A Comparison of Contemporaneous Airborne Altimetry and Ice-Thickness Measurements of Antarctic Ice Shelves

A.M. Chartrand, I.M. Howat
Byrd Polar and Climate Research Center, The Ohio State University, Columbus, OH, USA
Correspondence: Allison Chartrand <allisonchartrand@gmail.com>

Supplementary Material

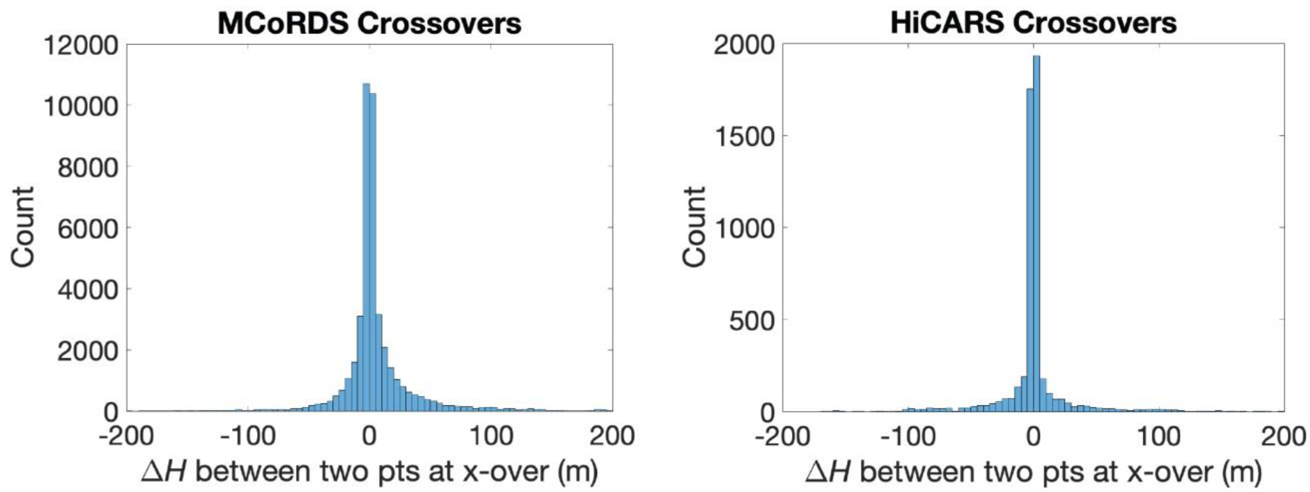

Figure S1. Histograms of the difference between any two points within 50 m of a crossover of IPR ground tracks. MCoRDS results (right panel) include all ice shelves in West Antarctica, while HiCARS results (right panel) include only Ross, Moscow University, Totten, and Shackleton Ice Shelves, as these were the only ice shelves with a sufficient number of intersecting ground tracks.

S1. RESULTS

S1.1. Comparison of hydrostatic residual between corrections scenarios

The firn air content taken from firn densification models (FDMs) is highly uncertain and significantly contributes to the hydrostatic residual. To evaluate the sensitivity of hydrostatic thickness estimates to H_a, we used the Institute for Marine and Atmospheric research Utrecht (IMAU) steady-state FDM (henceforth abbreviated sFDM) (Ligtenberg and others, 2011), forced at the surface by output of the regional climate model RACMO2.3p2 (van Wessem et al., 2018) and the transient Goddard Space Flight Center (GSFC) FDM (henceforth abbreviated tFDM) H_a values (Medley et al., 2022) to independently estimate H_E.

There is considerable difference between H_a from the sFDM results and the tFDM results averaged over time (3 Jan. 1980 to 26 June 2022) (Fig. S2). This leads to the disparities in H_E on the ice shelves discussed in the main text (Section 4.1.1). However, there is not a temporal pattern in either tFDM H_a or subsequent R values, and the tFDM Ha does not vary significantly throughout the time series (Fig. S1d).

Because the sFDM results are posted at 450 m (although this is interpolated from 5.5 km resolution) (Morlighem et al., 2020; Ligtenberg and others, 2011), and the tFDM at 12.5 km (Medley et al., 2022), the H_a and derived H_E varies smoothly over kilometers (Fig. S2). However, R values vary over similar sub-km scales for both FDMs. For all ice shelves, the tFDM H_a is thicker than the sFDM H_a from the sFDM, leading to thinner H_E values and more negative R values (Table 1, Table S1). This is because a thicker H_a represents a thicker firn column, which results in a lower ice density, so a thinner ice column is required for a given freeboard height.

Table S1. Ice Shelf hydrostatic residual results for the six cases with Ha and MDT corrections applied

	steady state FDM							transient firn model							No Firn					
		MDT			No MDT				MDT			no MDT			MDT			No MDT		
Shelf	**mean H_a**	**# points**	**mean R**	**σ R**	**# points**	**mean R**	**σ R**	**mean H_a**	**# points**	**mean R**	**σ R**	**# points**	**mean R**	**σ R**	**# points**	**mean R**	**σ R**	**# points**	**mean R**	**σ R**
Ronne Filchner	17.1	414534	10.9	28.4	414537	-0.2	28.4	19.8	422081	-10.7	36.1	422112	-21.8	36.1	420777	156.6	37.2	420816	145.5	37.2
Larsen	8.4	711968	26.6	50.6	711439	15.4	50.6	11.9	682443	0.0	63.9	681229	-11.2	63.9	707483	99.1	59.4	706652	87.8	59.4
George VI/ Wilkins/ Stange	8.8	221760	8.4	19.0	216887	-2.5	18.6	15.0	226162	-41.9	35.9	220385	-52.1	34.9	226248	84.4	47.3	221893	73.9	46.4
Abbot	16.1	175429	11.1	25.7	174846	0.6	25.7	21.0	179751	-29.6	40.1	179588	-40.1	40.1	178364	147.2	35.1	178152	136.7	35.1
PIG	10.2	274921	15.5	47.1	276091	5.4	47.5	21.7	271735	-80.9	49.1	272844	-91.1	49.4	276900	100.9	50.2	277969	90.8	50.5
Thwaites	11.5	60442	20.0	64.7	59464	9.1	64.5	21.6	59106	-65.4	73.9	58173	-76.0	74.0	60814	116.9	66.9	59816	106.4	66.8
Dotson/ Crosson	16.6	103437	-5.8	40.7	103385	-16.4	40.6	25.3	102449	-77.2	39.7	102399	-87.8	39.7	103658	135.2	39.5	103588	124.6	39.3
Getz	15.8	202547	11.3	26.7	208432	0.7	27.6	23.4	195898	-50.5	30.6	201766	-61.4	31.5	199533	145.1	29.2	205409	134.3	30.2
Nickerson	16.6	22007	-2.3	29.0	22164	-12.8	29.2	17.2	22761	-7.8	67.2	22944	-18.8	67.2	22191	137.5	34.6	22353	126.9	34.5
Western Ross/ McMurdo	13.5	83311	12.1	77.6	81949	1.4	78.1	20.2	85045	-44.9	80.4	83731	-56.3	81.0	86912	125.4	76.2	85498	114.1	76.8
Drygalski/ Nordenskjold	4.3	4932	30.2	75.3	4958	27.0	136.4	12.7	4968	-40.4	76.4	4994	-43.7	136.7	4923	66.1	77.3	4948	62.9	138.7
Cook	7.6	2061	28.8	19.0	2097	18.3	19.2	16.6	2043	-47.3	22.5	2068	-57.9	22.5	2039	92.5	17.2	2075	81.9	17.4
Ninnis	10.9	2089	44.9	104.4	2144	36.0	104.9	21.0	1636	-18.2	135.9	1680	-26.6	135.5	2051	137.9	122.7	2085	126.4	122.8
Mertz	12.4	1907	20.6	51.8	1920	8.1	52.0	20.1	1840	-44.5	52.8	1853	-57.2	53.3	1912	124.7	48.3	1924	112.2	48.5
Frost/Holmes	10.2	1674	52.3	73.0	1672	40.7	72.2	21.4	1438	-21.0	57.7	1427	-33.4	56.0	1673	137.8	76.1	1668	126.1	75.2
Moscow University	13.7	13380	33.7	84.8	13423	22.5	85.0	15.9	13196	15.3	92.8	13268	4.2	93.0	13665	148.5	99.8	13739	137.2	100.1
Totten	16.5	102302	41.2	113.6	102294	30.1	113.6	20.6	102194	8.1	110.6	102185	-3.1	110.5	102740	179.4	122.1	102733	168.3	122.1
Vincennes Bay/ Underwood	6.8	5662	-21.0	252.7	5662	-32.4	252.7	10.0	5255	-56.1	260.9	5255	-67.4	260.9	5605	35.0	256.3	5605	23.6	256.3
Shackleton	5.2	10455	11.0	53.8	11219	13.2	75.8	14.2	10371	-63.8	52.6	11137	-62.3	72.3	10265	53.8	58.3	11032	55.4	76.6
West	8.8	8248	17.5	33.5	7906	6.1	32.1	13.6	8503	-20.9	51.7	8103	-30.7	49.7	8342	94.3	50.9	7935	84.5	48.8
mean absolute value of columns	**11.6**		**21.3**	**50.5**		**14.9**	**50.9**	**18.2**		**37.2**	**64.1**		**45.2**	**64.2**		**115.9**	**63.5**		**106.0**	**63.7**

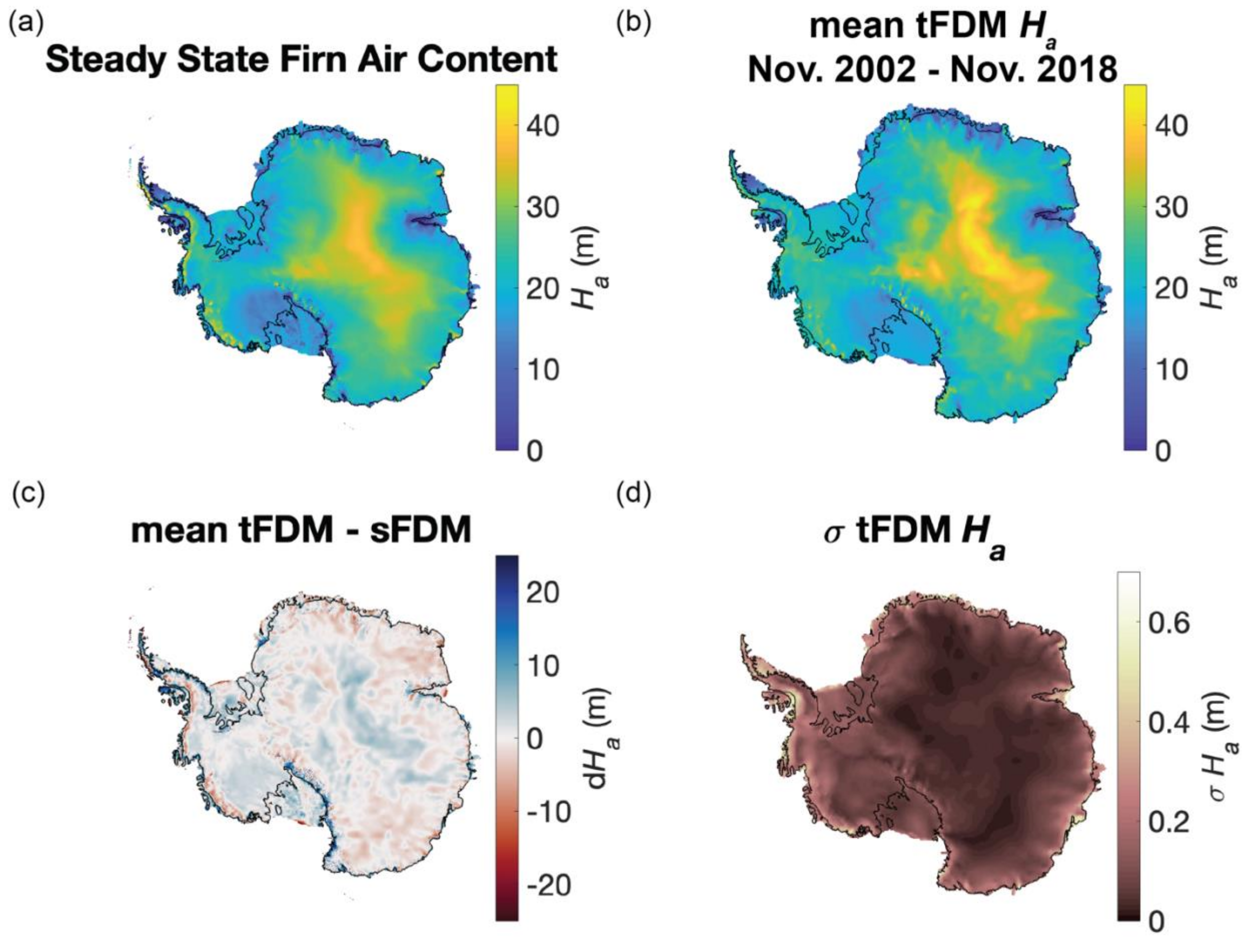

Fig. S2. (a) shows H_a from the sFDM, (b) shows the mean H_a from the time series of the transient firn densification model (tFDM), (c) shows the difference between the mean tFDM H_a and the sFDM H_a, and (d) shows the standard deviation of H_a throughout the tFDM time series.

Fig. S3. Interpolated and extrapolated MDT values for all floating IPR ground track coordinates.

S1.2 Descriptions of Ice Shelves and selected transects

S1.2.1. Ronne-Filchner Ice Shelf

Table S2. Overview of hydrostatic residual (*R*) and related statistics for all ice shelves for Ronne-Filchner Ice Shelf Sectors, where % Error = *R* / *H* * 100.

Sector	# Cam-paigns	# Points	Mean *H* (m)	Mean *R* (m)	σ R	Standard error	% Error
Bailey	5	39295	1076	8	16	0.1	0.7
Slessor	6	71492	956	5	21	0.1	0.7
Recovery	7	165166	835	15	32	0.1	2.2
Support Force	6	130394	1068	7	18	0.1	0.6
Foundation	7	225091	1191	7	25	0.1	0.6
Moller	3	48083	1040	10	12	0.1	1.0
Institute	2	178521	1092	15	15	0.0	1.3
Rutford/ Carlson	1	111229	1026	17	11	0.0	1.6
Evans	1	316190	1139	23	49	0.1	2.0

Most of the campaigns over the Ronne-Filchner ice shelf system were flown along and near the tributary ice streams. *R* is generally positive near the grounding line and negative further downstream in the ice shelf. An exception is in the center of the Filchner ice shelf, where there are several ground tracks in the Recovery Ice Stream sector showing that the surface is too high (positive *R*), particularly as the ground tracks approach Berkner Island (Fig. S4). These regions are associated with regions of low surface height/thinner ice in the western part of the Filchner ice shelf. The eastern part of the ice shelf, which is relatively thicker and smoother, shows that the surface is predominantly too low (negative *R*) along MCoRDS ground tracks. Along many of the ground tracks, *R* transitions smoothly from negative to positive over distances of 1-100 km, however, there is more variability near grounding lines.

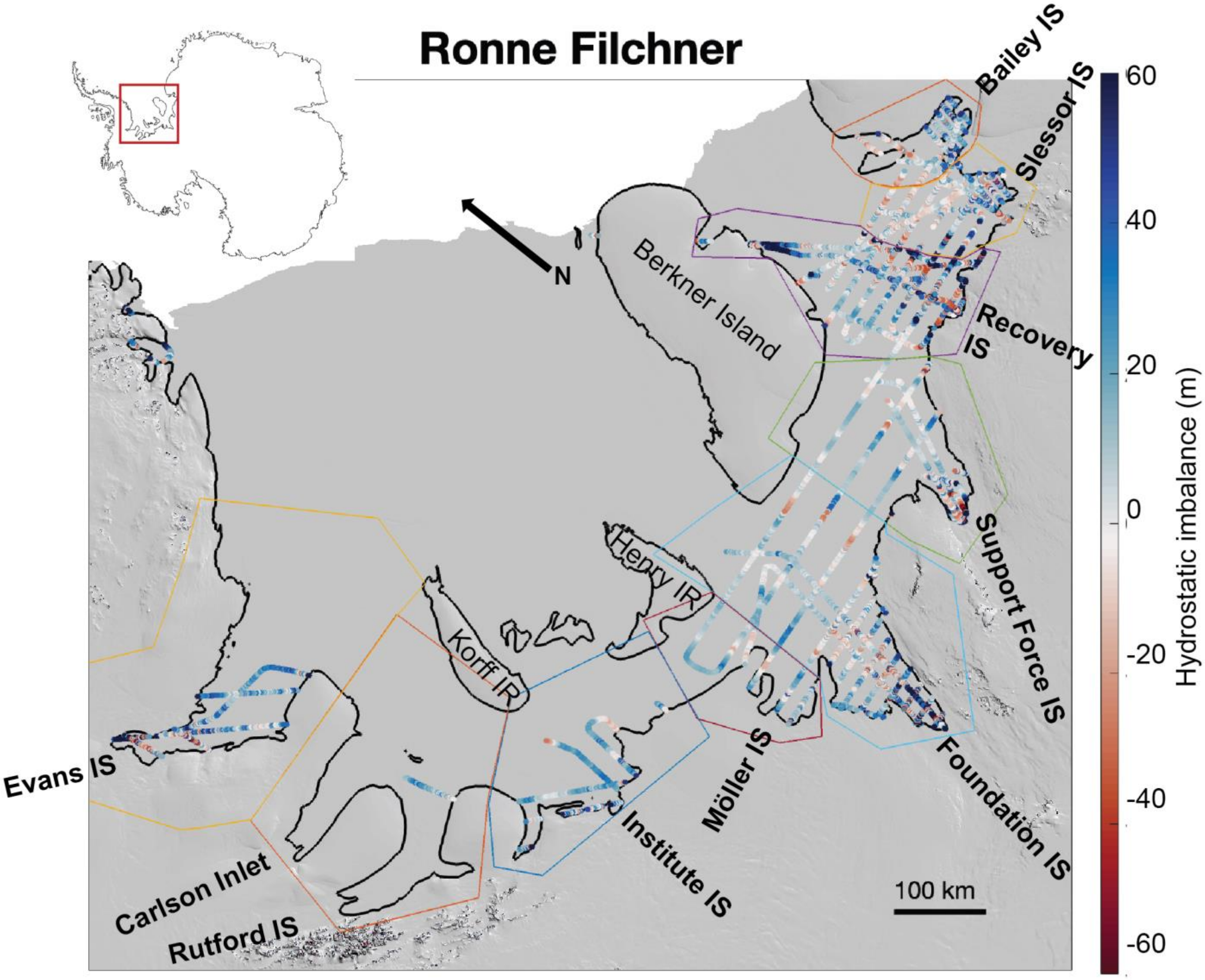

Fig. S4. DEM Hillshade image of Ronne-Filchner Ice Shelf System, with sectors delineated by different colored polygons. Magenta curves are the locations of basal channels; the continuous black curve is the 2007-2009 grounding line. Dots colored with the red-blue color scale are *R* values at MCoRDS coordinates.

The Ronne-Filcher region is topographically diverse, with several longitudinal basal channels (Fig. 7) and other longitudinal and transverse surface features spaced ~5 km apart with amplitudes up to 15 m. Disparate patterns to the Foundation basal channel are found around other basal channels, such as one along the Institute ice stream, at which the surface is too low at its head (*R* = -25 m for ~1.5 km on either side of the channel), and too high where the channel is intersected by a ground track ~35 km from its head Fig. S8b). Along a transect that intersects both the grounding line and a channel in the Möller ice stream, the surface is too low nearly everywhere except within the basal channel surface trough (Fig. S9). There are several channels which did not exhibit such clear patterns as well, but most are associated with other topographic features and highly variable *R*, especially near grounding lines and within ice streams. Going forward, we will describe the Ronne-Filchner ice shelf system by sectors delineated based on the major ice stream tributaries, going clockwise from Bailey Ice Stream (Fig. S4).

Bailey Ice Stream: Ice flow is to the west into the Filchner ice shelf. There are several across-flow ground tracks that intersect the side-wall grounding lines, and they show that the surface is too high for at least the first 0.5 km and up to 6 km along the transects into the middle of the ice stream. Transect a-a', which intersects the peninsula separating the two embayments of the Bailey Ice Stream, shows that changes in R are generally inversely related to changes in H, indicating that the surface topography is generally muted compared to the thickness profile. Just north of where the transect intersects the peninsula, it intersects a basal channel, above which the surface trough is too high for hydrostatic equilibrium and the flanks are too low, although the surface becomes too high as the transect approaches the peninsula grounding line (Fig. S5a). South of the peninsula, the surface is generally too high along transect a-a', except at a thick point in the ice that is not adequately reflected in the ice shelf surface (Fig. S5a). Further downstream, transect b-b' also shows that the surface is too high in the surface troughs of two basal channels, and too low along the surface flanks (Fig. S5b). The mean R across this transect is 17 m, and the median is 16 m, indicating that the surface is too high, although the surface topography is generally muted compared to the thickness profile (i.e. surface peaks are too low and surface troughs are too high). There are no apparent relationships between divergence and R, except for the first ~1 km from the true right/northern sidewall, where the flow regime is compressional and the surface is too high (Fig. S5b). In contrast, along-flow transect c-c' on the southern/true left side of Bailey Ice Stream shows that the surface is predominantly too low, and that the flow regime is predominantly extensional. There is no clear relationship on a small scale (<10 km), however.

Where the Bailey Ice Stream merges with the Slessor Ice Stream and strain rates are negligible, the surface is predominantly too low. The surface is also too low for hydrostatic equilibrium in between the continental grounding line and the island just northwest of the main trunk of Bailey Ice stream, except within 1 km from the grounding lines (Fig. S5 map near point c').

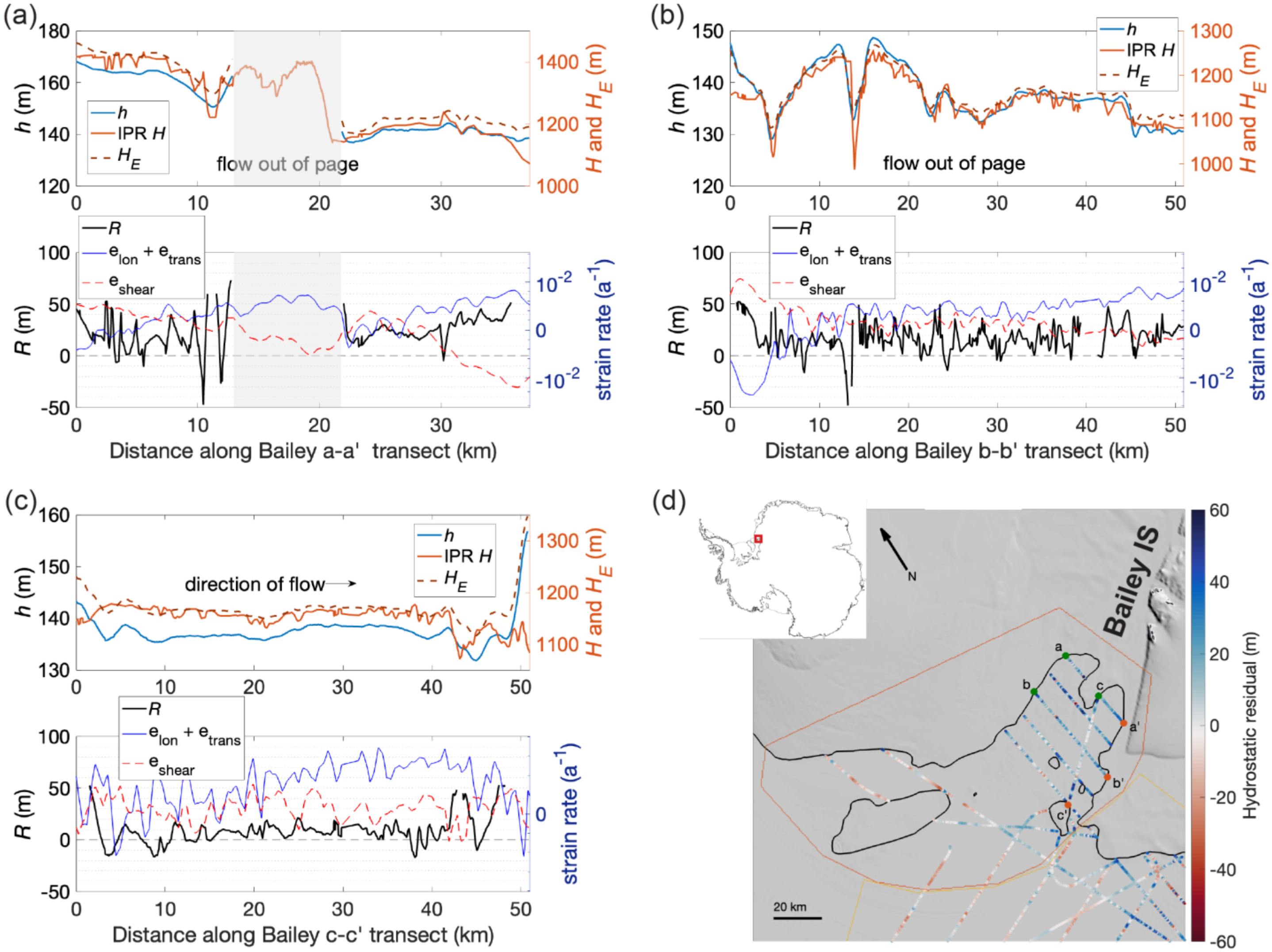

Figure S5. Bailey Ice Stream Sector of the Ronne-Filchner Ice Shelf. (a-c) Selected transects in the Bailey Ice Stream sector of the Ronne-Filchner Ice Shelf. Top panel of (a-c) shows surface height h (blue curve, left Y axis), IPR thickness H and hydrostatic thickness H_E (orange solid and red dashed curves, right Y axis), while the bottom panel shows hydrostatic residual R (black curve, left Y axis), and the sum of normal strain rates and the shear strain rates (solid blue and dashed red curves, respectively, right Y axis). The map shows the REMA DEM hillshade image. The continuous black curve is the 2007-2009 grounding line. Dots colored with the red-blue color scale are R values at airborne IPR coordinates. The transects in (a-c) are labeled, with the green and red circles showing the beginning and end of each transect. The Antarctic outline marks the region shown in the map with a red rectangle. All Figures S5-S42 are described similarly.

Slessor Ice Stream: similar to the Bailey ice stream, R is positive within ~1 km of the grounding line where ground tracks intersect the grounding line around most of the embayment. An exception is within the westernmost embayment, where the surface is too high for a few hundred meters along transect b-b' immediately adjacent to the grounding line but predominantly too low in the main trunk of the embayment, where strain rates are negligible (Fig. S6b). The end of transect a-a' in the easternmost embayment shows a loose inverse relationship between R and normal strain rates (R is negative/surface is too low where flow is extensional and too high where flow is compressional, Fig. S6a). Before the Slessor Ice Stream merges with the Bailey Ice stream, R is highly variable along transect c-c' (0-30 km), and changes in *R* are inversely related to changes in *H*, associated with a surface topography that is muted compared to the thickness profile (Fig. 6c). There are no strong relationships between *R* and divergence, except that the ice appears closer to hydrostatic equilibrium in areas where strain rates are near zero.

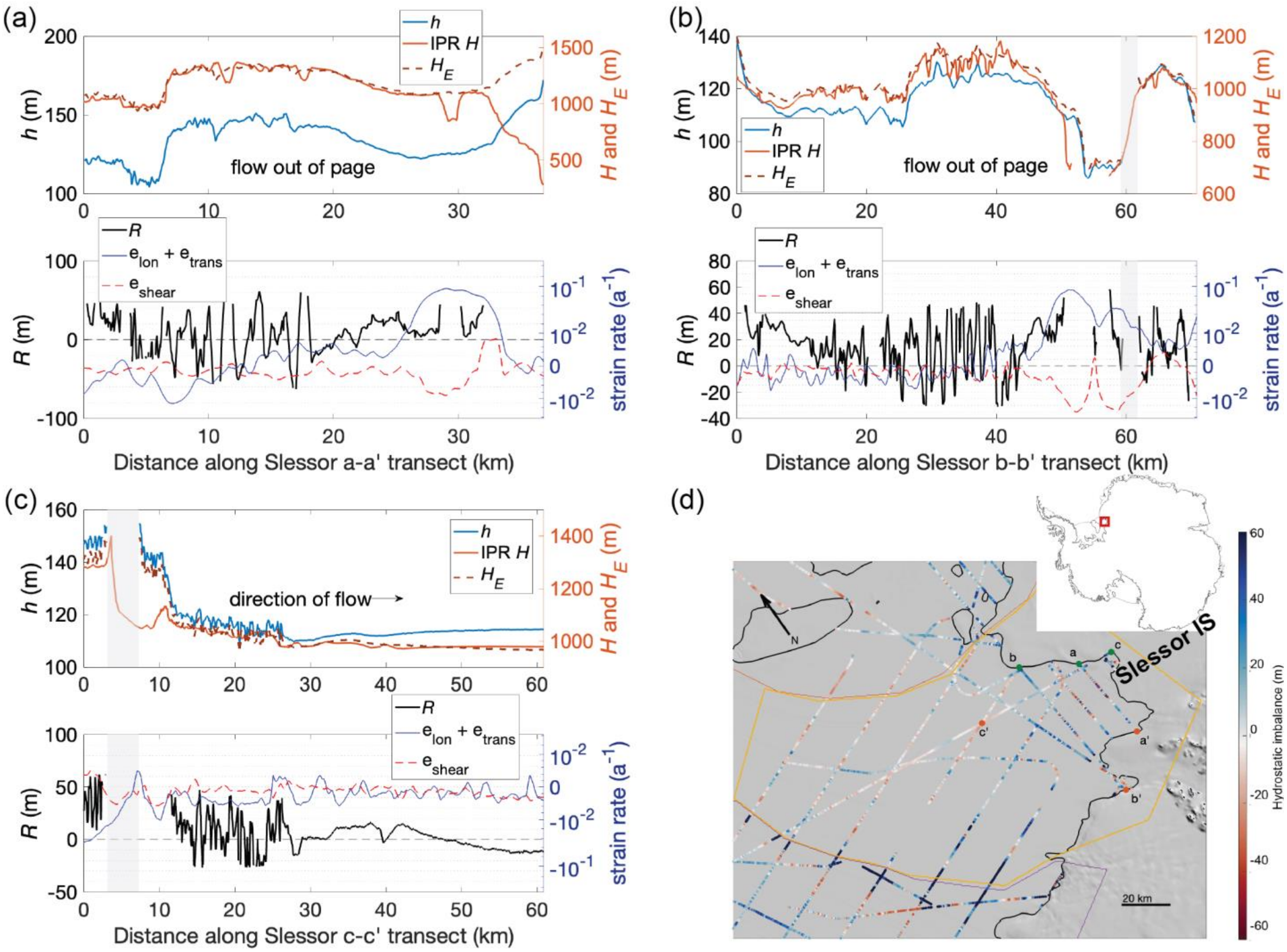

Figure S6. Slessor Ice Stream Sector of the Ronne-Filchner Ice Shelf.

Recovery Ice Stream: Transect a-a' following the main trunk of the ice downstream of Recovery ice stream shows that the surface is primarily too high (*R* is positive) except where the ice is locally thick. Strain rates are predominantly extensional along this transect, although decreases in normal strain rates are associated with the local increases in thickness and decreases in *R*. This is especially apparent within 45 km of the grounding line where large pressure ridges are abundant (Fig. S7a). The surface is predominantly too high in the slow-moving region between the grounding line and where Slessor Ice Stream and Recovery Ice Streams merge. Furthermore, the surface is too high along the western side of the main trunk of Recovery ice stream, where shear strain is high, and too low west of the shear zone where strain rates are negligible (Fig. S7c).

The ground tracks that lay transverse to flow along the main trunk of Recovery Ice stream, such as transect b-b' (Fig. S7b) show that *R* is highly variable, with changes in *R* and *H* having an inverse relationship and no apparent relationship to changes in divergence.

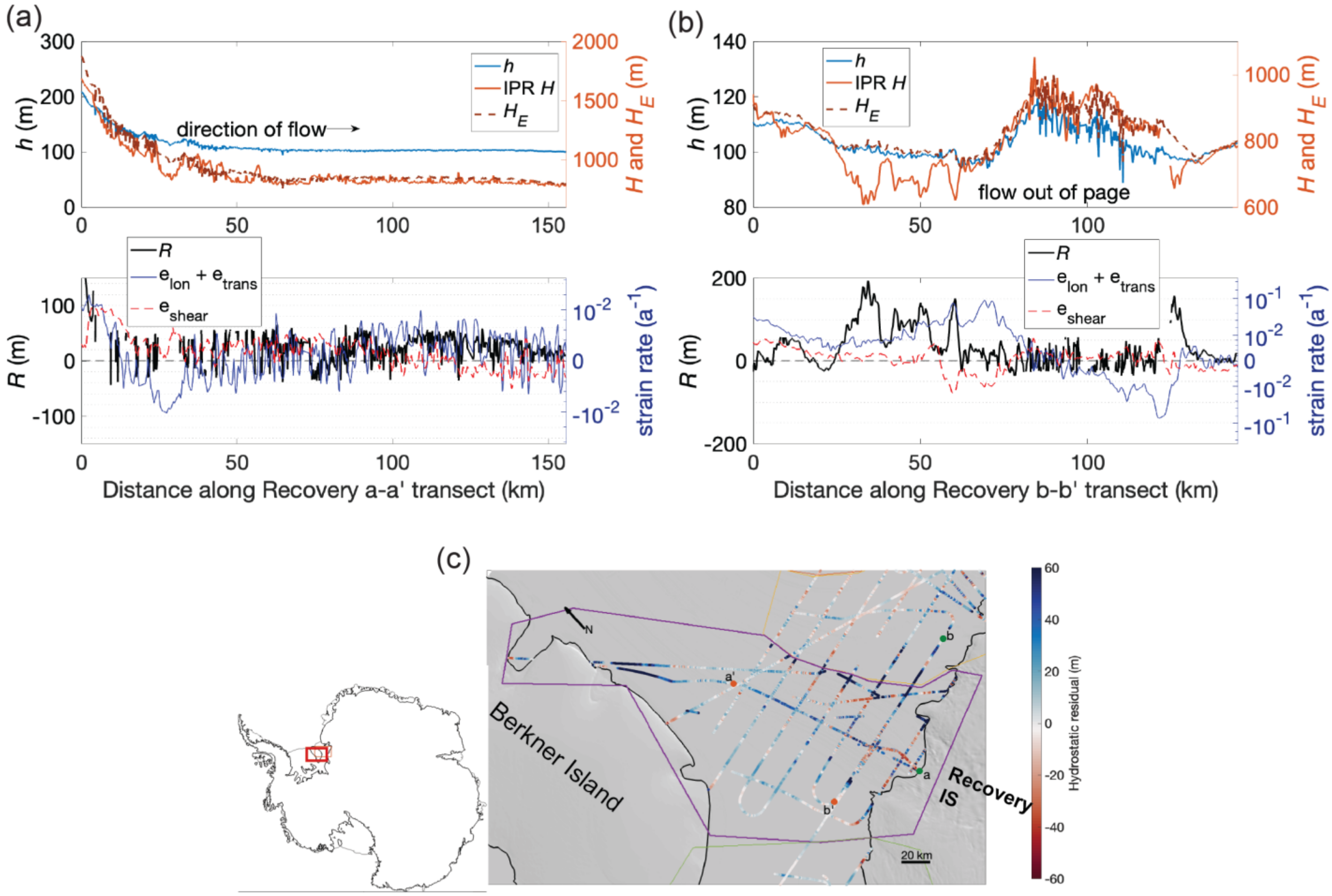

Figure S7. Recovery Ice Stream Sector of the Ronne-Filchner Ice Shelf.

Support Force Ice Stream: Within the embayment of Support Force Ice Stream, the surface is predominantly too low (*R* is negative), with some variability (Fig. S8a-c), except within 3-5 km of the grounding line on transect b-b', where the surface is primarily too high (*R* is positive, Fig. S8c). The flow regime along the main trunk is slightly compressional, although there is no apparent small-scale relationship between *R* and strain rates (Fig. S8a-c). When the ice shelf widens, the surface is predominantly too low, though close to balance, between Support Force Ice Stream and Berkner Island, especially from ~70-130 km along transect b-b' (Fig. S8c). Exceptions occur in the shear margins of the ice stream trunk, where the surface is predominantly too high. West of Support Force Ice Stream, there is a ~50 km wide region between the continental grounding line and Berkner Island where the ice is largely in balance, although it becomes imbalanced once more near the southern tip of Berkner Island, where Foundation Ice Stream contributes to the Ronne ice shelf.

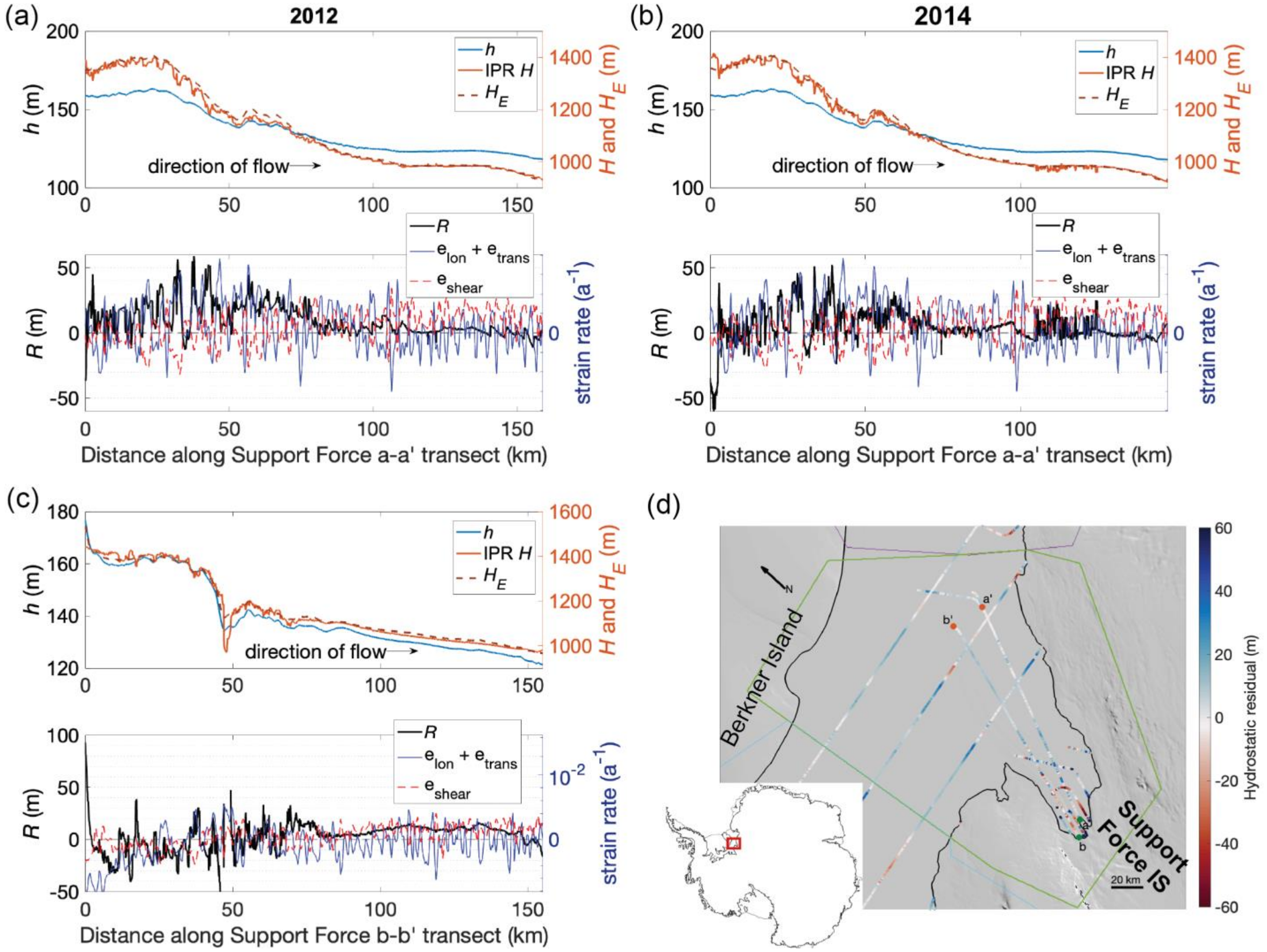

Figure S8. Support Force Ice Stream Sector of the Ronne-Filchner Ice Shelf.

Foundation Ice Stream: Overall, the surface in main trunk of Foundation Ice Stream transitions from too high near the grounding line to too low in the downstream part of the embayment, to nearly balanced where the ice shelf widens. However, the surface is predominantly too low along the eastern/true right side of the flow, where longitudinal strain rates are compressional, and too high along the western/true left side of flow, where shear strain is slightly elevated. Transect a-a' has two parallel, nearly overlapping ground tracks from 2012 and 2018 run from the grounding line along flow toward Berkner Island (Fig. S9a-b). This transect is parallel to, and possibly overlapping a previously mapped basal channel (Alley et al., 2016; LeBrocq et al, 2013) from about 90 - 117 km from the grounding line. In 2012, the surface was too high for hydrostatic equilibrium for the first 4 km from the grounding line, and then became too low over the next 7 km, coincident with a thick spot in the surface profile. In 2018, the surface is only too high for the first 1.7 km from the grounding line, after which two thick spots separated by a thin spot are associated with regions in which the surface is too low. In both campaigns, the ice thins rapidly past ~11 km from the grounding line, and the surface is predominantly too high (*R* is positive), particularly at high points in the surface and thin points along the thickness profiles. Indeed, changes in *R* and changes in *H* are generally inversely related, and changes in R and changes in h are generally positively correlated. After ~60 km from the grounding line, the surface is predominantly too low in 2012 and 2018 along the rest of the sampled transect, except for where there are local thin spots and surface troughs as the ground track presumably intersects flow lines and the large basal channel (Fig. S9a-b).

The surface is also too low on the west (true left) flank of a surface trough and too high on the east (true right) flank of two large surface troughs (> 3 km across) along transverse transect b-b' in the Foundation Ice Stream (Fig. S9c); the eastern trough is associated with the large basal channel. The rest of the ground track shows a negative relationship between changes in R and H. Along this ground track, there are some surface features that are not associated with anomalous features in the thickness profile, some surface features that exaggerate topography compared to the thickness profile, and some surface features that mute topography compared to the thickness profile (transect b-b' is also shown and discussed in the main text and Figure 7a). Further down, transverse transect c-c' shows that the large Foundation basal channel has widened to 10 km, but that the surface is predominantly too low within the channel, and along most of the eastern half of the transect (Fig. S9d). The western half of the transect, by contrast, shows a flat surface that is near balance (R is near zero), except for within the first 8 km of the grounding line, where the surface is predominantly too high except for a thick spot at ~1.5 km away.

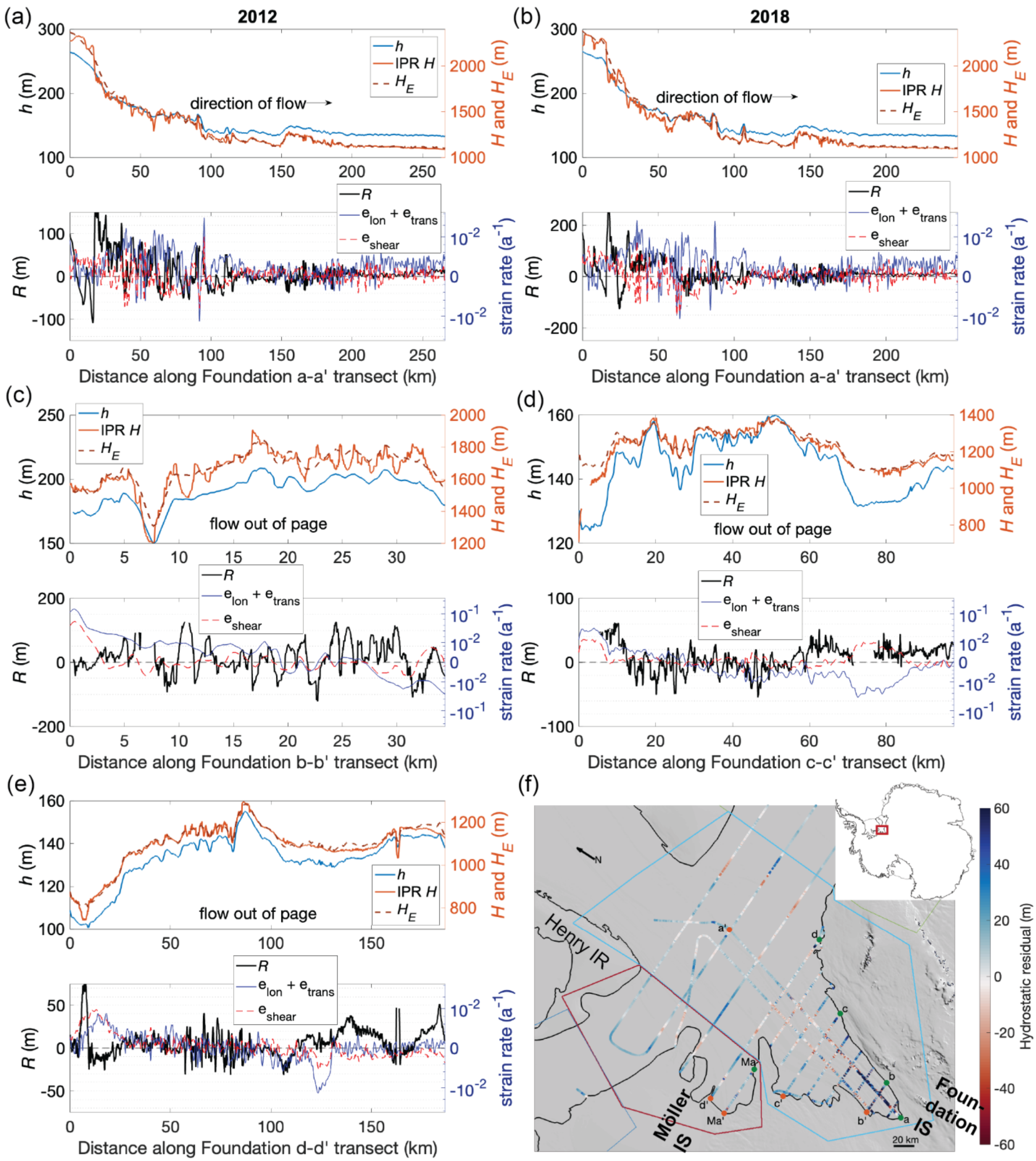

Figure S9. Foundation Ice Stream Sector of the Ronne-Filchner Ice Shelf.

Möller Ice Stream: Möller Ice Stream has a surface that is predominantly too low, with transect a-a’ showing negative *R* values from ~15 - 40 km from its intersection with the grounding line (Fig. S10). This transect shows that the ice surface is too low for about 3 km from the grounding line where the ice is thickest and the flow regime is slightly compressional. Foundation transect d-d' (Fig. S9e) intersects both the Möller ice stream (including its grounding line) and the Foundation Ice Stream. This transect shows that the surface is too high near the Möller grounding line and from 15-50 km along the transect, and too low across most of the Foundation Ice Stream. At the tip of the peninsula separating the ice streams, there is little change in thickness but a large dip in the surface that corresponds with the region of negative *R* values, and for the next ~30 km along the transect, changes in *R* and *H* are not inversely related as we've typically observed. The surface is especially too high at ~21 km along the transect, where it intersects with a previously observed basal channel, and at ~178 km along the transect, where it intersects another thin point just downstream of a peninsula, which may be a grounding-line sourced basal channel. There does not seem to be a strong relationship between *R* and strain rates in the Möller ice stream region.

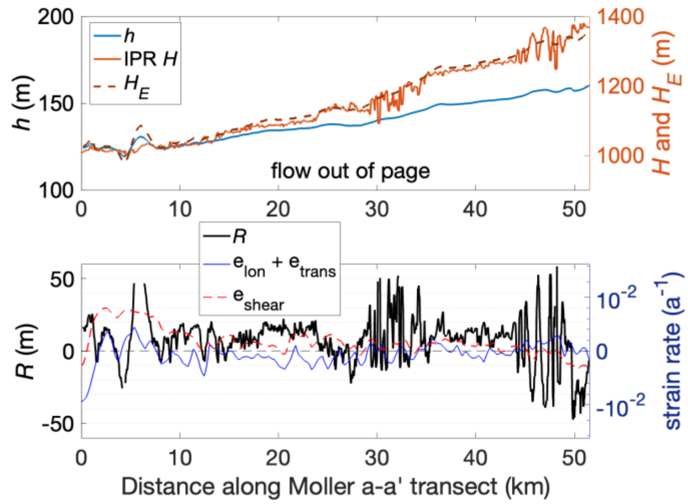

Figure S10. Möller Ice Stream Sector of the Ronne-Filchner Ice Shelf.

Institute Ice Stream: The surface is predominantly too high (R is positive) within the Institute Ice Stream, particularly within 5 km of the grounding line (Fig. S111a-b and map). Exceptions are along the eastern edge of the eastern shear margin, where strain rates are nearing zero, and within the western shear margin. Transects a-a' and b-b' run transverse to flow across Institute Ice Stream and show that changes in *R* and changes in *H* are generally inversely related on a small scale (1-10 km), but positively related on a larger (> 10 km) scale, so that thicker ice is generally associated with a surface that's too high and thinner ice is generally associated with a surface that's too low. Neither transect shows a clear relationship between *R* and strain rates (Fig. S11 a-b).

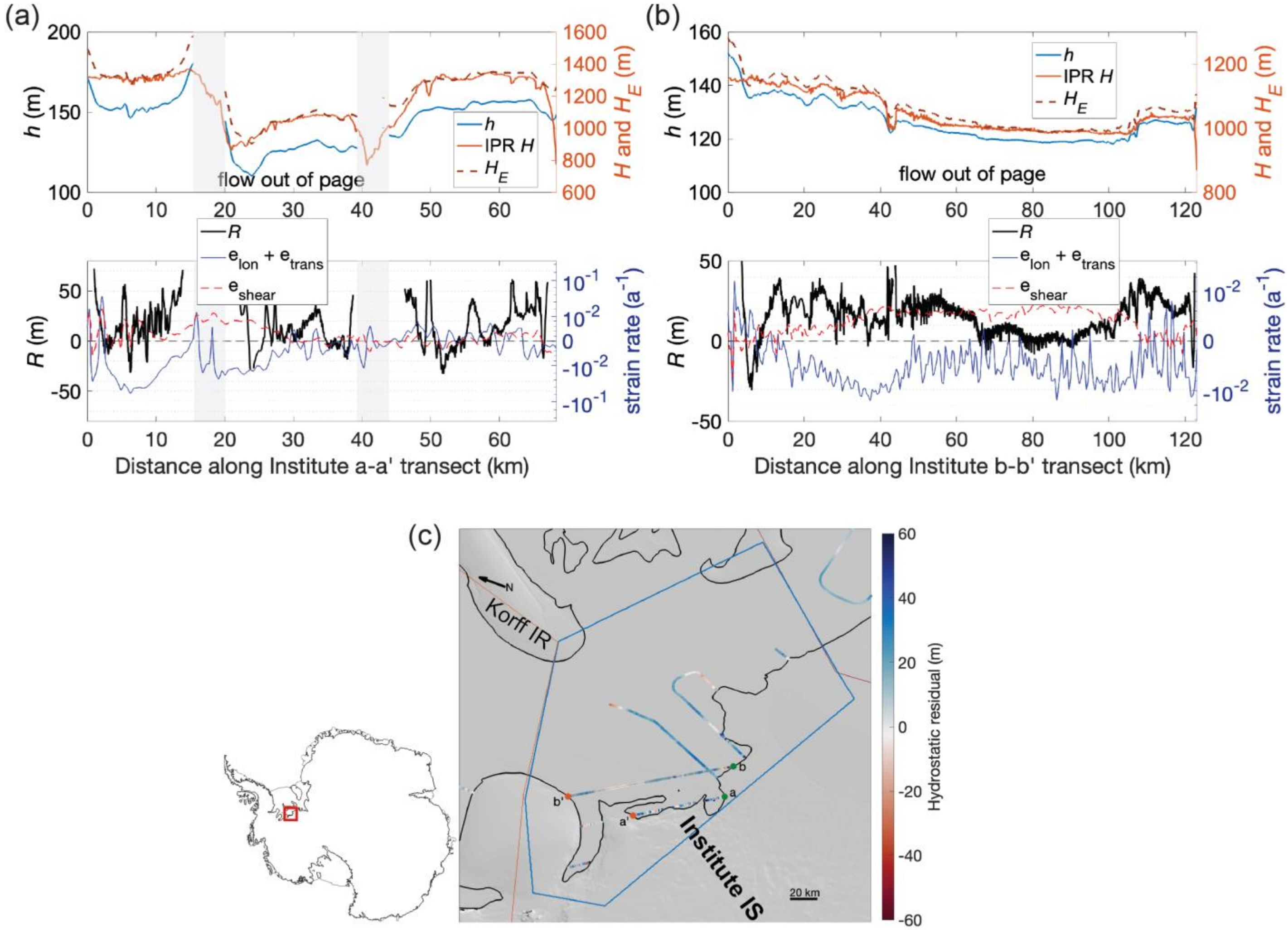

Figure S11. Institute Ice Stream Sector of the Ronne-Filchner Ice Shelf.

Rutford Ice Stream/Carlson Inlet: There is one across-flow ground track (transect a-a', Fig. S12) where Rutford Ice Stream widens into the main ice shelf that shows that the surface is predominantly too low for ~6 km from the grounding line in the eastern shear margin, and that the surface is generally too high further into the ice shelf. At 12 km from the start of the transect, the surface is too high at a thick spot in the thickness profile, but changes in *R* and *H* are generally inversely related on small scales along the rest of the transect. There is no strong relationship between changes in *R* and changes in strain rates.

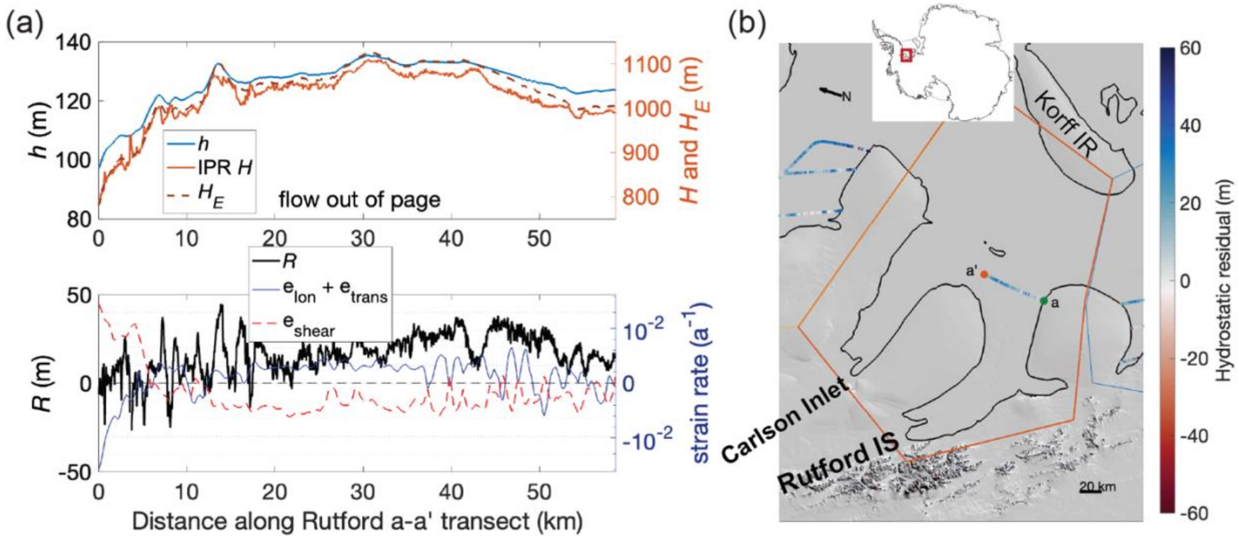

Figure S12. Rutford Ice Stream/Carlson Inlet Sector of the Ronne-Filchner Ice Shelf.

Evans: Ice flow is primarily to the east in Evans Ice Stream. The surface is predominantly too high near the deepest and most westerly embayment of the grounding line, for about 30 km in the along-flow direction and 10 km across flow. In the narrow part of the tributary, *R* is highly variable, but the surface becomes predominantly too high once the tributary widens to at least 50 km across, about 100 km from the grounding line (Fig. S13d). Transects a-a' and b-b' show that changes in *R* and changes in *H* are inversely related, and that surface features are generally muted compared to the thickness profile (i.e. the surface is too high within troughs and too low at surface peaks, Fig. S13 a-b). Transect c-c', which runs generally along-flow, also intersects a side-wall grounding line, and shows that the surface is too low for about 5 km upstream and downstream of the grounding line, but too high within a few hundred meters of the grounding line, as expected (Fig. S13c). Transverse transect a-a' shows that surface troughs do not line up exactly with thin points in the thickness profile, resulting in the surface being too high on the northern/true left flanks of surface troughs and too low on the southern/true right flanks, including at a basal channel about 36 km from the start of the transect (Fig. S13a). A similar pattern is observed at ~70 km from the grounding line on transect b-b' where it intersects a basal channel (Fig. S12b).

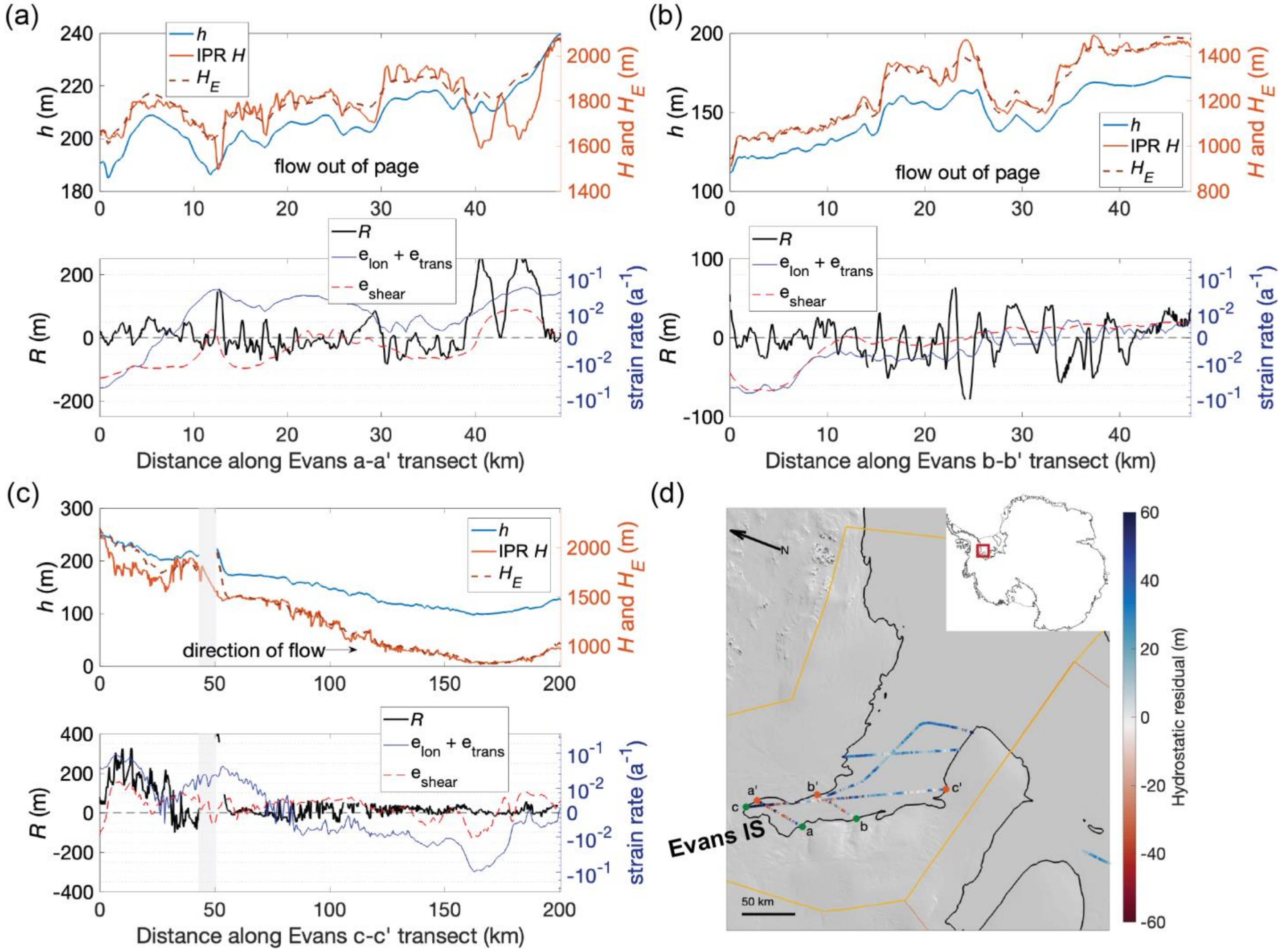

Figure S13. Evans Ice Stream Sector of the Ronne-Filchner Ice Shelf.

S1.2.2. Larsen Ice Shelf System

The Larsen ice shelf system was covered extensively by MCoRDS and ATM ground tracks. The surface is predominantly too high on the Larsen Ice C Shelf, particularly near the ice shelf front, where *R* reaches > 50 m (Fig. S14d, S15c). Along several ground tracks, the surface is predominantly too high within ~1 km from the grounding line, then too low for ~1-5 km (Fig. S14 b, c, d). *R* transitions from ~-25 m to 30 m over distances < 1 km to ~10 km along-track, with more variability in regions of topographic variability, and changes in *R* are predominantly inversely related to changes in *H* (Fig. S14, Fig. S15). The ice is near hydrostatic equilibrium (*R* is near zero) on the southern part of the shelf, to the north of Hillock-Kenyon Peninsula (Fig. S15c). In the embayment west of the Hillock-Kenyon peninsula, the surface is predominantly too high where the ice is thicker, and the surface is too low where the ice is relatively thinner (see transect c-c', Fig. S14c). In general, however, on Larsen C, the surface tends to be too low (*R* is negative) where the ice is more confined. The surface of the ice surrounding the islands near the ice shelf front is also too high for hydrostatic equilibrium. Transect d-d' shows that while the surface is predominantly too high, it is often too low within surface troughs, indicating that the surface topography is exaggerated relative to the basal topography (Fig. S14d). This is consistent with hypotheses that fracture on Antarctic peninsula ice shelves is driven by surface processes.

On the Remnant Larsen B ice shelf, the surface is predominantly too high on the eastern portion of the ice shelf and variable on the western portion of the ice shelf. Transect e-e' shows that changes in *R* and *H* are inversely related on short length scales, but thinner ice tends to be associated with a surface that's too low and thicker ice tends to be associated with a surface too high on scales longer than 10 km (Fig. S15).

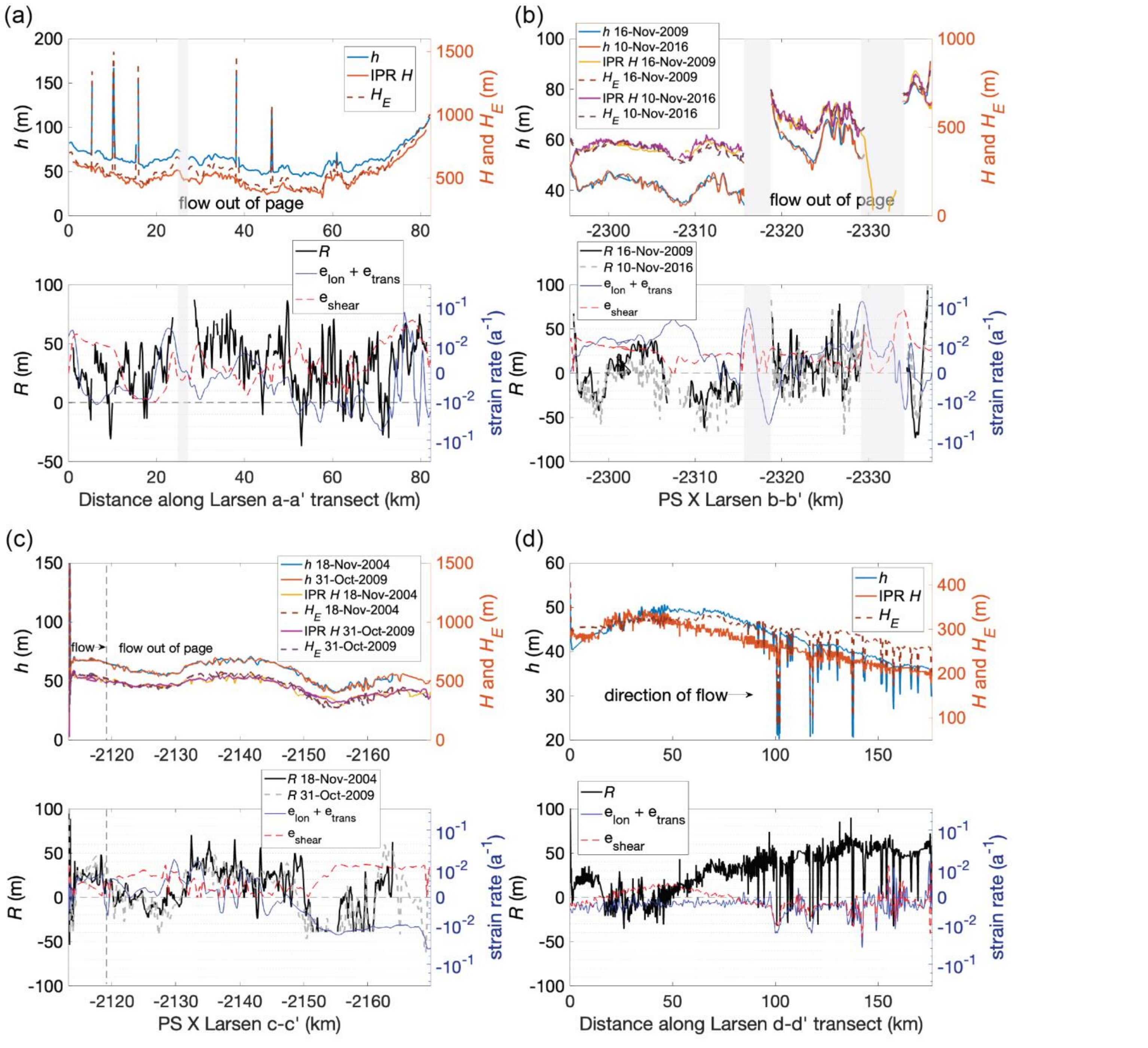

Figure S14. Larsen Ice Shelf System, transects a-a' - d-d'.

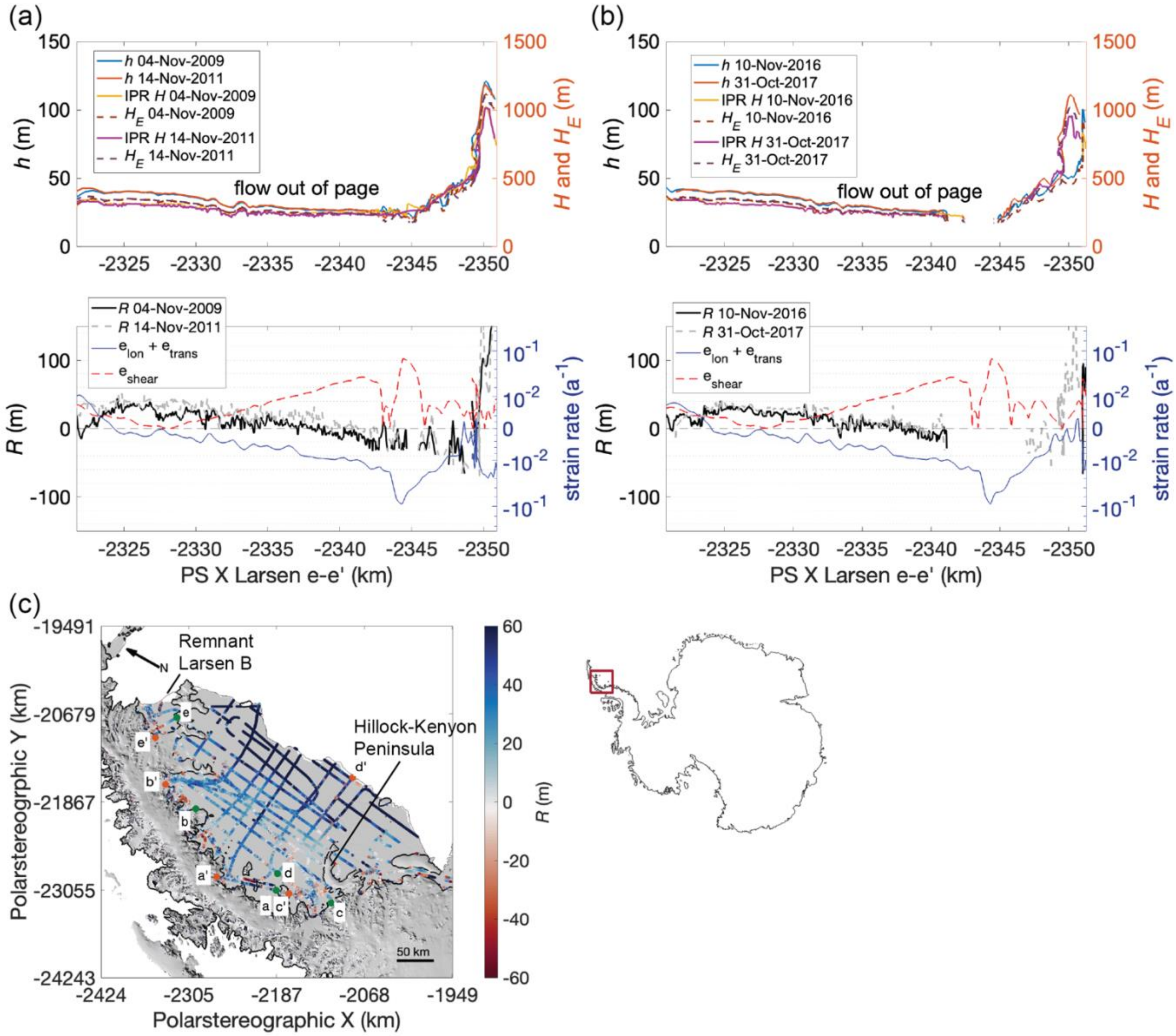

Figure S15. Larsen Ice Shelf System, transect e-e' and map.

S1.2.3. George VI, Wilkins, and Stange Ice Shelf System

The George VI and Stange ice shelves have systematic coverage both along and across-flow, and the Wilkins ice shelf has several along-flow ground tracks near grounding line embayments. All three ice shelves have several basal channels, and Wilkins and the western end of George VI have several islands.

In general, the George VI ice shelf is within 10 m of hydrostatic balance (the absolute value of R is < 10 m), with the surface being too low near the grounding line and in the middle, wide portion of the ice shelf (Fig. S16 map). However, in the narrower eastern portion of the George VI ice shelf, the surface is slightly too high (0 - 160 km on transect d-d', Fig. S16d). On the western portion, thinner ice is generally associated with a too low surface (more negative R values), and thicker ice is associated with a too high surface (more positive R values), except for near large thickness gradients, like basal channels), similar to Larsen ice shelf. Of the selected transects, a-a’ and b-b’ show the most variability in *R*, and this variability indicates that the surface topography is generally exaggerated compared to the thickness profile (Fig. S16a-b).

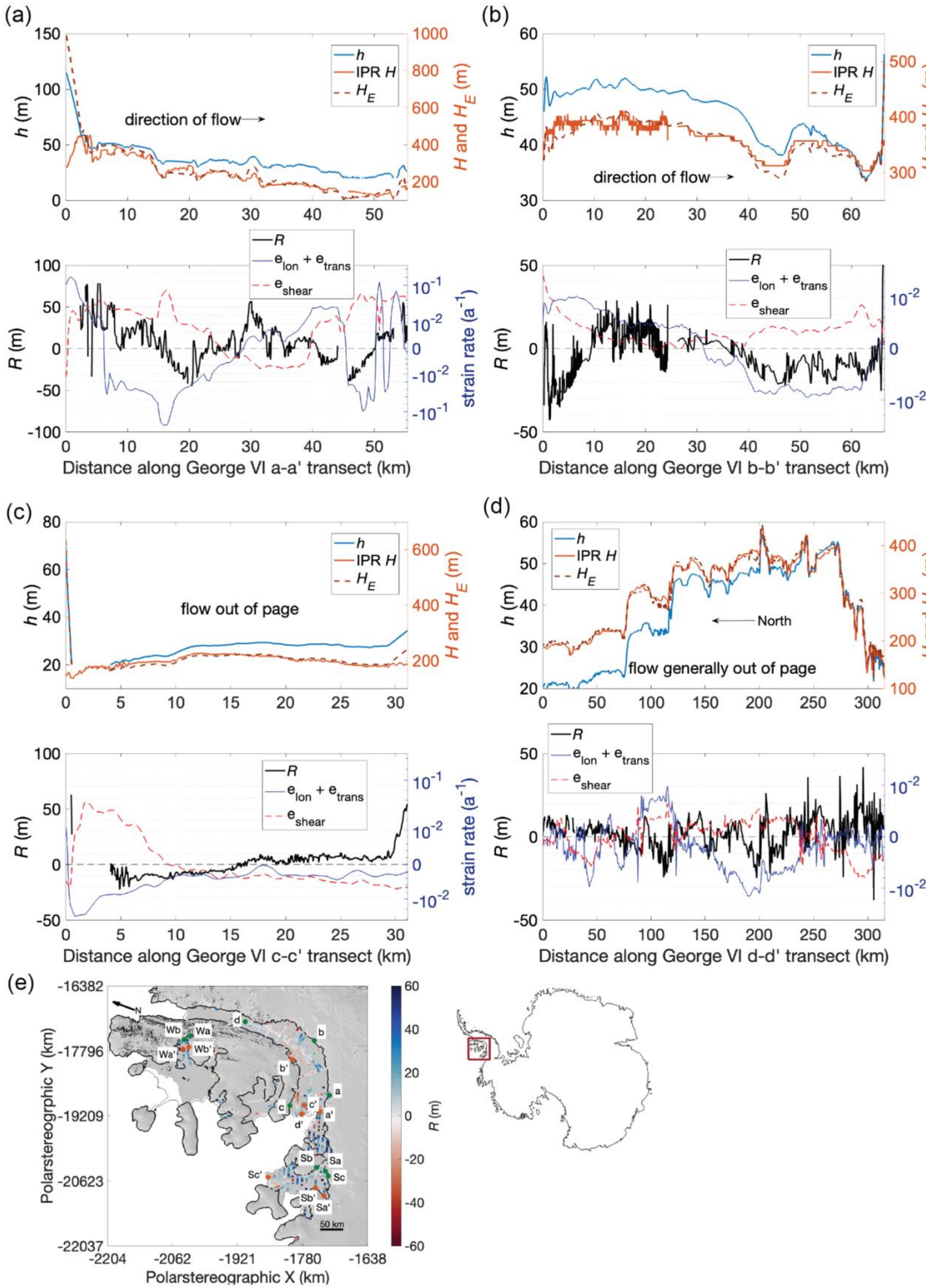

Figure S16. George VI/Wilkins/Stange Ice Shelf System, transects a-a' - d-d'.

On the Wilkins ice shelf, the northern portion of the ice shelf, including the embayment dotted with islands, exhibits a too high surface, with predominantly positive *R* values up to 50 m) (Fig. S17). In contrast, the southern portion of the ice shelf is associated with a surface that is predominantly too low (negative *R* values). Transect Wa-Wa' and most of Wb-WB' (10-30 km along track) show that changes in *R* are generally inversely related to changes in *H* (Fig. S17), in contrast to what was seen on the George VI ice shelf. This indicates that the surface topography is somewhat muted compared to the thickness profile.

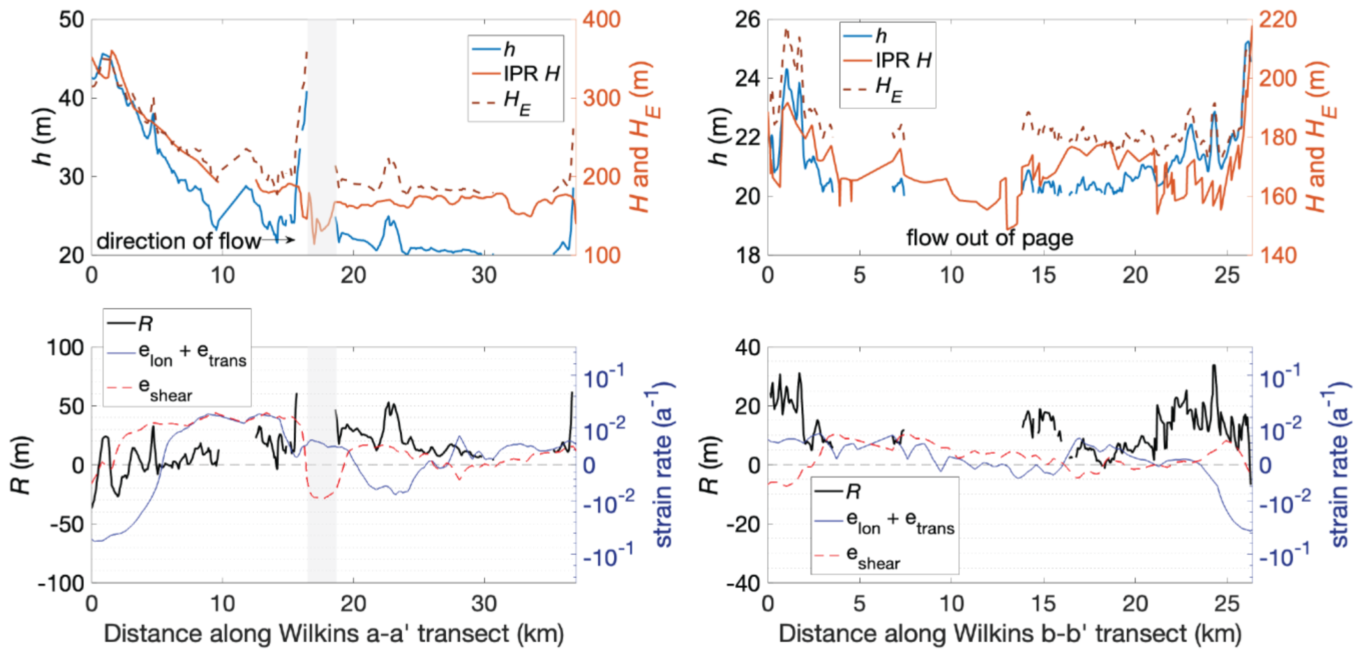

Figure S17. George VI/Wilkins/Stange Ice Shelf System, transects Wa-Wa' and Wb-Wb'.

On Stange Ice shelf, thickness gradients are dominated by basal channels, and nearly all ground tracks that intersect basal channels show negative *R* values within the channel trough and less negative *R* values from 0.5 - 1 km on either side of channels (10, 35, and 51 km along Sa-Sa' (Fig. S18a), ~24 and 26 km along Sb-Sb' (Fig. S18b), ~20 and 110 km along Sc-Sc' (Fig. S18c)). The selected transects in this region show a generally positive relationship between changes in *R* and changes in *H*, in contrast to the Wilkins ice shelf. This indicates that the surface topography is exaggerated compared to the thickness profile. Spots where the ice is especially thin and the surface is especially too low are often associated with compressional strain rates, such as at the basal channel at ~35 km along Sa-Sa' (Fig. S18a), the two basal channels at 20-30 km along Sb-Sb' (Fig. S18b), and the shear margin with Spaats Island at ~55 km along Sc-Sc' (Fig. S18c). The transects also show that the surface is generally too high within a few hundred meters from the grounding line and too low over the next ~1 km before transitioning back to being too high, but more prominent is the association of negative *R* with thinner ice and positive *R* with thicker ice over scales > 10 km.

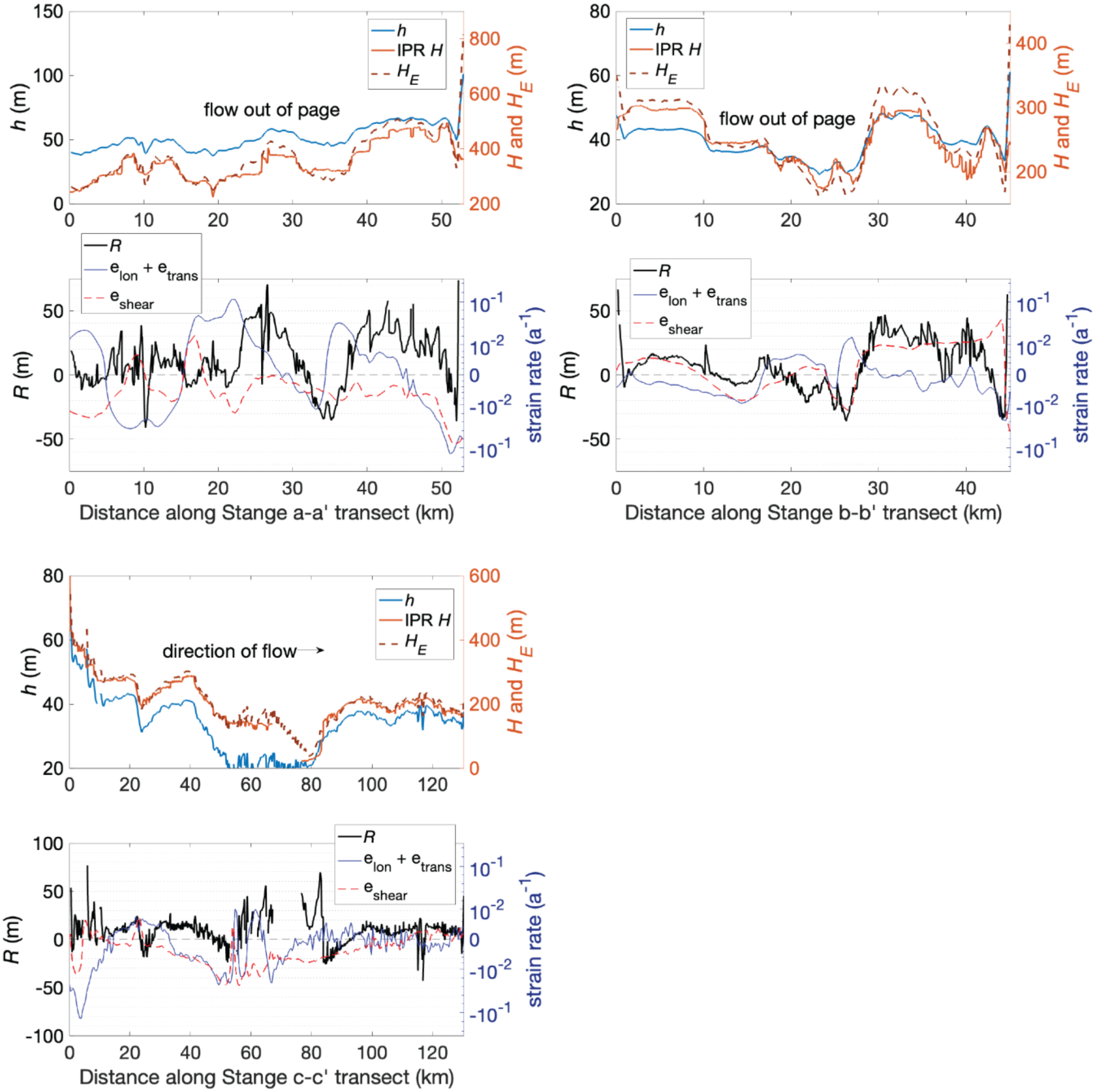

Figure S18. George VI/Wilkins/Stange Ice Shelf System, transects Sa-Sa' - Sc-Sc'.

S1.2.4. Abbot Ice Shelf

Abbot has coverage in a fairly regular grid. The easternmost part of the Abbot Ice Shelf is covered by several across-flow ground tracks, which show that the surface is predominantly too high, except within ~3 km of most intersections with the grounding line (Fig. S19 map). Some of the regions where the surface is too low close to the grounding line are characterized by surface troughs associated with previously mapped basal channels and high shear strain rates, such as at ~1 and 15 km along transect h-h' (Fig. S20d). However, transect h-h' shows that the basal channels at ~4 and 11 km further out in the ice shelf are associated with surface heights that are too high (*R* is positive). Changes in *R* are generally inversely related to changes in *H* over short length scales, but positively related over 10s of km in the faster flowing western trunk of this portion of the ice shelf (Fig. S19a and c).

In the central, less confined portion of the ice shelf, the surface is predominantly too low near the ice shelf front and near grounding lines and locally grounded zones around islands and ice rises (Fig. S19 map). The surface is predominantly too high where strain rates are low and ice velocity is relatively fast. Across-flow transect g-g' shows that changes in *R* and changes in *H* are generally positively related over length scales > 1km, so that the surface is generally too high when the ice is thick and too low when the ice is relatively thin, except at two very thin spots at about 42 km (between two small ice rises) and 56 km (just downstream of an ice rise) along the transect (Fig. S19b). Except for the two thin spots, this indicates that the surface topography is generally exaggerated compared to the basal topography. Along-flow transect a-a' intersects a fairly large, high island in the middle of the shelf and shows that *R* generally decreases from the grounding line to ice front, with an exception where the ice thins drastically from ~55-69 km and 80-85 km along the transect (Fig. S19a). The relatively flat, slow-moving portion of the ice shelf upstream and to the west of the island intersecting transect a-a' from ~45-55 km is very close to balance.

In the western, more confined portion of the ice shelf, flow is generally to the north, so most of the North-South ground tracks between Eights Coast and Thurston Island follow the direction of flow. Selected transects b-b' and c-c' show that the surface and thickness profiles are well-correlated, and that the *R* profile is somewhat correlated in that the surface tends to be too high in thicker parts of the ice shelf and too low in thinner parts of the ice shelf (Fig. S19b-c). Notable exceptions to this pattern occur around 39 km along transect c-c' (Fig. S19c), from 0-6 km along d-d' (Fig. S19d), and from 0-10 km along e-e' (Fig. S20e). There are also several instances along these transects where such thin spots are associated with a highly compressional flow regime, for instance at ~75 km along b-b' (Fig. S16b), ~13 km and 62 km along c-c' (Fig. S19c), ~35 km along e-e' (Fig. S20a). In general, the surface is too low (*R* values are largely negative) within 1-15 km of the grounding line and too high (*R* is positive) toward the center of the ice shelf, becoming more out of balance as the ice becomes less confined at the western ice front. Here again, along-track variability in *R* is associated with large-scale gradients in ice thickness, with relatively thinner ice associated with negative *R* and thicker ice associated with positive *R* over distances of 10-20 km.

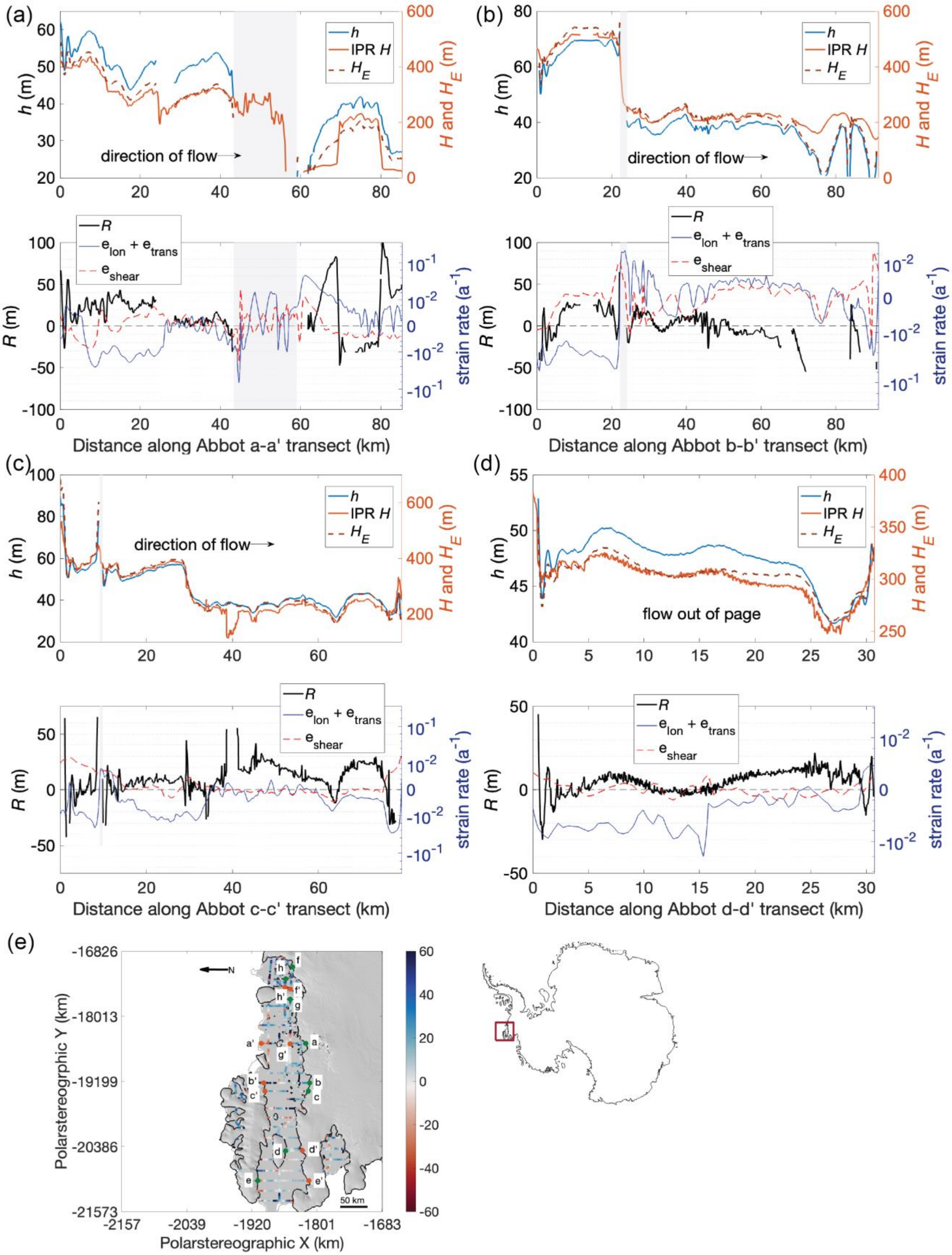

Figure S19. Abbot Ice Shelf System, transects a-a' - d-d'.

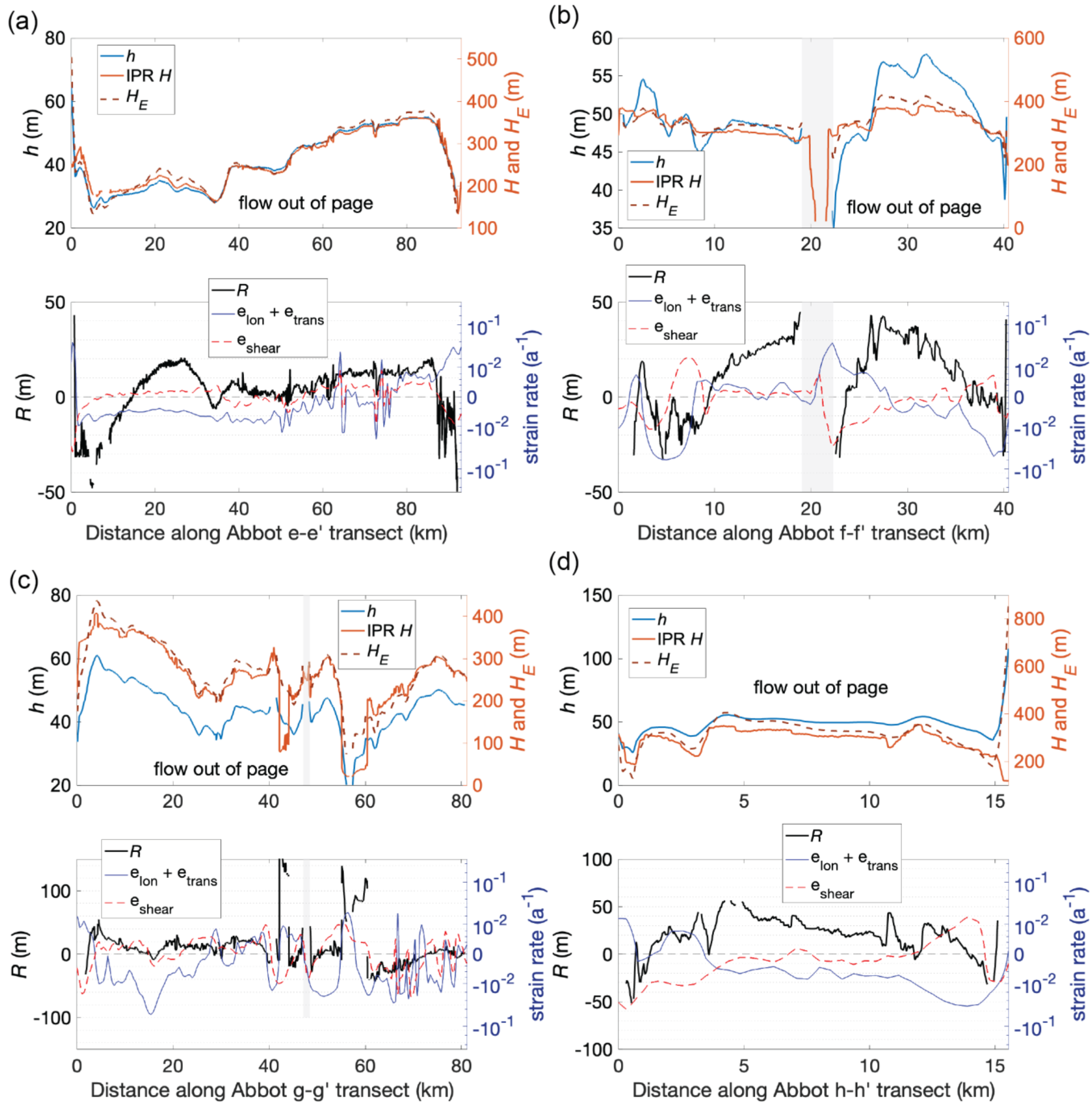

Figure S20. Abbot Ice Shelf System, transects f-f' - h-h'.

S1.2.5. Pine Island Glacier (PIG) Ice Shelf

PIG has OIB coverage in a fairly regular grid, as well as several oblique ground tracks and many tracks with repeat coverage. The surface is predominantly too high (*R* is positive indicating that the hydrostatic assumption overestimates ice thickness) on the PIG ice shelf, but there is large and small-scale variability (Fig. S21). The northern portion of the ice shelf (transect d-d', Fig. S21d and transect g-g', Fig. S22b) shows patterns similar to other shelves, exhibiting a surface too high (hydrostatic assumption predominantly overestimating ice thickness) within ~1-3 km of the grounding line, a surface too low (underestimating thickness) within ~3-10 km of the grounding line (see transect g-g', which is within 10 km of the grounding line along its length), and a surface too high (overestimating thickness) in the center of the ice shelf to the calving front. This portion of the ice shelf has three previously mapped basal channels, although OIB tracks intersecting the channels do not appear to show anomalous *R* values. However, at the northern end of the peninsula separating the northern and main portions of they ice shelf, there are transverse rumples (peaks with amplitudes of 10 - 20 m, separated by ~1.2 km) starting at about 5 km along transect d-d' that clearly show that the surface is too low where the ice is thinner, and too high were the ice is thicker (Fig. S21d).

On the main trunk of PIG ice shelf, the surface is predominantly too high in the center (transects a-a', and e-e', Fig. S21a and e) and along the edges of the floating ice where velocities are slow, and too low along the shear margins (transect f-f', Fig. S22a) and transect b-b' Fig. S21b). All along-track transects show that the surface is too high within 1-5 km of the grounding line, followed by a dip in *R* from ~0.5 - 5 km downstream. There is more small-scale variability in surface height, thickness, and *R* along transects f-f' and b-b' than the more central transects, and changes in *R* are more closely reflected by changes in surface height than changes in thickness, in contrast to other ice shelves (Fig. S21b, Fig. S22a). The relationship between changes in *R* and changes in *h* is generally positive for these two transects, indicating that the surface profile is generally exaggerated compared to the thickness profile. In contrast, changes in *R* along transect a-a' are more closely reflected by inverse changes in *H*, indicating that the surface does not accurately reflect the basal profile (Fig. S21a). Along e-e', changes in *h*, *H*, and *R* are well-correlated; from ~25-45 km along the transect, the surface is exaggerated (peaks are too high for hydrostatic imbalance and troughs are too low), and the surface is too high from ~50 km to the end of the transect where the ice surfaces are relatively flat (Fig. S22a). Across-flow transect c-c' also reflects the observations that the surface is too high close to the grounding line, too low in the shear margins, and predominantly too high in the relatively thicker center and western portions of the ice shelf (Fig. S21c).

There are several longitudinal basal channels in the main trunk of PIG, and those with heads that start near the grounding line are associated with higher *R* values on ~0.3 km on either side of intersecting MCoRDS ground tracks, however this is difficult to distinguish from the general variability in *R* across the ice shelf.

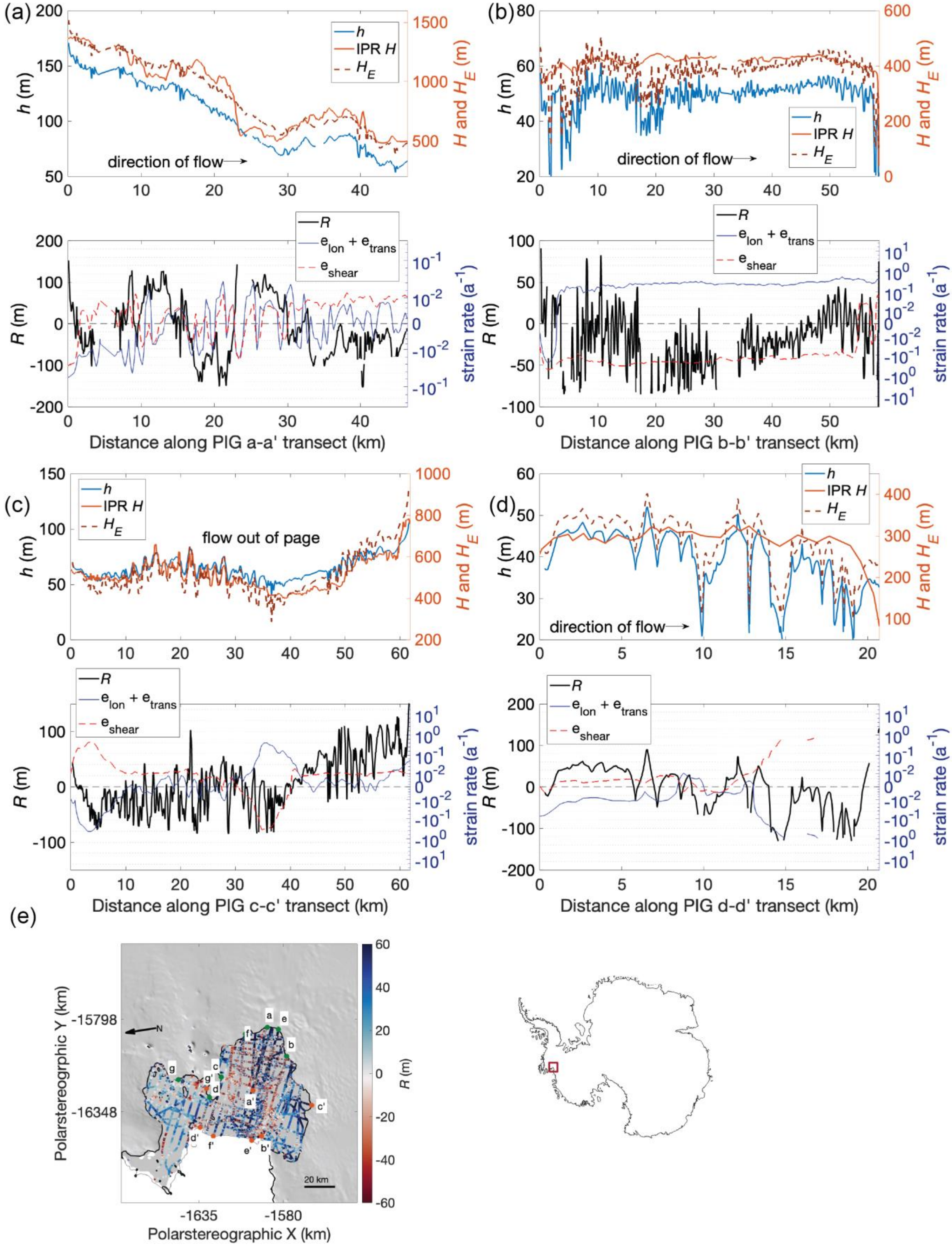

Figure S21. PIG Ice Shelf System, transects a-a' - d-d'.

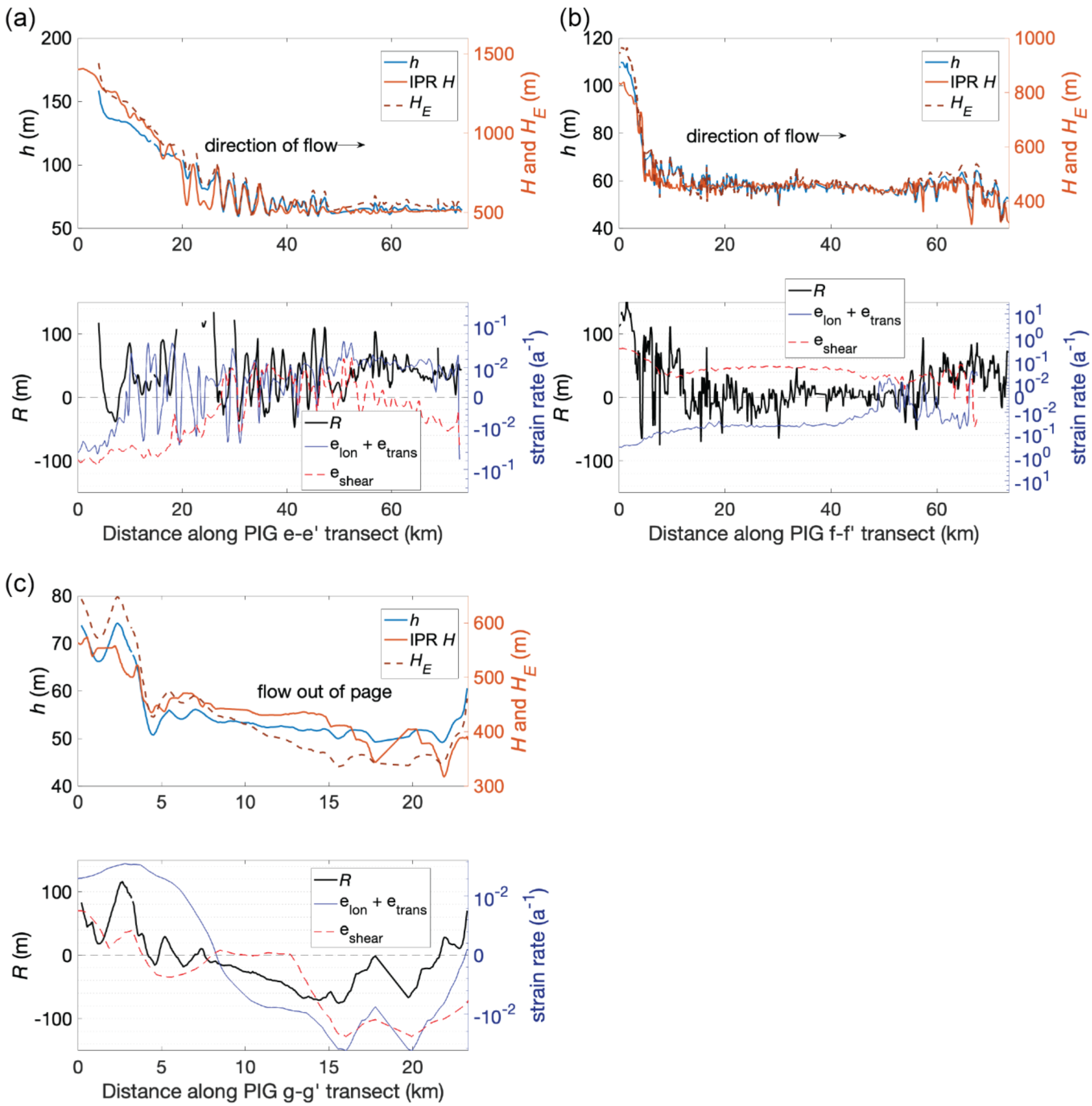

Figure S22. PIG Ice Shelf System, transects e-e' - g-g'.

S1.2.6. Thwaites Ice Shelf

There is irregular ground track coverage over the eastern part of the ice shelf, but close gridded coverage over the western part of the ice shelf. The eastern part of Thwaites ice shelf exhibits a surface that is predominantly too high (*R* is positive, Fig. S23f). Transect a-a' shows that the surface is too high within 1 km of the grounding line, and too low from 1-3 km of the grounding line, and that changes in *R* and changes in *H* are generally inversely related until ~17 km along-track, indicating that the surface topography is muted compared to the thickness profile, and generally positively related from ~15-30 km along track, indicating that the surface profile is exaggerated compared to the thickness profile (Fig. S23a). Transect b-b’ shows that the surface is too high at surface peaks and too low at surface troughs within 8 km of the grounding line, and that the surface is predominantly too high, particularly in the smooth midsection of the shelf (Fig. S23b). Transect b-b’ also shows that the surface is too low about 9 km upstream of the pinning point/island at the northern end of the eastern ice shelf, however thickness data is unavailable for the final ~4 km of the transect (Fig. S23b).

On the rougher, more broken up western part of the ice shelf, the surface is predominantly too high along smoother sections (Fig. S23e). Along rougher sections, particularly along transects d-d’ (Fig. S23d) and f-f’ (main text Fig. 5b), changes in R and changes in H are generally inversely related, indicating that the surface topography is muted compared to the thickness profile, or that surface lows are not well-aligned with thin points. Along transect c-c’, however, changes in R are more closely associated with changes in surface height, so that the surface is exaggerated compared to the thickness profile (Fig. S23c). In general, R values seem unrelated to strain rates, except for a few places where extremely compressive or extensional strain rates are associated with a surface too high or too low, respectively.

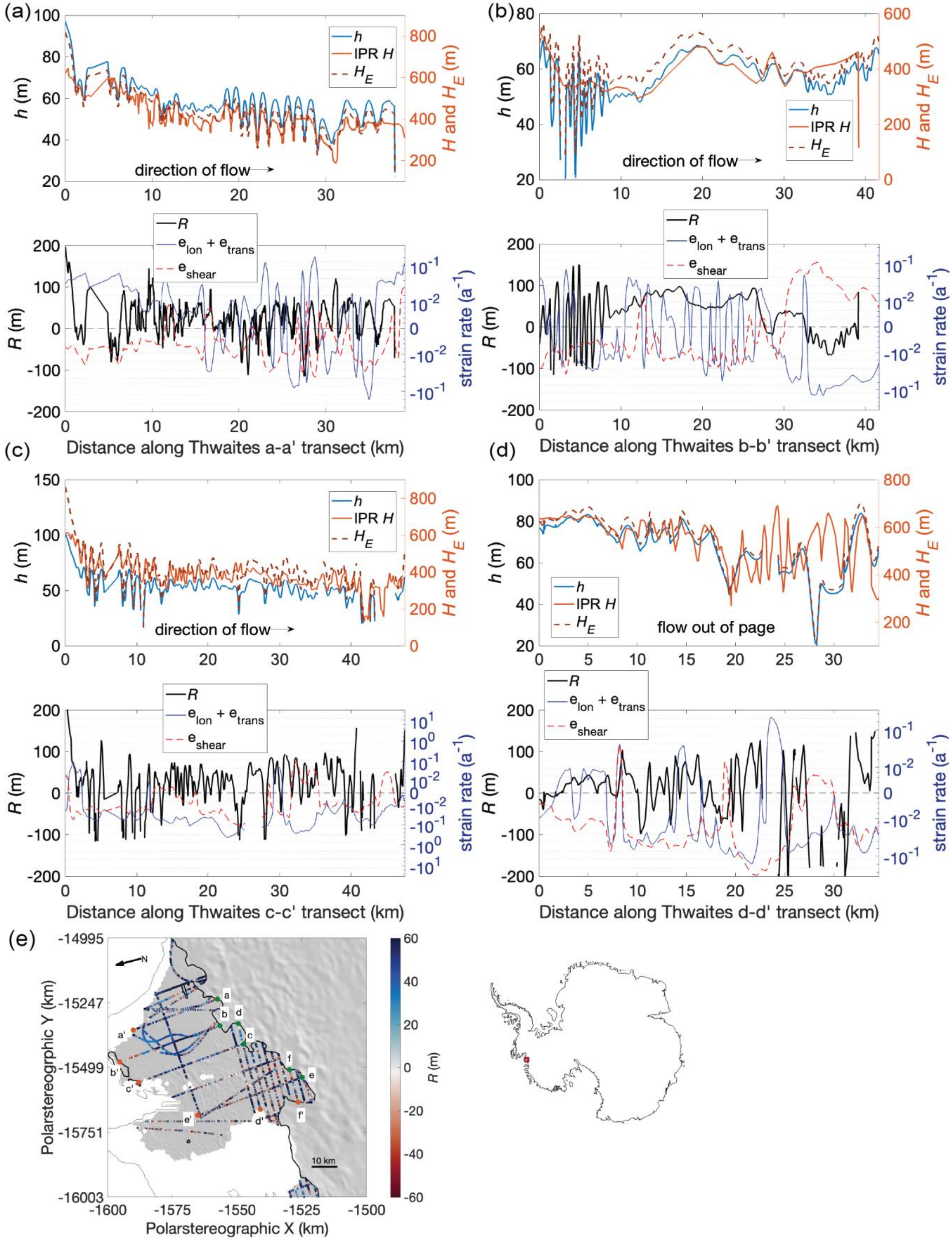

Figure S23. Thwaites Ice Shelf System, transects a-a' - d-d'.

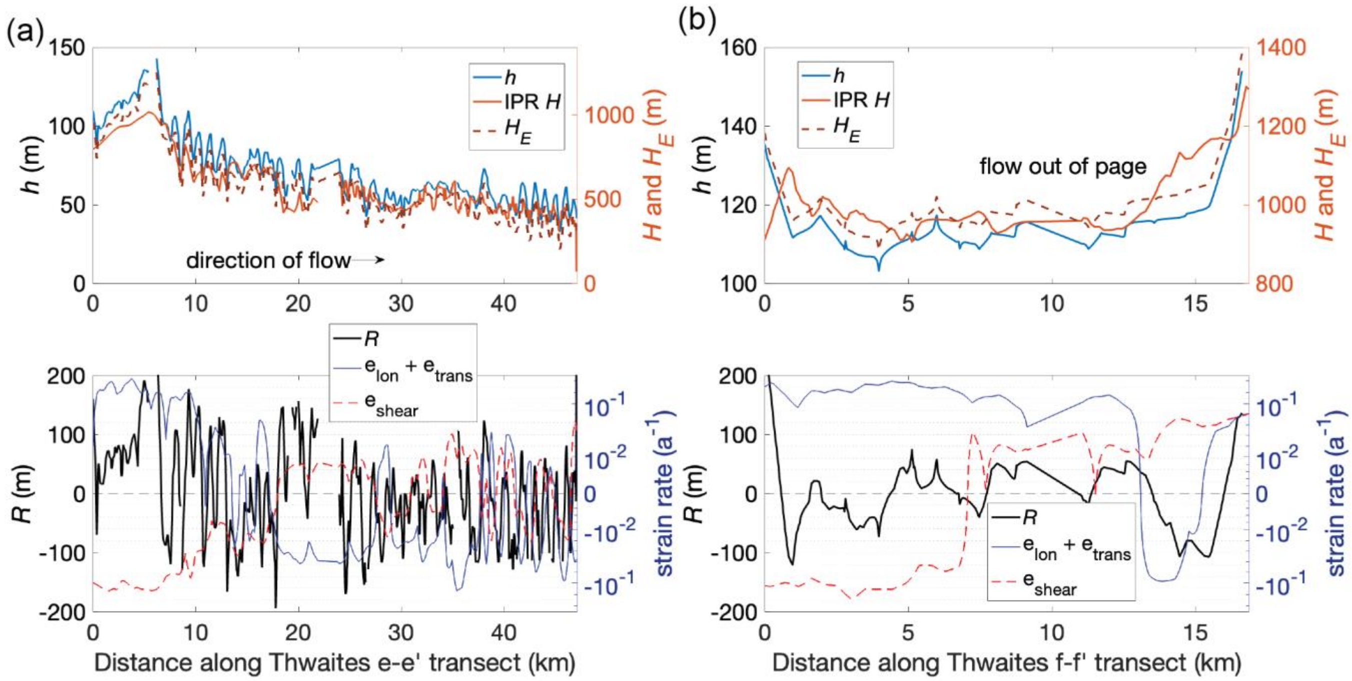

Figure S24. Thwaites Ice Shelf System, transects e-e' and f-f'.

S1.2.7. Dotson and Crosson Ice Shelf System

Overview: Ground tracks running north-south are spaced evenly across both ice shelves, although several on Crosson have insufficient data to calculate *R* across the entire ice shelf. There are fairly regular east-west ground tracks across both ice shelves. The negative median and mean *R* are dominated by Dotson ice shelf; Crosson ice shelf has mostly positive *R* values (Fig. S25e).

The usable OIB flight lines on Crosson ice Shelf are concentrated on the southernmost part, and exhibit largely positive *R* values, indicating that the ice surface is too high for hydrostatic equilibrium (Fig. S25e). Transect a-a' runs from west to east, starting where flow diverges between Crosson and Dotson ice shelves and continuing eastward to the Crosson calving front (Fig. S25a). This transect shows that the surface is predominantly too low within ~5 km of all grounding lines it intersects, and too high where the ice is relatively thinner near the Crosson calving front. However, from 0-~55 km along the transect, the surface is predominantly too high where the ice is relatively thicker and too low where the ice is relatively thinner, as has been observed on other ice shelves. Small scale variability generally indicates that the surface topography is muted compared to the thickness profile (Fig. S25a). Across-flow transects b-b', c-c', and f-f' (Fig. S25bd, S26b) also show that the surface is predominantly too low within ~5 km of the grounding line, although *R* is near zero or positive immediately adjacent to the grounding line. Transect b-b' also shows a clear inverse relationship between changes in *R* and changes in *H*, indicating that the surface topography is muted compared to the thickness profile (Fig. S25b), although c-c' shows that the surface is sometimes exaggerated and sometimes muted (Fig. S25c). The most notable exaggerations in transect c-c' are at the surface peaks at ~23 km, and the surface troughs/thin points at ~35 km and ~44 km. Similarly, changes in *R* along f-f' appear to be related to slight mismatches between surface peaks/troughs and thick/thin spots along the thickness profile, with some exaggerations in surface topography (e.g. surface peaks and troughs between ~10-20 km along the transect and the surface peak at ~29 km, Fig. S26b).

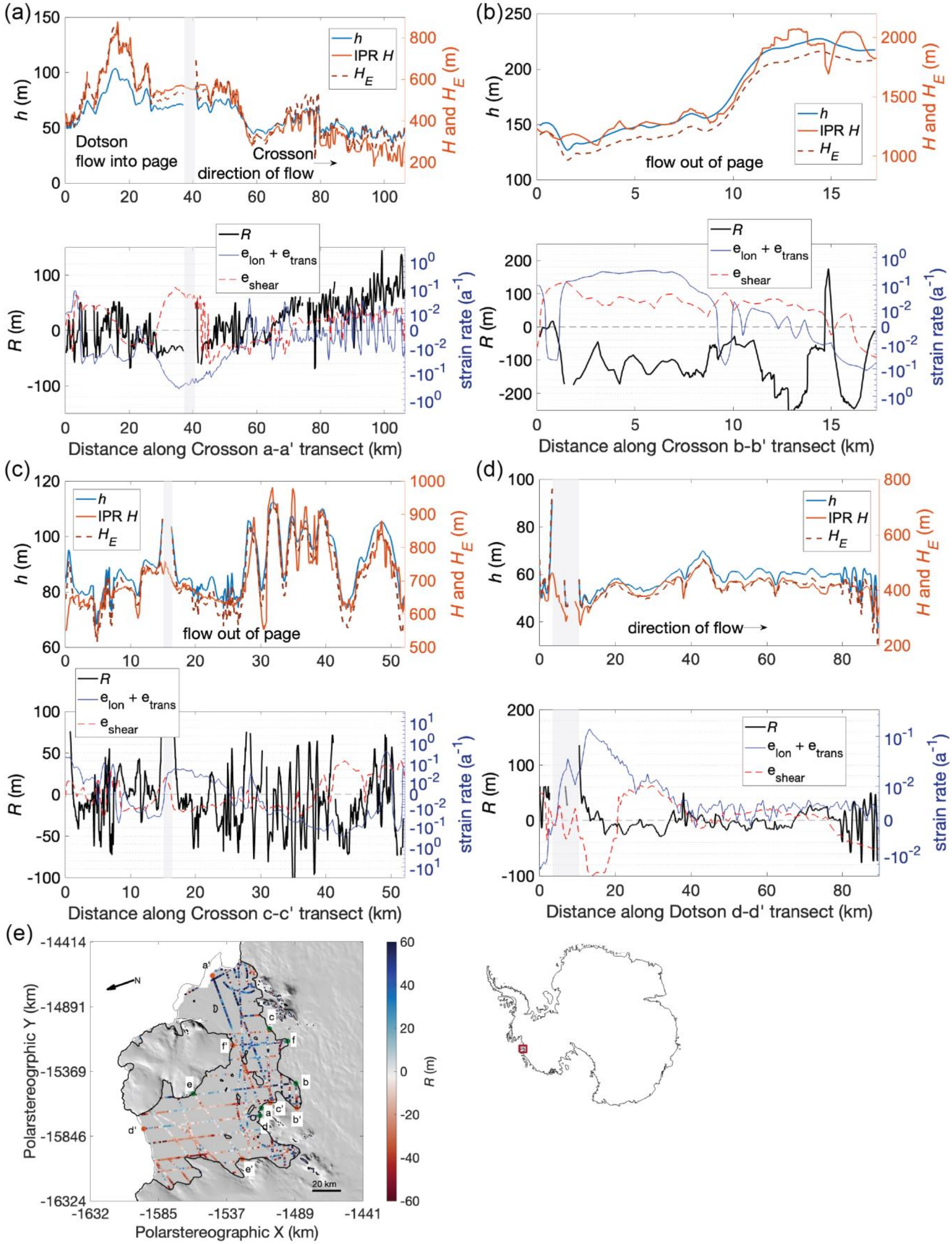

Figure S25. Dotson and Crosson Ice Shelf System, transects a-a' – d-d'.

The surface is too low for flotation (R is negative) in the shear zone where flow diverges between the Crosson and Dotson ice shelves and predominantly too low just north of the shear zone where the ice consistently flows north into Dotson ice shelf (Fig. S25e).

In the main trunk of the Dotson ice shelf, the surface is largely too low (R is negative) over most of the ice shelf, particularly over smoother sections (Fig. S25e). Transect d-d' exhibits no consistent relationship between changes in R and H or h, but show that the surface is predominantly too high surrounding the island it intersects, and predominantly too low along the rest of the transect except for the region between ~70-80 km along the transect (Fig. S25d). Transect e-e' shows that the surface is too low near its intersections with the grounding line (in shear margins), and it also intersects several basal channels (Fig. S26a). For the three more central basal channels/thin spots, the thinnest point is slightly west, or to the true left, of the deepest part of the surface trough, resulting in the surface being too low on the true right flank of the trough and too high on the true left flank, at ~25-40 km (Fig. S26b). This is somewhat surprising, since it seems that the confinement of Dotson tends to apply stresses which keep the surface lower than flotation; evidently local bridging stresses over 0.5-2 km distances are enough to keep the surface from settling due to the thinning from below. In contrast, the troughs/thin points at ~12 and 57 km along the transect align well, and the surface is too low on both flanks. Unlike most other ice shelves, the surface is not predominantly too high at the calving front despite undulations and fractures. There do not seem to be strong associations between R and normal or shear strain rates.

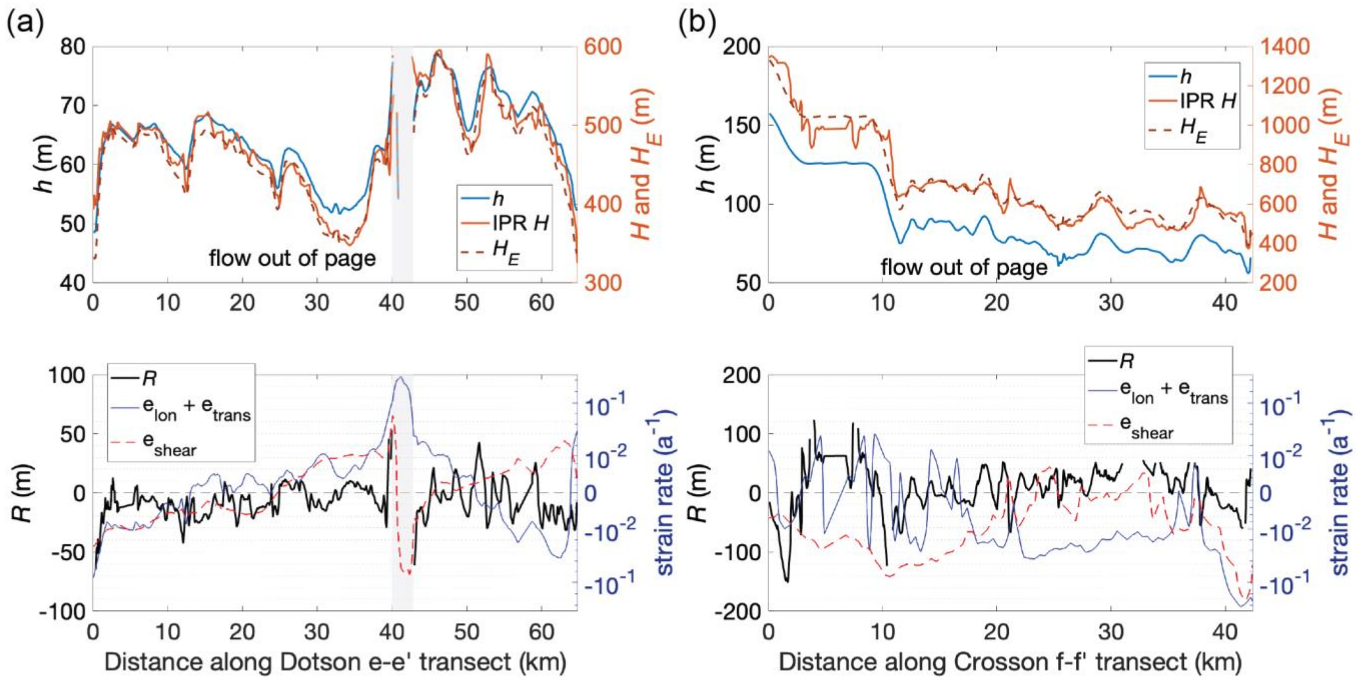

Figure S26. Dotson and Crosson Ice Shelf System, transects e-e' and f-f'.

S1.2.8. Getz Ice Shelf

There is fairly regular transverse coverage across the entire ice shelf, with some longitudinal ground tracks on the far eastern, central, and western portions of the ice shelf. The far eastern portion of the ice shelf exhibits a general pattern of the surface being too high within ~30 km of the southern grounding line and becoming too low as the ice thins toward the ice shelf front (transects a-a', b-b', and d-d', Fig. S27 a, b, and d). These three transects also show that the surface is too high where the transect intersects the grounding line, but too low at surface troughs located within ~3 km of the grounding line. This is consistent with the flexure of grounding zones that induces a low point in surface topography between the point at which the ice lifts off the bed and the point at which the ice floats freely. However, as observed downstream of Foundation ice stream (main text Fig. 6a) and Dotson ice shelf (Fig. S26b), several of the points where a-a' intersects basal channels show that the surface is too low on the true right flank of the surface trough and too high on the true left side, coincident with mismatched lows in the surface and thickness profiles and more compressive strain rates than the surrounding area (Fig. S27a at ~-1545 km and ~-1520 km). In general, changes in *R* are inversely related to changes in *H*, indicating that the surface topography is muted compared to the thickness profile, except for the final ~25 km of transect d-d', where the surface topography is exaggerated (Fig. S27d). Transect c-c' shows that relatively thicker ice tends to be associated with a surface that's too low and vice versa, in contrast to the other transects in this region (Fig. S27c). There does not seem to be a strong association between strain rates and *R* in this region, except for along c-c', where these quantities are loosely positively related.

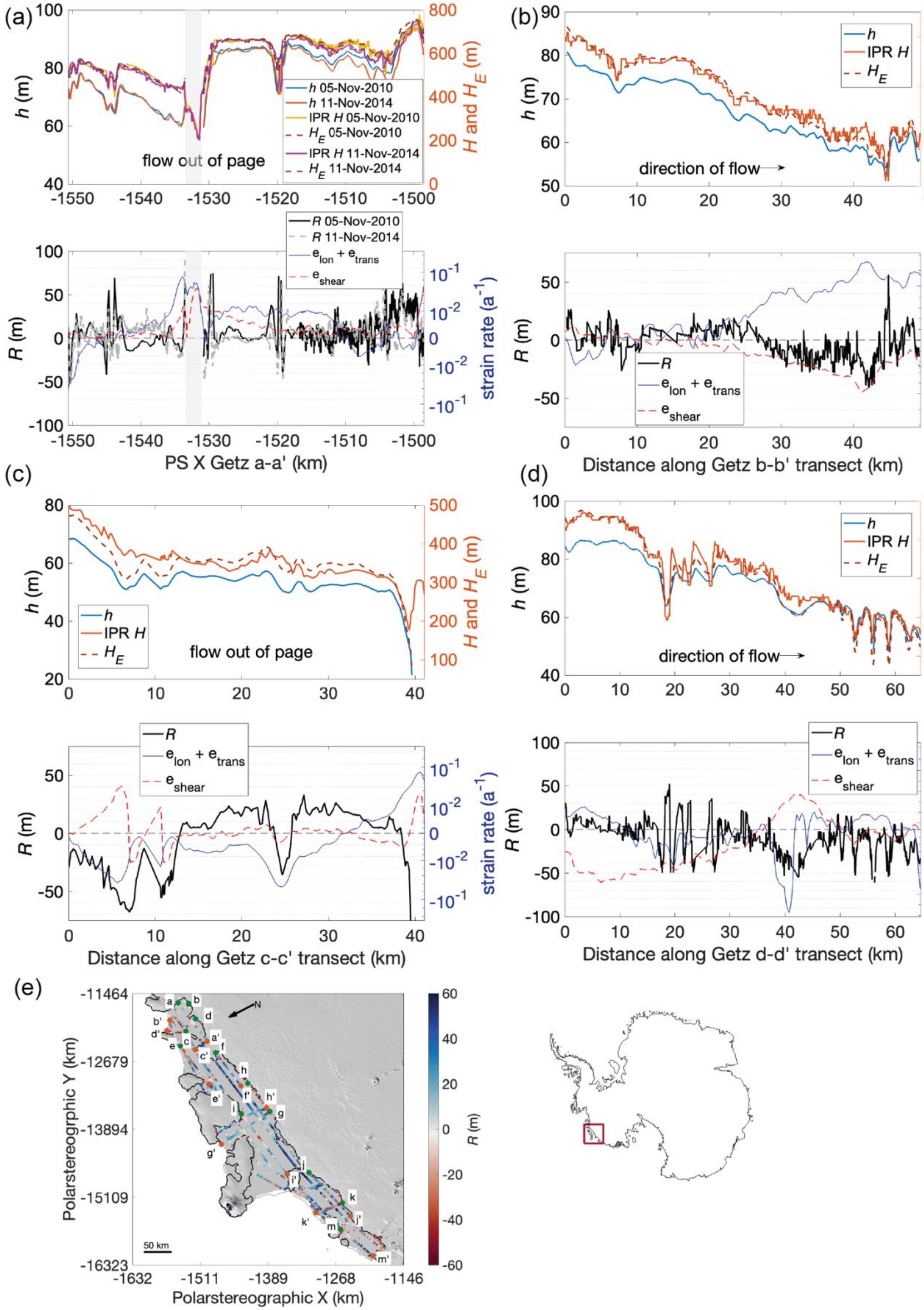

Figure S27. Getz Ice Shelf System, Eastern portion, transects a-a' - d-d'.

Moving west, transect e-e' shows a strong inverse relationship between changes in *R* and changes in *H*, indicating that the surface topography is largely muted relative to the thickness profile (Fig. S28a). The surface is generally too low where the ice surface is relatively smoother, such as between 4-12 km along-track and 65-80 km along track (shear zones), and too high within ~3 km of the grounding line. Upstream of transect e-e', the surface is consistently too high (positive *R* values), particularly where the ice is thicker and smoother (Fig. S27e). Transect f-f' intersects the relatively fast-moving ice flowing east of Carney island, and shows that the surface is predominantly too high, particularly past 20 km along-track (Fig. S28b). From 0-20 km along track, changes in *R* are positively related to changes in surface height, indicating the surface topography is exaggerated compared to the thickness profile. There are also two deep surface troughs (11 and 20 km along-track) that exhibit a surface too low on the true right flank of the trough and a surface too high on the true left flank, as has been seen elsewhere and is discussed in main text Section 4.2.3. These surface troughs are also associated with highly compressional strain rates. In contrast, a channel at ~55 km along track exhibits an anomalously high surface at the trough/thinnest spot (Fig. S28b). To the west of f', the ice moves relatively slowly, and flow diverges around Carney Island, moving northeastward to the east and northwestward to the west (Fig. S27e).

Transect g-g' runs along-flow in the trunk of the ice shelf between Carney and Siple Islands, and exhibits a largely positive relationship between changes in *R* and *H* over 10s of kilometers, but an inverse relationship over shorter distances (Fig. S28c). However, the surface is predominantly too high along this transect. Transect h-h' runs transverse to the slow flow of ice south of Carney Island, and shows that the surface is predominantly too low, except at relatively thick points at about 5 and 45 km along-track, and thin points ~15 km and 30 km along track, and where it intersects the southern grounding line at 33-36 km along-track (Fig. S28d). Here, the flow regime is predominantly compressional, and changes in strain rates are generally positively related to changes in *R*.

To the west of Siple Island, the ice flows northwestward and the surface is predominantly too high, although closer to balance than most of the rest of the ice shelf (Fig. S27e). Transect i-i' shows that *R* generally becomes more positive as thickness increases from 0-40 km along track, then becomes inversely related to changes in thickness from 40-90 km along track, and generally unrelated on a large scale for the rest of the transect (Fig. S29a). The surface is much too high where the transect intersects two basal channels (thin points/surface troughs) at ~5 km and 82 km along-track. Strain rates along this transect appear largely unrelated to *R* and thickness, except for highly compressional strain rates associated with the thin points at ~5 km along-track and ~95 km along-track. However, strain rates are near zero where *R* is predominantly too low (~45-60 km along-track, Fig. S29a).

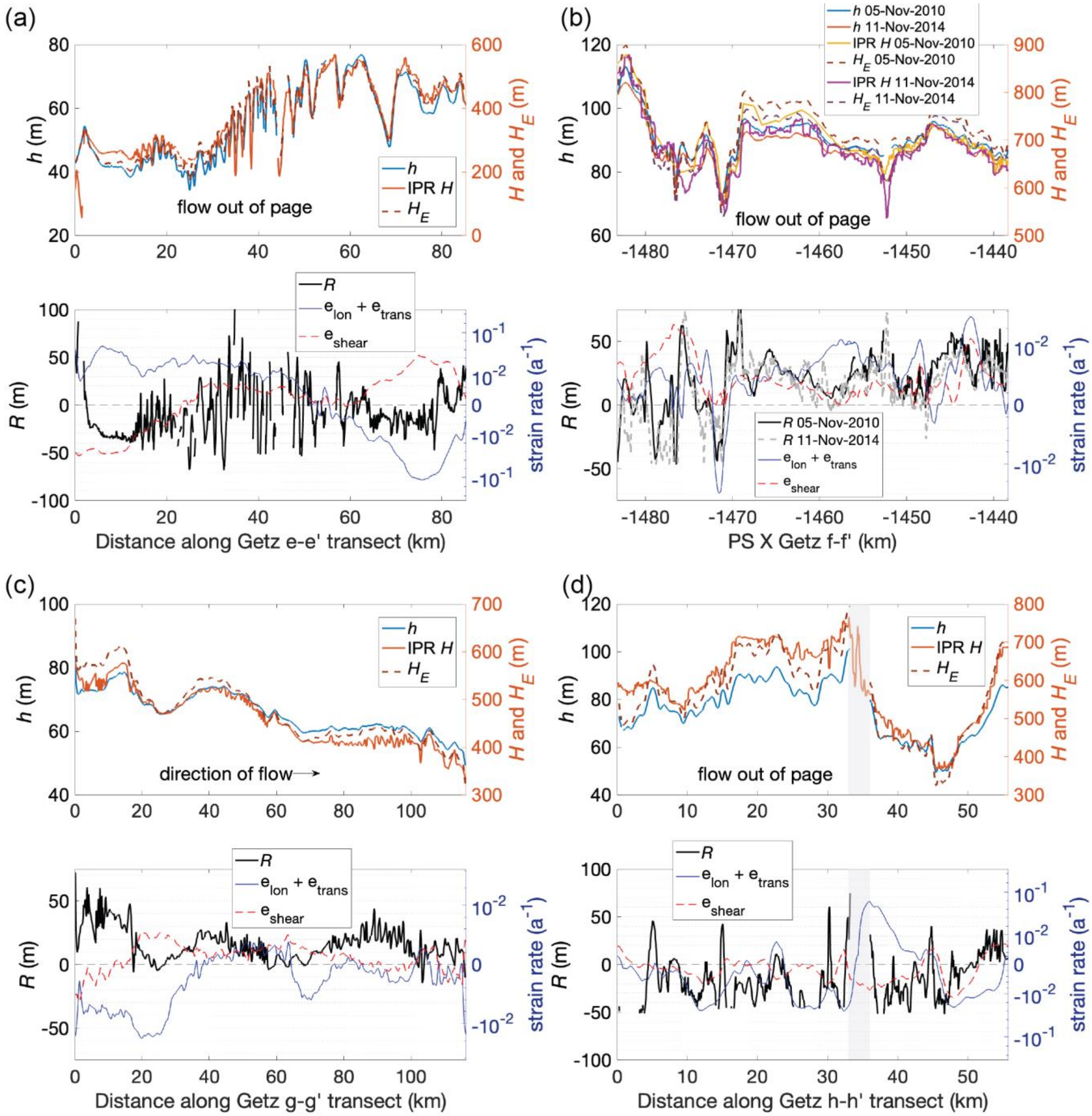

Figure S28. Getz Ice Shelf System, Central portion, transects e-e' - h-h'.

On the far western part of the ice shelf, the surface height is predominantly too high, but *R* is highly variable (Fig. S27e). Transect j-j' shows perhaps the greatest variability in *R*, but no clear general relationship between *R* and *H* (Fig. S29b). However, several thin spots/surface troughs show that the surface is too low on the true right/eastern flank, and too high on the true left/western flank of surface troughs (e.g. 5 km, 12 km, 40 km, 55 km, 72 km, 81 km), indicating that the surface and basal topography is mismatched. Like several transects on the far eastern portion of Getz, the surface is too high immediately near the grounding line, and too low at surface troughs ~5 km from the grounding line at both ends of the transect (Fig. S29b). Transect k-k' is similarly variable, and generally shows an inverse relationship between changes in *R* and changes in *H*, although there are some locations where the surface is exaggerated (too high at surface peaks and too low at surface troughs (Fig. S29c). On the furthest west portion of the Getz Ice Shelf, negative *R* values from ~1-30 km along transect m-m’ are associated with relatively thick, smooth, slow-moving ice where flow diverges around an island (Fig. S27e). Further west, changes in *R* are positively related to changes in surface height, indicating that the surface topography is exaggerated relative to the thickness profile. The intersection of transect m-m’ with the eastern grounding line exhibits a similar trough profile in which the surface is too low, but the intersection of the transect with the western grounding line shows that the surface is too high despite the presence of a surface trough and the thinnest ice along the transect. This region is also associated with extensional strain rates, unlike the eastern margin (Fig. S27e).

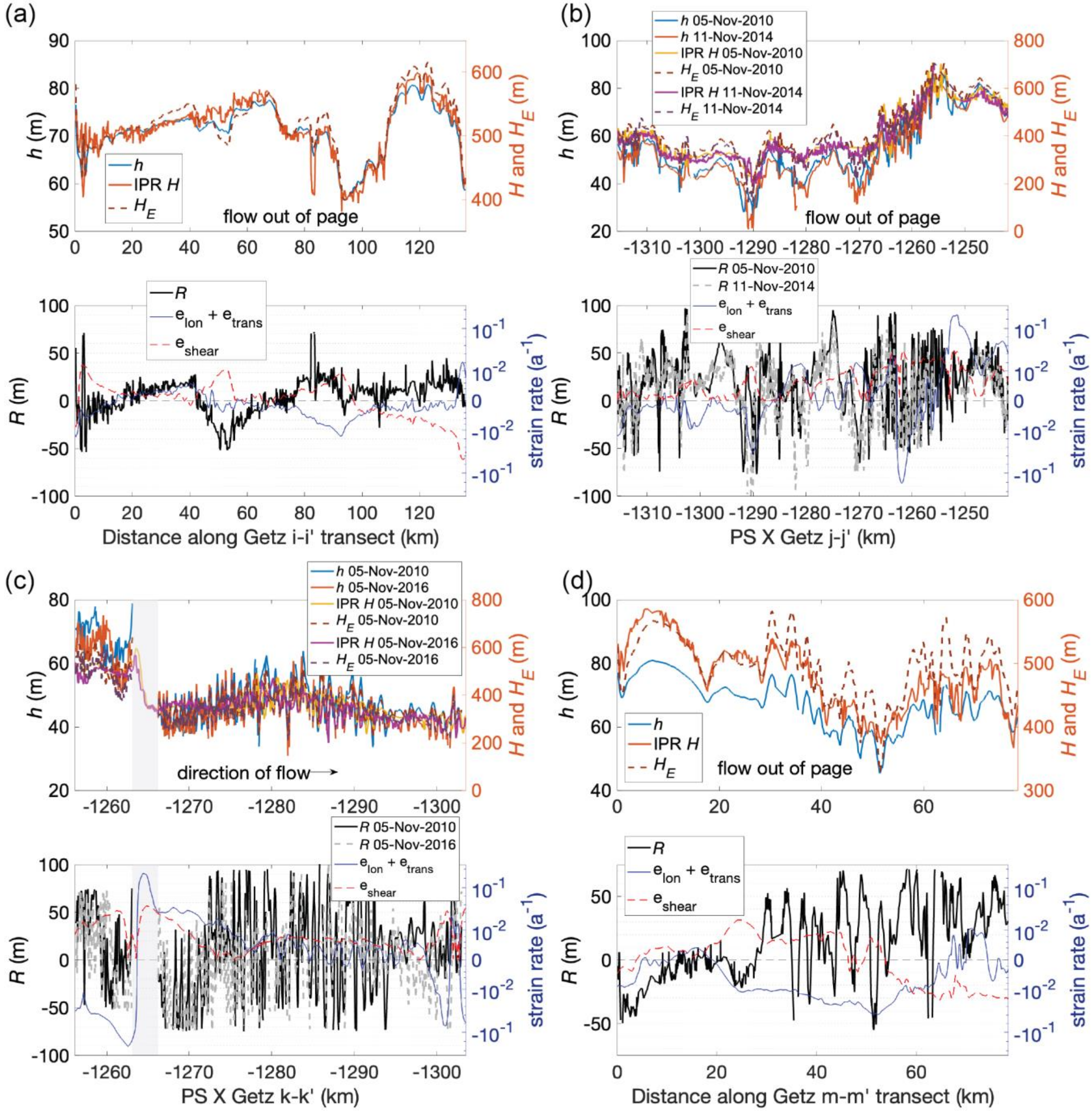

Figure S29. Getz Ice Shelf System, Western portion, transects i-i' - m-m' (the letter 'L' was skipped).

S1.2.9. Nickerson and Land Ice Shelf System

The Land Glacier ice tongue to the east of Nickerson has two along-flow ground tracks and four across-flow ground tracks. The Nickerson ice shelf has 4 across-flow ground tracks from 4 campaigns, with the most coverage in the center of the ice shelf. The Land Glacier ice tongue to the east of Nickerson ice shelf exhibits a surface that is predominantly too low near the grounding line, where ice is relatively thick, flat, and slow, transitioning to variable *R* as the surface becomes rougher downstream and strain rates become more extensional (Fig. S30d). Along-flow transect a-a' (Fig. S30a) and across-flow transects b-b' and c-c' (Fig. S30b-c) show that changes in *R* are generally inversely related to changes in H, indicating that the surface topography is largely muted compared to the thickness profile. Notably, where the across-flow ground tracks intersect with basal channels (~5 km, 7 km, and 13 km along b-b'; ~3 km, and 5 km along c-c'), the surface is too high for hydrostatic equilibrium, as observed on other ice shelves (Fig. S30b-c).

In the main portion of the Nickerson ice shelf, the surface is generally too low where the thickness and surface height profiles are rougher (transects d-d' and g-g', Fig. S30d, S31c) or near balance, particularly where the ice is relatively smooth (transects e-e' and f-f' Fig. S31a-b). Transect d-d' shows that the surface topography is generally exaggerated to the east of an ice rise near the shelf front, and too low to the west of the ice rise, where the ice is relatively thicker (Fig. S30d). Transects e-e', f-f', and g-g' all show that the surface is too low within ~3-8 km of grounded ice (Fig. S30). All transects in this region generally show an inverse relationship between changes in R and H over sub-km scales (except for the first few km of d-d'), although f-f' shows an inverse relationship between these quantities on a larger scale as well while g-g' shows a generally positive relationship over the entire transect. Based on the coverage available, there no clear association between R and strain rates on the Nickerson ice shelf.

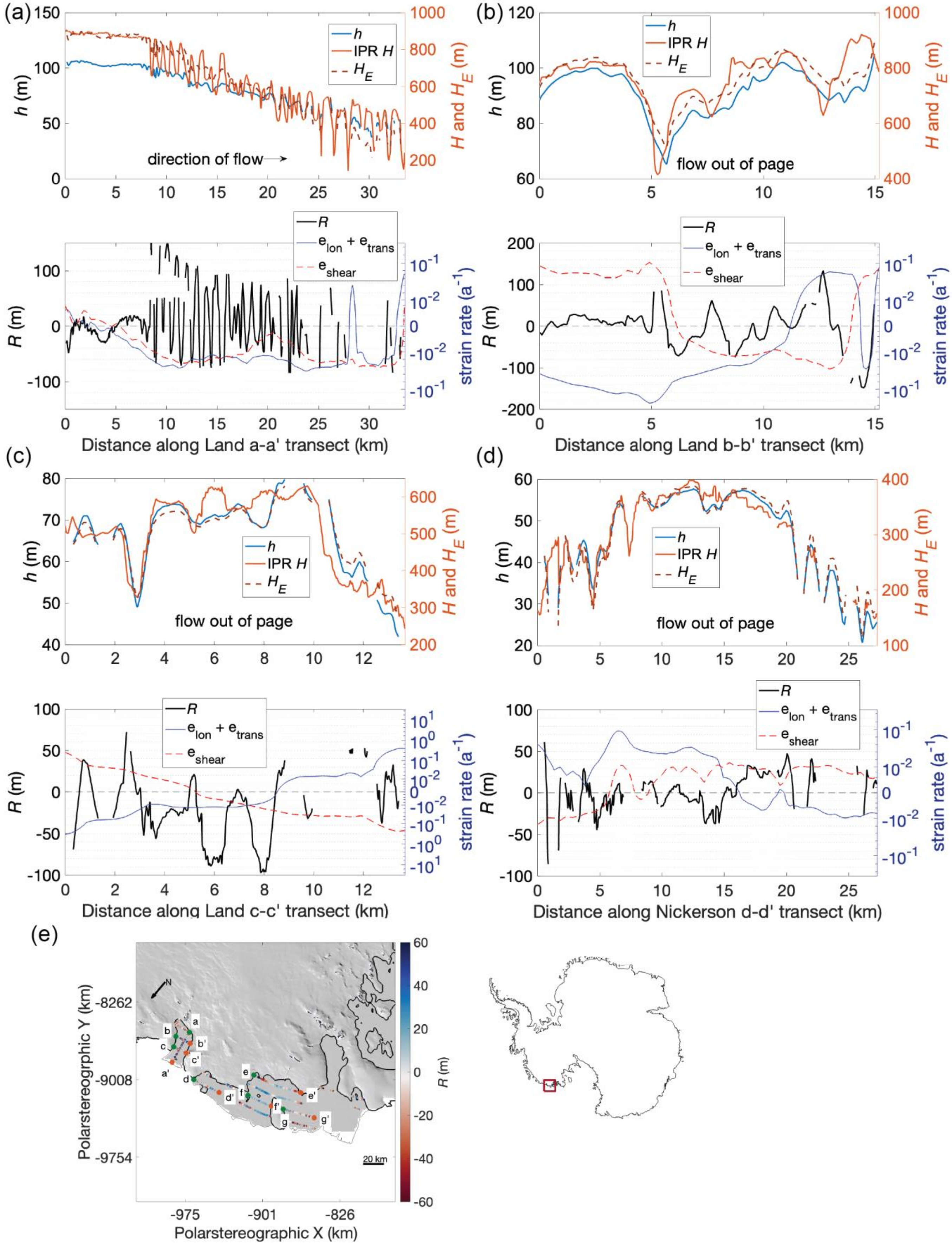

Figure S30. Nickerson and Land Ice Shelf System, transects a-a' - d-d'.

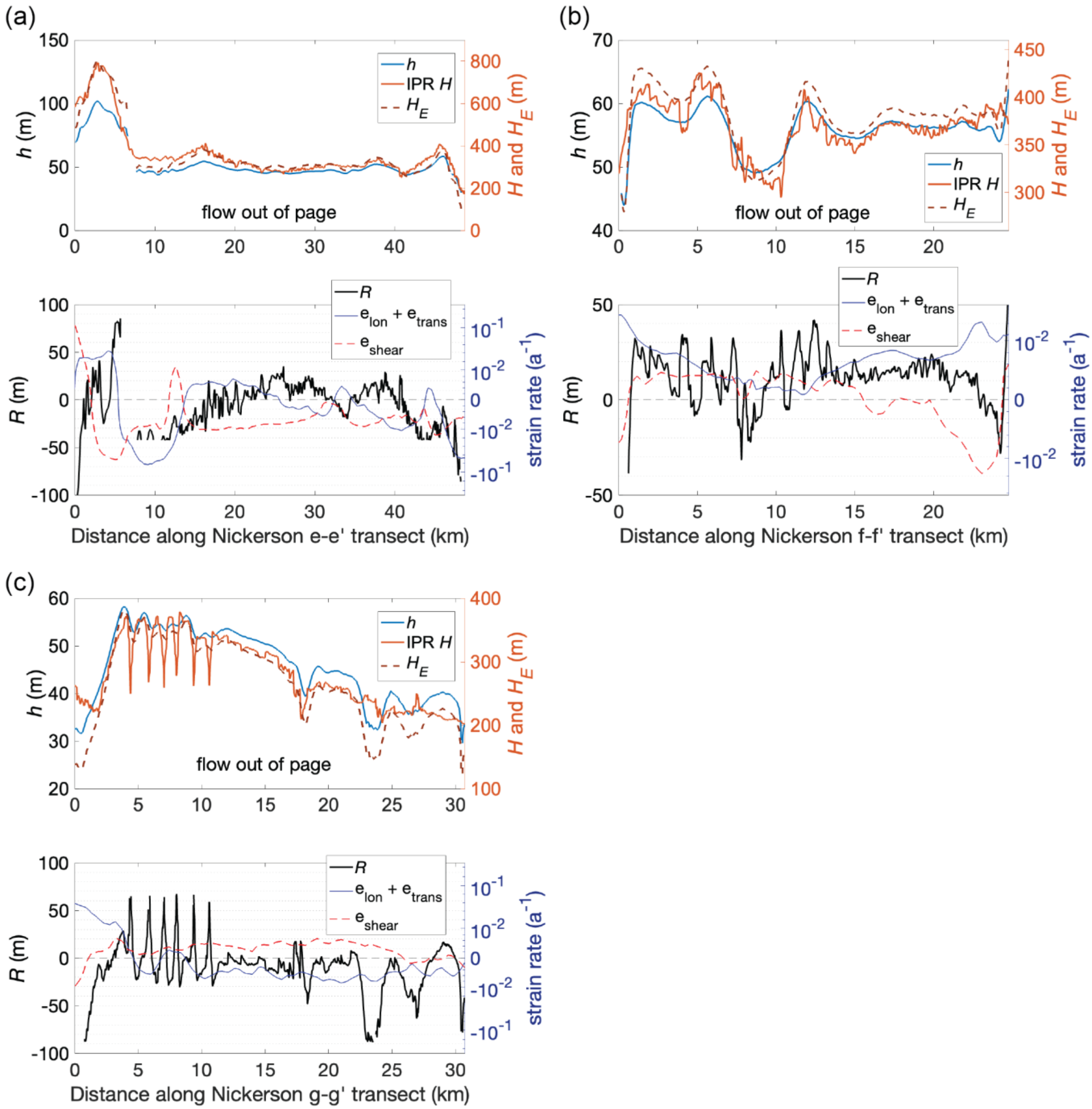

Figure S31. Nickerson and Land Ice Shelf System, transects e-e’ - g-g’.

S1.2.10. Western Ross and McMurdo Ice Shelf System

Overview: Coverage on Ross ice shelf is limited to a few ground tracks near the Hillary Coast along the Transantarctic Mountains, and a dense repeat grid on the McMurdo ice shelf just south of Ross Island. This area is covered by 39 campaigns. Along the Hillary Coast, *R* values are predominantly positive (indicating the surface is too high for hydrostatic equilibrium) along ground tracks covering relatively thick, smooth, and slow ice, with more variable *R* values where the ice surface is rougher (Fig. S30). Furthermore, the *R* values oscillate along transects a-a’ and b-b’, oriented parallel to flow, over lengthscales of < 2 km (Fig. S30a-b). In general, *R* is more positive (*h* is too high) where ice is thinner and more negative (*h* is too low) where ice is thicker along these ground tracks, indicating that the surface smooths out undulations in ice thickness.

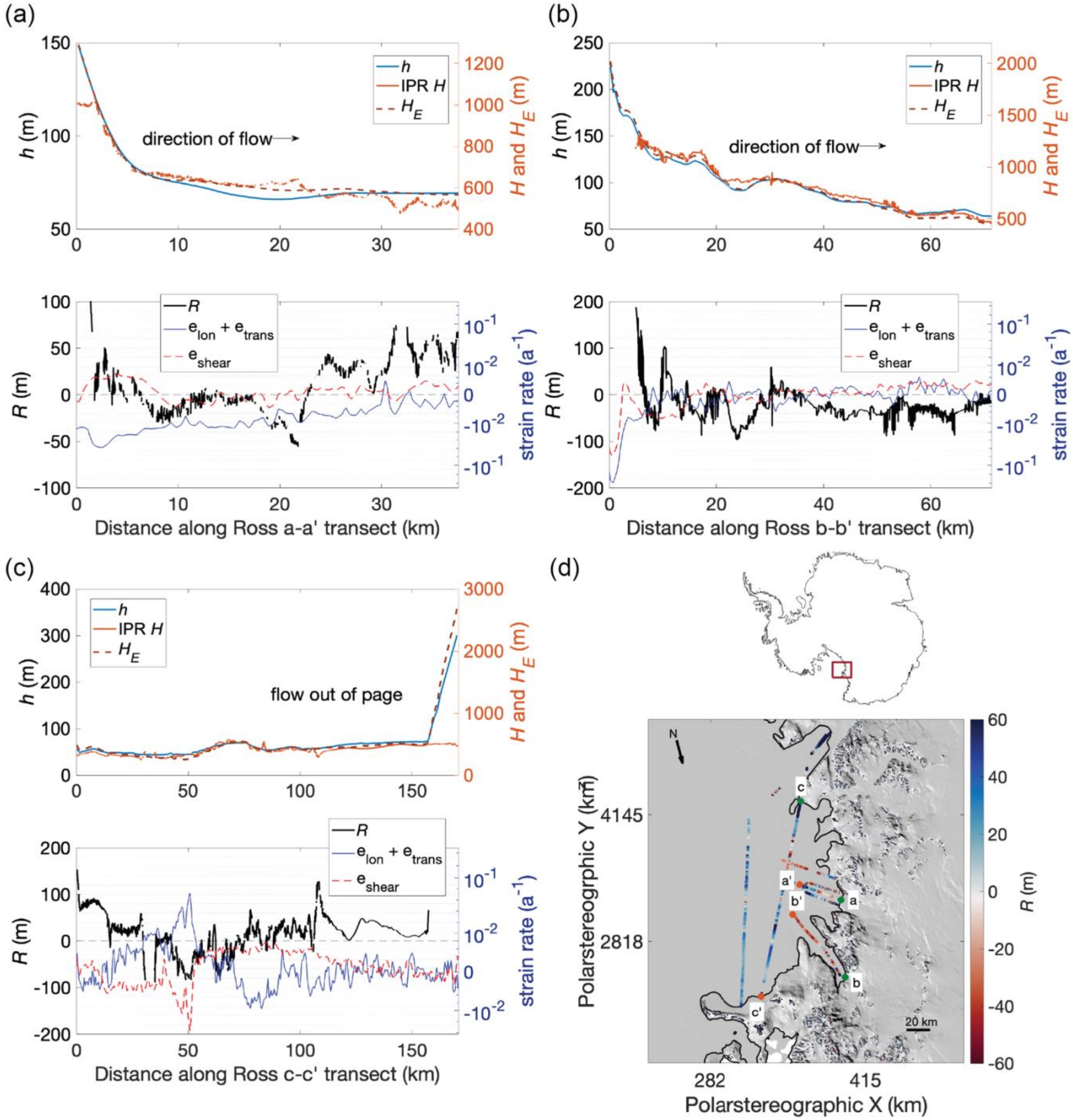

Figure S32. Western Ross and McMurdo Ice Shelf System, Western Ross, transects a-a' - c-c'.

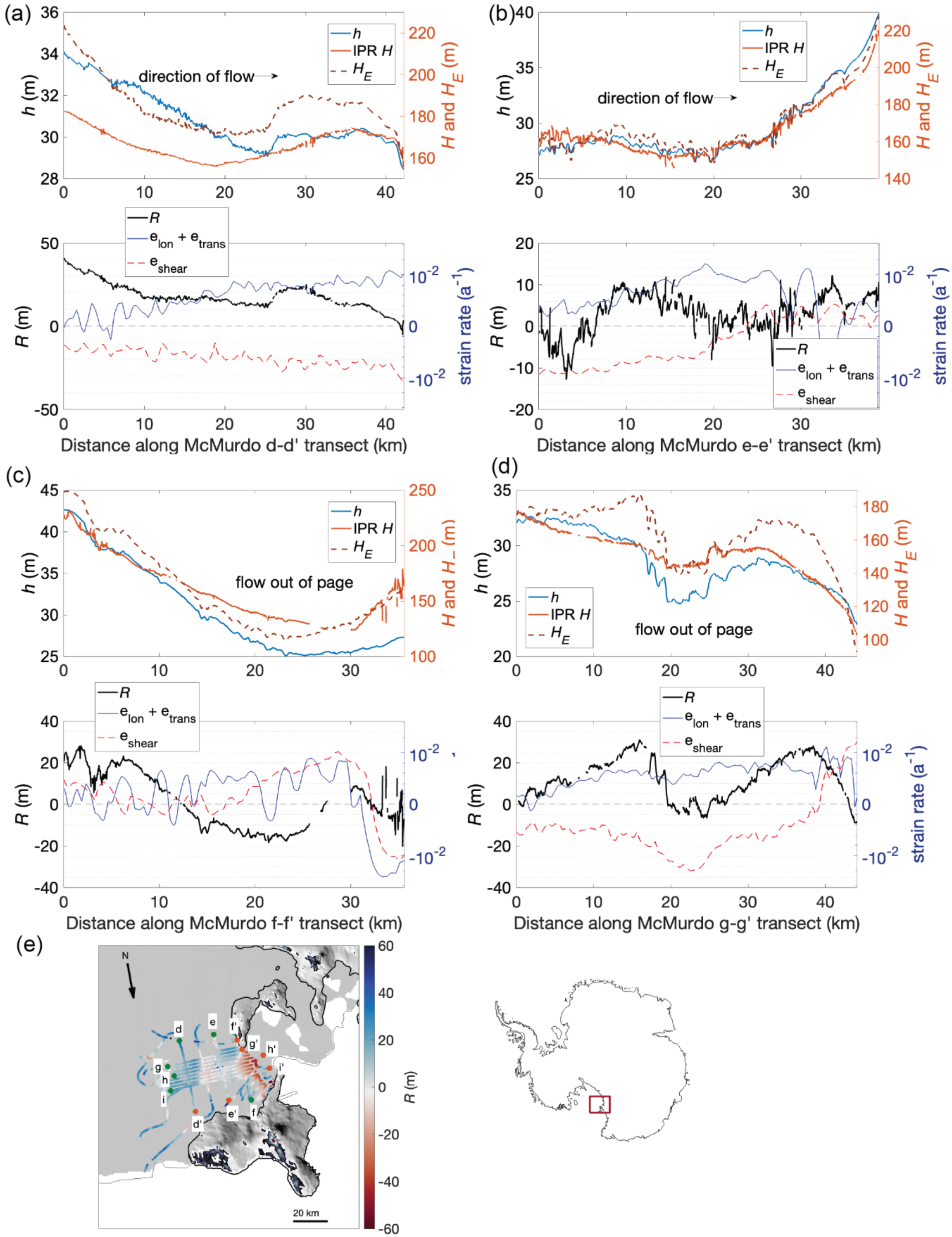

Figure S33. Western Ross and McMurdo Ice Shelf System, McMurdo region, transects d-d' - g-g'.

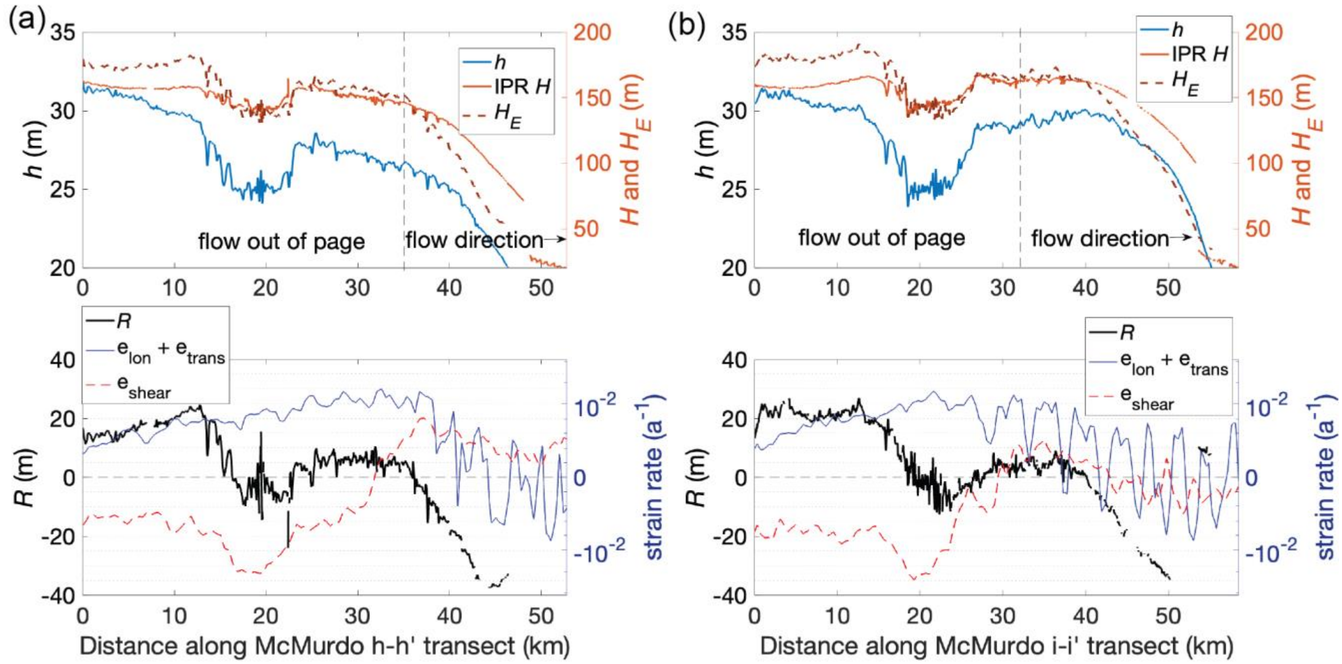

Figure S34. Western Ross and McMurdo Ice Shelf System, McMurdo region, transects h-h' - i-i'.

In the region of dense coverage near Ross Island, the crossovers of the HiCARS campaigns are very self-consistent, lending confidence to our assessment (see main text Section 5.1). The surface is consistently too low near the McMurdo/Scott Base peninsula (transect f-f', Fig. S33c; >20 km along transects g, h, and i (Fig. S33d, Fig. 34), with *R* becoming less negative and transitioning too positive to the east, as the ice becomes thicker and faster (Fig. S33e). The ice is largely balanced (*R* is close to 0) along the shear zone separating stagnant ice between the islands to northward-flowing ice to the east, around 20 km in transects g-g', h-h', i-i' (Fig. S33-S34). This region is largely flat, but small undulations (wavelength <1 km) at the surface are partly reflected in the ice thickness: i.e. when the ice is relatively thicker, *R* is relatively more negative (the surface is too low), and when the ice is relatively thinner, *R* is relatively more positive (the surface is too high), again indicating that surface undulations are not fully reflected in the ice thickness. This inverse relationship also occurs over longer distances along the transect d-d' near the easternmost end of Ross Island (Fig. 33a).

S1.2.11. Drygalski and Nordenskjold Ice Shelf System

Overview: Drygalski Ice Tongue and the smaller Nordenskjold Ice Tongue just south each have one along-flow ground track and one intersecting across-flow ground track. On Drygalski, the usable data does not extend to the unconfined ice tongue. For Nordenskjold Ice Tongue, *R* is predominantly positive, meaning that the surface is too high for hydrostatic equilibrium (Fig. S35a-b, e). However, on along-flow transect a-a', *R* is positive near the grounding line and transitions to negative from ~1-4.6 km downstream, coincident with a local minimum in the surface height, as has been observed on other ice shelves (Fig. S35a). The rest of the shelf exhibits variable *R* values corresponding with variable surface topography and ice thickness.

The Drygalski Ice Tongue likewise exhibits positive *R* values closest to the grounding line along the along-flow transect c-c’, although data is unavailable for the first 7 km of floating ice (Fig. S35c). As observed elsewhere, the change in *R* is inverse to the change in *H* along both transects. For the transect c-c’, there appears to be a regime change around 17 km from the upstream end of the transect: from 7.5-17 km, *R* is negative when *H* > ~1100 m, and past 17 km, the transition from negative *R* to positive *R* (and vice versa) occurs where the ice is ~900 m thick. The 17 km point is also where the longitudinal strain rate transitions from compressional to extensional (Fig. S35c). For the across flow transect d-d’, from 0-7 km, *R* is positive when *H* < ~1200, and from 7-15 km, *R* is generally positive where *H* < ~700 m thick, although some data is missing between 8 - 11 km along the transect (Fig. S35d).

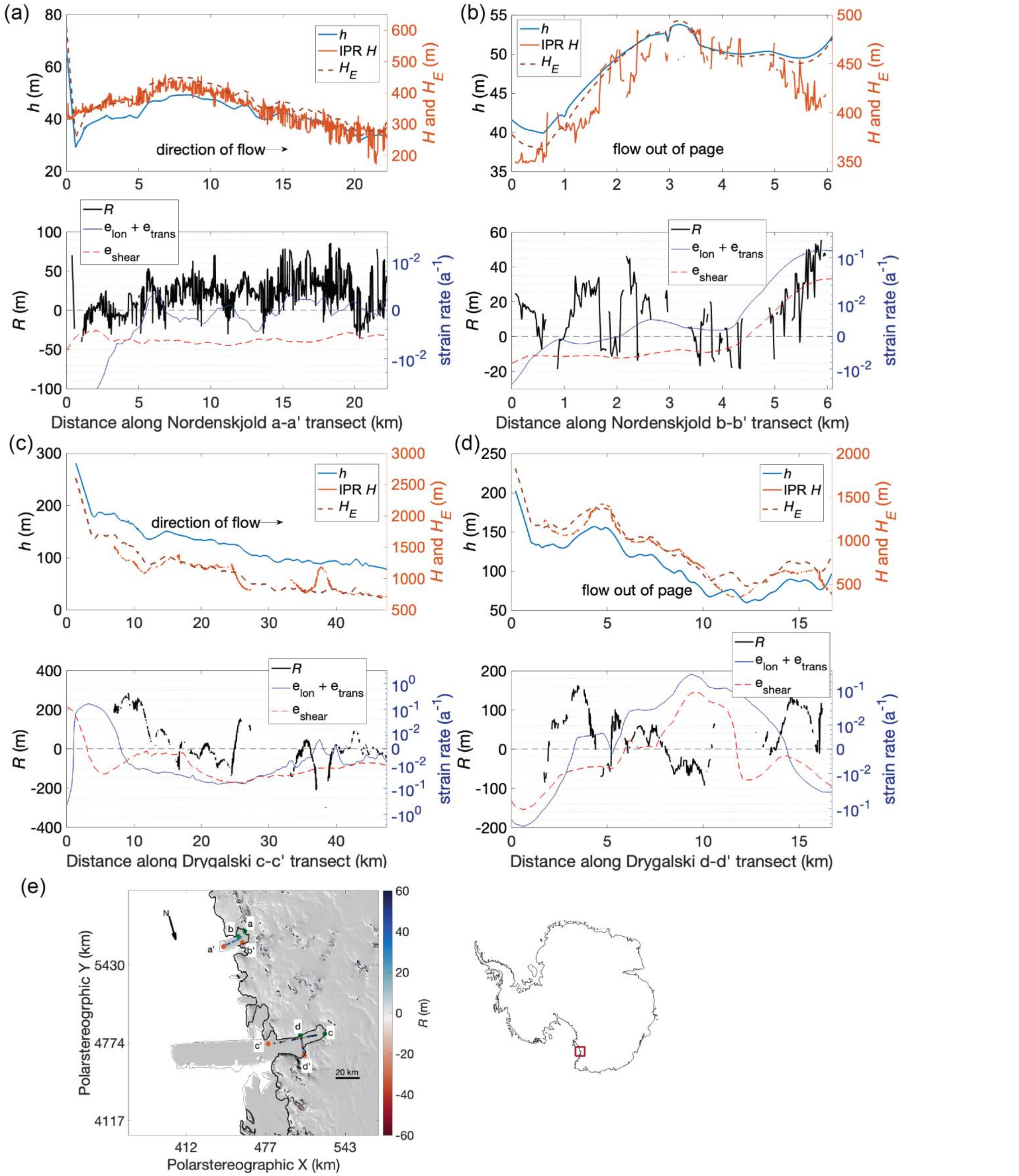

Figure S35. Drygalski and Nordenskjold Ice Shelf System, transects a-a' - e-e'.

S1.2.12. Cook Ice Shelf

There are two usable along-flow ground tracks from a single campaign from 04-Dec-2011. Both transects show mostly positive *R* values, indicating that the surface is too high for hydrostatic equilibrium/that thickness estimated using the hydrostatic equation overestimates ice thickness (Fig. S36). This is particularly evident as the ground tracks intersect several transverse surface features of amplitudes near 10 m spaced ~2 km apart: the surface is too high at surface peaks and and often too low at surface lows. Some of the surface peaks are associated with locally thinner ice, such as around 23 km and 25 km along transect b-b-', indicating that the surface does not accurately reflect the ice shelf base (Fig. S36b). On this largely unconfined ice shelf, it seems that the surface is predominantly too high for balance despite an extensional flow regime, indicating that strain rates may not be vertically uniform.

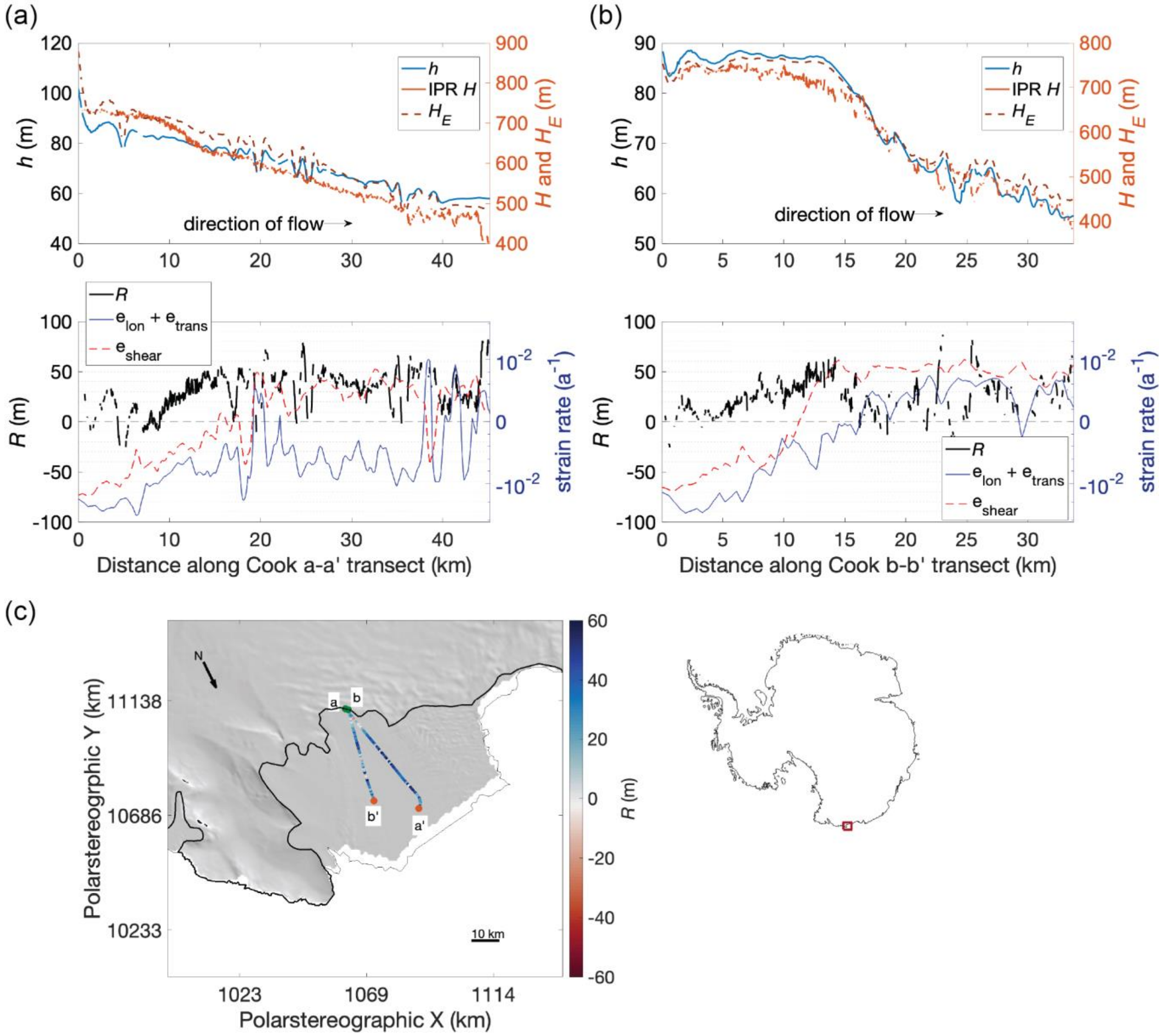

Figure S36. Cook Ice Shelf System, transects a-a' - b-b'.

S1.2.13. Ninnis Ice Shelf

There are two across-flow transects across Ninnis Ice Shelf, both from early December 2011. The *R* on Ninnis is predominantly positive, indicating that the surface is too high for hydrostatic equilibrium, although there is variability associated with surface topography (Fig. S37c). As seen on other shelves, changes in thickness and changes in *R* are inversely related, with thinner ice associated with a surface too high for hydrostatic equilibrium, and thicker ice associated with a surface too low for hydrostatic equilibrium. For transect a-a', the surface is too low (*R* < 0) within ~2 km of the southwestern grounding line, which is also a zone of compression along flow, while the surface is too high within ~2 km of the eastern grounding line, where there is extension along-flow (Fig. S37a). Transect b-b' also shows that the surface is too high at its peaks and too low at its troughs, indicating that surface features are exaggerated relative to basal features (Fig. S37b).

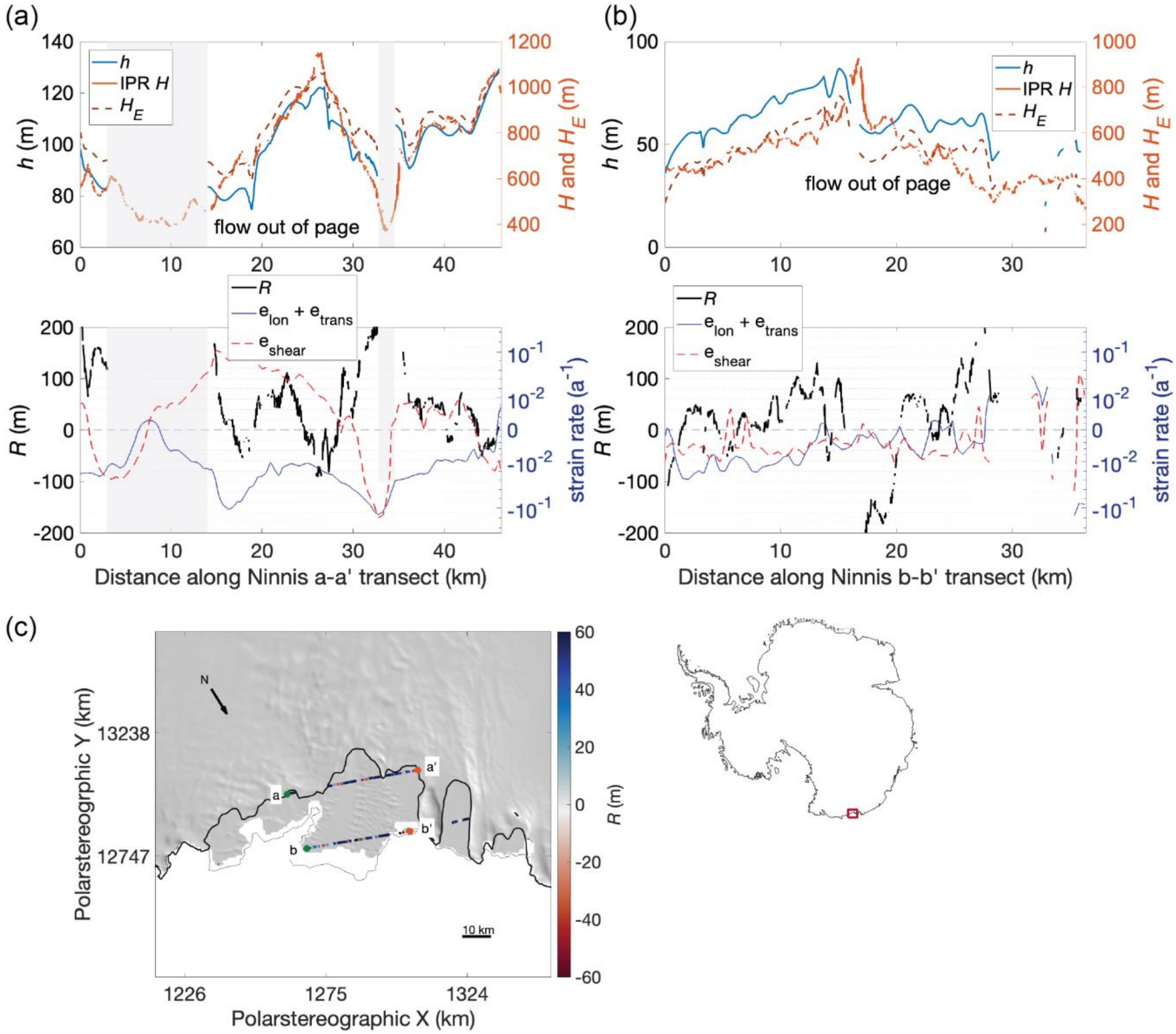

Figure S37. Ninnis Ice Shelf System, transects a-a' - b-b'.

S1.2.14. Mertz Ice Shelf

Overview: Mertz glacier has three across-flow ground tracks collected in early December 2011. The transects across Mertz exhibit similar patterns to Ninnis ice shelf: *R* is negative (surface is too low) where thickness is relatively high and the surface is relatively low), indicating that the surface overexaggerates highs and lows/thick and thin spots when used to estimate hydrostatic thickness (Fig. S38d). For transect a-a', the ice is thicker on the east side of the trunk, and the *R* is largely positive where along-flow strain is extensional, including near the grounding line on the east side (Fig. S38a). *R* is negative within 2 km of the grounding line on the west side, where normal strain rates are negative (compressional).

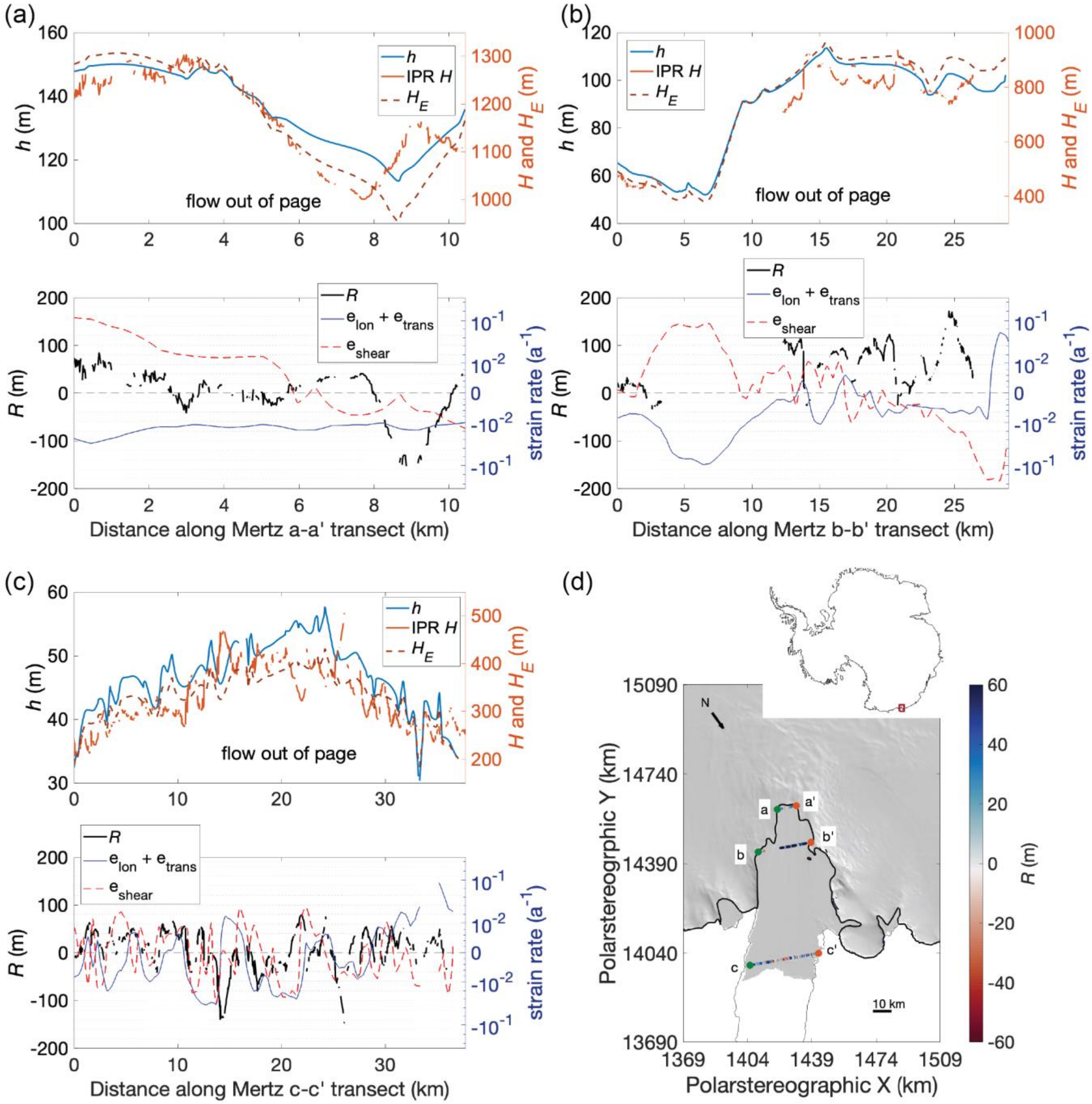

Figure S38. Mertz Ice Shelf System, transects a-a' - c-c'.

S1.2.15. Frost and Holmes Ice Shelf System

Overview: The ice shelves in Porpoise Bay were surveyed on 30-Dec-2009 and 03-Jan-2010, and six usable ground tracks are available. The ice shelves in this region are relatively rough and unconfined. Frost Glacier ice shelf in the east of the bay exhibits more variable *R* values than the larger Holmes Glacier ice shelf to the west (Fig. S39d). Transect a-a' shows a locally inverse relationship between changes in thickness and changes in *R*, although across the transect, *R* generally decreases as thickness and surface height decrease (Fig. S39a). The surface is too high (*R* is positive) at the eastern side of the embayment, and becomes too low at the western side, where the ice is thinner, and along-flow strain is extensional, transverse strain is compressional, and shear strain is high. Transect b-b' shows that the surface is generally too low for hydrostatic equilibrium (*R* is negative), and the surface troughs are exaggerated compared to the ice shelf base (Fig. S39b).

Holmes Glacier ice shelf in the western part of Porpoise Bay shows largely positive *R* values (surface is too high) along the two ground tracks there (Fig. S39d). Transect c-c' shows that the ice surface is too high nearly everywhere, including near the grounding line, and that the steep gradients in ice thickness drive the steep gradients in *R* (Fig. S39c). In this case, the ice is closer to balance at thick points in the ice, which in many cases correspond to surface troughs along the first 10 km of the ground track. In other words, undulations at the surface are muted compared to those in the ice shelf thickness/base (Fig. S39c).

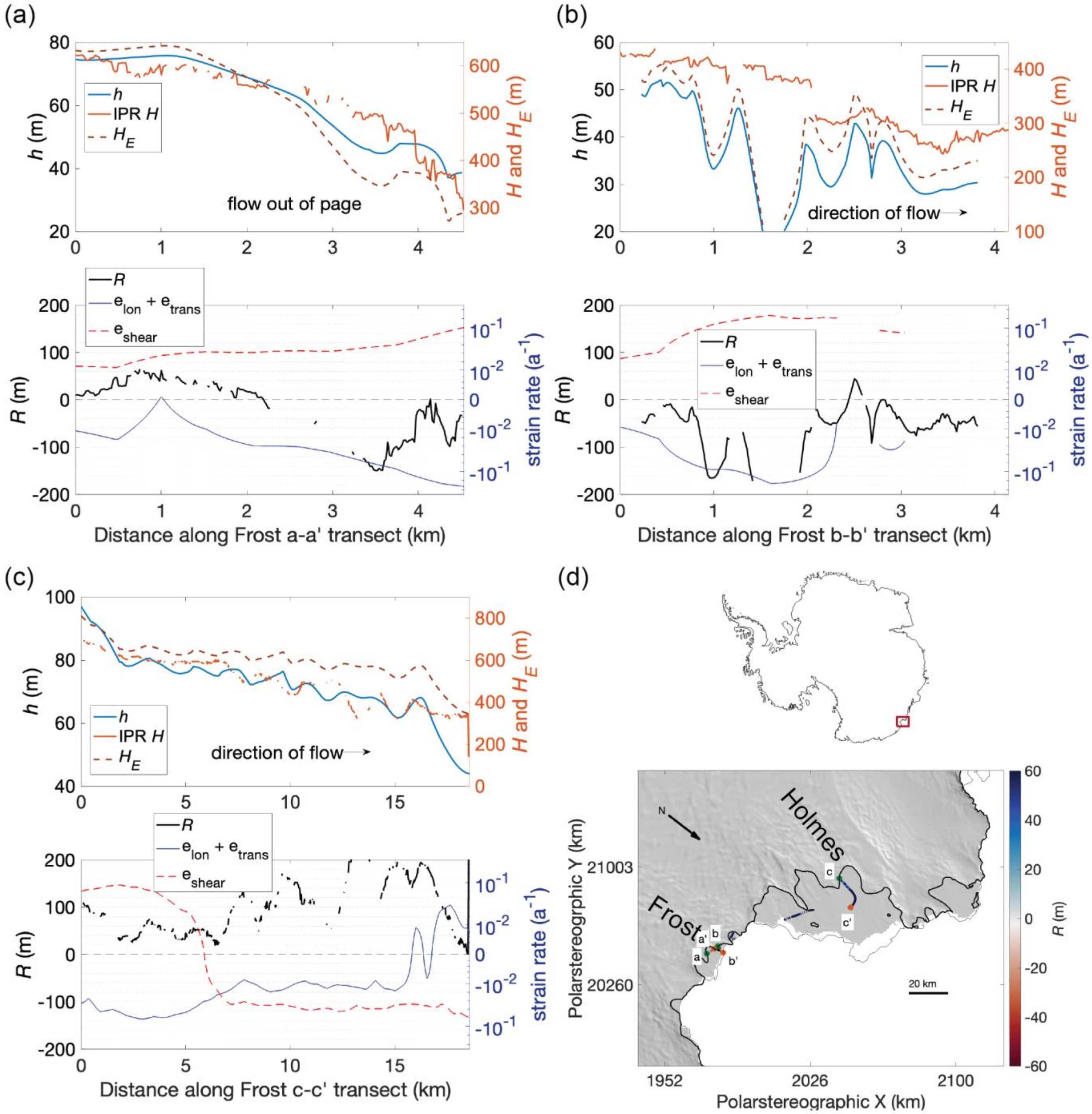

Figure S39. Frost and Holmes Ice Shelf System, transects a-a' - c-c'.

S1.2.16. Moscow University Ice Shelf

Moscow University ice shelf has several ground tracks providing along and across-flow coverage. The campaigns covering this region span from 14-Jan-2009 to 05-Dec-2012.

Moscow University ice shelf has predominantly positive *R* values, indicating that the surface is too high for hydrostatic equilibrium, particularly at the upstream end of the floating trunk, although the surface is too low within ~5 km the grounding line along the continental shear margin (Fig. S40e). This is especially evident along the across-flow transect b-b' (Fig. S40b). There are prominent basal channels on Moscow University ice shelf, and the surface is too high where transects a-a' and b-b' intersect three of them (~5, 8, and 12 km for transect a-a', Fig. S40a; ~6, 9, and 16 km in transect b-b', Fig. S40b), indicating that the troughs at the surface are muted compared to the ice shelf base, although this pattern diminishes for transect c-c' except for the narrow basal channels at ~23 and 26 km (Fig. S40c). Transect d-d' shows the common pattern of locally thick places being associated with lower *R* values, and exaggerated surface features compared to the ice base, but as the ice shelf becomes thinner overall along flow, the surface gets closer to balance (Fig. S40d).

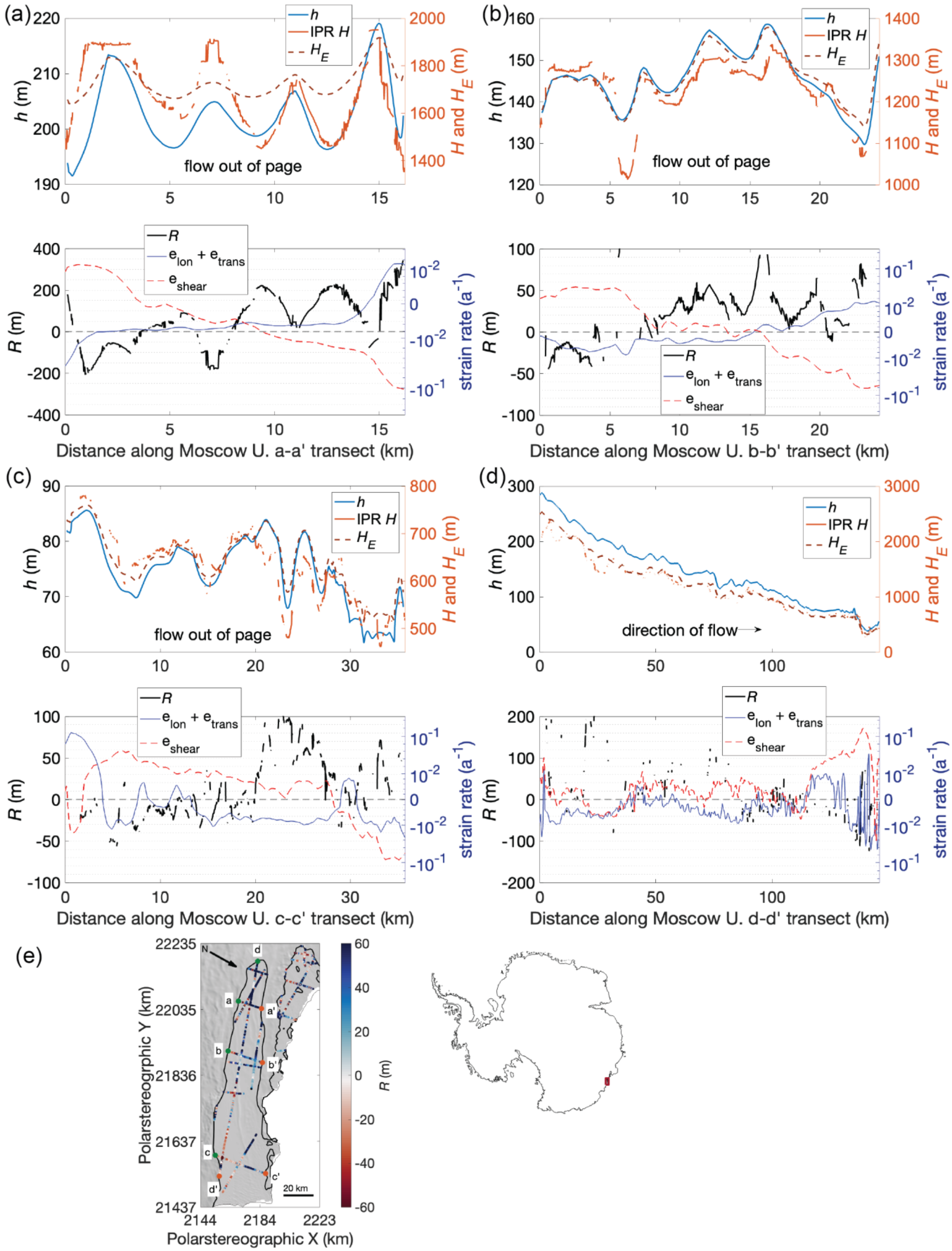

Figure S40. Moscow University Ice Shelf System, transects a-a' - d-d'.

S1.2.17. Totten Ice Shelf

Totten Glacier ice shelf has near complete coverage in a regular grid of along and across-flow ground tracks. Totten Glacier ice shelf exhibits similar characteristics to Moscow University. *R* values are predominantly positive, indicating that the surface is too high upstream, becoming more variable, but closer to balance downstream, with some notable exceptions (Fig. S41e). The surface tends to be too low along the southern side of the embayment where normal strain rates are high (extensional) and where shear strain is high, although this is not matched on the northern side of the embayment. The ice on either side of the peninsula separating the main trunk of Totten from the smaller embayment to the east is especially imbalanced. The surface is much too high, and this region also experiences strain rates near zero or compression.

Along-flow transects a-a', b-b', and c-c' show that overall, the ice is closer to hydrostatic equilibrium as it thins downstream and that gradients in thickness and *R* are inversely related on a shorter length scale (Fig. S41a-c). Across-flow transects e-e', f-f', and g-g' show that the surface and thickness profiles are generally in-phase, though the surface is muted compared to the basal topography (Fig. S42 b-d), but transect d-d' shows a large mismatch in surface and (assumed) basal shapes between 12-25 km such that hydrostatic thickness is greatly overestimated, and an explanation for this is not readily apparent (Fig. S42a).

Transect f-f' intersects an island in the middle of the ice shelf, and shows that the surface is predominantly too low to the south (true right) of the island, and too high to the north (true left), with *R* and *H* being mostly inversely related (Fig. S42c). Just south of the island, where the ground track intersects a basal channel at ~14 km, the surface is too high within the surface trough. The region to the south of the island does experience compressive transverse strain rates, while the region to the north experiences near-zero strain rates. Where the ground track intersects with another basal channel about 8 km north of the island (at ~24 km along-track), the surface is likewise much too high for the observed thickness.

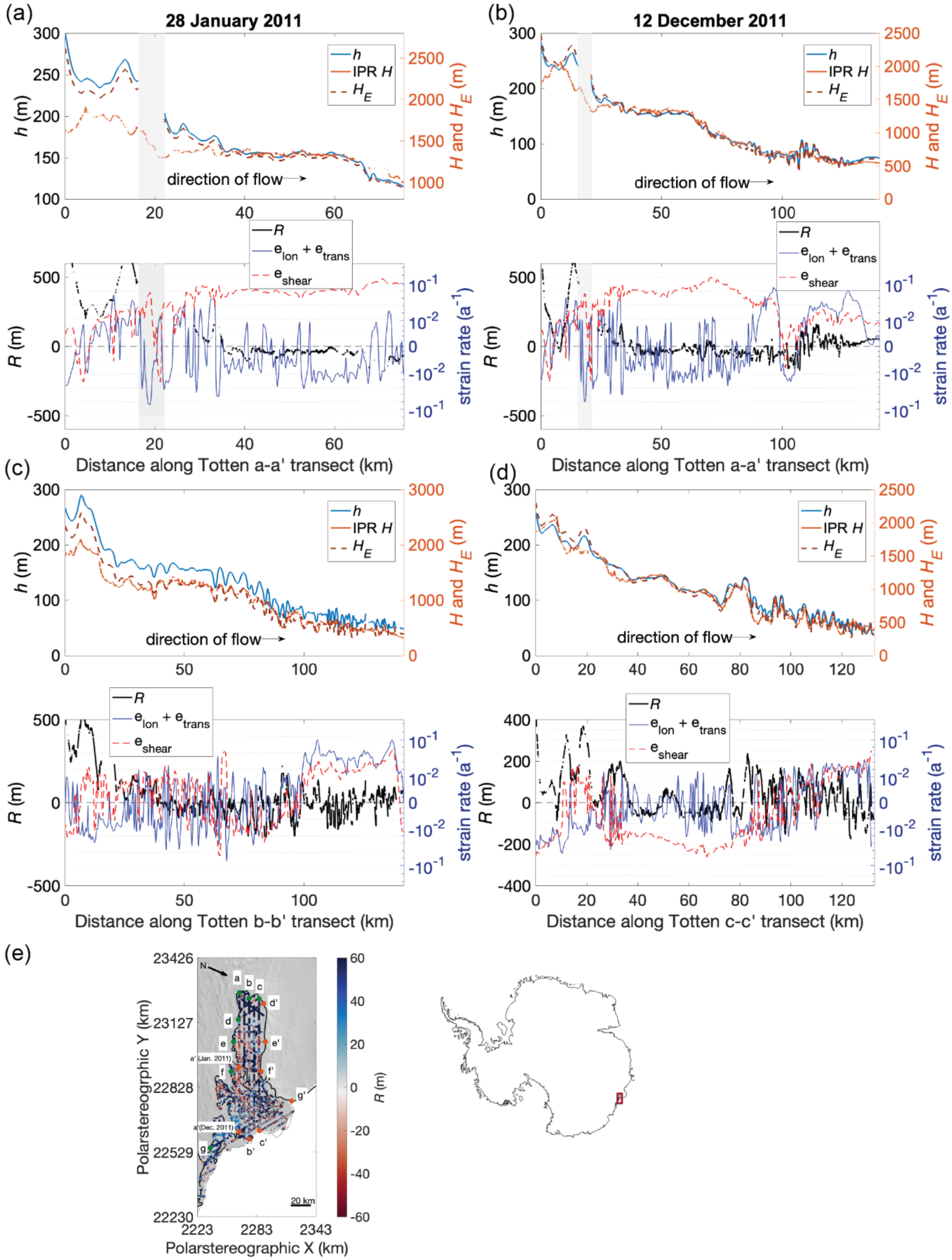

Figure S41. Totten Ice Shelf System, transects a-a' - c-c'.

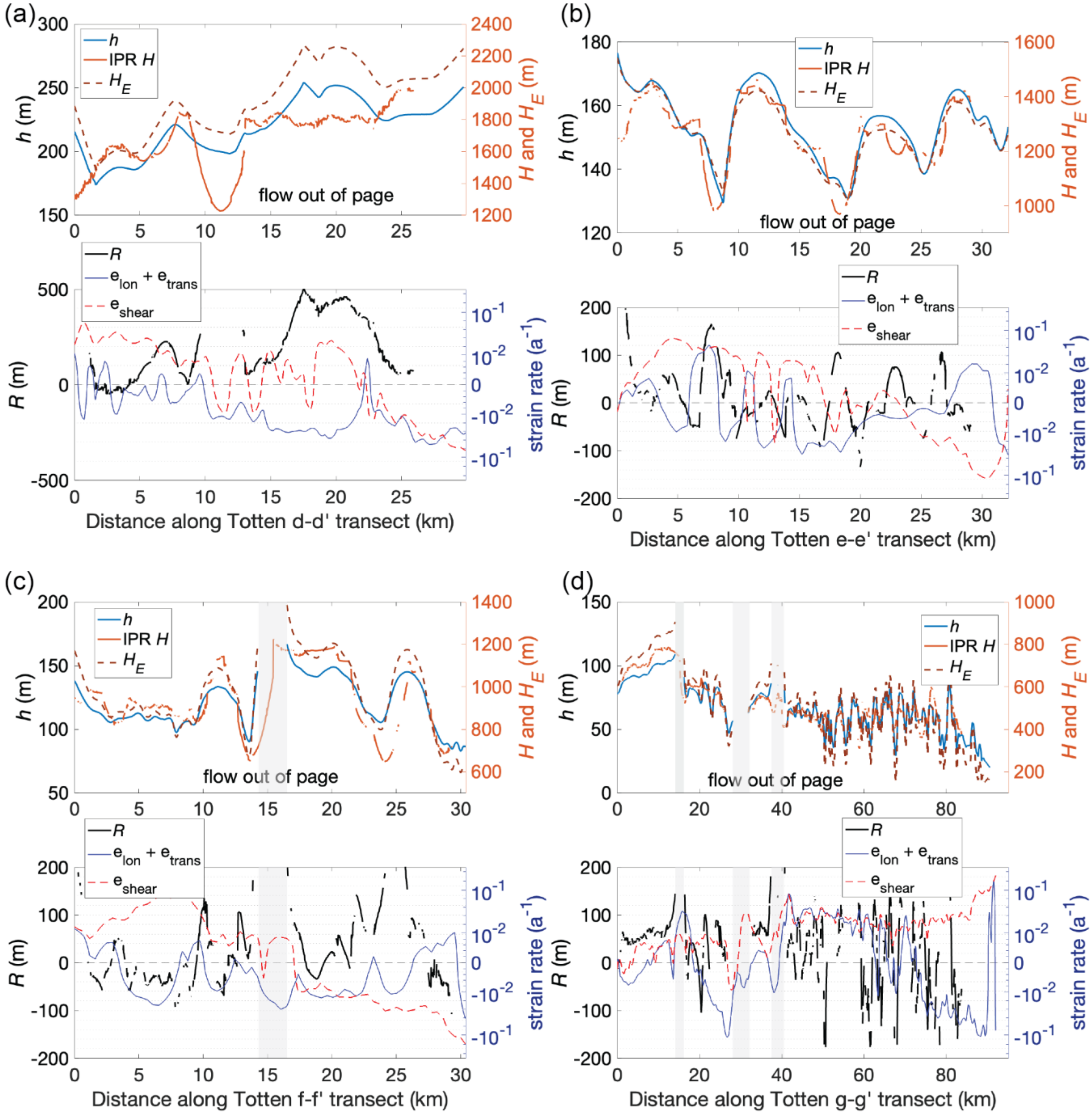

Figure S42. Totten Ice Shelf System, transects d-d' - g-g'.

S1.2.18. Vincennes Bay and Underwood Ice Shelf System

This region has several across-flow ground tracks and one along-flow ground track from 16 campaigns from 20-Jan-2009 to 27-Nov-2012. The ice shelf buttressing Vanderford and Adams glaciers is very rough, and changes in *R* and *H* are inversely related (Fig. S43a, b). Along transect b-b', the surface is further from balance (too high) closer to the shear margins between the two intersecting peninsulas than in the center of the ground track (~12 km, Fig. S43b). The surface is predominantly too high on the Underwood Glacier ice shelf (Fig. S40c). There is no apparent relationship between R and strain rates.

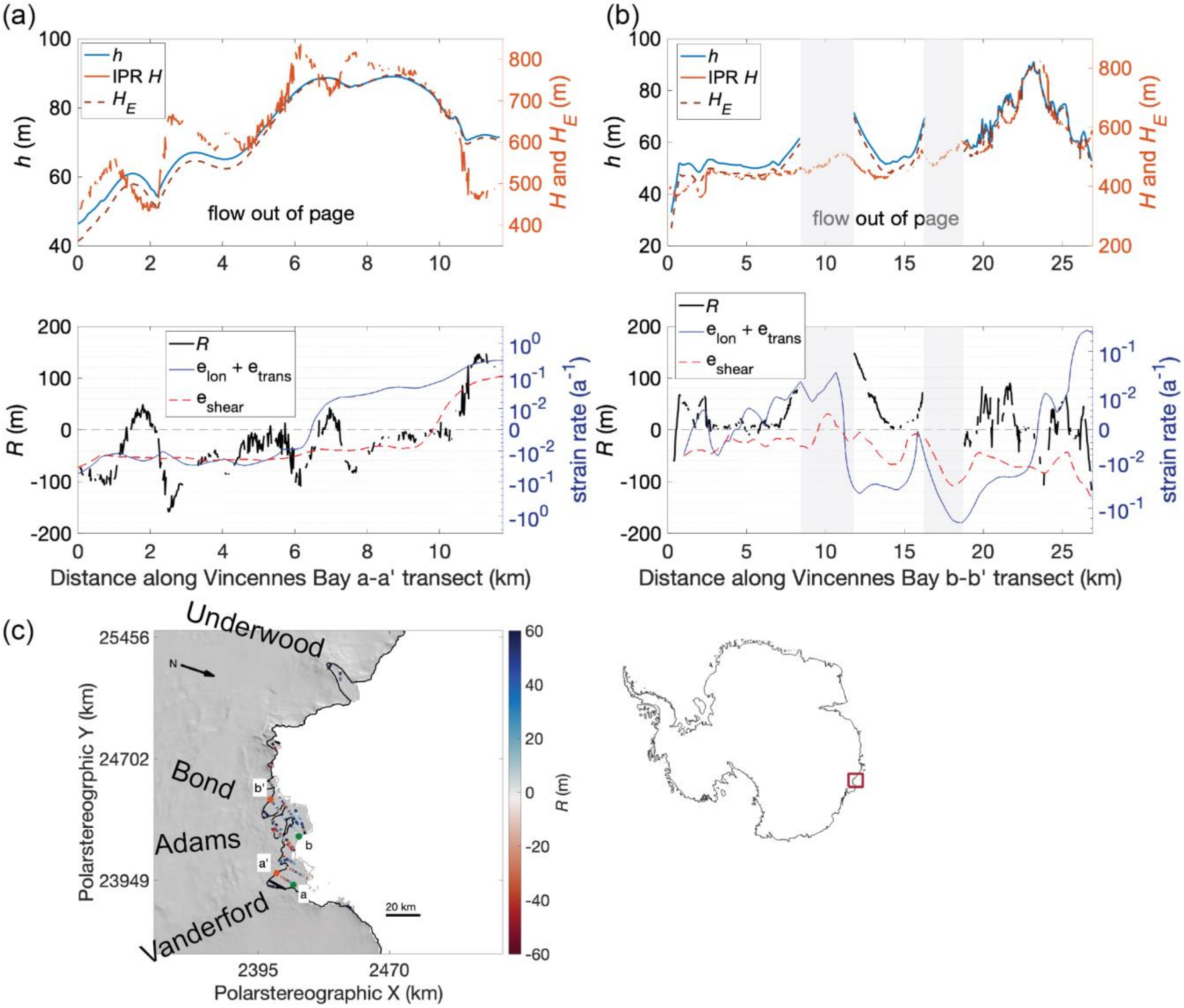

Figure S43. Vincennes Bay and Underwood Ice Shelf System, transects a-a' - b-b'.

S1.2.19. Shackleton Ice Shelf

Shackleton Ice Shelf has 10 ground tracks from 5 campaigns spanning 20-Dec-2009 to 01-Dec-2012. The Denman Glacier ice tongue has several across-flow ground tracks and one along-flow ground track. The Denman Glacier ice tongue feeding into the Shackleton ice shelf has predominantly positive R values, indicating that the surface is too high, except within ~4 km of the grounding line along the main trunk (Fig. S44d). Transect b-b' along the main trunk of the Denman ice tongue lacks IPR thickness data, but illuminates unique characteristics not seen elsewhere (Fig. S44b). About 22 km from the grounding line, there are two large surface ridges with a steep trough between them, and the thickness profile shows that the ridges are associated with two thin points below the surface ridges and a thick point below the surface trough (leading to a surface that is too low for hydrostatic equilibrium). This is a clear example of the observed ice surface not matching the thickness profile, and it produces extreme variability in R. Along the rest of the transect, surface peaks align well with thick points and surface troughs align well with thin points, as expected (Fig. S44b), and there is a predominantly inverse relationship between changes in thickness and changes in *R*, indicating that the surface topography is muted compared to the ice shelf base along most of the transect. However, around 57-60 km down the transect, thin points/surface troughs are associated with negative *R* and thick points/surface peaks are associated with positive *R*, indicating that the surface topography is exaggerated compared to the ice base. There is no clear relationship with strain rates in this region.

The end of across-flow transect a-a' and the beginning of transect c-c' show positive *R* values at the grounding line, and transect a-a' exhibits a surface minimum/break-in-slope at ~22 km associated with negative *R* values, as seen elsewhere (Fig. S44a, c). Transect a-a' shows that the ice is largely close to hydrostatic equilibrium in the center of the transect, although both transects exhibit a general pattern of positive *R* values associated with thicker ice and vice versa. Steep gradients in the surface and thickness profiles are associated with steep gradients in both the normal and shear strain rates, for instance at ~3 and ~22 km along transect a-a', and at ~10 and ~18 km along transect c-c' (Fig. S44a, c).

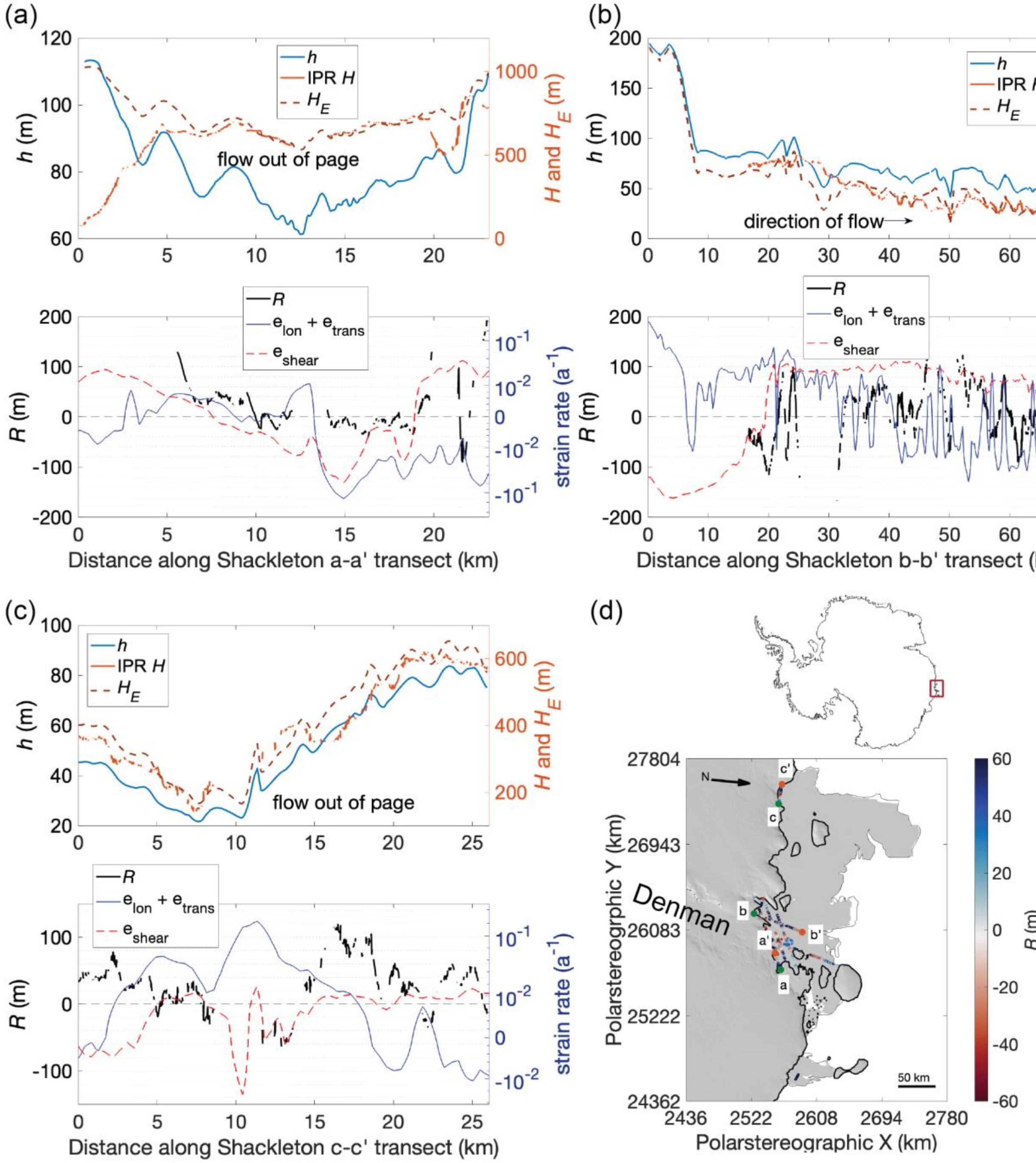

Figure S44. Shackleton Ice Shelf System, transects a-a' - c-c'.

S1.1.21. West Ice Shelf

West Ice Shelf has data along one across-flow ground track and one along-flow ground track east of Cape Penck from 24-Nov-2012. The surface is predominantly too high along most of West Ice Shelf, except in the rough portion of the western half (Fig. S45d). Transect a-a' shows that changes in *R* and *H* are generally inversely related, except in three spots: within 1 km of the grounding line, where ice thins and the surface is near balance before the ice thickens downstream, at about 8 km downstream, and at about 19 km downstream, where the surface is too low where the transect intersects a rift (Fig. S45a). Along most of the transect, the surface is generally too high at surface peaks and too low within surface troughs, although thick/thin points in the thickness profile do not generally align well with surface features, indicating that the surface topography is exaggerated compared to the thickness profile, except in the last 6 km of the transect, where the surface is muted compared to the thickness profile.

Across-flow transect b-b' also shows that changes in *R* and *H* are generally inversely related. The surface is generally too high, except for in several deep (> 10 m amplitude) surface troughs at ~2 and 7 km along the transect, some surface troughs at ~35-40 km along the transect, on the western flank of a large basal channel near 70 km along the transect, and two other likely basal channels at 100 km and 120 km along the transect (Fig. S45b).

Along the across-flow transect c-c', small length-scale changes in *R* and *H* are generally inversely related, but the large-scale (over 10s of kms) changes in these quantities are generally positively related (Fig. S45c). The transect begins near the grounding line, and there is a surface trough/thin point about 10 m along the transect where the surface is generally too low. This region is a shear zone with longitudinal extension and transverse compression. As stated above, the surface is generally too low in the thinner, rougher portion of this ice shelf (20 - 45 km), where strain rates are negligible, and much too low at the thinnest part of the ice shelf (~55 km along the transect). At this thinnest point, there are highly extensional longitudinal strain rates, compressional transverse strain rates, and minimal shear strain, although it is just downstream of a zone of high shear. The ice becomes thicker to the west, and the surface becomes too high in a region of moderately compressional longitudinal strain rates, moderately extensional transverse strain rates, and minimal shear strain (Fig. S45b).

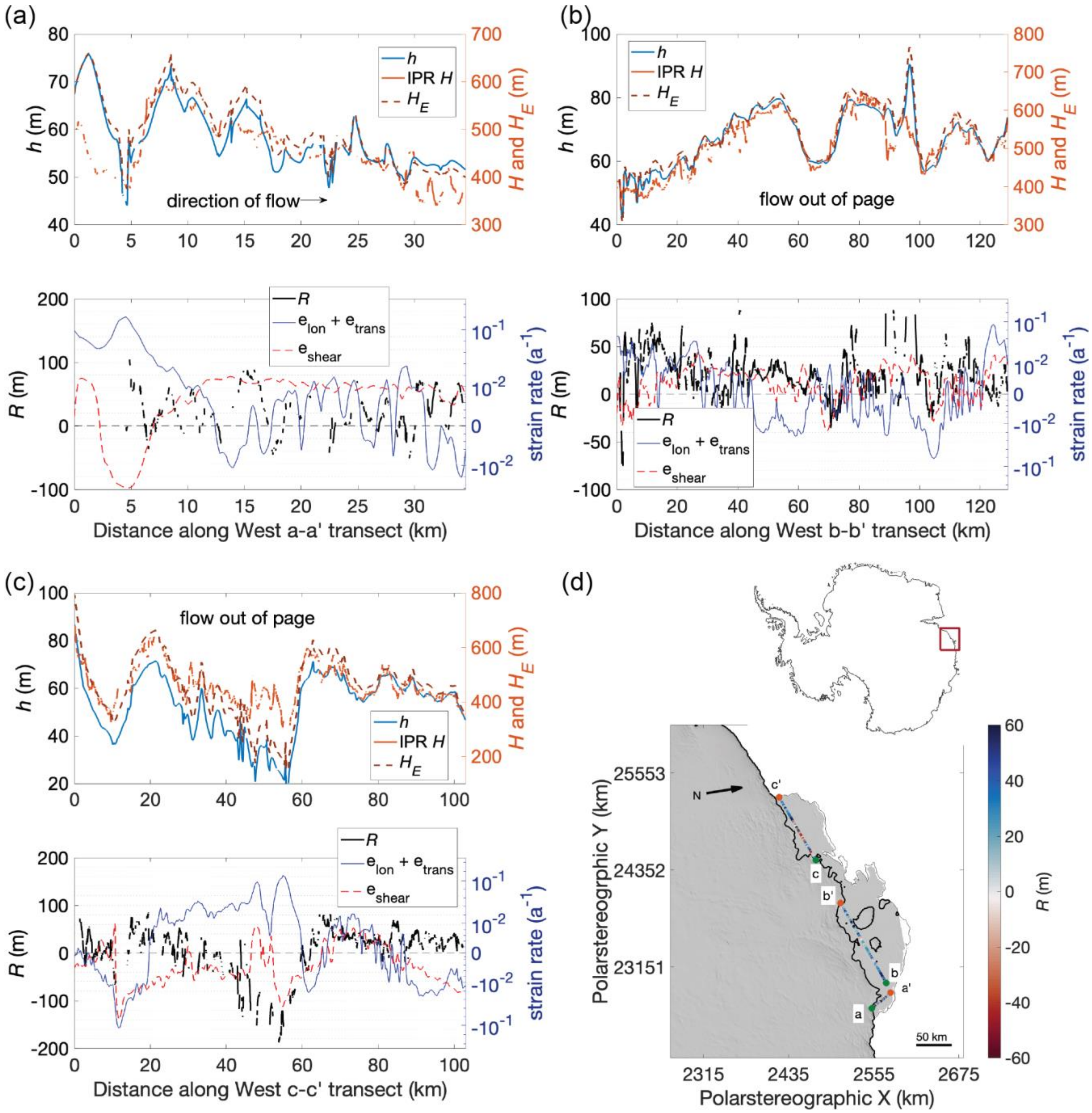

Figure S45. West Ice Shelf System, transects a-a' - c-c'.

S3. DISCUSSION

Table S3. Relationships between firn air column thickness/density and *R*

Shelf	sFDM with MDT: mean H_a (m)	sFDM with MDT: mean H_{aE} - H_a (ρ_a = 2 kg m^{-3})	sFDM with MDT: mean ρ_{aE} - ρ_a (H_a = model)	tFDM with MDT: mean H_a (m)	tFDM with MDT: mean H_{aE} - H_a (ρ_a = 2 kg m^{-3})	tFDM with MDT: mean ρ_{aE} - ρ_a (H_a = model)
Ronne Filchner	20	1	-73	17	-1	57
Larsen	12	3	-1635	8	0	-71
George VI/ Wilkins/Stange	15	1	-161	9	-5	323
Abbot	21	1	-73	16	-4	142
PIG	22	2	-194	10	-10	407
Thwaites	22	2	-204	12	-8	319
Dotson/Crosson	25	-1	13	17	-9	332
Getz	23	1	-92	16	-6	233
Nickerson	17	0	13	17	-1	-38
Western Ross/ McMurdo	20	1	-159	14	-5	232
Drygalski/ Nordenskjold	13	4	-1078	4	-5	334
Cook	17	3	-433	8	-6	304
Ninnis	21	5	-409	11	-2	99
Mertz	20	2	-224	12	-5	232
Frost/Holmes	21	6	-545	10	-2	105
Moscow University	16	4	-270	14	2	-83
Totten	21	5	-272	17	1	-30
Vincennes Bay/Underwood	10	-2	167	7	-7	484
Shackleton	14	1	-326	5	-8	514
West	14	2	-255	9	-2	165

Text S3.1 Relationship between R and strain rates

Specifically in West Antarctica, we see that strain rates tend to decrease with increasing $R > 50$ m, a pattern also found at Ronne Filchner, Larsen C, and George VI/Wilkins/Stange, Abbot, Thwaites, and Dotson/Crosson ice shelves (Fig. S46a-d,f, g). Between *R* values of -50 to 50 m, the near-zero and negative strain rates exhibited in Fig. 9a are reflected in the plots for all ice shelves except Larsen C and Thwaites, which are entirely extensional (Fig. S46b,f). For *R* values below -50 m, increasing strain rates with decreasing *R* are most prevalent on Ronne Filchner, Larsen, Thwaites, Dotson/Crosson, and Getz ice shelf systems (Fig. S46 a-b,f-h).

The pattern in East Antarctic ice shelves that the median $\nabla \cdot u$ is near zero for all values of R with more compressive strain rates associated with higher magnitudes of R (Fig. 10b) is generally reflected on all East Antarctic ice shelves (Fig. S47a-h), except for Shackleton and West Ice Shelves (Fig. S47f-k). Notably, all ice shelves except for the Ross, Totten, Vincennes Bay/Underwood, Shackleton and West ice shelves show predominantly compressive strain rates for all values of *R*. On the western Ross/McMurdo Ice Shelf system, *R* values near zero tend to occur in areas with both highly tensile and compressive strain rates, and near-zero strain rates are associated with *R* values > |50| m (Fig. S47a).

Higher shear strain rates are associated with higher magnitudes of R (Fig. 10). Specifically, individual West Antarctic ice shelves Ronne Filchner, PIG, Thwaites, Getz, and Nickerson also show consistently increasing shear strain rates with increasing *R* values > 0 (Fig. S46a, e, f, h, i). In East Antarctica, median shear strain rates tend to increase more as *R* becomes more negative (Fig. S47b-k), except for on the western Ross/McMurdo ice shelf system, where shear strain rates are low where *R* is high, and high where *R* is low (Fig. S47a). This result, however, may be due to the sparse data density over areas where we might expect high *R* values on the western Ross/McMurdo ice shelf system.

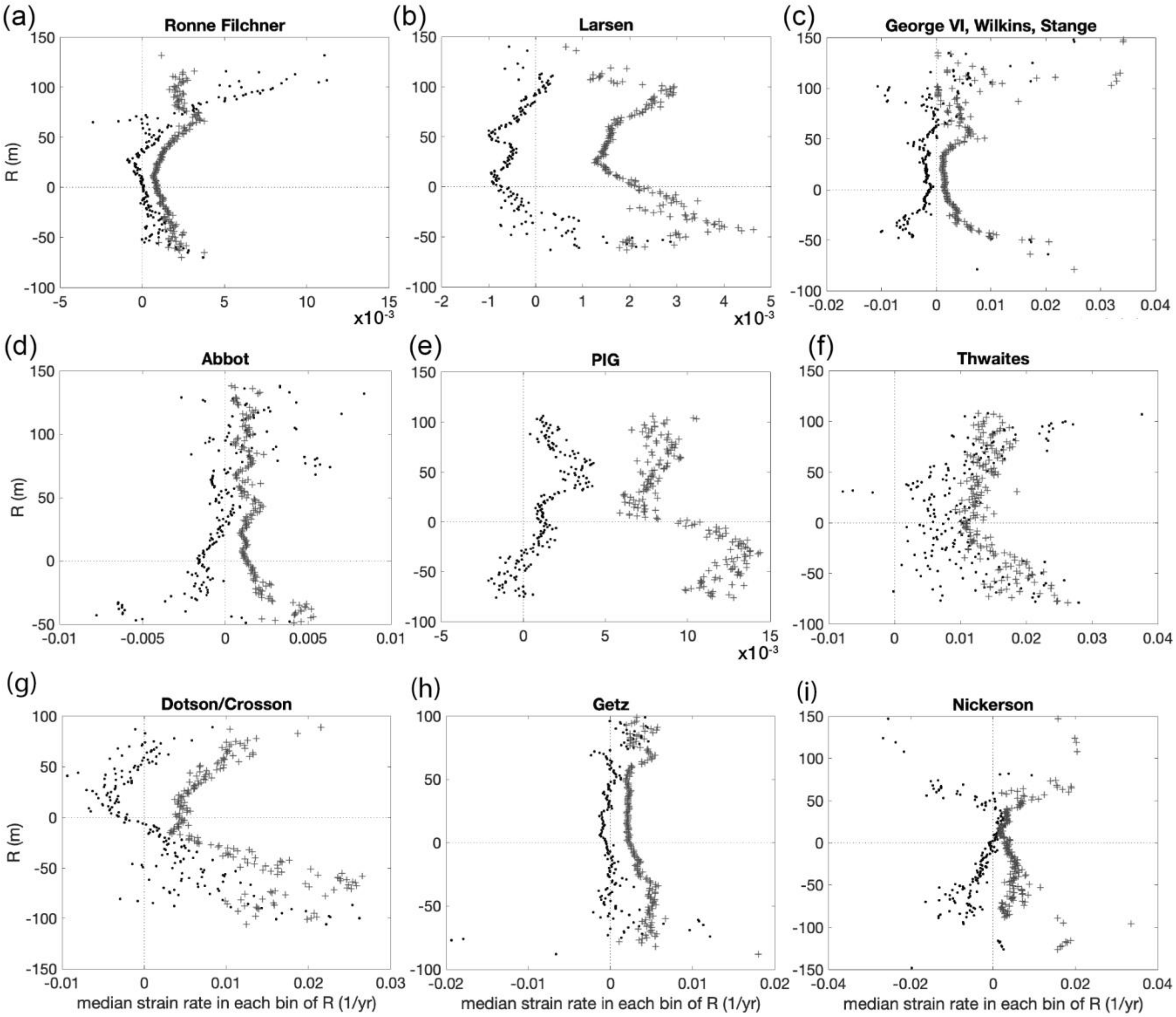

Figure S46. (a-i) Median normal strain rates ($e_{lon} + e_{shear}$, black dots) and absolute values of shear strain rates ($|e_{shear}|$, gray + signs) for points within bins of 1 m increments of *R* for all radar points on each West Antarctic ice shelf. (Bins containing fewer than the 40th percentile of N were excluded.

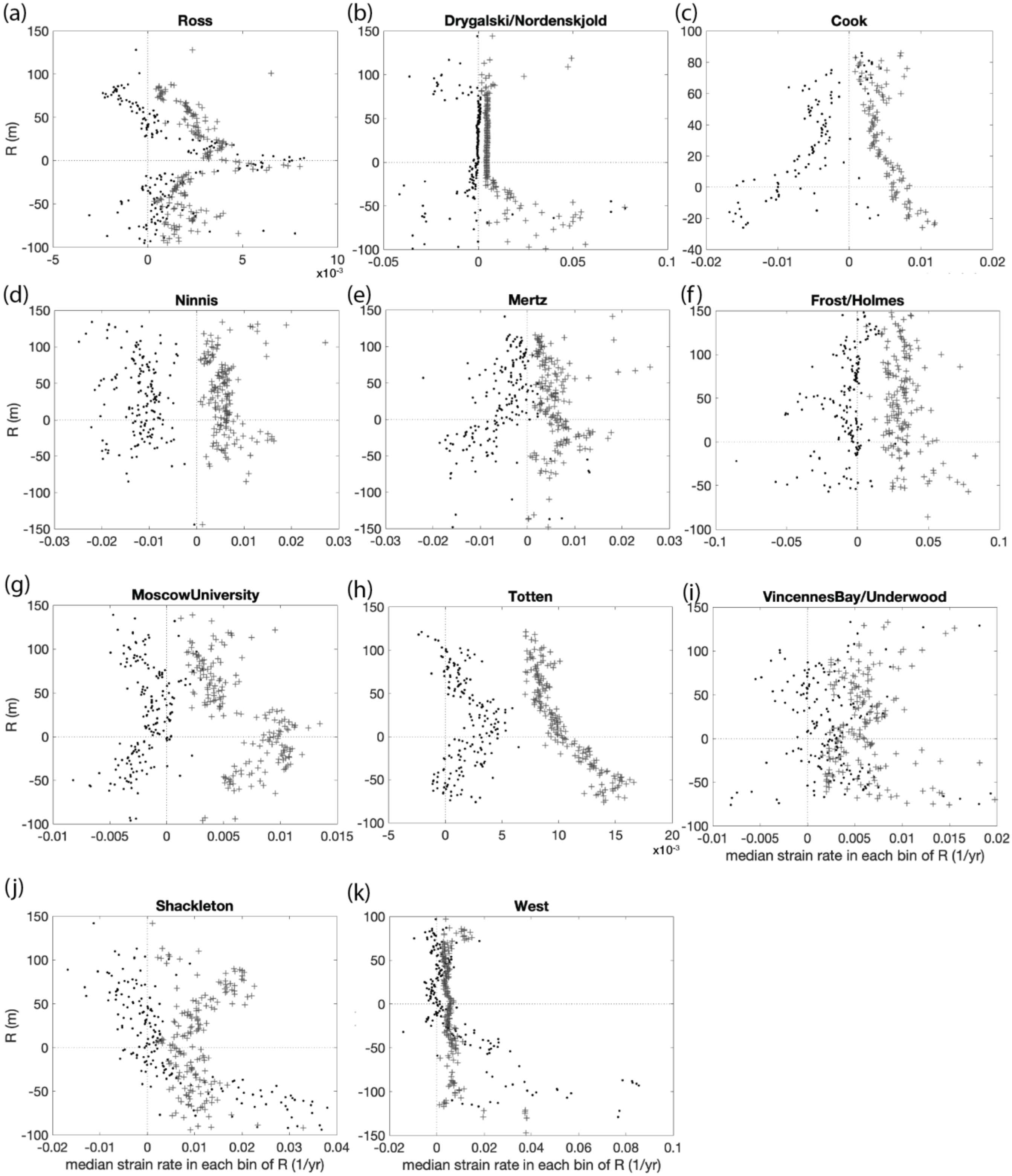

Figure S47. (a-k) Median normal strain rates (e_{lon} + e_{shear}, black dots) and absolute values of shear strain rates ($|e_{shear}|$, gray + signs) for points within bins of 1 m increments of *R* for all radar points on each East Antarctic ice shelf. (Bins containing fewer than the 40th percentile of N were excluded.

Table S4. Quantities related to impact of *R* on basal mass balance. Ice shelf regions with negative (compressive) median strain rates ($\nabla \cdot u$) are italicized.

Shelf	**mean R_{Mb}** (m w.e. a^{-1})	**median R_{Mb}** (m w.e. a^{-1})	**σ R_{Mb}** (m w.e. a^{-1})	**Median ($\nabla \cdot u$)**	**median Adusumilli M_{bE}**	**median $\vert R_{Mb} \vert / \vert M_{bE} - R_{Mb} \vert$*100**
Ronne Filchner	0.0	0.0	1.0	0.0	-0.2	4
Larsen	0.0	0.0	0.9	0.0	-1.2	3
George VI/ Wilkins/Stange	0.0	0.0	0.4	0.0	-2.9	1
Abbot	0.0	0.0	0.2	0.0	-1.1	2
PIG	-0.1	0.0	4.2	0.0	-4.7	3
Thwaites	0.3	0.1	6.6	0.1	-4.3	11
Dotson/Crosson	-0.1	0.0	3.7	0.0	-4.2	3
Getz	0.0	0.0	0.6	0.0	-3.5	2
Nickerson	0.1	0.0	1.0	0.0	-1.2	4
Western Ross/ McMurdo	0.0	0.0	0.3	0.0	-0.9	4
Drygalski/ Nordenskjold	-0.1	0.0	1.6	0.0	-	-
Cook	-0.1	-0.1	0.2	-0.1	-1.0	9
Ninnis	-0.9	-0.3	2.8	-0.3	-	-
Mertz	0.0	0.0	0.5	0.0	-3.5	4
Frost/Holmes	0.4	0.0	3.2	0.0	-12.4	5
Moscow University	-0.1	0.0	0.6	0.0	-4.2	3
Totten	-0.2	0.0	2.2	0.0	-6.9	6
Vincennes Bay/Underwood	-0.8	0.0	12.7	0.0	-	-
Shackleton	-0.3	0.0	2.5	0.0	-1.6	10
West	-0.2	0.0	1.7	0.0	0.2	16