Zeitschrift für Gletscherkunde und Glazialgeologie Bd. 13, H. 1/2 (1977), S. 111—125

RELATIONS BETWEEN MASS-BALANCE AND METEOROLOGICAL VARIABLES ON PEYTO GLACIER, ALBERTA, 1967/1974

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With 3 Figures and 5 Tables

SUMMARY

The eight-year record of mass balance of Peyto Glacier is correlated to meteorological data measured near the glacier and at Lake Louise 30 km to the south. The period investigated includes the highest and lowest accumulations for the past 40 years. The primary controls of net annual balance are seen to be the depth of the winter snow pack and the temperature record during the summer. Extensive summer snowfalls in the ablation area can slow down melt rates very considerably and affect the net annual balance positively. The variable nature of winter accumulation and its influence on snowline retreat and ice melt is illustrated by three years' data.

ZUSAMMENHÄNGE ZWISCHEN MASSENBILANZ UND METEOROLOGISCHEN VARIABLEN AM PEYTO GLACIER, ALBERTA, 1967—1974

ZUSAMMENFASSUNG

Die achtjährige Reihe der Massenbilanz des Peyto Glacier wurde mit meteorologischen Größen korreliert, die in der Nähe der Zunge und am 30 km entfernten Lake Louise registriert wurden. Die Untersuchungsperiode schließt die Jahre mit der höchsten und niedrigsten Winterakkumulation der vergangenen 40 Jahre ein. Die wichtigsten Bestimmungsgrößen der jährlichen Nettobilanz sind die Dicke der Winterschneedecke und die Sommertemperaturen. Ausgiebige Sommerschneefälle im Ablationsgebiet können das Schmelzen sehr verzögern und die Jahresnettobilanz positiv verändern. Der Schwankungsbereich der Winterakkumulation und ihr Einfluß auf Ausaperung und Eisschmelzen wird am Beispiel von drei Jahren gezeigt.

1. INTRODUCTION

1.1. EXPLANATION OF GLACIER MASS-BALANCE

Glaciers respond to changes in climate. Indeed, their very presence is indicative that a certain set of climatic conditions prevails. If the way in which glaciers respond to climate is fully understood, then it is possible to do two things. Firstly, by examining cores taken from the accumulation areas of glaciers and by tracing the former extent of glaciers through mapping the positions of moraines, it is possible to make inferences about past climate (Embleton and King, 1975 (Chapter 1)). Secondly, by postulating future climatic conditions, it should be possible to forecast the future extent and activity of glaciers. Thus, there are important practical reasons for trying to ascertain the links between climate and glacier response.

Some of the most fundamental work on this subject has been performed in Greenland, notably by Dansgaard (Dansgaard et al., 1969). On the upper part of the Greenland ice-sheet there are huge areas with very little surface relief. As a result, conditions of climate and snow accumulation display a minimum of variability over great distances. Because of this relative uniformity the researcher can be sure that what he is examining is truly representative of a large area — he is not confused by local variations in either mass-balance or climate.

The conditions in a high mountainous region are very different. The most striking thing about the alpine area is the great variety of relief, aspect and slope angle. The climatic inputs of precipitation and energy are highly variable over short distances. Variations in amounts of snow accumulation are intensified by the redistribution effects of wind and avalanche. The microclimate of energy transfer to the snow and ice is highly variable too, in response to local variability in glacier surface features. Not only does solar irradiance vary over the glacier surface, but reflectance varies too. These differences can lead to local glacier winds in some areas and pools of stagnant cold air in others. The intricate juxtaposition of rock and glacier surface with very different thermal characteristics leads to a complex heat flow from one to the other.

It is difficult enough to make measurements of precipitation and energy inputs or changes in mass-balance at a point. It is far more difficult to extrapolate these measurements areally, especially when it is obvious that the point sampling locations are not representative of the surrounding surfaces. This is the biggest difficulty in glacier mass-balance research in alpine areas — there is so much noise as a result of local variability in surface shape that it is difficult to distinguish features of overall importance from locally induced phenomena.

Although it is difficult to measure meteorological variables which are of importance to glacier response, attempts have been made to collect basic meteorological information as close to the glacier as possible so that at least simple models of climate — glacier response may be formulated. In this regard, it is probably more useful to maintain a simple program for many years in a standardized manner than to mount a sophisticated program for only a short duration.

1.2. THE CONTENT OF THE CURRENT RESEARCH

As part of the International Hydrological Decade (I. H. D.) program 1965/1974, five glacier basins on an east-west transect from the Rocky Mountains to the Coast Range in southern Alberta and British Columbia were intensively studied. The basins have been described by Østrem (1966) and the methods used for data collection, which included glaciological, meteorological and hydrological components, have been described in the manual by Østrem and Stanley (1969). Peyto Glacier was one of the more intensively studied of the five glaciers. A summary of basic data for Peyto in the form of graphs and maps has been given by Young and Stanley (1976).

1.3. PURPOSE OF THE CURRENT RESEARCH

The purpose of this research is to analyze simple linkages between the mass-balance and meteorological records collected over the 8-year period 1967/1974 in the Peyto Glacier basin. For reasons of measurement accuracy and so that the results of the analysis may be transposed to other research basins, emphasis is placed on simple linkages between mass-balance and the records of temperature and precipitation collected both near to the glacier and at Lake Louise, 30 km south of the glacier at an elevation of 1500 m a. s. l.

2. PEYTO GLACIER, LOCATION AND CHARACTERISTICS

Peyto Glacier, covering about 13.4 km^2, lies on the eastern flank of the Rocky Mountains in Alberta at longitude 116° 35′ W, latitude 51° 40′ N. It is one of several major outlet glaciers of the Wapta Icefield which straddles the Continental Divide. The map, figure 1, shows that the glacier ranges in elevation from 2100 m to 3200 m

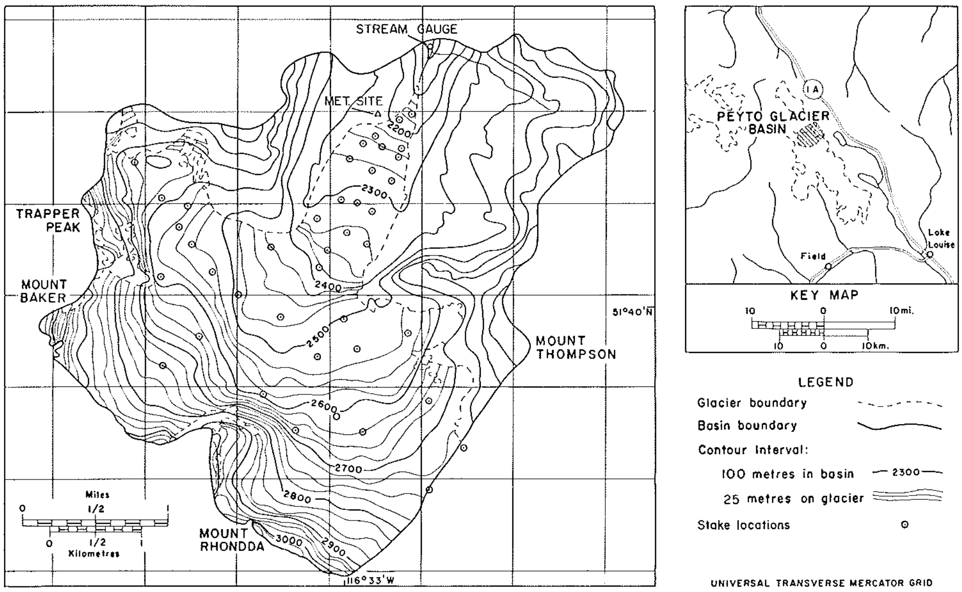

Fig. 1: The Peyto Glacier Basin.

above sea level. The three broad accumulation basins converge to flow over a small icefall at 2400 m a. s. l. to a relatively gently sloping ablation zone contained within steep valley walls. The general aspect of the glacier is to the north east. The short, steep terminus, surrounded by extensive ice-cored moraines, has been retreating up a gorge at a rate of about 10 m y^{-1}. The glacier has probably lost a few hundred m^2 (or about 1—2% of the total glacier area) over the period 1967/1974. Maps and areal estimates used in this paper have been taken from the 1:10,000 topographic map produced from the August 1966 aerial photography and no account has been taken of the relatively small changes in glacier extent in calculations of mass-balance. The base camp with its meteorological site is located at 2220 m a. s. l. on moraine close to bedrock on the northern side of the glacier terminus, about 100 m from the ice. The stream gauge, at which continuous discharge measurements have been made from late May until early September each year, is located at 1950 m a. s. l. The basin draining to the gauge has an area of 22.8 km^2.

Ease of movement on the glacier is shown in a simplified way in figure 2. Compared to many glaciers, accessibility to most parts of the glacier presents few problems. There are, however, some parts which are dangerous at certain times of the year because of avalanches and crevasses. This has affected sampling designs and thus the accuracy of some of the results.

3. MASS-BALANCE MEASUREMENTS

The method of collecting accumulation and ablation data as described in the manual by Østrem and Stanley (1969) has been employed throughout the I. H. D. A network of sampling locations, marked by aluminium stakes and shown in figure 1 has been maintained continuously. The number of stakes has varied from year to year, additional stakes being inserted for special studies, but only 38 stakes common to

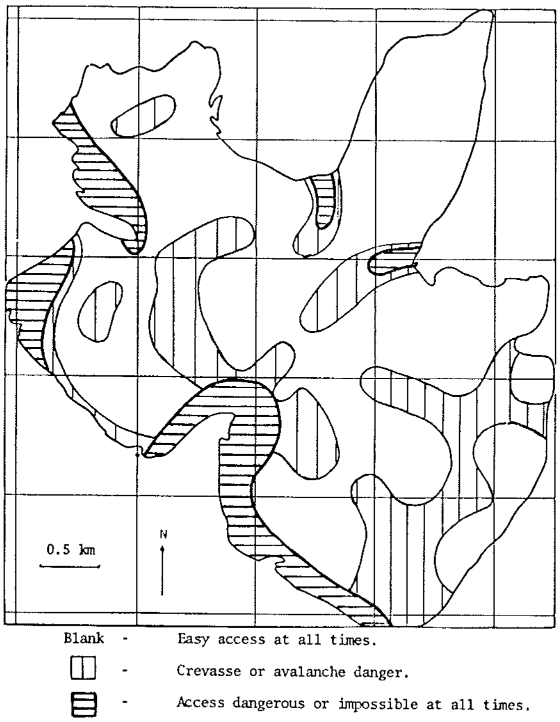

Fig. 2: Accessibility over Peyto Glacier.

all years have been used in the calculation of mass-balance quantities. In this way, results from different years can be better compared, although some accuracy has been lost in those years when the stake network was more extensive.

A fixed date system of measurement has been employed; winter accumulation measurements being made in mid-May, annual balance measurements in mid-September. The stakes have been visited every 10 days to 2 weeks between these dates to monitor ablation rates and snowline retreat.

3.1. ACCURACY OF MEASUREMENTS AT STAKE LOCATIONS

3.1.1 Accumulation measurements

On Peyto Glacier, measuring the net balance at the end of winter is perhaps the easiest task in the mass-balance measuring program. While the underlying summer surface is variable in character over the glacier, it is usually easily found everywhere and there are few complications of mass loss during the winter period. In the ablation area, the underlying summer surface is glacier ice while in the accumulation area it is firn. There may be complications due to the presence of superimposed ice or ice lenses formed during the winter but these tend to be more troublesome after melting of the pack has already begun. The old summer surface in the accumulation area is characterised by a distinct change in both texture and color from the newer snow above.

Snow depth has been measured by probing. Depth often varies markedly over short distances in the ablation area reflecting the complexity of the underlying summer surface: in the accumulation area, on the other hand, depth will vary little over short distances (except in crevassed areas) but does vary considerably from one part of the accumulation area to another, i. e. over distances of several hundred meters. Local variability has been accounted for by taking a number of probings around a particular stake; even in the accumulation area this is advisable, not because of variation of depth here, but because of occasional confusion between ice lenses and the summer surface. Three or four probings have been found sufficient to give a meaningful average depth in the ablation area and confidence that the summer surface has been reached in the accumulation area. Measurements of snow depth at stake locations have usually been supplemented by probings taken along lines between stakes. These additional measurements have been particularly useful in assessing whether or not individual stakes are representative of the areas around them.

Snowpack density measurements have usually been made at only 3 or 4 locations on the glacier, well separated in altitude. The method usually employed has been to dig pits and then take cores from the pit walls. This has not proven too laborious on Peyto, for even in the accumulation area pits are rarely more than 3—4 m deep. Although cores would suffice to give the bulk density of the pack, pits have been thought to give a more accurate density estimate and additional information on snowpack stratigraphy has been obtained from them. Making a complete snow survey of the glacier in mid-May usually takes 2—3 days. Ideally, the survey should be made simultaneously on all parts of the glacier, but a 3 day time spread at this time of the year is quite acceptable for the snowpack is usually very stable.

Typical snow depth figures for the end of winter on Peyto Glacier have been 1—2 m in the ablation zone and 2—4 m in the accumulation zone. Individual depth measurements in the ablation zone have nearly always been accurate to within ± 0.05 m as the snow/ice boundary is clearly defined, while in the accumulation zone the depth has only been accurate to ± 0.2 m. Mean pack density at the end of winter is usually about 430 kg/m^3 and at a particular snow pit is probably within 2% of the true value.

3.1.2 Ablation measurements

Snow melt and ice melt are monitored at stake locations throughout the ablation period usually at intervals of 10 days or 2 weeks. Errors in measurement over short time periods are not considered here. The accuracy of the final estimate of total summer melting and net annual balance at stake locations varies over the glacier surface. Accuracies in the ablation area are usually high, probably within a few percent of the true value. Total amounts of ice melt can be measured to within ± 0.02 m. The density of stakes is relatively high in the ablation zone and no major areas are devoid of stakes, so that while there is considerable variation in annual balance over short distances (reflecting variation in initial snow cover, in included dirt content of the ice and proximity to surrounding rock surfaces), a representative sample of points has always been available.

Accuracy of estimate of net balance in the accumulation area at stake locations is very much poorer. As stated above, the estimate of initial snow cover is poor. The stakes themselves sink into the firn during the ablation period, creating uncertainties in exactly what is being measured. Possibly the greatest uncertainty is concerned with internal alimentation. Meltwater drains from the seasonal snowpack but may be held for long periods of time in the underlying firn and thus not be lost

Table 1: Basic Mass-Balance data, Peyto Glacier, 1967/1974

Altitude Zone (m a. s. l.)	Area (km^2)	Number of Stakes	Stakes density (per km^2)	Specific net winter accumulation (m water equivalent) *Specific net annual balance (m water equivalent)* 1967	1968	1969	1970	1971	1972	1973	1974	Mean 1967-74
3100—3200	0.02	0	0	3.7	2.9	2.3	1.7	1.8	2.4	3.4	2.9	2.6
				3.7	*2.9*	*2.3*	*1.4*	*1.8*	*2.4*	*3.4*	*2.9*	*2.6*
3000—3100	0.17	0	0	3.3	2.6	2.1	1.5	1.7	2.2	2.9	2.5	2.4
				3.3	*2.6*	*2.1*	*0.6*	*1.7*	*2.2*	*2.9*	*2.5*	*2.2*
2900—3000	0.86	0	0	3.0	2.5	2.0	1.5	1.8	2.2	2.7	2.4	2.3
				3.0	*2.5*	*1.9*	*0.0*	*1.8*	*1.7*	*2.7*	*2.3*	*2.0*
2800—2900	1.77	0	0	2.7	2.2	1.8	1.4	1.6	2.0	2.4	2.1	2.0
				2.1	*2.1*	*1.2*	*– 0.5*	*1.1*	*1.1*	*2.4*	*1.8*	*1.4*
2700—2800	2.33	1	0.4	2.4	1.9	1.6	1.2	1.5	1.8	2.0	1.9	1.8
				1.1	*1.3*	*0.4*	*– 1.1*	*0.4*	*0.4*	*1.6*	*1.1*	*0.7*
2600—2700	2.62	4	1.5	2.1	1.7	1.5	1.1	1.4	1.7	1.8	1.7	1.6
				0.2	*0.5*	*– 0.3*	*– 1.6*	*– 0.3*	*– 0.2*	*0.8*	*0.4*	*– 0.1*
2500—2600	2.80	10	2.8	1.8	1.4	1.3	1.0	1.2	1.5	1.4	1.4	1.4
				– 0.9	*– 0.4*	*– 1.1*	*– 2.2*	*– 1.0*	*– 0.8*	*– 0.4*	*– 0.4*	*– 0.9*
2400—2500	1.25	5	4.0	1.5	1.2	1.1	0.8	1.0	1.4	1.2	1.2	1.2
				– 1.8	*– 1.1*	*– 1.7*	*– 2.7*	*– 1.6*	*– 1.4*	*– 1.2*	*– 1.0*	*– 1.6*
2300—2400	0.86	8	9.3	1.1	0.8	0.8	0.7	0.9	1.2	0.8	0.9	0.9
				– 3.0	*– 2.1*	*– 2.7*	*– 3.4*	*– 2.5*	*– 2.2*	*– 2.5*	*– 2.0*	*– 2.6*
2200—2300	0.65	8	12.4	0.9	0.6	0.7	0.6	0.8	1.1	0.6	0.8	0.8
				– 3.6	*– 2.7*	*– 3.1*	*– 3.7*	*– 3.0*	*– 2.6*	*– 3.1*	*– 2.4*	*– 3.0*
2100—2200	0.07	2	28.6	0.8	0.5	0.7	0.5	0.9	1.2	0.6	0.8	0.8
				– 4.0	*– 3.1*	*– 3.6*	*– 4.3*	*– 3.6*	*– 3.1*	*– 3.3*	*– 3.0*	*– 3.5*
Whole Glacier	13.40	38	2.8	2.1	1.6	1.4	1.1	1.3	1.7	1.7	1.6	1.6
				0.0	*0.4*	*– 0.4*	*– 1.7*	*– 0.4*	*– 0.3*	*0.4*	*0.2*	*– 0.23*

from the glacier. The extent of internal alimentation must vary greatly depending mainly on the extent of crevasses which form natural conduits for meltwater.

3.2. SAMPLING BIAS

Figures 1 and 2 and Table 1 show that there is considerable bias in sampling locations towards low-lying, accessible and gently sloping areas. Processes and quantities of accumulation and ablation vary greatly with altitude and slope angle and thus the sampling network cannot be treated as random. The sampling density is particularly poor in the accumulation area, in just the area where point measurements are most unreliable. In making estimates of overall mass-balance rather than mass-balance at points, the sampling bias assumes great importance. In fact, errors due to sampling bias are probably larger than errors due to inaccuracies in measurement at stake locations. The situation may be different on other glaciers where sampling bias may be of less importance.

3.3. ESTIMATES OF OVERALL MASS-BALANCE

From the measurements made at point locations, maps have been made of net winter accumulation and net annual balance by an algorithm described by Young (1976). Maps for each year are given in Young and Stanley (1976). The method involves the assumption that snow accumulation and ablation are associated with the surface shape of the glacier (altitude, slope angle and surface roughness). Associative equations are generated, linking surface shape to quantities of accumulation or melt at sampling locations. These equations are then applied to the known surface configurations at hundreds of points on a square grid covering the glacier and estimates of snow quantities are made. The mass-balance estimates 1967/1974 for the whole glacier and for each 100 m elevation zone on the glacier are shown in Table 1. Above approximately 2600 m the results become progressively less reliable, most especially the net annual balance estimates.

While there are these uncertainties about the overall mass balance of the glacier, there is sufficient information available to make some interesting and probably important observations about patterns of snow accumulation on the glacier. Over short distances, patterns of accumulation repeat themselves closely from one year to another (see Slupetzky, 1971). For example, there are areas in hollows close to the margin of the glacier which always contain deep snow drifts; other more exposed and wind blown areas have much lower accumulations. The ratios of snow depths at adjacent stake locations are closely repetitive from year to year. The patterns become obvious during the ablation period when deep snowdrifts are left as residuals surrounded by ice or firn.

On a larger scale, however, ratios of snow depths do not remain constant from year to year. Table 2 shows mean specific accumulations for two broad altitude zones on the glacier (2500—2700 m and 2200—2400 m a. s. l.). These zones contain 14 and 16 permanent stake locations respectively and thus the effects of any measurement errors should be minimized. When the ratios of snow accumulation between these zones are compared over the period 1967/1974, it is apparent that there is considerable variability.

Snow depth on the lower glacier is very important for overall melt rates. As long as there is snow cover, albedo remains relatively high. As soon as the snow cover disappears and ice is exposed, melt rates increase dramatically. Thus, deep snow on the lower glacier should delay melt and have considerable effect on mass balance.

Table 2: Specific net winter balance (mid-September to mid-May) in two elevation zones

	1967	1968	1969	1970	1971	1972	1973	1974	Mean 1967/74
(a) Specific Winter balance (m) 2500—2700 m a. s. l.	1.94	1.54	1.36	1.02	1.27	1.62	1.61	1.54	1.48
(b) Specific Winter balance (m) 2200—2400 m a. s. l.	0.99	0.74	0.79	0.64	0.81	1.14	0.70	0.83	0.84
(a)/(b)	1.96	2.08	1.72	1.26	1.57	1.42	2.30	1.86	1.76

4. METEOROLOGICAL RECORDS

4.1. METEOROLOGICAL MEASUREMENTS ON PEYTO GLACIER

For the summer months during the I. H. D. period, an instrument station was maintained at the Peyto Glacier base camp at 2220 m a. s. l. about 100 m from the glacier margin. Instruments always included maximum and minimum thermometers, thermohygrograph, totalizing pyranometer, totalizing anemometer, sunshine recorder and precipitation gauge. With few exceptions, instruments were checked once per day and on most days readings were taken four times per day at 08:00, 12:00, 16:00 and 20:00 hours mountain standard time. Basic temperature and precipitation data for Peyto Glacier and Lake Louise are shown in Table 3.

Table 3: Monthly weather data Peyto Glacier and Lake Louise

	1967	1968	1969	1970	1971	1972	1973	1974	Mean 1967/74
PEYTO GLACIER									
Temperature (°C)									
June	4.9	3.4	6.8	7.5	4.4	4.6E	4.3	6.2	5.3
July	7.8	7.8	6.3	9.0	8.0	6.3	7.9	7.7	7.6
August	9.4	6.0	7.1	9.3	8.9	9.0	8.8	7.8	8.3
June-August	7.6	5.8	6.8	8.6	7.1	6.6E	7.0	7.3	7.1
Precipitation (mm)									
June	53.4	95.6	76.0	70.6	87.2	Missing	51.5	65.3	71.4
July	56.4	42.9	77.2	80.5	46.5	27.2*	57.2	34.9	52.9
August	27.7	65.1	65.8	34.5	27.7	13.4*	39.2	76.0	43.7
June-August	137.5	203.6	219.0	185.6	161.4	Missing	147.9	176.2	168.0
LAKE LOUISE									
Temperature (°C)									
June	10.0	8.5	11.2	12.6	9.2	9.6	9.2	10.6	10.1
July	12.8	12.8	10.7	13.8	12.3	10.9	11.9	11.5	12.1
August	14.2	11.1	10.5	12.9	14.6	13.1	11.4	10.9	12.3
June-August	12.3	10.8	10.8	13.1	12.0	11.2	10.8	11.0	11.5
Precipitation (mm)									
June	50.3	52.6	58.7	33.8	69.3	101.3	16.8	32.8	52.0
July	29.2	35.1	59.2	67.3	36.1	56.9	41.4	40.6	45.7
August	15.2	68.1	38.6	11.7	20.8	21.6	46.2	34.5	32.1
June-August	94.7	155.7	156.5	112.8	126.2	179.8	104.4	108.0	129.8

E estimated from partial record and records of previous years
* unreliable data; probably underestimated by a factor of 3

This comprehensive and consistent set of records has proved invaluable as an index for meteorological conditions over the glacier basin. From it the periods of major precipitation and energy inputs to the basin can be determined. While records are generally consistent, there are constraints on measurement accuracy. Temperatures measured within the stevenson screen at base camp are probably accurate to within 1°C. Precipitation measurements, especially snowfall, are less reliable mainly because of problems of gauge undercatch. Absolute amounts of recorded precipitation should be viewed with caution; however, the timing of major precipitation events is reliable. A major drawback in the meteorological records is that the station is on rock, not on the glacier, and therefore does not monitor the local conditions found at the glacier surface. The fact that there are considerable differences in micro-climate from one part of the basin to another has been demonstrated by Foessel (1974) in a study in which several stevenson screens were maintained during the summer of 1973; some on the glacier and some on the surrounding rock. Goodison (1972a) has shown how global radiation income varies over the glacier.

In a general way, meteorological conditions at the base camp do reflect conditions over the whole basin — for example, when it is clear and warm at base camp, it is usually clear over the whole basin; similarly, when it is overcast at the base camp it is usually overcast over the entire basin. But to fully understand the glacier-climate relationship, much more information on heat transfer is needed. This can be done only by a detailed monitoring of processes at the glacier surface; such studies have been performed by Munro (1975) and Derikx (1975) for a glacier ice surface and by Föhn (1973) for a melting snowpack on the glacier. These studies and many more carried out on other glaciers show the complexity of the heat transfer processes and the difficulties in monitoring them effectively. Again, because they are studies at points, inferences still have to be made about conditions over the entire glacier surface.

4.2. ASSOCIATION BETWEEN VARIABLES

It would be expected that the eleven variables monitored in the meteorological program at the base camp would display a high degree of covariation. The correlation coefficients given in Table 4 show that this is indeed the case. The coefficients are based on the data collected in the eight 3-month periods, June-August 1967/1974. All pairs of variables have been considered and the maximum number of valid cases for each pair accounted for. The correlation coefficients for each pair of variables are based on between 528 and 704 valid cases. All coefficients greater than 0.10 are significant at the 99.9% confidence level. All statistical procedures used are found in SPSS (1975).

A factor analysis performed on the data (11 variables; 494 days in the June-August periods when there was no missing data; principal factoring with iteration; varimax rotation with Kaiser normalization) showed two important underlying factors which together accounted for approximately 70% of the total variance. The result of this analysis showed the importance of a temperature component and a precipitation component. For the sake of clarity, therefore, only two variables, mean daily temperature and daily precipitation are considered. Some information is lost in doing this, but the total information lost is small. An advantage in choosing these two variables is that they are the two most commonly measured variables at meteorological stations in the mountains and so comparisons between results from Peyto and data gathered elsewhere should be possible.

Table 4: Correlation coefficients showing interrelationships between meteorological variables at base camp, June-August 1967/1974

	V 1	V 2	V 3	V 4	V 5	V 6	V 7	V 8	V 9	V 10
V 2	−0.33									
V 3	−0.34	0.88								
V 4	−0.13	0.83	0.72							
V 5	−0.36	0.39	0.67	−0.03						
V 6	−0.33	0.99	0.88	0.81	0.39					
V 7	0.51	−0.62	−0.58	−0.39	−0.43	−0.64				
V 8	−0.49	0.59	0.64	0.31	0.58	0.59	−0.73			
V 9	−0.37	0.28	0.44	0.09	0.53	0.28	−0.41	0.62		
V 10	0.39	−0.53	−0.56	−0.29	−0.50	−0.54	0.63	−0.75	−0.50	
V 11	−0.10	0.19	0.15	0.25	−0.05	0.20	−0.28	0.09	0.03	0.01

V 1 Daily precipitation
V 2 Daily mean temperature
V 3 Daily maximum temperature
V 4 Daily minimum temperature
V 5 Daily temperature range
V 6 Melting degree days
V 7 Relative humidity
V 8 Sunshine hours
V 9 Incoming global radiation
V 10 Cloud cover
V 11 Wind run

Standard temperature and precipitation measurements have been collected on a daily basis since 1915 at Lake Louise, 30 km south of Peyto Glacier. The instrument site is in a broad, forested valley in which there is probably much more spatial homogeneity in terms of temperature and precipitation regimes than within the Peyto basin. It is quite possible that the record at Lake Louise gives a better indication of regional weather patterns than the site close to the glacier which is undoubtedly highly influenced by local conditions.

5. RELATIONSHIPS BETWEEN MASS-BALANCE AND METEOROLOGICAL INPUTS

5.1. RELATIONSHIPS BETWEEN MASS-BALANCE, SNOWLINE RETREAT, PRECIPITATION AND TEMPERATURE AT BASE CAMP AND DISCHARGE FROM THE BASIN

In this analysis the records of three individual years, 1967, 1970 and 1974 are examined. These years illustrate particular facets of the mass-balance/climate interrelationship very well; however, the same facets are found in other years too.

Figure 3 summarizes the relationship graphically. The specific winter and annual mass-balances for the whole glacier are shown; the winter balance for 1967 was the highest recorded during the I. H. D.; the 1970 winter balance was the lowest and 1974 showed an average winter balance for the decade.

Snowline elevation on the glacier is difficult to represent graphically in a simple fashion. The smooth curves shown here have been fitted to the record of when each stake on the glacier became snow free. Not taken into account in such a smoothing are those parts of the glacier which retain snow much longer than would otherwise be expected for a particular elevation or conversely those locations which lose snow more rapidly than surrounding areas. Also not shown are the temporary sudden lowerings in snowline elevation after a summer snowfall event. Despite these shortcomings the graphs readily illustrate the considerable differences in rate of snowline movement from year to year. For extra clarity, the elevation of the snout of the glacier and the equilibrium line of the glacier are shown.

The precipitation and temperature records at base camp are shown. In 1967 no records were kept in May and records in 1970 and 1974 cease in mid-September.

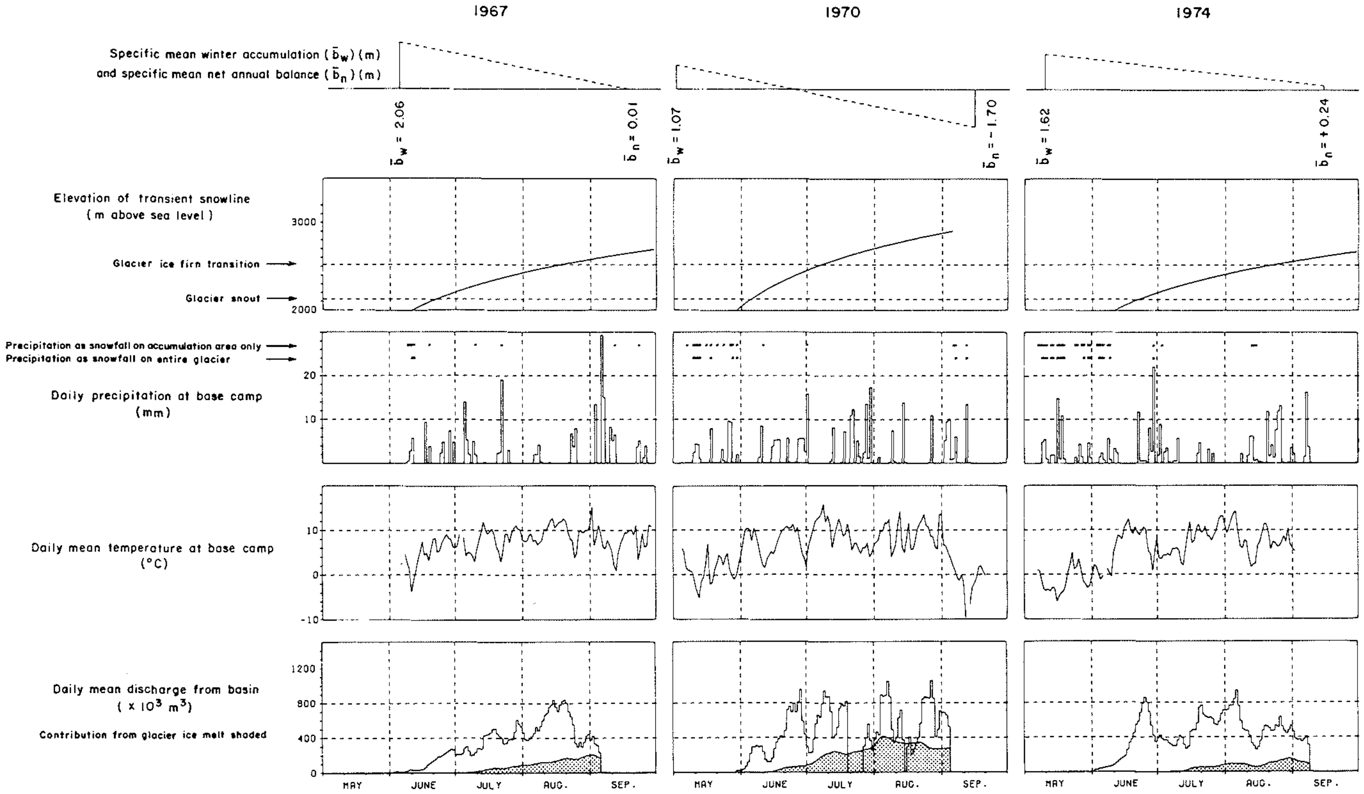

Fig. 3: Summary graphs for 1967, 1970 and 1974.

In addition to the standard precipitation record, precipitation falling as snow in the accumulation area only (rain in the ablation area) and precipitation falling as snow over the entire glacier are also shown.

Stream discharge from the entire Peyto basin in also shown. The discharge record is a composite of water originating from the glacier which covers 61% of the basin area and from the surrounding rock, ice cored moraine and perennial snow patches. It is also a composite in terms of seasonal precipitation, snowmelt and icemelt, each of which components has a different lag time in reaching the gauging station as shown by Stenborg (1970), Derikx and Loijens (1971) and Goodison (1972b). The discharge records all terminate in early September (although there is considerable flow into October) but are otherwise complete except for two short breaks in the record in July and August 1970. Superimposed on the streamflow record is an estimate of flow originating from melting glacier ice. This estimate has been made from the record of stake measurements taken every 10 days or so. It is therefore a smoothed curve and in fact water quantities from icemelt would vary considerably from day to day.

Perhaps the most striking thing about the illustration given by the records from these three years on Peyto Glacier is the very considerable variety from one year to another. Winter accumulation in 1967 was almost twice as much as in 1970. The amounts and timing of precipitation during the summer vary from year to year and, most importantly, the timing and quantities of summer snowfall show considerable contrast between years. Individual temperature records are all characterized by sudden changes from day to day, but there are also considerable differences in mean monthly temperature between years (see table 3).

The combined effects of these meteorological inputs lead to very real differences both in the discharge records from year to year and in the contribution of icemelt to discharge.

Many of the interrelationships between these variables are subtle and not readily apparent. There are, however, some relationships which are very clear and should be emphasized. The most striking is the effect of the winter balance on the rate of snowline retreat. Snowline retreat in turn largely governs the quantity of glacier icemelt which in turn is linked to net annual mass-balance. It is through the mechanism of snowline retreat that net winter balance is linked to net annual balance. Fluctuations in discharge over periods of a few days closely parallel fluctuations in the air temperature curve.

In sum, 1967, a year of very high winter snowfall became a year of no overall net gain because temperatures were slightly above normal and summer snowfall was low; 1970, a year of very low winter snowfall, became a very highly negative ballance year for temperatures were well above average and there was little summer snow; 1974, a year of average winter accumulation, became a year of slight positive balance for, despite temperatures being slightly above normal, a snowy spring and heavy snow in late June greatly retarded melt.

5.2. A SIMPLE MODEL FOR ESTIMATING NET ANNUAL BALANCE

It was shown in 5.1., above, that while the detailed interaction of glacier climate response is complex, some simple relations do emerge which to a great extent govern glacier behaviour. The amount of snow present at the end of winter is of very great importance; the general trend of air temperature throughout the summer is also of importance; the precipitation record, or more precisely the snowfall record, can be of significance to the final mass balance but is not so important as the temperature record. The aim of this section is to formulate a simple model using net winter balance and temperature data to estimate net annual balance.

Two analyses were performed. The first involved the net winter balance and the temperature record at Peyto to estimate net annual balance. The second involved the net winter balance and the temperature record at Lake Louise. The reason for the two analyses was that if estimates of annual balance could be made equally well from temperature data collected at Lake Louise and from near the glacier then the much longer records at Lake Louise could be justifiably used to reconstruct past mass-balance quantities.

The analyses were as simple as possible, involving mean monthly temperatures for June, July and August. The multiple regression equations used were as follows.

1. for Peyto data:
   Annual balance (m) = 1.03 (winter balance) − 0.23 (June temp.) − 0.19 (July temp.) − 0.13 (Aug. temp.) + 2.00
   Standard error = 0.50 m
2. for Lake Louise data:
   Annual balance (m) = 0.92 (winter balance) − 0.32 (June temp.) − 0.03 (July temp.) − 0.18 (Aug. temp.) + 4.10
   standard error = 0.26 m

A complete listing of inputs and predictions is listed in Table 5. From this it can be seen that, contrary to expectations, the Lake Louise temperature data gave better predictions than the Peyto temperature data. The sample sizes are small and the results should be viewed cautiously, but some justification is given the use of Lake Louise data for mass-balance estimates despite the distance from the glacier site. Undoubtedly, more sophisticated models would result in greater predictive accuracy,

Table 5: Estimates of net annual balance from net winter balance and temperature records

	Specific winter balance (m)	Mean monthly temperature (° C) Peyto Glacier			Mean monthly temperature (° C) Lake Louise			Specific annual balance (m) Actual	Specific annual balance (m) estimated from (1), (2), (3) and (4) (standard error = 0.50)	Specific annual balance (m) estimated from (1), (5), (6) and (7) (standard error = 0.26)
		June	July	Aug.	June	July	Aug.			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1967	2.06	4.9	7.8	9.4	10.0	12.8	14.2	0.01	0.25	−0.07
1968	1.63	3.4	7.8	6.0	8.5	12.8	11.1	0.35	0.61	0.56
1969	1.43	6.8	6.3	7.1	11.2	10.7	10.5	−0.40	−0.22	−0.33
1970	1.07	7.5	9.0	9.3	12.6	13.8	12.9	−1.70	−1.57	−1.63
1971	1.31	4.4	8.0	8.9	9.2	12.3	14.6	−0.41	−0.37	−0.56
1972	1.67	4.6E	6.3	9.0	9.6	10.9	13.1	−0.25	0.26	−0.06
1973	1.72	4.3	7.9	8.8	9.2	11.9	11.4	0.43	0.10	0.39
1974	1.62	6.2	7.7	7.8	10.6	11.5	10.9	0.24	−0.26	−0.06

but the results presented here do show that much can be done with very simple inputs.

There are indications of high correlations between winter balance on Peyto and measurements on surrounding snow courses. Some snow courses in the area date back to 1940. It is hoped, therefore, that the Peyto winter balances can be reconstituted from these snow course data and by also using the Lake Louise temperature record that estimates can be made of net annual balances. It is fortunate that the I. H. D. period in this geographical area contained the highest snowfall year (1967) and the lowest snowfall year (1970) since snow-course records began to be kept in 1937. Had the I. H. D. been ten years earlier, the variation between years would have been much lower and confidence in linking mass-balance to meteorological variables would have been much lower.

Using these simple relationships, it will also be possible to predict annual balance from winter balance if estimates of summer temperature are available. This technique may prove to be of more immediate practical value to the hydrologist interested in stream flow predictions than to those glaciologists whose prime interest is in the state of the glacier.

6. CONCLUSIONS

While the 8-year record is a very small sample from which to draw firm conclusions, the period investigated does include the highest and lowest winter accumulations for the past 40 years. The primary controls of net annual balance are seen to be the depth of the winter snowpack and the temperature record during the summer. Extensive summer snowfalls in the ablation area can slow down melt rates very considerably and, in those years when they do occur, affect the net annual balance positively.

Data for this study have been collected over a long period of time by the Glaciology Division. Many people have been involved in this process; however, special acknowledgement is due Dr. A. D. Stanley for his overall coordination of the project. The Water Survey of Canada collected and prepared the basic stream flow records. Parks Canada have given their support to the project throughout its duration.

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Manuscript received 8 September 1977, revised 10 October 1977

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