The status of our present understanding of mountain climates and our capabilities to detect and monitor climate change

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ABSTRACT

Climatic knowledge of mountain regions is limited by paucity of observations and insufficient theoretical attention to processes within these regions. Areas where our theoretical understanding is incomplete include orographic precipitation, especially extreme events, pollutant transport and deposition, and effects of forest cover on evapo-transpiration and runoff.

Direct and indirect evidence of past climatic conditions in many mountain areas of the world suggests substantial changes over the last one hundred years, as indicated most strikingly by glacial recession. Modeling approaches to assessing potential future climatic states are discussed in the context of mountain areas. Reductions in snow cover duration and changes in the amount of timing of snow melt runoff are described.

The survey concludes with a series of recommendations for necessary actions to improve our capabilities for monitoring and detecting climatic changes in mountain areas and for assessing their significance and possible impacts.

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I. INTRODUCTION

A. SCOPE OF THE PROBLEM

Our knowledge of the climatic characteristics of mountain regions is limited by both paucity of observations - short records that seldom span one hundred years and a sparse station network - and insufficient theoretical attention given to the complex interaction of spatial scales in weather and climate phenomena in mountains. Meteorological research has tended to focus on the influences of barriers on air flow and on orographic effects on weather systems rather than on conditions within the mountain environment. Small-scale elements of the landscape surface, such as vegetation canopy, large rocks and hollows, create microclimatic contrasts in surface heating, soil moisture or snow-cover duration that have longer lasting significance. The role of sunny and shaded slopes in influencing land use and settlement location in the Alps has been long recognized. Local wind systems, generated by radiational and thermal contrasts in complex terrain, are best developed when synoptic-scale pressure gradients are weak and there is little cloud cover; hence, they are intermittent components of the climate. Synoptic-scale weather systems - midlatitude cyclones and frontal zones, for instance - are extensively modified as they move across a mountain barrier. Modifications occur on a large scale in terms of changes in frontal structure and cloud systems, and on a local scale in terms of winds, such as Fohn (Chinook) occurrence, or precipitation intensity. Isolating these processes in order to understand their operation is vastly complicated by the inadequate data base for most mountain areas of the world.

Mountain influences on climate and related environmental features are a result of four basic factors: altitude, continentality, latitude and topography - each of which affects several important meteorological variables. The role of these factors are summarized schematically in Table 1 where the effects refer to responses to an increase in the factor listed. In turn, these climatic differences are expressed in vegetation type and cover, geomorphic, and hydrologic features. The particular influences of topography are complex and worthy of

further discussion. At a primary level, we need to distinguish between isolated peaks, mountain ranges that are large enough to modify the upstream and downstream airflow substantially, and extensive high plateaux that create major barriers to air motion and generate their own climates. High peaks experience similar temperatures to the free air of the same altitude, whereas elevated plateaux are heated in summer and cooled in winter by radiative processes. Valleys within uplands have 'enclosed' atmospheres that are diurnally modified by nocturnal cooling, especially in winter, and enhanced daytime heating.

Table 1 identifies one area important for human activities in high mountains, namely, the physiological stresses imposed by climate. The primary factors are reduced air pressure, which limits oxygen intake and working capacity, and low temperatures, which necessitate adequate clothing and shelter and place limits on crop production potential. However, these primary factors differ in their significance. Low air pressure is a permanent unavoidable condition, whereas low temperatures can be counteracted.

Table I: Climatic effects of the basic controls of mountain climate

Factors	**Primary Effects**	**Secondary Effects**
Altitude	reduced air density, vapor pressure; increased solar radiation receipts; lower temperatures	increased wind velocity (mid-latitude); increased precipitation (mid-latitude); reduced evaporation: physiological stress
Continentality	annual/diurnal temperature range increased; cloud/precipitation regimes modified	snow line altitude rises
Latitude	day length and solar radiation totals vary Seasonally	snowfall proportion increases; annual temperatures decrease
Topography	spatial contrasts in solar radiation/tempera- temperature regimes, and precipitation as a result of slope and aspect	diurnal wind regimes; snow cover related to topography

B. SPECIFIC MOUNTAIN CLIMATE DATA

1. The European Alps are by far the best-known mountain area of the world in terms of weather and climate and related environmental characteristics. Several summit observatories have records spanning 100 years and there is a dense network of regular observing stations and precipitation gauges. Detailed climatic atlases exist for the Tyrol and Swiss Alps. Complementary information exists on Alpine glaciers, hydrologic regimes, forest growth and other mars specific topics. The Alps have also been the locale for the meteorological research programme ALPEX (Alpine Experiment) of the Global Atmospheric Research Programme (GARP) of the World Meteorological Organization, conducted between September 1981 and November 1982, and many university research projects. Extensive studies also exist for the Carpathian mountains.

2. The island of Hawaii is-well-known climatically through observations made at Manna Loa Observatory since 1957 and various research programmes conducted on the windward and leeward slopes of the mountains in Hawaii and other islands. Similar data exist for Mount Fuji. Japan which also has a summit observatory. However, most of the detailed studies on Mount Fuji's climate are published in Japanese.

3. The climatic features of the Rocky Mountains and Coast Ranges in North America and the mountains of Scandinavia are known primarily through specialized university and other agency research programmes. Experiments on winter cloud-seeding and mountain lee-wave phenomena have been of particular importance in North America. Mountain-valley winds and orographic precipitation have been investigated in both Europe and North America. The station networks in these countries are moderately good but permanent mountain observatories are lacking. Detailed glacio-hydrological records are also available for Norway, in particular. The Colorado Rocky Mountains and Scandinavian Mountains have also been sites of ecological research under the International Biological Programmers Tundra Biome studies in the 1970s and in the former area, related work has continued through the U.S. National Science Foundation's Long-Term Ecological Research Program. A similar level of information is available for the Greater Caucasus in terms of climate and glacio-hydrological topics, but almost all of it is in Russian language articles and monographs.

4. A moderate level of information on the climate of very high mountains is available in the case of the northern Andes and Nepal Himalayas. The former area has a reasonable station network, including some high altitude stations; microclimatic studies, related to ecological conditions, have provided valuable supplementary information. The major lack is Serological sounding data for information on free air conditions. The large-scale climatic controls of this area are still poorly defined. In the case of Nepal, most stations are in the Himalayan valleys, but short-term measurements, particularly by recent

Japanese glaciological expeditions, have provided additional information. For the adjacent Tibetan (Qinghai Xizang) Plateau and Tian Shan there is now a growing meteorological literature, although several key studies are available only in Chinese.

5. Mountains where there have been discontinuous research programmes and only a sparse station network is available include such diverse areas as New Guinea, Ethiopia, Mt. Kenya, the Hoggar and the mountains of the Yukon and Alaska. In New Guinea, where there is only one permanent station above 2000 m, information on mountain environments has focussed on ecological conditions in the Bismarck Range and on the glaciers of Mt. Carstenz in Irian Jaya.

C. SELECTED ISSUES

This section provides a brief review of some selected topics of particular importance in mountain climatology. They are issues in the sense that incomplete knowledge of them may present problems in attempting to mitigate their consequences -for the mountain environment and its inhabitants.

1. Orographic Precipitation. Precipitation forecasting in mountain regions is nowadays performed using a combination of numerical model prediction and near-real time radar measurement of precipitation falling, wherever such technology is available. Various numerical models are available to calculate precipitation rates for air ascending adiabatically over a mountain slope and incorporating "spill-over" effects. The concept can also be extended for snowfall and for convective precipitation. Nevertheless, the climatology of precipitation (mean daily, monthly and annual values) is still inadequately known and mapped. There remain uncertainties as to the variation of mean precipitation amounts with altitude even in the Alps. Totals depend not only on elevation, but also on slope orientation and angle with respect to the prevailing wind, and the upwind sheltering of the site. Hence, our ability to assess changes in precipitation in mountain areas that might occur with global climatic change is severely limited since changes will occur in weather system frequencies, wind velocity, cloud cover etc..

Studies in the San Juan Mountains, Colorado, and in the Sierra Nevada, California, in the 1970s sought to evaluate possible ecological impacts of increased winter snow pack and of silver iodide used in cloud seeding on flora, fauna, hydrological and sedimentation processes. The studies in Colorado included intensive plot investigations where snow pack was increased several

fold by the use of snow fences. However, corresponding research on decreases in snow pack have not yet been repotted.

One of the major issues relating to precipitation is the recurrence of extreme events. An intense storm was responsible for the "Big Thompson" flood in the Colorado Front Range that caused at least 139 deaths and $35 million property damage in July 1976. Flooding in basins above about 2400 m altitude in Colorado is related to snow melt, whereas at lower elevations, floods result from intense rainstorms. The latter are caused either by slow-moving summer thunderstorm systems or by synoptic-scale cold lows, mainly in spring and autumn. At the higher elevations, summer stolen precipitation is about an order of magnitude less than in the foothills. Recent research contradict earlier ideas derived from simple transposition of storm models over the higher terrain. This has importance for water control structures and implies that reservoirs and culverts at higher elevations in the Rocky Mountains may have been over designed.

Extreme precipitation events have geomorphological significance in the Himalayas where they may cause widespread slope failure as occurred around Darjeeling in October 1968. The response of hydrological systems, erosion processes and sedimentation to climate change has only recently begun to be addressed.

2. Air quality and pollution deposition. Many mountain valleys are increasingly subject to the effects of air pollution originating from local settlements, industrial plants and automobiles, as well as from the regional transport of pollutants into the mountains from industrial conurbations. The diurnal wind regime in mountain valleys, during intervals of weak regional-scale pressure gradients, gives rise to upvalley and upslope motion by day that may transport pollutants into the mountains. At night the circulations are reversed but, typically, inversion conditions in valley bottoms and basins can lead to high concentrations of pollutants at low-levels. In winter, when solar heating is insufficient to remove them, such inversions can persist for most of the day.

Pollutants reach the surface by dry deposition and washout. In mountain areas, the orographic enhancement of precipitation rates can lead to increased washout and, in spring, snowmelt can result hi a 'flush' of acidity into surface runoff from "acid snow". Possible changes in wind-regimes, inversion frequencies and pollutant transport in a changed climate have received little attention.

3. Afforestation/deforestation of slopes. Studies of the effects of forest cover on local climate have received considerable attention, often showing conflicting results. The effects of differing vegetation cover on catchment hydrology have been studied for many years in Europe, North America and elsewhere. Studies of upland moorland areas transformed by coniferous

plantations have also been made in Great Britain. A survey of 94 paired catchment experiments, where trees were either removed by cutting or burning, or killed by application of herbicides, or the area was planted, concluded that the direction and magnitude of changes in water yield can be predicted with fair accuracy. Many of the experiments were at elevations of 1000 m or more in middle mountain terrain. Pine and eucalypti forest types give a change in annual water yield of about 4 cm per 10% change in forest cover, while deciduous hardwoods cause a 2.5 cm change in yield per 1056 change in cover. The changes are largest in areas of higher rainfall but increases in water yield following forest cover reduction are longer-lived in drier climates as the vegetation recovers more slowly. A further consideration in mountain areas, is that: winter snow packs are generally greater in forested areas than in clearings and they persist longer in the spring.

In some tropical and Mediterranean climates, forested mountain slopes can increase the available moisture through fog drip as a result of the vegetation removing cloud droplets from the airflow. This is an important determinant of the distribution of montane cloud forest, for example. However, the possible management of this moisture source appears to have received little attention.

II. PAST CLIMATE . A. SOURCES OF EVIDENCE

The major types of evidence for past climatic conditions in mountains are briefly summarized.

1. Alpine glaciers. Numerous studies are available in the various mountain areas of the world on glacier variations and past glacier extent. Changes in ice extent and inferred changes in snow line altitude can be interpreted via simple climate/ice models in terms of likely changes in ablation-season temperature and winter accumulation, although unique solutions cannot be derived. Statistical analyses of glacier data from western America show that cumulative deviations of mass balance from the mean value for each glacier are strongly correlated up to about 500 km distance, implying that useful regional climate information can be infected from glaciological observations.

2. Ice cores. The extraction of climatic and other atmospheric signals from ice cores has considerable potential in high-altitude ice bodies above the zone of melting. The ice preserves records of atmospheric gas concentrations, aerosols, pollen and volcanic dust, as well as isotopic composition of the snow (related to crystallization temperature of the atmospheric water vapor) and net accumulation rate. On alpine glaciers the records span a few thousand years. Ice core studies in mountain areas include those on Quelccaya Ice Cap, Peru; Colle Gnifetti and Mont Blanc, Switzerland; and Dunde Ice Cap, western China. Drawbacks are the limited number of suitable cold fire sites and the rather short records available from alpine ice bodies. The information is

representative of a regional-scale area and this may be valuable in assessing regional anthropogenic effects, such as pollution.

3. Tree Rings. Tree ring records provide annual or even seasonal resolution over hundreds to a few thousands of years. Two distinct techniques provide climatic information. The first, widely employed, dendroecological method is to measure annual ring width and the second is to analyze wood density. Ring width, when corrected for age trend, varies strongly in response to summer temperature towards the polar and upper attitudinal tree-lines, and to summer moisture near the lower attitudinal tree-line in arid regions. Detailed quantitative interpretation of the ring width or wood density information involves the development of numerical transfer functions, analogous to those for pollen studies, based on climatic records at nearby stations. Tree ring studies can also be used to determine fire histories and volcanic eruptions, as well as streamflow conditions using ring width - runoff calibrations.

4. Historical records. Direct reports of weather-related conditions are contained in personal diaries and official records in European countries, China, Japan, and elsewhere from the 16-17th centuries, as interest in natural science developed, or even earlier in association with documentation of agricultural production for taxation purposes. In the Alpine countries, Britain, and Scandinavia, in particular, some of these sources provide information on the climatic deterioration in mountain and upland areas during the Little Ice Age, AD-1550-1850, compared with the Medieval Warm Period. Extraction of quantitative material from such sources requires skilled knowledge of historical document interpretation (the necessity for primary sources, content analysis, and consistency checking) and means of standardizing incomplete or short-period records from a particular location with modem data.

5. Instrumental observations. Systematic observations at mountain observatories did not begin until the late l9th century. There are some 22 stations in Europe, 8 in Asia, and 37 in the USA above 1,500 m with long-term (>30 yr.) records. However, not all of these are mountain stations - some are on high plateaux and others in mountains valleys. Second-order and auxiliary stations with shorter records are perhaps ten times more numerous.

6. Remote Sensing. Airborne or satellite remote sensing provides spatially extensive views of surface conditions at specific time intervals. Examples of useful records include air photographs of glacier extent in remote alpine mountain areas and global satellite mapping of snow cover since about 1970. Operational snow mapping of 28 river basins in western North America is performed by NOAA/NESDIS using daily-coverage GOES 1 km-resolution data. Daily AVHRR data from NOAA polar-orbiting satellites are also used by many countries for similar purposes. In both cases, such data are usually supplemented by airborne gamma-radiation measurements and/or ground observations of snow depth and water equivalent. Cloud cover limits the use of

visible and infrared satellite data and passive microwave data currently lack the resolution needed for studies of mountainous regions.

B. PAST CONDITIONS

1. Glacier and Snow Cover Records. The glacier fluctuations identified in major mountain regions during the post-glacial period (the last 10,000 years or so) show broad similarities. However, the more detailed records of the last 1000 years show significant regional differences. The glaciological expression of climate fluctuations depends strongly on the continentality of the climate, with more pronounced fluctuations occurring in humid climates and lesser ones in drier areas.

Retreat of glacier fronts and negative mass balances characterized most glaciers in the Alps and other alpine areas from around 1900 until the 1960s-1970s with only brief interruptions. Smaller glaciers in the European Alps underwent some advance in the 1980s, in response to increased winter accumulation and slightly cooler summers, but this interval appears to have ceased. In contrast, large Alpine glaciers have continued to-retreat since the late nineteenth century; Maritime glaciers in west coast areas of North America and Scandinavia showed similar advances associated with precipitation increases during the 1980s whereas glaciers in continental interior locations mostly continued to retreat. Records of snow cover assembled for the Alps show variations in spring melt of up to a month over the last century. The period 1920-53 experienced particularly warm spring-early summer months at altitudes above 1,800 m to 2,000 m in the vicinity of Mount Santis becoming snowfree 3 to 4 weeks earlier than in the late nineteenth century. Later melt in 1954-80 was related primarily to a slight increase in precipitation (falling as snow). Overall, the snowline in the Grisons Canton is estimated to have risen 77 m + 51 m since 1850. The average number of days with snow cover at Sonnblick, Austria (3106 m) during May to September decreased from 82 days for 1910-25 to only 53 days for 1955-70. During the same interval, mean summer temperatures rose about 0.5°C.

2. The climate record. It is of interest to know what climate changes mountain regions have experienced. Mountain observations can provide an indication of changes in the free atmosphere for a much longer period than sounding data, but up to now, such records have received limited attention. Measurements on the Zugspitze and Sonnblick in the Alps provide such long-term series, but even at these stations there are problems of data homogeneity due to changes of instrumentation or observing practice. The 100-year record on the Sonnblick, Austria, shows the well-known early twentieth-century warming between 1900 and 1950 of about 2°C in spring and summer and 2.5°C between 1910 and 1960 in October. In winter, however, no clear trend is apparent although the 1970s were warmer than the early part of the century. This contrast with the general northern hemisphere trend, where the warming is most pronounced in winter,

may reflect the free-air lapse-rate conditions at the mountain summit. In the Pyrenees, the Pic du Midi de Bigorre observatory (now closed) reported a 0.83°C rise of mean annual temperature between 1878 and 1984, associated with increased cloudiness; the warming was greatest in here in spring and autumn. There was also a pronounced decrease in mean diurnal temperature range at this station, as reported elsewhere in association with greater cloudiness. Records for five valley stations in the Canadian Rocky Mountains covering a common period of 1916-88 show important topoclimatic differences. Only Banff, with almost a Midyear record, shows an overall positive trend in mean annual temperatures.

The climatic response to a given weather system may be quite different in the lowlands from that at higher altitudes. In winter, storm systems from the west bring rainfall and induce snow melt in the lowland but snowfall in the Alps, whereas during anticyclonic situations inversions with fog may maintain lowland snow cover, but permit melt above the inversion on south-facing slopes. In spring, the increased -amounts of- precipitation fall as-~ snow above 2,500 m, but only 50-60 percent of the precipitation falls as snow at 1,200 m. As a result of these complexities, changes in snow cover at lower elevations are often poorly correlated with those on neighboring mountains.

Records from mountain observatories enable us to compare the degree of parallelism and relative amplitudes of trends in the mountains and on the adjacent lowlands. Analyses illustrating trends of sunshine and snowfall in lowland and mountain regions of Austria are among the most complete such records available. Annual sunshine totals at Sonnblick (3,106 m) and Villach (2,140 m) show fluctuations similar in timing and amplitudes to those at four lowland stations. This agreement holds also on a seasonal basis, except in winter as a result of inversions associated with lowland fog and stratus. Variations in snow cover duration in Austria since 1900 show inter-regional differences with stations in western Austria and the southern Alps displaying patterns that are different from those in the northern Alpine Foreland and northeastern Austria.

There are quite long records of snow depth data at mountain stations in the Alps and at snow courses in the North American Rocky Mountains and Cordillera. However, in only a few instances have these been digitized and archived. Consequently, these records have been under-utilized for climatic analyses of temporal change. Two recent studies using such information serve to illustrate the potential complexity of spatio-temporal changes. Snow depth data at Davos (1540 m), Switzerland, are available since 1892. Snow depth on 1 January increased from S 50 cm in the 1890s to 80-90 cm around the 1920s, and declined to about 30 cm in the mid 1930s. Subsequently, depths increased again and have been more or less constant, around 50 cm, up to l990. Nevertheless, snow pack water equivalent on 15 April has substantially exceeded that on I January since about 1975, whereas the two values were

similar from 1950 to 1965 indicating more snowfall in late winter. In the southern and western Alps, 1988 and 1990 were particularly poor snow seasons in the early winter but the century-long Davos record shows that such short term anomalies are recurrent and need not indicate a warming trend.

Records from snow courses (on I April) at 275 high-elevation sites in Idaho, Montana, Wyoming, Colorado and Utah for 1951-1989 show that a shift in the north-south distribution of snowpack occurred in the mid-1970s. Winter seasons with heavy snowfall in the "northern" Rockies and low snowfall in the "southern" Rockies were confined to the period 1951-73, while seasons with the opposite pattern were likewise confined to the 1976-89 period. This appears to be a natural fluctuation associated with a change in the frequency of depression tracks. Long-term climate information for the high Andes is provided by ice cores collected from the Quelccaya Ice Cap in southern Peru (14°S, 71°W, 5670 m above sea level). Annual layers for the last 1500 years suggest that a recent decrease in precipitation may be associated with more-frequent El Niño events in the western Pacific. The interval A.D. 1500-1720 was identified as the wettest part of the record.

III. FUTURE CLIMATE

A. ASSESSING FUTURE CLIMATE

Assessments of potential future climatic conditions can be made by one of two main approaches:

1. Analogues. Analogues of previous events identified from observations, historical or geological records may serve as a basis for projecting possible future regimes. For example, warm/cold years or wet/dry years have been grouped either from individual extreme years or longer intervals of one or other regime as a basis for scenarios of regional conditions. However, the observational record is considered too short to represent potential future greenhouse gas-induced changes adequately.

2. Atmospheric models. Atmospheric models can be used to simulate the effect on global climate of various changes in climatic forcing (e.g., in solar radiation, greenhouse gas concentration, surface boundary conditions due to deforestation and desertification). They can incorporate the major physical processes that interact to determine regional climates. Nevertheless, many of the processes involving ocean-atmosphere and biogeochemical interactions are still treated rather crudely. Computing limitations also necessitate relatively coarse spatial resolution (equivalent to about 1° latitude at best) and therefore mountain terrain is often greatly smoothed. This is known to produce errors in the simulated wind and moisture fields and therefore in the distribution of clouds and precipitation in particular. Moreover, model climate outputs are conventionally presented for sea level and ignore conditions at the surface over

elevated mountainous regions. To address this problem, local climatic conditions may be assessed empirically using statistical relationships for the observed present climate. This assumes that-similar relationships would still obtain under a different global regime.

Recently, attention has turned to using a high-resolution limited area model nested within a GCM to examine regional climate change. GCM output is used to provide the boundary conditions for a limited area model that can provide a resolution of 10-100 km over areas of 1-25 x 106 sqkm. Such studies have been performed for the western United States and for western Europe. Investigations of regional greenhouse-gas induced climate change scenarios are planned with this methodology for the near future.

B. POTENTIAL SIGNIFICANCE OF CHANGES IN CLIMATE FOR MOUNTAIN ENVIRONMENTS

Mountain snow packs are of major significance in a number of respects. First, they are a primary water resource for adjacent lowlands in terms of agricultural use (irrigation), industrial use and drinking water, as in the western United States where about 70 percent of the water required by agriculture. Originates from mountain snow packs. A different water usage exists in Norway, for example. where snowmelt runoff is utilized for hydropower generation. Second, adequate snow depths and duration of snow cover are the essential elements of winter sports developments, now widespread in mountain regions of both hemispheres. Third, the snow pack characteristics are important in providing habitat for small animals and in creating a mosaic of microenvironments for plant cover in mountainous terrain. In human terms, the snowpack properties and climatic elements also determine the potential for avalanche occurrence and for drifting and blowing snow. Climatic factors that may cause significant changes in mountain snow cover are now considered in the context of the above concerns.

1. Snow cover duration. The duration of snow cover is almost linearly related to altitude in most mountain areas. A modest rise in mean snow line with a shorter snow cover duration would virtually eliminate the season for winter tourism in the Australian Alps. Meteorological factors combined with the modest elevation of this area also give rise to a large year-to-year variation in snow depths at present.

Using climate simulations from two GCMs for CO, -doubling, and climate data for two downhill skiing centres in Ontario, Canada, it is suggested that the ski season at Lakehead on the northwest shore of Lake Superior could be reduced 31 to 44 percent with economic losses approaching $2 million (Canadian) while in the Georgian Bay area further south, downhill skiing would be virtually eliminated. The Georgian Bay skiing resorts could lose $37 million annually and

the service centre a further $13 million (Canadian). Such conditions occur there at present during mild winters.

2. Snow depth. There are detailed analyses of snow depths in relation to altitude and aspect for Switzerland. Compared with a horizontal surface, depths in late March are twice as great on a 20° north facing slope, but only 30 percent of horizontal on a 20° south-facing slope. Such aspect differences need to be considered in any assessment of potential future changes in snowfall amount and snow cover duration. Less readily detectable in standard climatological records would be the character of recent winter seasons in the European Alps where the snowfall shows little change in amount but the timing of significant accumulation is delayed beyond late December - early January. Such shifts have major effects on winter sports.

3. Snowmelt runoff. Since most precipitation at high elevations falls as snow, the timing of runoff is primarily determined by snow melt and therefore spring temperatures and solar radiation. European runoff studies deal primarily with partly-glacierized basins. Discharge from-tributaries of the upper Rhine are inversely correlated with mean summer temperatures at valley stations such as Sion. A IOC lowering in mean May-- September temperature at Sion between 1941-5() and 1968-77 was associated with a 26 percent reduction in mean summer discharge. Estimates of the decreases in area and volume of ice cover in the Alps over the last century Suggest that the area shrank from approximately 4,368 km m the 1870S to 2,909 km in the 1970S (a decrease of 15 km/yr.) while the ice volume decreased 57 + 20 km3 to 140 + 10 km3 in the 1970S (a rate of -0.574 km3 yr.

Studies of changes in the hydrology of a medium-sized catchment in California, based on GCM simulations indicate some of the likely general characteristics that may be anticipated for a global warming. These include (1) decreased winter snowfall and reduced spring-summer runoff and soil moisture and (2) increased winter runoff, due to more winter rainfall and earlier snow melt. The seasonal distribution of runoff in watersheds with seasonal snow cover is mainly sensitive to temperature, which accelerates snow melt. However, total annual runoff is more sensitive to precipitation changes. Such investigations need to be carried for mountain watersheds in other parts of the world. Studies of basins with glaciers in the Alps indicate increases in runoff associated with any warming trend and changes in its seasonal distribution and magnitude.

C. DIRECT ANTHROPOGENIC IMPACTS VERSUS GLOBAL CLIMATE CHANGES

The relative importance of climatic factors versus human influences in causing environmental change is generally difficult to disentangle. The removal of vegetation cover, particularly forests, by logging is readily apparent. In a case study for the northern slope of the central Caucasus, an attempt has been made to calculate the relative effects of anthropogenic versus natural changes

on heat and water budgets. Between the second half of the nineteenth century and the 1980s, the forested area decreased from 32 percent to 14 percent in the Kabardin-Balkaria foothills between Mt. Elbrus and Nalchik and the snow/ice covered area shrank as the equilibrium line altitude rose. In the nival-glacial belt, a decrease in runoff has resulted mainly from an 11 to 12 percent reduction in precipitation. In the formerly forested areas, now steppe or meadow, where precipitation amounts have increased by 5 to 10 percent, evaporation has also decreased and runoff increased. At lower altitudes, anthropogenic impacts are more significant than the natural changes, whereas the converse is true at higher altitudes.

IV. STATUS OF KNOWLEDGE AND RECOMMENDATIONS

A. DATA

This survey indicates that there are significant gaps in the available data base on mountain climates. First, there is no convenient inventory of existing (or former) mountain climate stations, much less a catalogue of data collected by them. Assembling such information from national archives would he tedious but of modest cost relative to the value of a well-documented, accessible (computer-compatible) data base. It would need to be updated annually.

Second, there are many mountain areas, notably in the Noah and South American Cordillera, with very few permanent mountain stations. This situation will not be easily remedied, although the increased reliability of automatic weather stations operated by solar power offers a possible solution.

B. UNDERSTANDING OF PROCESSES

Theoretical studies of mountain meteorology have focused on the synoptic-scale effects of mountain terrain (cyclone and precipitation modification on the windward slopes; and lee cyclogenesis downstream), or on mesa-scale features such as local winds and lee waves. Studies within mountain regions have concentrated heavily on mountain-valley winds, the effects of topography on radiation, and weather modification. Many basic questions concerning the attitudinal variation of water balance components and energy budget components, for example, have been relatively neglected. Such questions are of great importance if climate model results are to be interpreted properly within areas of complex terrain. Investigations of mountain climate via the assembly of existing data, the synthesis of previous studies, and the installation of improved networks of stations collecting basic climatological data could contribute much to improved understanding.

Mesoscale numerical models suitable for studies of local circulation, diffusion and air quality, as well as of precipitation prediction, are well developed and have been applied to many regions or complex terrain, if not to high mountain

areas. The problem of using GCMs for climate change scenarios may be capable of resolution via the nested model strategy or statistical downscaling, but such work is only just beginning. The availability of suitable observational data for the validation of such analyses is likely to be a serious deficiency.

C. CONSTRAINTS

The limited progress in climatological studies in mountain legions is attributable primarily to insufficient funding. This has affected not only the maintenance of high-altitude stations, especially observatories, but also the training of scientific personnel. There has been a failure to recognize the need for climate studies in areas of complex terrain, where measurements may be difficult to interpret in a regional context and where operational costs may be high. Nevertheless, modern automatic weather stations and data loggers powered by solar panels are now available at modest cost and can operate reliably, unattended for long periods. Most climate research in mountain areas has been can-led out in connection with the assessment or prediction of water resources, forestry management, and pollution monitoring. Biological and physiological studies of attitudinal and climatic effects on flora, fauna, and human populations have also been performed in several areas, although these have generally been short-term programmes.

D. NEEDED ACTIONS

Several recommendations can be made based on this review and assessment of the status of mountain climate research. The following tasks are essential:

1. A thorough inventory of existing (or previously completed) climate observation programmes should be made. This survey should identify existing data, their period of record and variables measured, and the location and availability of existing data sets.

2. These data should be compiled, quality controlled and made widely available on convenient media (diskettes, tapes and/or CD-ROMs) preferably by national centers working with various institutions that may hold some of the records. This actively requires international coordination to ensure consistency of standards and procedures and timely delivery of the products to the user community.

3. The importance of sustained measurement and monitoring programmes in mountain regions needs to be communicated to appropriate national and international agencies, especially those concerned with global change-related studies. These agencies include national programmes concerned with climate, water resources and environmental quality, and international agencies such as the United Nations Environment Programme, the Man and Biosphere Programme and the Global Environmental Monitoring Programme of UNESCO,

the International Geosphere Biosphere Programme of ICSU, and the World Climate Programme of WMO. The last of these includes components for climate research, and impact assessments and also a developing plan for Global Climate Observing System (GCOS).

4. Building on such measurement and research programmes effectively will necessitate that efforts be made to develop the entire infrastructure of education and training programmes for mountain studies including building and maintaining appropriate facilities in mountain locations. One or more Regional Research Centres for the IGBP could, for example, be devoted to problems of mountain environments.

FIGURE CAPTIONS (figures not available)

Figure 1 Relationship between precipitation and elevation, and an envelope curve, for large storms in Colorado (from Jarrett, 1990)

Figure 2 Regional-scale diurnal wind reversals over the Rocky Mountains, Colorado, based on mountain-top observations of average resultant wind for (a) 12.00 to 15.00 MST for 26 August 1985 and (b) 00.01 to 03.00 MST for 27 August 1985. Notes: Each barb represents l ms and the triangle 5 ms. The 1500 and 3000 m height contours are shown (From Bossert et al., 1989 in Barry, 1992).

Figure 3 Changes in alpine glaciers and climate in the Alps, 1890-1986 (a). Percentage of glaciers advancing (black) or stationary (unshaded column) in the Austrian Alps; (b) same for the Swiss Alps (c) mean specific mass balance (cm) (d) temperature of ablation season May-Sept. at mountain stations, (e) decadal mean departures of annual precipitation from the 1931-60 mean in glacierized mountain areas of the eastern Alps (----- 1951-80 values for stations with annual totals > 1500 m; ---- for stations with < 800 mm/year.) (from Patzelt, 1987)

Figure 4 Temperature departures from the mean for 1887-1986 at Sonnblick (3106 m), Austria (Auer et al. 1990).

Figure 5 Snow depth on 1 January at Davos (1,540 m), Switzerland. Annual values for 1892-1989, and five-year running means (points) (from Föhn, 1990)

Notes to readers

This is an unpublished, early draft version of:

1. Barry, R.G., 1992. Climate change in mountains, IN: P.B. Stone. Ed., The State of the World's Mountains. A Global Report. Zed Books, Ltd., London. 359-380 pp.
2. Barry, R.G. 1992. Mountain climatology and past and potential future climatic changes in mountain regions: A review. Mountain Research Development. Volume 12, 71-86 pp.

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