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THE ALTITUDE EFFECT ON THE ISOTOPIC COMPOSITION OF SNOW IN HIGH MOUNTAINS

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Abstract. The stable isotopes oxygen-18 and deuterium in snow samples collected in four mountain regions (the South American Andes, the Central Asian Hindu Kush, the Himalaya, and Mounts Kenya and Kilimanjaro in Africa) have been measured. The altitude effect in fresh snow precipitation and in the snow-pack was determined for $\delta^{18}O$ as being within the range $-0.6‰$ to about $-1.0‰$ per 100 m of elevation, but this can be altered or even inverted by secondary factors. These factors are connected with conditions of snow-fall and post-depositional changes in the snow, which are strongly dependent on the topography of the sampled mountain slope and on climatic conditions. All these effects are discussed.

Résumé. *L'effet de l'altitude sur la composition isotopique de la neige en haute montagne.* On a mesuré les isotopes stables, oxygène 18 et deutérium, dans des échantillons de neige recueillis dans quatre régions montagneuses: les Andes sud-américaines, l'Indou Kouch en Asie Centrale, l'Himalaya, et les Mounts Kenya et Kilimanjaro en Afrique. L'effet de l'altitude sur les chutes de neige fraiche et sur la neige tassée a été déterminé comme étant pour $\delta^{18}O$ dans la gamme des $-0,6$ à environ $-1,0‰$ pour 100 m d'altitude, et peut cependant être modifié ou inversé par des facteurs secondaires. Ces facteurs sont liés aux circonstances de la chute de la neige et à des changements d'état de la neige qui dépendent fortement de la topographie de la pente montagneuse étudiée et des conditions climatiques. On discute tous ces effets perturbateurs.

Zusammenfassung. *Der Höheneffekt auf die Isotopenverteilung im Schnee des Hochgebirges.* Die stabilen Isotope Sauerstoff-18 und Deuterium wurden in Schneeproben aus vier Gebirgsgebieten, nämlich dem südamerikanischen Anden, dem zentralasiatischen Hindukusch, dem Himalaya, den Mounts Kenya und Kilimanjaro in Afrika, gemessen. Als Höheneffekt $\delta^{18}O$ in frischgefallenem und verfestigtem Schnee wurden Werte zwischen $-0,6$ und ca. $-1,0‰$ pro 100 m Höhenzunahme bestimmt. Sekundäreinflüsse können diese Werte jedoch ändern und sogar den Richtungssinn umkehren. Diese Einflüsse richten sich nach den Bedingungen bei der Ablagerung des Schnees und seiner nachfolgenden Umbildung; sie hängen stark von der Topographie des Probegebietes und seinen klimatischen Verhältnissen ab. Alle diese Störfaktoren werden diskutiert.

Introduction

Heavy oxygen and hydrogen isotope (^{18}O and deuterium) content in precipitation decreases with decreasing condensation temperature; this causes a seasonal variation in these values at high latitudes, as well as a depletion of heavy isotopes with increasing latitude and altitude. A relation between heavy isotope content in precipitation and mean annual air temperature has been reported, e.g. by Dansgaard (1964). There are also other factors resulting in a variation in the isotopic composition of precipitation, e.g. intensity of the precipitation, vapour- (or cloud-)transport distance, size of the droplets or snow-flakes, evaporation of the precipitate during the fall, etc. When the precipitation is sampled as snow, a serious effect can be caused by the post-depositional changes, such as wind drift; in the case of snow-pack sampling, evaporation and sublimation of the snow and its firnification, which is strongly dependent on climatic conditions and exposure to the sun, may cause enrichment or depletion of heavy isotopes in the sample.

The altitude effect on the isotopic composition of precipitation has been investigated by many authors, e.g. by Dansgaard (1961), Ambach and others (1968), Lorius and others (1969), Gonfiantini (in Moser and Stichler, 1970, p. 56) quoting data from Kraicsowitz and Tongiorgi, Moser and Stichler (1970), Árnason (1976), Moser and others (1976), and Bortolami and others (1979). Rain-water or snow samples have been collected in the mountains of the Northern or Southern Hemispheres and at different latitudes: from Mount Kilimanjaro to Greenland or Antarctica. All results show a general increase in the negative $\delta^{18}O$ and deuterium values (relative to SMOW) with increasing altitude, which means that the heavy isotope content in precipitation is decreasing with increasing altitude. This decrease seems to be dependent on latitude, and is greater at high and less at low latitudes. Some authors have

indicated secondary factors (the continental effect, or the post-depositional changes in snow), which may dominate over the altitude effect. According to some results, changes in the snow cover, i.e. melting and evaporation, may lead either to overcompensation and inversion of the altitude effect, or preserve or even intensify this effect (Moser and Stichler, [1975]). On the other hand, absence of the altitude effect may be caused not only by evaporation or melting processes in the snow cover but also by snow-fall from a horizontal and high cloud formation or by dry snow-drift caused by wind (Moser and Stichler, 1970; Behrens and others, 1971; Moser and others, 1972).

Scientific mountaineering expeditions, organized or sponsored by the Kraków Branch of the Polish Society for Earth Sciences, to high mountains in South America, Central Asia, and Africa, have enabled the authors to gather snow samples from different high-mountain regions at different northern and southern latitudes.

Experimental

The snow samples were collected—usually while descending the climbed peak—in four high-mountain regions: the South American Andes, the Central Asian Hindu Kush, the Himalaya, and Mount Kenya (and Mount Kilimanjaro) in Africa.

The snow samples were collected either in plastic bags and then transferred into glass bottles, 20 ml in volume, or directly in the bottles. During experiments performed in the Tatra mountains no difference in isotopic composition of the snow samples packed directly into the bottles and those previously collected in plastic bags has been observed (however, only when the snow in the bags was not melted). The altitudes of thes ampling localities were measured using an altimeter and corrected to the summit altitude of the climbed peak. Therefore, the accuracy of the absolute altitude values depends on the topographic data from the maps, the accuracy of which may be doubtful in some cases. The error of the relative altitude values can be estimated at about 20 m.

All samples were measured by the Micromass 602C at the Mass-Spectrometry Laboratory of the Instytut Fizyki i Techniki Jądrowej, Akademia Górniczo-Hutnicza im. S. Staszica, Kraków (Barański, 1976). For the measurements reported in this paper, the one standard deviation errors are estimated as $\pm 0.15‰$ for $\delta^{18}O$ and $\pm 1.5‰$ for δD determinations. All results are related to the SMOW standard.

Results and discussion

The Andes

The Andean part of this project includes the snow samples collected during July and August 1975 from three peaks:

Nevado Pisco Oeste (5 752 m a.s.l.), Cordillera Blanca, Peru; lat. 9° 00′ S., long. 77° 38′ W.

Nevado de Copa (6 188 m a.s.l.), Cordillera Blanca, Peru; lat. 9° 15′ S., long. 77° 29′ W.

Nevado Illimani Sur (approximately 6 480 m a.s.l.), Cordillera Real, Bolivia; lat. 16° 39′ S., long. 67° 47′ W.

In all cases the samples were collected from the snow-pack, 5–10 cm below the snow surface, approximately one week after the last light snow-fall (dry period in Peruvian and Bolivian Andes).

Nevado Pisco Oeste

The snow-pack samples were collected descending from the summit by the broad south-west ridge to the col between Nevado Pisco Oeste and N. Huandoy Este, and then by the south slope to Cook Glacier.

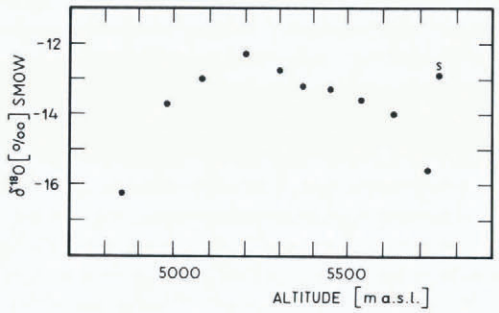

Fig. 1. Oxygen-18 content versus altitude; Nevado Pisco Oeste, Cordillera Blanca, Peru.

Air temperature changed from approximately −5°C at the summit to +5°C for the lowest sample. The results, $\delta^{18}O$ versus altitude, are given in Figure 1. Three groups of samples can be distinguished, according to the different topography of the route: the summit, forming a rather flat platform exposed to strong winds (one sample marked by "s"), the south-west ridge, being partly a broad face of the peak with an average slope not exceeding 25° (seven samples), and the slope (glacier) below the col (the lowest three samples). The results for the south-west ridge samples yield an approximately linear relation between $\delta^{18}O$ and altitude with a slope of approximately −0.6‰ ($\delta^{18}O$) per 100 m elevation difference. The summit sample does not fit this line. The samples from the glacier below the col indicate an inverse relation, suggesting quite different conditions in the post-deposition snow changes, over-compensating the isotopic composition of the fresh snow precipitation.

Nevado de Copa

The samples (snow-pack) were collected descending from the north-west summit, beginning 15 m below its highest point (a sharp cornice). The first three samples belong to the north-west face of the mountain (slope of about 40° or more). Then there is a large broad plateau ("Copa"), inclined near the mountain face and horizontal in the centre. The three lowest samples were collected from the steep south glacier, falling down to the valley Legia Qocha. Air temperature was about −5°C on and above the Copa, and a strong wind caused significant horizontal snow-drift, especially on the Copa plateau, forming snow-banks and dunes, and resulting in variations in the type of snow.

The results (oxygen-18) are given in Figure 2. The samples collected from the north-west face of the peak and from the plateau area seem to belong to one group, and their delta-oxygen

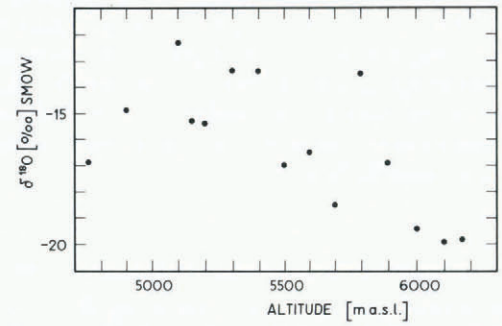

Fig. 2. Oxygen-18 content versus altitude; Nevado de Copa, Cordillera Blanca, Peru.

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numbers as related to the altitude show an average gradient of about $-0.7‰$ ($\delta^{18}O$) per 100 m. A significant spread of the results seems to confirm the influence of the snow-drift and variation in the type of snow. The samples collected from the steep south glacier indicate an inverse slope as in the case of Nevado Pisco Oeste.

Nevado Illimani Sur

The samples were collected descending from the summit of Nevado Illimani Sur to Marquiviri. The samples can be divided into four or five groups, according to the topography of the route: the summit (one sample, marked on the graph by "s"), the north slope of the dome between the peak and the col between N. Illimani Sur and Central (three samples between 6 100 and 6 300 m a.s.l.), the west ridge of N. Illimani Sur (six samples between 5 100 and 6 100 m a.s.l., excluding four samples collected in the range 5 300–5 700 m), the steep face falling from the ridge to the south-west (the above-mentioned four samples), and the lowest sample consisting of moist snow-pack, from a snow-bank near the road. The temperature in the higher part of the route was below freezing point, falling to about −15°C at the summit.

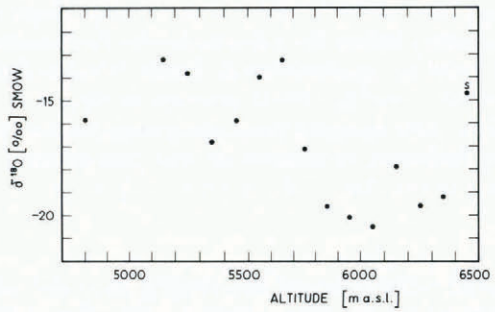

Fig. 3. Oxygen-18 content versus altitude; Nevado Illimani, Cordillera Real, Bolivia.

The results (oxygen-18) are given in Figure 3. The spread of the points seems to follow the topography of the route, e.g. the four "west-face samples" (5 300–5 700 m) form a group with an inverse slope related to the altitude. Also, the summit sample and the lowest one should be treated separately. For the rest of the samples, the delta-oxygen results can be related linearly to the altitude, with a slope equal approximately to $-0.7‰$ ($\delta^{18}O$) per 100 m but within this group the dome samples can be easily distinguished.

The relation between the $\delta^{18}O$ and deuterium results for the Andean snow samples is given in Figure 4. This graph also includes two other results for the Cordillera Blanca snow samples: one from the summit of Nevado Huascaran Norte (6 655 m a.s.l.) and the second from Garganta Pass (6 010 m a.s.l.; the col between N. Huascaran Norte and N. Huascaran Sur). Both of these locations lie in the vicinity of N. Pisco Oeste and N. de Copa. Comparing the results for the N. Huascaran Norte sample, one finds the same effect as that for other summit samples; the snow is enriched in heavy isotopes compared with other samples collected at a similar elevation but on the mountain slopes.

Central Africa

The snow samples were collected at two localities (January–February 1977):

Mount Kilimanjaro (Uhuru, 5 895 m a.s.l.) lat 3° 04′ S., long. 37° 21′ E.
Mount Kenya (Nelion, 5 185 m a.s.l.) lat. 0° 09′ S., long. 37° 19′ E.

The *Mount Kilimanjaro* snow samples were not related to altitude, because all sampling sites were close to one another within the elevation range of 5 700–5 890 m a.s.l. The mean values for 17 samples were: −1.45‰ ($\delta^{18}O$) and −8.0‰ (δD), relative to the SMOW sample. The standard deviation of these mean values, equal to 0.47‰ ($\delta^{18}O$) and 2.5‰ (δD), indicate a significant spread of the individual numbers due to variation in the type of snow sampled; however, no altitude effect was recorded.

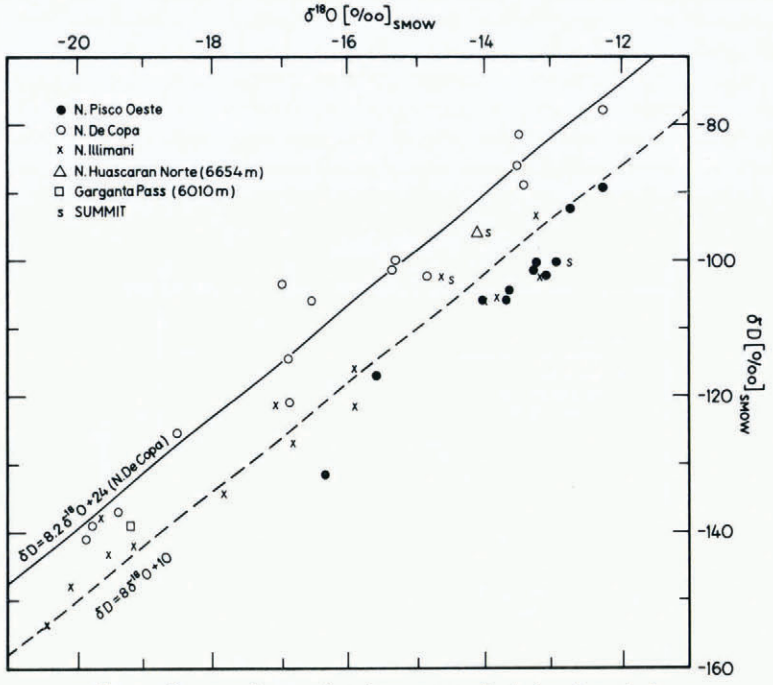

Fig. 4. Oxygen-18 versus deuterium content; South American Andes.

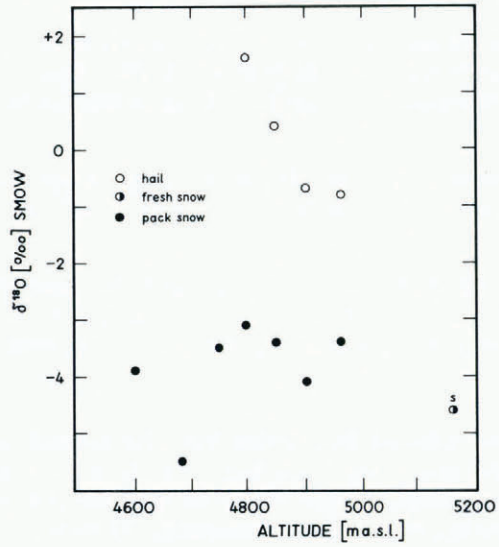

Fig. 5. Oxygen-18 content versus altitude; Mount Kenya, Kenya.

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The *Mount Kenya* snow samples were collected while descending from the Nelion summit to Point Lenan and then by the southern slope (Lewis Glacier to its lowest point at an altitude of 4 580 m a.s.l.). Two kinds of sample were collected: fresh precipitation from the previous day, mainly as a hail, and snow-pack ice from a depth of about 10 cm below the snow-pack surface.

The results (oxygen-18) are given in Figure 5. The points corresponding to hail samples can be linearly related to altitude, with a slope of about $-1.5‰$ ($\delta^{18}O$) per 100 m. The summit fresh snow sample (marked by "s" in the graph) seems to fit to this line. Other snow-pack samples are more depleted in heavy isotopes and do not indicate any altitude effect. The relatively high concentration of heavy isotopes in hail samples can be interpreted as having been caused by a short continental transport of moist air masses.

These hail samples also form a separate group of points on the graph in Figure 6, presenting the relation between $\delta^{18}O$ and deuterium values. The point representing the mean value for the Mount Kilimanjaro samples can also be treated as belonging to this group.

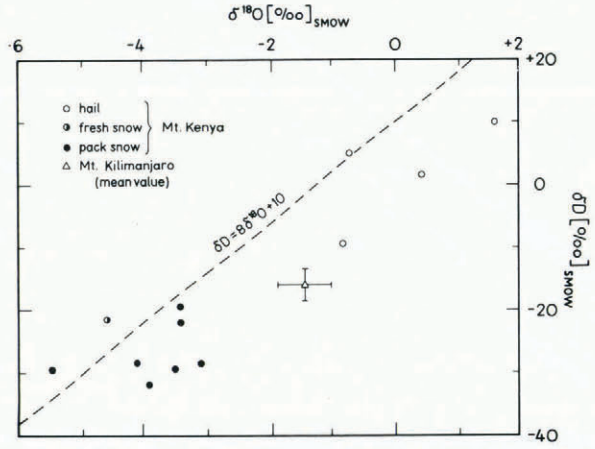

Fig. 6. Oxygen-18 versus deuterium content; Mount Kenya and Mount Kilimanjaro.

The Hindu Kush

The snow samples were collected by three climbing teams in two parts of the Hindu Kush in Afghanistan, the first two peaks in the high Hindu Kush (August 1976) and the others in the central Hindu Kush (Nuristan; July 1977). The sampling locations were as follows:

High Hindu Kush:

Kōh-i Noshāk (7 492 m a.s.l.); lat. 36° 26′ N., long. 71° 50′ E.
Kōh-i Langar-i Jam (approximately 7 000 m a.s.l.); lat. 36° 36′ N., long. 72° 07′ E.

Central Hindu Kush:

Kōh-i Sūrākh-i Sard (5 697 m a.s.l.); lat. 35° 54.5′ N., long. 71° 06.5′ E.
Kōh-i Morusg (6 120 m a.s.l.); lat. 35° 52′ N., long. 71° 04′ E.
Kōh-i Do-sar-i Suyengal (5 360 m a.s.l.); lat. 35° 50′ N., long. 71° 10.5′ E.

Kōh-i Noshāk

The snow samples were collected descending from the summit of Kōh-i Noshāk by the "normal" route, i.e. by the south ridge and west arm (face) to the Qāẓī Dih valley (1–3 August 1976). The weather conditions were rather hard for the climbers; it was snowing with a strong wind, especially during the first day of sampling. Therefore, the sampled snow comes

mainly from the heavy snow-fall of 31 July and the snow-storm of 1 August but some admixture of snow-pack in the sample cannot be excluded. Wind during (and after) the snow-fall caused disturbance of the fall direction (horizontal and even inverse fall), as well as the post-depositional snow-drift. Also, the topography of the sampling locations was variable; there were samples collected from the summit (sample marked in Figure 7 by "s"), from a sharp ridge, rocky parts and steep snow faces, and from a glacier. Air temperature was not measured, probably being below −10°C in the upper part of the route and above freezing point below 5 500 m altitude.

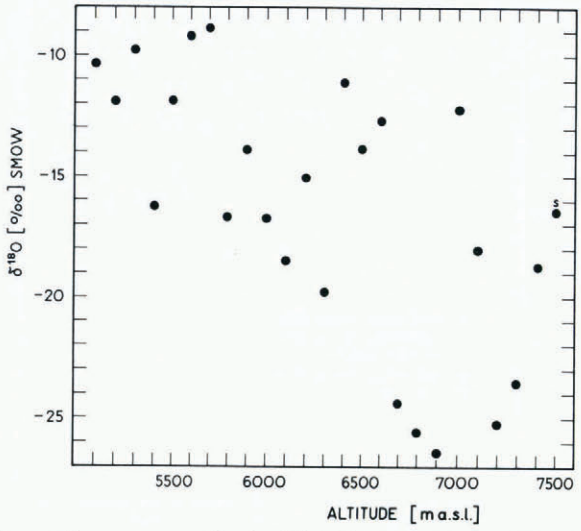

Fig. 7. Oxygen-18 content versus altitude; Kōh-i Noshāk, high Hindu Kush, Afghanistan.

The results (oxygen-18) are given in Figure 7. The spread of points reflects the variable topography and fall conditions, as well as possible admixtures of the snow-pack or firn to the fresh snow samples collected. The slope of the linear relation between the $\delta^{18}O$ values and the altitude, if any, can be estimated as being approximately −1‰ ($\delta^{18}O$) per 100 m.

Kōh-i Langar

The snow samples were collected during an expedition to the group of Kōh-i Langar peaks (Langar-i Jam and others). Three samples were collected on 4 August during a windless light snow-fall, on the route from camp 2 to camp 3 (i.e. between peak L-9 and Langar Plateau), one sample being of snow-pack (or snow-ice). The next group of samples was taken on 16 August, descending from the Central Langar Peak (about 6 840 m a.s.l.) via the west slopes to the upper part of the Langar Plateau (Langar Col), camp 4 at about 6 400 m a.s.l. It was the second day of a heavy snow-fall with a strong wind (being very strong in the lower part—the plateau). The samples from the lower part of the route were taken on 18 August, while descending from camp 4 to camp 1 (about 5 200 m a.s.l.), via L-9 peak and its south arm.

Also, during the upper part of this route it was snowing with a strong wind; only the last (lowest) four samples were of snow-pack from the snow-fall of 18 August. Only at these lowest locations was the air temperature above freezing point, falling in the highest parts to about −15°C.

The results (oxygen-18) are given in Figure 8. The samples of different origins are marked on the graph separately and form distinct groups of points; therefore, it is impossible to determine any general relation between the $\delta^{18}O$ values and the sampling altitude. Comparing the mean values for the group of samples representing the snow-fall of 18 August and that of 16 August, one can estimate the altitude effect as being about −0.8‰ ($\delta^{18}O$) per 100 m of altitude.

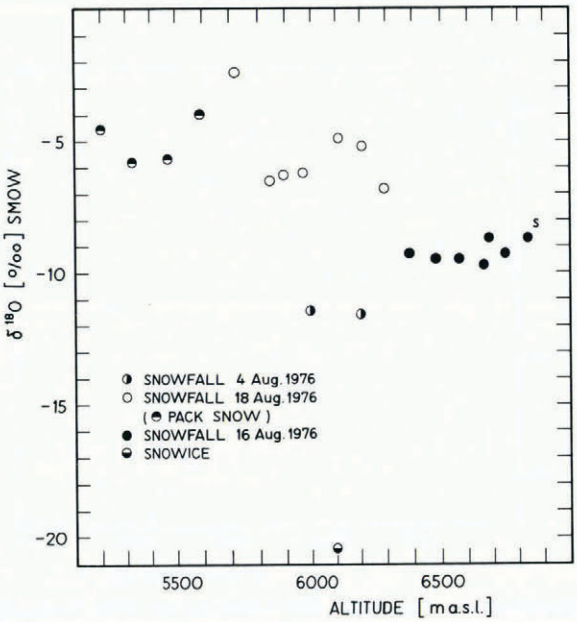

Fig. 8. Oxygen-18 content versus altitude; Kōh-i Langar-i Jam, high Hindu Kush, Afghanistan.

The relation between the $\delta^{18}O$ and deuterium values for both Kōh-i Noshāk and Kōh-i Langar peaks is given in Figure 9. The separation of the samples from Kōh-i Langar, representing the two snow-falls of 16 and 18 August, is very distinct. The samples corresponding to earlier snow precipitation on Kōh-i Langar generally fit with the samples from Kōh-i Noshāk collected almost on the same days, despite the distance between these two mountains. The observed differences between these groups of samples suggest different origins of the air moisture responsible for the sampled precipitation.

The central Hindu Kush

All samples collected in this area correspond to the firn-like snow-pack usually from the vertical snow forms, sometimes called *penitentes* in the Chilean Andes, about 10 cm below the snow surface or the top of the *penitentes*. It was a dry period in the mountains and the last snow-fall had occurred at least one month before the samples were collected. The snow temperature at the sampling locations was within the range of about −2°C to 0°C.

The results (oxygen-18) are given in Figure 10. The topography for each of the climbed peaks was different. The route to Kōh-i Sūrākh-i Sard peak was by a shadowed, steep couloir falling down to the west from the north rocky ridge of the mountain. The sampling sites for Kōh-i Morusg and Kōh-i Do-sar-i Suyengal peaks were generally located along the steep snow ridges, exposed approximately to the south and east, respectively. The results indicate an

inverse relation between $\delta^{18}O$ and altitude as for example in the Andean peaks for the lowest parts (glaciers). The summit samples (marked on the graph by "s") do not fit in with this correlation but, contrary to the results from the other localities described in this paper, they are relatively light in comparison with the rest of the samples.

The $\delta^{18}O$ values versus δD data for all the central Hindu Kush samples are given in Figure 11.

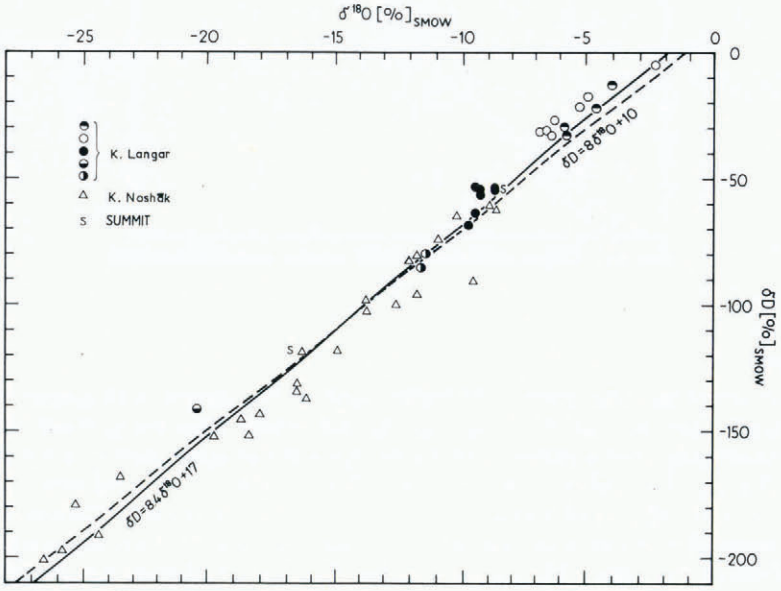

Fig. 9. Oxygen-18 versus deuterium content; high Hindu Kush.

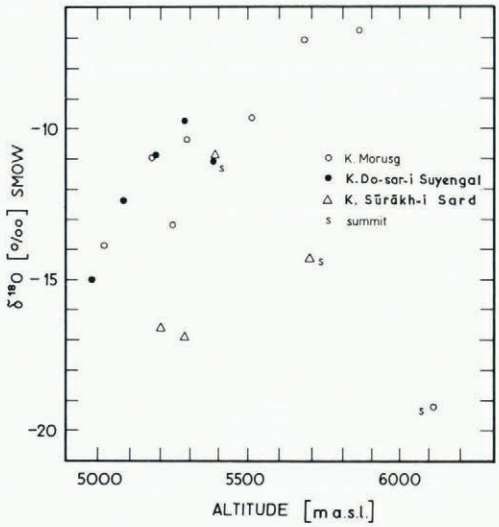

Fig. 10. Oxygen-18 content versus altitude; central Hindu Kush (Nuristan), Afghanistan.

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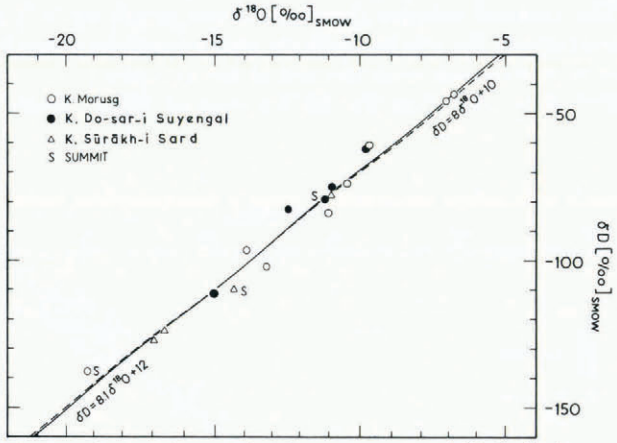

Fig. 11. Oxygen-18 versus deuterium content; central Hindu Kush.

The Himalaya

The snow sampling took place in October 1978 on the slopes of Dunagiri, 7 066 m a.s.l. (Garhwal, India; lat. 30° 32′ N., long. 79° 52′ E.) while descending from the north-west ridge to the Gannakhui-Nala valley. The topography of the sampling locations was as follows. The highest five samples (above 5 700 m) were collected on the steep northern arm, descending from the north-west ridge to Gannakhui-Nala, the first of them being collected from the ridge up to an altitude of 6 070 m a.s.l. The next five samples (above 5 100 m) are from the steep north-east slope of this arm. The lower samples were collected from the generally less steep Gannakhui Glacier. All but three samples represent fresh snow, from the windless light snow-fall during the sampling (the samples up to 5 700 m a.s.l. in altitude) or from precipitation of the previous day (the higher samples); there were snow-falls every afternoon, from the high cloud formation, extending from the glacier up to the summit. These three exceptional snow samples are: the 6 050 m a.s.l. sample of dry, blown, gypsum-like snow, and two 4 430 m a.s.l. samples, one being of moist (slush) snow and other of blue glacial ice from the lowest part of the glacier. The air temperature was slightly below freezing point above 5 800 m, rising up to about +10°C at the lowest sampling site.

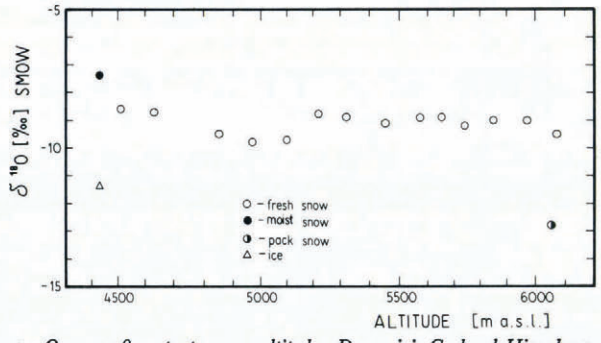

Fig. 12. Oxygen-18 content versus altitude; Dunagiri, Garhwal Himalaya, India.

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The results (oxygen-18) are given in Figure 12. All fresh snow samples form a horizontal line on the graph and no altitude effect is observed. Also, the δD data do not depend on altitude, as can be seen on the graph given in Figure 13. Only the above-mentioned three samples do not fit into this group, the lowest slush sample being the heaviest, and the glacial ice and dry snow-pack snow being lighter than the fresh snow.

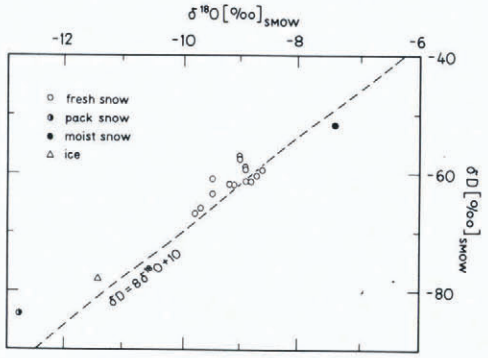

Fig. 13. Oxygen-18 versus deuterium content; Dunagiri, Garhwal Himalaya.

Conclusions

The large number of snow-sample analyses described in this paper enables the authors to draw some general conclusions, in spite of the fact that geographical and climatic conditions were very different for almost every sampling site.

Generally, it can be stated that an altitude effect for stable isotopes, if it exists in snow precipitation in high mountains, can be preserved in accumulated snow and observed from the snow-pack analyses. For $\delta^{18}O$ this effect was determined as being within the range —0.6‰ to about —1.0‰ per 100 m of altitude. No relation between these numbers and the sampling latitude has been observed. These data are in good agreement with the stable-isotope altitude effect determined by other authors for polar regions, although at lower latitudes results of about —0.2‰ per 100 m have been usually reported.

The data corresponding to the fresh snow analyses indicate a strong dependence on fall conditions. Samples collected during a snow-storm or even a wind-driven snow-fall give a picture such as obtained in the cases of Noshāk (Fig. 7) or Langar (Fig. 8). Such weather conditions in high mountains cause variable directions of air-mass movement and therefore no air stratification can be observed. Also, fresh snow sampled from wind-free precipitation, such as in the case of Dunagiri (Fig. 12), may show no altitude effect on isotopic composition, but this absence of altitude effect is only possible when the snow-fall originated from high cloud covering the whole slope of the mountains.

The graphs also indicate two other phenomena, overcompensating the altitude effect, which are the so-called "inversion effect" and "summit effect". The inversion of the slope of $\delta^{18}O$ data, which is dependent on the altitude difference, can be observed in all cases in which the snow-pack was sampled from steep slopes where the sun or high air temperature caused severe melting and/or evaporation processes. Therefore, this effect was connected with both the topography of the "sampling route" (in most cases it was within the ablation zone of the glaciers) and with the climatic conditions during sampling; it can be seen in practically all of the cases described in this paper, especially for all the samples collected in Nuristan. It can be explained that in such places the melting and evaporation processes occur in such a way that the snow sampled at the higher locations is heavier isotopically. The

same effect is observed during firnification of the snow cover (e.g. Árnason, 1976; Niewodniczański and others, 1980); therefore, it can be stated that this change in the snow occurs more dynamically on some types of mountain slope (during a dry season) at the higher locations. The results obtained in Nuristan indicate the same mechanism in the case of snow being in the form of *penitentes*.

Unusual results for summit samples have also been observed for all mountains, where snow was sampled from their summits. Usually the summit snow samples are heavier in comparison with snow samples from the slopes; only in Nuristan, where the altitude effect was inverted, are the summit snow samples lighter than the others. These results show that snow deposited on the summit is exposed to exceptional climatic conditions, connected mainly with the winds blowing over the mountain top. Also, the age of such snow-pack is difficult to determine and usually does not correspond to the age of the snow sampled on the slopes.

The absolute data for the stable-isotope content also indicate other effects, e.g. so-called continental effect, depending on the air-masses transport distance. In the case of Langar (Fig. 8), it can be seen that the snow-falls of 16–18 August and of 4 August originated from different air masses coming to this region, e.g. from India or Siberia, and therefore varied in transport distance and probably in temperature. The snow samples collected on Noshāk on 31 July and 1 August correspond to the precipitation of 4 August on Langar.

No latitude effect on isotopic composition has been observed but the climatic conditions in high mountains depend on many parameters, of which the latitude is the least important. It should be pointed out that all samples were collected in similar climatic periods from the point of view of sun exposure and temperature; in the Andes (lat. 9–17° S.) it was winter in the Southern Hemisphere (July–August) and in Central Asia (lat. 30–36° N.) the same months correspond to summer in the Northern Hemisphere. The only exceptions are the equatorial snow samples from Mounts Kilimanjaro and Kenya, which are significantly heavier than the other samples; however, this could be due to topography rather than to latitude. Especially heavy are the hail samples from Mount Kenya which range up to +10‰ for δD and +2‰ for $\delta^{18}O$. The explanation could be the short distance of air-mass transport as well as the long fall of rain drops (in high-temperature air strata), which froze as hail pellets shortly before the fall; this explanation seems to be in agreement with the air-movement patterns for the equatorial zone of East Africa. The absence of an altitude effect in the African samples could be explained by the fact that the precipitation there is formed by severe turbulence and not by orographic mechanisms.

From the graphs giving the oxygen-18 versus deuterium analysis data, it can be seen that almost all of the samples correspond to the world precipitation according to Craig (1961), e.g. the computed regression lines for the Hindu Kush samples. The observed differences, e.g. for Nevado de Copa (Fig. 4), are difficult to explain at this stage of the research.

The large amount of experimental material requires more detailed analysis and discussion; only a general review of the results is given in this paper and this indicates that a number of physical problems are involved in the isotopic altitude effect when determined for snow from high mountains. For a proper quantitative interpretation, more theoretical considerations and laboratory investigations are needed.

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REFERENCES

Ambach, W., *and others*. 1968. The altitude effect on the isotopic composition of precipitation and glacier ice in the Alps, by W. Ambach, W. Dansgaard, H. Eisner, and J. Møller. *Tellus*, Vol. 20, No. 4, p. 595–600.

Árnason, B. 1976. Groundwater systems in Iceland traced by deuterium. *Visindafélag Íslendinga*, 42, p. 60–66.

Barański, L. 1976. Spektrometria masowa trwałych izotopów tlenu, węgla i wodoru dla potrzeb hydrogeologii i geochemii [Mass spectrometry of stable isotopes of oxygen, carbon, and hydrogen for hydrology and geochemistry]. *Instytut Fizyki i Techniki Jądrowej AGH* [*Kraków*]. *Raport* INT 104/1.

Behrens, H., *and others*. 1971. Study of the discharge of Alpine glaciers by means of environmental isotopes and dye tracers, by H. Behrens [and 7 others]. *Zeitschrift für Gletscherkunde und Glazialgeologie*, Bd. 7, Ht. 1–2, p. 79–102.

Bortolami, G. C., *and others*. 1979. Isotope hydrology of Val Corsaglia, Maritime Alps, Piedmont, Italy, by G. C. Bortolami, B. Ricci, G. F. Susella, and G. M. Zuppi. (*In Isotope hydrology 1978. Proceedings of an international symposium on isotope hydrology jointly organized by the International Atomic Energy Agency and the United Nations Educational, Scientific and Cultural Organization and held in Neuherberg, 19–23 June 1978*. Vienna, International Atomic Energy Agency, Vol. 1, p. 327–50.)

Craig, H. 1961. Isotopic variations in meteoric waters. *Science*, Vol. 133, No. 3465, p. 1702.

Dansgaard, W. 1961. The isotopic composition of natural waters with special reference to the Greenland ice cap. *Meddelelser om Grønland*, Bd. 165, Nr. 2.

Dansgaard, W. 1964. Stable isotopes in precipitation. *Tellus*, Vol. 16, No. 4, p. 436–68.

Lorius, C., *and others*. 1969. Variation in the mean deuterium content of precipitation in Antarctica, by C. Lorius, L. Merlivat, and R. Hagemann. *Journal of Geophysical Research*, Vol. 74, No. 28, p. 7027–31.

Moser, H., *and* Stichler, W. 1970. Deuterium measurements on snow samples from the Alps. (*In Isotope hydrology 1970. Proceedings of a symposium on the use of isotopes in hydrology held by the International Atomic Energy Agency in co-operation with United Nations Educational, Scientific and Cultural Organization in Vienna, 9–13 March 1970*. Vienna, International Atomic Energy Agency, p. 43–56.)

Moser, H., *and* Stichler, W. [1975.] Deuterium and oxygen-18 contents as an index of the properties of snow covers. [*Union Géodésique et Géophysique Internationale. Association Internationale des Sciences Hydrologiques. Commission des Neiges et Glaces.*] *Symposium. Mécanique de la neige. Actes du colloque de Grindelwald, avril 1974*, p. 122–35. (IAHS–AISH Publication No. 114.)

Moser, H., *and others*. 1972. Messungen des Deuterium- und Tritiumgehaltes von Schnee-, Eis-, und Schmelzwasserproben des Hintereisferners (Ötztaler Alpen), von H. Moser, W. Rauert, W. Stichler und W. Ambach, H. Eisner. *Zeitschrift für Gletscherkunde und Glazialgeologie*, Bd. 8, Ht. 1–2, p. 275–81.

Moser, H., *and others*. 1973. Measuring the isotope content in precipitation in the Andes, [by] H. Moser, C. Silva, W. Stichler, and L. Stowhas. (*In* [International Hydrological Decade.] *The role of snow and ice in hydrology. Proceedings of the Banff symposia, September 1972*. Paris, UNESCO; Geneva, WMO; Budapest, IAHS, Vol. 1, p. 14–23. (Publication No. 107 de l'Association Internationale d'Hydrologie Scientifique.))

Niewodniczański, J., *and others*. 1980. Stable isotopes and tritium profile of the glacier Broggi in Cordillera Blanca, Peru, by J. Niewodniczański, J. Grabczak, and L. Barański. *Prace Mineralogiczne* (Kraków), No. 64, p. 7–13.