31 *The Gorner glacier with the 1850 lateral moraines clearly visible at the areas indicated*
This and next photo: H. D. Schwartz

Advance and retreat of Alpine glaciers

K. Schwartz

Every glacier is controlled by the sequence of atmospheric conditions, the climate. This causes seasonal changes of the ice. On the whole, a glacier is at 'low tide' during the summer, since melting then by far surpasses new supplies. Accordingly the lower end will retreat, the surface falls in and the temporary snowline moves uphill. Even the firn areas are frequently affected by thaws. During winter, on the other hand, nearly all surface melting usually stops and the whole glacier becomes an area of new supply. It will therefore gain in volume and the lower end will advance often resulting in small, so-called winter moraines. In the case where summer retreat and winter advance compensate each other a glacier is said to be stationary. Now, it is only one step from these seasonal changes to long-term changes. A greater ice supply over a long period will cause a glacier to advance more than its usual annual share with more than its normal speed due to the higher pressures caused by the additional supply.

An increase in accumulation in the firn area does not always have to result in advance though. A small glacier reacts fairly quickly after only small changes of its supply whereas a bigger one needs greater changes over longer periods. Then, while the 'flood wave' of additional supply is still travelling down-glacier the accumulation area may well have changed back to a less favourable state or much stronger melting may occur at the snout when the weakened wave arrives so that the glacier will merely remain stationary.

Extreme melting conditions, when thaw surpasses supply over several years will force the lower end of a glacier back. The snout grows flatter and usually becomes covered by stones melting from the ice as well as those carried on the surface anyway, and eventually will start to recede.

Historical summary of long-term changes

Seasonal as well as long-term variations can be traced fairly accurately during the last centuries, and in some cases back to the last ice age. At the end of the Wuerm, the last ice age, about 12,000 years ago, a long period of ice retreat started. It took place in many phases and glaciation reached a minimum during a post-glacial warm period between 8000 and 6000 years ago with the snowline about 1000 ft higher than nowadays and only one-quarter of today's glaciation. Antiquity and Middle Ages also were periods of little ice cover, with still less than two-thirds of today's ice-covered area. Then, around 1600, with the climatic snowline between 150 and 250 ft below today's the greatest advance (with exceptions, as goes for all generalised statements in this paper) in recent times took place, the so-called Fernau stage, named after a glacier in the Stubai Alps. This advance caused the formation of huge terminal moraines sometimes more than a mile down-valley from the below-mentioned 1850 stage.

A fairly extensive glaciation was maintained during the seventeenth century. The eighteenth century also had several forward movements, especially between 1760 and 1790. The nineteenth century was characterised by two maxima. One between 1811 and 1822, called the 1820 stage. The other one between 1840 and 1856. The 1850 stage, as the latter is generally called, was on the whole slightly larger than the 1820 advance in the Eastern Alps, whereas the earlier forward thrust was more extensive in the Western Alps, generally speaking.

Then, after about 1855, came a well known, almost continuous and often rapid retreat lasting till about 1950, interrupted only by several short stops and some isolated small advances, as around 1890, 1910 to 1915, 1926 and 1940 to 1945. Nevertheless, these short periods did not change very much the aspect of the general fast decay of glaciation, during which the Alps lost twenty per cent of their ice cover between 1870 and 1930 alone. Only in most recent years has a tendency of slower retreat been noticeable—since 1948, with local stationary behaviour around 1955. 1964 and 1965 again were rather bad years, with considerable losses. But since then a slight increase of mass in the firn areas has been recorded in some parts of the Alps with many glaciers being fairly stationary just now, a few advancing slightly, but many still retreating.

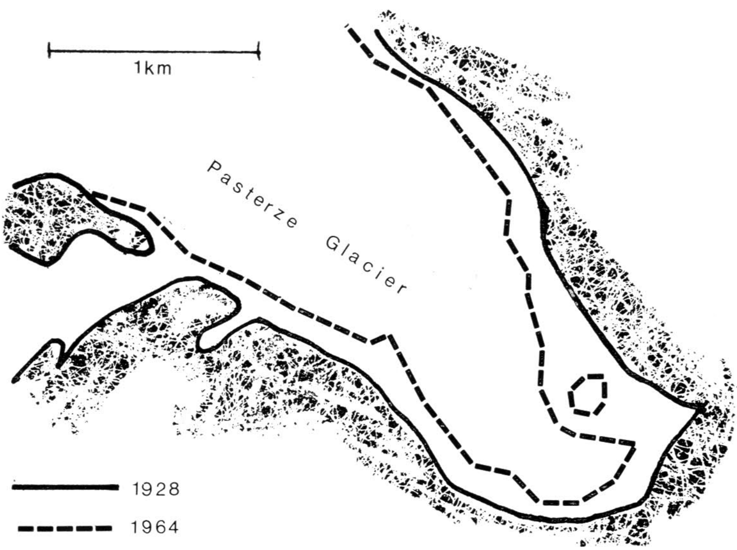
From a closer examination of these glacier changes some common characteristics of the general behaviour of ice masses during times of variation can be recognised:

1 The more pronounced the advance or retreat, the more widespread it occurs; that is, nearly all glaciers take part, as last happened in 1820 and 1850.
2 The weaker the advance or retreat, the more common are irregularities and local discrepancies; that is, even adjoining glaciers can show different behaviour, as happened for example in 1890 or 1910.
3 Periods of stationary glaciers always show many local variations, either limited advance or slight retreat.
4 Periods of advance usually are markedly shorter than the corresponding phases of retreat. For example, the 1820 advance lasted eight to ten years, whereas the retreat afterwards spread over more than twenty years.
5 Glaciers, which compared with the average advance earlier or later, will also start their retreat earlier or later. A good example is the Suldenferner in the Ortler Alps which started its advance as late as 1856 (when other glaciers were already receding) and consequently began its retreat much later, in about 1870.
6 Small glaciers react faster and with seemingly bigger changes than larger ice streams.

Climatic causes for changes

So far no reasons for the changes of glaciers have been mentioned. Yet naturally these are of great interest for their understanding. The main causes to spring to mind (and, in fact, the most obvious reasons), are climatic ones, some of which will be related to variations of glaciation in the following part of the article.

Straight away we are confronted with a difficulty here. Exact meteorological records of mountain ranges exist only from 1886 onwards when the Sonnblick observatory, at a height of 2835 m, was opened in the Hochnarr–Goldberg area just E of the Glockner mountains. The comparison of some observations made at the Sonnblick observatory with the records of a low-level station, such as for example Vienna, makes it possible though to calculate earlier values for higher altitudes fairly accurately, since some results of observations made at the stations mentioned are more or less parallel. This analogy is especially striking for the average annual temperature of both observations (diagram 1). Therefore, the temperature curve before 1886 has been regarded as being parallel to the one of Vienna.

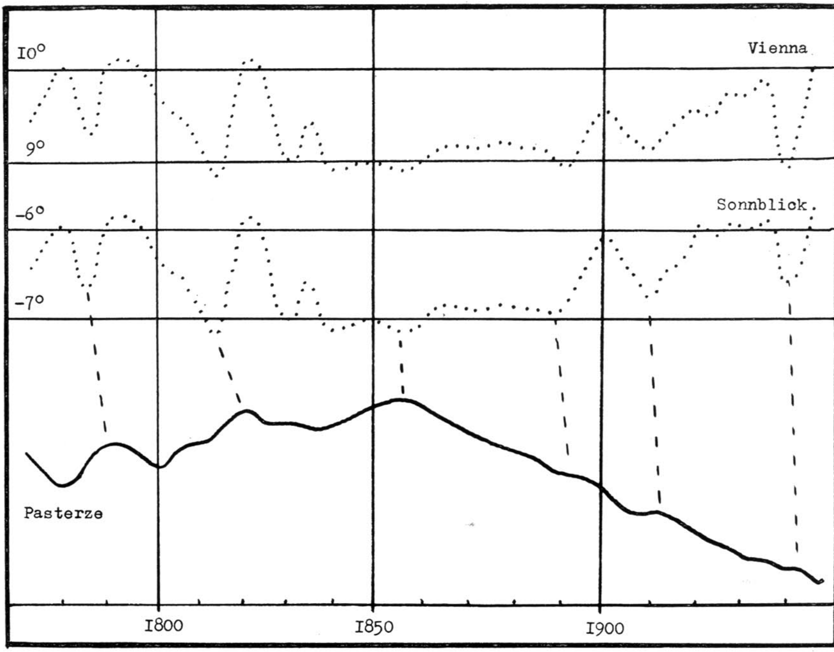


The Pasterze glacier (from DOAV map 1:25000)

A good choice for a comparison of the average yearly temperature at the Sonnblick station (and, indeed, for all later discussion as well), with the behaviour of a big glacier, is the Pasterze in the Glockner Alps, because it is not very far from the above-mentioned observatory and its main mass is situated at roughly the same height.

A closer look at temperature at Pasterze reveals a marked decrease in temperature of 1.5°C between 1796 and 1814, corresponding well with the obvious advance of the glacier up to the 1820 stage. The rise of temperature from 1814 till 1820 is followed by the retreat after 1824. A new reduction of the temperature over a long period with low readings is answered by a steady thrust forward from 1826 onwards, only interrupted once due to a warmer period in 1835, up to its last maximum between 1856 and 1858. Since then we can trace an irregular

Diagram I

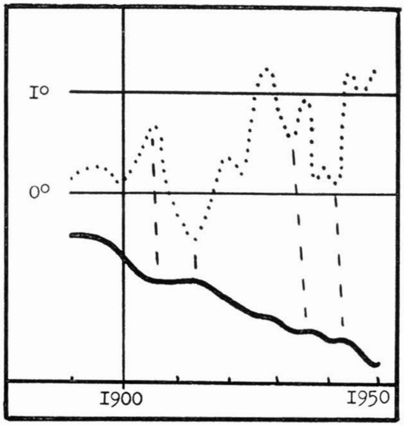


Average Yearly Temperature (Centigrade) of Vienna and Sonnblick
black line indicates changes of the Pasterze
(up = advance, level = stationary, down = retreat)

retreat rather parallel to variations on the temperature diagram. So the fall in temperature in about 1890 led to a stationary attitude and there was a slight advance during another cooler period around 1910, and so on.

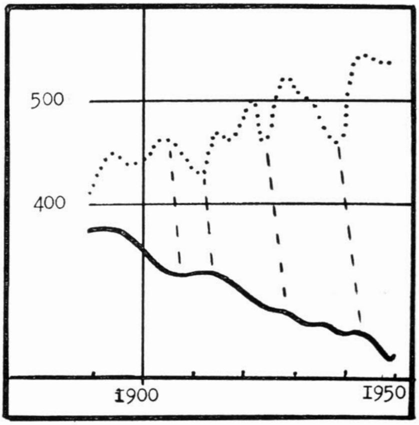
This comparison shows very clearly that the Pasterze follows the variations of the mean annual temperature quite accurately and with a delay of three to seven years. A better explanation supporting the above facts can be found from a closer investigation of the average summer temperature. It seems to be most important for the budget of an ice mass, since it does not really matter how cold a winter may be because temperatures then are well below freezing point anyway with only a very limited thawing within and below the ice due to pressure and friction. Indeed, the strong retreat after 1858, in addition to the rather small increase in the average yearly temperature, can be understood much better as a result of the much warmer summers. Even small variations in the behaviour of the Pasterze, again of course delayed, are well explained by the corresponding changes of the mean summer temperatures. Thus the rise of more than 1 °C between 1890 and 1950 is one of the main climatic reasons for the fast receding action during that period, especially since the average rose from near freezing point, a temperature favourable for glaciers, to well above this crucial mark. In addition to the marked rise of the summer temperature mentioned above, the rather noticeable increase in the average summer sun-

Diagram 2



Average Summer Temperature (Centigrade) on Sonnblick and changes on the Pasterze

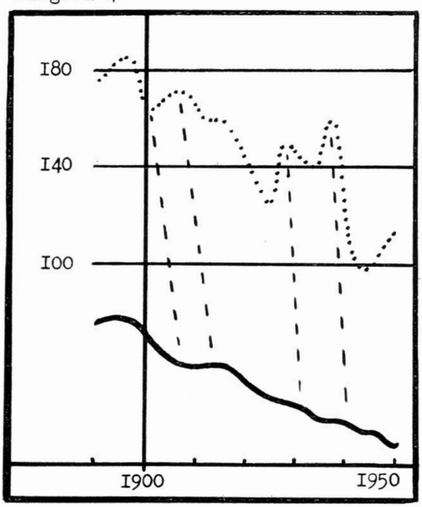
Diagram 3



Average Sunshine (hours) on Sonnblick, June to August

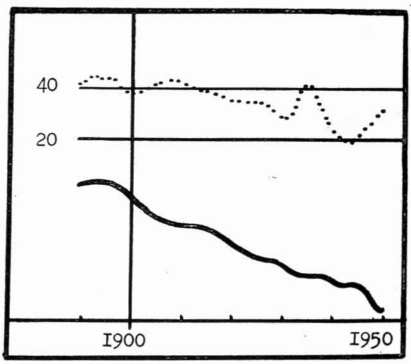
shine of more than 100 hours per year could only have intensifying effects on the shrinking of Alpine ice-streams. Further explanation can then be found when the average yearly precipitation is taken into consideration. Only readings after 1886 can be taken into account though, since there is no analogy between observations of low- and high-level weather stations. Readings show an irregular decrease from 1890 until 1942, and a small increase since the latter date. This climatic change again is mirrored in the behaviour of the Pasterze and most Alpine glaciers.

Diagram 4



Average Yearly Precipitation (cm) on Sonnblick

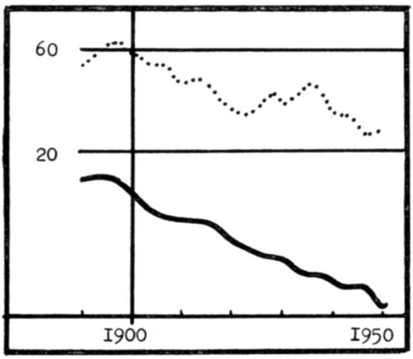
Diagram 5



Average Winter Precipitation (cm) on Sonnblick

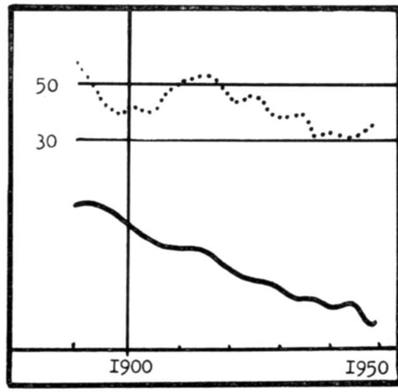
Average autumn, winter and spring precipitation, especially the latter two, are of great importance for every glacier because they provide the major part of all new supplies. Winter and spring values both show a diminishing tendency since the beginning of the regular observations on mountain weather stations.

Diagram 6



Average Spring Precipitation (cm) on Sonnblick

Diagram 7



Summer Days with Snowfall on Sonnblick

So far not much research has been done on the effects of the different types of radiation. For example, the influence of direct sunlight as well as its more diffuse re-radiation from the clouds or surrounding slopes. Or the capacity of different types of ice to reflect infra-red rays, the so-called albedo, is almost unknown. But these are just the factors which are very important for the budget of an ice mass. The albedo for new snow, for example, lies between 0.9 and 0.8 (albedo of a pure white substance would be 1.0), meaning that almost all rays are reflected. On the other hand, it can be as low as 0.1 for old, greyish or dust-covered ice, ie nearly all rays will be absorbed. Therefore the number of summer snowfalls is also of considerable influence. And it is not only their number which is of interest, but also their regularity. Naturally, it would be advantageous to have a new snowfall every time the last layer had melted away so that the glacier ice would hardly be affected throughout the summer. Though no record of regularity was available the fact that the days with summer snowfall became rarer also coincides with the shrinking of the Pasterze.

Influence of winds, regional and local ones, is yet another factor which has hardly been examined. Wind can, for example, keep dust away, thus avoiding an increase of albedo or, on the other hand, can transport dark particles on to the ice, decreasing its reflecting capacity, with stronger melting as result. Continuous winds can, of course, also influence local temperatures. To blame warm S–N Foehns for the general retreat of Alpine ice is incorrect, because the number of these particular winds fell from 90 to 40 a year between 1910 and 1945 alone.

To summarise this short discussion of some climatic influences on changes of glaciers roughly the following can be said:

1. Changes are the result of long-lasting (long lasting in the sense of several years) meteorological variations. Short-term irregularities such as a single cool and damp year or just one hot one are of no obvious and measurable influence. The smaller the glacier the shorter climatic changes have to be to take effect.
2. Glacier retreat is the result of a number of warm, sunny continental summers with long periods of possible thaws and with little precipitation in winter and spring.
3. Glacier advance is the result of a number of cool, cloudy oceanic summers with frequent snowfalls combined with winters and springs rich in precipitation.

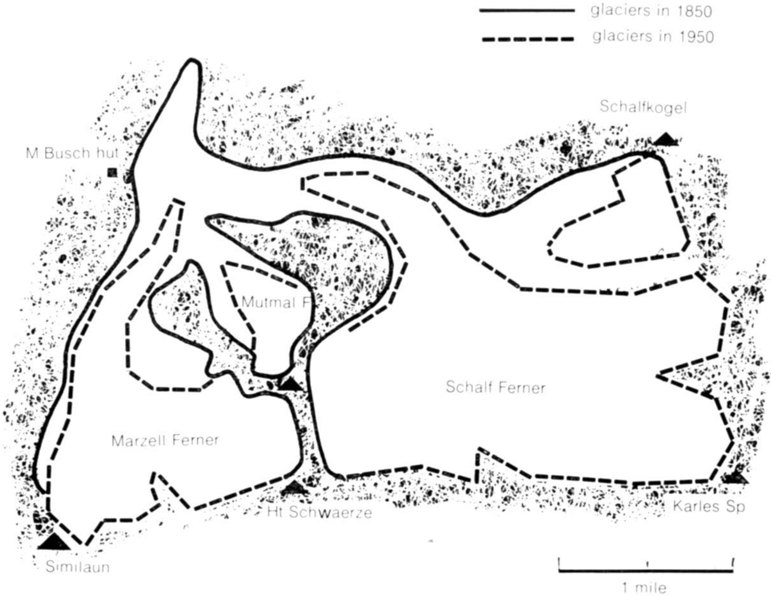
Irregular behaviour of adjoining glaciers

Up to now we have investigated some meteorological influences causing retreat or advance of a glacier which are only of limited help when we try to explain different tendencies of even neighbouring ice fields at one and the same time.

Indeed, there are many other reasons apart from climatic ones affecting glaciers and their behaviour. For example, the different situation with all its variable aspects such as the inclination of the ice stream, its exposure to sun or wind, surrounding slopes or sheltering ridges, and the glacier bed itself, to name but a few. To illustrate their influence an example of two adjoining glaciers from the Oetztal Alps is given: the Schalfferner (ferner = glacier) and the Marzellferner (well documented in F. Rohrhofer's 'Untersuchungen an Oetztaler Gletschern ueber d. Rueckgang 1850–1950' in *Geographischer Jahresbericht aus Oesterreich* 1953–4).

During the climatic favourable period between 1840 and 1850 the big firn supply area of the Schalfferner produced and delivered much more ice to the relatively small tongue than the smaller supply area of the Marzellferner to its comparatively big tongue. Accordingly the lower end of the Schalfferner did swell more and pushed forward faster and further down-valley, with both tongues joining as a result. With dwindling supplies the effects had to be graver on the Schalfferner, since there a much bigger amount of supplies went missing. Thus the first reason for the different attitude of these two adjoining ice-streams is the varying relation of their supply to their loss areas.

A closer survey shows further aggravating effects also causing faster and more substantial retreat of the Schalfferner. Its tongue is exposed to the W, thus the angle of incidence of rays of the sun during the morning is reduced by the inclination of the ice-stream and melting therefore is minimal. Around midday with the sun in the S this effect does not exist any longer. Neither is the Mutmalkamm (the ridge N of the Mutmal F) high and steep enough to protect it. At the same time there is also strong reflection from the southern slopes of the Diemkoegel (just N of the Schalfferner and W of the Schalfkogel) resulting even in a lateral inclination of the tongue towards these slopes, melting therefore is strong and prolonged. During the afternoon the sun freely shines on to the westward-sloping tongue to the same effect.



The changes of a century

The Marzellferner shows a northerly exposure. The morning sun hardly affects it because of the protection given by the Mutmalkamm and Mutmalspitze. Around noon there is a marked moderating effect to all melting due to the reduction of the angle of inclination of the rays of the sun by the angle of the tongue. Thus the maximum possible angle for the lower part of this glacier is 54° as against a possible 66° on a level surface, the first being similar to the height of the sun over southern Norway at the same time. During afternoon and early evening the ice-stream is protected by the Marzellkamm (just W and parallel to the glacier) whereas the Schalfferner is still hit by the sun. Here we have the much more optimal S–N direction of a glacier and the less favourable E–W exposure. This, together with the different relation between accumulation and ablation areas, made the Marzellferner shrink in length by only 3750 ft between 1856 and 1951, with the Schalfferner retreating by more than double the amount, namely 7500 ft during the same time.

The Mutmalferner, a hanging glacier situated between the two described ice-streams, retreated relatively quickly at first but reached, because of its steepness, more favourable climatic surroundings fairly fast, and its shrinkage since then has been slower compared with that of its neighbours.

These are just a few possible differences in local topography as well as climate which can, at times, even result in opposite tendencies of adjoining glaciers, one advancing and the other one stationary or retreating.

Results of glacier advance and retreat

The loss or gain of an ice-covered area can easily be seen in the field or could equally be calculated by map comparison, yet it is much more difficult to assess true advance or retreat values, since this involves the estimation of glacier volumes. This is especially true for the variable amounts of snow and firn supply. The immediate cause of changes therefore remains usually unnoticed by the layman. He will almost always see only some of the results of the variations, and that the better the more regularly he visits the same region.

Amongst the most striking results of the 1850 advance and the subsequent vast retreat during the last 100 years are the huge areas of ground moraine often lined by very big lateral moraines, the outside of which usually are completely grown over by now but with only a few pioneering plants on the still rather unconsolidated flanks towards the glacier. These moraines also show former confluences of two tongues, as they do with Schalf and Marzellferner and many others throughout the Alps. Sometimes even a lake is enclosed between them and the slope on the inside of the junction, which is the case at the Morteratsch and Pers glaciers in the Bernina Alps.

Terminal moraines sometimes are still intact, occasionally forming a dam for a natural reservoir between them and the glacier snout, as did the Sella glacier in the Bernina in 1963. On the other hand they have more often been partially or completely washed away by the glacier streams.

Even visible proof of moraine or ice-dammed lakes in side valleys, the former Gurgler Eissee (Eissee = ice lake) in the Oetztal Alps being an example, as well as the damming of lakes in the main valley by ice masses protruding from side valleys, still exist. Both types, but especially the latter, often caused widespread catastrophic damage in the populated valleys below when the water masses burst their dam during or after the ice's retreat. The best known is the Vernagt or Rofensee (also Oetztal), sometimes up to one mile long, 300 yd wide and 300 ft deep, which burst on several occasions with devastating results, as in 1600, 1678, 1680 and the last time in 1847.

Glaciers also have been known to cause direct damage to forests and cultivated land, i.e. either by advance or break-off of enormous ice masses. The Upper Grindelwald glacier moved over two houses and five barns in 1600, and as recently as 1965 a work camp below the Allalin glacier near Saas Fee was destroyed with the loss of nearly 100 lives.

Other less terrifying and spectacular results of glacier changes can be noticed very often during phases of retreat on slopes too steep to hold morainic sediments close below the snout. The bare rock there shows little or no signs of weathering, with clear marks of ice polishing sometimes combined with good examples of recent striation. Fresh plucking can also be seen on the downhill sides of steeper steps of the once ice-covered rock.

Quite frequently parts of a receding tongue become separated from the main ice stream which was, for example the case with the Triebenkarlasferner in the Stubai Alps in 1960, and sometimes remain for years as so-called *Toteis* (dead ice) usually in sheltered spots as well as generally well covered by moraine debris and without apparent movement of their own before eventually melting

32 *Grenz glacier with the Lyskamm N face above revealing more and more rock in recent years*

away, leaving a kettle hole as a result. The loss of vertical thickness of ice can often lead to extensive crevasse formation and, as advance warning, to the cutting off of 'dead ice' or the thawing out of so-called *Felsenfenster* (rock windows). The appearance of a genuine nunatak, as for example the Zinne in the Gepatschferner in the Oetztal Alps, due to immense losses of the vertical thickness of an ice-field is a very much rarer occurrence. Loss of ice depth in the firn region sometimes terminates a former transfluence, the connection of two glaciers over an usually rather gently sloped ridge, leaving often a very broken and shattered ridge behind.

Above the randkluft, the cleft between ice and the surrounding rock, we sometimes find ice-smoothed rock reaching many feet above the present level of the glacier, also indicating its loss of thickness. Steeper ice-walls and ridges above the firn area show changes as well. Thus at times former pure ice-walls show nowadays a lot of rock, with often considerable stone fall. For example the N face of the Similaun in the Oetztal only twenty years ago was praised as a superb ice-climb but is now a dangerous undertaking on mixed ground. All these mentioned phenomena, resulting from the non-stationary behaviour of glaciers, are just a few. There are many other less noticeable changes.

Some methods of measuring glacier changes

Most of the results of glacier variations mentioned above are quite easily traced on good maps. Especially so when two or more fairly accurate maps of the same region surveyed at different times are available. Therefore the close study of cartographic material is an important means of establishing glacier retreat or advance. Loss of area is quite easily seen and measured. On the other hand, loss of depth can only be calculated fairly reliably when the maps concerned show accurate contour lines which enable a rough estimate of loss of volume. Similarly, the comparison of pictures of one and the same ice-stream taken at different times are a valuable help of assessing its behaviour during the period covered by the photographs.

Moraines as a help towards measuring changes have been mentioned earlier. Often, terminal moraines were used as starting points for annual measurements of retreat, the single phases of which were marked each year with a cairn, paint or some other markers. Botanists use the sequence of pioneering plants arriving one after another on the scene below a retreating snout to estimate the time the area has been clear of ice.

Reduction of volume, but mainly ice speeds, used to be calculated by measuring longitudinal as well as lateral profiles marked with lines of painted stones on the glacier's surface. Also, occasional drillings to ascertain the thickness of ice have been made. Both the above methods are hardly used any longer for the calculation of volume since photogrammetrical survey of maps has gained in popularity. Today aerial photography also plays a part here. Measuring depth of ice is now done by seismic echo work, where the time it takes explosion waves from the ice surface to be reflected from the rock bed

33 *The Tiefen glacier (W Urner Alps) with the Galenstock above, taken in 1973 from point reached by the glacier in 1952, about 250 yards below the present snout* Photo: K. Schwartz

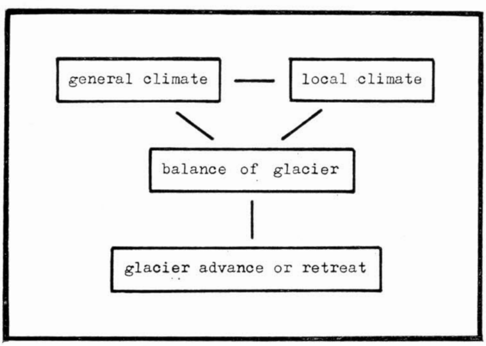
below is measured and the result then easily transformed into actual thickness values. These modern methods, as briefly described here, are accurate to a high degree and thus will add further towards the better understanding of glacier behaviour and all the questions involved.

Summary

Glacier advance and retreat, with all their different and varied effects on our Alpine landscape are, as we have seen, the delayed outcome of long-term (in the sense of several years) changes of the general climate and the average meteorological conditions over a large area, with the local topography as an additional influencing factor.

The often different behaviour of adjoining glaciers with similar mass balance can be explained by their individual response characteristics caused by topographical facts and the strong influence of the local climate, the micro-conditions on the glaciers and their immediate surroundings with its effect on accumulation and the loss of snow and ice, respectively.

Diagram 8



Glacier Advance or Retreat

Newer research stresses the importance of the micro-climatic problems and the near-uselessness of readings from distant weather stations for the study of the local climate. Tests with automatic recording instruments near and on the ice itself are under way now and will, no doubt, help in solving the intricate ways in which the budget of a glacier is determined by local climate, general climate and the additional problem of how far an ice-stream modifies its own meteorological environment.

All these facts are indeed fascinating for scientist as well as mountaineer. The above paper but outlines some of the main factors of all the complex problems involved. Many questions are barely touched and much research remains to be done.