THE INFLUENCE ON RELIEF AND VEGETATION ON SNOW DEPOSITION IN THE ALPS WITH SPECIAL REGARD TO THE EFFECTS ON SKIING AREAS

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In the Alps the boundaries between snow covered and snow free sites are more or less clearly opposed. It is possible by this means to join sites with the same average snow regime characteristics and thereby to delimit the characteristics of locations with positions of the same or similar snow character. The buildup and reduction of a coherent wintry snow cover in a mountain area differs basically in its differentially adjusted line trends.

Considering next the appearance of snow cover of our mountain world, so is shown, that the boundary lines of snow covered and snow-free areas can be delineated by means of lines of elevation zones. These horizontal snow cover boundaries advance rapidly into valleys with the season and contrary to relief difference, that is relief related factors have no influence on the snow cover isolines. The snow line is influenced by macrorelief through the position in the mountains, it is in relation with center or boundary with the same elevation earlier or later identifiable. The autumn snow isolines progress at an imperceptible slant - almost horizontal - against lines of equal elevation and are therefore shown as level oriented.

During the process of dissipation in Spring it becomes clear that only relief and indeed the meso- and microrelief give the isolines of snow disappearance characteristic, regular features. The spring disappearance isolines follow the form of the small and microrelief and are shown as relief oriented. Small and mesoscale relief are decisive for the distribution of snow. The disappearance of snow gives a visible impression in the snow dappled landscape (Schneefleckenlandschaft). The further redistribution following every snowfall and finally the deposition of snow is a function of wind, to which the snow depth of the different areas of relief clearly correspond, the time of disappearance results predominantly from the wind caused snow thickness. Areas with convex surfaces (in a vertical line), those are vaulting lands, ridges, crests and ribbed areas, are as a condition of their location earlier free of snow in that they are exposed primarily to the effects of the reducing forces (wind, temperature, radiation). Concave surfaces, land indentations, troughs, trenches, gullies and similar features become clear later, since they develop greater snow depth because of the relief effect on snow deposition.

The duration of snow cover is that time period between the dates of snowing in and its disappearance. The thickness of a snow cover and its duration varies according to elevation and relief position namely through the position in macro- and microrelief.

It is characteristic of the length of duration of the snow cover that neither of these two factors is decisive by itself, rather they both work together, supporting or diminishing each others effect. In addition, in general, a plentiful fall of precipitation is a prerequisite for the formation of snow cover, in the course of which the temperature must remain below the freezing point for a longer time. The importance of the joint action of humidity and temperature for the formation of a snow cover is very obvious in the example of the high plateaus in Central Asia. These areas remain snow free because of their dry climates in spite of their great elevation and low winter temperatures. As a rule the duration of snow cover increases with increasing elevation whereby large scale climatic boundaries (as Oceanity, and Continentality) must be considered. The regular increase of the duration of the snow cover with increasing altitude leads to fixed deviations on distinct sites within the framework of the overall relief. Relief is the distributive element with regard to the partitioning of precipitation and heat. The effect of large scale relief respectively windward and lee side and the Continentality are shown in Table 1.

Table 1. Comparison of Locations (A) Exposed to West Winds on the Border of the Alps (Schoppernau) and (B) A Protected Alpine Valley (Landeck). (After Turner, 1963)

	Schoppernau	Landeck
Elevation	835M	818M
Average Precipitation	1850MM	782MM
Hygric Continentality	24°	44°
Number of Frost Days	144	114
Number of Ice Days	31	28
Number of Summer Days (25°C)	24	54
Number of Tropical Days (30°C)	2	12
Number of Days with Snowcover		
1-15CM	140	74
15-30CM	120	28
30+ CM	101	12
Average Maximum Snow Depth	107CM	26CM

The effect of being on the lee side in the large scale relief is clearly visible in Table 1, Shoppernau and Landeck are separated by the Arlberg. Because of the protection from the precipitation bearing gradient winds by chains of mountains, important variations in the length of the snow cover period not infrequently appear in otherwise comparable situations. For this reason the increase in the persistence of the snow cover with increased altitude when it occurs at all, does not result in the same measurement. Longterm observations have shown, for example, that on the border of the northern Limestone Alps between 500 and 1000 meters in elevation the increase in duration of snow cover is more apparent than between 1000 and 1500 meters. In the central areas of the Eastern Alps one sees a considerable extension of duration over 1500 meters, and between 1500 and 2000 m a further increase is experienced. The increase in the persistence of the snow cover amounts to an average of 14 days per 100 meters increase in elevation for the northern border of the Alps. For the Inn Valley near Innsbruck the increase in persistence is achieved more slowly; 9.5 days per 100 meters increase. For the southern part of the Eastern Alps 6.5 days are calculated.

The longer period of snow cover at similar elevations in the northern Alps also clarifies the difference in the elevation of timberline as compared to the central Alps. In the ocean-influenced northern Alps the timberline averages 1700 meters; in the continental climate of the central Alps, 2400 meters. The restriction in the growing conditions for the vegetation through the depression of timberline is not only accounted for by the greater amount of precipitation but also indirectly through associated phenomena such as decreased temperature and the cloudiness (lack of transparency) of the atmosphere. This example from the Alps indicates the snow cover characteristics in the overall relief and these may be carried over on a large scale on the whole, to all mountain chains of the world. In the microrelief, with its relief zonal regularity, precipitation breaks in the region of the microclimate near the ground achieve prominence. For the most part snow during a storm is only slightly carried by the wind but afterwards is often moved with greater intensity. Depending upon the differential wind effect in terms of direction and velocity there is a contrast between snow deficient windward sides in microrelief (because of their being blown free of snow) and the snow rich windward sides in large scale relief. In this sense also is indicated - as previously shown (Table 1) -- snow deficient lee sides in the large scale relief and abundant snow in leeward sites in the microrelief. The influence of microrelief on the redistribution of snow through wind action is so important above timberline that one may speak of a dominating position of microrelief as compared to macrorelief. This influence of wind associated with relief is strongest in the tension zone of the forest and decreases completely in the area of tree growth or occurs only in a weakened form, because the forest in its inner zone calms the wind and largely equalizes the microclimate contrasts.

(Fig. 1). The wind determines the snow strength characteristics according to exposition in microrelief so clearly and with such sharp distinctions that in later dissipation all other factors such as temperature, radiation etc. largely are of less importance. We know that the two factors temperature and radiation in time cause the snowcover to completely disappear, the time of total disappearance is dependent upon the snow depth as the wind determined it.

In addition to the primary effect of relief there is the secondary effect of tree vegetation. The influence of forests on the windfield near the ground and subsequently the snowcover and snowcover persistence is in another form from that of relief. The cause may be seen in the fact that the forest (especially the tree growth) presents a flexible elastic wind barrier which produces a turbulent change in the streamline movement of the air mass near the ground. This leads, for example, in winter to the deposition of large amounts of snow on the ridges stocked with young growth; snow which would otherwise be delivered to the neighboring hollow for deposition leaving the ridge snow-free. In the wind profile we can see the relationship between wind speed, snow depth, snow deposition, and the presence of young tree growth.

The results, depicted above are found above the forest edge up to the timberline in the so-called forest tension zone. The various elevation and relief associated factors are clearly discernible and therefore also possible to correlate. On the contrary the results below the edge of the forest zone and finally in the actual forest are completely different. As one descends from the forest limit into the more or less open stands it appears that here the differential snow disposition is no longer stored according to the microrelief. The branches, stems and leaves, as is well known, reduce wind movement -- especially the strong gusty winds -- by which a small scale horizontal and vertical separation of the snow is achieved without a correspondence to the relief. Through the reduction in the wind in the trees a more uniform distribution and a lower density of the snow cover is achieved than in the open. If one compares the snow depths of open land and forest one generally sees a plus in favor of the stand. Considering the snow deposition the level of stocking determines to what degree a stand comes close to the results in the open. The snow disappearance in the forest lacks the typical regularity of that found on surfaces above the timberline. The effects of microrelief are indicated most strongly there where the most severe influencing factor, the wind, is not able to develop fully its power to modify the snow cover. Above the timberline the yearly cycle of the snow isolines follows the regularity determined by the microrelief.

The modern widespread interest in skiing places specific demands on the design and construction of the ski trails. In spite of the fact that there is a continuing increase in skiers modern ski trails may not become more difficult because skiers now ski more rapidly, fall more readily and may be injured more easily than previously. That is, modern ski areas must from the planning stage meet the following demands: they must be easily supervised, wide, not too steep, (rather tending toward the flat than toward steep), without crossing slopes at a right angle (machines will slide off sideways!) and sharply uneven soil should be smoothed. Without snow - no skiing. We can see it here as a basic condition in consideration of the invested capital and the derived returns that it is necessary to plan ski trails in the right exposition. In areas above the forest border where the snow cover is a result of a complex of wind and relief, one must seek the troughs favored by snow in contrast to the snowless wind influenced ridges. On the whole we have to assume that we should avoid south and southwest exposures in planning downhill ski trails. In the last relatively snow-poor years in the Alps we have seen that such ski trails and their mechanical lifts have been barely used one time. This, in spite of the fact that local residents guaranteed the almost certain appearance of snowcover in the planned area. In building near the valley floor we should plan ski trails only on north, northwest and northeast exposures and these should lay to the windward of major features of the relief and to the lee of the microrelief. Ski trails in the valley at elevations of less than 1,000 meters will be useable for skiing only a short time - 3 to 4 months. In such situations it is necessary to prefer a higher elevation ski development in order to pay interest on the invested capital. Beside the character of the surface of the planned trail and an acceptable slope angle the area must be suitable to develop. Protection forests, avalanche tracks, torrents (especially if they carry mudflows), nature protection areas, and landslide slopes must

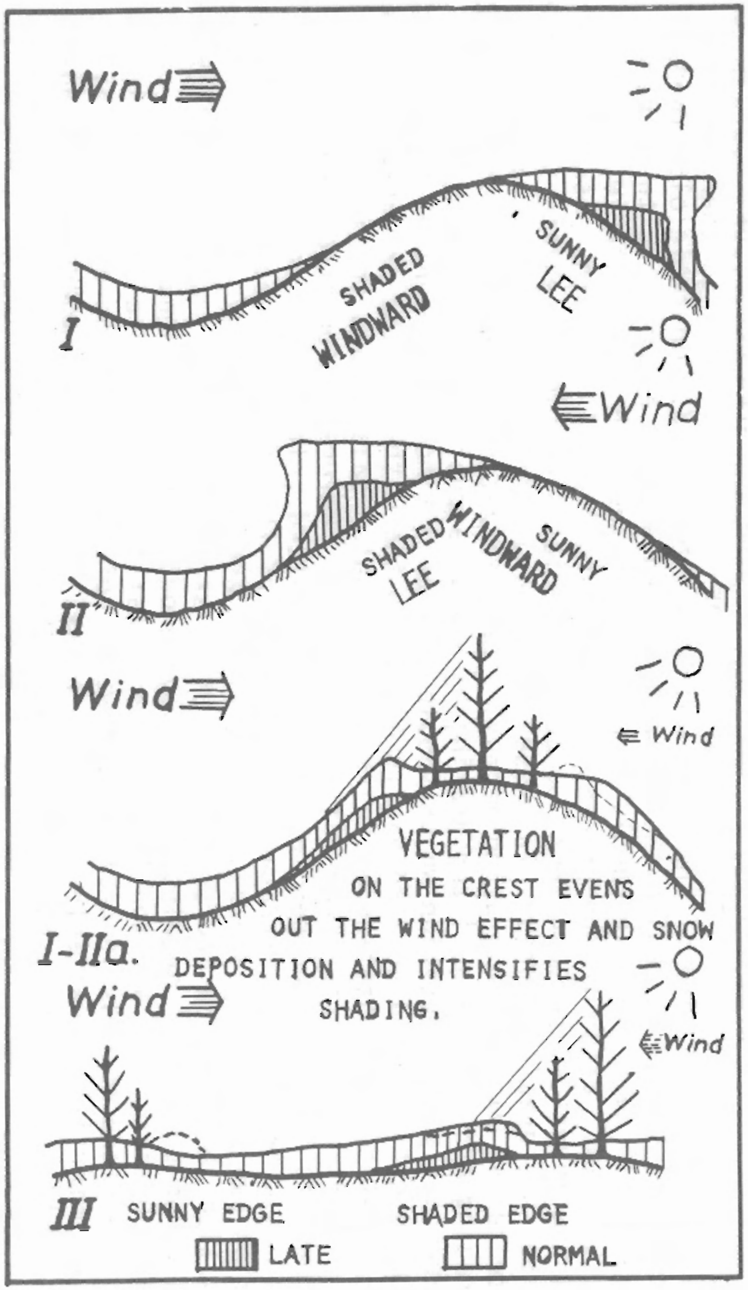

Fig. 1: Schematic diagram of the relief- and vegetation-influenced snow deposition on ridges under the influence of sun and wind.

Case I : Sun and wind come from opposite directions.
Case II : Sun and wind come from the same direction.
Case I-IIa: Influence of vegetation on the crest leads in both cases to a balanced snow cover.
Case III : The snow characteristics on the edges of an opening in the forest are more in balance than on the ridge.

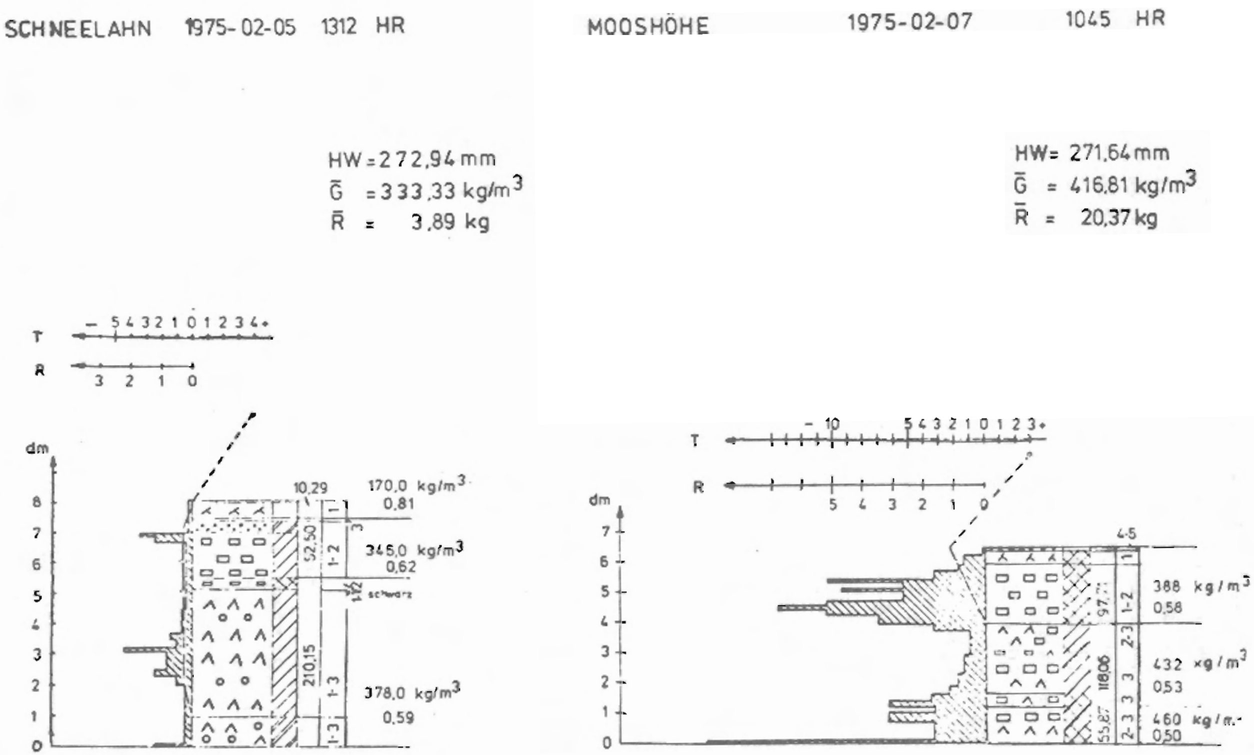

Fig. 2: Build up of snow cover in forest ("Schneelahn" left) and on an open area ("Mooshöhe" right) under similar climatic conditions and equal elevation. The water equivalent is the same, snow depth, density and ram resistance differ. The build up of snow cover in the open area is much more stable than that in the forest stand. The open area snow cover was not mechanically stabilized.

be avoided in all cases. In studying the area it is necessary to draw on the experts to get a solution which will be optimal from the skiers' standpoint and acceptable from the corresponding experts and foresters standpoint. In all planning it stands to reason that you have a long snowcover that you can work on with technical measures. It is not always possible to follow the above mentioned directions for ski trails. Therefore, technical provisions will be necessary under certain environmental conditions. In avalanche correction we know a type of building which is exceedingly suitable for the improvement of the snow conditions on ski trails. If a ski trail leads along wind blown snowless ridges and crests it is possible by building a 2 to 3 meter raised fence to produce a 10 to 30 meter wide deposit of snow for the ski trail. We produce an artificial lee zone - which in the microrelief promotes snow deposition and snow cover duration. Ski trails across forested areas, and these are almost all of those in the Alpine areas which reach to the valleys, are produced by clearing an artificial lee in the microrelief where there is no interception by the forests and the snow deposition on the ground will increase. On modern ski trails where the development of snow cover continues by mechanical preparation, the development of the snow cover takes another course from that in forest stands. In the early winter the density of deposited snow is higher on the ski trails than in the neighboring forests. In late winter the ripening process causes higher snow density there than in the nearby stands. An essential aspect can be seen in the lack of sensitivity of the snow cover to sudden periods of warm air. This resistence of the mechanically formed snow cover makes for the certainty of snow on the ski trail. The snow depth remains constant during the winter, often maintaining a specific height compared to the varying snow depth in the neighboring stand. The development of ice lenses near the soil not only reduces the percolation of melt water but also prevents, when soil frost is absent, the upward movement of soil heat. Snow melt proceeds on the prepared ski trails with a delay of one to two weeks as compared to the neighboring stand, that means that the ski trails become open when snow cover of the surrounding area is between 50 and 100 meters higher.

No other development in the landscape stands out more sharply than a large scale ski area. A favorable setting in the landscape and the forest below the timber line is one of the greatest needs. Long straight clearings, as straight as a string in the fall line, are in all cases to be avoided, even if they are a suitable solution from the skiing standpoint. Each ski area through the forest zone should be so planned that windthrow danger is minimized. Of greatest significance is the presence or the development of a mantled stand border. By this means is not only great damage such as sun scald, the oxidation of the soil surface and similar diseases reduced, but also the visible impression on a skier is a better one. It is often possible to include well mantled stand borders through a minor movement of the ski track, thereby minimizing the probability of disturbing impacts in the forest. The ski area developer should in this case accede to the wishes of the forester. After the forest cuttings there may be unstable trees at the side of the track which must be felled. Unstable old stands which are cut through by trails should be harvested as soon as possible to prevent possible windthrow. The site should then be reforested with a more stable mixture of tree species. Often in the process of developing the ski trail the possibility exists to free the forest of certain legal burdens. Special significance exists there where the forest has grazing rights. In these cases the possibility should be explored to separate forest rights and grazing access. The utilization of the ski trail for wildlife grazing and to obtain winter grazing is always a possibility. Without agreement for compensatory reforestation which should be 2 or 3 times the amount of the cleared area the forester should not ordinarily accede to the wishes of the ski area developer. The compensatory reforestation is to restore the water balance and to minimize the greater variation in surface run-off which results. Reforestation areas near the ski trails need to be protected before skiing is permitted. If this is not done the reforestation will be harmed by scraping and breaking of the terminal shoots of the plants. Protection can be done by fences, tables, stakes and other measures. Grassing and its conservation should be of course carried out on ski trails and ski areas. Earlier methods of grassing like seeding and the laying out of sods or compact turf are rarely used today because they are too laborious and cost too much. Above the timberline we have to use these methods in part because we do not have yet an appropriate seeding material commercially available. Grassing of ski trails will be therefore without humus or with little humus grassing methods. The maintenance of the surface soil deserves the greatest attention. Above the timberline it is very important because the buildup of surface soil requires centuries. Currently used grassing method on large scale ski areas are normal seeding, spraying procedures, and mulch-seed. Normal seeding should only be used on sites where the climate is favorable (in terms of humidity and soil moisture) and where a layer of humus is still available. The seed must be worked into the soil after seeding. Hydroseeding or spraying procedures are methods in which the seeds are sprayed on the area with fertilizer, soil improving material and a sticker mixed in water. The possibility of using this method depends on the size of the seeder and the size of the trail. On ski trails it is only rarely used. Mulch-seed uses the effect of a straw cover which protects the layer of air near the ground and the young seed from mechanical changes. They are carried out on ski areas by hand and have also been successfully used on areas which had no layer of humus. The less fine material there is in the soil also the more you have to use mineral and organic fertilizer. The grassing must be carried out in consideration of the individual case and particular sites and working conditions. Therefore it is not possible to give a simple single recipe for the seeding of the area. The most favorable time of the year for seeding in the alpine areas are the months of May to the middle of August. All grassing activities need additional care. It is especially important to remove immediately new, freshly appearing erosion rills in order to prevent worse damage.

When a grassed surface is not adequately fertilized the sod becomes sparse and more and more stones are brought to the surface by frost, so that the money saved (on ferilizer) must be spent on removing stones. The grass must be cut short before winter. It is most useful to permit grazing on the area. The steeper the slope of the trail the lighter must be the grazing animals. If it is not possible to graze the area, in Fall it must be mowed. On areas which are not used or which are unusable, restriction on growth must be practiced by means of fertilization, a complete grass cover must be secured but a too-strong growth of grass must be prevented.

The careful planning and the even more careful execution of drainage of water moving downslope and water falling on the surface is, of greatest significance in the interest of holding the ski slope in place. One must not overlook the strong retardation of the melt process in spring which is caused through the compaction of the snow cover on the ski trail. Also, through the retardation of melt a shift to a warmer time may occur, so that the snowmelt takes place when there is a thunder shower and thereby suddenly quickly flows off. By means of artificial precipitation investigations in the Bavarian Alps runoff values were obtained which amounted to 80% of the rainfall amount. In order to reduce the pronounced concentration of water or collection, especially in steep areas, the ski trail should be slightly domed or sloped to one side in cross section, and must not be built in the form of a depression. Piles of material and opposing embankments must be avoided. Because of the possible danger of sliding one must take special pains with dumps for excavated material in sloping areas. Care must be taken in advance to develop an effective water drainage system and the security of the bases of slopes. In the tension zone of the forest special care is required in cutting. In the interest of a regulated pattern of water movement, areas influenced by torrents should be avoided. Water disposal on grassed ski slopes is most convenient with simple ditches with which adequate width must be obtained. According to the land and soil characteristics, the slope of the ditch may be as much as 20%, the distance between ditches in the fall line should not exceed 40 meters. At the end of the drain the water must be carried further in an open ditch or pipe until it percolates or can flow off without damage into a stream channel. Seeps must be drained generally by small French drains, with which a disposal of the water without damage must also be achieved. If a small stream channel crosses a ski slope this may be more easily accomodated by the use of a small dam in loose stone or gabions. It is to be recognized that through the disturbance of the normal sediment movement the stream bed may be lowered below the dam. The slope base or a fill or cut slope may be stabilized by the use of log and rock cribbing or a gabion retaining wall. Also channel works of armored concrete block may be used.

Summary

With the clarification achieved by the use of the snow covering and snow disappearance isolines, the primary importance of relief and the secondary effect of tree vegetation on

snow deposition in the Alps is demonstrated. The effect of windward and lee sides in macro- and microrelief is considered. The differences in snow deposition above timberline, in the tension zone of the forest, in openings in the forest and in closed stands are shown. Proceeding from the bases of the regularity of the appearance and disappearance of the snowcover, the significance of the direction of exposure in the case of ski areas is developed. The bases in planning and construction of ski trails including the maintenance operations in the forests on both sides of the ski trail, the grassing operations and the water disposal to reestablish an orderly water system are derived.

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