GLACIER MASS BALANCE AND RUNOFF RESEARCH IN THE U.S.A.

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ABSTRACT. Research on glacier mass balance began in the U.S.A. about 50 years ago. More complete studies of climate, snow and ice balance, and the hydrology of glaciers were initiated for the IGY in 1957 and the IHD in 1966. Investigations included the magnitude and geographic distribution of normal mass balance processes and unusual phenomena such as outbursting, accumulation of ice by freezing of water in firn, and ablation of glacier ice by volcanic activity and by calving. Glacier size has been found not to be a simple function of climate as is widely imagined. Glaciers can increase with a warming of climate and can shrink due to calving instability mechanisms. Numerical modeling of glacier balance and runoff have appeared in the past decade only. Glacier research has also produced a new understanding of the nation's climate, water resources, and flood hazards because glaciers exist in very moist rather than very cold climates and produce very high runoff rates.

Introduction

The scientific literature on mass balance and runoff of glaciers began in the U.S.A. in the 1930's with numerous small publications in mountaineering journals (Mazama and Sierra Club) and reports of the Committee on Glaciers published in the Transactions of the American Geophysical Union. The data were point measurements of balance and glacier flow at glaciers in California, Oregon, and Washington. An example of this literature is an article on the melt rate of Eliot Glacier, Mt. Hood, Oregon, authored by two of the leaders of those studies, Matthes and Phillips, (1943). Prior to 1930, glacier research in the nation consisted of studies on glacier extent, advances, and retreats only. Research on the hydrology of glaciers had been undertaken earlier in Europe and Asia. From 1943 until the beginning of the International Geophysical Year (IGY) in 1957, a few additional studies were made, such as by Sharp (1951) on the Malaspina Glacier, Alaska, and by Meier (1951) on Dinwoody Glacier, Wyoming, however, no continuous studies of the natural variability of glacier climate, glacier snow and ice balance, or glacier runoff were undertaken until 1957.

During the 27-year period from 1957 to the present, the major part of the literature developed. This literature includes the results of research planning meetings, overviews of the science, introduction of new theory, adventures in speculation and predictions, development of instrumentation and interpretive techniques, presentation of observational data, interpretation of the processes, proposals and documentation for numerical models, and transfer of this technology to the general public through resource appraisals and non-technical but well-illustrated books.

Glacier research has produced a new understanding of the nation's climate, water resources, and flood hazards, because routine hydrologic studies had not been undertaken in glacierized mountainous areas before glacier research programs began. The studies indicate that the glacier climate is much more moist than anticipated, rather than being simply very cold. Furthermore, glaciers in the U.S.A. release 2 to 10 times more water in a year than adjoining non-glacier areas, runoff rates decrease with altitude, and unusual flooding by outbursting of stored water is common. These facts are not universally recognized yet because they cannot be anticipated from the well-developed hydrologic principles for vegetated lands, and the glacier environment is not inhabited.

Information on glacier mass balance and runoff is sparse, therefore, some papers such as University theses and "Final Reports" to government agencies, which are not part of the normal scientific literature, are included in this summary. The papers discussed here present major contributions of new knowledge. Other papers not discussed generally contain only bits of information, yet these may be essential to detailed studies as they may contain the only published fragments of mass balance information available to date.

Research planning meetings

Planning meetings to develop mass balance studies were held by University and federal govern-

ment agency scientists at the beginning of the IGY when the science was new in the nation. It was important for the participants to report early findings, so some observational information was recorded on Blue Glacier and South Cascade Glaciers in Washington, and Lemon and McCall Glaciers in Alaska (Field, 1958: Heusser, 1958; Keeler, 1958; and Meier, 1958). Since then the results of studies presented at planning sessions have not been published.

Results of research published for the public

Glaciologists in the U.S.A. have provided several summary papers which convey a broad understanding of glaciology to both scientists and the general public. These fall into three categories; (1) brief yet thorough technical summaries in texts with graphs, formulae, and illustrations (Meier, 1974) (2) atlases or compendia volumes as the Inventory of Glaciers in the North Cascades, Washington (Post, Richardson, Tangborn, and Rosselot, 1971), the atlas of mountain glaciers of the northern hemisphere (Field, 1975), an annotated bibliography of arctic water balances (Dingman, 1973), an atlas of glacier dammed lakes and outburst floods in Alaska (Post and Mayo, 1971), the compendium on water balance of North America (Dreyer, 1978), a summary of glacier fluctuations from 1970 to 1975 (Muller, 1977), and the guidebooks of the Richardson and Glenn Highways, Alaska (Pewe, 1965; and Pewe and Reger, 1983); and (3) non-technical yet well illustrated books to both entertain and teach principles of glaciology, such as Austin Post and E.R. LaChapelle's (1971) *Glacier Ice* and R.H. Bailey's (1982) *Planet Earth Glaciers*.

Mass balance of glaciers

Glacier mass balance measurements are difficult and complex because a program to observe the details of mass exchange throughout a year on a real glacier involves understanding and measuring continually numerous physical processes and their results under difficult weather conditions. For this reason, several sets of mass balance terminology have been proposed to bring to attention the most important aspects of the measurements while possibly simplifying the field measurement procedures.

Meier (1962) proposed measuring time-transgressive stratigraphic units or processes for a balance year as determined by the weather each year. This system is easy to apply to measurements made at individual sites on glaciers, but can lead to conceptual ambiguities for an entire glacier. For instance, are measurements to be made at the time of the glacier-average minimum balance or at the different times of balance minimum at each site? The system works well at small glaciers where the stratigraphic units are time-transgressive for only short time periods. The measurement dates vary from year to year which creates difficulties in relating the glacier mass balance data to climatic and river flow measurements.

The fixed-date and stratigraphic systems of measurements were proposed and compared (UNESCO, 1970) in an attempt to reduce the ambiguities of numerous other systems and facilitate studies of climate, mass balance, and runoff.

The advantages of both systems were combined by Mayo, Meier, and Tangborn (1972) by continuing use of the well-defined stratigraphic units and proposing definitions and terms for the small amount by which these measurements differ from fixed-date system results. For example, if old ice ablation occurs after October 1 (the beginning of the "hydrologic year") and before winter snow arrives, then both the stratigraphic "net balance", which is time-transgressive, and the fixed-date "annual balance", which is *not* time-transgressive, are known. This is required to conduct logical glacier measurement programs and proper analyses of that glacier balance data with climate and streamflow data. Moreover, the system works equally well on small glaciers such as South Cascade Glacier, Washington, where the summer season typically ends with a single snowfall event that covers the entire glacier and large glaciers such as Columbia Glacier, Alaska, where the maximum or "winter balance" is time-transgressive between April and August and the summer surface is time-transgressive between August and November. Tangborn (1980a) further modified the terminology to allow seasonal fixed-date units. Meier, Mayo, Trabant, and Krimmel (1980) added internal accumulation as a new balance term.

Accepted mass balance terminology is incomplete, yet important studies of other important balance processes are underway; for example, accumulation of mass and reduction of ablation by large landslides (Post, 1967; Bull and Marangunic, 1968; and Reid, 1969); ablation by calving (Brown, Meier, and Post, 1982); and accumulation of mass by avalanching (Post, 1967) can be

significant factors in the balance of certain glaciers. Furthermore, sub-glacial ablation by volcanic heating (Frank, Meier, and Swanson, 1977; and Benson and Motyka, 1978) is also important locally, not only for the mass balance of glaciers, but also for using glaciers as a natural calorimeter in volcanic heat-flow studies.

Studies of ablation rates on snow are subject to errors due to snow compaction and how a balance stake in the snow rides in this collapsing snow. This problem was recognized by LaChapelle (1959). The rate of snow melt on glaciers can be influenced by rock debris on the surface. This problem was particularly important after the 1980 eruption of Mount St. Helens, and was studied by Driedger (1981).

Mass balance and runoff measurements at glaciers have required new precipitation and streamflow instrumentation (Tangborn, 1963) so continuous data could be obtained for long times by automatic recording systems (up to 6 months). A self-mixing antifreeze solution for precipitation gages was developed to solve the problems associated with freezing of density-stratified gage catches (Mayo, 1972). Long-term balance measurements can be made or checked by volumetric change information (Hamilton, 1965; Meier, 1966; and Johnson, 1980); by hydrologic methods (Tangborn, 1966); or by combining all methods (Tangborn, Krimmel, and Meier, 1975).

Satellite imagery has been evaluated for mapping the snowcover on glaciers (Krimmel and Meier, 1975), but it is of limited usefulness because of frequent cloud cover. The more frequent images produced by weather satellites have not been used for mapping snowcover on glaciers in the USA. The results of experiments to utilize a number of remote-sensing techniques to measure snow on glaciers was summarized by Meier (1975).

Studies of glacier mass balance or runoff have been made on 40 glaciers in the nation (see Table 1). Continuous studies have been accomplished at 7 glaciers in Alaska, with 6 continuing at present; at 1 in California; at 9 in Colorado; at 3 in Montana; at 8 in Washington, with 2 continuing at present; and at 1 in Wyoming.

Continuous balance measurements and balance calculations at three glaciers (figure 3) provide a sample of information about the variations of glaciers for several decades in historic time. The remarkable thinning of South Cascade Glacier from 1912 to 1970 was due in large part to calving of the terminus into a lake. Wolverine Glacier and Columbia Glacier, Alaska, (also shown on figure 3) have displayed less variability than South Cascade Glacier, but have had different balance histories even though they are located near each other. The recent decline of Columbia is associated with an increase in calving into ocean water. Both Columbia and Wolverine experienced unusually large accumulations of snow from 1976 to 1981, but only Wolverine Glacier thickened because this glacier terminates on land.

The controlling balance mechanism for calving glaciers remained an enigma until recently. Mercer (1961) proposed that firn-line altitude changes caused the rapid and asynchronous changes observed for tidal glaciers of Alaska, but Post (1975) proposed that calving was the more important, critical factor. Mayo, Zenone, and Trabant (1977) found that calving dominates the balance of Portage Glacier which terminates in a lake, rather than possible changes in the equilibrium-line altitude. Meier, Rasmussen, Post, Brown, Sikonia, Bindschadler, Mayo, and Trabant (1980) predicted that Columbia Glacier could begin a massive recession during this decade which would be controlled by calving. Thus it is clear that calving, and probably other local influences such as glacier geometry and dynamics can have a significant effect on the overall balance of a glacier, and that all glaciers may not react similarly nor simultaneously to the same regional variations in weather and climate.

Altitude variations of balance

Altitude has a large influence on glaciers, so several different approaches to generalizing important aspects of glacier balance with altitude have been presented. Although these generalizations give considerably less precise information about glacier balance than direct measurements, they are useful primarily because they are simple and can be used over wide areas containing thousands of individual glaciers.

The gradient of mass balance with altitude (figure 4) of measured glaciers shows that the gradients are noisy, but that generalizations are possible. Gradients tend to be steeper in the ablation zones than in the accumulation zones. The "balance gradient" of a glacier, as a specific number, applies only to a specific altitude zone of that glacier. In the case of Columbia Glacier, the balance

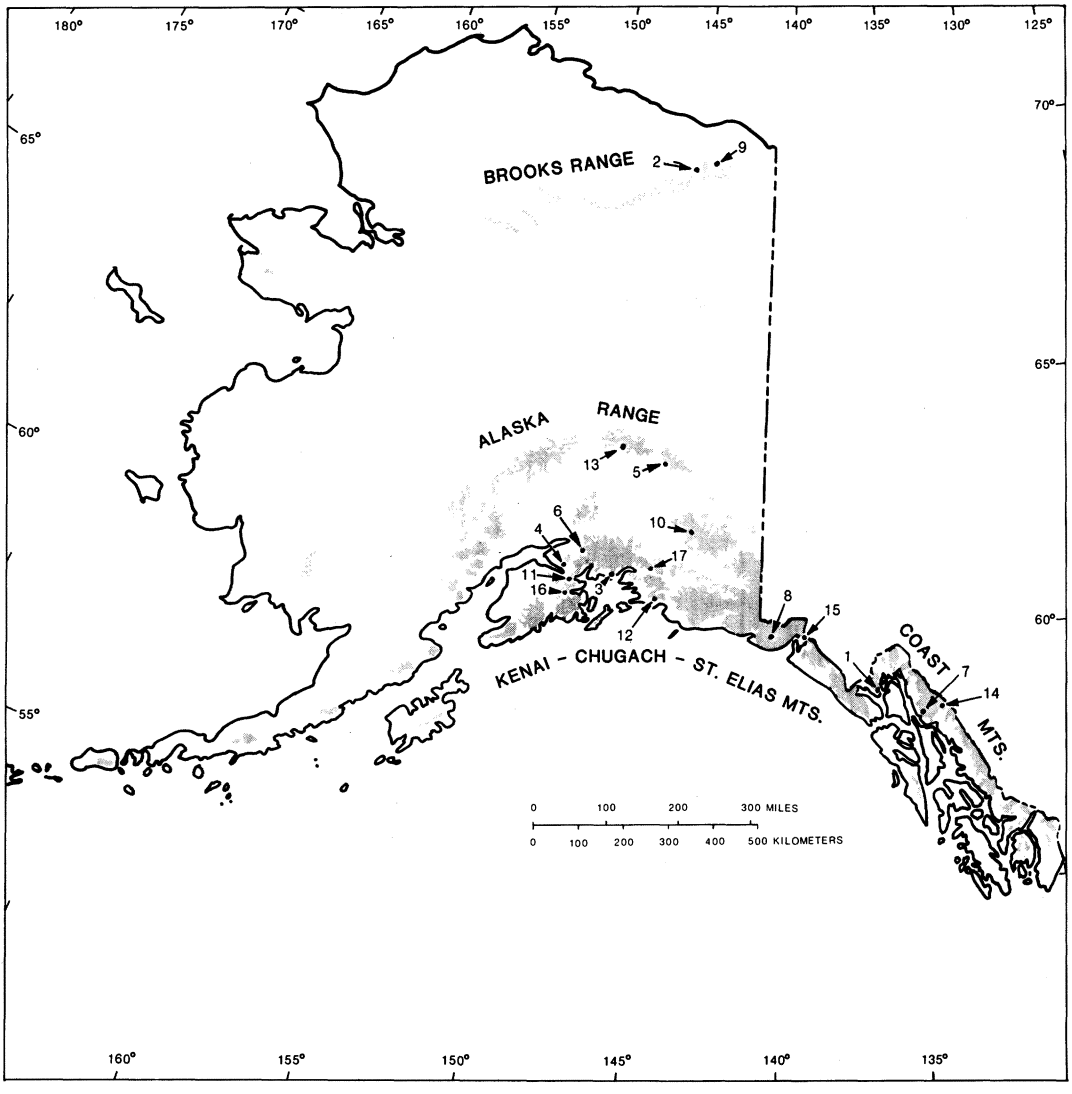

Fig. 1. Map showing locations of research glaciers in Alaska. Shaded areas are glaciers. Numbers refer to glaciers listed in Table 1.

gradient is a continuous curve from sealevel to 3600 meters altitude.

A series of related, but different, sets of concepts have been used to describe the altitude of glaciers. They are the "average glacier altitude", the "equilibrium line altitude" (ELA), the "firnline altitude", "snowline altitude", and the "glaciation limit". All tend to have the same geographic pattern. The "accumulation area ratio" (AAR) relates area rather than altitude, but is a function of the ELA for each individual glacier.

Glaciers in the nation, excluding Alaska, occur at lower altitudes with increasing latitude (Meier, 1960b). This trend extends north to southern Alaska, but then reverses because precipitation decreases from south to north in Alaska. The Arctic Ocean is not an important source of moisture for glaciers in Alaska.

LaChapelle (1962) discussed monitoring annual variations in snowline position by aerial photography as a fast method of studying regions. Meier and Post (1962) mapped the 1961 ELA (equilibrium line altitude) and the AAR (accumulation-area ratio) in Western North America, which

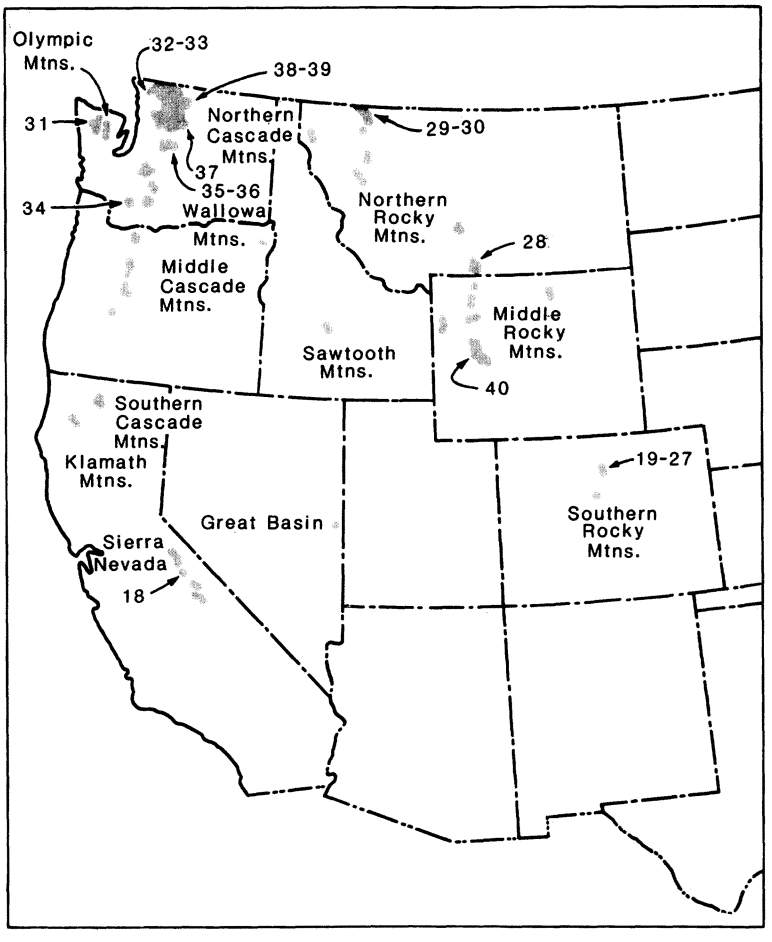

Fig. 2. Map showing locations of research glaciers in Washington, Oregon, California, Idaho, Nevada, Montana, and Wyoming. Shaded dots are individual small glaciers; irregular blobs indicate numerous small glaciers. Numbers refer to glaciers listed in Table 1.

showed that important regional differences in balance can occur for any given year over large areas.

Pewe and Reger (1972) mapped both present and Wisconsin Glacial Stage snowline altitudes as interpreted by geomorphology in southern Alaska. The gradient on these maps is approximately equivalent to the direction of the moisture source for precipitation. Pleistocene snowlines in Alaska were 200 meters lower than at present in the south and 600 meters in the north. A related but different concept presented by Østrem, Haakensen, and Ericsson (1981) was utilized in mapping the minimum altitude of terrain that supports glaciers in southern Alaska. The patterns produced by these two concepts are similar, but the altitudes are different. Porter (1966) and Ellis and Calkin (1979) have studied the snowline altitudes in the Brooks Range of northern Alaska. Zwick (1980) analysed the modern and Pleistocene snowline altitudes in Montana and Wyoming, and Meierding (1982) mapped late Pleistocene snowlines in Colorado.

Glacier temperature

Glacier temperature can control mass balance processes. The importance of superimposed ice accumulation (above a summer surface), and internal accumulation (below a summer surface) are increasingly important with altitude and latitude, ie., at colder temperatures. Black Rapids Glacier is temperate (Harrison, Mayo, and Trabant, 1973) even though the mean annual air temperature is –5.5C at the equilibrium line and permafrost is extensive. At McCall Glacier in the Brooks Range,

Table 1. Glaciers in the USA with published mass balance and glacier runoff information. For most glaciers, only the most recent, comprehensive references are listed. Numbers refer to locations shown on Figures 1 and 2.

No.	Glacier	Continuous data	Primary References
	ALASKA		
1.	Burroughs		Larson, 1978
2.	Chamberlain		Rainwater and Guy, 1961
3.	Columbia	1977–present	Mayo, Trabant, March, and Haeberli, 1979
			Brown, Meier, and Post, 1982
4.	Flute		Long, 1972
5.	Gulkana	1965–present	Mayo and Pewe, 1963
			Meier, Mayo, Trabant, and Krimmel, 1980
6.	Knik		Mayo and Trabant, 1982
7.	Lemon Creek		Heusser and Marcus, 1964a, and 1964b
8.	Malaspina		Meier and Post, 1962
9.	McCall	1969–1972	Orvig and Mason, 1963
			Wendler and others, 1975
			Wakahama, Kuroiwa, and Hasemi, 1976
10.	Mt. Wrangell	1961–present	Benson and Motyka, 1978
11.	Portage		Mayo, Zenone, and Trabant, 1977
12.	Sherman		Bull and Marangunic, 1968
13.	Susitna	1980–present	Harrison and others 1983
14.	Taku		Wu, 1968
15.	Variegated	1973–present	Bindschadler and others, 1977
16.	Wolverine	1966–present	Tangborn, Mayo, Scully, and Krimmel, 1977
			Mayo and Trabant, 1984
17.	Worthington		Streten and Wendler, 1968
	CALIFORNIA		
18.	Maclure	1966–1972	Meier, Mayo, Trabant, and Krimmel, 1980
	COLORADO		
19.	Andrews		Outcalt, 1965
20.	Arapaho		Waldrop, 1964
21.	Arikaree		Muller, 1977
22.	Fair		Muller, 1977
23.	Hendersen		Muller, 1977
24.	Isabelle		Muller, 1977
25.	Navahoe		Muller, 1977
26.	St. Vrain		Muller, 1977
27.	Front Range		Johnson, 1979
	MONTANA		
28.	Grasshopper		Alford and Clark, 1968
29.	Grinnell	1960–1969	Johnson, 1980
30.	Sperry	1961–1965	Johnson, 1980
	WASHINGTON		
31.	Blue	1957–present	LaChapelle, 1965
32.	Coleman		Meier, 1960
33.	Mt. Baker		Frank and Krimmel, 1978
34.	Mt. St. Helens		Brugman and Meier, 1981

No.	Glacier	Continuous data	Primary References
35.	Mt. Rainier		Burbank, 1982
36.	Nisqually		Burbank, 1982
37.	Vesper		Dethier and Frederick, 1981
38.	South Cascade	1957–present	Meier and Tangborn, 1965 Tangborn, Krimmel, and Meier, 1975 Tangborn, Mayo, Scully, and Krimmel, 1977 Meier, Mayo, Trabant, and Krimmel, 1980
39.	Thunder Creek		Tangborn, 1980a
	WYOMING		
40.	Dinwoody		Meier and Post, 1962

the firn temperature is –1 to –2C (Trabant, Harrison, and Benson, 1975) at an average air temperature of about –12C. These negative temperatures influence the mass balance and heat balance (Orvig and Mason, 1963) and the transformation of snow into glacier ice (Wakahama, Kuroiwa, and Benson, 1974). Water percolation into firn warms the glacier and partly refreezes producing significant amounts of internal accumulation (Meier, Mayo, Trabant, and Krimmel, 1980).

Balance models and predictions

Two numerical models for estimating climate-glacier relationships have been developed by Tangborn (1980a) in the North Cascade Mountains of Washington. These models followed concepts developed by Tangborn (1968) in which he compared measured precipitation with streamflow as an indication of glacier and snow mass balance. Another model of glacier balance has been proposed for the ablation season only (Williams,

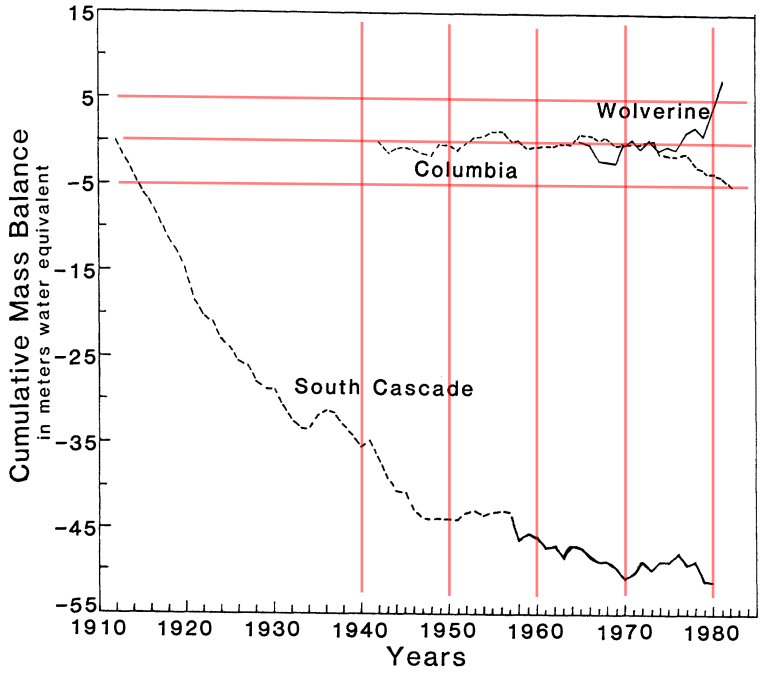

Fig. 3. Cummulative mass balance of three glaciers near the North Pacific Ocean. Wolverine Glacier measurements by the author and D.C. Trabant (1984), Columbia Glacier calculations by the author and D.C. Trabant. South Cascade calculations and measurements by W.V. Tangborn (1980a). Dashed lines indicate the results of mass balance calculations; solid lines indicate measured balances.

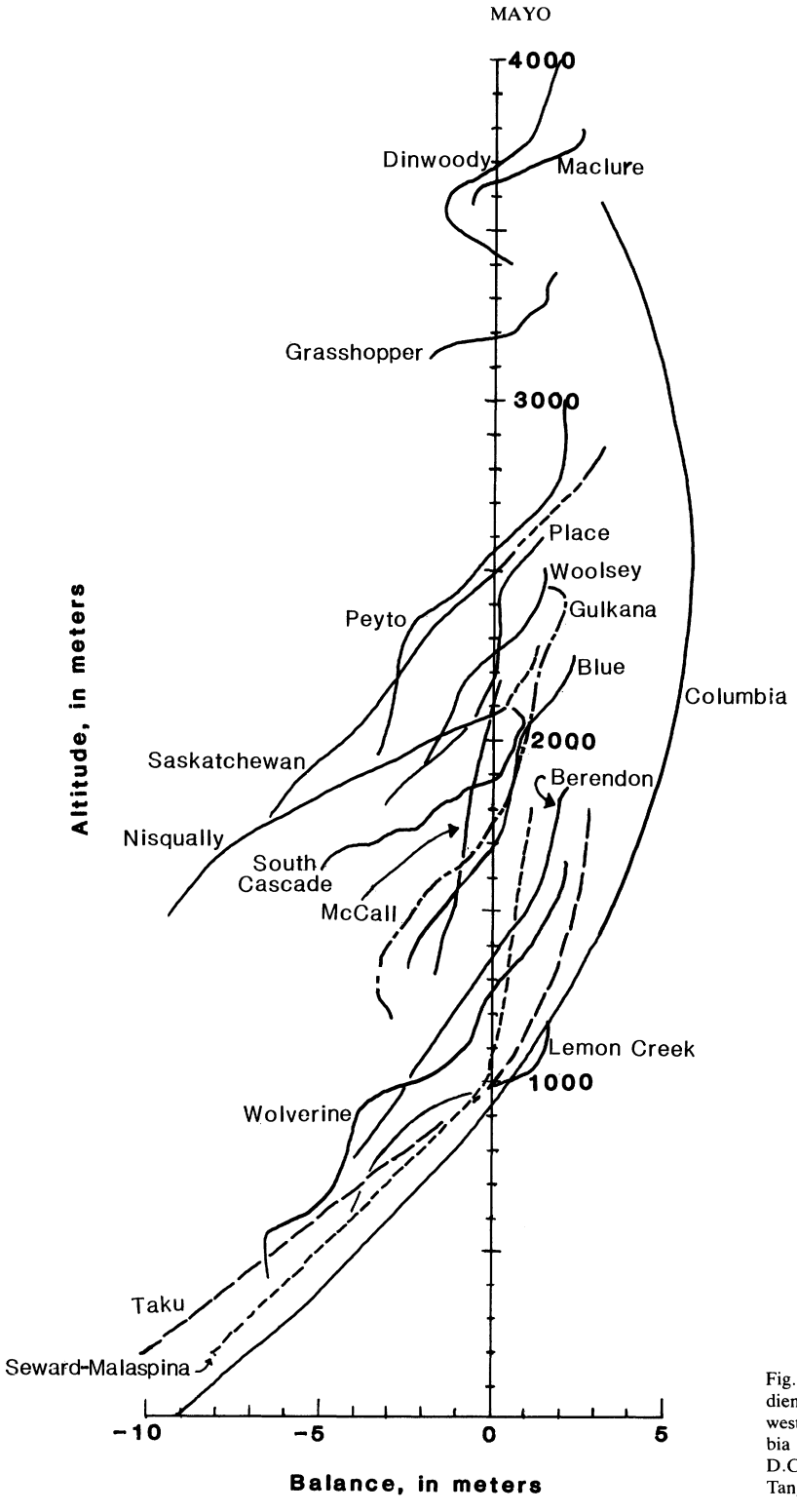

Fig. 4. Annual mass balance gradients of glaciers measured in the western North America. Columbia Glacier by the author and D.C. Trabant; others from Meier, Tangborn, Mayo, and Post (1971).

1974). Numerical models of glacier flow have assumed a constant glacier balance flux as part of their forcing function (Campbell, and Rasmussen, 1969; Rasmussen and Meier, 1982; and Sikonia, 1982).

A prediction of Portage Glacier (Mayo, Zenone, and Trabant, 1977) indicates that ablation by calving into Portage Lake will dominate the glacier balance for the next four decades. Likewise, the prediction for Columbia Glacier (Meier, Rasmussen, Post, Brown, Sikonia, Bindschadler, Mayo and Trabant, 1980; and Rasmussen and Meier, 1982) is that calving into ocean water will dominate the balance, producing a 40-kilometer retreat of this large glacier in the next four decades.

A prediction was made after the March 1964 Alaska Good Friday earthquake that Sherman Glacier would advance due to a large landslide that covered part of the ablation zone (Bull and Marangunic, 1968).

The rise in atmospheric CO2 may cause climatic warming especially in high latitude areas. A simple model to estimate the effect of climatic warming in southern Alaska on Wolverine Glacier (Mayo and Trabant, 1984) indicates, that atmospheric warming of 1 to 6C would produce glacier growth and increased glacier runoff. This is based on the observation that positive mass balance is associated with greater precipitation that occurs during warm winters.

These few models are undoubtedly the first of a new era in glaciology in which climate, glacier balance, glacier runoff, and glacier flow behavior are calculated by increasingly sophisticated numeric models that may replace the need to constantly observe mass balance and glacier behavior.

Glacier runoff and glacier ice as a resource

Glaciers contribute to the nation economically by producing large amounts of water at high altitudes during hot, dry weather. The major hydro-power projects that profit include those along the Columbia River in Washington and Oregon. In Alaska, glacier runoff produces an important component of the power at Snetisham in southeast Alaska, at Solomon Gulch near Valdez, and Eklutna near Anchorage. New power projects proposed below the glaciers at Bradley Lake and the Susitna Basin have glacier research programs associated with them (Harrison, Drage, Bredthauer, Johnson, Schoch, and Follett, 1983).

Glacier runoff has long been recognized as a valuable source of water for irrigation, municipalities, and power generation (Meier, 1960b; and 1969). Jackson (1961) analysed the potential for power generation in Alaska of only one of the many potential power sites which would utilize glacier runoff.

Glacier ice was harvested in Alaska about 70 years ago and shipped to west coast ports for sale as a refrigerant (Schultz, 1974). There is no such industry in the nation today.

Glacier runoff

The subject of glacier runoff has attracted more interest by a wider group of people than mass balance because glacier-derived streamflow is useful for irrigation, water supply, and power generation; and the water is hazardous during outburst flooding or volcanic eruptions.

A theory of water flow through glaciers was presented by Shreve (1972). Glacier melt and rain water begin by percolating through snow as a wave phenomenon (Colbeck, 1974). The liquid flow through an entire glacier system behaves as though the glacier were a porous medium obeying the Darcy Flow Law (Campbell and Rasmussen, 1973). Some of the water is stored in the ice if it is not colder than 0 C (Larson, 1978). The flow through South Cascade Glacier has been traced by dye techniques (Krimmel, Tangborn and Meier, 1973). Water at the base of a glacier is important for both runoff and glacier sliding (Hodge, 1976). The development of meltwater streams on top of a glacier is affected by the variability of diurnal flow (Pinchak, 1966).

Glacier runoff tends to be greatest during sunny weather, whereas non-glacial runoff tends to be greatest during cloudy storms with rainfall. Krimmel and Tangborn (1974) found that basins with 30–50 percent glacier area have lower variability of streamflow due to the mixing of these opposite trends. This factor causes glacier runoff in the Columbia River Basin to have considerable economic importance (Tangborn, 1980b). The volume of runoff from selected river basins in the North Cascade Mts., Washington, has been calculated by Post, Richardson, Tangborn, and Rosselot (1971).

Glacier-derived runoff has been regularly underestimated; because it is usually not measured and because it is much greater than the runoff

from more familiar environments. Anderson (1970) calculated that glacier runoff in central Alaska was 47 percent of the Tanana River runoff even though glaciers cover only 5 percent of the area. This suggests an order of magnitude difference between glacier and non-glacier runoff in central Alaska. In the headwaters of the Tanana River, from 1967 to 1979, the measured runoff from Gulkana Glacier Basin averaged 2.02 meters per year, whereas the runoff from non-glacial basins average 0.24 meters per year (averages calculated from data by U.S. Geological Survey, 1961–1981). In maritime regions glacier runoff is commonly about twice that of non-glacial basins.

Unfortunately, the concept that high runoff comes from high altitude zones can be taken too far. Freethey and Scully (1980) mapped the runoff of the Cook Inlet area of Alaska, and concluded that runoff increases with altitude on glaciers and that the runoff rate was 1.4 meters per year at high altitude. However, in July 1980, measurements by the author at 2900 meters altitude on Spurr Volcano in the Cook Inlet drainage showed that the snow was dry and there was no liquid runoff possible for the entire year. It is always necessary for glaciologists to teach principles of glacier hydrology to others. Summaries of principles are readily available (Meier, 1965 and Meier and Tangborn, 1961). The hydrologic significance of glaciers on runoff in the North Cascade Mountains, Washington, was summarized by Post, Richardson, Tangborn, and Rosselot (1971) as part of an inventory of glaciers in the area.

Floods from glaciers

Floods can be produced by combined rainfall and snow and ice melt, such as in central Alaska in 1967 when widespread flooding inundated Fairbanks and other communities along the Tanana River. The measured peak flow from Gulkana Glacier was 2.08 cubic meters per second for each square kilometer area, whereas the Chena River discharged a peak flow of only 0.41 cubic meters per second for each square kilometer of basin area (U.S. Geological Survey, 1967). Thus, the peak flow can be 5 times greater from a glacier than from a forested basin during the same flood-producing storm.

Flooding due to outbursts from glaciers in Alaska was analysed first by Stone (1955). Later, an atlas of 750 glacier dammed lakes in Alaska of larger than 0.1 square kilometer size and the known flood paths brought full recognition of the widespread nature of the problem (Post and Mayo, 1971). These flood events can begin suddenly. One of Alaska's most hazardous glacier dammed lakes, Berg Lake at Bering Glacier released in November 1981 and in July 1983, which were its first outbursts in historic times. Outburst series can end just as abruptly. Recently, knowledge of glacier dammed lakes and outburst flooding has been recognized in regional resource appraisals (Freethey, and Scully, 1980). Furthermore, outburst floods are beginning to be recognized as a separate class of events by hydrologists who analyze flow characteristics of rivers by statistical techniques (Chapman, 1982).

Lake Chakachamna, Alaska, is dammed by Barrier Glacier. The lake was proposed as a hydropower site (Jackson, 1961) and was later discovered to be a periodically outbursting lake (Lamke, 1972). Floods at Mt. Rainier, Washington, are caused by release of water stored within or beneath glaciers (Richardson, 1973).

Volcanic heat, even during the non-eruptive phase, is capable of melting considerable amounts of snow and glacier ice. Observations of such melting have been made at Mt. Baker, Washington (Frank, Meier, and Swanson, 1977) and at Mt. Wrangell, Alaska (Benson and Motyka, 1978). During the eruptive phase at Mt. St. Helens, Washington, snow and glacier ice melted which contributed some water to mudflows and flooding (Brugman and Post, 1981), but the amount of water contributed to this flooding by glacier melt is uncertain even though several glaciers lost their upper reaches during the eruption in May 1980.

A glacier-related flood wave in Lituya Bay, Alaska, was caused by a landslide associated with glacier recession and produced a severe and unexpected major calamity (Miller, 1960). This wave rose 500 meters on a mountain ridge, then washed fishing boats at anchor in Lituya Bay across a mature spruce forest at the mouth of the Bay. Some boats and their occupants survived because the wave lofted the boats completely over the forest and into the open Pacific Ocean. This illustrates that any body of water which occupies a recently deglaciated depression may be potentially hazardous.

Glacier runoff models

A numerical model to predict runoff from basins with glaciers was proposed by Tangborn and Ras-

mussen (1976), following an analysis of runoff by Rasmussen and Tangborn (1976). The model is based on the difference between precipitation and runoff from a basin, which is an estimate of snow and glacier ice storage.

A predictive model has been proposed in which the outburst flood peak flows in the Snow River, Alaska, can be forecast after the early stages of the floods have been measured (Chapman, 1981).

Conclusions

The scientific literature on glacier mass balance and runoff in the U.S.A. is composed of approximately 180 papers, many of which are reviewed briefly in this paper. Compared with most other sciences, this is a very small literature, and many of these papers contain only brief information on the subject or are basically review papers themselves. Only a few present significant, new scientific knowledge. The total knowledge of mass balance and glacier runoff in the U.S.A. is small relative to the value of the resources, the potential hazards and associated risks, the complexity of the subject at hand, and the extent of glaciers.

The science began in the United States between 1943 and 1957, and is still young. The present state of knowledge, should a modest shift in climate occur, is insufficient for reliable predictions to be made of the balance and runoff from most gaged and ungaged glaciers and glacier-fed rivers. Present knowledge is also insufficient to predict the changes in glacier mass balance and runoff that could occur if other stresses were imposed on the systems, such as weather modifications or creation of large, new lakes.

Reliable measurements on the hydrology of glaciers are costly, require unique skills, and can be potentially hazardous, therefore, future research should concentrate on the formulation and perfection of glacier balance and runoff models that are driven by easily obtainable weather and climatic data. This effort will require testing and calibration, so some carefully planned measurements will be critical to the development of the science. Application of highly qualified numerical models of balance and runoff could enable reliable predictions, particularly when the dynamics of the glaciers are also understood.

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