JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. B9, PAGES 8961–8968, AUGUST 10, 1987

Columbia Glacier, Alaska: Changes in Velocity 1977–1986

ROBERT M. KRIMMEL AND BRUCE H. VAUGHN

U.S. Geological Survey, Project Office Glaciology, Tacoma, Washington

The Columbia Glacier, a grounded, iceberg-calving tidewater glacier near Valdez, Alaska, began to retreat about 1977. Drastic retreat occurred in 1984, and by early 1986, retreat amounted to 2 km. The glacier has thinned more than 100 m since 1974 at a point 4 km behind the 1974 terminus position. Between 1977 and 1985 the lower glacier ice velocity increased from 3–8 m/d to 10–15 m/d. Ice velocity in the region 0.5 km above the terminus was highest near the time the glacier was most receded (late fall), and lowest near the time of maximum length (early summer), for years 1977–1982. Velocity in the region 52–57 from the head of the glacier was highest in mid-spring, and lowest in early fall from 1977 to 1985. Through the years 1983–1985, the dates of maximum and minimum velocities within 0.5 km of the receding terminus tended toward the dates of the 52–57 km maximum and minimums. This occurred because as the terminus receded, it was no longer strongly influenced by the reverse slope of the terminal moraine shoal. Velocities near the terminus fluctuated by 2–3 m/d during summer and fall, when liquid water input was variable, and were relatively constant during winter. Hourly variations in ice velocities are controlled by liquid water input to the glacier hydraulic system and tide stage. Velocity increases near periods of high surface water input and decreases during periods of high tide as a result of hydrostatic back pressure.

Introduction

Columbia Glacier, a grounded, iceberg-calving tidewater glacier in Prince William Sound, Alaska, was approximately 66 km long from the time its terminus position was first mapped in 1794 [*Vancouver*, 1798] until the late 1970s. In the early 1980s a slow retreat that started during the late 1970s began to accelerate, and between November 1983 and November 1984 there was a recession of nearly 1 km [*Meier et al.*, 1985*a*]. By 1984 the glacier had receded into deep water, and the retreat was considered to be drastic (A. Post, written communication, 1986).

From 1910 to 1975 there were minor changes in the terminus position and shape [*Post*, 1975]. Since 1977, and possibly before 1977, although not as well documented, there has been a seasonal variation in glacier length, with a maximum length in late spring and a minimum length in late fall. Seasonal length variation has been 0.5 km, and this variation has increased in magnitude as retreat has continued. The average annual date of maximum length from 1977 to 1985 is June 7 and of minimum length is November 22.

This paper describes changes that have occurred in the velocity field of the lower Columbia Glacier as the drastic retreat has begun. An attempt is made to relate the changing buoyancy (as the glacier thins and retreats into deeper water), the changing hydrostatic support (as the tide changes), and the changing water input (from ice melt and rain) to the observed ice velocity.

The lowest 14 km of Columbia Glacier is shown in Figure 1. The numbers on Figure 1, 52 km through 66 km, indicate the distance of these locations from the head of the glacier. This scheme is used throughout this paper to define the position along the centerline. The length of the glacier is shown in Figure 2.

Surface Altitude of the Lower Glacier

The lower Columbia Glacier was mapped from vertical aerial photographs taken July 1974, September 1981, and September 1983. In addition, the altitudes of 10 points in August 1984, 3 points in August 1985, and 1 point in April 1986, all between 60 and 65 km, were measured by optical surveys using theodolites and electronic distance measuring (EDM) equipment. The surface of the lower glacier is rough with typical serac top to crevasse bottom relief of 25 m [*Meier et al.*, 1985*a*]. The surveyed altitudes were of markers placed on serac tops. Longitudinal profiles were prepared using the maps; most of the surveyed points were close to the longitudinal profile, and those that were not show similar changes. Longitudinal profiles along the centerline are shown in Figure 3. The altitude of the glacier surface at a point 63 km from the head of the glacier (Figure 1) decreased more than 100 m between 1974 and 1986 and at a rate of more than 20 m/yr since 1983.

Velocity of the Lower Glacier

Displacements of specific points, over time intervals ranging from 10 min to 108 days have been measured on the lower glacier. Measurements as frequent as every 10 or 15 min were made using an automated laser EDM (electronic distance measurement) system and are limited to a small number of markers for less than 30 days in each year 1984–1986 [*Vaughn et al.*, 1985]. The displacement of up to 30 points near the terminus was measured from oblique photographs taken daily with automated cameras. Interpolation within gaps caused by bad weather allowed ice velocities to be determined with daily resolution [*Krimmel and Rasmussen*, 1986]. Measurements with a time resolution of about 1–3 months were made using periodic vertical aerial photography [*Meier et al.*, 1985*b*].

Velocity data from June 1977 through August 1981 (Figure 4) are taken directly from *Meier et al.* [1985*b*] but are presented here in a different format. Between August 1981 and October 1982 the data were obtained using precision stereo plotter as described by *Meier et al.* [1985*b*]. From October 1982 to March 1986 the velocity data were obtained using the less precise photograph overlay method described by *Meier et al.* [1985*b*]. The velocity versus time curves at each kilometer interval are similar to each other. The maximum and minimum annual velocities at the 52–57 km and 66

Paper number 6B6105.

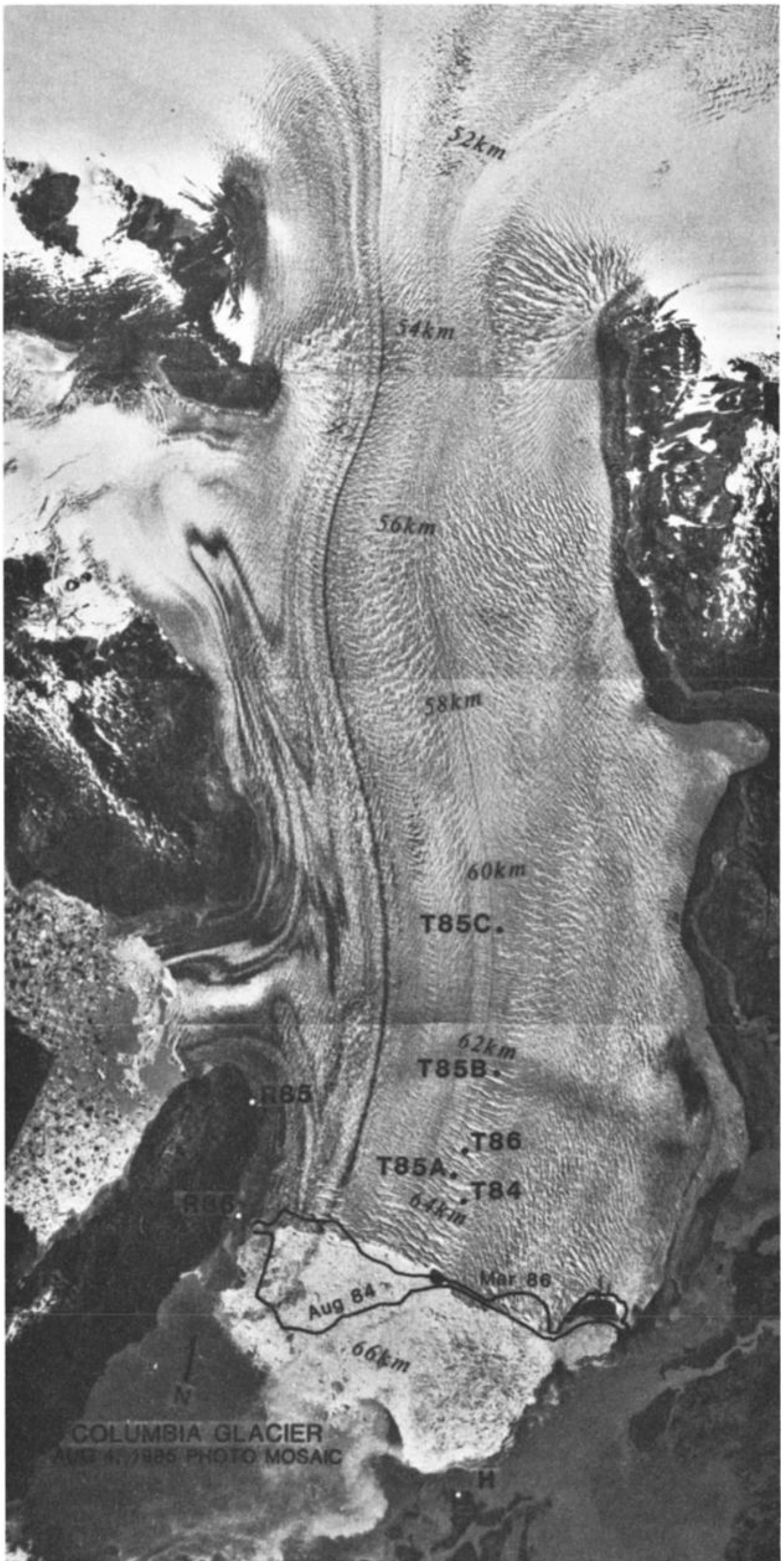

Fig. 1. Columbia Glacier photo mosaic, August 4, 1985. The locations of 52 km to 66 km numbers are distances along the centerline of the glacier, with 0 km at its head. Terminus positions for August 1984 and March 1986 are shown as heavy lines. H is location of the instrument station used for velocity experiments 1984–1986. R85 and R86 are locations of reference stations, and T84, T85A, T85B, T85C, and T86 are approximate reflector locations, with years specified.

km locations are indicated on Figure 4. The average date of occurrence of the maximum velocity from 52 to 57 km was May 4, and for the minimum velocity was September 27. At 66 km the date the maximum velocity averaged December 5, and minimum velocity averaged July 1, for the years 1977–1982. Through 1982, maximum velocity at 66 km usually occurred shortly after the date of minimum glacier length, which averaged November 17, and minimum velocity occurred shortly after the date of maximum length, June 13. Because the terminus was receding, the 66 km location no longer existed after 1983; after early 1982 a point remaining about 0.5 km above the terminus was substituted for the 66 km location, this point moved up-valley as the glacier receded. Table 1 summarizes the dates on Figure 4.

In 1983 the velocity at about 0.5 km above the terminus increased from about 3–8 m/d to 10–15 m/d. This velocity increase was evident from both the vertical photography and the daily sequential oblique photography (Figure 5). The daily data generally show the same long-term trends as the several-month data and also show a higher-frequency velocity variation of 1–3 m/d over periods of several days. The variations tend to be less in the winter and spring seasons than during summer and fall.

The high-frequency velocity variations, with resolution of less than 1 hour, were measured for three periods, August 11 to September 5, 1984, August 7 to September 2, 1985, and March 25 to April 9, 1986. In each measurement sequence the distance of the target (a reflector) along a trajectory at a given time was measured using an automated EDM. The measured distance had an error of about 1 cm [*Vaughn et al.*, 1985]. For each of the time-distance data sets the velocity was determined using the derivative of a smoothing cubic spline [*Reinsch*, 1967]. This method tends to underestimate the maximum and overestimate the minimum velocities. Thus the absolute amplitude of the apparent velocity variations are less than actual, but the relative amplitude variations and timing are more accurate.

During 1984 a single reflector was placed about 1.3 km above the terminus. Velocity was affected by rain, with a 50% increase in velocity associated with an intense rain. The highest velocity occurred about 12 hours after the most intense rain. Velocity maxima corresponding to low tide and velocity minima corresponding to high tide were also evident. On every day except during periods of precipitation, the afternoon or evening peak velocity was higher than the morning peak velocity (Figure 6).

In 1985, three reflectors were placed at 1.3, 2.8, and 4.6 km (Figure 7: A, B, and C, respectively) above the terminus and gave similar results as in 1984. The A and B targets were strongly influenced, nearly synchronously, by the tide. The tide influence was not clear at the C target. During the 1985 measurement period the precipitation events were less episodic than in 1984, nonetheless velocities tended to be higher shortly after rainstorms (Figure 7).

In March and April 1986, during a period of mostly below freezing temperatures, one reflector was placed near the position of the 1984 and 1985A reflectors. Velocity variations were nearly synchronous with the Valdez, Alaska, predicted tide (Figure 8). Figure 9 shows the inverse of Valdez predicted tide along with the velocity variations.

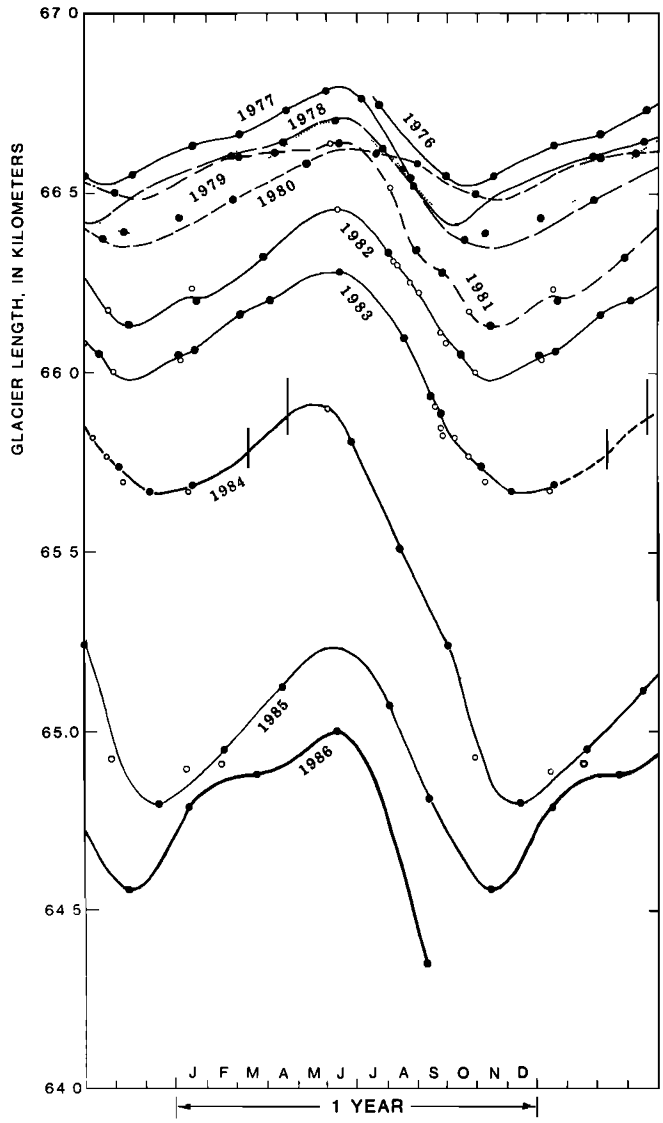

Fig. 2. Changing terminus position of Columbia Glacier, 1977–1985. All points represent an average of 20 points across the terminus. Solid circles are from aerial photographs and open circles are from on-site surveys. Length accuracy is 25 m, and the curve through the points is accurate to about 50 m. Vertical bars in 1984 represent uncertainty in the terminus position because of areas of floating ice tongue. This figure updated from Figure 3 of *Meier et al.* [1985*a*].

Bed Configuration

The glacier bed is known to some extent by bathymetry, subsequent to recession from the moraine shoal (A. Post, written communications, 1979–1984); and by radar overflights [*Brown et al.*, 1986]. As seen in Figure 3, the smoothed centerline bed becomes progressively deeper, to a maximum of about 330 m below sea level, at the 62-km location. Therefore the glacier must slide uphill from the 62-km location to the terminus.

The terminus is generally grounded; however, for periods during the winters of 1984 and 1985, tongues of floating ice, still attached to the glacier, were observed. During other periods, local areas along the calving ice face were no more than a few meters above sea level, suggesting the possibility of local flotation. These areas have never been observed to include more than about 20% of the terminus width.

During the 1985 and 1986 short-term velocity experiments the vertical angle between the reflectors and a bedrock point was measured at times of high and low tide. The surveys showed no vertical changes associated with tide stage,

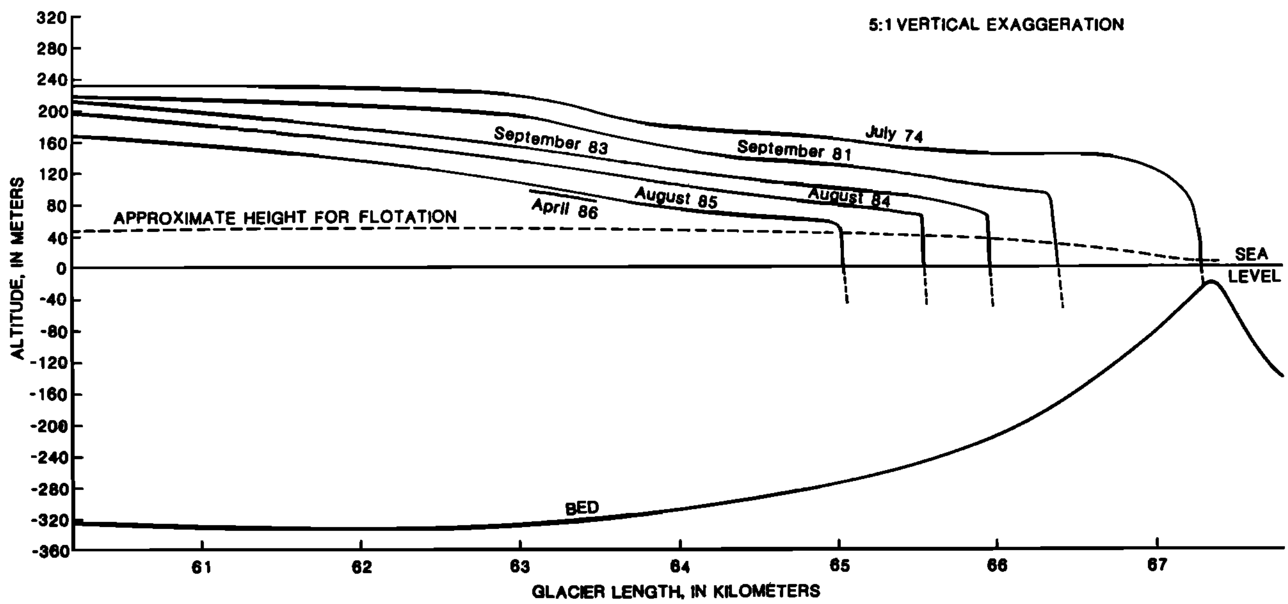

Fig. 3. Longitudinal profile of the terminus region of Columbia Glacier, 60–67 km. Profiles are centerline and smoothed. Bed profile is from airborn radar soundings [*Brown et al.*, 1986]. July 74, September 81, and September 83 surface profiles are from topographic maps. August 84, August 85, and April 86 surface profiles are from point surveys.

indicating that the glacier, at the location of the reflectors, was not floating with the tide.

Discussion and Conclusion

The three types of ice velocity data, long term, daily, and high frequency, are all consistent with one another. By looking at the longterm data (Figure 4), it is evident that from 1977 to 1983 the ice velocity followed approximately the same seasonal pattern and magnitude from year to year. However, beginning in 1983 and continuing through 1985, the ice velocity near the terminus increased by a factor of 2–3 but with the same seasonal pattern. This near-terminus velocity increase is also evident in the daily data (Figure 5). In addition, the daily data show fluctuations of up to 2 m/d over a period of a few days. This fluctuation occurs mostly during the summer and fall seasons when liquid water input (rain and ice melt) is more variable. The high-frequency data (Figures 6–8) show dependence on tide and liquid water input, with the liquid water input effect disappearing during the cold season.

Up to 1982, velocity in the area of 52–57 km has been maximum in mid-spring and minimum in early fall. Velocity near the terminus, from 1977 to 1982, followed a similar pattern but very different in timing. At the 66-km location the average maximum and minimum velocities were at December 5 and July 1, respectively, several months out of phase from higher up the glacier but nearly in phase with the inverse of the glacier length; when the glacier was short, the velocity was at its maximum. This can be explained by consideration of the longitudinal bed profile near the terminus (Figure 3). As the glacier slides toward the terminus, it rides up the reverse sloping moraine. As the ice rides up the moraine, it becomes thinner and flows faster, approximately the same ice flux must pass through a reduced cross section. The moraine is acting to confine the glacier, when the glacier is riding up the moraine the moraine itself is offering resistance to the ice up valley and tends to prevent rapid flow. When the glacier is reduced in length, by calving, this effect is reduced, allowing the glacier to increase velocity. The subsequent advance results in increased basal resistance, reducing velocity. The calving rate, which is likely driven on a seasonal basis by subglacial water discharge [*Sikonia and Post*, 1980], thus controls velocity very close to the terminus where this reverse slope basal configuration exists.

The short-term velocity measurements provide additional support to the idea that increased resistance at the terminus significantly slows the glacier near the terminus. In this case, velocity is reduced by about 10% during high tide. The hydrostatic pressure against the ice cliff, rather than basal friction, is the dominating cause of short-term velocity fluctuation.

The reverse bed slope has been progressively less important to the terminus velocity fluctuation since 1982, and this can be seen in a change in the timing of maximum and minimum velocities at a point near the terminus. Each year, 1983–1985, the minimum velocity near the terminus has occurred later in the summer, and while not as regularly, the maximum terminus velocities have occurred later as well. Since 1982, the terminus has been behaving progressively more like the region of 52–57 km.

The long-term velocity increase observed in 1983 may be

TABLE 1. Average Dates of Maximum and Minimum Velocities and Glacier Length Compiled From Figure 4

	Glacier Length, km	Min Velocity	Max Velocity	Min Length	Max Length
1977–1982	52–57	Sept. 27	May 4	Nov. 17	June 13
1977–1982	66	July 1	Dec. 5		
1983	0.5*	June 24	Jan. 7	Dec. 5	June 2
1984	0.5*	Aug. 11	March 18	Dec. 16	May 11
1985	0.5*	Sept. 9	Jan. 14	Nov. 14	June 6

* Above terminus.

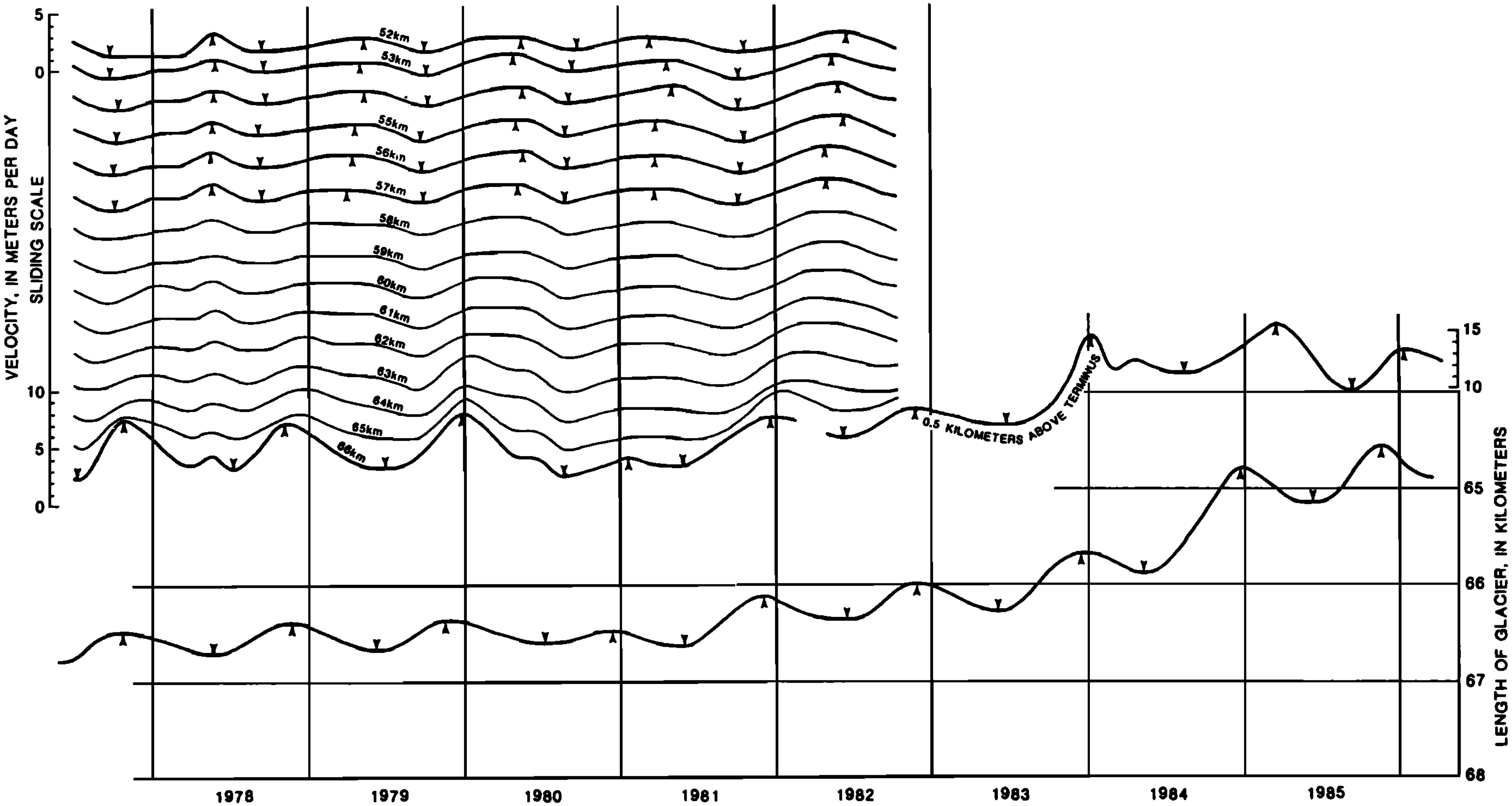

Fig. 4. Velocity at several locations on lower Columbia Glacier and glacier length. Data obtained from sequential aerial photographs [*Meier et al.*, 1985*b*]. Velocity scale slides, with absolute scales shown for 66 and 52 km only. Arrowheads indicate maxima and minima, the dates of which are summarized in Table 1. The dates of the maxima and minima are accurate to 30 days.

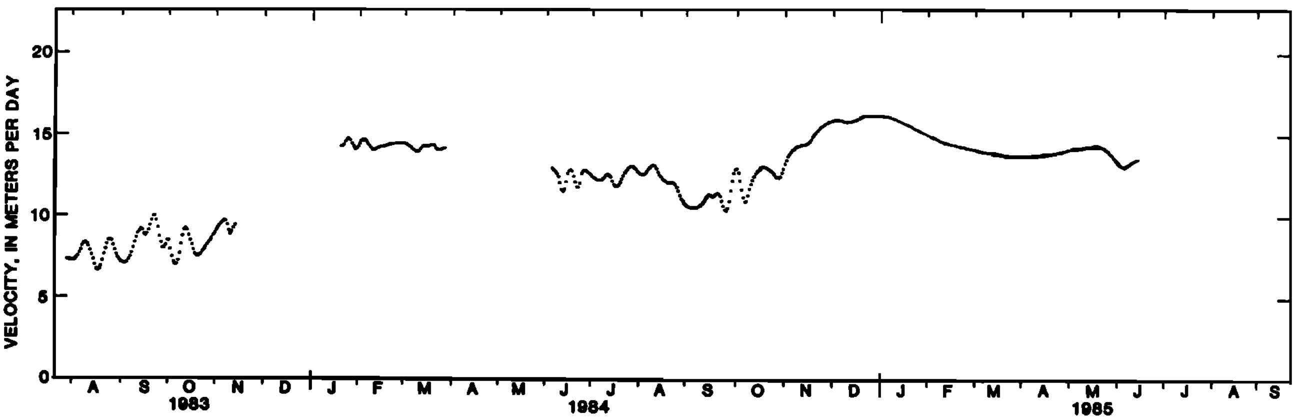

Fig. 5. Daily velocity of Columbia Glacier, generalized for lowest 1 km. Data are obtained from automatic cameras and are accurate to 1 m/d. Data gaps caused by bad weather were filled by interpolation [*Krimmel and Rasmussen*, 1986].

the result of reduced basal fraction as the overburden pressure of the ice is reduced. The glacier has thinned tremendously since 1974. As thinning has occurred, the height of ice unsupported by buoyancy has been reduced. The ultimate release of bed friction occurs when flotation occurs, at which time velocity of the still grounded ice behind the newly floated tongue would be expected to increase because that part of the terminus would no longer offer any basal resistance.

The 1-km recession in 1984 was followed by a 0.25-km recession by October 1985. Although the 1985 retreat was not as spectacular as that of 1984, it is unlikely that the retreat is ending, but rather that it is not regular from year to year. The retreat rate is influenced by many factors, which

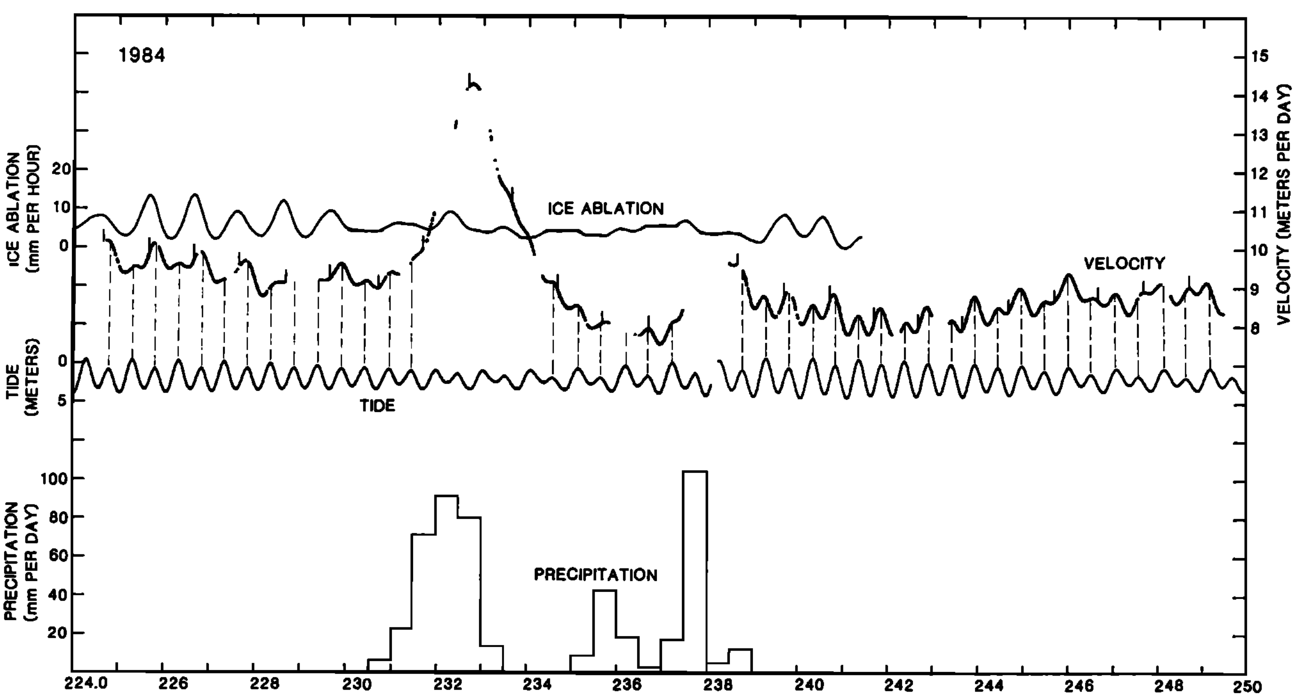

Fig. 6. The 1984 short-term velocity measurements. A single target was located 1.3 km above the terminus. Velocity, precipitation, inverse tide, and ice ablation are plotted. A dashed line between low tide and the velocity curve is included to help show the relation between tide and velocity. Short vertical lines above the velocity curve at 1500 LT the time of maximum ice ablation, help show that the evening velocity maximum is greater than the morning velocity maximum. Gaps in the velocity curve result when poor visibility prevented data acquisition. The tide record is measured tide within 5 km of the Columbia Glacier terminus until day 238. After day 238, the tide is adjusted from NOAA Valdez tide records. The tide is plotted with low tide up. Precipitation and ice ablation were measured within 5 km of the terminus.

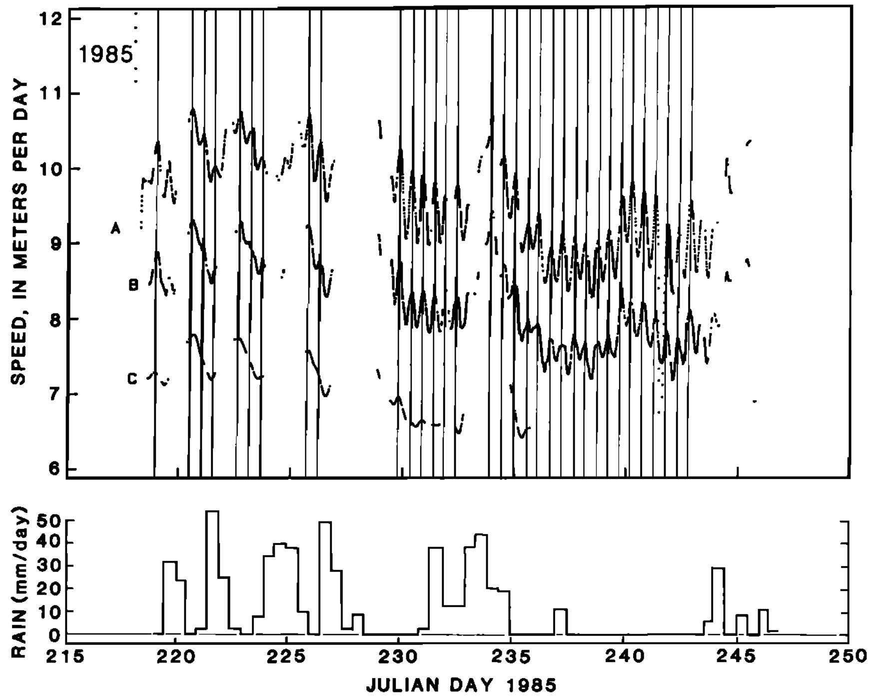

Fig. 7. The 1985 short-term velocity measurements. Target A was 1.3 km, target B was 2.8 km, and target C was 4.6 km above the terminus. Vertical lines are at the peak velocities at target A. Precipitation was measured at site H (Figure 1).

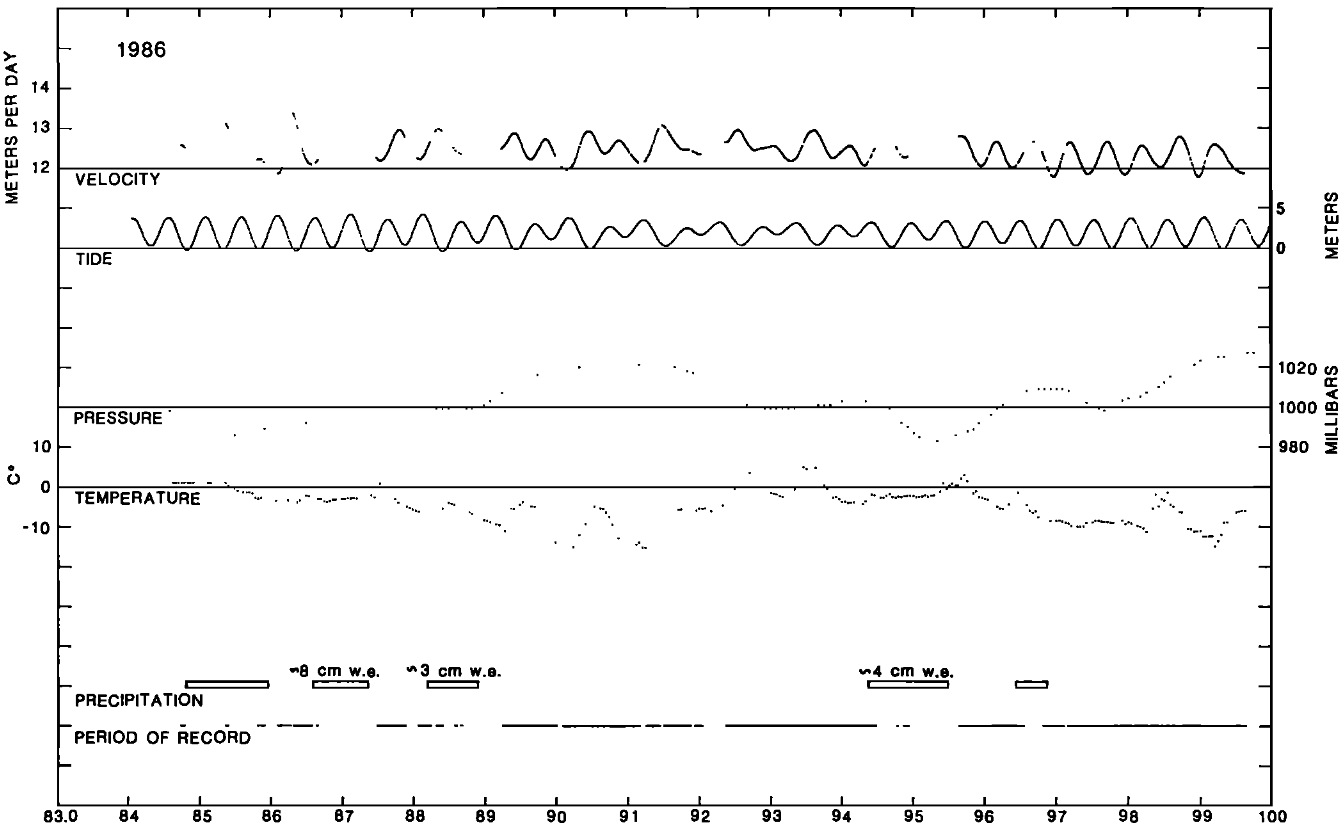

Fig. 8. The 1986 short-term velocity measurements. A single reflector was located 1.8 km above the terminus. Air temperature, air pressure, and precipitation were measured at site H (Figure 1). High and low tide are plotted from Valdez, Alaska, predicted tides, plotted low tide down.

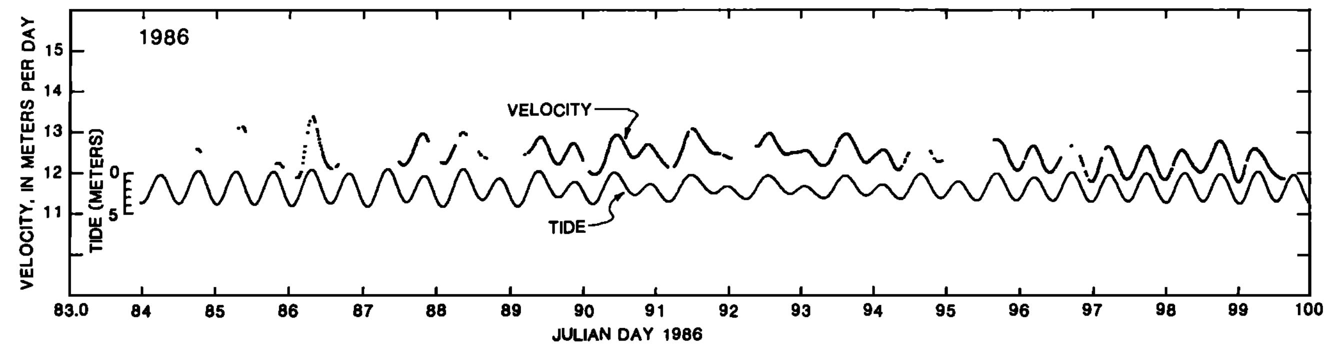

Fig. 9. Velocity at the 1986 target plotted with the inverse of Valdez, Alaska, predicted tide. Low tide is plotted up, high tide down, so that the inverse correspondence of tide and velocity can be more easily seen. The time scales are slightly offset for the same reason. At time = 0 for velocity, time = 77 min for tide.

may include geometric irregularities in the bed and valley, ice-dammed lake levels and outbursts, and meteorological variables.

REFERENCES

Brown, C. S., L. A. Rasmussen, and M. F. Meier, Bed topography inferred from airborne radio-echo sounding of Columbia Glacier, Alaska, *U.S. Geol. Surv. Prof. Pap., 1258-G*, 56 pp., 1986.

Krimmel, R. M., and L. A. Rasmussen, Using sequential photography to estimate ice velocity at the terminus of Columbia Glacier, Alaska, *Ann. Glaciol., 8*, 117–123, 1986.

Meier, M. F., L. A. Rasmussen, and D. S. Miller, Columbia Glacier in 1984: Disintegration underway, *U.S. Geol. Surv. Open File Rep., 85-81*, 17 pp., 1985*a*.

Meier, M. F., L. A. Rasmussen, R. M. Krimmel, R. W. Olsen, and David Frank, Photogrammetric determination of surface altitude, terminus position, and ice velocity of Columbia Glacier, Alaska, *U.S. Geol. Surv. Prof. Pap., 1258-E*, 41 pp., 1985*b*.

Post, A, Preliminary hydrography and historic terminal changes of Columbia Glacier, Alaska, *U.S. Geol. Surv. Hydrol. Invest. Atlas, 559*, 3 sheets, 1975

Reinsch, C.H., Smoothing by spline functions, *Numer. Math., 10*, 177–183, 1967.

Sikonia, G. W., and A. Post, Columbia Glacier, Alaska: Recent ice loss and its relationship to seasonal terminal embayments, thinning, and glacial flow, *U.S. Geol. Surv. Hydrol. Invest. Atlas, HA-619*, 3 sheets, 1980.

Vancouver, G., *A Voyage of Discovery to the North Pacific Ocean and Round the World in the Years 1790–1795*, vol. 3, printed for G. G. and J. Robinson, Paternoster-Row, and J. Edwards, Pall-Mall, London, 1798.

Vaughn, B. H., C. F. Raymond, L. A. Rasmussen, D. S. Miller, C. A. Michaelson, M. F. Meier, R. M. Krimmel, A. G. Fountain, W. W. Dunlap, and C. S. Brown, Short-term velocity measurements at Columbia Glacier, Alaska: August–September 1984, *U.S. Geol. Surv. Open File Rep., 85-487*, 29 pp., 1985.

R. M. Krimmel and B. H. Vaughn, U.S. Geological Survey, Project Office Glaciology, 1201 Pacific Avenue, Suite 450, Tacoma, WA 98402.

(Received June 6, 1986;
revised October 7, 1986;
accepted November 5, 1986.)