

## CORRESPONDENCE

The Editor,

*Journal of Glaciology*

SIR, *Reply to Meier's letter on "Variations in velocity of Athabasca Glacier with time"*

Dr. Meier (1965) has made some pertinent comments on a part of my paper (Paterson, 1964). I should like to make a few comments in reply, in the hope that this discussion may contribute a little to the understanding of an interesting problem. The question at issue, the travel time of subglacial run-off, appears to offer wide scope for speculative discussion, as a result of the extreme difficulty of making any direct observations on the phenomenon.

Unfortunately, I did not see Mathews's papers (1964[a], [b]) on run-off from Athabasca Glacier until a few months after my paper had been submitted. The pronounced diurnal variation in stream flow during the summer months is undoubtedly the most conspicuous feature of the record. I certainly ought to have mentioned this in my paper, even though I was dealing with weekly measurements of ice velocity and therefore averaged the stream flow over the same period.

The large diurnal variation in stream flow and the occurrence of the peak in stream flow a few hours after the daily peak in the rate of ice melt are established facts. However, I fail to see that they prove that a large part, or even any, of the water flowing past the gauge on a particular day was produced by melting at the glacier surface on that same day, rather than say a few days earlier. It seems probable that melt water which does not penetrate below the glacier surface will reach the gauging station within a few hours. Examples of this are water which drains directly off the terminus into the lake and water which drains off the surface into marginal streams at the edge of the lower part of the glacier. Meier's dye experiments on South Cascade Glacier show that some melt water which drains into moulins also has a travel time of a few hours. I understand, however, that these experiments were conducted within about 1 km. of the glacier terminus. They are perhaps not entirely representative of conditions on the glacier as a whole. In short, I agree that some melt water reaches the gauging station in a few hours. I think it is still an open question whether this constitutes a "major", or even a large, part of the total melt water.

To deal with Meier's other points: Mathews (1964[a]) showed that it was possible to relate the mean stream flow,  $Q$ , on any particular day to the mean daily air temperature,  $T$ , at the weather station nearest to Athabasca Glacier. Mathews's formula is

$$Q = a + b \sum T_n k^n.$$

Here  $a$ ,  $b$  and  $k$  are constants,  $n = 0$  refers to the day in question,  $n = 1$  to the preceding day, and so on. The sum is taken from  $n = 0$  to  $n = 11$ . Mathews found that, for the period to which my velocity measurements refer (July and August 1960), the best value of  $k$  was 0.7. Thus the weightings assigned to  $T_0, T_1, T_2, \dots$  are 1, 0.7, 0.49, .... The sum of the weightings is 3.3. A larger weighting is certainly given to the current day's temperature than is given to that of any other day, as Meier says. That weighting is however only one-third of the sum of all the weightings. This suggests to me that temperatures, and hence the amount of melting, on the preceding few days have quite an important effect on the stream flow on any given day.

As Mathews says, the discharge can fall by more than 50 per cent from 7.00 p.m. to 7.00 a.m. the following day. This refers to the difference between the maximum and minimum instantaneous discharges. It gives perhaps a slightly exaggerated impression of the difference between the stream flow over periods of a few hours around the times stated. It may be surprising that the difference between maximum and minimum discharges is as large as this. If, as Meier claims, the major part of the melt water escapes from the glacier within a few hours, it is perhaps equally surprising that discharge maintains as high a value as it does throughout the 24 hr. Melting is reduced to virtually zero during the night, except under exceptional weather conditions.

To sum up, I think it is quite possible that the travel time of a substantial part of the subglacial melt water may be an order of magnitude greater than Meier's "few hours". This view appears to be supported by results from the Gornergletscher (personal communication from G. R. Elliston).

The existence and size of Weertman's hypothetical thin film of water at the glacier bed is a separate,

but related, question. I felt, and still feel, that it was worthwhile to point out that my results might be relevant to this question, even though Meier thinks that this is unlikely.

I certainly support Dr. Meier's plea that high priority be given to further investigation of the flow of water at the bed of a glacier. The whole question of the distribution and flow of water in a temperate glacier deserves further study as soon as possible.

I wish to acknowledge the kindness of Dr. G. R. Elliston in letting me see the draft of a paper of his prior to publication. This has been most helpful.

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23 March 1965*

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## REFERENCES

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SIR,

### *Advance of Walsh Glacier*

In May of 1952 the writer walked eastward up the north side of Logan Glacier (St. Elias Range, Yukon Territory), crossed Walsh Glacier and continued up Logan Glacier *en route* to King Peak. Only about 6 hr. were required to cross the 1.5 miles (2.4 km.) of stagnant ice of the Walsh Glacier terminus where it adjoins Logan Glacier.

In August 1964 he traveled down Logan Glacier and attempted to cross Walsh Glacier at the same place as in 1952. More than 10 hr. of extremely difficult walking was required to detour at least 3 miles (4.8 km.) farther down Logan Glacier because of impassable seracs and crevasses caused by a recent spectacular advance of Walsh Glacier.

*Location.* Walsh Glacier is located in the St. Elias Range between long.  $140^{\circ} 15'$  and  $141^{\circ} 15' W.$  and at lat.  $60^{\circ} 55' N.$  near the Alaska-Yukon border (Fig. 1). Walsh Glacier is about 35 miles (56 km.) long and flows from east to west to its confluence with Logan Glacier in Alaska. The total area occupied by Walsh Glacier is about 160 sq. miles (415 km.<sup>2</sup>). The accumulation zone is complex and consists of many small "feeder" glaciers with a total area not exceeding 70 sq. miles (180 km.<sup>2</sup>). Most of the small tributary glaciers of the accumulation zone are north of the main ice stream, which flows slightly north of due west in almost a straight line for more than 30 miles (48 km.).

In 1952 the terminus of Walsh Glacier was stagnant and consisted of hills and pinnacles of ice covered with 2-4 ft. (0.6-1.2 m.) of moraine. Numerous melt-water lakes and streams also indicated a stagnant condition. The average elevation of the glacier surface was much lower than that of Logan Glacier. Vegetation, consisting mostly of willow and small flowering plants, had started to grow on large areas of stabilized moraine.

Studies of air photographs taken in 1951 show that upper Walsh Glacier had many well-developed medial moraine ridges consisting of a thick cover of rock debris on ice. The lateral moraine area of the north side of the glacier was quite wide and contained many melt-water lakes. Debris-free ice lanes between the medial moraines were relatively smooth and became more extensive farther up-glacier.

In 1964 the terminal area of Walsh Glacier had become a tremendous maze of chaotic seracs and crevasses with an average surface elevation at least 150 ft. (45.7 m.) higher than the pre-advance surface. The terminus of Walsh Glacier has pushed out and has over-ridden Logan Glacier for at least 2 miles (3.2 km.) beyond its former position (Fig. 2).