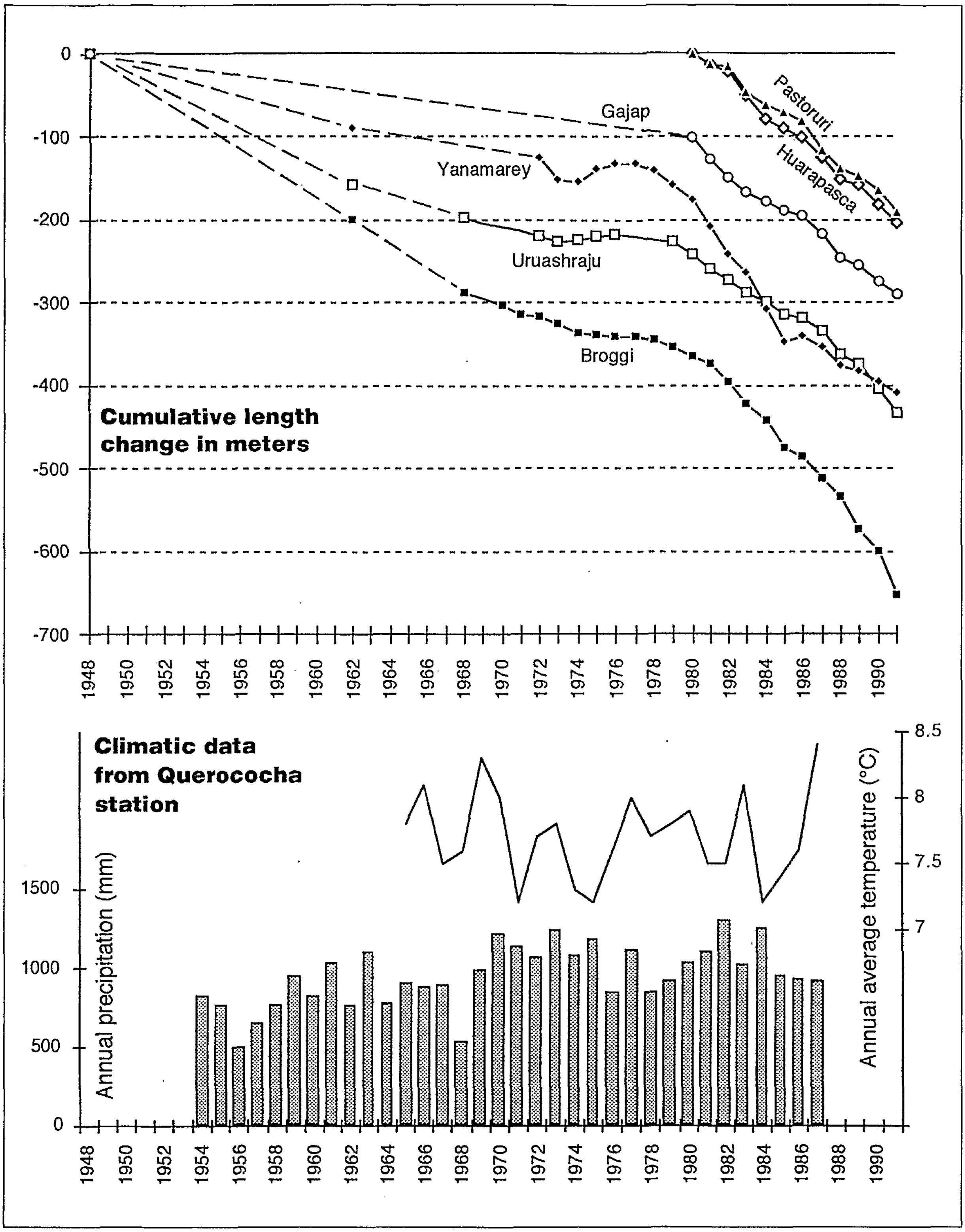


Figure 8.5 Cumulative length changes of glaciers in the Cordillera Blanca and climatic record from the station at Querococha. In the upper diagram, dashed lines show length changes inferred from aerial photographs. The 1948 snout positions are taken as zero.

1 km to 2.5 km, changes in balance were almost immediately followed by changes in terminus position. An acceleration in the rate of retreat is evident for all these glaciers starting from 1982 (Table 8.5): the rate of the retreat is three times that of the average retreat in the preceding decades. It is possible to compare this acceleration to that measured by photogrammetry on the terminus of Quelccaya Ice Cap. According to Brecher and Thompson (1993), the rate of retreat was three times faster between 1983 and 1991 than between 1963 and 1978, while the mass volume loss was seven times greater.

Since 1991, there has been an ongoing programme of glacier monitoring and hydrology in the Cordillera Real of Bolivia, the Cordillera Blanca of Peru and some volcanoes in Ecuador, under the auspices of the French Scientific Research Institute for Development in Cooperation (ORSTOM) (Francou *et*

TABLE 8.5 Length variation of 3 glaciers of Cordillera Blanca (1948–1993)

Length Variation	*Broggi*	*Uruashraju*	*Yanamarey*	
1948–1993	–16.0	–11.0	–9.0	(1)
1948–1981	–11.0	–8.0	–6.0	(1)
1982–1993	–30.0	–19.6	–18.6	(1)
Total Length in 1982	1.2	2.5	1.6	(2)

(1) metres per year
(2) kilometres
Source: Oficina de Recursos Hidricos; Electroperú, Huaraz, Peru.

al., 1995). The results obtained in Bolivia from monthly measurements of glacial and hydrological balances of the Zongo and Chacaltaya Glaciers are sufficiently definitive to be taken as references for other glaciers in the Tropical Andes. These results present the only measurements of mass balances and hydrological balances of glacierized basins available to date in the Central Andes. Despite the exceptional historical documentation dating from the 18th century available on glaciers in Ecuador (Hastenrath, 1981), it is still impossible to provide a precise explanation for the glacial retreat which started at the end of the Little Ice Age. All we can ascertain from the work of Meyer (1907), confirmed by information collected by Broggi (1945) in Peru, is that glacial retreat has been occurring since at least 1870. The disappearance of numerous glaciers from a number of volcanoes which were ice-covered during the 19th century, such as Pichincha and Sincholagua, suggests that the snow-line on the Western Cordillera rose, between 1800 and 1975, from 4,650 m to 4,950 m (Hastenrath 1981). The readvance of Peruvian glaciers around the mid-1920s is equally documented in Bolivia (Müller, 1985; Jordan, 1991). The analysis of the compelling ground-based photographic archives assembled by Kinzl (1940*a*) in 1930 and 1940 will allow, in the near future, precise determination of the variations of glaciers' termini in the Cordillera Blanca twenty years before the first aerial photographs.

On the Chacaltaya Glacier (Francou, unpublished data), according to photographic documentation, a guide mark dating from 1982 and topographic measurements at the terminus every year since 1991, the retreat is estimated at 2.0 m/year between 1940 and 1993. It ranges from an average of 0.95 m/year for the period 1940–1982 to 6.05 m/year (a ratio of 1 to 5) for the period 1982 to 1993. These results tally with those obtained for the African glaciers in the Ruwenzori (Kaser and Noggler, 1991) and on Mount Kenya (Hastenrath and Kruss, 1992). They suggest that, if the tendency is to persist, numerous minor glaciers may disappear in the next two or three decades. The balance of glaciers at medium and high latitudes is determined, above all, by the temperature level of the ablation season (summer), which lasts approximately 3–4 months (Martin, 1977; Lefauconnier and Hagen, 1990). In the Tropics, because the warm season (which favours ablation) is synchronous to the rainy season (which favours accumulation), the effect of seasonal climatic variability, which could influence the net yearly balance, stretches over at least six months. To analyse the influence of seasonal variability, the present authors have measured ablation and accumulation on a monthly basis on the Zongo and Chacaltaya Glaciers, two glaciers under study in the Cordillera Real of Bolivia (Fig. 8.6 and 8.7). The results obtained over three years and partially published (Francou *et al.*, 1995) show that, with respect to net balance, a year can be divided up into three periods (Fig. 8.8).

1) The early summer months of October, November and December, preceding the rainy period, are months of strong ablation. Ablation is also strong during the 1 or 2 months at the end of the rainy season, March and April. In November-December, the firn line is situated at more than 5,500 m, well within the accumulation zone. The heavy rate of ablation during this period is due to a combination of factors, amongst which: the large quantity of energy at the top of the atmosphere (months around the summer solstice); the mostly cloud-free skies; the not very high albedo because the ice is still incompletely covered with snow, and the contribution of sensible heat owing to the increase in the hygrometry.
2) The months of accumulation, January-February (sometimes March), correspond to the highest levels of rainfall. It should be noted that the energy available for melting, by direct radiation or by sensible heat, remains sufficiently high to induce strong ablation in the lowest part of the glacier, close to the terminus. Since, at the same time, a period of high accumulation dominates over the greatest part of the surface, the activity coefficient of the glacier is high for this season, close to 0.25 m / 100 m in water-equivalent.
3) The months of winter, May–August, which are generally dry and cold, are months in which the net balance ought to remain stable. Cloud cover is low but the energy at the top of the atmosphere is 30 % less than in summer and it is just able to melt or sublime the snowfall accumulation over the period. The energy available for melting is all the more insufficient in that the amount of sensible heat is also very low. It should be noted, however, that winter is the season in which the quantities of energy received by the opposite facing

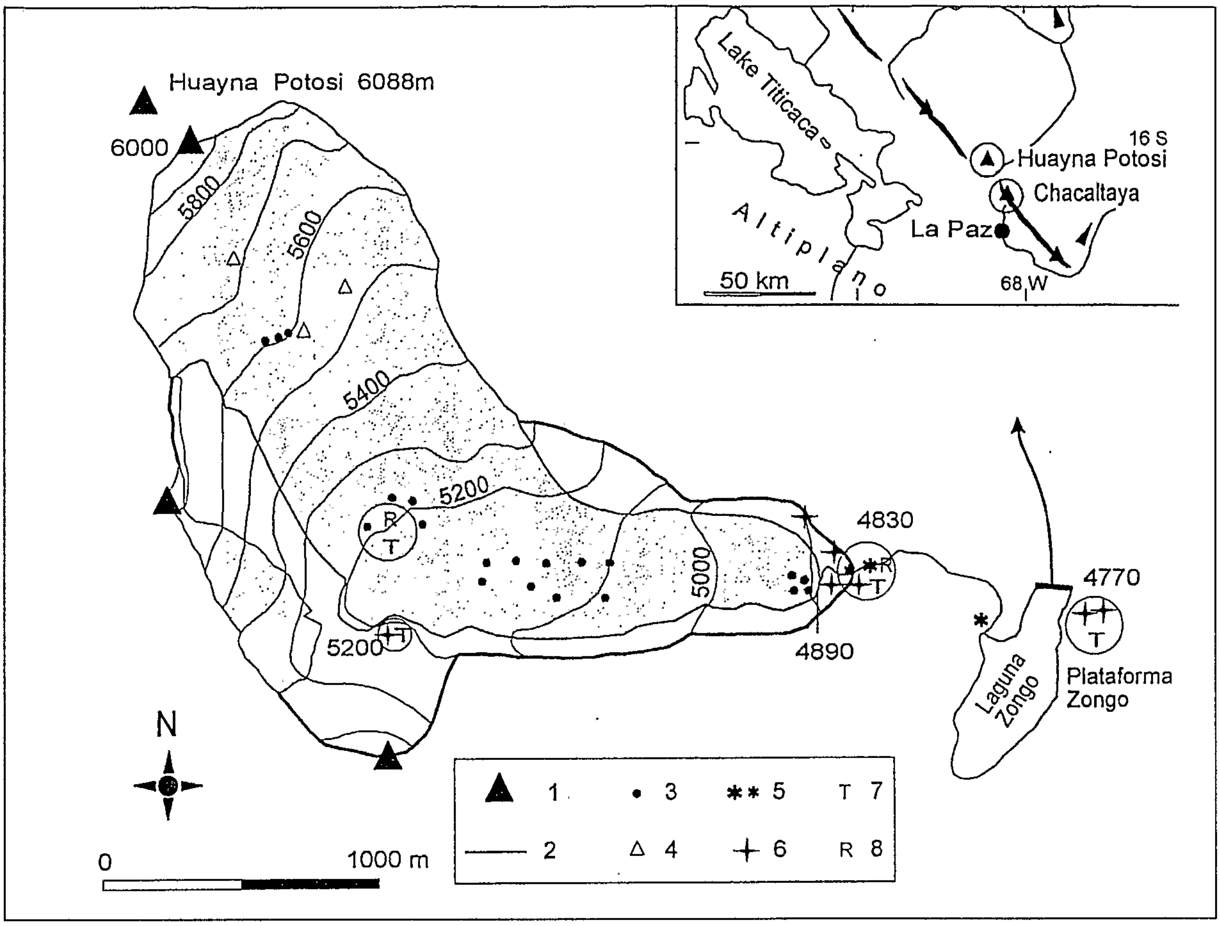


Figure 8.6 Zongo Glacier and the survey system in 1993.
1. Principal peaks – 2. Limits of basin – 3. Stakes – 4. Pits – 5. Water-level records – 6. Rain gauges – 7. Thermographs – 8. Pyranometers.

slopes present the greatest contrasts. This explains a difference of approximately 300 m in the ELA of glaciers of most contrasting slopes, which are the NE and SW slopes. However, in August 1994 and in July–August 1995, notable ablation rates were measured on Zongo Glacier (Francou and Ribstein, unpublished data).

The highest instantaneous discharges from glacier torrent of Zongo Glacier have been measured in the summer, usually in November-December, at the end of dry periods (Fig. 8.9). These events represent the highest values of ablation registered on a daily basis. The frequency and length of these 'dry periods' in the warm season seem to be the important factors in determining the value of the annual net balance.

Using ice cores taken from Quelccaya Ice Cap (Peru), Thompson *et al.* (1984) demonstrated the effects of the El Niño phenomena (ENSO events) on the accumulation balances of glaciers at high altitudes; every ENSO event is marked in the Central Andes by a reduction in accumulation rates. This result tallies with the significant decrease in precipitation during the ENSO episodes (Francou and Pizarro, 1985). During the ENSO event of 1991–1992, monthly measurements of balance taken from the Zongo and Chacaltaya Glaciers also show that the ablation rate during these events is significantly high, even at great altitudes (Fig. 8.8 and 8.9).

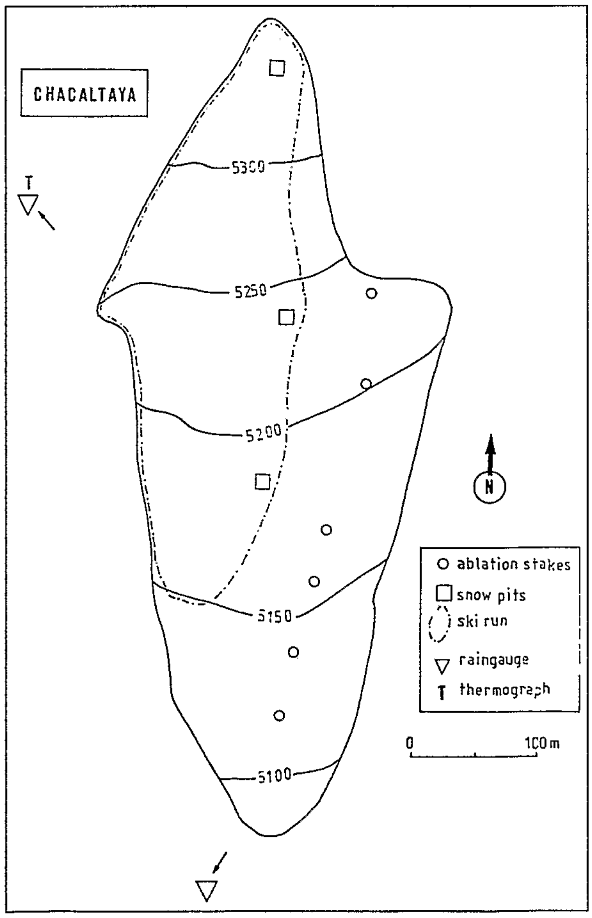


Figure 8.7 Chacaltaya Glacier and the survey system in 1993.

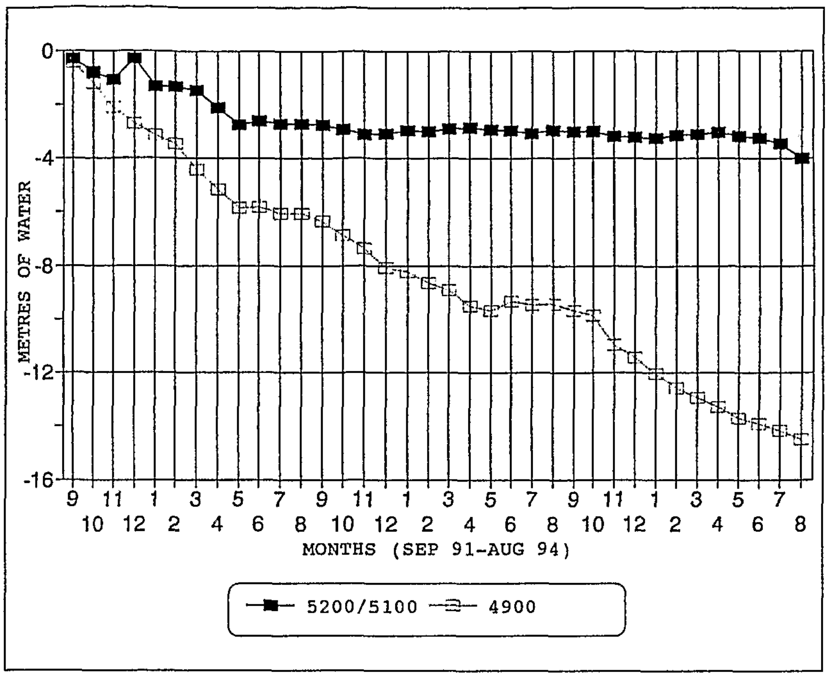


Figure 8.8 Cumulative net balance for the 36 months from September 1991 to August 1994 at Zongo Glacier: 5,200-5,100 m elevation range (black rectangles); 4,900 m (white rectangles).

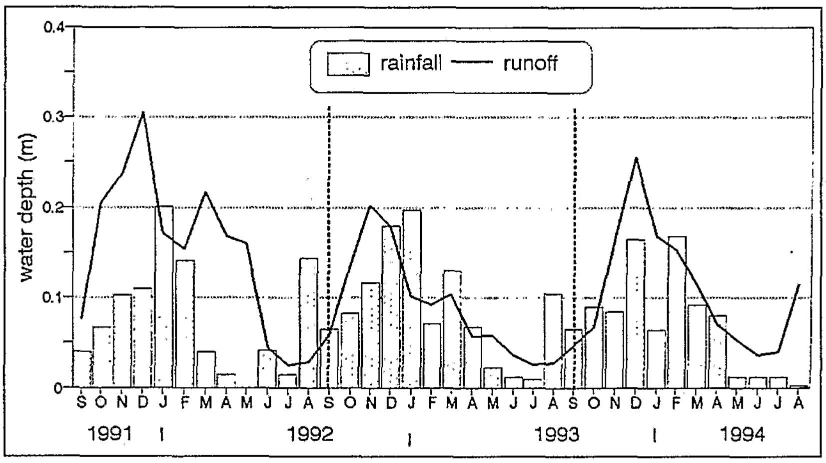


Figure 8.9 Monthly precipitation (average from 4 rain gauges) and runoff on Zongo Glacier.

Therefore, both terms of the balance, accumulation and ablation are influenced by the phenomena. The ENSO effect can be appreciated on Zongo Glacier by comparing the values obtained for specific net balance, precipitation, specific ablation, specific runoff, the Equilibrium Line Altitude and the Accumulation Area ratio for 1991–92, 1992–93 and 1993–94 (Table 8.6). It is noteworthy that 1992–93 and 1993–94 are not ENSO years: the specific net balance was equilibrated during the first period and negative during the second.

A comparison of the three years reveals that the ablation values are significantly different, while the accumulation values, given by the amount of precipitation, are more uniform. More than by a reduced amount in total precipitation, the ENSO year 1991–92 has been marked by 1) a rainy season shorter than normal – at Plataforma de Zongo (4,770 m), only 4 months received more than 50 mm instead of the usual 7 months during a normal period and 2) a reduction in cloud cover during the warm season, which resulted in high average radiation values linked with above-average maximum temperatures (values between 1 and 2 standard deviation). The short rainy season, restricted to January-February, resulted in two periods of strong ablation, a first one in November-December, stronger than normal, and a second one, more attenuated, in March. These two peaks are well reflected in the runoff values of the glacier torrent (Fig. 8.9).

Table 8.6 also shows that the ablation (Ag) and runoff (Q) values for the three years are similar, which implies that the sublimation rate would be relatively weak on this type of glacier. It is, however, unquantifiable, given the imprecision of the measurement.

The balance of Zongo Glacier has been reconstructed using measurements taken at the limnimetric station in 1991–93 and using readings taken every day since 1973 (that is, over 20 years) in a canal that recollects the waters of the glacier (Ribstein *et al.*, 1995). Fig. 8.10 shows that, for every ENSO event, given by a significant negative value of the South Oscillation Index, there is a correspondingly high negative balance value with a possible delay of a few months. This suggests that, in this part of the Andes, ENSO events directly control variations in glacier balances. ENSO events explain 4 periods with very negative balances: 1977/78, 1982/83, 1987/88 and

TABLE 8.6 Zongo Glacier (1991–1993): net balance, ablation, runoff, precipitation, ELA and AAR

Year	*Bn (1)*	*P (2)*	*Ag (3)*	*Q (4)*	*ELA (5)*	*AAR (6)*
1991–92	–1.38	0.92	2.30	2.25	5,300	58
1992–93	0.02	1.06	1.04	1.18	5,100	86
1993–94	–0.73	0.85	1.58	1.56	5,200	67

(1) specific net balance (m of water)
(2) precipitation measured near the glacier (4,800–5,200 m) (m of water)
(3) specific ablation: Ag = P – Bn (m of water)
(4) specific runoff (surface of the glacier: 2.1 km^2) (m of water)
(5) Equilibrium Line Altitude (in m)
(6) Accumulation Area Ratio (in %)

1991/92 (only the negative balance of 1979–80 does not correspond to an ENSO event).

Subtracting the estimated average amount of rainfall received by the glacier every year (i.e., 1.062 m of water) from the average runoff value (i.e., 1.472 m of water) gives an average deficit balance of 0.41 m apparent during this period of 20 years for Zongo Glacier. Sublimation seems to be low but, if it were taken into account, this deficit would be even more negative. Over these 20 years, only three have had net positive balances, 1974–75, 1975–76 and 1986–87. For the same three years, the termini of the small glaciers being monitored in the Cordillera Blanca have not retreated, indicating that their balances have been positive or in equilibrium (Fig. 8.5).

This study suggests that the present retreat of Bolivian glaciers, such as those of Cordillera Blanca (Francou *et al.*, in press), is strongly influenced by ENSO events. In between these events, periods of positive or in-equilibrium balances may occur but their duration is not such as to reverse the tendency for these glaciers to retreat. At the most, they can slow down the process but only for a short time.

An accelerated glacier retreat has also been reported from the Andes de Mérida in the northwestern part of Venezuela (Schubert, 1992; 1993).

8.5 SPECIAL EVENTS

Some glaciers in the Central Andes of Argentina have experienced rapid advances over several hundred metres and are considered surging glaciers. Examples include the glaciers in the Mendoza basin. Horcones Inferior Glacier on the southern flank of Mt. Aconcagua surged in 1985 (IAHS(ICSI)/UNEP/UNESCO, 1993; Llorens and Leiva, 1994). In the Río del Plomo basin at 33°S, Grande del Juncal Glacier surged in 1910 and at some time between 1934 and 1955. Grande del Nevado Glacier surged at the end of 1933, between 1963 and 1974, and again in 1984. It dammed up a lake in January 1985 (Helbling, 1919; 1935; 1940; Espizua, 1986; 1987; Espizua and Bengochea, 1990; Bruce *et al.*, 1987; Prieto, 1986; IAHS(ICSI)/UNEP/UNESCO, 1988; 1993). The Glaciar Innominate advanced 2,900 m between 1986 and 1991 (Llorens and Leiva, in press). In the Río Tupungato basin, an unnamed glacier to the south of Tupungato Glacier known as Glacier B has advanced 1,100 m since 1985/1986, the position of the front remaining unchanged between 1991 and 1994. From the Mesón San Juan ice plateau, a glacier tongue advanced 750 m from 1985 to 1986 but did not present the characteristic chaotic surface (low reflectance through analysis of Landsat image) found on other surging glaciers (Llorens and Leiva, 1994).

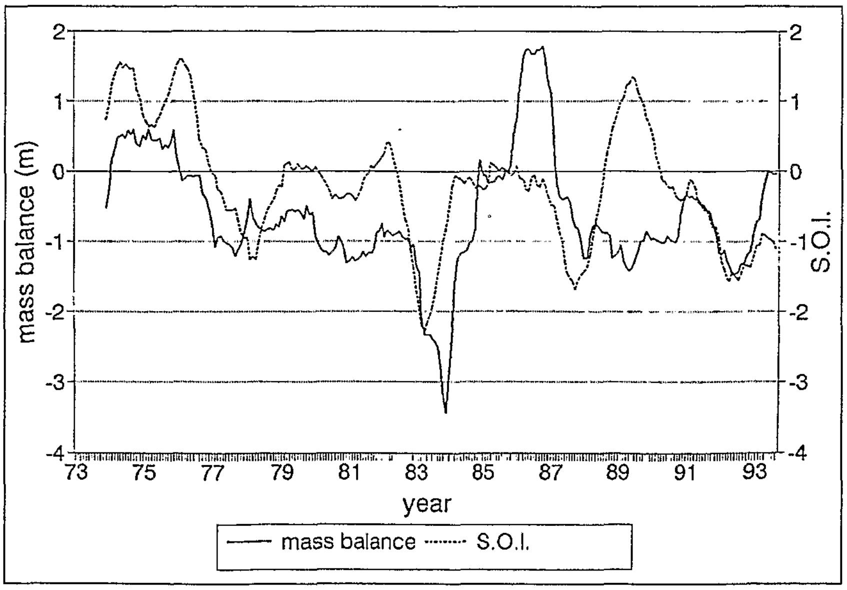


Figure 8.10 Mass balance of Zongo Glacier vs. South Oscillation Index (SOI). Mass balance is reconstructed using hydrological data. SOI is the difference in pressure between Tahiti and Darwin in standardized values. Both curves represent 12-month running means.

TABLE 8.7 Catastrophes produced by glaciers in Peru. All events are from the Cordillera Blanca unless otherwise noted. Where no literature reference is given, the source is personal records by Ames.
Abbreviations: IA = ice avalanche; LOF = lake outflow

Date	*Origin of catastrophe (mountain, lake, etc.)*	*Place of greatest damage (e.g., town)*	*Type of catastrophe*	*Approx. number of victims*	*Reference*
March 4, 1702	?	Huaraz	flood	?	Alba Herrera, 1969
January 6, 1727	Nevado Huandoy	Town of Ancash	earthquake, probably IA, flood	1,500	Alba Herrera, 1969; Silgado, 1978
January 6, 1727	?	Huaraz	earthquake, perhaps flood caused by IA	more than 1000	Alba Herrera, 1969; Silgado, 1978
February 27, 1869	Cerro San Cristobal	Monterrey (near Huaraz)	LOF, flood	11	Alba Herrera, 1969
June 24, 1883	Lake Tambillo (Rajucolta)	Macashca	LOF caused by IA	'many'	Alba Herrera, 1969
January 22, 1917	Nevado Huascaran	Villages Shacsha and Ranrahirca	IA	?	Alba Herrera, 1969
March 14, 1932	Lake Solteracocha (Cordillera Huayhuash)	planting fields in the Quebrada Pacllon	LOF	?	Alba Herrera, 1969; Kinzl, 1940*c*
January 20, 1938	Lake Artesa (Pakliashcocha)	bridge destroyed near Carhuaz	LOF	none	Kinzl, 1940*c*
April 20, 1941	Lake Suerococha (Cordillera Huayhuash)	planting fields destroyed	LOF	none	Alba Herrera, 1969
December 13, 1941	Lakes Acoshcocha and Jircacocha	Huaraz	LOF	4,000	Lowther and Giesecke, 1942; Track, 1953; Buse, 1957; Fernandez, 1957; Oppenheim, 1947; Heim, 1948
January 17, 1945	Lakes Ayhuiñaraju and Carhuacocha	Chavin de Huantar	LOF caused by rock slide from Nev. Huantsan	300	Indacochea and Iberico, 1947; Spann, 1946
October 20, 1950	Lake Jankarurish	Hydroelectric power station of Huallanca	LOF, possibly caused by IA	200, perhaps 500	Ghiglino, 1950
June 16, 1951	Lake Artesoncocha	no damage, water absorbed by Laguna Paron	LOF (first, see below)	none	Fernandez, 1957
October 28, 1951	Lake Artesoncocha	as above	LOF (second, see above)	none	Fernandez, 1957
November 6, 1952	Lake Milluacocha	minor damage in planting fields	LOF	none	
? 1953	Lake Tullparaju	no damage downvalley	landslide, waves erode artificially modified lake outlet	none	
December 8, 1959	Lake Tullparaju	minor damage in planting fields	as above	none	
January 10, 1962	Nevado Huascaran	Ranrahirca and 9 smaller villages	IA	4,000	Dollfus and Peñaherrera, 1962; Patzelt, 1985
December 22, 1965	Lake Tumarina	Quebrada Carhuascancha	LOF, probably caused by IA	several	
May 31, 1970	Nevado Huascaran Norte (west face)	Yungay, Ranrahirca and Matacoto	earthquake causes large rock and IA	20,000	Lliboutry, 1971, Plafker *et al.*, 1971; Patzelt 1985; Welsch, 1970
May 31, 1970	Huascaran Norte (north face)	Quebrada Llanganuco	earthquake causes rock and IA	14	
August 31, 1982	Lake Milluacocha	bridges and planting fields destroyed	lake outburst caused by IA	none	
December 16, 1987	Nevado Huascaran	road blocked	IA	none	
January 20, 1989	Nevado Huascaran	road and bridge damaged, planting fields destroyed	IA	none	

At 34°S, Laguna Glacier in the Río Atuel basin advanced 1,400 m between 1970 and 1982 (Cobos and Boninsegna, 1983). In the Southern Patagonia Ice Field, the position of Moreno Glacier has been studied in detail owing to the cyclical damming and periodic catastrophic drainage of the southern arm of Lago Argentino.

In historic times, most of the catastrophic floods and ice avalanches in Peru were recorded in the Cordillera Blanca and Huayhuash. This is only partially due to the relatively large extent of the ice masses. Perhaps equally important is the unusually high population density, in particular in the Santa Valley on the west side of Cordillera Blanca. Perhaps nowhere else in tropical high mountain ranges is there such an intense interaction between glaciers and man. Subsistence agriculture in the mountain areas of Peru is in part dependent on glacial runoff for irrigation (some people even make a living from transporting blocks of glacier ice down to local markets where it is used to produce ice cream and to cool drinks). Therefore, a significant part of the population lives within reach of glacial floods and, in some cases, even within the runout distances of ice avalanches. In other Peruvian Cordilleras, catastrophic events are noted less frequently but do occur. The origins are diverse. Lake outbursts have various kinds of triggering mechanisms. However, most of them have in common that the lakes initially formed as a result of the general retreat of the glaciers (Oppenheim, 1947; Heim, 1948; Track, 1953; Fernandez, 1957; Ames *et al.*, 1994). Typically, they are dammed by poorly consolidated morainic material and perhaps sometimes even by buried stagnant ice. Extreme rainfall may then weaken the dam until it fails spontaneously. In many cases, landslides and ice avalanches have fallen into the lakes, causing waves which erode the lake outlet. Exponential increase of discharge then leads to the sudden drainage. The so-called «aluvion», a turbulent mixture of rock, finer sediment and water then rushes downvalley causing destruction and often the loss of many lives. Table 8.7 summarizes all known major events (including ice avalanches) as far back as the beginning of the 18th century. Some lakes were made less dangerous by lowering the water level and strengthening the outflow. Successful examples of such work are Laguna Safuna (Lliboutry, 1977; Lliboutry *et al.*, 1977*a*; 1977*b*) or Laguna Llaca above Huaraz. A major problem during projects of this kind was the steep topography. Usually, the first task was the construction of a road in steep and difficult terrain from the Santa valley to the construction site. Not all lake modifications were without problems. On October 20, 1950, Lake Jankarurish in the Quebrada Alpamayo produced an aluvion which completely destroyed the installations of the Huallanca hydroelectric power plant under construction at the time on the lower Santa River. A tunnel was filled with debris and the main bridge and three railway bridges were washed away. Officially, 200 people were reported dead but other estimates give figures of 500. At the time of the flood, a group of workers employed by the official institution in charge of preventing floods was lowering the lake level. The immediate cause of the disaster was, most probably, a large wave triggered by an ice avalanche from a glacier on the western slopes of Nevado Alpamayo, causing progressive erosion of the overflow channel. The outburst volume was estimated at some 4 million m^3, increasing downvalley as material from the riverbed and sides got carried along. The material rushed towards Santa River at a speed of about 30 km/h (Ghiglino, 1950).

8.6 GAPS AND NEEDS

A basic task to be undertaken is the completion of the glacier inventory in Chile and Argentina, as much remains unknown. There is a need to know the mass balance of more glaciers along the Andes of Chile and Argentina, not only near Santiago and Mendoza as is presently the case, but also in other parts of the country.

Continuity in the inventorying of glaciers and in glacier mass balance studies has to be established. In addition, an interconnected research cooperative programme is needed to ensure the continuity and enhancement of present glaciological research. Training courses are another must.

8.7 SUGGESTED FUTURE DEVELOPMENT OF MONITORING ACTIVITY

The observed strong glacier retreat in the Peruvian Andes, as well as in other parts of South America (e.g., Central Andes of Argentina since the beginning of the century), is considered an impressive example of the importance of glacier fluctuation measurements, particularly in tropical or subtropical areas. In remote regions or areas with few or no systematic climatological data records, such measurements provide a highly sensitive indicator of recent or subrecent climatic changes. Continued glacier retreat is expected to further affect the local population: new terminal lakes will probably form, thereby creating new potential sources of catastrophic flooding. A further loss in ice masses will, at the same time, temporarily add to the amount of water available for agriculture and hydroelectric power production. In the long run, however, runoff must decrease. Efforts should be made to continue taking these valuable measurements, particularly in view of a potentially persistent trend of atmospheric warming. However, the very limited financial means, coupled with the small number of personnel trained to carry out this work, poses a serious problem.

The marked sensitivity of tropical glaciers to climatic changes means that they are particularly well suited as indicators in the current research on global warming. The high resolution with which the glacier transmits this information makes it a unique instrument with few equivalents in the tropical continental environment. To follow these processes, it is essential to establish a long-term network of studied glaciers in the Central Andes. With this network as a starting point, research should be directed towards the following:

1) A better understanding of the functioning of tropical glaciers must be developed by studying their balances at shorter time intervals (days, months): energy balance, glacial balance, hydrological balance.
2) The possible effects on tropical glaciers of an increase in temperature, as estimated by global circulation models, must be analysed.
3) The impact of ENSO events according to the latitude (Equator–Tropics) and the areas of climatic influence in the Cordillera (Amazon and Pacific) must be quantified.
4) A rapid and broad glacial retreat for the high Andean catchments must be analysed from the viewpoint of potential consequences for the hydrological regimes and the effects on water resources of a possible increase in the risk of glacial hazards (avalanches, overflow of glacial lakes).

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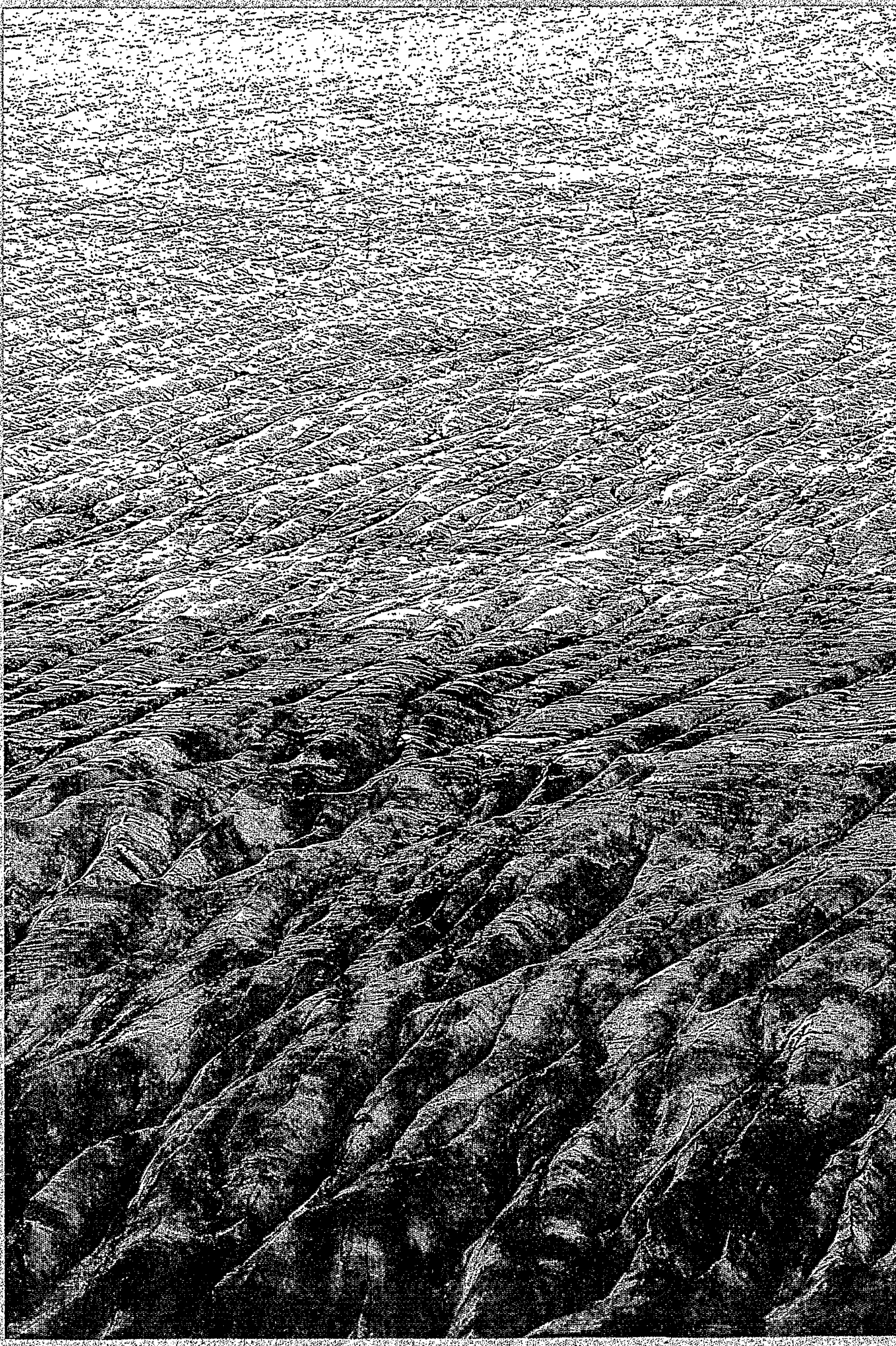
Into the second century of worldwide glacier monitoring: prospects and strategies



Studies and reports in hydrology 56

UNESCO

Into the second century of worldwide glacier monitoring-prospects and strategies

A contribution to the
International Hydrological Programme (IHP)
and the
Global Environment Monitoring System (GEMS)

Prepared by the World Glacier Monitoring Service
Edited by W. Haeberli, M. Hoelzle and S. Suter

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Preface

Although a total amount of water on Earth is generally assumed to have remained virtually constant, the rapid growth of population, together with the extension of irrigated agriculture and industrial development, are putting stress on the quality and quantity aspects of natural systems. Because of the increasing problems, society has begun to realize that it can no longer follow a 'use and discard' philosophy – either with water resources or any other natural resource. As a result, the need for a consistent policy of rational management of water resources has become evident.

Rational water management should be founded upon a thorough understanding of water availability and movement. Thus, as a contribution to the solution of the world's water problems, UNESCO, in 1965, began the first world-wide programme of studies of the hydrological cycle – the International Hydrological Decade (IHD). The research programme was complemented by a major effort in the field of hydrological education and training. The activities undertaken during the Decade proved to be of great interest and value to Member States. By the end of that period, a majority of UNESCO's Member States had formed IHD National Committees to carry out relevant national activities and to participate in regional and international cooperation within the IHD programme. The knowledge of the world's water resources had substantially improved. Hydrology became widely recognized as an independent professional option and facilities for training hydrologists had been developed.

Conscious of the need to expand upon the efforts initiated during the International Hydrological Decade and further to the recommendations of Member States, UNESCO launched a new long-term intergovernmental programme in 1975: the International Hydrological Programme (IHP).

Although the IHP is basically a scientific and educational programme, UNESCO has been aware from the beginning of a need to direct its activities towards the practical solutions of the world's very real water resources problems. Accordingly, and in line with the recommendations of the 1977 United Nations Water Conference, the objectives of the International Hydrological Programme have been gradually expanded in order to cover not only hydrological processes considered in interrelationship with the environment and human activities, but also the scientific aspects of multi-purpose utilization and conservation of water resources to meet the needs of economic and social development. Thus, while maintaining IHP's scientific concept, the objectives have shifted perceptibly towards a multi-disciplinary approach to the assessment, planning, and rational management of water resources.

As part of UNESCO's contribution to the objectives of the IHP, two publication series are issued: 'Studies and reports in hydrology' and 'Technical papers in hydrology'. In addition to these publications and in order to expedite the exchange of information in the areas in which it is most needed, works of a preliminary nature are issued in the form of technical documents.

The purpose of the continuing series 'Studies and reports in hydrology', to which this volume belongs, is to present data collected and the main results of hydrological studies, as well as to provide information on hydrological research techniques. The proceedings of symposia are also sometimes included. It is hoped that these volumes will furnish material of both practical and theoretical interest to water resources scientists and also to those involved in water resources assessment and planning for rational water resources management.

Contents

Foreword

International coordination of long-term glacier observations is a century-long tradition. It started with the establishment of the International Glacier Commission during the 6th International Geological Congress at Zurich, Switzerland in 1894. The goals of this worldwide glacier monitoring programme were defined by F.-A. Forel from Geneva, the first president of the Commission, in a remarkable article entitled *Les variations périodiques des glaciers. Discours préliminaire*, published on pp. 209–29 of the Archives des sciences physiques et naturelles (Geneva, Vol. 34).

Since 1894, the goals of internationally coordinated glacier monitoring have evolved and multiplied. Today, the evolution of glaciers and ice caps is recognized as one of the key variables relating to early detection strategies in view of possible man-induced climatic change. The general shrinkage of mountain glaciers during the 20th century is a major reflection of the fact that rapid secular change in the energy balance of the Earth's surface is taking place on a global scale.

As a contribution to the International Hydrological Programme (IHP) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) and to the Global Environment Monitoring System (GEMS) of the United Nations Environment Programme (UNEP), the World Glacier Monitoring Service (WGMS) of the International Commission on Snow and Ice (ICSI/IAHS), as one of the permanent services of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS/ICSU), collects and publishes standardized glacier data.

The present publication was prepared to mark the occasion of the centenary of worldwide glacier monitoring. Scientific review of the text was accomplished by the consultants and national correspondents of WGMS via correspondence. On 12-13 October 1995, a two-day workshop with invited experts from various countries and representatives of sponsoring agencies was held at the Federal Institute of Technology (ETH), Zurich, Switzerland, in order to complete the final editing of the manuscript and, especially, to formulate recommendations for the future.

The volume presented here opens with an original article written by F.-A. Forel and is followed by a selection of thematic and regional chapters. As complete coverage of all glacierized areas of the world was beyond practical possibilities, characteristic examples are given from all continents, including the special cases of the continental ice sheets. The conclusions and recommendations chapter was discussed, edited and agreed upon by the participants in the 1995 expert meeting at ETH Zurich. The Appendices contain lists of the consultants and national correspondents to WGMS as well as a list of the experts participating in the 1995 meeting and the programme.

Thanks are due to ETH Zurich and UNEP for funding the expert meeting, to UNESCO for enabling the present publication and to all authors and reviewers who contributed in one way or another. The expression of our special gratitude and admiration goes to all those individuals and national/international organizations who have initiated, planned, supported and carried through a unique task for ten decades, and hopefully into many more to come. . . .

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