Thickening of the ice stream catchments feeding the Filchner-Ronne Ice Shelf, Antarctica

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[1] Earlier ice-sheet mass-balance estimates disagree with satellite-altimeter-measured thickening of the catchment area that feeds the Filchner-Ronne Ice Shelf, Antarctica. In an effort to reconcile these differences, we generated a new flux-gate mass-balance estimate, using improved elevation and velocity data. Our results show a 39 ± 26 Gton/yr thickening, whereas earlier flux-gate results indicated minor thinning. Our results are consistent with altimeter-derived estimates of elevation change. This suggests that altimeter-observed thickening on the East Antarctic plateau may be the result of some combination of a 20th Century accumulation increase and a continuing response to the ~50% accumulation increase that began in the early Holocene.

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1. Introduction

[2] While Antarctica's response to climate change is one of the major uncertainties in sea level projections for the next several centuries [*Church and Gregory*, 2001], significant progress is being made in understanding ice sheet's current mass balance. For example, satellite altimeters have measured an average 1.4 cm/yr thickening from 1992 to 2003 [*Davis et al.*, 2005]. East Antarctic thickening is partially offset by West Antarctic thinning [*Davis et al.*, 2005], largely in response to rapid thinning along the Amundsen Coast [*Rignot and Thomas*, 2002; *Shepherd et al.*, 2002]. Here we examine the mass balance of the ice-stream catchments feeding the Filchner-Ronne Ice Shelf (Figure 1), which comprise approximately 22% of the grounded ice sheet's area.

[3] In addition to satellite altimetry, ice sheet mass balance can be estimated by comparing an ice stream's annual discharge to the ocean (discharge flux) with the total annual accumulation over its catchment (accumulation flux). With this method, discharge flux is determined through a gate across the ice stream where ice velocity and thickness are known. An earlier application of this "flux gate" method to several of the ice streams in our study area suggested a net thinning of 3.6 ± 9.1 Gton/yr [*Rignot and Thomas*, 2002], whereas altimetry results show thickening [*Davis et al.*, 2005].

[4] To reconcile differences between previous estimates, we re-evaluated the mass balance of the Filchner-Ronne ice streams using the flux-gate method. In doing so, we improved ice-stream catchment delineations using new ICESat laser altimeter coverage that extends to 86°S. We also have determined the mass balance for Möllereistrom and Support Force ice streams as well as two smaller catchments near the Ellsworth Mountains (E1 and E2 in Figure 1). Inclusion of all adjacent catchments is an important element of our study because individual catchment errors cancel when results are summed over all catchments.

2. Mass Balance Estimates

[5] We used a new, 1-km resolution Antarctic DEM (J. L. Bamber, unpublished data) to determine the divides for a contiguous set of ice-stream catchments. While we evaluated the individual ice-stream catchments, we also consider the larger, multiple-ice-stream catchments referred to in other studies. Specifically, we examine basins J″K (Bailey, Slessor, Recovery, and Support Force), J′J″ (Foundation, Möllereistrom, Institute, and E2), and JJ′ (E1, Rutford, Carlson, and Evans) [*Giovinetto and Bentley*, 1985]. While this set of drainage basins is commonly used, the boundaries differ slightly among various studies. Our delineation of J″K and J′J″ includes the area traditionally included in these basins, whereas in JJ′ we neglect several small glaciers along the ice shelf's western edge.

[6] We assumed a ±5-km uncertainty in our estimates of the divide locations. This yields small errors for the largest basins (e.g., 5% for Recovery), but larger errors for the smaller basins (e.g., 50% for E1). Errors are small for the grouped catchments (e.g., 4% for J″K) since uncertainties along interior boundaries are eliminated. In general, our catchment boundaries are similar to those from other studies. A notable exception is that we estimate an ~75% larger catchment for Foundation Ice Stream and correspondingly smaller catchment for Support Force compared to earlier results [*Rignot and Thomas*, 2002].

[7] Two Antarctic accumulation maps have been produced using nearly all available accumulation measurements [*Giovinetto and Zwally*, 2000; *Vaughan et al.*, 1999]. While these maps are based on nearly the same sparsely sampled data, they rely on different interpolation methods, resulting in significant differences [*Giovinetto and Zwally*, 2000; *Vaughan et al.*, 1999]. To determine the best map, we compared them with thirteen recent independent accumulation estimates that lie in or close to our study area

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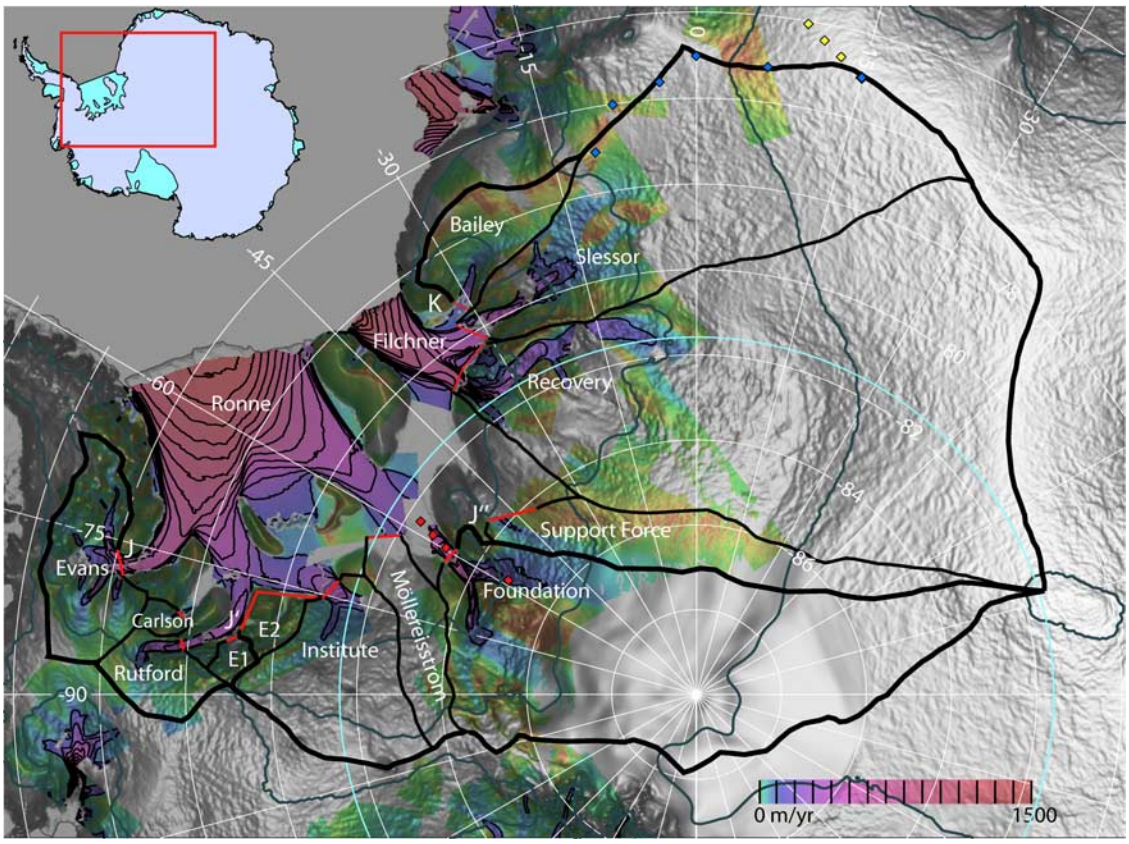

Figure 1. Ice stream speed (color and thin black 100-m/yr contours) over shaded DEM surface. Blue line indicates the ERS altimeters' southern limit (81.6°S). Red lines show flux gates, thick black lines show catchment boundaries, and thick grey lines show 1000-m elevation contours. Ice core locations used to evaluate accumulation maps are shown with yellow [*van den Broeke et al.*, 1999], blue [*Hofstede et al.*, 2004], and red [*Graf et al.*, 1999] diamonds.

(Figure 1) [*Graf et al.*, 1999; *Hofstede et al.*, 2004; *van den Broeke et al.*, 1999]. Based on this comparison we selected the Giovinetto and Zwally map because it yielded smaller root mean square differences (1.9 cm/yr) with the ice core data than did the Vaughan et al. map (4.5 cm/yr).

[8] We integrated the accumulation map over each ice stream catchment to determine the accumulation fluxes (Table 1). Giovinetto and Bentley estimate an error of 10% for accumulation averages. We have applied this uncertainty to all our accumulation estimates, which is twice the value used by *Rignot and Thomas* [2002].

[9] We used the same flux gates and velocity data used by *Joughin and Padman* [2003]. For the gates on floating ice (Bailey, Slessor, Recovery, and Möllereistrom), we used

Table 1. Mass Balance for Individual Ice Streams[a]

		Discharge Flux		Accumulation Flux		Mass Balance			
Ice Stream Drainage	Area, km^2	Gton/year	Error	Gton/year	Error	Gton/year	Error	cm/yr(i.e.)	Error
Bailey	75000	4.7	0.5	8.0	1.8	3.3	1.8	4.8	2.7
Slessor	486000	24.8	2.5	29.8	3.9	5.0	4.6	1.1	1.0
Recovery	1003000	35.0	3.5	43.7	5.0	8.7	6.1	1.0	0.7
Support force	143000	5.6	1.7	8.8	2.2	3.2	2.8	2.5	2.1
J″K Subtotal	1707000	70.1	4.6	90.3	9.8	20.2	10.8	1.3	0.7
Foundation	566000	33.0	3.3	44.2	5.6	11.2	6.5	2.2	1.3
Möllereistrom	67000	6.4	1.9	9.4	2.4	3.0	3.1	4.9	5.0
Institute	151000	21.6	2.2	22.7	3.8	1.1	4.4	0.8	3.2
E2	21000	2.2	0.2	3.6	1.3	1.4	1.3	7.4	7.0
J′J″ Subtotal	804000	63.2	4.4	79.9	10.1	16.7	11.0	2.3	1.5
E1	10000	1.8	0.2	2.2	1.2	0.4	1.2	4.5	13.8
Rutford	47442	17.8	1.8	15.1	3.9	−2.7	4.3	−6.3	10.0
Carlson	9000	2.4	0.2	2.6	1.5	0.2	1.5	2.5	18.3
Evans	104000	35.7	3.6	40.0	7.8	4.3	8.6	4.6	9.1
JJ′ Subtotal	170000	57.7	4.0	59.9	11.7	2.2	12.3	1.4	8.0
Total	2681000	191.0	7.5	230.1	25.3	39.1	26.4	1.6	1.0

[a]Mass balance estimates expressed as thickening rates (column 9) are given as ice (910 kg/m^3 density) equivalent (i.e.) values. The Carson discharge value is from *Rignot and Thomas* [2002].

the improved ICESat DEM to compute new thicknesses based on an assumption of hydrostatic equilibrium. In most cases, our revised fluxes changed by less than the uncertainty in the original estimates. We assumed a 10% discharge flux uncertainty except for Möllereistrom, where the gate was far from the grounding line, and Support Force, where the thickness data were of poor quality. For these cases, we assumed a 30% uncertainty.

[10] We estimate an average ice-equivalent thickening rate of 1.3 ± 0.7 cm/yr for basin J″K (Table 1), which is ~22% of the accumulation rate. Both Bailey and Support Force ice streams share common tributaries with their adjoining basins, making it more difficult to determine their shared boundaries. As a result, the larger thickening values for these two basins may reflect catchment divide errors. The basin J′J″ ice-equivalent thickening rate is 2.3 ± 1.5 cm/yr, which is ~21% of the accumulation rate. Again, we estimate larger thickening in the smaller catchments, which may indicate either catchment divide uncertainty or less spatial averaging of accumulation rates. Basin JJ′ shows negligible thickening of 1.4 ± 8 cm/yr (4% of the accumulation rate). For all three basins, we estimate a total thickening of 39 ± 26 Gton/yr (1.6 ± 1 cm/yr), which is equivalent to a sea-level reduction of 0.11 ± 0.07 mm/yr.

[11] The accumulation map we used was derived from snow pits, snow stakes, and ice core data [*Giovinetto and Zwally*, 2000]. The maps from these data represent accumulation rates averaged over periods of a few years to centuries. In addition, these data were collected over a period of several decades, largely prior to the satellite altimeter acquisitions. Thus, the accumulation fluxes we derived from these data roughly represent averages over the 20th Century, with perhaps a slight bias toward the latter half of the century, when most of the data were collected.

[12] Some ice streams have accelerated or decelerated over periods of a few years [*Joughin et al.*, 2004; *Joughin et al.*, 2002; *Rignot et al.*, 2002], but such changes usually are accompanied by strong localized thickening or thinning of the fast moving regions [*Shepherd et al.*, 2002; *Thomas et al.*, 2003]. There is no evidence for such changes on the ice streams in our study area [*Davis et al.*, 2005], and it is likely, therefore, that they have maintained steady rates of flow over at least the last century. If so, then our results are representative of mass balance over a period covering at least the last several decades.

3. Discussion

[13] Our estimated thickening differs substantially from the minor thinning (3.6 Gton/yr) estimated for a subset the ice streams in Figure 1 (all but Support Force, Möllereistrom, E1, and E2) [*Rignot and Thomas*, 2002]. Considering just the common subset, we still estimate a 34 Gton/yr thickening, with two factors accounting for the difference. First with the improved topography for the areas of interest, we estimated larger catchments for Foundation and Recovery ice streams, which accounts for a 22 Gton/yr difference. The other difference is that we estimate 14 Gton/yr less discharge from the ice steams common to both studies, mostly from an 11 Gton/yr difference for Evans Ice Stream. To confirm our result, we estimated flux through three additional gates on Evans Ice Stream with thicknesses determined from original radio-echo sounding data from the BEDMAP database [*Lythe and Vaughan*, 2001] and obtained results that are consistent with the value in Table 1.

[14] In comparing our results with those from altimetry, it is important to consider how the ice sheet surface responds to a change in accumulation. A 1 cm/yr step increase in the water-equivalent accumulation rate initially will cause thickening at the firn-equivalent accumulation rate (e.g., 2.8 cm/yr for a 350 kg/m^2 firn density) that eventually tapers off to the ice-equivalent accumulation rate as firn compaction reaches a new equilibrium. For a 10% increase in accumulation at Byrd Station, Antarctica, model results suggest that 16 years are required to reach the halfway point to a new equilibrium [*Arthern and Wingham*, 1998]. With an accumulation rate comparable to that at Byrd, this adjustment period should be similar for J′J″. Lower accumulation rates for J″K approximately double this period, while the higher rates for JJ′ reduce it by about a factor of three.

[15] In response to a step increase in accumulation, the ice sheet's internal dynamics will reduce the ice-equivalent thickening to zero as the ice sheet evolves toward a new steady state. This response is much slower than that of firn compaction, with various estimates suggesting that the East Antarctic plateau is still responding to increased accumulation rates at the onset of the Holocene [*Goodwin*, 1998; *Huybrechts et al.*, 2004].

[16] If the *Davis et al.* [2005] elevation changes result from increased accumulation over the observation period, then firn density (~350 kg m^{-2}) should be used to scale elevation change to mass change. If the changes are longer term (multi-decadal or greater), however, then glacial ice density (910 kg m^{-2}) should be used. In practice, observed elevation changes likely reflect a combination of short and long-term changes. Thus, without independent knowledge of the time scale over which changes are occurring, a 1-cm elevation change could imply a water-equivalent change of anywhere from 0.35 to 0.91 cm. To address this issue, *Davis et al.* [2005] used European Centre for Medium-Range Weather Forecasting re-analysis data (ERA-40) to determine accumulation anomalies over their observation period. These results suggest that recent accumulation increases are responsible for at least some of the elevation change. Consequently, they used the density of firn to determine a net 45 Gton/yr mass imbalance for the ice sheet area north of 81.6°S.

[17] We estimate an ice-equivalent thickening rate of 1.3 ± 0.7 cm/yr for J″K, which is similar to the 1.9 ± 0.4 cm/yr rate of elevation change over the 54% of the basin with altimeter coverage [*Davis et al.*, 2005, supporting online material]. Assuming no ice-discharge variability, then our estimates effectively pre-date the altimeter results. Thus, the agreement of our multi-decadal estimate with the altimeter decadal average suggests a longer than decadal-scale thickening trend. This conclusion is consistent with the lack of a significant ERA-40 accumulation anomaly for J″K [*Davis et al.*, 2005]. There is enough uncertainty in our estimates, however, that we can not exclude the possibility that some of the measured thickening in J″K resulted from accumulation increases during the 11-year period of altimeter observations.

[18] Results from six ice cores along the northern edge of the Slessor catchment indicate that decadal-to-centurial-

scale accumulation rates have varied by about ±5% over the last millennium, with rates for the latter half of 20th Century ~6% higher than the millennial average [*Hofstede et al.*, 2004]. If this trend is widespread over basin J″K, it would yield an approximately 0.4 cm/yr ice-equivalent elevation change or just under 1 cm/yr of firn equivalent change. In this low accumulation region, the firn compaction probably has not fully re-equilibrated so it is likely that the rate of elevation change is somewhere in the middle of this range. It is important to apply caution when extrapolating the results from these six cores because they lie at the edge of our study area, and they exhibit considerable spatial variability [*Hofstede et al.*, 2004]. Nevertheless, the results suggest that accumulation increases over the latter half of the 20th Century may explain a significant fraction of the thickening that we estimate and that the radar altimeter measures.

[19] Model and other results suggest that the East Antarctic Ice Sheet plateau has not full equilibrated to the ~50% increase in accumulation from the beginning of the Holocene [*Goodwin*, 1998; *Huybrechts et al.*, 2004]. Thus, part of the estimated thickening and observed elevation increase may be a response to an accumulation increase at the onset of the Holocene.

[20] For basin J′J″ the altimeter coverage (7%) is too limited to make a direct comparison with our data. Our results combined with results for the Ross ice stream catchments [*Joughin and Tulaczyk*, 2002], however, suggest that there is significant thickening over much of the region beyond the southern limit of the ERS altimeters.

[21] The altimeter data indicate a similar thickening to that of J″K over much of the East Antarctic plateau, where any accumulation anomaly over the observation period is small. This suggests that much of the plateau outside our study area also may be undergoing prolonged thickening over at least several decades and possibly in response to the increased accumulation throughout the Holocene [*Goodwin*, 1998; *Huybrechts et al.*, 2004]. If thickening has been sustained over many decades, then elevation changes in this region should be scaled to mass changes using ice rather than firn density, which would yield a more positive Antarctic mass balance estimate than predicted by *Davis et al.* [2005].

[22] Over the JJ′ basin, we estimate an ice-equivalent thickening of 1.4 ± 8 cm/yr, which is not significantly different than zero and is less than the 8.1 ± 0.5 cm/yr altimeter measurement [*Davis et al.*, 2005]. While the uncertainty in our estimate might account for this difference, the ERA-40 accumulation anomalies for this basin also are large enough to account for much of the difference. Furthermore, rapid ice flow (see Figure 1) extends deep into the catchment, making it likely that this part of the ice sheet already has reached equilibrium with the early Holocene accumulation increase [*Huybrechts et al.*, 2004]. Thus, while our results suggest there may be some long-term thickening, much of the altimeter-determined change in this region may result either from short-term variability or the recent onset of a longer-term increase in accumulation.

[23] The uncertainties in our estimates are dominated by the large uncertainties in Antarctic accumulation rates, illustrating the need for further efforts to improve accumulation estimates. Satellite altimetry and flux gate methods both reveal different aspects of shifts in ice-sheet mass balance. Joint interpretation of results from these methods provides a much more powerful means with which to ascertain the state of ice-sheet mass balance than does either method alone.

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