# Changes in Mass Balance of South Cascade Glacier, North Cascades, 1959 to 1994

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**Abstract:** Annual, winter, and summer mass balance measurements at South Cascade Glacier in the North Cascade Mountains of Washington State constitute a continuous time series 36 years long, from 1959 to 1994. The glacier net balance, the difference between the winter balance (total accumulation) and summer balance (total ablation), decreased abruptly in 1977, from an average of −0.09±0.90 m/yr for 1959-1976, to −1.02±0.71 m/yr for 1977-1994. The decrease in this average, −0.91 m/yr, exceeded its standard deviation (1s) for both periods. However, an even more statistically significant decrease occurred in the winter balance, which averaged +3.00±0.60 m/yr for 1959-1976, but only +2.27±0.46 m/yr for 1977-1994, the decrease in the average clearly exceeding either standard deviation. The summer balance does not show any significant abrupt change, averaging −3.09±0.55 m/yr before 1977 and −3.27±0.55 m/yr after, but linear fits to the data show that since the late 1970s the summer balance has been decreasing about 0.045 m/yr, about three times faster than the winter balance has been increasing. These results suggest that the winter snowpack in the Washington Cascades underwent an abrupt decrease between 1976 and 1977, and has remained at about the new lower level since 1977. This decrease appears to have occurred because of a change in conditions that prevented snow from accumulating, rather than because of a change in total regional winter precipitation. The long-term trends at South Cascade Glacier are decreased winter accumulation and increased summer ablation, neither of which is conducive to glacier growth, so the trend in the Pacific Northwest is clearly away from an ice-age type of climate at the current time. The data also demonstrate that a glaciologically significant long-term change in snow precipitation can occur rapidly, in as short an interval as 1 year, much more rapidly than changes in temperature.

South Cascade Glacier is a small valley glacier near the crest of the North Cascade Range in north-central Washington State (Figure 1). It is at the head of the South Fork of the Cascade River, a tributary to the Skagit River. It lies in a coastal, maritime climate where winter precipitation, mostly in the form of snow, is heavy and can exceed 4.5 meters annually. Although the glacier is only about 2 km$^2$ in area, it occupies about 34 percent of a north-facing basin and, thus, is larger and lies at a lower elevation than most other glaciers in the region.

Since 1959, the U.S. Geological Survey has measured winter, summer, and net mass balances at this glacier. These data, one of the longest such records on any glacier outside Europe, are shown in Figure 2. The results are published in annual data reports; for example, Krimmel (1993).

The winter balance is the net snow accumulated above the previous summer surface at the end of the winter season, which usually occurs in late April or early May on South Cascade Glacier. It is not the same as total winter snowfall, nor necessarily total annual snowfall, since some winter precipitation can occur as rain and some snowfall can occur in the summer. Nevertheless, it is equivalent to, and somewhat representative

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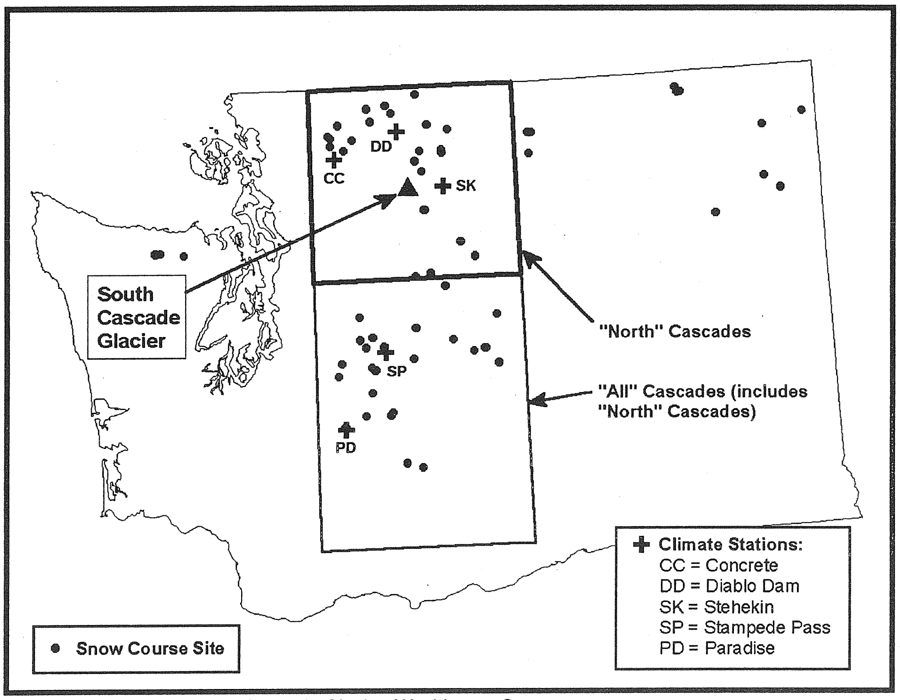


Figure 1 Location of South Cascade Glacier, Washington State.
The USDA snow course sites and NCDC climate stations used in this paper are also indicated.

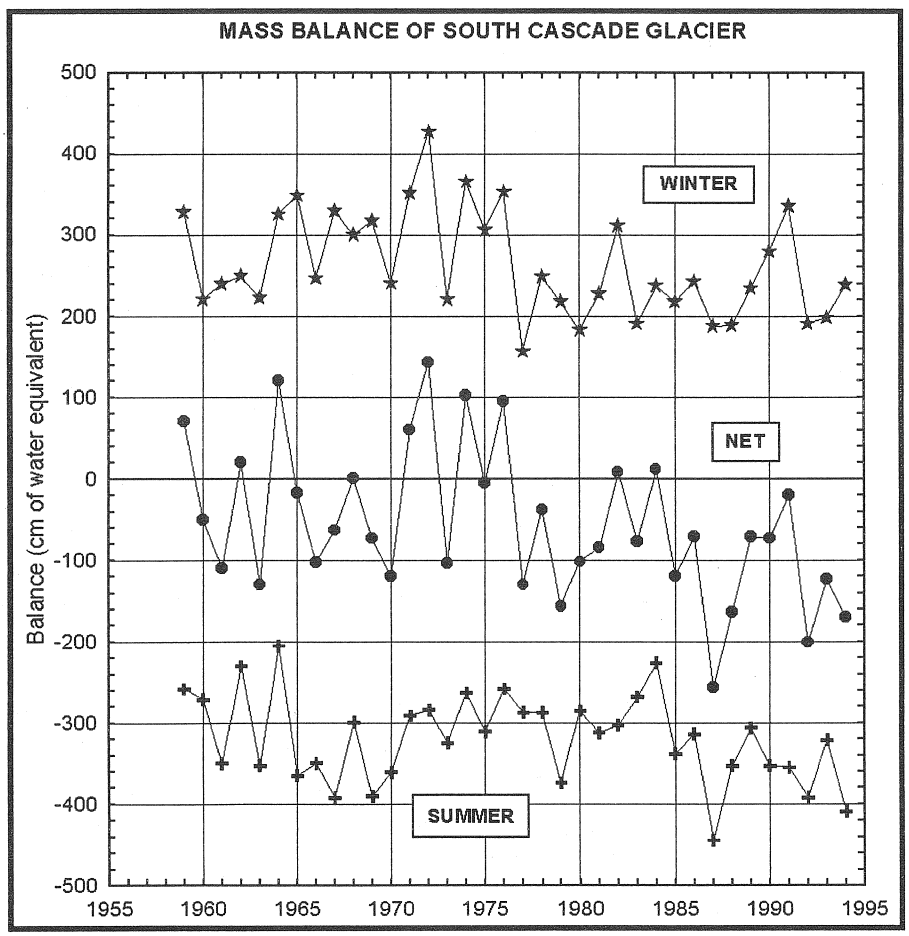


Figure 2 Winter, summer, and net mass balance of South Cascade Glacier, measured since 1959 by the U.S. Geological Survey.
This is one of the longest such records (36 years) on any glacier outside of Europe.

of, the total amount of water in the regional high-elevation snowpack at the end of winter. The net balance is the net change in total mass of the glacier between two successive summer surfaces, which are formed at the end of each melt season, usually sometime in October. The summer balance is the difference between the two: winter minus net. All balance values are averaged over the glacier area and expressed in units of depth of water equivalent. The data are assigned to the calendar year in which the melt season ends; the winter balance thus represents accumulation that commenced during the fall of the previous calendar year. Errors depend upon the year but typically are 0.1-0.2 meters/year.

## Analysis and Interpretation

The net mass balance of South Cascade Glacier decreased abruptly in 1977, from an average of –0.09±0.90 meters/year for 1959-1976 to –1.02±0.71 meters/year for 1977-1994. The decrease in the average, –0.93 meters/year, exceeded its standard deviation (1σ) for both periods. However, an even more statistically significant decrease occurred in the winter balance, which averaged +3.00±0.60 meters/year for 1959-1976 but only +2.27±0.46 meters/year for 1977-1994. The decrease in the average, –0.73 meters/year, clearly exceeded either standard deviation. The summer balance does not show any significant abrupt change: it averaged –3.09±0.55 meters/year for 1959-1976 and –3.27±0.55 meters/year for 1977-1994. Since 1977, the net balance of South Cascade Glacier was positive in only 2 years, but only by a small amount (about +0.01 meters/year).

These results are more readily evident when the data are normalized as standard deviates (the departure of a value from the average, divided by the standard deviation). The standard deviates in Figure 3 were computed using the entire time series. The thick horizontal lines are the average standard deviate computed separately for the periods 1959-1976 and 1977-1994. The thick dashed lines are linear fits to the post-step data; these were added because this is a better approximation to the trend after the step, especially for the winter and net balance.

The winter balance underwent predominantly a step decrease between 1976 and 1977 and has been increasing slowly since 1977, about +0.015 meters/year. On the other hand, the summer balance does not show a similar step change. Instead, since the late 1970s it has been decreasing about –0.045 meters/year, about three times faster than the winter balance has been increasing. The net balance of South Cascade Glacier has, thus, continued to decrease slowly since 1977.

This abrupt change is, fortuitously, now in the middle of the complete South Cascade Glacier mass balance time series, with 18 years of data on either side of it. Thus, this change is not an artifact caused by unequal sampling periods.

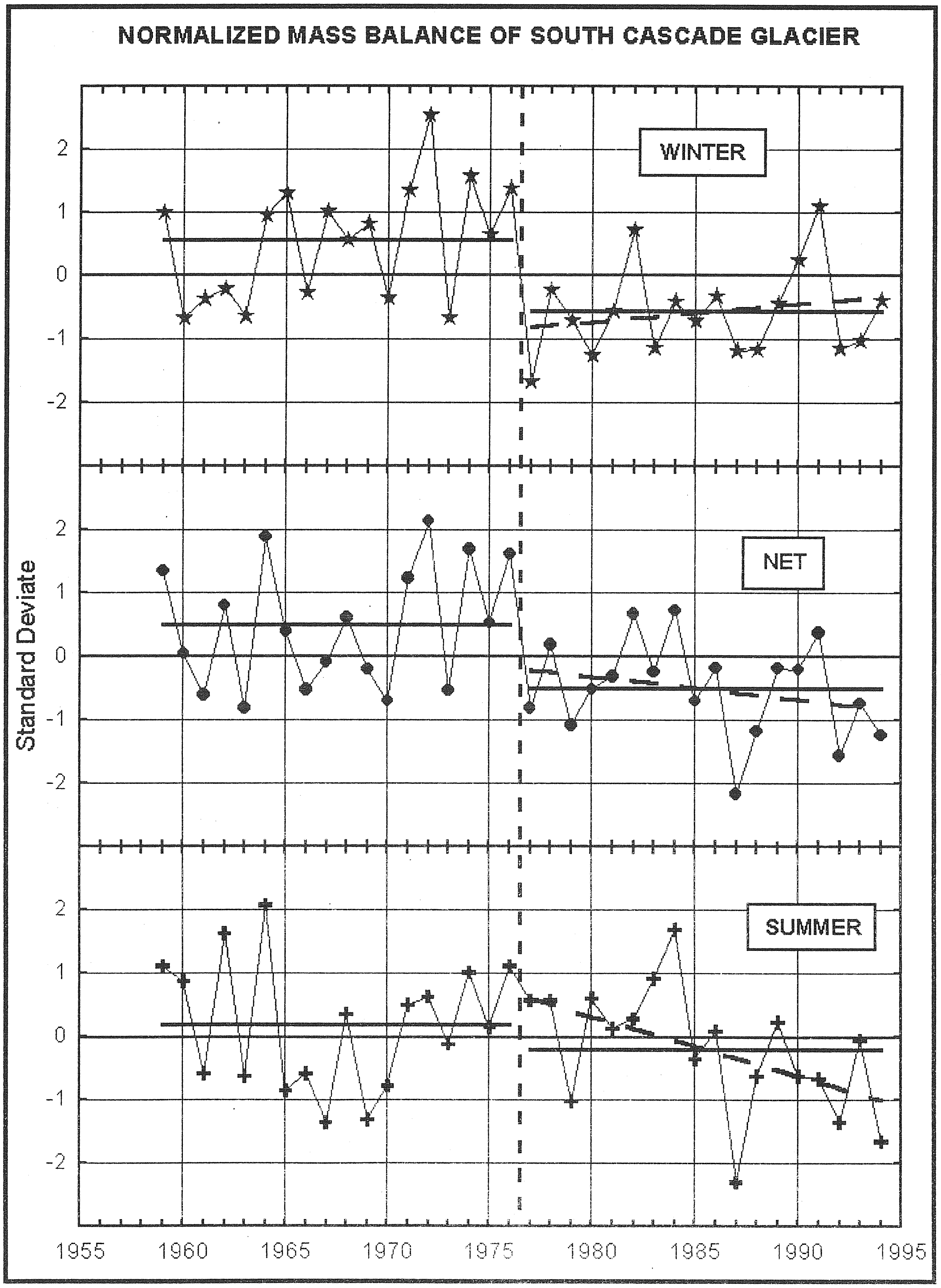


Figure 3 Winter, summer, and net balance of South Cascade Glacier, normalized as standard deviates.
Standard deviates are computed relative to the average for the entire data record. Average values before and after an assumed step change between 1976 and 1977 are shown as thick horizontal lines. Linear fits to the post-step data are shown as thick dashed lines.

These results are consistent with similar ones found from a large number of other environmental variables elsewhere in the Pacific Northwest (Ebbesmeyer *et al* 1991), including snowpack measurements made at USDA snow course sites (Dracup *et al* 1994). Figure 4 shows average snowpack at the end of March for all snow courses in the Washington Cascades (the "all Cascades" region defined in Figure 1) for the same period, 1959-1994, as the South Cascade Glacier balance measurements. All sites not having sufficient data to cover this period were excluded. The data were obtained from the Snow Survey Program, U.S. Department of Agriculture, Portland, Oregon. A step change between 1976 and 1977 is readily apparent in the overall snowpack.

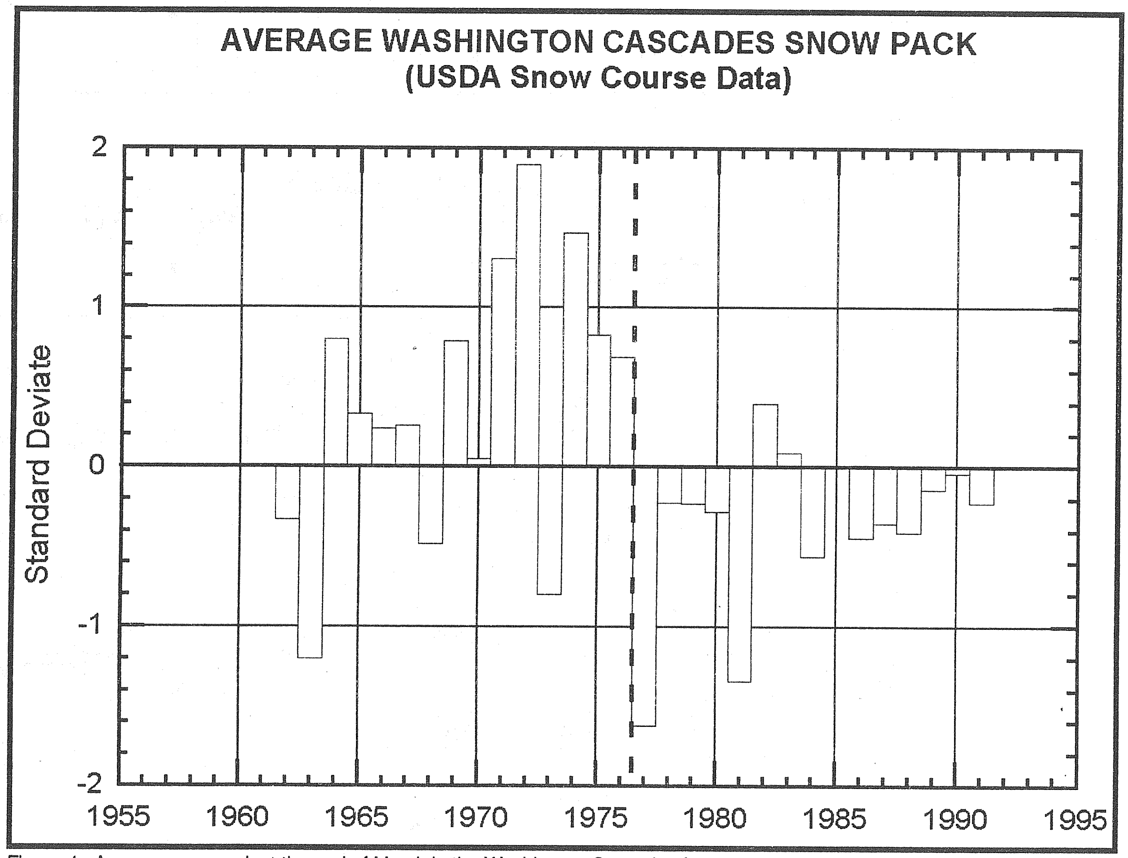


Figure 4 Average snowpack at the end of March in the Washington Cascades for 1962-1991, almost the same period as the South Cascade Glacier balance measurements.
Data are from USDA snow courses; sites that were used are shown in Figure 1.

Figure 5 shows the same data processed with techniques similar to those used for the mass balances, with the average value before and after the 1976-1977 step shown as thick horizontal lines. The data were filtered in various ways, by elevation, by "north" versus "all" Cascades, and by "March-only data" versus "all months of data". In all cases, a step decrease in 1977 is evident in the snow course data.

Accumulation and ablation on a temperate maritime glacier such as South Cascade Glacier are usually considered to be related primarily to regional winter precipitation and summer temperature, respectively (Paterson 1981). Figures 6-9 show average winter and summer temperature

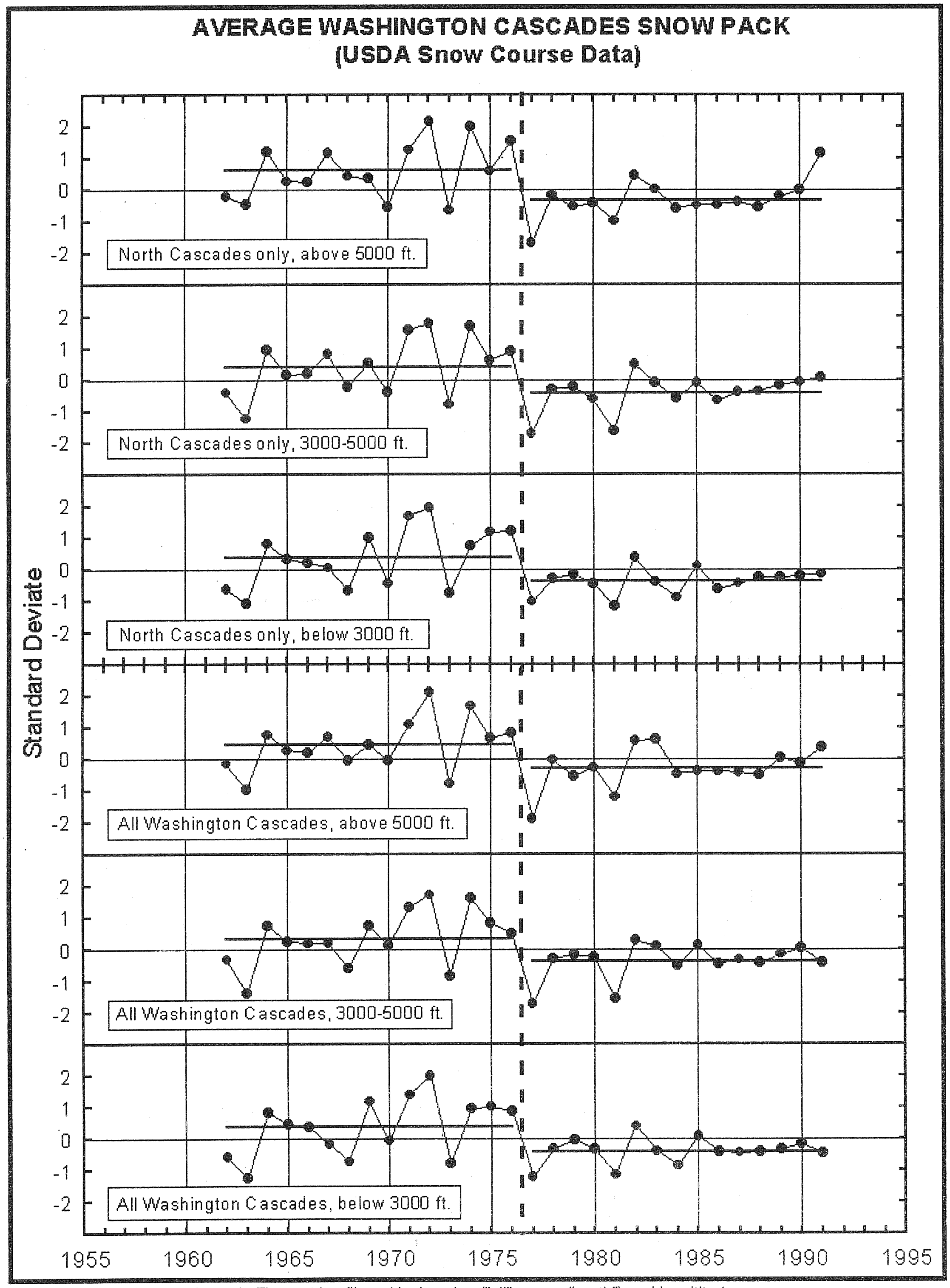


Figure 5 Same data as shown in Figure 4 but filtered by location ("all" versus "north") and by altitude.
Average values before and after an assumed step between 1976 and 1977 are shown as thick horizontal lines.

and precipitation for five climate stations: Paradise, Stehekin, Stampede Pass, Diablo Dam, and Concrete. These stations were selected because they are relatively close to South Cascade Glacier in either altitude or horizontal distance. Figures 6-9 also show regionally-smoothed data for

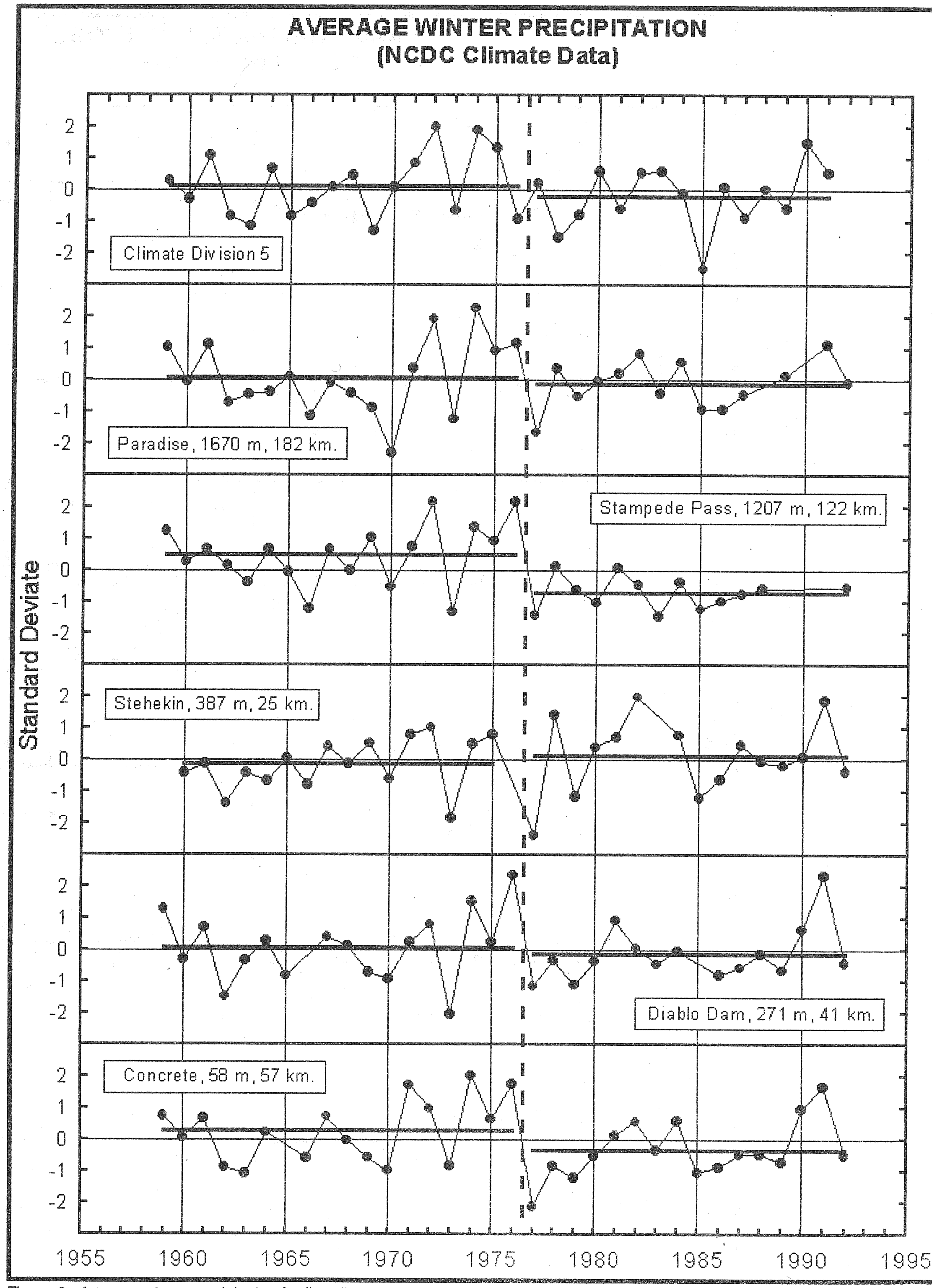


Figure 6 Average winter precipitation for five climate stations and regionally-smoothed data for the west slope of the North Cascades (Climate Division 5).
Altitude (m) and distance (km) from South Cascade Glacier are indicated after each station name.
Locations of the five climate stations are shown in Figure 1.

the west slope of the North Cascades (climate division 5). The data are from the National Climate Data Center, files TD-3200 (climate station data) and TD-9640 (climate division data). Daily values of climate station data and monthly values of climate division data were averaged to give

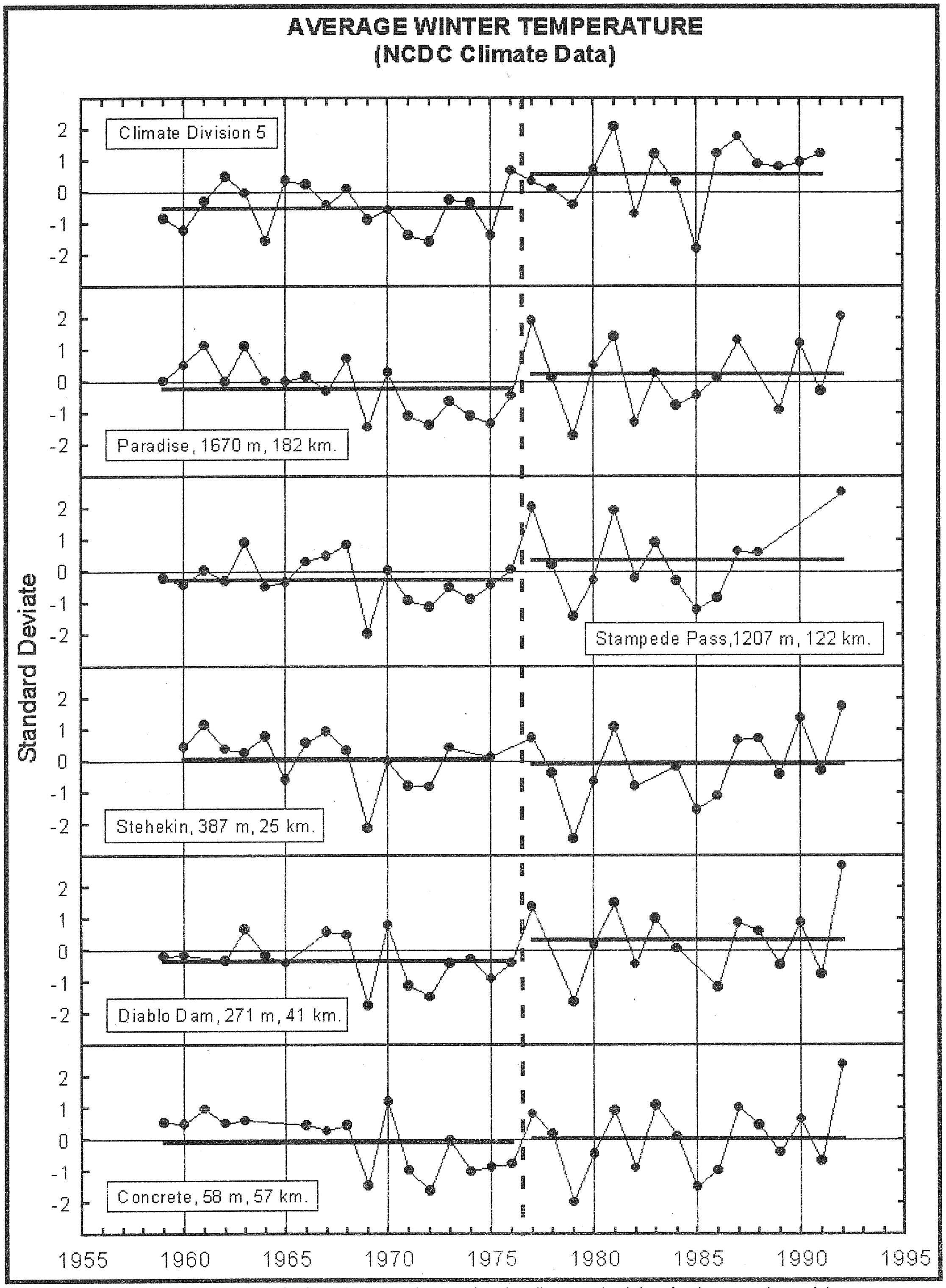


Figure 7 Average winter temperature for five climate stations and regionally-smoothed data for the west slope of the North Cascades (Climate Division 5).
Altitude (m) and distance (km) from South Cascade Glacier are indicated after each station name.
Locations of the five climate stations are shown in Figure 1.

winter and summer means for each year. Winter was defined as November through April, and summer was defined as May through October — the same periods as the balance seasons on South Cascade Glacier.

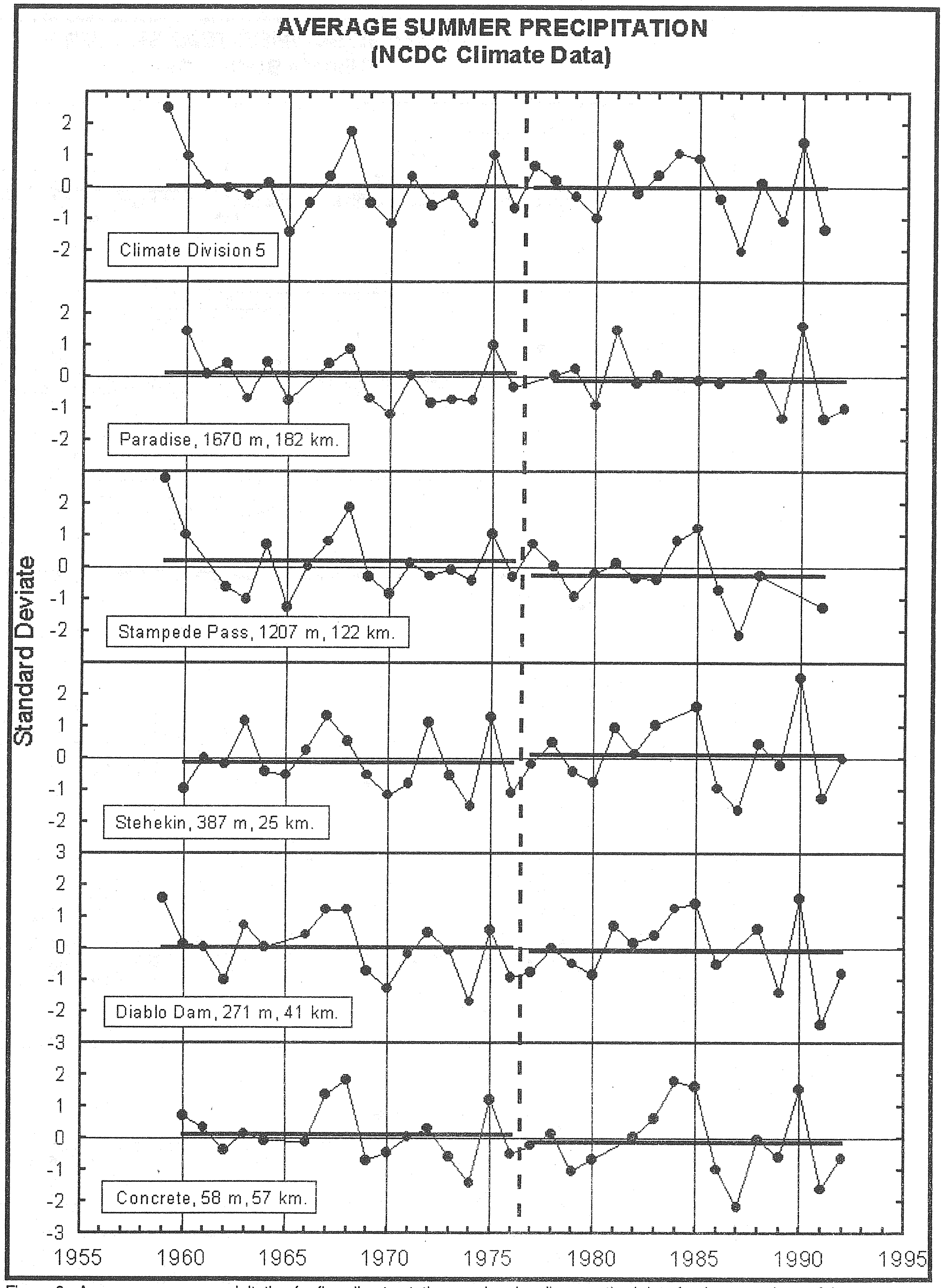


Figure 8 Average summer precipitation for five climate stations and regionally-smoothed data for the west slope of the North Cascades (Climate Division 5).
Altitude (m) and distance (km) from South Cascade Glacier are indicated after each station name.
Locations of the five climate stations are shown in Figure 1.

Even though only constant values were fitted to the data, to maintain consistency with Figures 3 and 5, it is clear that in all cases the average temperature, both in winter and in summer, has been increasing since 1977, and in most cases more rapidly in summer than in winter. This is

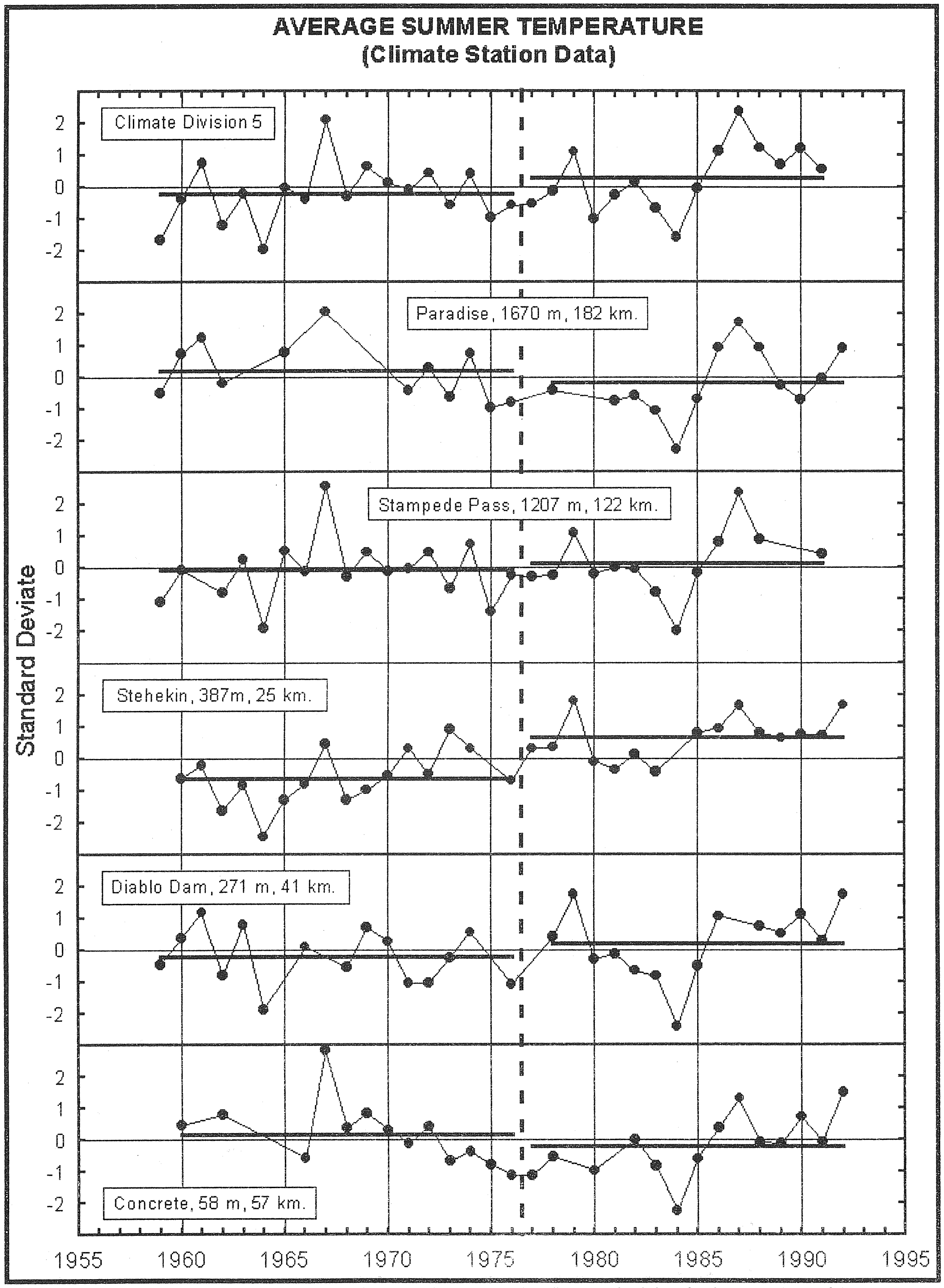


Figure 9 Average summer temperature for five climate stations and regionally-smoothed data for the west slope of the North Cascades (Climate Division 5).
Altitude (m) and distance (km) from South Cascade Glacier are indicated after each station name.
Locations of the five climate stations are shown in Figure 1.

consistent with our observations of steadily decreasing summer balance on South Cascade Glacier since 1977 and supports the concept that the summer ablation on a glacier in a temperate maritime regime is coupled to the regional summer temperature. However, except for Stampede Pass, the average winter precipitation does not show any evidence for a step-like change similar to that observed in the South Cascade Glacier winter mass balance or the snow course measurements, so the link between winter snow accumulation and regional winter precipitation is not as clear.

## Discussion

Winter snowpack precipitation in the Washington Cascades, as indicated by either snow course or glacier mass balance measurements, underwent an abrupt decrease between 1976 and 1977, and has remained at about the new lower level since 1977. However, because this same decrease is not evident in the climate station winter precipitation, which is total precipitation regardless of form (rain or snow), it appears that the snowpack in the Washington Cascades must have decreased because a change in conditions prevented snow from accumulating.

Rising winter temperatures could be one such condition, since they would cause not only more precipitation to fall as rain rather than snow but also more mid-winter melting of snow (enough to cause runoff, not just refreezing). However, the fact that a step change occurred only in winter snow accumulation and not in regional winter temperature indicates that either other processes are involved or the overall mechanism is simply very sensitive to small perturbations, too small to be evident in regional climate data.

Neither of the trends observed at South Cascade Glacier, decreased winter accumulation or increased summer ablation, is conducive to glacier growth. The present trend is clearly away from an ice-age type of climate.

More important, however, regardless of the cause of observed trends, the data clearly demonstrate that a glaciologically significant long-term change in snow precipitation can occur very rapidly — in as short an interval as 1 year, much more rapidly than changes in temperature. Similar conclusions about extremely rapid transitions in accumulation rate from glacial to interglacial conditions, possibly in as little as 1 to 3 years, have been deduced from deep ice cores recently drilled in Greenland (Alley *et al* 1993).

Mass balance measurements on a glacier are, in effect, a direct measure of the particular combination of climate conditions, whatever they may be, that lead to or away from an ice-age type of climate. Our data indicate that such "glacial climate" can vary rapidly.

## Conclusions

- Winter snowpack in the Washington Cascades underwent an abrupt decrease between 1976 and 1977 and has remained at about the new, lower level since 1977.
- This decrease occurred because of a change in conditions that prevented snow from accumulating, rather than because of a change in total regional winter precipitation.
- The long-term trends at South Cascade Glacier are decreased winter accumulation and increased summer ablation. Neither is conducive to glacier growth, so the current trend in the Pacific Northwest is clearly away from an ice-age type of climate.
- A glaciologically significant long-term change in snow precipitation can occur rapidly — in as short an interval as 1 year — much more rapidly than changes in temperature.

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