Glacier Mass Balance

The purpose of this exercise is to illustrate features about glaciers mass balance and changes in glacier geometry. The glacier of interest here is South Cascade Glacier located on the crest of the North Cascade Range of Washington. It takes about 2.5 - 3 hours to drive to the nearest trailhead from Seattle. The glacier is SE of Mt. Baker and N of Glacier Peak and is within the Skagit River drainage basin. Just on the other side of the crest, water flows to Lake Chelan in eastern Washington and then to the Columbia River.

South Cascade Glacier has the longest history of mass balance measurements in North America and second longest in the world after Storglaciären in Sweden. Mark Meier initially selected South Cascade for long-term study in 1958 after reviewing a number of other candidate glaciers. Favorable features of the glacier (see attached figures) include 1) the glacier geometry is simple and almost all parts of the glacier are accessible; 2) not too large, about 4 km^2 when the study started (note the gauging station at the end of the lake, 3) the glacier is relatively easily accessible by trail; and 4) the glacier resides in a hydraulically well-defined basin. Since 1958, the glacier has been the site of many studies on mass balance, ice flow, and glacier hydrology. As part of the basic monitoring program, yearly measurements are made of mass balance, terminus change, and surface topography. Hourly measurements are made of the weather, and runoff. This is one of 3 sites in the US measured in detail by the US Geological Survey.

A few articles on the glacier include:

Meier, M.F., Tangborn, W.V., Mayo. L.R., and Post, Austin, 1971. Combined ice and water balance of Gulkana and Woverine Glaciers, Alaska, and South Cascade Glacier, Washington, 1965 and 1966 water years. U.S. Geological Survey Professional Paper 715-A, 23 p. The nitty gritty of mass balance calculations. Not suitable for children or young adults.

Meier, M.F., and Tangborn, W.V., 1965. Net budget and flow of South Cascade Glacier, Washington. Journal of Glaciology, 5(41), 547-566. This paper in many ways set the stage for how we think about alpine glaciers. Often referenced in textbooks.

The Krimmel series of annual reports starting in 1989, the most recent of which is, Krimmel, R.M. 1999. Water, Ice, Meteorological and Speed Measurements at South Cascade Glacier, Washington, 1998 balance year. US Geological Survey Water-Resources Investigations Report 99-4049. 36 p. Good overview of mass balance methods combining traditional and modern methods, with up to date data for the basin.

Reports will be typed (font 11 pt and larger) and each answer will follow the numbering system of the questions and be in consecutive order. Graphs need to be adequately labeled including axis labels with units. All features in a graph or drawing must be identified. Neatness counts and all pages need to be stapled.

PART I

Field measurements of mass balance rest on knowing the density of the near surface material and the depth of change. For a winter snow pack, a density profile might look like that in the table. Please read it from top to bottom and from left to right.

Depth cm	Density g cm^{-3}		Depth cm	Density g cm^{-3}
10	0.418		3	0.9
10	0.427		2	0.490
2	0.9		2	0.9
10	0.395		10	0.554
10	0.468		10	0.560
10	0.475		10	0.565
10	0.487		9	0.571
10	0.500		2	0.9
8	0.503		4	0.580

This table lists the density of the snowpack at depth increments found on May 1. A 10-cm long snow sampler was used. Ice layers were encountered and the sampler could not be driven through them. The first increment is at the surface and the last increment is the snow layer sitting on the firn surface. These data represent the winter accumulation at that point.

1. (3 pts) When this pit was dug on May 1, the whole snowpack depth was isothermal at 0^oC. Briefly explain the presence of the ice layers and how they might have formed.

2. (5 pts) Plot the snowpack density as a function of depth. Use the surface as 0 and positive numbers for the depth. Describe the trend of density with depth, ignoring the ice layers, and speculate on why.

3. (3 pts) What is the winter balance, in m weq? Assume the density of water is 1 g cm^{-3}. What is the mean density of the snowpack?

4. (5 pts) If the snowpack depth, at this same point, remaining at the end of the summer is 20 cm with a density of 0.6 g cm^{-3}, what is the net balance at that point and what is the summer balance?

Part II

5. (4 pts) Examine the two net balance maps of South Cascade Glacier for the years 1965 and 1966. Contour the position of the equilibrium line for each map. Do not attempt to achieve every little wrinkle. Turn in the maps for this answer. What is the ELA for each year? What can you immediately infer from ELA about the net mass balance for the two years?

6. (6 pts) Compile a histogram for each year with the net mass balance on the x-axis and altitude on the y-axis. Calculate the average balance for each contour interval and plot it at those intervals. On the same graphs, using the same y-axis, compile a histogram of glacier area with elevation. To estimate the area for each contour interval first calculate the average width -- the average length of the two contour lines that bound the interval. The average length of the interval is equal to the average of 3 lengths, one at each edge of the glacier and one midway between. For consistency between people, set the pair of dividers to 100 m length. (NB. This isn't the most accurate way of doing this but for our purposes it is fine) You can assume that the area of the glacier or between intervals does not change between the years so the area-altitude histogram has to only be calculated once, but plotted twice. Complete your plots for only the trunk glacier, ignoring both the tributary glacier on the west side and the ice patch on the east side. Assume that the glacier terminus is at 1650 m and the top of the glacier is 2150 m (the limit of our measurements).

7. (6 pts) From the plots you constructed in (6), determine the net mass balance for each year.

8. (2 pts) Approximately what altitude does the ELA have to be at for the glacier to be in equilibrium?

Part III

Examine the two figures of South Cascade Glacier and the longitudinal profile of the glacier. The lake, South Cascade Lake, did not exist in 1928 when the glacier was almost to the present day position of the gauging station. Note that the profile is a drawing to scale.

On both figures, we can see the snowline. Note the dates of the photos. Clearly they are at the end of the season. We can assume that the snowline is a close approximation of the annual equilibrium line.

9. (2pts) Under what condition is the snowline not the equilibrium line?

10. (3 pts) Draw on each photograph, in colored pencil or ink (not black) the boundary between the accumulation and ablation zones. Ignore the small snow and ice patches away from the main glacier. During the time that has elapsed between the two dates has the equilibrium line remained stationary, or moved to higher or lower elevations? Please note that there may be small year-to-year variations in the ELA without a significant change in ELA. For the purpose of this exercise, you are not concerned with the specific details of the exact ELA position, rather whether the ELA has changed significantly.

11. (1pt) In a different colored pencil or ink delineate the terminus in the 1983 photo. In no place is the glacier covered with debris.

12. (3 pts) If the straight-line width of the glacier at the snowline in 1983 is 2 km, roughly how far has the glacier retreated since 1960? Show your work. This is only a rough estimate since the scale in the photograph in not consistent for oblique photos.

13. (5 pts) Please describe how the glacier has thinned over the whole glacier and retreated, giving features on both photos as evidence. Denote the features on the figure with numbers and lines (or arrows) and refer to these in the text. Include on the longitudinal profile on the page with the 1960 photo your estimate of the surface of the glacier in 1983.

14. (5pts) Based on your answers in (10) and (13) what is going on climatically? They seem to provide contradictory answers. Or do they?

15. (3pts) Attached is the mass balance data from South Cascade Glacier (Krimmel, 1999). Put these values into a spreadsheet with the columns in the following order: Year, Summer Balance, Winter Balance, Net Balance. Don't forget the units. Krimmel provides winter [b_m(s)] and net values [b_n], please calculate summer values. Print out a copy of the table for inclusion in your report. Does the data here and the plots in the following questions cause you to revise your answer in the previous question?

16. (2pts) Before we get started, the unit Krimmel uses for balance is meters. Meters of what? Krimmel doesn't specifically say, and he should. But what is your guess based on the class presentation of mass balance data?

17. (5pts) Plot the values in the table onto a single plot. Do you note any trends in any of the 3 traces? Identify a year of net positive mass balance, a year of net negative mass balance, and a year where the glacier mass change is near equilibrium. Is summer or winter a greater determining factor in the net mass balance? Discuss your results.

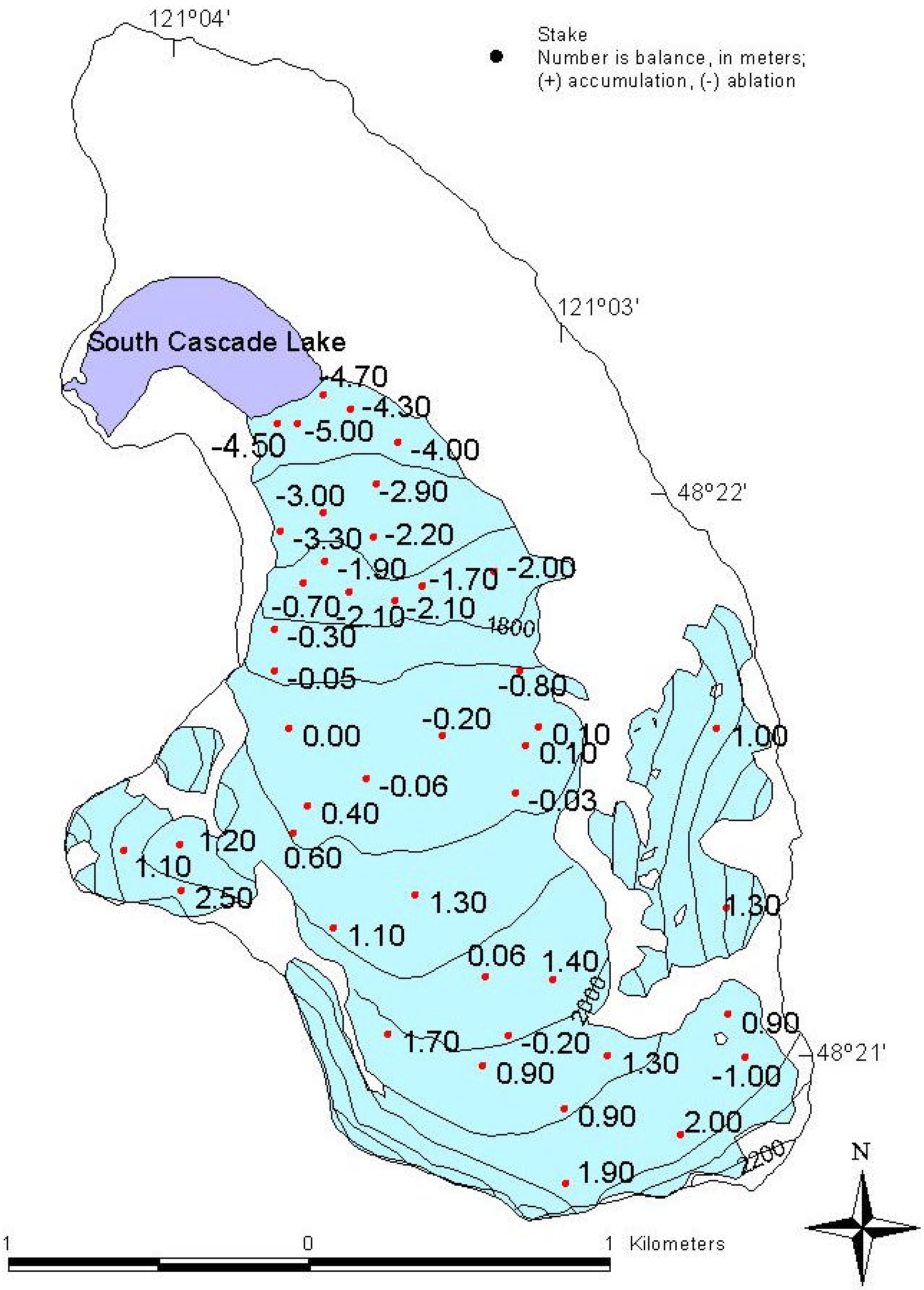
18. (3pts) Sum the values of net balance for a summation curve. That is, for 1959, the value for that year is the starting value of 0.70. For 1960, it is the sum of the values for 1959 and 1960, for 1961 it is the sum of the values for 1959,1960, and 1961, and so on. This technique allows you to quickly see if the glacier is increasing or decreasing mass. Show your plot.

19. (3pts) What is the overall mass change for South Cascade over the period of record? What is the mass change between the years photographed from 1961 through 1983? Briefly discuss this value in relation to the change in glacier position identified in question 12 and the change in glacier geometry in question 13.

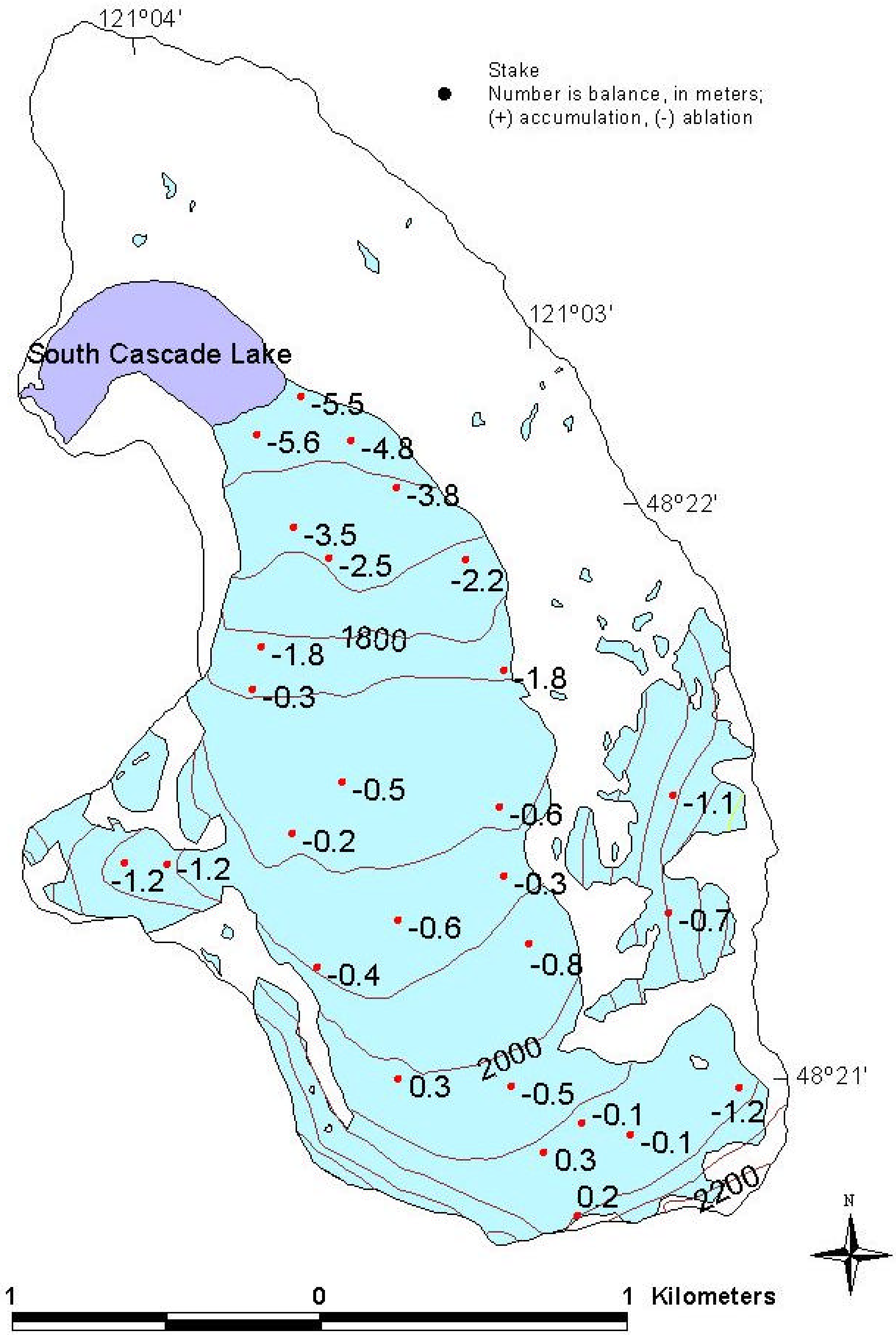
20. (5pts) Since the photo in 1983 what is the mass change? From this value, what happened to the glacier since the photo taken in 1983?

For your information there are two obvious moraines, one lateral and several terminal "push moraines".

South Cascade Glacier
Total mass net balance, November 2, 1965

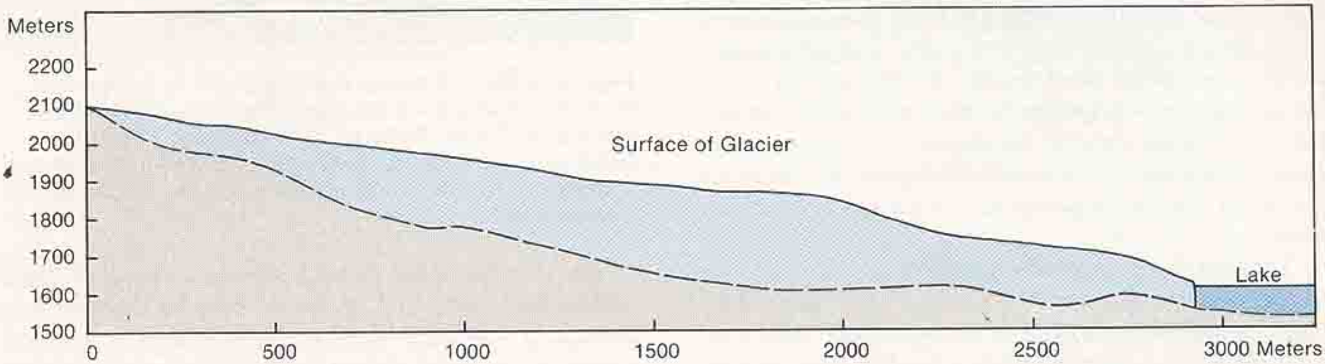


South Cascade Glacier
Total mass net balance, October 16,1966

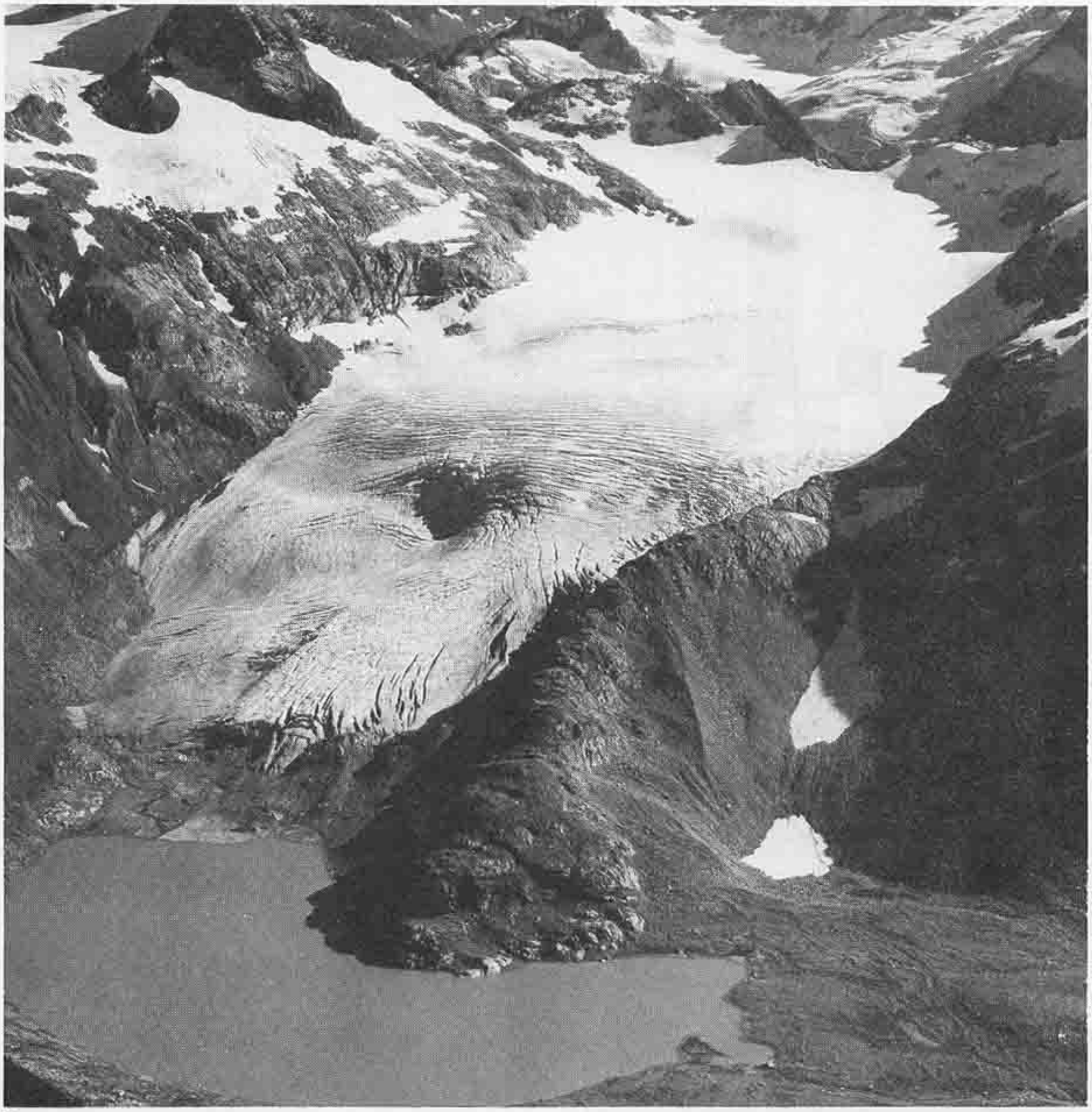


A

Oblique aerial photographs of the South Cascade Glacier, Washington. (*A*) September 27, 1960; Neg. No. FR6025-50. (*B*) October 10, 1983; Neg. No. 83R1-188. (Courtesy of Andrew G. Fountain, U.S. Geological Survey, Tacoma, Washington.)



Longitudinal profile of the South Cascade Glacier during the 1965-66 budget year. No vertical exaggeration. (Based on U.S.G.S. Professional Paper 715-A, 1971.)



B

TABLE 16. Mass balance time series at South Cascade Glacier

[For years 1986-91, net balance, $\bar{b}_n$, was determined by the index regression method discussed in Krimmel (1989) and has an error of 0.23 m. For years 1959-64 and 1968-82, winter balance, $\bar{b}_m(s)$, was determined from unpublished snow accumulation maps and has an error of 0.12 m. For years 1983-1991, $\bar{b}_m(s)$ was determined using the index station regression discussed in Krimmel (1989) and has an error of 0.23 m. For years 1992 to 1998, $\bar{b}_n$ and $\bar{b}_m(s)$ were determined by the grid-index method (Krimmel, 1996b)]

Year[1]	$\bar{b}_m(s)$ (meters)	$\bar{b}_n$ (meters)	Year[1]	$\bar{b}_m(s)$ (meters)	$\bar{b}_n$ (meters)
[2]1959	3.28	0.70	1979	2.18	-1.56
1960	2.21	-0.50	1980	1.83	-1.02
1961	2.40	-1.10	1981	2.28	-0.84
1962	2.50	0.20	1982	3.11	0.08
1963	2.23	-1.30	1983	1.91	-0.77
1964	3.25	1.20	1984	2.38	0.12
[3]1965	3.48	-0.17	1985	2.18	-1.20
1966	2.47	-1.03	1986	2.43	-0.71
[4]1967	3.29	-0.63	1987	1.88	-2.56
[5]1968	3.00	0.01	1988	1.89	-1.64
1969	3.17	-0.73	1989	2.35	-0.71
1970	2.41	-1.20	1990	2.80	-0.73
1971	3.51	0.60	1991	3.35	-0.20
1972	4.27	1.43	1992	1.91	-2.01
1973	2.21	-1.04	1993	1.98	-1.23
1974	3.65	1.02	1994	2.39	-1.60
1975	3.06	-0.05	1995	2.81	-0.69
1976	3.53	0.95	1996	2.94	0.10
1977	1.57	-1.30	1997	3.71	0.63
1978	2.49	-0.38	1998	2.76	-1.86

1 Balance year (for example, 1959 is from the minimum balance in 1958 to the minimum balance in 1959, and the 1959 $\bar{b}_m(s)$ occurred in the spring of 1959)

2 $\bar{b}_n$ for years 1959 through 1964 from Meier and Tangborn (1965)

3 Years 1965 through 1966 from Meier and others (1971)

4 Year 1967 from Tangborn and others (1977)

5 $\bar{b}_n$ for years 1968 through 1985 from Krimmel (1989)

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