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1 MOUNTAINS AND THEIR CLIMATOLOGICAL STUDY

1.1 INTRODUCTION

It is the aim of this book to bring together the major strands of our existing knowledge of weather and climate in the mountains. The first part of the book deals with the basic controls of the climatic and meteorological phenomena and the second part with particular applications of mountain climatology and meteorology. By illustrating the general climatic principles, a basis can also be provided for estimating the range of conditions likely to be experienced in mountain areas of sparse observational data.

In this chapter we introduce mountain environments as they have been perceived historically, and consider the physical characteristics of mountains and their global significance. We then briefly review the history of research into mountain weather and climate and outline some basic considerations that influence their modern study.

1.1.1 *Historical perceptions*

The mountain environment has always been regarded with awe. The Greeks believed Mount Olympus to be the abode of the gods, to the Norse the Jötunheim was the home of the Jotuns, or ice giants, while to the Tibetans, Mount Everest (Chomo Longmu) is the "goddess of the snows." In many cultures, mountains are considered "sacred places;" Nanga Parbat, an 8125 m summit in the Himalaya, means sacred mountain in Sanskrit, for example. Conspicuous peaks are associated with ancestral figures or deities (Bernbaum, 1998) – Sengem Sama with Fujiyama (3778 m) in Japan and Shiva-Parvati with Kailas (6713 m) in Tibet – although at other times mountains have been identified with malevolent spirits, the Diablerets in the Swiss Valais, for example. This dualism perhaps reflects the opposites of tranquility and danger encountered at different times in the mountain environment. Climatological features of mountains, especially their associated cloud forms, are represented in many names and local expressions. On seeing the distant ranges of New Zealand, the ancestral Maoris named the land Aotearoa, "the long white cloud." Table Mountain, South Africa, is well known for the "tablecloth" cloud that frequently caps it. Wind systems associated with mountains have also given rise to special names now widely applied, such as föhn, chinook and bora, and others still used only locally.

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Today, the majestic scenery of mountain regions makes them prime recreation and wilderness country. Such areas provide major gathering grounds for water supplies for consumption and for hydroelectric power generation, they are often major forest reserves, as well as sometimes containing valuable mineral resources. Mountain weather is often severe, even in summer, presenting risks to the unwary visitor and, in high mountains, altitude effects can cause serious physiological conditions. Concerns over sanctity and safety explain why mountains remained largely unexplored, except by hunters or mineral and plant collectors for much of human history. Scientific exploration of mountains began in earnest in the late-eighteenth century.

Despite their environmental and societal significance, and the fact that mountain ranges account for about 25 percent of the Earth's land surface, the meteorology of most mountain areas is little known in detail. Weather stations are few and tend to be located at conveniently accessible sites, often in valleys, rather than at points selected with a view to obtaining representative data.

Climatic studies in mountain areas have frequently been carried out by biologists concerned with particular ecological problems, or by hydrologists and glaciologists interested in snow and ice processes and melt runoff, rather than by meteorologists. Consequently, much of the information that does exist tends to be widely scattered in the scientific literature and it is often viewed only in the context of a particular local problem.

1.2 CHARACTERISTICS OF MOUNTAIN AREAS

Definitions of mountain areas are unavoidably arbitrary (Messerli and Ives, 1997, p. 8). Usually no qualitative, or even quantitative, distinction is made between mountains and hills. Common usage in North America suggests that 600 m or more of local relief distinguishes mountains from hills (Thompson, 1964). Such an altitudinal range is sufficient to cause vertical differentiation of climatic elements and vegetation cover. Finch and Trewartha (1949) propose that a relief of 1800 m can serve as the criterion for mountains of "Sierran type." Such a range of relief also implies the presence of steep slopes. In an attempt to provide a rational basis for definition, Troll (1973) delimits *high mountains* by reference to particular landscape features. The most significant ones are the upper timberline, the snow line during the Pleistocene epoch (which gave rise to distinctive glacial landforms) and the lower limit of periglacial processes (solifluction, etc.). It is apparent that each of these features is related to the effects of past or present climate and to microclimatic conditions at or near ground level.

On the basis of Troll's criteria, the lower limit of the high mountain belt occurs at elevations of a few hundred meters above sea level in northern Scandinavia, 1600–1700 m in central Europe, about 3300 m in the Rocky Mountains at 40° N, and 4500 m in the equatorial cordillera of South America (see Figure 1.1). In arid central Asia, where trees are absent and the snow line rises to above 5500 m, the only feasible criterion remaining is that of relief.

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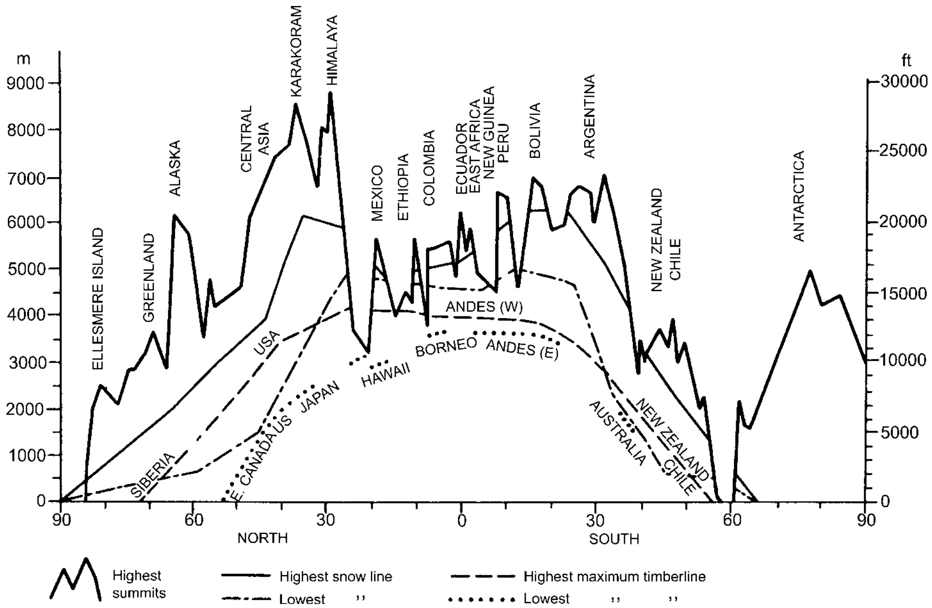

Fig. 1.1 **Latitudinal cross-section of the highest summits, highest and lowest snow lines, and highest and lowest upper limits of timberline (from Barry and Ives, 1974).**

Troll's approach derives from the German distinction between *Hochgebirge* (high mountains), such as the Alps and Tatra, and the lower and gentler ridges of the *Mittelgebirge*, which include the Riesengebirge and Vosges. It is not altogether suitable from the climatological standpoint since, although the altitudinal limit varies with latitude in such a way as to define *alpine* areas and their biota (cf. Barry and Ives, 1974), it is the altitudinal and slope effects, which cause many of the special features of mountain climates. It is worth noting in passing that "alpine" denotes above tree line, although in some mountains this may be ambiguous due to the absence of tree species at high elevation. A climatologically predictive use of tree line altitude (disregarding land use, fire, and a few special genus-specific effects) has been demonstrated by Körner and Paulsen (2004). Data they collected at 46 mountain sites between 42° S and 68° N show that the growing season mean 10-cm soil temperature at the climatic tree line averages 6.7 °C, with only small departures in different climatic zones (5–6 °C at equatorial tree lines and 7–8 °C in mid-latitudes and the Mediterranean zone). The alpine zone gives way to the *nival* zone where vascular plants are largely absent. An alternative terminology uses *eolian* zone, where wind plays a major role; this zone may be seasonally affected by nival (snow-related) conditions and processes, but also has extensive rock cover or rock and snow patches. These characteristics are important for biology and geomorphology, as well as for microclimates, but need not concern us further here.

Table 1.1 The global area of mountains and high plateaus.

	Mountains	Plateaus (10^6 km^2)	Mountains/land surface (%)[a]
3000 m[b]	– 6 –		4.0
2000–3000 m	4	6	2.7
1000–2000 m	5	19	3.4
0–1000 m	15	92	10.1
Total	30	117	20.2

[a] The total land surface is about 149 million km^2, oceanic islands covering 2 million km^2 are not included in the listed areas.
[b] All land above 3000 m.
Source: after Louis (1975).

Table 1.2 Mountain relief based on roughness classes, and the degree of dissection, both shown as percent of the land surface excluding Greenland and Antarctica.

(Very)/high mts	4.4%	(Very)/high plateaus	1.0%
Middle mts	10.1	Middle plateaus	3.3
Low mts	10.5	Low plateaus	8.3
Hills	8.6	Platforms	14.3
Rugged lowlands	3.2	High/middle plains	10.9
		Plains, lowlands	25.4
Extremely dissected	0.4%		
Highly dissected	5.8	Plateaus/plains	25%
Low/mod. dissection	32	Flat/very flat	37

Source: after Meybeck *et al.* (2001).

The treatment in this book emphasizes high mountain effects, due to altitude, although since airflow modifications that arise at even modest topographic barriers can cause important differences between upland and lowland climates, such effects are also discussed.

The geomorphologist H. Louis (1975) estimated that the land surface occupied by mountains is about 20 percent. His simple breakdown is shown in Table 1.1. A recent calculation based on the degree of dissection and altitude range has been made using 1-km digital terrain data for non-glacierized areas of the world aggregated to $30' \times 30'$ cells (Meybeck *et al.*, 2001); Antarctica, Greenland and the Caspian and Aral seas are excluded. Relief roughness (RR) is defined as maximum minus minimum elevation in a cell divided by half the cell length (in units of m/km or ‰). Mountains are defined as having $\mathrm{RR} > 20‰$ for a mean elevation 500–2000 m and $\mathrm{RR} > 40‰$ at higher elevation. Their results (Table 1.2) indicate that mountains make up 25 percent of the land area. Mountains are also shown to provide 32 percent

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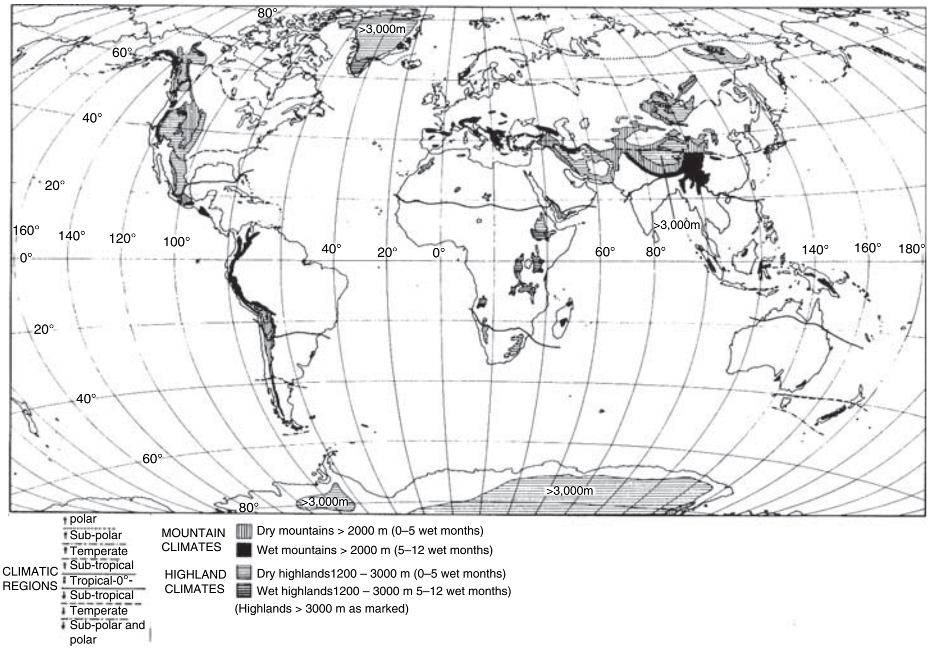

Fig. 1.2 Alpine and highland zones and their climatic characteristics (after N. Crutzberg, from Ives and Barry, 1974).

of global runoff; appropriately they have been dubbed "water towers of the twenty-first century" (Mountain Agenda, 2002). Moreover, 26 percent of the world's population lives in mountain and high plateau regions.

The locations of the major mountain ranges and highland areas of the world and their climatic zonation are shown in Figure 1.2. The most latitudinally extensive mountain chains are the cordilleras of western North and South America. The most extensive east–west ranges are the Himalaya and adjoining ranges of central Asia. Reference should also be made to the vast highland plateau exceeding 4000 m in Tibet and the even larger ice plateaus of Greenland and Antarctica. All of these regions have major significance for weather and climate at scales up to that of the general circulation of the atmosphere. In contrast, major, but isolated, volcanic peaks that occur in east Africa and elsewhere, have their own distinctive effects on local weather and climate.

1.3 HISTORY OF RESEARCH INTO MOUNTAIN WEATHER AND CLIMATE

Intensive scientific study of mountain weather conditions did not begin until the mid-nineteenth century although awareness of the changes in meteorological elements with altitude came much earlier. The effect of altitude on pressure was proved in September 1648 when Florin Périer, at the request of his brother-in-law

Blaise Pascal, operated a simple Torricelian mercury tube at the summit and base of the Puy de Dôme in France. In August 1787, H. B. de Saussure (1796), who was a keen mountaineer, made observations of relative humidity during an ascent of Mont Blanc using the hair hygrometer, which he had developed. His instruments are on display in Geneva (Archinard, 1980, 1988). In July 1788, he and his son maintained two-hourly meteorological observations on the Col du Géant (3360 m) near Mont Blanc while comparative observations were made at Chamonix (1050 m) and Geneva (375 m). Carozzi and Newman (1995) give information on these ascents and de Saussure's other journeys around Mont Blanc, including his observations about snow and glaciers. From these data, de Saussure was able to study temperature lapse rate and its diurnal variation, obtaining an estimate close to that of Julius von Hann a century later. His writings discussed eighteenth-century theories of the reason for low temperatures in the mountains and he came closer to modern views than most physicists of his day (Barry, 1978). De Saussure also attempted to measure altitudinal variations of evaporation and sky color and was fascinated by numerous other mountain weather phenomena and human response to high-altitude conditions. He can rightfully be regarded as the "first mountain meteorologist."

In the 1850s, meteorological measurements begin to be made systematically on high mountains, often in association with astronomical studies, as on the Peak of Tenerife (Canary Islands) (Smyth, 1859). In the United States, the earliest extensive observations were those made in the summers of 1853 to 1859 on Mt. Washington, New Hampshire (1915 m) (see Stone, 1934). The establishment of observatories by the US Signal Service soon followed on Mt. Washington in 1870 and on Pike's Peak, Colorado (4311 m) in 1874 (Rotch, 1892). Observations were also made on Mt. Mitchell, North Carolina (2037 m) in the summer of 1873 (Howgate and Sackett, 1873). In Europe, similar developments took place following a suggestion made by J. von Hann at the second International Meteorological Congress in Rome, in 1879. The major European countries established observatories (Rotch, 1886; Roschkott, 1934), particularly in the Alps, where many of these stations are still operating. The impressive location of the Sonnblick Observatory, Austria (Böhm, 1986; Auer *et al.*, 2005) is shown in Figure 1.3. A summary of the location and periods of operation of the major observatories/weather stations is given in Table 1.3.

After the initial enthusiasm for mountain weather data in the United States, a number of problems led to a decline in interest in maintaining mountain observatories (Stone, 1934). On the technical side, the telegraph lines were hard to maintain, while a suitable basis for incorporating the data into the synoptic weather-map analyses, then based almost solely on surface weather observations, did not exist. Both Mt. Washington and Pike's Peak were closed by the Weather Bureau in the 1890s, and in Scotland the same fate befell the Ben Nevis Observatory in 1904, due to a lack of funds (Roy, 1983). The value of such observatories in connection with upper air studies was raised again in the 1930s when aerological

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Fig. 1.3 **The Sonnblick Observatory in April 1985 (R. Boehm).**

networks were first being established (Bjerknes *et al.*, 1934). Mt. Evans, Colorado, for example, was used as a site for ozone measurements and new determinations of ultraviolet radiation (Stair and Hand, 1939). Mountain stations can operate in any weather conditions and collect data for 24 hours of the day, whereas soundings are made only twice per day and may be restricted by weather conditions. Partly as a result of such concerns, the Mount Washington Observatory was re-established during the International Polar Year 1932–33 and continues in operation (Smith, 1964, 1982). The only recent development is the establishment of Mauna Loa Observatory (Price and Pales, 1963), which has assumed major importance as a bench mark monitoring station for solar radiation and atmospheric gases. The Zugspitze Observatory in Germany has served as a base for aerosol, atmospheric electricity and radioactivity studies (Reiter, 1964) and the Weissfluhjoch in Switzerland for snow research (*Winterberichte No 15*, 1950).

In other areas of the world, mountain weather data were primarily collected by survey parties, such as those in the Himalaya (Hill, 1881), or by expeditions like those from Harvard University to the Peruvian Andes between 1893 and 1895 (Bailey, 1908). There were many such scientific expeditions, some specifically for meteorological purposes. These included early attempts to determine the extra-terrestrial solar radiation (see p. 35). In addition, climatic records have been collected from many second-order or auxiliary stations in mountain regions around the world. For long-term records (with published climatic mean data for 1931–60), there are about twenty stations around the world located above 2000 m according to Lauscher (1973). However, some of these are situated on high plateaus, in

Table 1.3 Principal mountain observatories.

Name	Country/state	Location	Elevation[a](m)	Records	References
Asia					
Mt. Fuji	Japan	35° 21′ N, 138° 44′ E	3716	1888–1931 (summers) 1932–	Fujimara (1971)[b]; Solomon (1979); Ohmura and Auer (2004)
O Mei Shan	China	29° 28′ N, 103° 41′ E	3383	1932–3	Lauscher (1979b)
Europe					
Fanaräken	Norway	61° 31′ N, 7° E	2062	1932–[d]	Spinnangr and Eide (1948); Manley (1949)[b]
Haldde	Norway	69° 56′ N, 22° 58′ E	893	1902–26	Brekke (2004)
Ben Nevis	Scotland	56° 48′ N, 5° 0′ W	1343	1893–1904	Buchan and Omond (1890–1910)[b]
Brocken	Germany	51° 48′ N, 10° 37′ E	1142	1895–[d]	
Fichtelberg	Germany	50° 26′ N, 12° 57′ E	1213	1891–	Pleiss (1961)[b]
Sniezka (Schneekoppe)	Poland	50° 44′ N, 15° 44′ E	1603	1881—→[d]	Hellman (1916)
Hohenpeissenberg	Germany	47° 48′ N, 11° 01′ E	989	1781–[c]	Grunow *et al.* (1957)[b]; Lauscher (1981)
Zugspitze	Germany	47° 25′ N, 10° 59′ E	2962	1900–[c]	Hauer (1950)[b]
Sonnblick	Austria	47° 03′ N, 12° 57′ E	3106	1886–[c]	*Jahresbericht des Sonnblick – Vereines* (1892–); Steinhauser (1938); Böhm (1986); Auer *et al.*, 2005
Hoch Obir	Austria	46° 30′ N, 14° 29′ E	2044	1847–1943[c]	Lukesch (1952)
Rudolfshuette	Austria	47° 08′ N, 12° 38′ E	2315	1960–7. 1967–summers, 1980–synoptic	Slupetsky (2004).

Villacher Alp	Austria	46° 34′ N, 13° 39′ E	2140	1929–(1971). 1994– AWS	Boehm (2004)
Säntis	Switzerland	47° 15′ N, 9° 20′ E	2500	1882–[c]	
Jungfraujoch	Switzerland	46° 33′ N, 7° 58′ E	3577	1923–[c]	Maurer and Lütschg (1931)[b]
Davos Weissfluhjoch	Switzerland	46° 50′ N, 9° 49′ E	2540	1936–[d]	*Winterberichte* (1950–); Zingg (1961)
Lomnicky Stit	Slovakia	49° 12′ N, 20° 13′ E	2635	1940–, 1996– AWS, 2000– synoptic	Nieplovo and Pindjak (1992); Stasny (2004)
Moussala	Bulgaria	42° 11′ N, 23° 35′ E	2925	1932–	Tzenkova-Bratoeva (2004)
Kredarica	Slovenia	46° 23′ N, 13° 51′ E	2514	1897–1912 (climate data), 1954–	Cegnar (2004)
Bjelasnica	Yugoslavia	43° 42′ N, 18° 15′ E	2067	1895–1915	Forster *et al.* (1919); Muminovic (2004)
Mont Blanc	France	45° 50′ N, 6° 52′ E	4359	1887–93 (summers)	Vallot (1893–98); Hann (1899) Tutton (1925)[b]
Pic du Midi de Bigorre	France	42° 56′ N, 0° 08′ E	2860	1881–[d]	Klengel (1894); Bücher and Bücher (1973)
Puy de Dôme	France	45° 47′ N, 2° 57′ E	1467	1878–	Woeikof (1892)
Monte Rosa	Italy	45° 56′ N, 7° 53′ E	3560	1927–39, 1952–8	Mercalli (2004)
Plateau Rosa	Italy	45° 56′ N, 7° 12′ E	3480	1951–2000	Mercalli (2004)
Monte Cimone	Italy	44° 12′ N, 10° 43′ E	2165	1887–(discontinuous until 1945)	Mercalli (2004)
Mt. Etna	Italy	37° 44′ N, 15° 0′ E	2950	1892–1906	Obermayer (1908)
Izana	Tenerife	28° 18′ N, 16° 30′ W	2367	1915–[c]	Tzchirner (1925); Lauscher (1975); Cuevas (2004)
Mt. Olympus	Greece	40° 03′ N, 22° 21′ E	2817	1963– (summers)	Livadas (1963) Kyriazopoulos (1966)

Table 1.3 (cont.)

Name	Country/state	Location	Elevation[a] (m)	Records	References
North America					
Mt. Washington	New Hampshire	44° 16′ N, 71° 18′ W	1914	1890–2; 1932–	Stone (1934)[b]; Smith (1964), (1982); Leitch, (1978); Mount Washington Observatory (1959); Grant *et al.* (2005)
Pike’s Peak	Colorado	38° 50′ N, 105° 02′ W	4311	1874–88; 1892–4	US Army, Chief Signal Officer (1889)
Lick Observatory (Mt. Hamilton)	California	37° 20′ N, 121° 38′ W	1283	1880–	Reed (1914)[b]
Mauna Loa	Hawaii	19° 32′ N, 155° 35′ W	3399	1959–	Price and Pales (1963); Miller (1978)[b]
South America					
El Misti	Peru	16° 19′ S, 71° 23′ W	5822	1893–5	Bailey (1908)[b]
Corrido de Cori	Argentina	25° 06′ S, 68° 20′ W	5100	1942	Miller (1976)
Cristo Redentor	Argentina	32° 50′ S, 70° 05′ W	3800	1935–[c]	Prohaska (1957)
Collahuasi	Chile	21° 0′ S, 68° 45′ W	4810	1914–15	Lauscher (1979a)
Chuquicamata	Chile	21° 07′ S, 68° 31′ W	2710	1914–15	Lauscher (1979a)

[a] The largest published station reference height is given where possible. Elevations may differ by a few meters in different sources; sometimes this is due to reference to the corrected barometer height.

[b] These references generally describe the site and the history of the installation. They also include data tabulations in most cases.

[c] Annual values for these stations are contained in World Weather Records (Clayton 1944a, b, 1947; US Dept of Commerce 1959, 1966, 1968)

[d] Annual values for these stations are contained in Meteorological Office (1973) which also lists sources (in most cases for the period 1931–60).