# Twentieth century climate change: Evidence from small glaciers

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**The relation between changes in modern glaciers, not including the ice sheets of Greenland and Antarctica, and their climatic environment is investigated to shed light on paleoglacier evidence of past climate change and for projecting the effects of future climate warming on cold regions of the world. Loss of glacier volume has been more or less continuous since the 19th century, but it is not a simple adjustment to the end of an "anomalous" Little Ice Age. We address the 1961–1997 period, which provides the most observational data on volume changes. These data show trends that are highly variable with time as well as within and between regions; trends in the Arctic are consistent with global averages but are quantitatively smaller. The averaged annual volume loss is 147 mm·yr$^{-1}$ in water equivalent, totaling 3.7 × 10$^3$ km$^3$ over 37 yr. The time series shows a shift during the mid-1970s, followed by more rapid loss of ice volume and further acceleration in the last decade; this is consistent with climatologic data. Perhaps most significant is an increase in annual accumulation along with an increase in melting; these produce a marked increase in the annual turnover or amplitude. The rise in air temperature suggested by the temperature sensitivities of glaciers in cold regions is somewhat greater than the global average temperature rise derived largely from low altitude gauges, and the warming is accelerating.**

Evidence for rapid climate changes in the past has been derived from many sources, including glaciers and ice sheets. Here we investigate the relation between the relatively well documented changes in modern glaciers and their climatic environment. The climatic processes affecting glaciers, both modern and those of the past, are unique to high altitudes and/or high latitudes, areas with few instrumented climate stations. Therefore, an examination of this relationship may be instructive for the study of paleoglacier evidence as indicative of past climate, and for projecting the effects of future climate warming on cold regions of the world. The volume of a glacier changes constantly because of variations in mass inputs (accumulation, mainly from atmospheric precipitation) and mass losses (ablation, mainly melting and evaporation). In this paper, we do not consider the ice sheets of Greenland and Antarctica.

The importance of understanding the relation between glacier fluctuations and climate variations has long been recognized, and led to the founding of the International Commission on Glaciers (now the International Commission on Snow and Ice) in 1894 (1). Some short term and sporadic measurements of volume change were carried out in the late 19th and early 20th centuries in the Alps (2) and in the early 20th century in the Arctic (3). Thorarinsson in 1940 (4) was the first to attempt a global analysis of a wide range of glaciological information (e.g., front positions, area changes) and to extend that analysis back into the 18th century. He also apparently made the first calculation of glacier volume change from 1850 (believed to be the maximum glacier extension since the Ice Age in some areas) and its contribution to sea-level rise. The general conclusions from this analysis, that the present glacier shrinkage is a universal phenomenon and that the global recession of glaciers has taken place in several stages of ever increasing intensity, interrupted by intervals of stagnation or advance, are still valid.

A bridge between these early conclusions and our present-day knowledge of glacier regime is found in time-series modeling of volume changes that extend from the observations of the 1960s–1990s back to the end of the 19th century. These are calculated by glaciometeorologic (precipitation–temperature) models, described in detail by, for instance, Tangborn (5). We use only time series calibrated with direct observations for the last 30 or more years. These measured-reconstructed curves (Fig. 1) show predominantly volume shrinkage and at an increasing rate. They also show temporal and spatial variability in the rate of volume changes, from periods of sharp gains to periods of major losses of mass, and simultaneous advances and retreats of different glaciers. One can conclude that the present-day wastage of glacier volume is, on the average, part of a continuous process started in or before the 19th century, after the end of Little Ice Age maximum. Climate became warmer, and glaciers continued losing volume in response to this change. However, the rate of loss has been accelerating recently; this suggests that it is not just a simple adjustment to the end of an "anomalous" Little Ice Age, as some have claimed.

Here we present an analysis based on data of volume change of small glaciers collected since the end of World War II. The main goal of this study is to advance understanding and provide new information on climate change as shown by modern glaciers.

**Data Sources for Analysis.** The main sources of data are series of annual glacier mass-balance values. These measurements started after 1946 on a regular basis. Before the International Geophysical Year (1957–1959), fewer than 10 glaciers were observed. The number of measured glaciers has grown rapidly since the International Geophysical Year and reached a maximum of 70–90 time-series annually in the middle of the 1970s. Mass balances of more than 260 glaciers have been measured at one time or another. All of these data are included in our analyses, but we emphasize the 1961–1997 period of time because this period is provided with the most observational data. The length of mass balance measurement records varies from 1 to 37 yr with an average duration of 10 yr.

Our database has been compiled from many sources of information, including the seven existing volumes of "Fluctuations of Glaciers" and five "Glacier Mass Balance Bulletins" published by the World Monitoring Service (6). Many additional publications and some unpublished data were used to create what is probably the most complete global data set. Data were digitized, quality-checked, and analyzed. A description of the data used is given in our recent publications (7–9) and by Cogley and Adams (10), and will soon appear on the Institute of Arctic and Alpine Research web site (Instaar.colorado.edu/Geoglacier/).

The glaciers involved in this study are sparsely distributed over many mountain and subpolar regions, but most of the information on glacier volume change is from the Northern Hemisphere, particularly from Northwestern North America, the Canadian Archipelago, Scandinavia, European Alps, Svalbard, Iceland,

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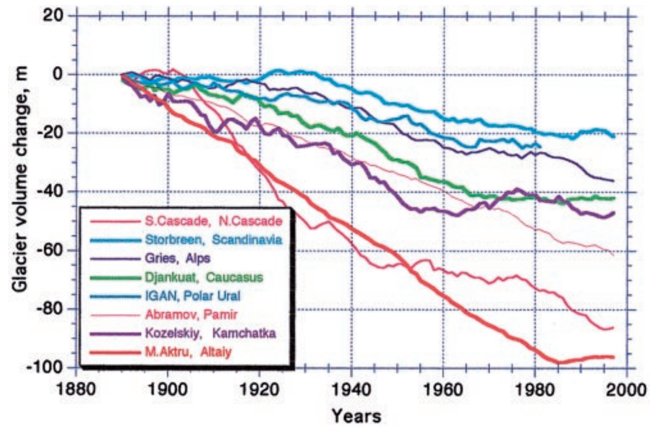


**Fig. 1.** Selected long-term series of cumulative volume changes for glaciers in different geographical regions: South Cascade (North Cascades, Washington), Gries (Alps, Switzerland), Storbreen (Jotunheimen, Norway), Abramov (Pamir, Kirgizstan), Kozelskiy (Kamchatka, Russia), Djankuat (Caucasus, Russia), Maliy Aktru (Altaiy, Siberia, Russia), IGAN (Polar Ural, Russia). All values are relative to 1890.

East Africa, Caucasus, Central Asia, Altaiy, Kamchatka, and Polar Ural Mountains. Very short time series are available from the Russian Arctic, Labrador, Pyrenees, South America, Subantarctic islands, New Zealand, and New Guinea. Therefore, we emphasize results from the Northern Hemisphere.

**Changes in Glacier Volume.** Here we report mass (water-equivalent volume) changes per glacier area per year, $\Delta\mathbf{V}$, in dimensions of millimeters (or meters) per year, instead of the more usual units of annual or net mass balances, which should be but are not always identical. We calculate $\Delta\mathbf{V}$ by using the reported or interpolated glacier area for the year of observation, to avoid the problem of considering the dynamic response of a glacier to a history of non-zero mass balances. Glaciers constantly change in area, length, and thickness, but the precipitation input minus the melting output (the annual or net mass balance) integrated over the instantaneous area is, by continuity, a true measure of the change in volume; this is especially important for studies of their effect on current sea level. Some mass balance values in the literature are point values integrated over an unchanging area, an approach we reject. The actual dimensions of a glacier at any moment, of course, reflect a dynamic adjustment to a mass balance history with an e-folding time of a few years to several decades or so (11), which is important for reconstructing a history of climate variations.

The 37 longest, directly measured, time-series of volume change $\Delta\mathbf{V}$ are presented in Fig. 2. These curves for 1961–1997 resemble those shown in Fig. 1 but give more detail with greater accuracy (the error in measurements is about $\pm$ 0.1–0.2 m in water equivalent per year for glaciers presented here). Internal accumulation (refreezing of meltwater within the glacier) has been considered where it is likely to be a significant process. Several features can be recognized:

Trends are different within each of the regions and between regions; some glaciers gaining mass at the time others are shrinking [see, for instance, the Alps and Scandinavia (Fig. 2 *c* and *d*). One interesting example is Maliy Aktru glacier (Altaiy, Southern Siberia). Fig. 1 illustrates the large decrease in volume from the end of the 19th century to the beginning of the 1980s for this glacier, but the trend has recently changed toward mass gain (Fig. 2*e*).

The differences between cumulative values of $\Delta\mathbf{V}$ for the period 1961–1997 for individual glaciers in mainland North America reaches 40 meters and 30 meters in the Alps and in Scandinavia (including Svalbard), suggesting differences in large-scale or mesoscale climatic conditions.

Glaciers in cold and dry regions (e.g., Canadian Arctic) demonstrate trends of shrinkage that are internally rather consistent, but with relatively low changes in $\Delta\mathbf{V}$ due to the precipitation regime (Fig. 2*a*). Koerner and Lundgaard (12), who are responsible for obtaining most of these data, imply that the "warming trend" indicated by changes in these glaciers in the last 100 yr ". . . is part of natural variability of climate rather than due to anthropogenic effects" (ref. 12, p. 434) Without commenting on the cause of this warming, we note that the volume-change trends in this region are consistent with those elsewhere in the world and that a global cause seems likely. The Canadian Arctic sample presents cold ice caps in which thickness change is not as large as in more maritime climates and in which spatial differentiation also is not as large as in the other regions.

Glaciers situated at high altitudes in Asia (low temperature and relatively dry climates) also show a common trend of reducing volume (Fig. 2*e*), especially glaciers in Central Asia (Pamir and Tien Shan). On the other hand, many glaciers in moist, maritime regions (e.g., Blue, Nigards, Ålfot, Hardanger) are growing (Fig. 2b, c).

In addition to these long and continuous time series of volume change, we use all direct measurements of glacier mass balance, because we found a rather strong correlation (r 0.90) between long-term mass-balance series (50 glaciers with $\Delta\mathbf{V}$ time-series longer than 20 yr) and series with all 260 glaciers. This has helped to expand the time series over the period of time from 1961 to 1997, in spite of some gaps in data and the fact that many records from 1994 to 1997 are not yet complete. We use these time series to calculate annual values of glacier mass balance and $\Delta\mathbf{V}$ averaged for all time series (Fig. 2*f*). This was done by averaging the mass balances of all glaciers within six major glacier regions (and in a number of subregions), then calculating a hemispheric average weighting each region by the glacier area in that region. The averaged annual decrease in glacier volume has been $-147$ mm·yr$^{-1}$ in water equivalent. This specific value multiplied by the estimated area of all small glaciers ($680 \times 10^3$ km$^2$) (13) gives about $-100$ km$^3$·yr$^{-1}$, or about $3.7 \times 10^3$ km$^3$ of volume loss over 37 yr. This is our most recent estimate of a global total.

Obviously, this is an imperfect estimate of the sum of glacier wastage, because the data are sparse and not homogenously distributed. However, this estimate includes all available data and recognizes the substantial differences between different regions. It is difficult to estimate the error in the cumulative sum because of the possibility of both random and systematic errors (10). The apparent variances in individual years causes a standard error of estimate of the total of only 30 mm (0.5% for 99% probability) for our sample, but other errors surely raise this number to at least several percent. We note that Oerlemans' calculation by a very different method matches our results closely (14).

Additional evidence of pervasive glacier wastage is shown by the decrease in the average value of the ratio between accumulation area and total glacier area (AAR) from about 0.55 to about 0.42 during the period 1968–1975. Note that a glacier with an AAR $<$0.56 is not likely to be in a steady-state condition (15). Along with this, the averaged equilibrium line altitude (ELA, the altitude separating the accumulation and ablation areas) has increased by about 480 m. The decrease in AAR and increase in ELA has exposed larger ice areas with low albedo and increased ice melting with a further tendency to reduce glacier volume, a positive feedback pointed out by Bodvarsson (16).

**Climate Analysis Based on Time Series of $\Delta\mathbf{V}$ and Related Characteristics.** *The 1961–1997 time series.* The time-series of $\Delta\mathbf{V}$ allow a more detailed climate analysis, especially when combined with information derived from other glaciological variables. Winter balance, $b_w$, is a measure of the amount of snow precipitated on

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SPECIAL FEATURE

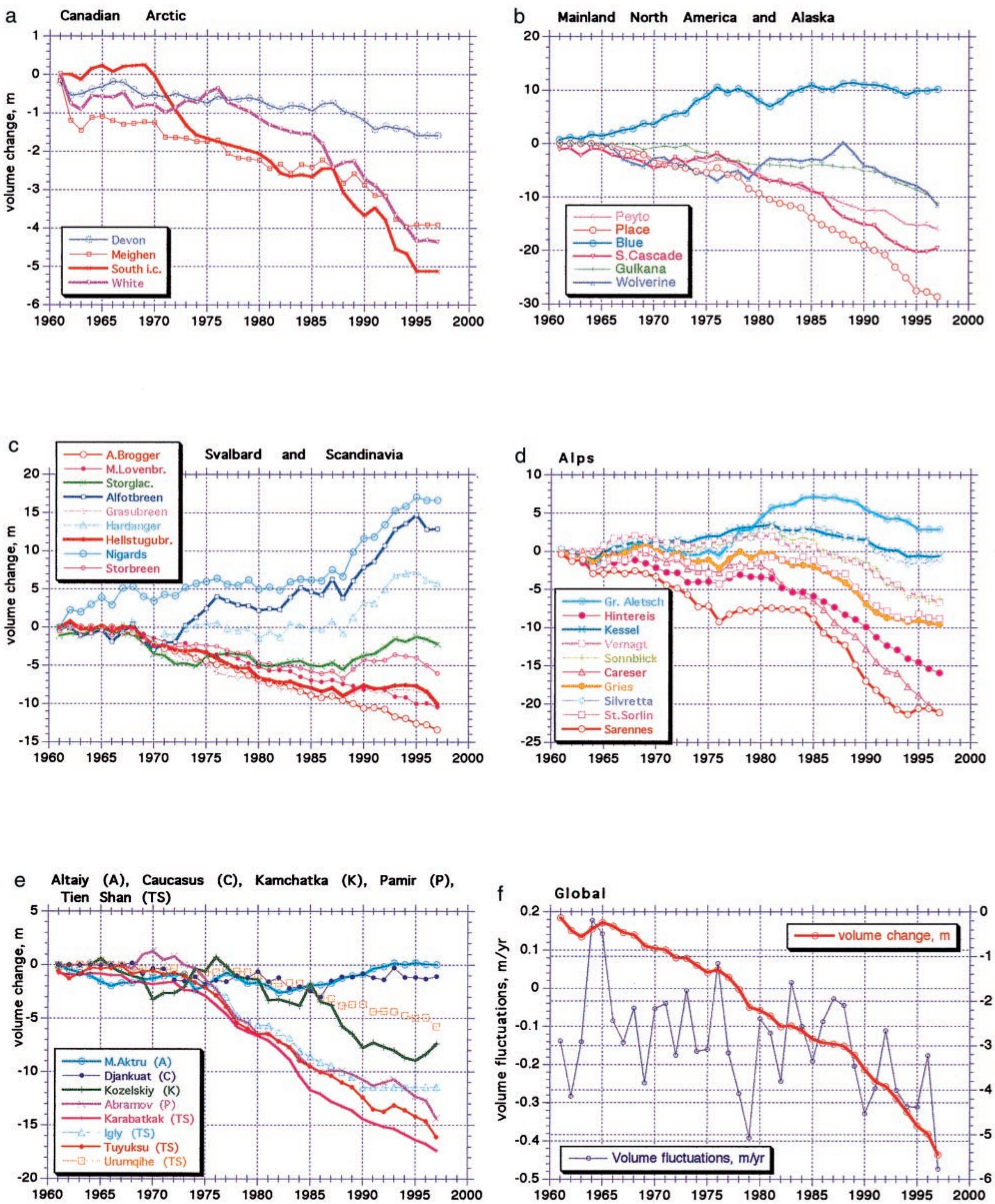


**Fig. 2.** Change in glacier volume, $\Delta$**V**, derived from mass balance measurements on 37 glaciers in five regions in the Northern Hemisphere in recent decades, and a global average. (*a*) All glaciers are in Queen Elizabeth Islands (Arctic Canada). (*b*) Peyto (Rockies, Alberta, Canada), Place (Coast Mountains, British Columbia, Canada), Blue (Olympics, Washington), South Cascade (North Cascades, Washington), Gulkana (Alaska Range, Alaska), Wolverine (Kenai, Alaska). (*c*) A. Broggerbreen and M. Lovenbreen (Svalbard, Norway), Storglaciären (Kebnekaise, Sweden), Ålfot-, Gråsu-, Hardanger-, Hellstugu-, Nigards-, and Storbreen (Norway). (*d*) Hintereis-, Kesselwand-, and Vernagtferner (Eastern Alps, Austria), Gr. Aletsch, Sonnblick, Gries, and Silvretta (Alps, Switzerland), Careser (Alps, Italy), St. Sorlin and Sarennes (Alps, France). (*e*) M. Aktru, Djankuat, and Kozelskiy (Russia) Abramov and Karabatkak (Kirghizstan), Igly and Tuyuksu (Kazakstan; Ürümqihe (China). (*f*) A global estimate showing cummulative volume change (red) and year-to-year fluctuations (purple).

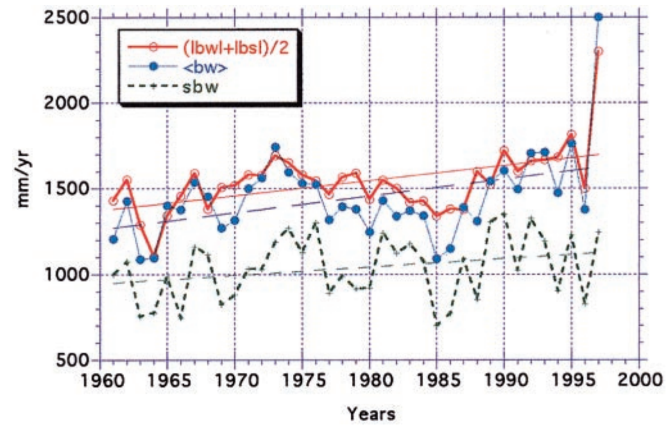


**Fig. 3.** Annual amplitude or turnover of glacier volume change $\alpha = (|b_w| + |b_s|)/2$ calculated from long-term series (23 glaciers) of winter ($b_w$) and summer ($b_s$) glacier mass balances; also shown are annual fluctuations of globally averaged winter balance and their year-to-year standard deviation ($sb_w$).

a glacier surface from October until May (in the Northern Hemisphere). Summer balance, $b_s$, is related to glacier meltwater runoff plus evaporation from June to September. (This is not strictly true for iceberg-calving glaciers or those which exist at a temperature below the freezing point because some meltwater is refrozen and becomes accumulation.) These two variables are closely related to climate; both balances are averaged here for the 23 glaciers with long, continuous measurements. The annual turnover or amplitude $\alpha$ [$= (|b_w| + |b_s|)/2$] characterizes the glacier regime (17). Our calculation shows that $\alpha$ has not been constant over the period of study but has increased substantially (Fig. 3). This increase is possibly related to increased heat energy absorbed, accompanied by increased moisture production because the amount of snow accumulation has increased in high mountain and in subpolar regions (9). The increase in $\alpha$ is also accompanied by increases in the interannual variances of $b_w$ (Fig. 3). This variance is computed as the standard deviation of all measured balances from the mean balance for each year.

*A shift in volume-change trend in the late 1970s.* The time series of change in global glacier volume suggest a significant shift during the late 1970s. The cumulative sum of departures from the value of −118 mm/yr, as area-weighted averages over the 30-yr climatologic reference period 1961–1990, are presented in Fig. 4. These departures show the change in the late 1970s toward a significant trend of decreasing glacier volume. This shift in the late 1970s corresponds with a shift in climate reported in several recent publications. Miller *et al.* (18) identified an abrupt shift in the basic state of the atmosphere–ocean climate system over the North Pacific Ocean during the 1976–1977 winter season. Trenberth noted that the Aleutian Low deepened, causing storm tracks to shift southward and to increase storm intensity (19). This shift in climate was illustrated by Ebbesmeyer *et al.* (20) in a composite time-series of 40 environmental variables, which suggests an abrupt change in climate during the winter 1976–1977. McCabe and Fountain (21) determined that the mid-1970s climate shift was followed by a decrease in net mass balance of South Cascade Glacier (Washington State) and a simultaneous increase in the net mass balance of Wolverine Glacier (Alaska). Hodge *et al.* (22) confirmed statistically that this was a significant change in mass-balance series for three glaciers in Alaska and Washington. Cao (23) found an abrupt change in glacier mass balance in the Tien Shan and attributed this change to a mid-1970s climate transition that was initiated in the tropical Pacific Ocean. Our volume change data from small glaciers supports these conclusions on the global scale and demonstrates the usefulness of short-term glacier-volume fluctuations for detection of climate changes.

*Glacier wastage and climate change since 1977.* The changes in glacier mass balances, as well as global temperature, during the 20 yr 1977–1997 may be unprecedented. This period bears examination because it may provide insight to the behavior of the climate/glacier relationship in the future. This period included the warmest decade and several of the warmest years in the history of the instrumental record (24). The average annual mass balance changed from $-81$ mm·yr$^{-1}$ during the period 1961–1976 to $-198$ mm·yr$^{-1}$ during the 1977–1997 period; this is equivalent to a change in the rate of sea-level rise attributable to glacier wastage from 0.15 to 0.37 mm·yr$^{-1}$. The rate of change of the global annual mass balance during this period was modestly negative ($-5.9$ mm·yr$^{-2}$). The mass balance sensitivity, the partial derivative of annual balance with respect to air temperature,§ measured over this interval was $-0.37$ m·°C$^{-1}$·yr$^{-1}$, lower than most of those reported in the literature (26, 27).

The seasonal mass balance changes (9) and seasonal sensitivities based on them (27) are interesting. During this period, the winter balances became more positive and the summer balances became more negative, which caused a marked increase in the annual amplitude (Fig. 3). The apparent winter balance sensitivity was high (1.31 m·°C$^{-1}$·yr$^{-1}$) as was the summer balance ($-0.99$ m·°C$^{-1}$·yr$^{-1}$). (The sum of these seasonal sensitivities is slightly different from the value given above for the annual sensitivity because different time-series aggregations had to be used.) Although this period may have been unusual, these significantly different sensitivities suggest that any attempt to project glacier behavior into the future, for instance, to estimate sea-level rise, will need to consider the seasonality of glacier mass balances and climate.

In addition to the shift in the winter of 1976–1977, the data presented in Fig. 4 illustrate a trend to even more negative **ΔV** since the end of the 1980s. In terms of air temperature, it was reported that the end of the 1980s and 1990s have been the warmest years of this millennium for the Northern Hemisphere (24, 28). The change in global **ΔV** was not uniform in the 1990s (Fig. 4). In 1992 and 1993, **ΔV** was close to zero (Fig. 2*f*), possibly because of the explosive eruption of Mt. Pinatubo (June, 1991). The cooling of global surface temperature after the eruption reached a maximum of $-0.3$ to $-0.5$°C during 1992 (24). In terms of the global water balance, this short-term cooling equates to 360 km$^3$ of water stored by glaciers, or to 1 mm of sea-level fall.

**Spatial Pattern of Glacier Volume Changes.** Many glacier–climate studies focus on studies of the relations between local or regional climate and **ΔV** or mass balance of glaciers (e.g., refs. 21, 22, and 29–31). These studies are useful for understanding physical interactions between climate and glaciers on regional to global scales. The process interrelating atmospheric circulation, surface meteorological parameters (e.g., air temperature and precipitation), and glacier **ΔV** is very complex. We found that the spatial covariance among glaciers of annual **ΔV** may range from strong to weak, and positive or negative, over the Northern Hemisphere (9). Distant glaciers may correlate more strongly than neighboring glaciers, showing the existence of teleconnections involving regional atmospheric circulation patterns. The correlation structure of **ΔV** with atmospheric pressure anomalies is partly explained by changes in the winter balance ($b_w$). A principle components analysis (32) shows that 46% of the $b_w$ variability is explained by the first two primary circulation modes, which are

§This a different sensitivity than that used by the International Panel on Climate Change (25) that involves a change between two steady states.

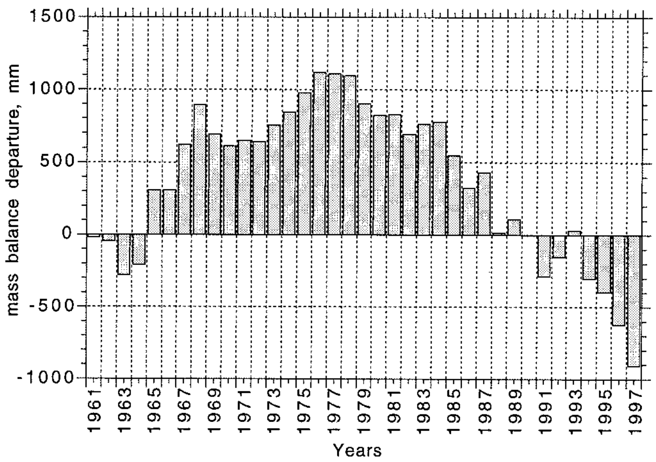


**Fig. 4.** Cumulative departures of globally averaged annual glacier mass balances relative to 1961–1990 "climatological normal" period. Long-term time series (20 and more years) have been used.

also correlated with the Arctic Oscillation Index and the Southern Oscillation Index. This analysis also explains the current growth in certain maritime glaciers (Fig. 2 *b* and *c*). The other components of variability may be explained by summer mass balance ($b_s$) and local glacier properties.

**Discussion.** On short time scales, e.g., annual, $\Delta\mathbf{V}$ of glaciers respond to change in climate with little delay. Autocorrelation analysis of our time series of $\Delta\mathbf{V}$ shows that, within the confidence level of 0.95, there is about a 1-yr lag between volume changes in consecutive years. This is to be expected because the albedo effect of a non-zero balance year may have some carryover effect to the next year (22). Note that this analysis avoids the problem of multiyear or longer dynamic response times (11) because $\Delta\mathbf{V}$ is always related to the instantaneous glacier area. Annual changes in volume can thus be considered to be almost simultaneous with annual changes in weather. Therefore, glacier volume changes can be attributed to (*i*) changes in atmospheric circulation patterns (atmospheric pressure fields) at regional or global scales; and/or (*ii*) changes in local weather patterns and/or peculiarities of glacier topography and size, which may involve local variables, such as changes in wind regime and local precipitation trajectories, snow avalanches, changes in albedo, moraine cover, and others.

The 37-yr time series showing both increased melting and accumulation (Fig. 3) is especially interesting. Oerlemans and Fortuin (33) pointed out that the sensitivity of glacier volume changes to temperature ($\partial b_a/\partial T$) is a function of precipitation (high-precipitation regions have higher sensitivity). Our global-average data, showing increases in both melting (related to temperature) and accumulation (related to precipitation), are in agreement with this result. The increase in $b_w$ is particularly remarkable because it has occurred in spite of a reduction in the size of the accumulation area. Thus, significantly increased precipitation at high altitudes is indicated.

The increase in both accumulation and ablation does not seem to have been noted for previous periods of observation. The earlier analyses, e.g., ref. 4, did not show such a phenomenon. This may be because previous workers did not have as complete and detailed data sets. But it is also possible that the relationship between glacier mass balance components and climate elements has changed in recent decades because of global warming. The increase in mass turnover shown by $\alpha$ in Fig. 3 may be attributable to additional energy received by glacier surfaces in recent decades. This extra latent heat used to increase melting has been accompanied by increased snow accumulation on glacier surface, which stores latent heat in the glacier (potential heat required to melt the extra snow). We are also witnessing an interesting process in which glacier wastage in some regions is accompanied by glacier growth in other areas.

The annual-balance sensitivity to temperature ($\partial b_a/\partial T$) is used for most projections of glacier wastage and its contribution to sea-level rise. Typical published values of mass-balance sensitivity unadjusted for precipitation change range from about 0.3 to 1 $m \cdot {}^\circ C^{-1} \cdot yr^{-1}$ with an average of about 0.7 $m \cdot {}^\circ C^{-1} \cdot yr^{-1}$ (e.g., refs. 26 and 27). Using the observed change in glacier volumes, this suggests a temperature rise of 0.34°C over 37 yr, or 0.009 $^\circ C \cdot yr^{-1}$. Oerlemans (34) uses glacier dynamics modeling of measured glacier retreats, scaled by region, to estimate an annual temperature rise of 0.62°C from 1884 to 1978. The rise of global average surface temperature change for 1901–1997 was about 0.62°C or 0.0065$^\circ C \cdot yr^{-1}$ (24).

Because of the range of volume-change variability among glaciers (Fig. 2), sensitivity values derived from a limited number of glaciers must be used with caution. The sensitivities suggest that the recent rise in air temperature in glacier regions is somewhat greater than the modeled global average derived largely from low altitude gauges, and the warming is accelerating.

**Conclusions.** Loss in glacier volume on a global scale started in the middle of the 19th century and continued in several stages of ever-increasing rates, interrupted by short intervals of stagnation or growth. The acceleration of glacier wastage is not inherited from previous epochs.

Time series of volume changes show much spatial and temporal variability. Changes in winter balance are correlated in part with spatial and temporal distributions of atmospheric circulation patterns. Glacier volume changes currently seem to show increased snow accumulation and positive volume changes in some maritime regions, especially in the last several decades. Those in continental regions generally are losing volume at an accelerating rate. Thus, glaciers demonstrate different trends of volume change in different geographical locations.

The climate in Northern Hemisphere glacier areas became warmer and more humid during the last decades, especially since a climatic shift around 1977. This appears to be an unusual change, possibly of anthropogenic origin. Winter accumulation and summer melting have both increased with time, as has their temporal variability. We emphasize that this increase in the intensity of glacier regime (mass exchange) leads to a continuing addition to sea-level rise and a reduction in the speed of wastage.

It is, however, clear that carefully measured glacier data are limited both temporally and spatially. Existing records need to be expanded to better understand the relations between glacier volume change and climatic driving forces.

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