Global Warming and Mountain Environment

Masatoshi YOSHINO

Professor Emeritus, University Tsukuba, Japan
and
Senior Programme Advisor (Environment and Sustainable Development), UNU
e-mail: mtoshiyo@poplar.ocn.ne.jp

Abstract

This study first reviews development of mountain research on climate and environment changes under the influence of global change. International programmes related to mountain climates and environments were established in the 1970s, *e.g.,* 'the High-Altitude Geoecology Commission' of the IGU, and 'MAB-6' by UNESCO, and in the 1980s, *e.g*., 'ALPEX' of 'the WCP.' These, however, were not concerned with the effect of global warming. Since the latter half of the 1980s, an IIASA programme, global warming has become oen of the main topics. Representative activities inclade 'the WCC', 'IPCC', 'Mountain Agenda' and 'MA (Millennium Assessment)'. It should be pointed out that global warming was one of the topics discussed at international symposiums, meetings and conferences by experts in the 1980s, but international cooperative studies and programmes have taken place mainly since the 1990s. Secondly, this discusses recent changes in physical environments from the viewpoint of global scale, taking examples from air temperatures, snow accumulation, glaciation and vegetation. Thirdly, this study discusses the possible impacts of global change on a regional scale, taking examples from Temperate Asia. Physical as well as human-sociological systems like tourism, agricultural land use and forestry, water resource use and other activities are considered and summarized in a table. The last part of the study discusses changes in daily maximum, minimum and mean air temperature and air temperature lapse rates, taking examples of Mt. Fuji and other mountains in Japan. The study concludes by presenting, items for future needed studies.

Key words: climate change, global warming, Japan, mountain environment, temperature lapse rate

1. Introduction

Global warming has been evident in recent years. As has been pointed out, increases in air temperature are more pronounced in the higher latitudes than in the lower latitudes. It has been not yet discussed, however, whether they are clearer at high altitudes or not.

Studies of changes in mountain environments are important to assessing the impacts of climate change on physical systems and also on human activities in mountain areas (Beniston, 1994; Beniston *et al*., 1996). The present paper firstly reviews chronological development of research and international programmes. Recent problems with mountain environments are discussed in the second part of the paper, from the viewpoint of a global scale as well as a regional scale for temperate Asia and on the local scale for Japan. The secular changes in mean, maximum and minimum air temperature and their lapse rates in Japanese mountains have been studied for the last several decades.

2. Global View

2.1 Development of studies

Mountain environments in connection with climatic conditions have been a subject of observation among scientists and mountaineers as well as local governmental officials in charge of inspection and leaders of religion groups for many years. Of course, the early studies did not consider the impacts of global warming.

Table 1 lists the main studies discussing mountain climates and environments. At the end of the 19th century, Ratzel (1889) discussed altitudinal limits of some factors, zonal structure and the effects of slopes in high mountains. In the first half of the 20th century, comprehensive studies on mountain geography appeared (Peattie, 1936). Climatologists also began to discuss the mountain conditions in the 1930s (Conrad, 1936). After the War, the International Geographical Union (IGU) established the Commission of High-altitude Geoecology to carry out landscape ecology and geoecological studies in high mountains

Table 1 Development of studies on climates and environments.

Year	Name of researcher	Theme
1889	Ratzel, F.	Altitudinal limits or zones of high mountains in European Alps
1936	Peattie, R.	Book on mountain geography, including climates and environment
1936	Conrad, V.	Topography and climates of mountains
1959	Troll, C.	Landscape ecology of high mountains in tropics
1972	Troll, C.	Geoecology of high mountains in Eurasia
1972	Veyret, P.	Description of Eurasian Alps. Model devoid of the deterministic implications
1974	Ives, J.D. & Barry, R.G.	Mountain ecosystems and climates
1975	Yoshino, M.	Book on climates and environments on local and micro-scales in mountain regions
1981	Barry, R. G.	Book on mountain weather and climate
1981	Price, L. W.	Book on mountains and man
1984	Uhlig, H. & Haffner, W.	Comparative geography and geoecosystems of high mountains
1988	Allan, N. J. R.	Human impact on mountains
1989	Hewitt, K.	Hazards, water resources, geomorphic processes from the viewpoint of human ecology
1989	Ives, J.D. & Messerli,B.	Book on dilemma in the Himalayan mountains
1991	Nilsson, S. & Pitt, D.	IIASA activities on mountain research
1992	Allan, N. J. R.	Special Issue of '*GeoJournal*' on mountain environments
1992	Stone, B.	State of the world's mountains
1995	Hewitt, K.	Risk in mountains
1995	Price, M. F.	Results of MAB mountain research in Europe
1997	Diaz, H. F.	Climate change on mountains
1997	Messerli, B. & Ives, J.D.	Mountains of the world
1997	Price, M.F. & Barry, R.G.	Climate change on mountains of the world
2002	Watanabe, T.	Special Issue of '*Global Environmental Research*' on 'Global warming and sustainable use of mountain resources in Asia'
2005	Greenland, D.	Mountain climates
2005	MacCracken, M. C.	Climate change and global warming

under the leadership of C. Troll, who engaged in tropical mountain studies intensively (Troll, 1959). He published summaries of the studies of his groups in Eurasia (Troll, 1972). Some aspects of models, ecosystems and climates of mountains were described in the first half of the 1970s (Veyret, 1972; Ives & Barry, 1974). Yoshino (1975) discussed local and small-scale climatic conditions comprehensively, taking into consideration examples from around the world. Figure 1 shows a picture taken of the IGU Commission's High-altitude Geoecology activities in the Caucasus in 1976, when C. Troll (the former chairman) and J. D. Ives (the new chairman) both attended.

In the 1980s, vertical zone structure, weather, climates and human impacts were reviewed and summarized from the standpoint of human geography, climatology vegetation science, etc. The main contributors included, among others, (in alphabetical order) N. J. R. Allan, R. G. Barry, H. Ellenberg, J. D. Ives, K. Hewitt, W. Lauer, B. Messerli, L. W. Price, M. F. Price, H. Uhlig, M. Yoshino.

Fig. 1 Lunch time on the field excursion at the Jancuat (Dzhankuat) glacier observation station (2,700 m a.s.l.) in the Northern Caucasus, organized by the 'High-altitude Geoecology Commission' of the IGU on 24 July, 1976. Fourth (with silver hair) on the right-hand side is Prof. C. Troll and fourth (with sun glasses) on the left-hand side is Prof. J.D.Ives.
(photographed by M. Yoshino)

2.2 Development of international programmes and conferences

Global warming has gradually taken its place among the topics at international programmes and conferences since the 1980s, but there was talk of it before this.

UNESCO initiated a fourteen-phase programme, in a sense a follow-on to the International Biological Programme (IBP), in 1972. One of the fourteen phases was Man and the Biosphere (MAB) Project 6 entitled: The impact of human activities on mountain ecosystems.

In early 1973, a panel of experts meeting was held in Salzburg, Austria. Development of mountain studies among the MAB was presented in a book (Price, 1995). The research was directed mainly at vegetation, tourism, shi-areas, forestry, agriculture, modeling and their relation to climatic influences. They produced lots of valuable results, but there was no consideration of the impact of global warming.

From the standpoint of atmospheric sciences, the Alpine Experiment (ALPEX) was a noteworthy early international programme in the 1980s. The human impact on mountain environments has been thoroughly studied summarizing the previous results (Allan *et al*., 1988). The 'Mountain Agenda' was created for consideration at UNCED 1992 in Rio de Janeiro after the 1972 Stockholm Conference on the environment. Status reports were presented again in a special issue of *GeoJournal* Volume 27, No.1 (Allan, 1992). Because the results mentioned were produced in the 1970s and 1980s, they contained almost no discussion of the relationship to climatic change or global warming.

2.3 Consideration of global warming

Human-induced 'global warming' has been a more popular topic since the early 1960s, but more rapidly and strongly mentioned at international conferences in the 1980s. It was made a first goal for action at the second World Climate Conference in 1990. Of particular importance was an international scientific assessment prepared by the Intergovernmental Panel on Climate Change (IPCC), which was established in 1990 under the auspices of the United Nations.

The International Institute for Applied System Analysis (IIASA) prepared a report on the impact of global warming on agricultural production worldwide in order to contribute to the IPPC (Nilsson *et al*., 1991). The report discusssed water supplies, water quality, hydropower, flood protection, navigation, tourism and health in the case of doubling of CO_2 levels. As seen in Table 2, consideration for global warming started during the 1980s.

Studies on mountain environments in relation to climate change have been carried out by Barry (1981), Beniston (1994), Beniston *et al*. (1996), Diaz *et al*. (1997), and Ives and Barry (1974). The recent status of the results of research is given by Price and Barry (1997), Greenland (2005) and MacCracken (2005). It should be stressed that, as seen in Tables 1 and 2, the scientific community was aware of global warming and its impact in the 1980s, but studies have taken them up as topics mainly since the 1990s.

3. Recent Changes in the Physical Environment as Seen on a Global Scale

3.1 Increasing rate of air temperature rise during the last decades

Diaz *et al*. (1997) studied the relationship between altitude and air temperature change in the mountains of Europe and Asia showing a clear increase. An analysis of the records observed at about 5,400 stations worldwide since 1950 has shown that the monthly mean daily maximum temperature is increasing at a rate of 0.88°C/century; the monthly mean daily minimum temperature, 1.86°C/century; and the daily range of temperature, 0.84°C/century.

Omasa *et al*. (2001) presented the secular change in air temperature at the top of Mt. Fuji during the last several decades. They observed some cyclic changes among a long-term increasing trend, which was similar to the change in free atmosphere at 3,000 m (700 hPa) altitude over Wajima, located near Mt. Fuji. Natori (2005) analyzed a series of observed air temperature data from 1961 to 1990, and showed that the rate of increase on Mt. Fuji was much greater than the average rate of increase at the ground surface level worldwide. The secular change in air temperature at the top and foot of Mt. Fuji and other mountains in Japan will be discussed in detail in Section 5.1.

Du (2001), using various statistics, studied air temperature changes on the Tibetan Plateau. An increasing trend at most stations is clear in autumn and winter. The increase in daily minimum temperatures is more

Table 2 Establishment of international programmes, conferences, and cooperative activities related to climates and environments of mountains.

Year	Programme, conference, or cooperative activity	Scope or note
1972	Commission on the 'High-altitude geoecology' of the IGU	Mountain geoecology and landscapes.
1972	MAB-6 of UNESCO	Impact of human activities on mountain ecosystems.
1980s	ALPEX	Mountain meteorology in European Alps.
1980s	IIASA	Impact of global warming.
1990	WCC (II World Climate Conference)	Second meeting of international conference by experts and policy makers.
1991	IPCC (Inter-governmental Panel on Climate Change)	Internationally, the most authorized summaries. The fourth issue is now (2006) under review.
1992	UNCED-92, Mountain Agenda	The most effective agenda.
2005	MA (Millennium Assessment)	The best summaries at present on climates and environments in the chapter on mountains.

than that of maximum temperatures. An increasing in daily maximum temperature occurs in summer in contrast to that in daily minimum temperature in winter. The linear trend in warming of annual mean air temperatures is 0.23°C/decade in the altitude zone above 4,000 m a.s.l., but relatively small, 0.11°C/decade below 3,000 m a.s.l. So that, it can be said that the increase in annual mean temperatures has been more striking in the zone above 4,000 m a.s.l. in the Tibetan Plateau during the last 40 years. Studies on the temperature change in South China made clear similar results (He *et al*., 2005).

3.2 Snow accumulation

The impacts of changes in snow accumulation on wild animals and vegetation are very big. Therefore studies of changes in snow accumulation under the influence of global warming will be indispensable. Inoue and Yokoyama (1989) estimated changes using a regional climate model. The percentage of solid precipitation to total precipitation, in the case of 2°C warming, will decrease by 16% in high mountains. When the snowfall fraction, number of days with snowfall and snow cover duration are expressed by linear relations in terms of altitude (Conrad, 1935; Konček, 1959; Yoshino, 1975; Lauscher *et al*., 1978-1980; Barry, 1981), we can estimate changes occurring in the case of global warming.

3.3 Glacier or ice cover changes

During the meeting of PAGES at Davos, Switzerland, on 25-28 June, 2001, one topic of discussion was quantifying and understanding the ongoing retreat of mountain glaciers worldwide, as exemplified by the case of Kilimanjaro (Editorial PAGES News, 2001). Namely, the extent of ice cover on Mt. Kilimanjaro decreased by 81% between 1912 and 2000. It was reported that the debate on the retreat centered around whether this indicated increasing local ambient temperatures and increased long-wave radiation from the dark caldera's surface (higher melt rates) or increased short-wave radiation leading to enhanced sublimation, one possible explanation for the special perpendicular inward facing walls of these ice fields. There have been lots of discussions on glacial retreat in the mountains, but they are omitted due to limitation of space.

Anomalous expansions in Karakoram have been confined to the highest relief glaciers and have appeared suddenly and sporadically (Hewitt, 2005). This suggests a need to explore distinctive responses of snow and ice to high-altitude warming bringing thermal changes to thermally complex glaciers. Warming and greater transport of moisture to higher altitudes may explain the growth of these glaciers.

3.4 Vegetation changes

Changes in high mountain ecosystems can be expected as consequence of global warming (Harasawa *et al*., 1999). Warming poses a serious threat to alpine flora. The sensitivity of plants to climatic factors and water stress in the summit region of Mt. Kinabaru, Borneo, the highest mountain in SE Asia, has been studied (Kitayama, 1996; Daimaru *et al*., 1996; Ohsawa *et al*., 1998). They concluded that peat buried in soil layers under snow patches was formed as a result of shrinkage of the snowpatch area and development of grassland vegetation during the medieval warming period around the 10th century. It is one good example of how vegetation has changed as caused by snow accumulation changes in the mountains in the historical period.

4. Possible Impacts of Global Warming

4.1 In temperate Asia: an example on a regional scale

Possible impacts of global warming on various aspects in the mountain regions of Temperate Asia are shown in Table 3 (Yoshino *et al*., 1998). They are summarized by physical system and socio-economic system separately. The former is concerned with hydrology, the cryosphere, abnormal weather, topographical processes and the biological world or vegetation. The latter comprises mountain agriculture, hydrological power, forestry, tourism and transportation.

It has been indicated that in the mountain regions of Temperate Asia, glaciers will provide extra runoff when the ice disappears. In general, the extra runoff may persist for a few decades and in areas with very large glaciers, it may last for a century or more. It is projected that in 2050, the volume of runoff from glaciers in Central Asia will increase threefold. However, glacial runoff will eventually taper off or even cease. The projected glacial runoff in 2100 is about 69 km^3/year, compared with the present value of 98 km^3/year (Yoshino *et al*., 1998).

4.2 In Japan: an example on the local scale

Fujiwara and Box (1999) came to the conclusion that evergreen broad-leaved forests in warmer regions will invade deciduous forests in cooler climatic regions. On the other hand, wild grass will invade evergreen broad-leaved forests, sustained by the faster shifting ability of wild grasses. As has been made clear in studies on distribution of plant communities in the mountains of Hokkaido, snow accumulation plays a basic role in their local differences (Yoshioka *et al*., 1963). Tanaka and Taoda (1996) estimated changes in distribution areas of beech (*Fagus crenata*) in the case of changing air temperature and snow accumulation under the condition of global warming. The vertical distribution zone and degree of domination of beech differ between the Pacific side and the Japan Sea side of Honshu, Japan, due mainly to different snow accumulation resulting from opposite situations, windward or lee side relative to the winter monsoon.

On the Japan Sea side, snow accumulation will decrease, due to weakening of the winter monsoon under global warming, and this will result in shrinkage of upper altitudinal zones and decreasing domination of beech forests. On the contrary, on the Pacific side, snow accumulation will increase due to increasingly frequent visitation of cyclones, which, together with the warming effect, will result in widening as well as elevating the altitudinal zones and increasing domination of beech forests. Detailed reviews have been given elsewhere (Nishioka *et al*., 1997; Omasa *et al*., 2001). On the other hand, Kojima (1996) considered the effect of an increase in annual mean air temperature of 3°C (3.5°C in winter and 2.5°C in summer) on vegetation area in the mountains of Toyama Prefecture, central Japan. He showed that the area of creeping pine (*Pinus pumila*) distribution will decrease to 9% of the present area.

The impacts of global warming on natural ecosystems in the Japanese mountains have been classified into three groups: (a) a group sensitive to temperature changes such as *Abies,* in particular, *Abies Mariesii,* (b) a group sensitive to snow accumulation as well as temperature changes, such as *Sasa kuriensis, Camellia japonica, C rusticana, Fagus crenata*, and (c) a group sensitive to topography and soil rather than temperature changes, such as creeping pine (*Pinus pumila*), *Tsuga diversifolia,* and *Thuja standishii.*

The distribution of dwarf bamboo in Japan sharply reflects snow accumulation. The maximum height, resistance to snow cover and low temperatures, recovery after damage to above-ground organs and their relation to winter climate, particularly, duration and depth of snow accumulation are clear (Yoshino, 1978), so that changes in snow as caused by global warming can be detected by dwarf-bamboo conditions (Tanaka, 2002).

In Table 4, possible impacts of global warming on vegetation (grasslands, shrubs and plant communities) in the high mountains mainly in Japan are summarized for the cases of 2°C increase, decrease in daily range,

Table 3 Possible impacts of global warming on mountain regions in Temperate Asia.

	Field	Impacts
Physical System	Hydrology	a) Increase in air temperature and decrease in precipitation in summer b) Increase in rate of rainfall/snow and decrease in depth and duration of snow accumulation c) Upward shift of maximum precipitation zone on mountain slopes
	Cryosphere	a) Direct effect of elevated temperature b) Increasing density of snow accumulation and longer snow-free duration
	Abnormal Weather	a) Significant increase in frequency of strong winds and torrential rains b) Warm and dry spring and summer, causing increased fire risk
	Topographical Process	a) Increase in precipitation maximum over mountain slopes, causing increased landslides, mud flow, soil erosion, groundwater pressure, etc. b) Thawing of permafrost, causing increased grade and frequency of landslides
	Biological World/ Vegetation	a) Changes in main species of mountain plants and animals, causing increased stress on mountain ecosystems b) Easier upward shift of main species of mountain plants, due to short shift distance and less stress of adaptation to light conditions within shift elevation c) Effects of changing snow accumulation on plants and animals
Socio-Economic System	Mountain Agriculture	a) Decrease in existing crops b) Changes in cultivation calender along mountain slopes
	Hydrological Power	a) Changes in available water power due to seasonal changes in hydrology b) Increased demand for electric power in summer and decreased demand in winter
	Forestry	a) Changes in economically predominant species b) Increased damage by wildlife, pests, viruses, diseases, etc.
	Tourism	a) Changes in elements dominating mountain landscape b) Decreased length of skiing season
	Transportation	a) Increased accessibility due to reduced amount and period of snow accumulation in winter b) Possibility of accidents and damage by freezing for traffic and transmission systems

Table 4 Possible impacts of global warming on vegetation (plant communities) in high mountains in various cases.

	In the case of					
	2°C increase in ann. mean air temp.	Decrease in daily range of air temp.	Increase in max. (min.) air temp.	Increase in precip. amount and intensity	Earlier phenological changes in spring	Increase in tropical cyclone freq. and intensity
Grassland community in windy area	Decrease	Increased altitude of lower limits on the mountain slopes*. Decrease in diversity*	Decrease	Increase in diversity	Increase in diversity	Development of erosion on slopes
Shrub community in windy area	Increased altitude of upper and lower limits on slopes	Area will become narrow*	Develop	Develop	Invasion of tall trees	Area will become narrow*
Plant community in snow patch area	Invasion of other species	Area will become narrow*	Increasing diversity, due to short snow accumu. period and depth	(Same as on left)	Invasion ofther species	Almost no effect*
Plant community in stony area	Slight decrease	No change*	No change*	Development	Development	Widening
Others (animals)	Increasing grazing damage by animals	?	Increasing grazing damage by animals	Increasing grazing damage by animals	?	?

Notes: Original table was made by T. Masuzawa. Revised by a Committee at the Ministry of the Environment, Japan, 1998-1999, chaired by M. Yoshino. Translated by M. Yoshino in June, 2006. Mark* means 'Questionable in some cases.'

increase in maximum temperature, precipitation changes, etc. Changes in phenological dates and typhoon frequency and intensity (Omasa *et al*., 1996) were also taken into consideration.

5. Long-term Trend in Air Temperatures in the Japanese Mountains

5.1 Secular variation of air temperatures

Table 5 shows the rate of increase, as calculated by linear regression equation, in the long-term trend in mean air temperature in winter (December, January and February) and summer (June, July and August) on six Japanese mountains during 1971-2000. One can see from this Table that (a) an increase is clear without exception, (b) the rate of increase on high mountains above 3,000 m (Mt. Fuji) was small, and (c) the largest rate of increase was found in winter at Mts. Ibuki, Kawaguchi and Nikko, which are located in central Japan, crossed by a strong winter monsoon (in other words, on the mountains in Shikoku and Kyushu, SW Japan, the rate was smaller than those in the central part of Japan), (d) in summer, the rate of increase was the smallest on Mt. Fuji, and (e) the rate of increase was smaller in summer than in winter, with the exception of on Mt. Tsurugi. The reason, it was as exception, is not clear at present, but the local climatic phenomena (Yoshino, 2005) must influence strongly on the conditions of these mountains.

As mentioned above, the higher mountains in Europe and Asia have shown a clear increasing trend in daily mean air temperatures (Diaz *et al*., 1997). Comparing the rates they obtained, we may conclude that the Japanese mountains, as far as the data analyzed show, also the same increasing tendency, but the rate of increase is relatively greater than that in Europe and Asia in general. The reason is thought to originate from the winter monsoon blowing as part of the middle latitude westerlies, which develop most strongly over Japan as compared with the rest of the northern hemisphere. This winter monsoon has been weakening in accordance with global warming.

The same analysis was made, but for the period from the beginning of the observations to 2000, and the results are given in Table 6. Because of the different period analyzed, the results cannot be compared mountain to mountain, but the rate has been generally observed to be larger in winter than in summer at all mountains with the exception of Mt. Tsurugi. It is also interesting to note that the annual mean rate of increase has been relatively smaller at Mt. Fuji.

Secular variations in air temperature at the mountain top and foot from the initial year of the observations to 2000 are shown in Figs. 2, 3 and 4. One can clearly see that the inter-annual fluctuation is greater in winter than in summer and slightly greater on the top than at the foot of the mountains.

5.2 Secular variation of air temperature lapse rate

The air temperature lapse rate is calculated from the differences in air temperature and altitude between mountain top stations and nearby foot stations for each year for the two periods, 1971-2000 and beginning of observatinos to 2000. The results are shown in Table 7.

It can be concluded that there is a long-term increasing trend in air temperature lapse rate. One of the reasons may be the heat island effect on the mountain foot stations, but that needs further study.

Table 5 Trends (°C/year) in mean air temperature in winter (DJF) and summer (JJA) at Japanese mountain observatories during 1971-2000. [Positive indicates an increase]

Name of observatory	Altitude a.s.l.	Rate of increase (°C/year)		
		Winter	Summer	Difference betw. winter and summer
Mt. Fuji	3,775.0 m	0.017	0.013	0.003
Mt. Tsurugi	1,944.8 m	0.024	0.029	– 0.005
Mt. Ibuki	1,375.8 m	0.037	0.026	0.010
Nikko	1,291.9 m	0.030	0.024	0.006
Mt. Aso	1,142.8 m	0.026	0.013	0.013
Kawaguchiko	859.8 m	0.039	0.034	0.005

Table 6 Long-term trends (°C/year) in winter, summer and annual mean air temperature at Japanese mountain observatories.

Name of observatory	Altitude a.s.l.	Rate of increase (°C/year)				Observation period
		Winter	Summer	Annual	Difference betw. winter and summer	
Mt. Fuji	3,775.0 m	0.017	0.002	0.010	0.015	1935 - 2000
Mt. Tsurugi	1,944.8 m	0.000	0.009	0.009	– 0.008	1944 - 2000
Mt. Ibuki	1,375.8 m	0.019	0.007	0.015	0.012	1919 - 2000
Nikko	1,291.9 m	0.013	0.011	0.014	0.002	1944 - 2000
Mt. Aso	1,142.8 m	0.014	0.008	0.012	0.006	1933 - 2000
Kawaguchiko	859.8 m	0.028	0.014	0.022	0.014	1933 - 2000

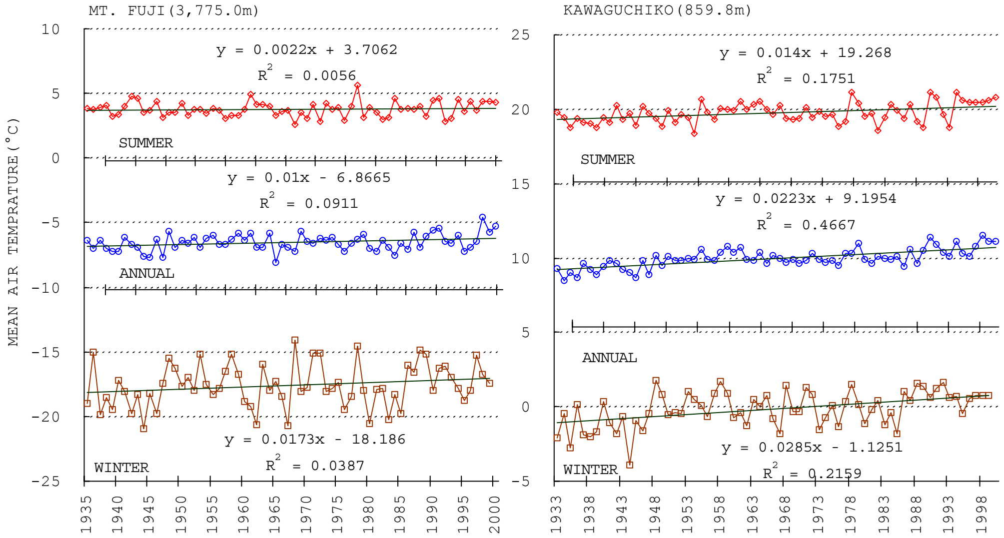

Fig. 2 Secular changes in air temperatures at the top and foot of Mt. Fuji.

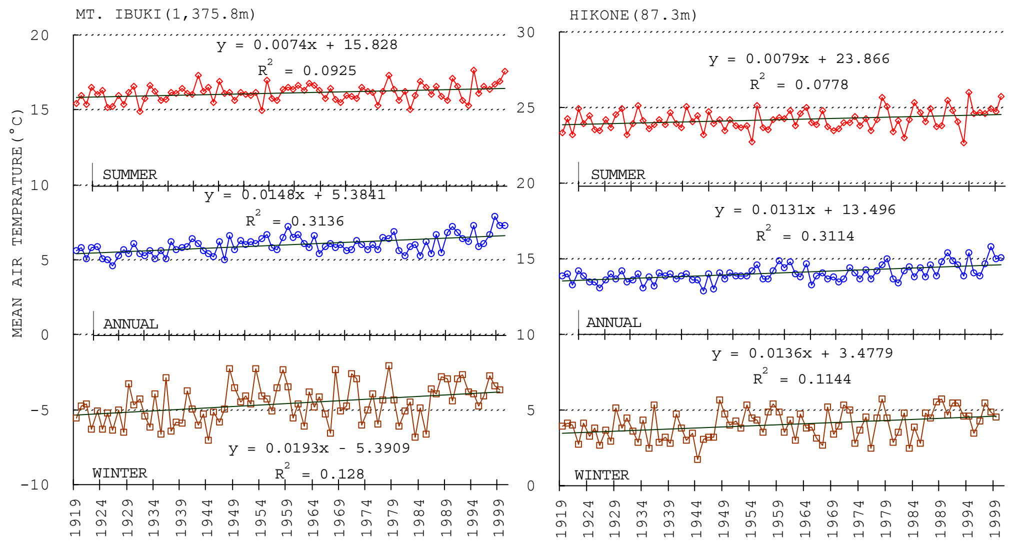

Fig. 3 Secular changes in air temperatures at the top and foot of Mt. Ibuki.

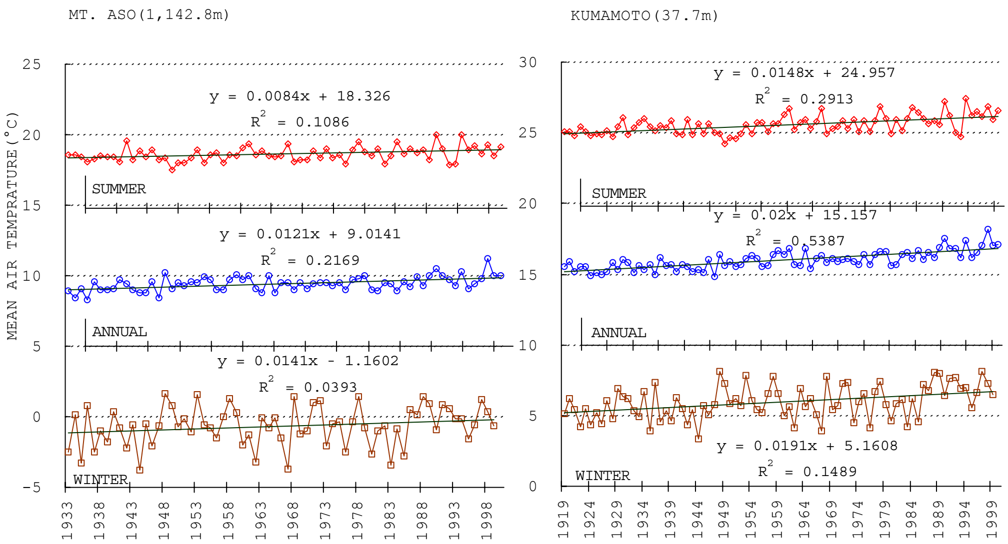

Fig. 4 Secular changes in air temperatures at the top and foot of Mt. Aso.

5.3 Vertical distributions of some climatic elements as seen from diurnal changes

One of the noteworthy features of high mountain climates is diurnal change patterns, which differ from those at low altitudes.

The diurnal temperature range is small in high mountains, as shown by an example observed at the top of Mt. Fuji (Huzimura, 1971; Yoshino, 1975). There is no clear boundary between the high mountain pattern and the low mountains, because we have no detailed observations along the slopes, but based on the results of a temporal observation in January 1951, the low-mountain pattern of diurnal temperature change was found at up to 1,300 m a.s.l. A transitional pattern of diurnal change can be recognized at up to 2,000 m a.s.l. The high mountain pattern appears at altitudes higher than 2,100 m a.s.l. (Owada *et al*., 1972).

In the case that the year-to-year rate of increase in air temperature in winter continues similarly to the last 30 years, air temperatures at 1,300-2,000 m a.s.l. on the slope of Mt. Fuji will warm by roughly 1.5°C and on the top, by 0.8°C by 2050, as estimated from Table 5 and Fig. 2. These warming values can be interpreted to mean that the boundary on the slope will become 150-200 m higher in 2050 than at present, if we do not take into consideration the effects of condensation levels (cloud or fog layers) on the diurnal change in air temperatures on mountain slopes.

Humidity is determined by air temperature and the amount of water vapour. The water vapour content decreases rapidly with altitude, due to the rapid decrease in air temperature. In the free atmosphere, the amount of water vapour decreases by half at about 1,500 m above the ground. The vertical distribution is as follows: the maximum of relative humidity on mountains appears at 1,500-2,000 m in both winter and summer. In August, the minimum relative humidity is seen at 400-500 m. This vertical distribution corresponds approximately to the vertical distribution of the number of foggy days on the slope (Yoshino, 1975).

The diurnal changes in water vapour pressure and relative humidity at the summit of Mt. Fuji differ from those on lower parts of the slope. It is said that the wind velocity at the top of Mt. Fuji is the highest among those at mountain observatories around the world (Price, 1981). In particular, strong winds are predominant in cold-half years. The diurnal change in wind velocity on high mountains differs from that in lower areas. In general, the maximum appears at night and the minimum, in the daytime in the mountains. In winter, these daily changes are obscured because of the strong winter monsoon, which prevails regardless of diurnal changes in the vertical exchange of atmosphere between the higher and lower layers.

In the case of global warming, the boundary of diurnal change patterns in wind velocity between the higher and the lower parts of mountain slopes will shift to a higher altitude because of increasing vertical exchange in the atmospheric layer near the slope. However, this estimate should also be re-examined by taking into consideration changing frequencies of synoptic weather patterns.

5.4 Summary for the mountains of Japan

Summarizing the facts mentioned above, I have attempted to compile them in Table 8. Classifying

Table 7 Trends in air temperature lapse rate (°C/100m) at several mountains in Japan. [Positive indicates an increase]

Mt. Top station / Foot station	Difference of altitude	Trend of lapse rate (°C/100m/100year)						Initial year of obs.
		Annual mean		Winter		Summer		
		1971-2000	Start-2000	1971-2000	Start-2000	1971-2000	Start-2000	
Mt. Fuji / Kawaguchiko	2,915.2 m	0.044	0.039	0.077	0.036	0.071	0.044	1935
Mt. Tsurugi / Tokushima	1,943.2 m	0.044	0.087	0.087	0.099	0.039	0.071	1944
Mt. Ibuki / Hikone	1,288.5 m	– 0.053	– 0.013	– 0.039	– 0.044	0.024	0.004	1919
Nikko / Utsunomiya	1,172.5 m	0.183	0.122	0.261	0.177	0.098	0.031	1944
Mt. Aso / Kumamoto	1,105.1 m	0.174	0.094	0.206	0.068	0.142	0.069	1933

Table 8 Impacts of global warming on climates on Japanese mountains.

	Top of Mt. Fuji (3,776 m)	Other lower mountaines or slopes (1,100-2,000 m)
Air temperature increase, 1971-2000 (°C/year)	0.02 (winter) 0.01 (summer)	0.03-0.04 (winter, C-Japan) 0.02-0.03 (winter, SW-Japan) 0.01-0.03 (summer, C-, SW-Japan)
Air temperature lapse rate increase, 1971-2000 (°C/100m/year)	0.08 (winter) 0.07 (summer)	0.09-0.26 (winter) 0.02-0.18 (summer)
Estimated temp. warming (°C) by 2050	1.5 (winter)	0.8 (winter)
Interpreted vertical shift of boundary betw. high and low mountains Diurnal change pattern of temperature Diurnal change wind velosity	 shifting 150-250 m higher shifting slightly higher	
Maximum zone of precipitation, cloudiness, number of foggy days	shifting higher	

altitudes into two zones, the top of Mt. Fuji (3,776 m) and the mountain slopes or relatively lower mountains (1,100-2,000 m), it shows air temperature increases and increases in air temperature lapse rate in winter and summer. The temperature in 2050 is estimated to be 1.5°C warmer at the top of Mt. Fuji in winter, but 0.8°C warmer in the lower mountains of Japan.

The interpreted vertical shift of the boundary between the high and low mountains will be 150-200 m higher for the diurnal change pattern in air temperatures, and slightly higher for wind velocity and for the zones of maximum precipitation, cloudiness and number of foggy days.

6. Conclusion

It is clear that the global warming impact on mountain environments will affect vegetation change, glacial retreat, etc. The disappearance of significant portions of mountain glaciers and shortages in water supplies in Temperate Asia are of importance for consideration regarding the future environment. Strong effects on warming on air temperatures have been observed in the mountains. However, the degree of effects differs regionally and locally from mountain to mountain, because the locations and altitudes differ with regard to upper atmospheric circulation conditions on global scale, which change seasonally. Further studies are needed on these points.

Also, studies of the interactive effects of factors such as tourism, agriculture, forestry and other industries should be carried on urgently.

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