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ABSTRACT: The largest concentration of glaciers in the American Rocky Mountains occurs in the Wind River Range of Wyoming, but the contribution of glacier meltwater to flow in headwater streams of the Green River and Wind River drainages has not been documented. The present study documents the loss of ice in Dinwoody and Gannett Glaciers since the 1930's and the importance of glacier meltwater to overall water supply in the Green River and Wind River drainages. Both glaciers have retreated and lost thickness in the last five decades, but repeat photography revealed that Dinwoody Glacier has responded more dramatically than Gannett Glacier to the unfavorable climatic conditions. This contrast can be explained by the difference in area-elevation curves between the two glaciers. The estimated glacier meltwater from Dinwoody and Gannett Glaciers amounts to 27 percent of the September runoff and 32 percent of the October runoff in lower Dinwoody Creek. The July-October runoff from glaciers in the Wind River Range is approximately 70 x $10^6 m^3$, or eight percent of the average runoff in the Wind River and Green River basins during that four-month period.
(KEY TERMS: glaciers; runoff; climate change; Wind River Range.)

INTRODUCTION

The Wind River Range is an unbroken 160-kilometer long barrier in west central Wyoming that is host to 63 glaciers covering 44 square kilometers in area (Figure 1). Seven of the ten largest glaciers in the American Rocky Mountains are found in the Wind River Range, while the total area of glaciers in the Wind River Range is larger than that of all other glaciers in the American Rockies (Meier, 1951; Davis, 1988). Glaciers contribute an undocumented amount to streamflow in Wyoming. Glaciers can be considered as natural reservoirs which store water in the winter and release it in the summer. Glacier runoff is likely to be most important during the late summer and early fall when low flows are critical for consumptive water users and instream flow needs. The percent of runoff from snow versus glacier ice will change during the summer ablation season as the snowpack thickness and albedo changes. In addition, glaciers may release especially large quantities of water in years of low precipitation when water from other sources such as winter snowpack may be in short supply.

A great deal of effort has been directed toward the interpretation of Holocene fluctuations in glaciers of the Wind River Range, summarized by Davis (1988). The generally accepted reverse chronology, with approximate dates is as follows: Gannett Peak advance (Little Ice Age; 100-300 years B.P.), Audubon advance (3,000 years B.P.), Altithermal (6,000 to 4,000 years B.P.), Indian Basin advance (6,500 to 7,940 years B.P.),

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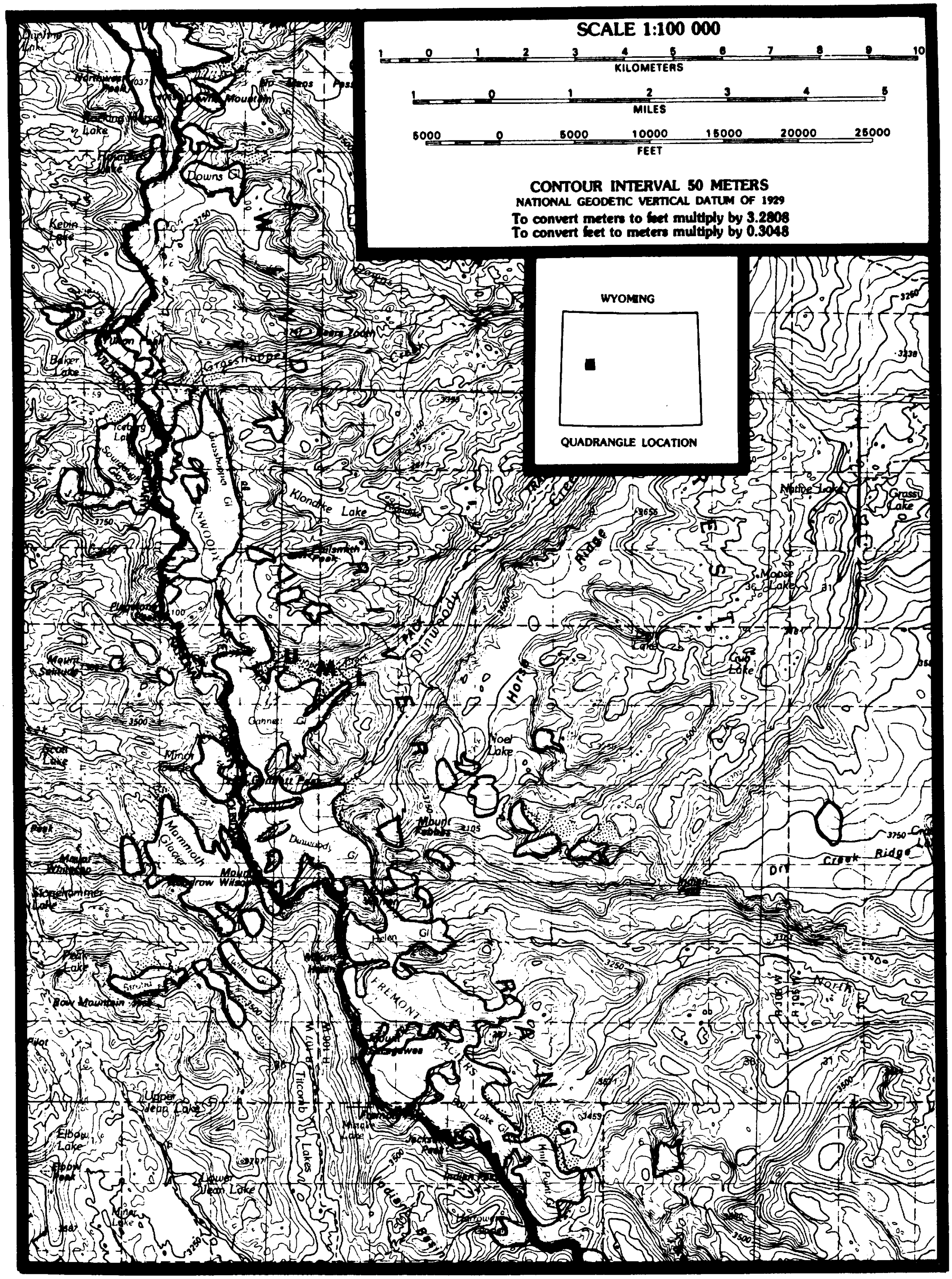


Figure 1. Glaciers of the Wind River Range. Note the position of the upper (U), middle (M), and lower (L) ice lobes on Gannett Glacier to the north of Dinwoody Glacier.

Temple Lake advance (late Wisconsin; 9,000 to 12,000 years B.P.). Love and Thompson (1987,1988) cite evidence that the ice in glaciers of the Wind River Range is Neoglacial in age, dating back to the Audubon advance.

According to most authors (e.g., Meier, 1951; Dyson, 1952; Mears, 1972), glaciers in the Wind River Range have generally been in a negative regime since 1850. While the most pronounced retreat occurred in the late 1930's, the glaciers continued to retreat, some at an alarming rate. Dyson (1952) reported that glaciers in the Wind River Range were retreating at a rate of 7 to 41 percent per year. The remaining ice volume in Dinwoody Glacier has been estimated using the contrasting area-volume formulae of Post, et al. (1976), Muller, et al. (1976), Macheret and Zhuravlev (1982), and Driedger and Kennard (1986a). Values of 95 x $10^6 m^3$, 34.8 x $10^6 m^3$, 9.12 x $10^6 m^3$, and 100 x $10^6 m^3$ were derived, respectively. Driedger and Kennard (1986b) measured a volume of 80 x $10^6 m^3$ using a backpack radio echo-sounder.

Systematic studies of glacier mass balance have not been conducted on Wind River glaciers since the one or two-year long studies in the 1950's. Trends in glacier regime over the last four decades need to be documented and modeled relative to external and internal controls to better understand the implications of long-term trends for water supply in the Green and Missouri River drainages and obligations under interstate compacts. Love and Thompson (1987, 1988) discussed trends in the recession of glaciers in the Wind River Range during the past two decades, but no systematic study was pursued of the underlying causes for these trends. The trends reported by Love and Thompson run counter to the trends for glaciers in the remainder of the United States reported by Wood (1988). Wood shows that 46 percent of the 50 glaciers examined actually advanced between 1960 and 1980, with only 26 percent receding.

Meier (1969) has estimated that the total July-August streamflow derived from glaciers in Wyoming averages approximately 132 x $10^6 m^3$, although the estimate does not appear to be based on measurements and the methods used to arrive at the estimate were not described. Meier was careful to state: "These data are approximate only." Assuming that this estimate is reasonably correct, this amount would be approximately 13 percent of the average combined flow for July and August from the Green River, Clarks Fork of the Yellowstone River, and the Big Horn River which are the rivers receiving the majority of the Wyoming glacier runoff. Meier (1969) also demonstrated the effect of glaciers on the seasonal distribution of runoff from a drainage basin. Using results from three drainage basins in western Washington, the annual runoff curve for a low-elevation drainage basin was shown to closely follow the precipitation curve which peaked in the wet winter months. The runoff curve for a higher altitude drainage basin without glaciers had two nearly equal peaks in April and July. Finally, the runoff curve for a basin with glaciers had an extreme peak occurring in June and July. The results emphasize that the primary importance of glaciers is their tendency to store water and release it at a later time especially during the heat of midsummer, or during dry years, when the need is greatest.

Rango (1980) has used Landsat imagery to define the snow cover for input to a snowmelt-runoff model. The model was used for hydrograph simulation during the April through September snowmelt period for two basins in the Wind River Range. The model simulated seasonal runoff volumes for two years within five percent of measured runoff while explaining 82-86 percent of the variation in daily runoff. Maars (1985) also used Landsat imagery to measure snowmelt and estimate snowmelt runoff in the Wind River Range and elsewhere in Wyoming. However, neither Rango (1980) nor Maars (1985) made an effort to distinguish between snow and glaciers as the source of runoff. We feel that this distinction may prove to be significant when considering the irreversible depletion of water storage in glaciers that occurs with progressive climatic warming.

Much effort has been expended to define the relationships between glaciers and climate. It is evident that the relationship between climate change and glacier response is partially confused by other factors extrinsic and intrinsic to the glacier. Among these factors are the area-elevation distribution of the ice, lag time in glacier response to shifts in mass balance (glacier inertia), kinematic waves, surges, and valley topography (Sugden and John, 1976). Nevertheless, climate remains the dominant control, especially when expressed in terms of total precipitation and percent of precipitation that falls as snow (Tricart, 1969). In terms of meltwater production, climatic controls dominate as well. Mathews (1964), for example, has defined the relationship between mean daily discharge and temperature for the Sunwapta River in the Rocky Mountains of Canada which receives water from the Athabasca Glacier. The relationship was moderately successful in predicting mean daily discharge. Radiation exchange is usually considered the single most important climatic factor affecting the rate of meltwater production (Paterson, 1969; Price, 1973; and Marston, 1983).

The purpose of the present study is to determine the importance of glacier meltwater to overall water supply in the Green River and Wind River drainages, and trends in glacier mass balance over the last five decades. Specific objectives of the present study are to:

1) use repeat ground photography and aerial photography to detect changes in the areal extent and thickness of glaciers in the Wind River Range during the past five decades;
2) analyze temporal trends in snowdepth and water equivalent for all appropriate climatic stations in the Wind River Range;
3) analyze temporal trends in runoff from existing streamflow gaging stations affected by glacier runoff and snowmelt from the Wind River Range; and
4) perform field measurements of runoff from glaciers in the Wind River Range.

METHODS

Dinwoody and Gannett Glaciers were selected as study sites for the present study for several reasons. Inspection of contour maps for Dinwoody and Gannett Glaciers reveals a dramatic contrast in area-elevation relationships, with most of the area of Dinwoody Glacier situated at lower elevations and most of the area of Gannett Glacier at higher elevations (Figures 1-2). This provides an opportunity to test the hypothesis that the adjacent glaciers respond in a different manner to climate change. Ease of access and availability of historic photographs which could be rephotographed, and availability of aerial photography were other factors considered in the site selection process. The areas of Dinwoody and Gannett Glaciers were measured from 1983 aerial photographs at 2.66 km^2 and 2.78 km^2, respectively. Gannett Glacier has the largest area of any glacier in the American Rockies and splits into three ice lobes in the downglacier direction (Figure 1).

Aerial photographs covering Dinwoody and Gannett Glaciers were obtained from the Shoshone National Forest in Dubois, Wyoming (1958 stereopairs); the EROS Data Center in Sioux Falls, South Dakota (1966 stereopairs); and the Remote Sensing Center in the Department of Geology and Geophysics at the University of Wyoming (1983 stereopairs). The areal extent of glacier ice and the position of the terminus on all glaciers were mapped from aerial photos of each date and compared to the maps produced in 1950 by Meier (1951). Repeat photography was undertaken using photographs taken over the last five decades and obtained from the American Heritage Center at the University of Wyoming. The photo positions were reoccupied during our field visits to Dinwoody and Gannett Glaciers in July, 1988.

Data on snow depth, snow water equivalent and runoff for all stations on the east slope of the Wind River Range were acquired from the Water Resources Data System at the Wyoming Water Research Center. Temporal trends in the data were analyzed using standard time series statistical techniques: moving means (to reduce the amount of scatter in the data set), residual mass curves (to show cumulative departures from the mean value for a data set), and double-mass curves (for analyses of consistency in data between stations). Regression analysis was employed with runoff as the dependent variable and either snow depth or water equivalent as the independent variable. Transfer functions were applied to account for the lag time between meltwater production and effects on the downstream hydrograph.

Streamflow measurements were performed on the proglacial streams emanating from Dinwoody and Gannett Glaciers as part of our field program in July 1988. Using rough

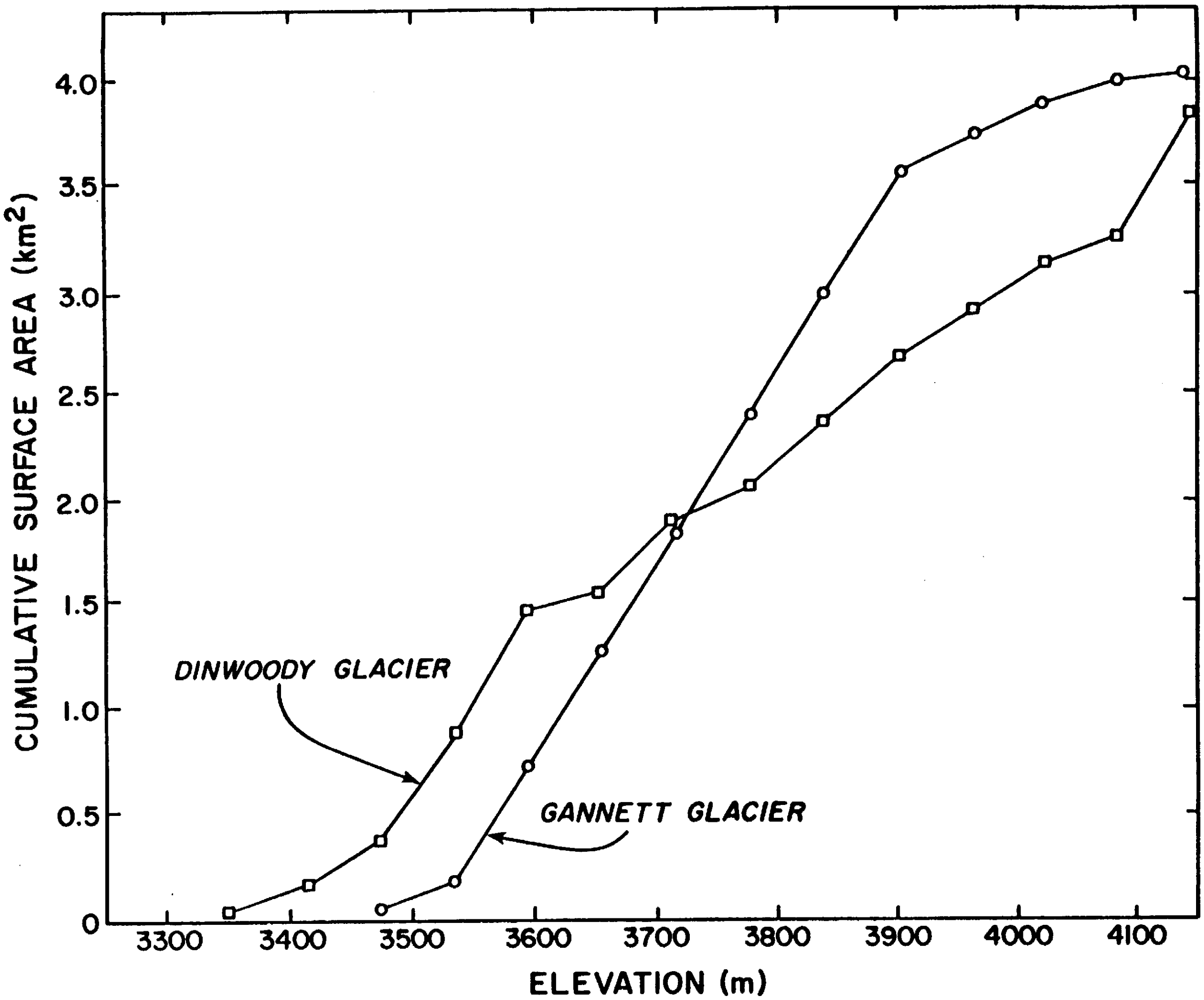


Figure 2. Area-elevation curves for Dinwoody and Gannett Glaciers.

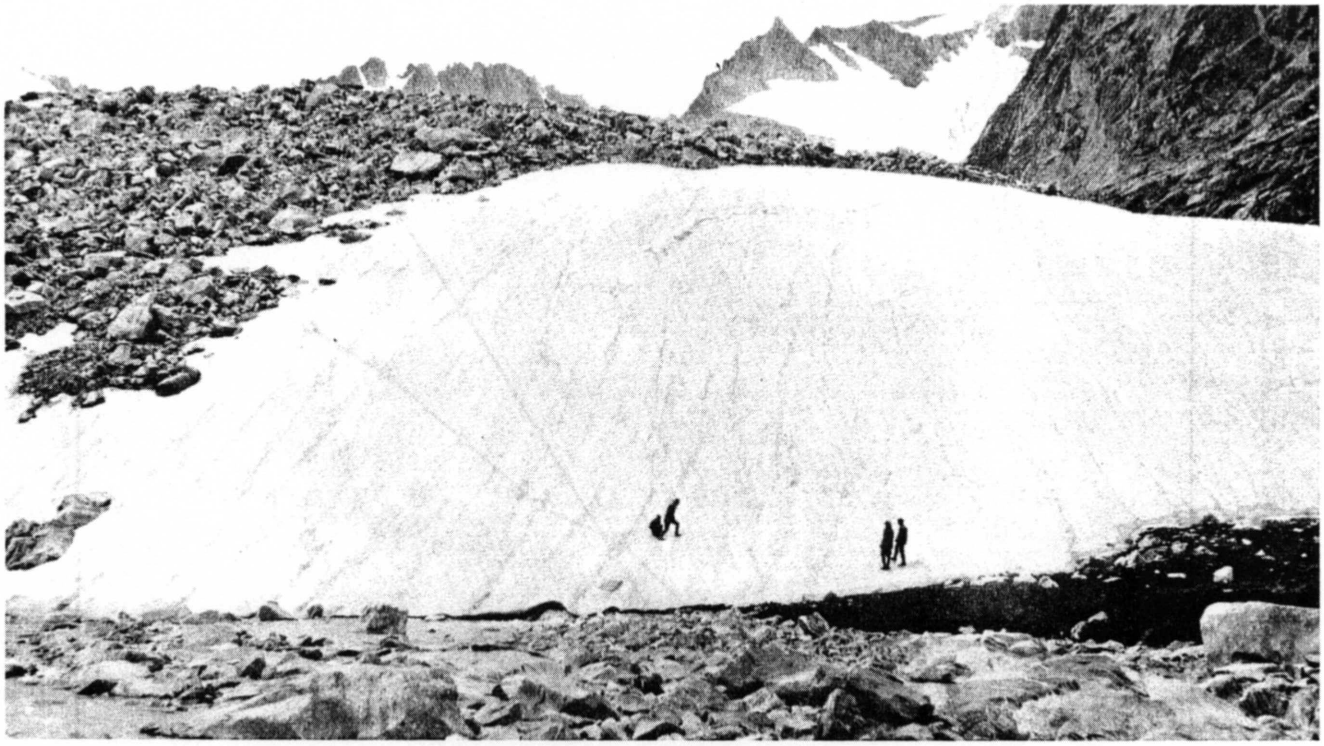
estimates of the annual distribution of runoff given by Meier (1969), calculations could be made of the contributions of Dinwoody and Gannett Glaciers to the monthly measured flows of Dinwoody Creek near the outlet to the 228 square kilometer watershed.

RESULTS

Plan view mapping from the aerial photographs revealed that the rate of retreat in termini of Gannett Glacier varied directly with the elevation of various ice lobes separated as they flow downslope (Table 1). The single terminus of Dinwoody Glacier is situated at a lower elevation than the lower most terminus of Gannett Glacier so it will retreat more strongly when the glaciers are in a negative mass balance regime. The upper lobe on Gannett Glacier displayed the greatest retreat which can be attributed to the relatively small area of its accumulation zone.

The repeat photography confirmed the pattern of termini retreat for the two glaciers. The retreat in Dinwoody Glacier between 1935 and 1988 (Figure 3) was much more dramatic than that for the lower and middle lobes of Gannett Glacier between 1958 and 1988 (Figure 4), even after accounting for the difference in time spans.

Data from six climate stations were used for investigating temporal trends in snow water equivalent: Burroughs Creek, Dinwoody, DuNoir, Geyser Creek, Hobbs Park, and Little



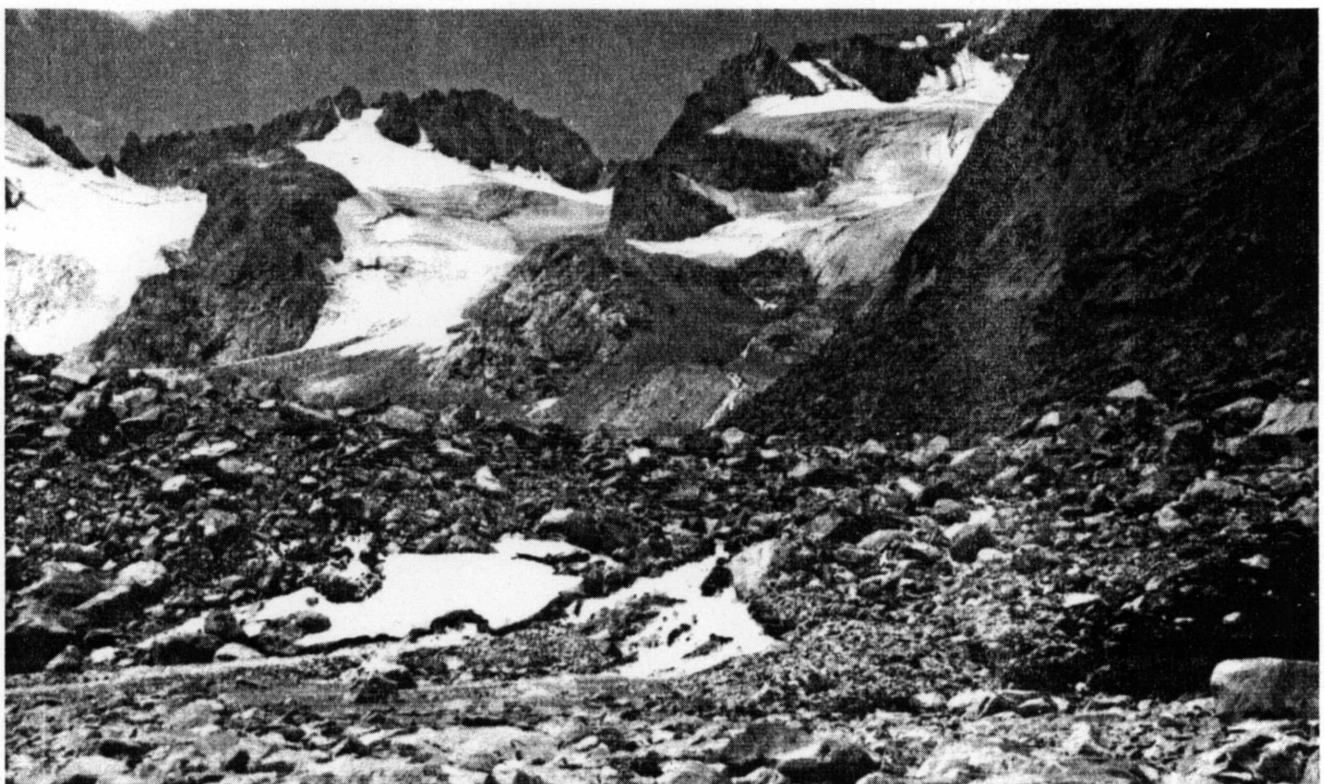


Figure 3. The terminus of Dinwoody Glacier photographed in 1935 (top) by C.W. Brandon (courtesy of the American Heritage Center, University of Wyoming) and the repeat photograph from the same viewpoint in 1988 (bottom). The ice-cored moraine has dropped approximately 8 meters in elevation.

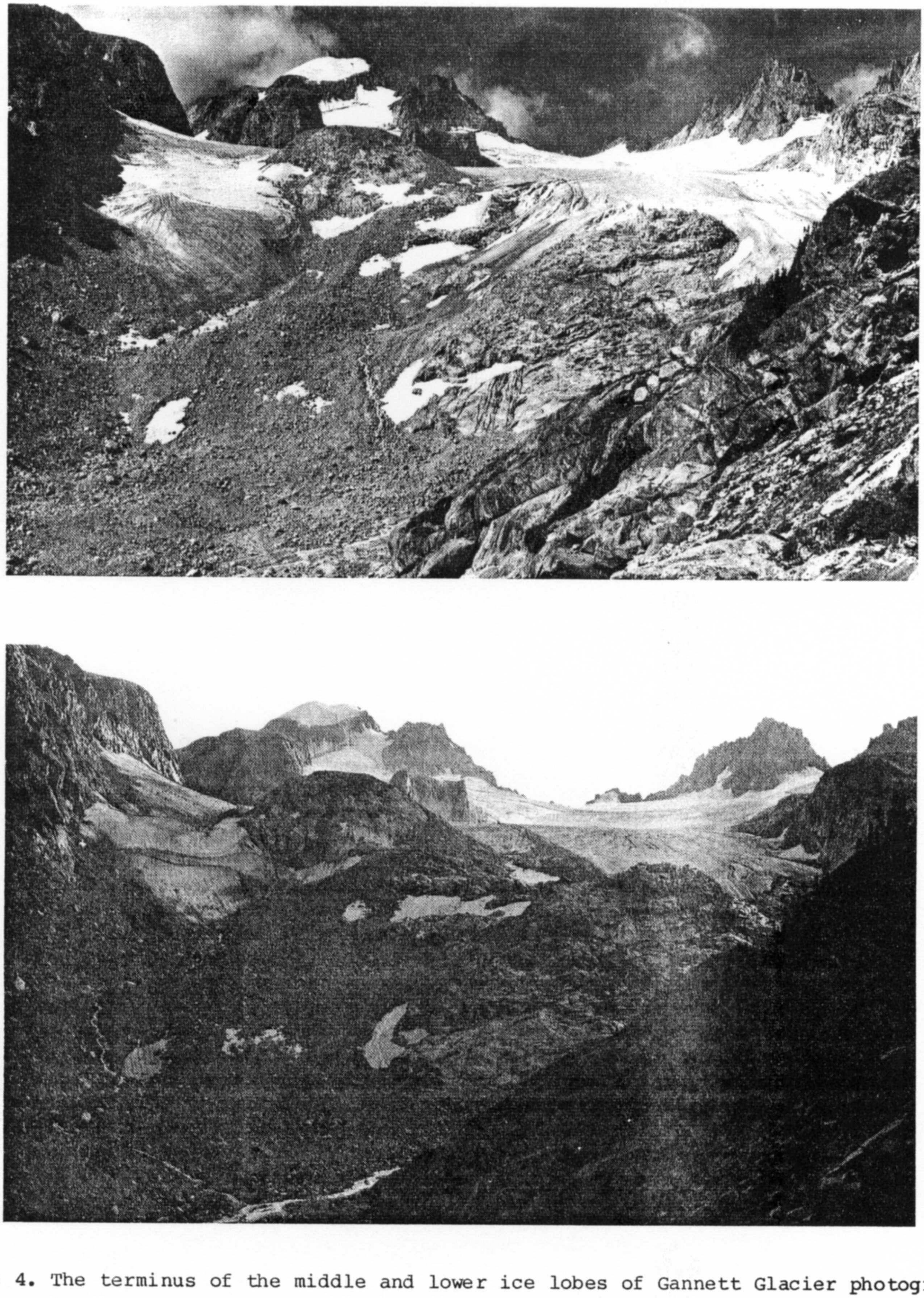


Figure 4. The terminus of the middle and lower ice lobes of Gannett Glacier photographed in 1958 (top) by D.W. Greenberg (courtesy of American Heritage Center, University of Wyoming) and the repeat photograph from the same viewpoint in 1988 (bottom).

TABLE 1. Termini retreat of Dinwoody and Gannett Glaciers, 1950-1983.

Glacier	Time Span and Retreat (in meters per year)			
Dinwoody	1950-58	1958-83		1950-83
	17.1	1.6		5.4
Gannett	1950-58	1958-66	1966-83	1950-83
upper lobe	24.8	24.8	4.6	14.4
middle lobe	9.9	7.4	3.1	5.8
lower lobe	3.6	7.4	2.3	3.8

Warm. The Dinwoody station was selected since it was the station closest to Dinwoody and Gannett Glaciers. The other five stations were included because the data from these stations were correlated fairly high with that from the Dinwoody station. Temperature data from the Dubois and Lander stations were also examined. Inspection of the five-year moving means of temperature and snow water equivalent for the six stations reveals a cyclic, out-of-phase pattern for temperature and water equivalent (Figure 5). This indicates some year to year persistence of climate patterns. As one would expect, the rate of glacier retreat parallels the trends in temperature and snow water equivalent. The rate of retreat for Dinwoody and Gannett Glaciers was greatest for the period 1950-66, a time of below average snow water equivalent and above average temperatures. It is noteworthy that the period 1966-83 experienced above average snow water equivalent and below average temperatures, but both glaciers continued to retreat.

Dinwoody Creek streamgage data are limited to the period 1958 through 1977. Monthly flow data are available for all twelve months of the year, but only the months May through October, which are the six highest flow months, were considered for this analysis. Monthly snow depth and water equivalent measurements were available for the four months of February through May. Regressions were performed for monthly streamflow, total early summer season runoff (May through July), total late summer season runoff (August through October), and total summer runoff (May through October) versus various combinations of snow depth and water equivalent including May data, April data, April through May averages, March through May averages, and February through May averages. It was assumed that late spring (May and/or April) snow depth and water equivalent measurements would best reflect the availability of water for the summer runoff period. Therefore, regressions were not performed for runoff versus the February and March snow data as done for the April and May snow data. Regression results clearly indicate poor correlations between runoff and either snow depth or snow water equivalent. Thus, glacier icemelt must be accounting for a significant portion of the variation in streamflow at the Dinwoody gage.

Flow measurements were taken for Dinwoody and Gannett Creeks in July, 1988. Measurements were taken for both creeks near their confluence, which is about three kilometers from Dinwoody Glacier and about five kilometers from Gannett Glacier. The July 22, 1988 flow measurements have been used in combination with flow measurements made in the Cascades in the Northwest U.S. to extrapolate flow estimates over the season. The seasonal flow estimates must be recognized as being very approximate since they are based on an extremely limited number of measurements. The estimates do provide a measure of the potential impact of glacier meltwater on the annual runoff from the Wind River Range. More measurements will be required to either confirm or adjust these estimates.

The distribution of runoff for South Cascade Glacier in the North Cascade Range of Washington from Meier (1969) is given in Table 2 along with the calculated distribution

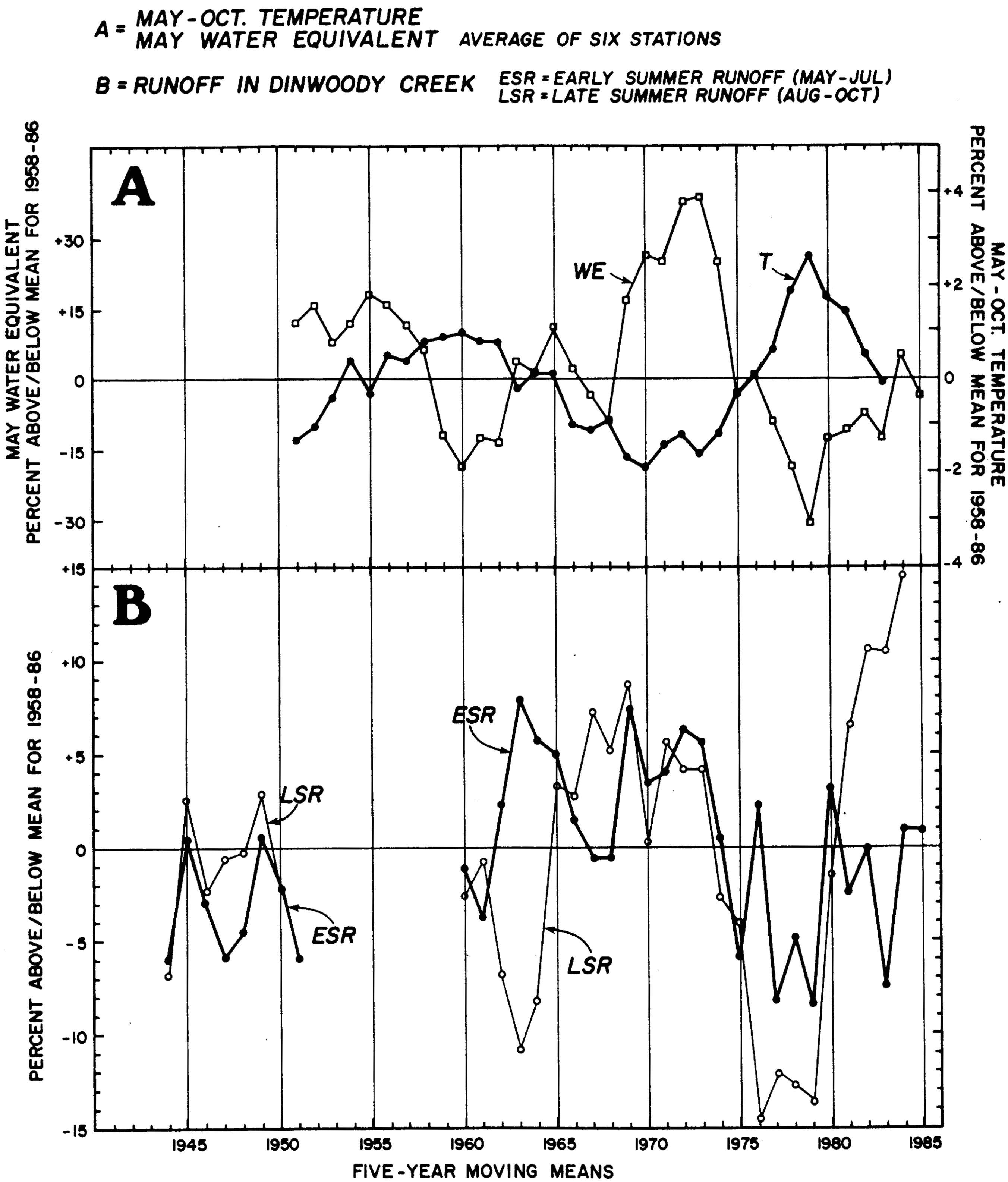


Figure 5. Trends in temperature, snow water equivalent, and runoff in the vicinity of the Wind River glaciers.

of runoff for Dinwoody Creek above the confluence with the Wind River. The total July runoff for Dinwoody Creek above the confluence with the Wind River amounts to 5.03 x $10^6 m^3$, based on the July gaging in the present study. If one assumes that the same distribution of ice melt runoff, expressed as a percentage of the total seasonal icemelt, applies to Dinwoody and Gannett Glaciers as exists for South Cascade Glacier, it is possible to calculate the ice melt contribution to runoff in Dinwoody Creek above the confluence with the Wind River.

TABLE 2. Distribution of Runoff during Summer Months

	South Cascade Glacier*		Dinwoody Cr. above Confluence with Wind River			
Month	% of Total Runoff from Ice Melt	% of Total Ice Melt	Total ($10^6 m^3$)	Ice Melt ($10^6 m^3$)	% of Total Runoff from Ice Melt	% of Total Ice Melt
JUN	1.7	6.3	34.3	0.85	2.5	6.3
JUL	10.0	37.2	37.8	5.03**	13.3	37.2
AUG	8.0	29.8	24.6	4.03	16.4	29.8
SEP	5.2	19.3	9.8	2.61	26.7	19.3
OCT	2.0	7.4	3.1	1.00	32.3	7.4
TOTAL	26.9	100.0	109.6	13.52	12.3	100.0

*Source: Meier (1969)
**Based on field measurements; all other values in this column are calculated using values for the distribution of total runoff from ice melt

Comparison of the estimated ice melt with Dinwoody Creek streamflow measurements permits a rough estimate of the contribution of Dinwoody and Gannett Glaciers to the overall Dinwoody Creek streamflow. The Dinwoody Creek flow measurements used are the averages for 1958 through 1978. The glaciers were estimated to contribute approximately 27 percent of the September and 32 percent of the October flows to Dinwoody Creek. The July-October runoff from all glaciers in the Wind River Range, extrapolated from the Dinwoody and Gannett contribution on the basis of area, was calculated to be approximately 70 x $10^6 m^3$, or eight percent of the runoff in the entire Wind River and Green River basins for that four-month period.

CONCLUSIONS AND DISCUSSION

Dinwoody and Gannett Glaciers have retreated and lost thickness in the last five decades. Some contrast in response of the two glaciers to climate trends was detected, and this contrast can be explained by area-elevation distribution of the glaciers and by position of the multiple termini. Glaciers of the Wind River Range contribute an estimated eight percent of the runoff to the Wind River and Green River drainages.

The preliminary findings generated by this study will be of use to the Wyoming State Engineer, Wyoming Water Development Commission, Wind River Indian Reservation, Wyoming Department of Game and Fish, and other state and regional agencies in the Colorado River basin and Missouri River basin who administer the state instream flow programs, irrigation water allotments, and monitor interstate water compacts. In particular, this project will generate results with implications to the Colorado River Compacts of 1922 and 1948 and the Yellowstone River Compact of 1922. Finally, the results will help clarify the complex links between climate and glaciers in the Rocky Mountain region.

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