arrangement of the molecules and/or monomer segments at the shearing interface occurs during continuous sliding over large distances (many molecular dimensions)—that is, steady-state conditions do not occur instantaneously or even after a short shearing distance. Despite the apparent complexity of the adhesion and friction results, a fairly consistent and rational picture nevertheless emerges that can be understood in terms of the changing molecular configurations and motions of polymer chains and their segments at adhering and shearing junctions.

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Rapid Wastage of Alaska Glaciers and Their Contribution to Rising Sea Level

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We have used airborne laser altimetry to estimate volume changes of 67 glaciers in Alaska from the mid-1950s to the mid-1990s. The average rate of thickness change of these glaciers was −0.52 m/year. Extrapolation to all glaciers in Alaska yields an estimated total annual volume change of −52 ± 15 km^3/year (water equivalent), equivalent to a rise in sea level (SLE) of 0.14 ± 0.04 mm/year. Repeat measurements of 28 glaciers from the mid-1990s to 2000–2001 suggest an increased average rate of thinning, −1.8 m/year. This leads to an extrapolated annual volume loss from Alaska glaciers equal to −96 ± 35 km^3/year, or 0.27 ± 0.10 mm/year SLE, during the past decade. These recent losses are nearly double the estimated annual loss from the entire Greenland Ice Sheet during the same time period and are much higher than previously published loss estimates for Alaska glaciers. They form the largest glaciological contribution to rising sea level yet measured.

Mountain glaciers (*1*) constitute only about 3% of the glacierized area on Earth, but they are important because they may be melting rapidly under present climatic conditions and may therefore make large contributions to rising sea level. Previous studies (*2–7*), based on observations and model simulations of glacier mass balance, estimated the contribution of all mountain glaciers to rising sea level during the last century to be 0.2 to 0.4 mm/year. The range of uncertainty is large, and it stems from insufficient measurements of glacier mass balance: Conventional mass balance programs are too costly and difficult to sample adequately the >160,000 glaciers on Earth. At present, there are only about 40 glaciers worldwide with continuous balance measurements spanning more than 20 years (*8*). High-latitude glaciers, which are particularly important because predicted climate warming may be greatest there (*7*), receive even less attention because of their remote locations. Glaciers that are monitored routinely are often chosen more for their ease of access and manageable size than for how well they represent a given region or how large a contribution they might make to changing sea level. As a result, global mass balance data are biased toward small glaciers (<20 km^2) rather than those that contain the most ice (>100 km^2). Also, large cumulative errors can result from using only a few point measurements to estimate glacier-wide mass balances on an individual glacier.

Glaciers in Alaska and neighboring Canada (labeled "Alaska" glaciers herein) cover 90,000 km^2 (*9*), or about 13% of the mountain glacier area on Earth (*10*), and include some of the largest ice masses outside of Greenland and Antarctica. Additionally, many of these glaciers have high rates of mass turnover. However, they are underrepresented by conventional mass balance studies, which include only three or four long-term programs on relatively small glaciers. Dyurgerov and Meier (*5*), by necessity, extrapolated the data from these few small glaciers to estimate the contribution of all Alaska glaciers to sea-level change, and they specifically pointed to the need for further data in this region, especially on the larger glaciers. Here, we use airborne laser altimetry to address this problem. We have measured volume and area changes on 67 glaciers, representing about 20% of the glacierized area in Alaska and neighboring Canada, and we use these data to develop new estimates of the total contribution of Alaska glaciers to rising sea level.

Our altimetry system consists of a nadir-pointing laser rangefinder mounted in a small aircraft and a gyro to measure the orientation of

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the ranger, and uses kinematic Global Positioning System (GPS) methods for continuous measurement of aircraft position (*11*). Profiles are flown along centerlines of the main trunk and major tributaries of a particular glacier at altitudes of 50 to 300 m above the surface; in some cases, more than one profile is flown to determine cross-glacier variations in elevation change. These profiles are compared to contours on 15-min U.S. Geological Survey (USGS) and Canadian Department of Energy, Mines, and Resources topographic maps made from aerial photographs acquired in the 1950s to early 1970s (depending on location). Differences in elevation are calculated at profile/contour line intersection points. If more than one profile is flown along a given glacier, averages are taken at each elevation and applied to the appropriate areas. Digital elevation models (DEMs) derived from the 15-min maps are used to determine the area-altitude distribution of each glacier at the time of mapping. We calculate volume changes by assuming that our measured elevation changes apply over the entire area within the corresponding elevation band. These changes are then integrated over the original area-altitude distribution of the glacier. Glacier-wide average thickness changes are found by dividing the total volume change by the average of the old and new glacier areas (*12*). Changes in glacier length (and area) are determined by comparing the mapped terminus with that determined from our measurements.

We have estimated volume and area changes during the period from about the 1950s to 1993–1996 (the "early period") for the 67 glaciers, which we have categorized into seven geographic regions (Fig. 1). Our sample includes 12 tidewater, 5 lake-terminating, and 50 land-terminating glaciers (table S1). Three of the land-terminating glaciers have historically exhibited surge behavior. Since 1999, we have reprofiled 28 glaciers, covering about 13% of the glacierized area in Alaska, that were first profiled during 1993–1996. Reprofiling involves flying the aircraft along the path of an earlier profile, repeatable to within a transverse distance of ±15 to 25 m, using differential GPS navigation. We try to fly the new profile at the same time of the year as the older profile (usually within the same week). Comparisons are then made at the crossing points between the old and the new profiles, providing measurements of glacier change during the intervening 5 to 7 years (the "recent period") (*13*).

Some of the sources of error in our results have been discussed previously (*11, 14–16*). For early-period comparisons, the primary errors are those in the topographic maps. These errors can be large, especially in accumulation areas where photogrammetric contrast is poor or in locations with poor geodetic control. Errors in the recent-period measurements are dominated by errors in the areal extrapolation of one or a few altimetry profiles across an entire glacier surface. Altimetry system errors, which depend on the orientation of the aircraft relative to the glacier surface, are generally small. We have quantified the random component of map, areal extrapolation, and altimetry system errors for each glacier in our sample (table S1). Systematic offsets may substantially increase these errors in some cases, but they are difficult to quantify for each glacier. Substantial early-period measurement errors may also occur because we do not always know the precise dates at which the aerial photographs used to create the maps were acquired (*17*).

Most glaciers in our sample thinned over most of their lengths during both the early and recent periods (Fig. 2), while fewer than 5% thickened. Some thinned drastically, in particular rapidly retreating tidewater glaciers such as Columbia Glacier, which, near the terminus, thinned 300 m during the early period and 150 m during the last 5 years (*18*). Tazlina and Turquoise glaciers are more representative of typical valley glaciers; these thinned at the terminus by 100 to 150 m during the early period and by about 20 m during the ~1995 to 2001 period.

These thickness changes translate to volume changes by integration over the area-altitude distribution, which describes the total glacier area in each elevation bin (typical area-altitude distributions are shown in fig. S1). The glacier-wide average rate of thickness change (table S1) is the volume change divided by the average of the old and new glacier areas and is directly comparable with annual mass balance measurements from conventional measurement programs (here we use ice equivalent units instead of the conventional water equivalent units, because we have directly measured changes in ice thickness). We found that most glaciers during the early and recent periods had negative thickness changes, indicating overall surface lowering (Fig. 3). Comparing only those glaciers for which we have early- and recent-period measurements shows that, during the past 5 to 7 years, glacier thinning was more than twice as fast (–1.8 m/year) as that measured on the same glaciers from the mid-1950s to the mid-1990s (–0.7 m/year). This increase in average thinning rate exceeds our error limits and is significantly larger than typical variations in 5-year averages of long-

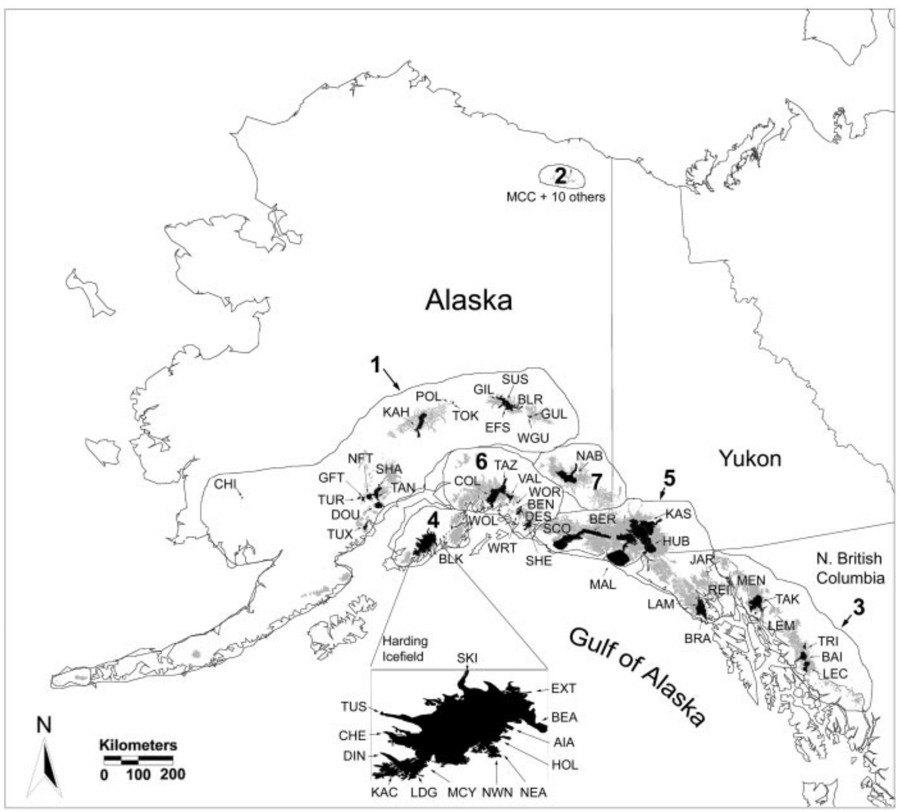
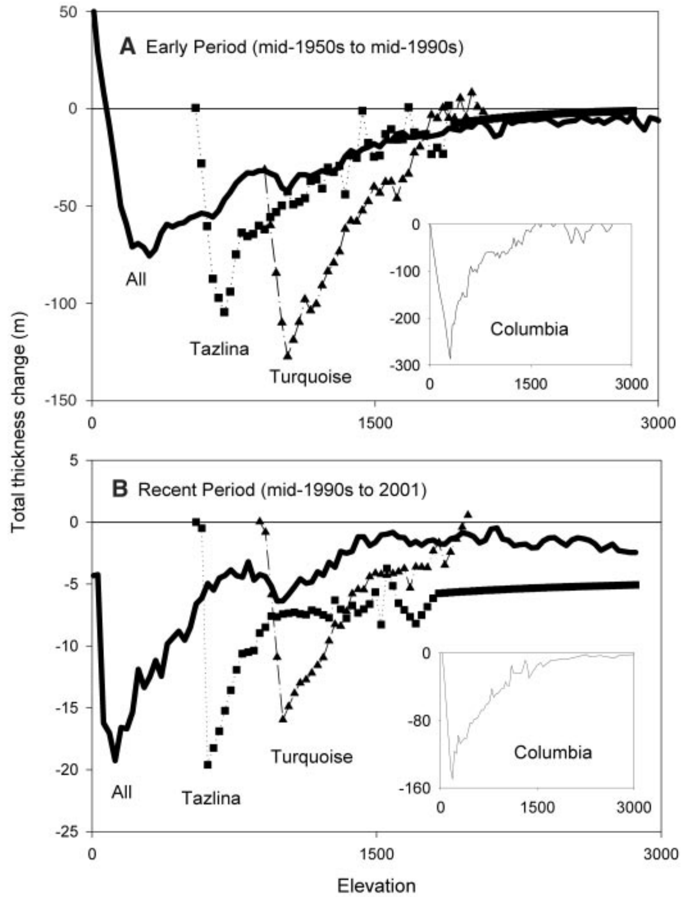


Fig. 1. Location of 67 surveyed glaciers, shown in black, separated into seven geographic regions: 1, Alaska Range; 2, Brooks Range; 3, Coast Range; 4, Kenai Mountains; 5, St. Elias Mountains (includes Eastern Chugach Range); 6, Western Chugach Range; and 7, Wrangell Mountains. Glacier names associated with three-letter codes are in table S1. Fifty-five glaciers are located entirely in Alaska, 11 span the border between Alaska and Canada (Yukon Territory and northwest British Columbia), and one is entirely located in Yukon Territory. The total surface area of glaciers in our sample is about 18,000 km^2; the total area of glacier ice in Alaska, Yukon, and northwest British Columbia (north of 54°N latitude), shown in gray, is 90,000 km^2. Glaciers outside the seven regions account for 0.2% of the total glacier area.

term mass balance records of Alaska glaciers. Some conventional mass balance studies have also shown a similar trend toward more negative balances over the past decade (*19*).

To estimate the contribution of Alaska glaciers to rising sea level, we extrapolated our measured thickness changes within each region to all unmeasured glaciers in that region. Extrapolations were made using a single thickness change profile for a region (solid black curves in fig. S1), calculated by averaging the thickness changes of all measured glaciers at each elevation band within that region. The total extrapolated volume change was found by integrating the average measured thickness changes over the area-altitude distribution of all unmeasured glaciers in that region (solid blue curves in fig. S1) (*20*). This extrapolated value was then added to the measured changes to give a total volume change in each region. Columbia, LeConte, Hubbard, and Taku glaciers were considered as separate "regions" because they have recently been subject to tidewater glacier dynamics, characterized by large instabilities. An estimate of the error in this extrapolation was obtained by considering the total of the errors for each measured glacier (table S1), the scatter of the measured changes within each elevation band in a given region (gray bars in fig. S1), and the differences between two methods of performing the extrapolation—one that weights the average thickness changes by area and one that does not. We combined these possible errors with estimated systematic errors to obtain our total extrapolation error (*17*).

Fig. 2. Thickness change versus elevation during the early (**A**) and recent (**B**) periods. "All" denotes average of all glaciers (not including Columbia, Hubbard, LeConte, and Taku tidewater glaciers); Tazlina is a large valley glacier; Turquoise is a small valley glacier; and Columbia is a large, retreating tidewater glacier (plotted on a separate axis because of exceptionally high rates of thinning). The profiles show substantial thinning at low elevations, with a nearly exponential decrease in thinning up to higher elevations, where the thinning approaches zero. The sharp reduction in thinning at low elevations occurs because the thin ice that existed at the terminus was removed completely as the terminus retreated, leaving unchanging bedrock that was later profiled.



We estimated the total annual volume change of Alaska glaciers for the early and recent periods to be –52 ± 15 km^3/year and –96 ± 35 km^3/year water equivalent, equivalent to a rise in sea level (SLE) of 0.14 ± 0.04 and 0.27 ± 0.10 mm/year, respectively (*21*). Glaciers bordering the Gulf of Alaska in the Chugach and St. Elias Mountains and Coast Ranges made the largest contribution of all Alaska glaciers. These glaciers are large, and they have very high rates of mass turnover due to their maritime environment. It is interesting to note that about 75% of the total measured volume change over both periods is accounted for by a few large and dynamic glaciers (Columbia, Malaspina, Bering, LeConte, and Kaskawulsh glaciers).

Our estimates of the contribution from Alaska glaciers to rising sea level during the early period (0.14 ± 0.04 mm/year) are larger than the 0.02 mm/year estimated by Dyurgerov and Meier (*5*) by a factor of 7 for the period from 1961 to 1990. This is not surprising because these authors used only data from Wolverine Glacier to represent the glaciers bordering the Gulf of Alaska (*22*). The USGS mass balance program reported an average thickness change of –0.18 m/year (ice equivalent) for Wolverine Glacier, but most of the Gulf of Alaska glaciers that we measured had thinning rates that were much larger than this. Also, Dyurgerov and Meier used a slightly smaller value (75,000 km^2) for the total area of glacier ice in Alaska.

Our ~1995 to 2001 estimated annual volume loss is nearly twice that estimated for the entire Greenland Ice Sheet during the same period [–51 km^3/year or 0.14 mm/year SLE (*23*)]. Our results indicate that Alaska glaciers contributed about 9% of the observed rate of sea-level rise [1.5 ± 0.5 mm/year (*7*)] over the past 50 years and about 8% or more of the increased rate of sea level rise [possibly as large as 3.2 mm/year (*24*)] over the past decade or so.

Most (but not all) glaciers in our sample retreated. The total area of the measured glaciers decreased 0.8% (131 km^2) during the early period and decreased 0.4% during the past 5 to 7 years (table S1). It is sometimes assumed that such changes in glacier length and area can be used to infer changes in glacier mass balance and response to climate, with retreat indicating an overall loss in glacier volume. However, we have found that during both the early and recent periods, about 10% of the sampled glaciers either advanced while simultaneously thinning or (during the early period) retreated while thickening (table S1). Even for those glaciers with the more "normal" response of retreat while thinning, we found a very low correlation between the rate of length change and the rate of thickness change. This indicates that flow dynamics must be taken into consideration when examining changes in glacier length (and area) at time scales of ~10 to 40 years. In the approximation that glacier response to a change in climate can be characterized by a single time constant (*25, 26*), our results suggest that the response times of most glaciers in our sample are greater than ~40 years. Caution is evidently required when making inferences about mass balance from changes in glacier length (or area) alone.

The large standard deviation of the average rates of thickness change within some regions (fig. S1) indicates that a number of factors must control glacier mass balance, including local climate and glacier geometry. Our geographical classification of glacier regions does not consider regional climatic zones. For instance, we examined recent period changes of a subset of five glaciers in the southern Alaska Range. These glaciers are located within a radius of 30 km, and if they were to experience similar climate conditions, then their mean thickness changes would be dictated by their area-altitude distributions alone, at least over time periods

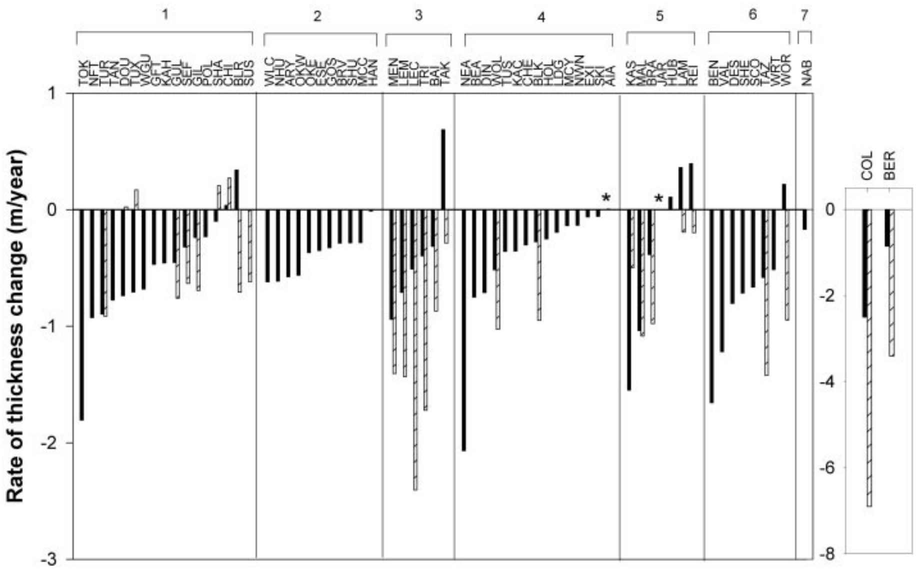


Fig. 3. Rate of glacier-wide average thickness change of 67 glaciers in Alaska during the early period (~1950 to 1995; solid black bars) and 28 glaciers during the recent period (~1995 to 2001; hatched bars). Glaciers (see table S1 for full names) are arranged according to their regions as given in Fig. 1; two large glaciers are plotted separately because of their exceptionally high rates of thinning. Asterisks denote thickness changes not resolved by the scale of the plot.

that are short relative to mass redistribution by flow. For these glaciers, the average thickness change showed no significant correlation with the area-weighted mean elevation. This suggests that climate variability occurs on a small spatial scale, such as with distance from the coast. In contrast, Rabus and Echelmeyer (*16*) found that, in a similar-sized region, elevation changes on one glacier in the Brooks Range (McCall Glacier) were representative of other glaciers.

Our observations of rapid glacier wastage during the early period, and of increased rates of thinning during the recent period, may be linked to climate warming during the past several decades (*7*), but other factors are involved. The large rates of thinning we observed for some tidewater glaciers are due to their unstable dynamics of rapid retreat and slow advance and are not simply linked to climate warming, although retreat is likely initiated by negative mass balance. Periodic thickness changes characteristic of surge-type glaciers are also not simply linked to climate warming. For example, there was a large downglacier ice flux during the 1993–1995 surge of Bering Glacier, leading to a thickening on the eastern segment of the piedmont lobe, but overall the glacier thinned from 1972 to 1995. A few glaciers in our sample thickened, and in most cases these were located near other glaciers that thinned; almost all of these anomalous glaciers are tidewater or paleo-tidewater (e.g., Hubbard and Taku glaciers) and are probably in a stage of advance associated with unstable tidewater glacier dynamics. Nevertheless, nearly all of the measured glaciers experienced increased thinning rates during ~1995 to 2001 relative to the ~1950 to 1995 period. This is consistent with the results of conventional mass balance studies on Gulkana and Wolverine (*27*), McCall (*16*), Taku (*28*), and Lemon Creek (*29*) glaciers, which show increased negative balances during the past decade.

Compared with the estimated inputs from the Greenland Ice Sheet (*23*) and other sources (*2, 7*), Alaska glaciers have, over the past 50 years, made the largest single glaciological contribution to rising sea level yet measured. We suggest that other glacierized regions, with the possible exceptions of West Antarctica and Patagonia, may lack sufficient ice mass and/or mass turnover to produce sea-level contributions of equivalent magnitude during these time periods. Mountain glaciers may be contributing a substantial fraction of the increased rate of sea-level rise suggested by satellite observations from 1993 to 1998 (*24*). Although the large glaciers bordering the Gulf of Alaska are the most important in determining the sea-level contribution, the different rates of thinning observed in the various Alaska regions may be important in characterizing patterns of climate change.

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12. We define the area of a glacier as its ice extent within its hydrologic basin, except for the very large Bering/Bagley and Malaspina/Seward glaciers, where we limit the volume change calculations to the measured elevation ranges (about 1500 m and 2300 m, respectively; see fig. S2).
13. Crossing points between the old and new profiles are determined in three steps: (i) a single elevation measurement (Z_1) on the old profile is selected; (ii) elevation measurements from the new profile that fall within a 20- to 60-m (transverse) by 3-m (longitudinal) rectangular window centered on this old profile data point are designated as crossing points, and are averaged to a single new elevation (Z_2); (iii) the elevation change is calculated as $Z_2 - Z_1$. These three steps are repeated for all elevation measurements on the old profile. Typically we find 10,000 to 20,000 crossing points distributed over the elevation of a glacier. This method assumes that transverse variations in elevation change are small within the averaging window.
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17. Methods, including a detailed description of our error analysis, can be found as supporting online material at *Science* Online. Note that we do not include the viscoelastic response of the solid earth under the changing ice loads.
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21. Although the measured glaciers had a rate of thickness change during the recent period that was nearly three times the rate measured during the early period, the increase in the rate of loss is smaller when we extrapolate to all glaciers because of the regional area-altitude extrapolation methods used. Also, the uncertainty in the recent period extrapolation is larger than for the early period because there are fewer measured glaciers during the recent period.
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Supporting Online Material
www.sciencemag.org/cgi/content/full/297/5580/382/DC1
Supporting Text
Figs. S1 and S2
Table S1

3 April 2002; accepted 5 June 2002

Freshening of the Ross Sea During the Late 20th Century

S. S. Jacobs,* C. F. Giulivi, P. A. Mele

Ocean measurements in the Ross Sea over the past four decades, one of the longest records near Antarctica, reveal marked decreases in shelf water salinity and the surface salinity within the Ross Gyre. These changes have been accompanied by atmospheric warming on Ross Island, ocean warming at depths of ~300 meters north of the continental shelf, a more negative Southern Oscillation Index, and thinning of southeast Pacific ice shelves. The freshening appears to have resulted from a combination of factors, including increased precipitation, reduced sea ice production, and increased melting of the West Antarctic Ice Sheet.

General circulation models of a moderately warmer climate typically show larger changes at high latitudes, such as increased precipitation and ice sheet growth, a reduced but possibly thicker sea ice cover, and weaker deep ocean convection (*1*, *2*). A freshening of 0.001 per year (a^{-1}) in Antarctic intermediate water (AAIW) in the South Pacific over ~25 years, coincident with a salinity increase at shallower depths, has been attributed mainly to an intensification of the atmospheric hydrological cycle (*3*). That salinity decrease implies a large increase in the freshwater flux at high southern latitudes where intermediate water is formed. Changes in precipitation minus evaporation may be inferred from mixed layer salinity, but near-surface salinity variability is high in regions where sea ice forms and melts every year. The production of sea ice adds brine to waters over the continental shelf, and its northward export and melting lowers the salinity of the upper ocean between the shelf and Polar Front. A slower stage of the hydrological cycle returns fresh water to the ocean by the melting of ice shelves and icebergs. Climatic perturbations of these processes and of the upwelling rate of deep water can alter the salinity of waters that originate in the Southern Ocean.

In the Pacific sector of the Southern Ocean, sea ice formation and export is strongest in the southwest Ross Sea (Fig. 1), where persistent winter polynyas are located near the Ross Ice Shelf and Victoria Land coast (*4*, *5*). A substantial decrease in shelf water salinity has occurred in that region over the past four decades (Fig. 2), extending eastward near the ice front (Fig. 3A) and throughout the western continental shelf (*6*). Formed at the sea surface in winter, the shelf water is vertically stabilized by salinities that increase with depth, but the entire water mass has shifted toward lower values since the 1960s. Although the saltiest water in the Southern Ocean has historically been found in the southwest Ross Sea, this lengthy decline has relocated that maximum to the Weddell Sea (*7*).

Sea ice production over the Antarctic continental shelf depends mainly on wind strength, air temperature, and shelf area. Lengthy wind measurements are lacking, but temperatures have risen ~1.0°C on Ross Island since 1957 (*6*). That is ~5% of the difference between the –20°C annual mean and the sea surface freezing point, which may thus account for a small fraction of the observed salt deficit. A concurrent northward advance of the Ross Ice Shelf covered ~6% of the open shelf region where sea ice can form, but any resulting decrease in sea ice production may have been partly compensated by more marine ice growth beneath a larger ice shelf (*8*).

The volume of sea ice exported from the continental shelf can be roughly estimated from ice thickness measurements (*9*) and mean National Centers for Environmental Prediction surface winds of ~6 m s^{-1} in the northwest sector since 1985 (*10*). This export is equivalent to a mean thickness of 2.5 ± 0.8 m a^{-1} over 9 months and a 400,000 km^2 shelf area, assuming a 10% uncertainty in ice and wind measurements and exit gate width. For comparison, shelf water freshening that resulted entirely from reduced sea ice production would require an export decline of ~3.1 m in recent decades. This seems unrealistic, because it would imply a large and undocumented reduction in wind strength, which in turn could result in thicker ice and a slower ocean circulation, with the latter likely to increase shelf water residence time and salinity.

A major decrease in sea ice production also appears inconsistent with reported increases in ice extent, ice concentration, and length of the sea ice season in the Ross Sea since 1978 (*11*, *12*). Those changes depend mainly on areas north of the continental shelf, however, and could mask a thinner ice cover resulting from changes in surface forcing. East of the Ross Sea, a larger atmospheric warming trend and substantial declines in sea ice extent and season have been documented over recent decades (*12*, *13*). Most of that sea ice change has occurred above the eastward-flowing Antarctic Circumpolar Current, but if the regional warming in that sector reduced ice production further south, it would have lowered the salinity of the westward coastal current.

The salinity of shelf water in the Ross Sea is less influenced by precipitation and local ice shelf melting than by sea ice export. For 8 to 9 months each year, most precipitation will also fall on sea ice that is advected off the continental shelf. Where that precipitation is sufficient to sink the ice freeboard, snow-induced sea ice production and brine drainage would cause a salinity increase in the water column. Net melting as high as 25 cm a^{-1} beneath the ~500,000-km^2 Ross Ice Shelf (*14*) would compensate for <20% of the brine derived from the sea ice cycle. Moreover, modeling sensitivity studies indicate that ice shelf melting would decrease in response to a weaker thermohaline circulation associated with lower salinity (*15*). Plausible changes in local precipitation and glacial ice melting therefore cannot explain the large decline in shelf water salinity.

The only other important sources of freshening for the Ross Sea continental shelf are waters imported by the coastal current and waters along the southern edge of the Ross Gyre. Evaluating salinity changes in these surface waters encounters problems of high spatial and temporal variability, along with sparse historical ocean measurements east of the Ross Sea. As an alternative, we have focused on salinity at the temperature minimum (T_{min}) within the Ross Gyre. The T_{min} is a well-defined subsurface feature in most off-

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