Overview of the MOSAiC expedition – Snow and Sea Ice

Supplemental material

Content of this document

S1 Sea ice and snow work and concept

The realization of the field program by the highly interdisciplinary ICE team required an extraordinary amount of coordination and interaction. This effort succeeded and initiated manifold new collaborations and scientific exchange. One of the main challenges was to ensure consistency in methodology and data quality of the individual observations over the year, typically including four to five different principal investigators on board and large teams on land, covering a broad range of expertise and specific questions to the same data set. As a result, the task structure, as described in Section 2, is not fully consistent as it merges topics, instruments and ice types, but was found to be most practical in the organization of the daily work in the field. This structure mostly represents how different groups structured their work (operational principles) and data sets.

During the field phase, the ICE team was represented with 12 (Leg 1), 14 (Leg 2), 11 (Leg 3), 14 (Leg 4), 11 (Leg5) berths on *Polarstern* and with 9 berths on *Akademik Fedorov* (Leg 1a). In addition, the ICE team was represented by (co-) cruise leaders on Legs 1 and 2 on board of Polarstern and Leg 1a on *Akademik Fedorov*. Overall, 66 different persons participated on both ice breakers. Beyond direct participation on board, strong support was given from land before, during and after the field experiment. Overall, approx. 150 people were involved in the snow and sea ice work and contributed in various ways to the planning, design and successful completion of the work program.

A particular preparation phase was based on the broad experience and expertise across the participating researchers. A main process was the agreement on observational protocols for all field tasks and methods prior to the expedition. Additional workshops and training programs for team members were critical components in preparation for the field experiment. Week-long field training courses were held to cross train team members on the full suite of snow and sea ice measurement protocols and to perform dedicated instrument tests. These courses were held in Hailuoto, Finland (February 22 to March 07, 2019) and Utqiagvik, Alaska (April 07 to 13, 2019). More specialized trainings were performed for flight training and system testing (particularly for navigation systems) for the unmanned aerial systems near

Longyearbyen in April 2019. Various cross-calibration initiatives were also realized before and after the field phase.

During the drift, the daily work was organized along weekly plans with designated time slots per task. Each team member was assigned specific tasks on each day of the week. The same task was mostly carried out by the same people throughout each leg to maintain the highest possible consistency. The work on board was supported by the task members at home, especially by those who carried out the same measurements on earlier or later legs. Snow and sea ice tasks in the field were often supported by volunteers from the other scientific teams as well as by the logistics team. Intense observation periods or case studies were incorporated into the weekly routine to increase the spatial and/or temporal resolution of existing tasks or to capture certain events. A more detailed definition of events during MOSAiC is under development by the project coordinators. An example of an intense observation period is also discussed in Section 4.2.

Figure S1 shows how the work from the different tasks was distributed over the respective week. In addition to the task work (colored time slots), approximately 1/3 of the time slots were used for data work, basic tasks incl. supplemental observations, additional work without immediate task relation (FLEX time), and free time. The week of July 06, 2020, included an intensive observation period of a 24-hour continuous sampling to capture the diurnal cycle under polar day conditions, complementing a similar study during polar night on Leg 1. The different schedules for both case studies demonstrate the general realization of the work program organized through specific tasks over the entire year. The comparison of these two weeks shows how the weekly plans changed over seasons: additional optical measurements ('OPTICS') were carried out under daylight conditions. The rapid changing surface conditions daily snow pit (including surface properties), very frequent 'TRANSECT' and additional 'POND' work in July. The remote sensing work ('REMOTE') was allocated more time in January, for example when a larger suite of instruments was operated on the ice. Different project and process related foci were realized on individual legs like 'RIDGE' and 'POND' work in summer (Leg 4) or 'DYNAMICS' work in winter (Leg 2). The concept of 'FLEX' time, time that was not pre-allocated before the respective leg, turned out to be most beneficial and at the same time essential to enable the planned work program. This time allowed reaction on the continuous changes and challenges in the field. Also allocating sufficient time for in-field data documentation and early processing, as well as dedicated time slots for laboratory work were budgeted and needed. Pre-assigned half days off on Sunday mornings, or on other days when applicable, paid off given the long field phases and continuous high workloads.

Week 20-26 January

Morning

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
DATA	DATA	DATA	DATA	DATA	DATA	FREE
DATA	DATA	DATA	STAKES	DATA	DATA	FREE
DATA	DATA	DATA	STAKES	DATA	DATA	FREE
DATA	LAB	SNOW	STAKES	DATA	LAB	FREE
DATA	LAB	SNOW	STAKES	SNOW	ROV	FREE
HELI	HELI	SNOW	DYNAMIC	SNOW	ROV	FREE
CORES	STAKES	STAKES	DYNAMIC	SNOW	ROV	FREE
CORES	STAKES	STAKES	DYNAMIC	SNOW	LIDAR	FREE
SNOW	STAKES	DYNAMIC	REMOTE	RIDGES	LIDAR	FREE
SNOW	ROV	DYNAMIC	REMOTE	RIDGES	DYNAMIC	FREE
SNOW	ROV	REMOTE	REMOTE	RIDGES	DYNAMIC	FREE
SNOW	ROV	REMOTE	REMOTE	RIDGES	REMOTE	FREE
REMOTE	ROV	REMOTE	REMOTE	REMOTE	REMOTE	LIDAR
REMOTE	DYNAMIC	REMOTE	REMOTE	REMOTE	REMOTE	LIDAR

Afternoon

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
DATA	DATA	FLEX	HELI	BASIC	DATA	FLEX
DATA	DATA	FLEX	DYNAMIC	DATA	DYNAMIC	FLEX
CORES	DATA	FLEX	DYNAMIC	SNOW	DYNAMIC	FLEX
CORES	LAB	BASIC	DYNAMIC	SNOW	DYNAMIC	FLEX
HELI	LAB	DATA	TRANSECT	SNOW	DYNAMIC	FLEX
SNOW	LAB	DATA	TRANSECT	RIDGES	LIDAR	FLEX
SNOW	HELI	DATA	TRANSECT	RIDGES	LIDAR	FLEX
SNOW	ROV	DATA	TRANSECT	RIDGES	ROV	FLEX
SNOW	ROV	DYNAMIC	TRANSECT	RIDGES	ROV	FLEX
SNOW	ROV	DYNAMIC	TRANSECT	REMOTE	ROV	FLEX
REMOTE	DYNAMIC	REMOTE	TRANSECT	REMOTE	REMOTE	FLEX
REMOTE	DYNAMIC	REMOTE	TRANSECT	REMOTE	REMOTE	FLEX
REMOTE	REMOTE	REMOTE	TRANSECT	REMOTE	REMOTE	FLEX
REMOTE	REMOTE	REMOTE	TRANSECT	REMOTE	REMOTE	FLEX

Week 6-12 July

Morning

Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday
FLEX	FLEX	FLEX	FLEX	FLEX	FLEX	FREE
BASIC	BASIC	BASIC	FLEX	FLEX	FLEX	FREE
BASIC	BASIC	BASIC	FLEX	FLEX	FLEX	FREE
HELI	LAB	LAB	BASIC	FLEX	BASIC	FREE
CORES	HELI	HELI	BASIC	FLEX	BASIC	FREE
CORES	SNOW	SNOW	LAB	BASIC	LAB	FREE
CORES	ROV	DYNAMIC	HELI	BASIC	LAB	FREE
SNOW	ROV	PONDS	DYNAMIC	HELI	LAB	FREE
STAKES	ROV	PONDS	RIDGES	STAKES	HELI	FREE
STAKES	PONDS	STAKES	RIDGES	STAKES	SNOW	FREE
STAKES	PONDS	STAKES	RIDGES	RIDGES	OPTICS	FREE
STAKES	DYNAMIC	OPTICS	RIDGES	RIDGES	OPTICS	FREE
REMOTE	REMOTE	REMOTE	RIDGES	TRANSECT	REMOTE	FREE
REMOTE	REMOTE	REMOTE	PONDS	TRANSECT	REMOTE	FREE

Afternoon

Monday	Tuesday	Wednesday	Thursday	Friday *	Saturday **	Sunday
HELI	FLEX	FLEX	FLEX	FLEX	FLEX	FLEX
CORES	BASIC	FLEX	BASIC	FLEX	FLEX	FLEX
CORES	DATA	FLEX	DATA	FLEX	BASIC	FLEX
CORES	LAB	BASIC	HELI	BASIC	DATA	FLEX
PONDS	HELI	BASIC	SNOW	DATA	HELI	FLEX
PONDS	ROV	BASIC	LIDAR	HELI	LIDAR	FLEX
STAKES	ROV	DATA	LIDAR	SNOW	LIDAR	FLEX
STAKES	ROV	LAB	RIDGES	ROV	ROV	FLEX
TRANSECT	OPTICS	HELI	RIDGES	ROV	ROV	FLEX
TRANSECT	OPTICS	SNOW	RIDGES	ROV	ROV	BASIC
OPTICS	OPTICS	TRANSECT	PONDS	OPTICS	PONDS	DATA
OPTICS	SNOW	TRANSECT	PONDS	OPTICS	PONDS	HELI
REMOTE	TRANSECT	PONDS	REMOTE	REMOTE	OPTICS	OPTICS
REMOTE	TRANSECT	PONDS	REMOTE	REMOTE	OPTICS	DYNAMIC

*24-hour sampling period began; **24-hour sampling period ended

Figure S1: *Weekly work plans for snow and sea ice observations.*
Schematics from the weeks starting January 20, 2020, (left) and starting July 6, 2020, (right). Each line represents one person. Workdays were split into morning and afternoon blocks. Colors are consistent with the sites in Figure 2. Abbreviations refer to the tasks, as described in Section 2 of the main manuscript, in addition the following terms are used: 'FLEX' for flexible tasks, 'DATA' for data documentation and processing, 'BASIC' for routine work, 'LAB' for (freezer) laboratory work.

S2 Methods and field set-up details

The MOSAiC snow and sea ice program was based on a large number of specialized instruments and methods, which are usually referred to in abbreviations or acronyms. In addition, the field work concept included terminology (and abbreviations) that are unknown to many external readers. All these terms are compiled in Table S1 to ease reading of the manuscript. Abbreviations for all remote sensing instruments are given in Table 2 in the main text; here only names mentioned in the text are listed.

Table S1: Instrument names and abbreviations used in the text.

Short name	Full name / description
ALS	Airborne Laser Scanner
ARIEL	Airborne Radiometer in L-band / used on a mobile sled on transects
CO	Central Observatories (existence of CO1 to CO3)
DN	Distributed Network (existence of DN1 and DN2)
EM	Electro Magnetic
EM-Bird	Helicopter-towed electro-magnetic sounding instrument
FYI	First Year (sea) Ice
GEM	EM induction sounding instrument
GNSS (-R)	Global Navigation Satellite System (and Reflectrometry)
HELiPOD	Helicopter-towed atmospheric sensor suite
HUTRAD	Helsinki University of Technology Radiometer / Microwave radiometer at Remote Sensing site
IMB	(Sea) Ice Mass-balance Buoy
IR	Infrared
LIDAR	Light detection and ranging
Micro-CT	X-ray Micro Computer Tomograph
MOSAiC	Multidisciplinary drifting Observatory for the Study of Arctic Climate
NIR	Near Infrared
ROV	Remotely Operated Vehicle
RS	Remote Sensing
SAR	Synthetic Aperture Radar
SCAT	Scatterometer
SMP	Snow Micro Pen
SSL	Surface Scattering Layer
SYI	Second Year (sea) Ice
TIR	Thermal Infrared
TLS	Terrestrial Laser Scanner
UHI	Underwater Hyperspectral Imager

Sea ice coring

Photographs of the conditions at the coring sites from winter and early summer are shown in Figure S2. The sea ice data used to create Figure 15, is given in Tables S2 and S3.

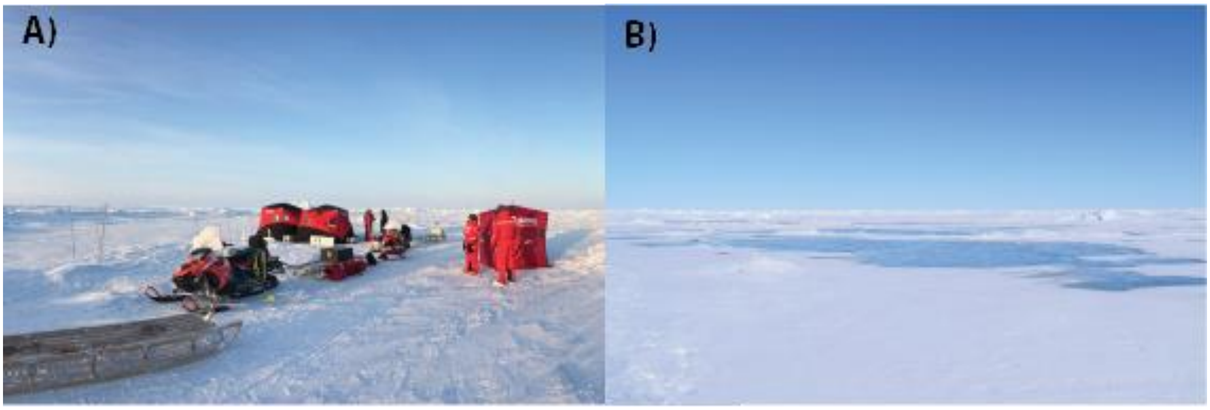

Figure S2: *Sea ice coring sites.*
Photographs of the coring site during (A) Leg 3 on March 21, 2020, and (B) Leg 4 on June 22, 2020. The photo from the spring Leg 3 also shows the shelters that were temporarily set up for the coring work.

Table S2: *Sea ice core data: winter*
Salinity (S) and temperature (T) profile for first year (FYI) and second year (SYI) of the 1_10 coring event on December 02, 2019. The upper (z0) and lower (z1) boundary of the salinity section depth, and the depth of temperature measurements (z) are given in m relatively to the ice surface. The graph is shown in Figure 16.

FYI					SYI				
z_0	z_1	S	z	T	z_0	z_1	S	z	T
m	m	-	m	°C	m	m	-	m	°C
0.000	*0.050*	6.9	*0.025*	-15.3	*0.000*	*0.050*	0.9	*0.025*	-8.3
0.050	*0.100*	5.8	*0.075*	-13.0	*0.050*	*0.100*	0.5	*0.125*	-7.8
0.100	*0.150*	5.9	*0.175*	-12.0	*0.100*	*0.150*	0.9	*0.225*	-6.5
0.150	*0.200*	4.1	*0.275*	-8.5	*0.150*	*0.200*	1.1	*0.325*	-6.1
0.200	*0.250*	3.5	*0.325*	-7.4	*0.200*	*0.250*	1.2	*0.375*	-6.2
0.250	*0.310*	4.8	*0.375*	-7.1	*0.250*	*0.290*	2.4	*0.425*	-5.8
0.310	*0.360*	4.8	*0.425*	-6.4	*0.290*	*0.350*	2.3	*0.545*	-5.0
0.360	*0.410*	4.8	*0.475*	-5.5	*0.350*	*0.400*	3.9	*0.645*	-4.3
0.410	*0.455*	4.5	*0.525*	-5.3	*0.400*	*0.450*	1.7	*0.745*	-3.3
0.455	*0.500*	5.5	*0.625*	-3.1	*0.450*	*0.500*	1.2	*0.845*	-1.9
0.500	*0.550*	4.6	*0.675*	-2.3	*0.500*	*0.550*	3.1	*0.870*	-1.7
0.550	*0.600*	4.7	*0.695*	-1.9	*0.550*	*0.600*	1.6		
0.600	*0.650*	5.6			*0.600*	*0.650*	1.2		
0.650	*0.705*	7.9			*0.650*	*0.700*	1.5		
					0.700	*0.750*	3.4		
					0.750	*0.800*	4.3		
					0.800	*0.850*	5.3		
					0.850	*0.900*	8.0		

Table S3: *Sea ice core data: summer*
Salinity (S) and temperature (T) profile for first year (FYI) and second year (SYI) of the 4_46 coring event on July 06, 2020. The upper (z0) and lower (z1) boundary of the salinity section depth, and the depth of temperature measurements (z) are given in m relatively to the ice surface. The graph is shown in Figure 16.

FYI					SYI				
z_0	z_1	S	z	T	z_0	z_1	S	z	T
m	m	-	m	°C	m	m	-	m	°C
0.000	0.050	0.2	0.025	-0.1	0.000	0.050	0.2	0.025	0.1
0.050	0.105	0.3	0.050	0.1	0.050	0.100	0.0	0.125	0.5
0.105	0.160	0.3	0.150	0.0	0.090	0.150	0.0	0.225	0.0
0.160	0.210	0.8	0.250	-0.1	0.140	0.200	0.1	0.325	0.0
0.210	0.260	1.9	0.350	-0.5	0.190	0.250	0.1	0.425	0.0
0.260	0.310	2.8	0.450	-0.7	0.240	0.300	0.1	0.525	0.0
0.310	0.360	3.3	0.550	-0.6	0.290	0.350	0.1	0.625	0.0
0.360	0.410	3.6	0.650	-1.0	0.340	0.400	0.1	0.725	0.0
0.410	0.460	3.8	0.750	-1.1	0.390	0.450	0.1	0.790	0.0
0.460	0.510	4.3	0.850	-1.2	0.440	0.500	0.1	0.850	0.0
0.510	0.560	4.3	0.950	-1.3	0.490	0.550	0.1	0.925	0.0
0.560	0.610	4.9	1.050	-1.4	0.540	0.600	0.1	1.025	-0.1
0.610	0.660	4.1	1.150	-1.1	0.590	0.650	0.1	1.100	0.0
0.660	0.710	4.3	1.250	-1.1	0.640	0.700	0.2	1.150	-0.1
0.710	0.760	4.3	1.350	-0.9	0.690	0.750	0.2	1.225	-0.1
0.760	0.810	4.3	1.450	-0.7	0.740	0.800	0.4	1.325	-0.3
0.810	0.860	4.0	1.550	-0.7	0.790	0.850	0.3	1.425	-0.2
0.860	0.910	4.0	1.620	-0.5	0.840	0.900	0.1	1.525	-0.1
0.910	0.960	3.8			0.890	0.950	0.1	1.625	-0.5
0.960	1.010	3.7			0.940	1.000	0.2	1.725	-0.9
1.010	1.060	3.9			0.990	1.050	0.2	1.825	-1.0
1.060	1.110	3.5			1.040	1.100	0.2	1.925	-1.2
1.110	1.160	3.5			1.090	1.150	0.2	2.025	-1.4
1.160	1.210	3.6			1.140	1.210	0.2	2.125	-1.4
1.210	1.260	3.5			1.190	1.260	0.3	2.210	-1.2
1.260	1.310	3.1			1.240	1.310	0.2		
1.310	1.360	3.2			1.290	1.360	1.1		
1.360	1.410	2.9			1.340	1.410	1.7		
1.410	1.460	3.2			1.390	1.460	1.0		
1.460	1.510	2.6			1.440	1.510	2.3		
1.510	1.545	1.6			1.490	1.560	2.0		
1.545	1.605	2.2			1.540	1.610	0.2		
					1.590	1.660	0.5		
					1.640	1.710	1.1		
					1.690	1.760	1.3		
					1.750	1.810	1.3		
					1.800	1.860	1.4		
					1.850	1.910	3.3		
					1.900	1.960	3.2		
					1.950	2.010	3.4		
					2.000	2.060	3.3		
					2.050	2.110	2.9		
					2.100	2.160	3.1		

Remotely operated vehicle (ROV)

The ROV has been operated from different sites due to the dynamic icescape: Site ROV 1.0 was never used for scientific dives, being immediately replaced by ROV 2.0 during Leg 1 (CO1). Site ROV 3.0 was used on CO1 during Legs 2 and 3, sites ROV 4.0 and 4.5 were operated on CO2 during Leg 4, and site ROV 5.0 was operated on CO3 during Leg 5. Figure S3a shows exemplary photographs of the set up (Leg 2 and Leg 5) and maps to illustrate linkages to other measurements during spring.

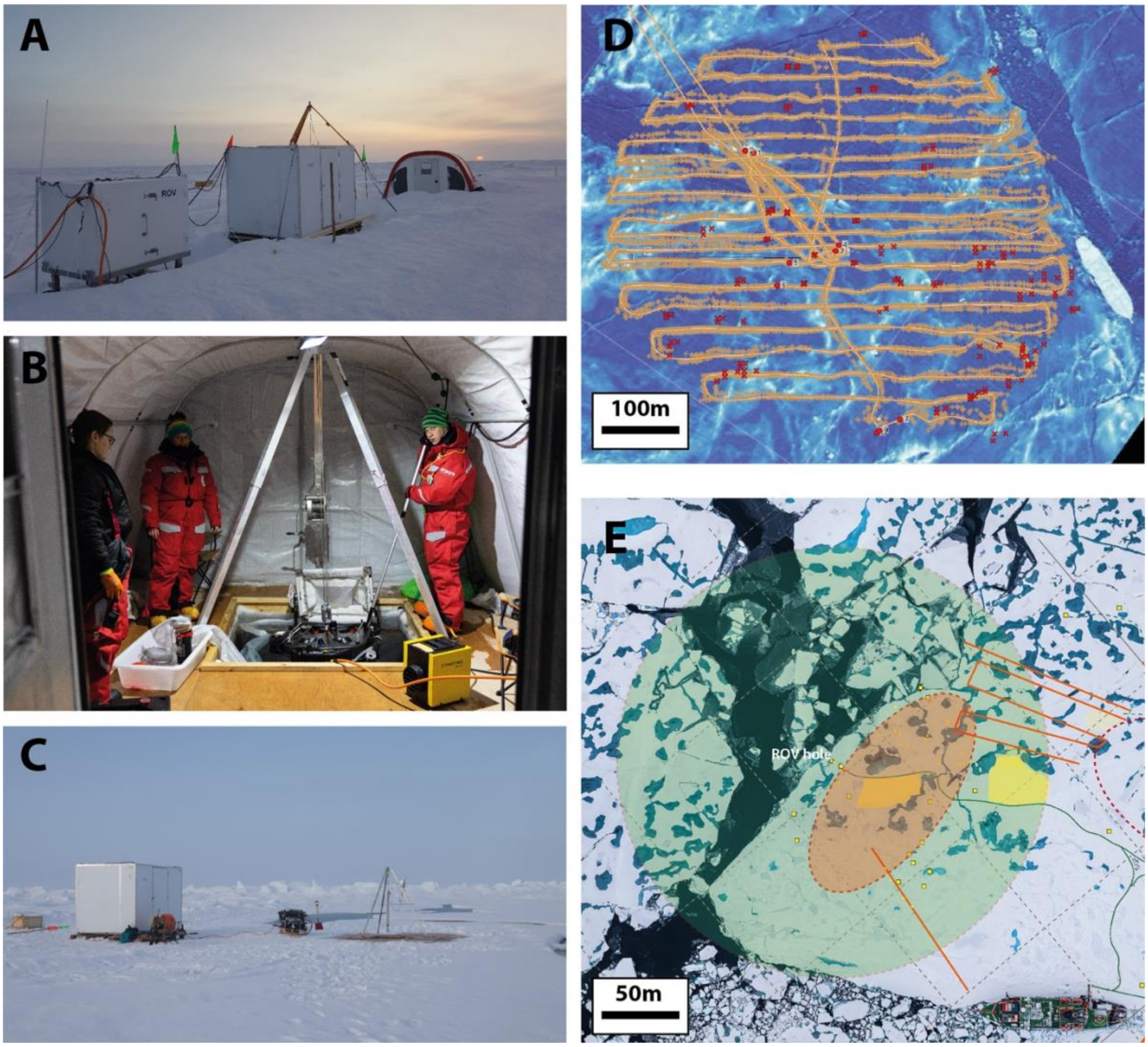

Figure S3: *ROV observations.*
(A) Remotely operated vehicle (ROV) site consisting of the power hub, the surface unit (white hut), the tent over the hole (photo March 14, 2020), (B) inside the ROV tent (photo December 07, 2019), (C) ROV site consisting of the surface unit and the hole without tent (photo August 25, 2020), (D) dive track (yellow line) and excluded acoustic navigation fixes (red dots) as overlay on the airborne laser scanner topography surface map (dive on February 04, 2020), (E) schematic overview of the ROV dive range (green circle) during autumn (Leg 5, aerial photo from September 06, 2020). Other sites: TLS area in orange ellipse, transects in orange lines, snow and surface studies in yellow patches, other installations and sites as small yellow squares.

On-ice remote sensing

The concept of the on-ice remote sensing measurements was to observe the same snow and sea ice surface, or at least the same surface type, with all instruments. In addition, other manual measurements were co-located on the same site (Figure 2) and ice conditions. Figure S4 shows the arrangement of the individual sensors around the observation site.

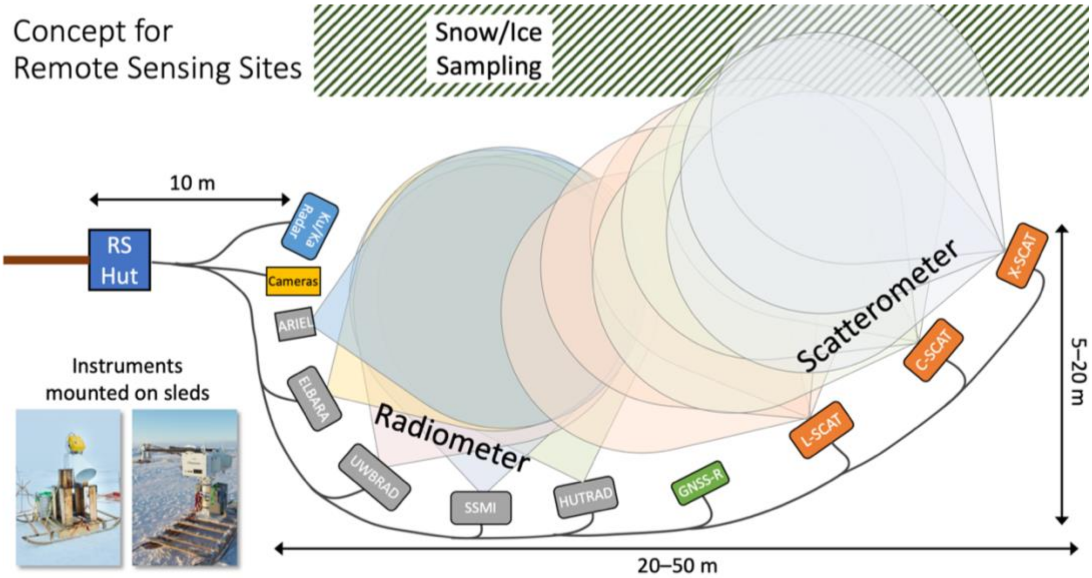

***Figure S4:** On-ice remote sensing concept.*
Conceptual layout used for the Remote Sensing Sites on the MOSAiC ice floe. For comparability all instruments looked at similar ice and snow. Physical ice and snow properties were sampled in the vicinity. Photographs of the Remote Sensing Site are shown in Figure 10. Additional sea ice remote sensing observations were performed from Polarstern.

Sea ice drift forecasts

A near-real-time drift forecast product for the MOSAiC floe was provided by the Year of Polar Prediction (YOPP; Jung et al., 2016) Sea Ice Drift Forecast Experiment (SIDFEx). Several operational forecast centers and institutes contributed drift forecasts in near-real-time for lead times ranging from days to a year. For MOSAiC a consensus ensemble forecast product, based on the different forecast systems, was used. Typically, about five different short-term (7–10 days) single-trajectory forecasts, which in particular use recent wind forecasts for driving the ice drift, and one seasonal, climatological forecast were merged into a seamless ensemble forecast. The consensus forecasts were provided onboard *Polarstern* through the MapViewer system to support decision making, and on land through an online tool (https://sidfex.polarprediction.net), for placing orders for satellite imagery. Figure S5 exemplifies the consensus forecasts product, showing the forecast issued on February 24, 2020.

Beyond the drift phase, forecast products from fully coupled models were provided on a daily base as well as ensemble predictions of sea ice conditions for the coming months (https://nps.edu/web/rasm/predictions). All these sea ice model applications were most supportive for the highly complex logistical operations of the supply vessels. Advancing the fidelity of different models with the hierarchy will allow for the development of optimized observational networks, as they may be used for sea ice monitoring or advanced field programs in the future.

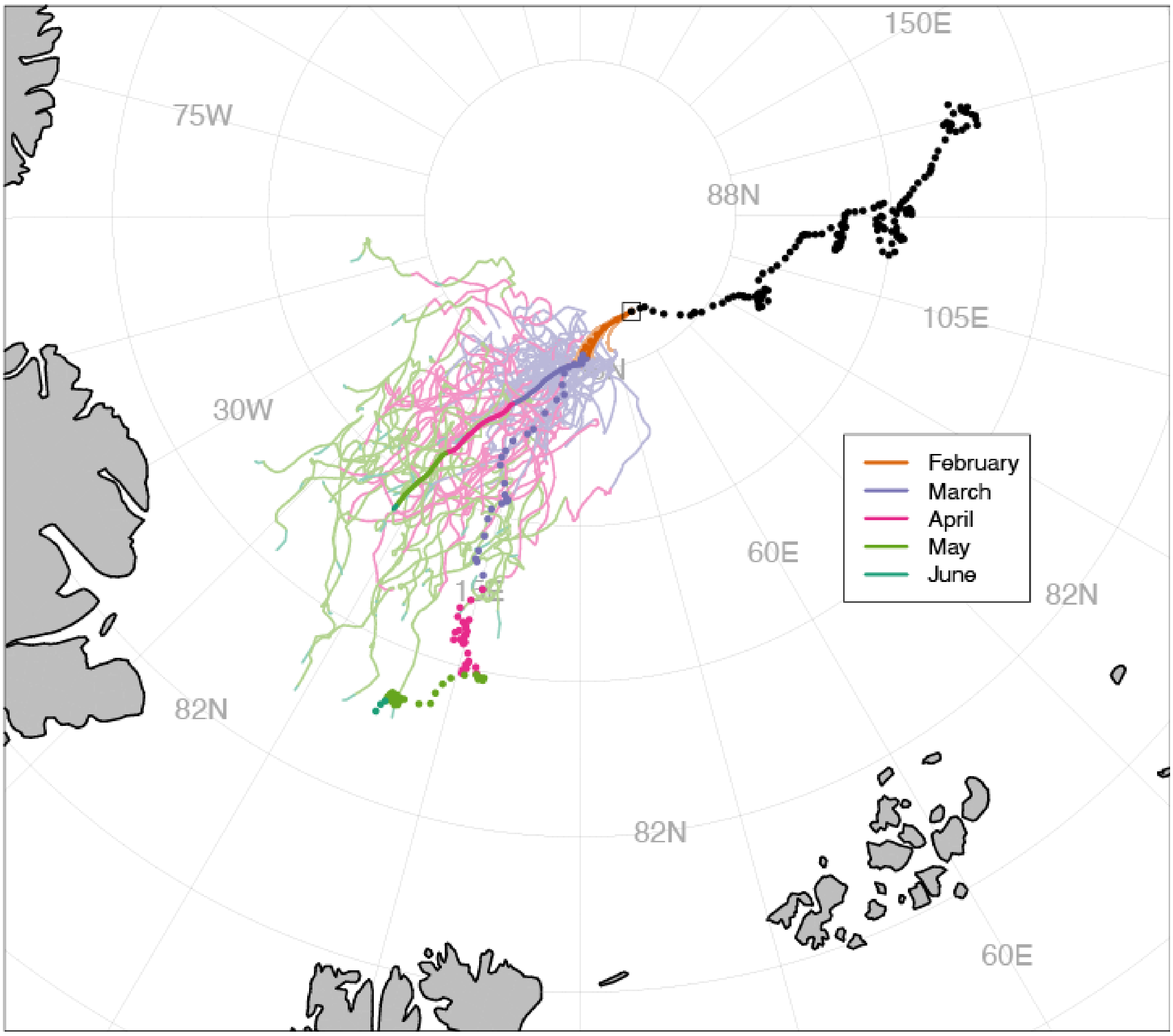

Figure S5: *The SIDFEx consensus drift forecast for the MOSAiC central observatory (CO1). The forecast of the Sea Ice Drift Forecast Experiment (SIDFEx, https://sidfex.polarprediction.net/) starts on February 24, 2020, at 00:00 UTC, when Polarstern was at the given position (grey square). Thin solid lines denote individual (merged) forecast ensemble members and the corresponding thick solid line denotes the ensemble mean (centroid). Lines are colored by calendar month. Dots denote daily observed positions of Polarstern before (black) and after (colored by calendar month) February 24, 2020.*

Technological challenges

The year-long operations in the central Arctic resulted in specific (technological and methodological challenges), in particular with respect to automated systems.

Challenges were observed in flying the Mavic and Spectra drones close to the North Pole, where operators needed to apply the manual mode because the compass reading was not correct. However, similar problems were not encountered using the HELiX drone, albeit at lower latitudes. Future studies should consider developing and leveraging advanced navigation systems such as the D-GPS navigation employed by the DataHawk unmanned aerial system deployed to make atmospheric measurements, to avoid the challenges encountered by the Mavic and Spectra copters. In addition to challenges posed by the navigation systems, other factors, including fast ice drift velocities, fog, and icing conditions resulted in a difficult operating environment for drone systems. Despite these challenges, the systems deployed combined to provide unique perspectives on broadband and spectral albedo and their evolution during the melt and refreezing seasons.

Many complex instruments, e.g., most of the remote sensing sensors, were designed for shorter campaigns. Operating them continuously for a full year led to some instrument failures, which only partly could be repaired in the field, and thus led to data gaps or a complete stop of measurements for some channels (Figure 3b). This was partly compensated by the large suite of complementary measurements, but a larger pool of spare parts and more trained personnel could have reduced these downtimes.

References

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