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SUPPLEMENTARY INFORMATION

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Bathymetry constrains ocean heat supply to Greenland's largest glacier tongue

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Supplementary Information

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Supplementary Discussion

SD1. AIW layer thickness determines heat supply

Our moored records suggest a drastic change in the heat supply occurring between mid-November 2016 and beginning of January 2017: While the 1.2 °C isotherm lifts by more than 50 m on top (Fig. 3b) and downstream (Fig. 3a) of the sill, maximum inflow velocities increase from 40 cm/s to 60 cm/s. This resulted in an enhanced overturning circulation accompanied by almost a doubling of the heat that goes into melting the glacier tongue from below, from a mean of 135 ± 43 GW in October to a mean of 271 ± 70 GW in December (Fig. 3b). Time series recorded further offshore on the inner and mid-shelf (50 and 250 km upstream of the 79 North Glacier (79NG), respectively) show that temperatures increased simultaneously over the entire shelf in winter 2016/2017 (Fig. S1), suggestive for a large-scale thickening of the AIW layer.

SD2. Hydrography and bathymetry at Zachariæ Isstrom

At Zachariæ Isstrøm (ZI), i.e., the glacier neighbouring the 79NG, a persistent mélange of icebergs and fast-ice (Fig. S2a) makes the area between the calving front and an island chain inaccessible to ships. Prior to 2016, bathymetric charts therefore presumed this area to be 50 m deep which would prohibit AIW from getting into contact with ZI's ice. Conversely, we speculate that the oceanic flow to ZI may also be constrained by a local sill. This is suggested by temperature profiles (Fig. S2b) taken for the first time in the vicinity of ZI in summers 2016 and 2017 showing depths of more than 600 m (Fig. S2c). Our observations suggest a well-mixed layer of 1.5 °C-warm AIW in front of the calving front of ZI at depths below 480 m. This roughly agrees with the theory that if the time period over which inflow properties change at the sill is larger than the residence time inshore of the sill, a well-mixed layer gets established below the grounding line (450 m for ZI[16]). However, further east of the glacier, similar well-mixed characteristics are found at much shallower depth (i.e., below 350 m).

This compares well to temperature profiles taken upstream and downstream of the critical sill observed offshore the 79NG. We speculate that one or two sills (between Schnauder Ø, Franske Øer and Pariserøerne) in the depth range of 350 to 480 m (i.e., deeper than the 325-m-deep sill upstream the 79NG) critically control the heat supply to ZI. We hypothesize that the observed warming of AIW already triggered the collapse of Zachariæ Isstrøm's ice tongue half a decade ago[16].

Supplementary Methods

SM1. Temperature time series from the inner- and mid-continental shelf. The temporal evolution of temperatures recorded at 271 m depth close to the calving front of the 79NG (79°35.06'N/19°20.56'W) is compared to temperatures recorded at 79°40.15'N/16°53.36'W at 267 m depth (inner shelf) and 78°10.59'N/15°43.26'W at 266 m depth (mid shelf) (Fig. S1a, d). Quality-checked data were filtered with a lowpass-filter using a Hann window of 30 days.

SM2. Historic hydrographic measurements. In order to assess potential long-term changes in Atlantic water properties on the Northeast Greenland continental shelf (i.e., the supply region of the waters approaching the 79NG), we use a data compilation[24] with all available hydrographic profiles recorded in the past. Within our region of interest (black box in Supplementary Fig. S1) ship-lowered CTD casts were carried out aboard USCGC *Westwind* (1979), USCGC *Northwind* (1984), R/V *Lance* (2008, 2013, 2014, 2015), and R/V *Polarstern* (1993, 2008, 2014, 2016, 2017). All campaigns were taken within late summer/early autumn of the respective year[24]. The depth of the 27.82 kg/m^3 isopycnal, indicative for an upper interface of well-mixed AIW layer flowing via Norske Trough on the continental shelf toward the 79NG has been calculated for each temperature profile before computing the mean and standard deviation of measurements taken within the same year inside our region of interest. Mean maximum temperatures were computed accordingly.

SM3. Volume transport based on hydraulic control theory using historic data.

Hydraulic control theory allows us to estimate volume transports across the sill upstream of the 79NG (Methods) based on density profiles upstream and downstream of the sill. In earlier years, CTD profiles were taken on the continental shelf adjacent to the 79NG. Under the assumption that changes in the thickness of Atlantic waters approaching the 79NG account for similar changes in bifurcation depths (Methods), we can estimate changes in the volume flux into the subglacial cavity as follows: The time-mean bifurcation depths of 226 ± 21 m computed from our moored measurements between 2016 and 2017 compares well to the depth of the 27.82 kg/m^3 isopycnal at 219 ± 49 m in Norske Trough (Fig. S1b). This depth represents the interface between Atlantic waters flowing into the cavity and a more quiet layer on top (Fig. 1c). The interfaces were approximately 15 m deeper in earlier years (Fig. S1b), which goes along with cooler Atlantic waters on the continental shelf (Fig. S1c). Assuming an uplift of the 27.82 kg/m^3 isopycnal to equal the change in bifurcation depth, we estimate that the mean bifurcation depth was at approximately 241 m in earlier years. Using this information we compute a volume flux of 28.5 mSv (assuming g' to remain constant, see Methods), compared to a mean transport of 40.3 mSv for the 15 m shallower bifurcation depth in recent years.

SM4. Temperature profiles from Zachariæ Isstrøm. In the vicinity of ZI, vertical temperature profiles were collected with a temperature/pressure logger (RBR*duet* T.D | fast 16) in 2016 and a CTD (RBR*concerto*) in 2017 lowered via a fishing rod through holes in the fast-ice/ice mélange. Stations were reached by helicopter from R/V *Polarstern*. Instruments were calibrated before the expeditions from the manufacturer achieving high-quality data with an accuracy of 0.002 °C (ITS-90).

Supplementary Figures

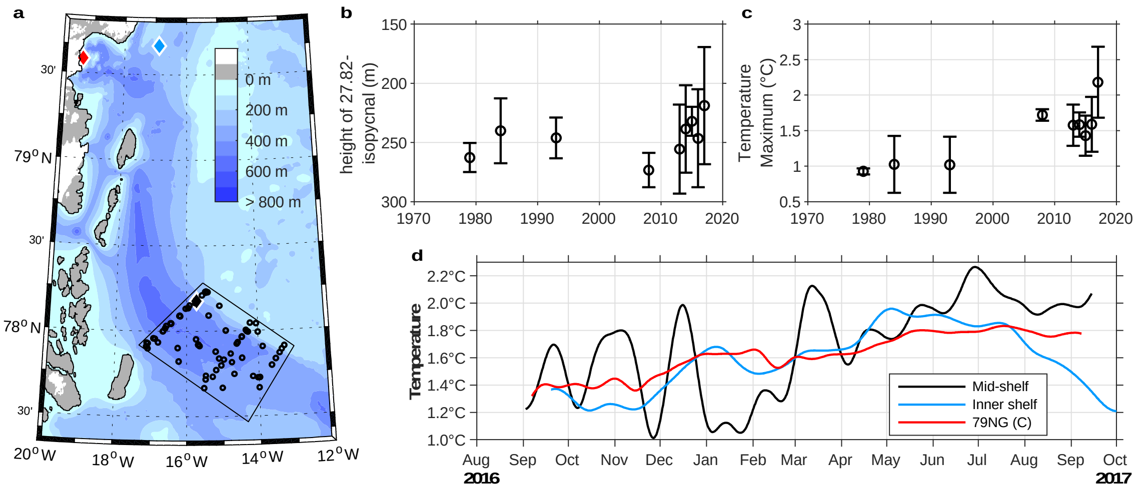

Figure S1: Temporal evolution of temperatures measured upstream of the 79 North Glacier (79NG). (a) Bathymetric map of the inner Northeast Greenland continental shelf upstream of the 79NG. Locations of moored temperature recorders (diamonds) are marked with colours as used in **d**. CTD profiles measured in summers 1979, 1984, 1993, 2008, and 2013-2017 within a defined region in Norske Trough are indicated by black circles (used in **b** and **c**). (b, c) Temporal evolution of the mean height of the 27.82 kg/m^3 isopycnal and the mean maximum temperature. Error bars indicate respective standard deviations. (d) Temperature times series (filtered with a lowpass-filter and a cut-off at 30 days) recorded at 270 m depth.

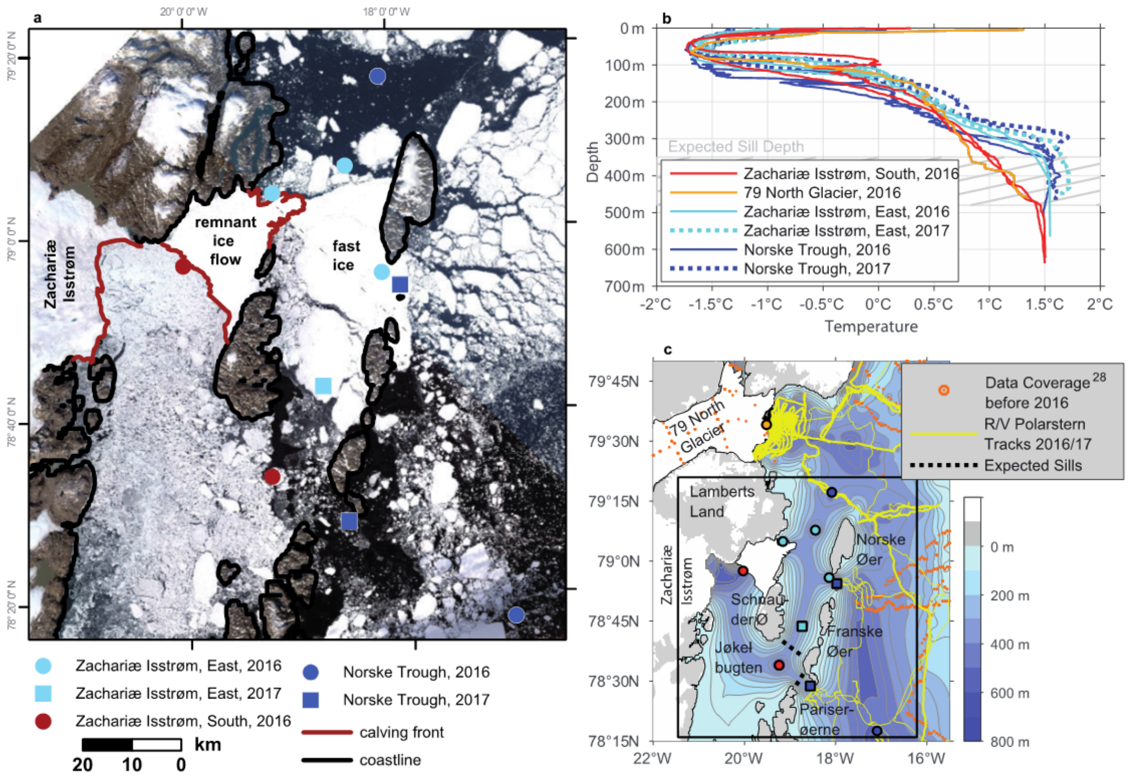

Figure S2: Oceanic temperature profiles taken at Zachariæ Isstrøm. (a) Satellite image recorded by Landsat 8 on 07 September 2016 showing Zachariæ Isstrøm and its surroundings. The ocean surface between the calving front and the chain of islands located east/southeast of Zachariæ Isstrøm is filled by (partly) broken up fast-ice and icebergs. Coloured circles/squares indicate temperature/CTD profiles. (b) Temperature-depth profiles taken in the vicinity of Zachariæ Isstrøm, in Norske Trough and at the 79 North Glacier calving front. (c) Best estimate bathymetry incorporating the information from the profiles in **b** and multibeam measurements from R/V *Polarstern* expeditions PS100 and PS109 in the RTopo-2 data set[37].

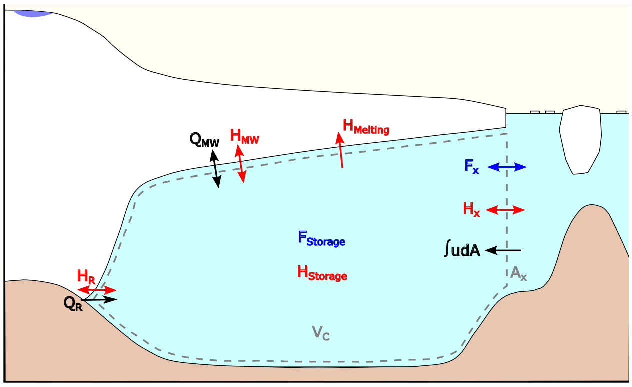

Figure S3: Schematic of a subglacial cavity indicating all relevant terms in the mass (black), heat (red), and salt (blue) budgets[41]. Budget terms are given for a control volume V_c (grey dashed box) which contains all liquid water within a subglacial cavity. Advective volume ($\int u \, dA$), heat (H_x), and salt (F_x) fluxes enter the cavity only through the calving front section, i.e., the cross-section A_x.

Supplementary Table

Table S1: Overview of moored instruments deployed at gateways A, B, C, and D along the calving front of the 79 North Glacier. T: temperature, C: conductivity, p: pressure, u: eastward velocity, v: northward velocity.

	Mooring position	**Instru-ment**	**Measurement depths [m]**	**Measured variables**	**Time step**	**Record length (dd/mm/yyyy)**
A	79° 26.4' N/ 19°46.64'W 326 m	SBE37	201	p, T, C	10 min	23/08/2016 until 21/09/2017
		SBE56	236, 266, 296	T	30 sec	
		ADCP, 150 kHz	Instrument: 320 Bins: 38:4:314	p, u, v	1 hr	
		SBE37	322	T, C	10 min	
B	79°31.17'N/ 19°25.83'W 293 m	ADCP, 75 kHz	Instrument: 286 Bins: 3:8:275	p, u, v	30 min	23/08/2019 until 23/09/2017
		SBE37	291	p, T, C	15 min	
C	79°34.13'N/ 19°27.58'W 474 m	SBE37	201	p, T, C	10 min	23/08/2016 until 21/09/2017
		SBE56	227:30:407, 427	T	30 sec	
		ADCP	Instrument: 447 Bins: 4:8:436	p, u, v	1 hr	
		Aqua-dopp	457	p, u, v, T	20 min	
		SBE37	460	T, C	10 min	stopped 11/10/2016
D	80°08.92'N/ 17°24.56'W 172 m	ADCP, 300 KHz	Instrument: 168 Bins: 60:4:164	u, v	1 hr	29/08/2016 until 08/03/2017
		SBE 37	169	T, C	10 min	29/08/2016 until 20/09/2017

E	79°35.06'N/ 19°20.56'W	SBE37	185, 359	p, T, C	10 min	26/08/2016 until 21/09/2017
			226	T, C	1 min	
		SBE56	271, 316	T	30 sec	
		ADCP, 300 kHz	358	u, v	2 hr	