SUMMARY

PS122.2 (or Leg 2) was the midwinter leg of the international Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC). It comprised two voyages on board the Russian supply icebreaker *Kapitan Dranitsyn* from Tromsø to the *Polarstern* and back, with a total length of seven weeks, and an eleven week long observational period and drift on board the *Polarstern,* from December 13, 2019, to March 6, 2020. The supply voyages were the northernmost known ship operations ever performed in the Arctic during winter. The drift of the *Polarstern* was the northernmost known winter drift of a surface vessel ever, and reached a position of 88°36'N, 59°15'E, on Feb 24, 2020, only 84 nautical miles from the North Pole. During the drift of the *Polarstern* the comprehensive, interdisciplinary measurements of atmosphere, ice, ocean, and ecosystem properties and processes were continued and extended from Leg 1, above, in, and under the ice. The unprecedented observational program was very successful and delivered on all goals despite the continuous darkness of the polar night and some of the coldest conditions experienced during MOSAiC. Together with the continued measurements during all other legs these observations will lay the foundation for adequately improving climate models to pave the way for a better understanding and prediction of Arctic and global climate change.

ZUSAMMENFASSUNG

PS122.2 (oder Leg 2) war der Mitwinter-Fahrtabschnitt des internationalen Multidisciplinary drifting Observatory for the Study of Arctic Climate Programmes (MOSAiC). Er bestand aus zwei insgesamt sieben Wochen langen Fahrten mit dem russischen Versorgungseisbrecher *Kapitan Dranitsyn* von Tromsø zur *Polarstern* und zurück, sowie einer elf Wochen langen Drift mit Polarstern vom 13. Dezember 2019 bis 6. März 2020, während der umfangreiche wissenschaftliche Messungen durchgeführt wurden. Die Versorgungsfahrten waren die nördlichsten bekannten Schiffsoperationen aller Zeiten im Winter, und der nördlichste Punkt der Polarstern-Drift war der nördlichste jemals erreichte Punkt eines treibenden Schiffes. Dieser wurde am 24. Februar 2020 bei einer Position von 88°36'N, 59°15'E erreicht, nur 84 Seemeilen vom Nordpol entfernt. Während der Drift der Polarstern wurden die umfangreichen, interdisziplinären Messungen von Eigenschaften und Prozessen in der Atmosphäre, im Eis, im Ozean, und um Ökosystem über, im, und unter dem Eis weitergeführt und ausgeweitet, die bereits während dem ersten Fahrtabschnitt (PS122.1) vorbereitet und begonnen wurden. Das bisher unvergleichliche Beobachtungsprogramm war sehr erfolgreich und hat sämtliche Ziele erreicht, trotz permanenter Dunkelheit der Polarnacht und einigen der kältesten Bedingungen, die während MOSAiC angetroffen wurden. Zusammen mit den Messungen während aller anderen MOSAiC Fahrtabschnitte werden diese Beobachtungen die Basis für verbesserte Klimamodelle bilden, um das Verständnis und die Vorhersage des arktischen und globalen Klimawandels maßgeblich voranzutreiben.

1. OVERVIEW, DRIFT AND SET UP

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1.1 MOSAiC introduction and objectives

The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) is an international Arctic Research initiative that is broadly motivated by the dramatic changes in the Arctic climate system over the last few decades, highlighted by significant losses of sea ice, and generally deficient model representations of the important processes responsible for, and responding to, these changes. The ultimate goal of the initiative is to enhance understanding of central Arctic coupled atmosphere-ice-ocean-ecosystem processes to improve numerical models for sea ice forecasting, extended-range weather forecasting, climate projections, and climate change assessment. This goal will be achieved by carrying out the most comprehensive, most accurate, most continuous, and most systematic interdisciplinary *in-situ* and airborne observations in the Arctic Ocean to date, and by obtaining these over a full seasonal cycle including the winter freezing and summer melting seasons.

At the core of MOSAiC the German research icebreaker *Polarstern* was frozen into the ice in the northern Laptev Sea in October 2019, and was then drifting with the Transpolar Drift until reaching the ice edge near Svalbard in the summer/fall of 2020. *Polarstern* served as a high-tech, comfortable research base from which the surrounding ice, water, and air could be easily explored. Only with such a base the demanding scientific activities could be realized, in contrast to, e.g., ice camps which provide less capable infrastructure and which can only support somewhat limited research agendas.

Leg 2 arrived at the MOSAiC ice camp on December 13, 2019, and left on March 6, 2020 (Table 1.1). It had special significance as it was the midwinter observational period of MOSAiC, the season during which the least information about atmosphere-ice-ocean-ecosystem processes existed so far. Leg 2 was truly the summit of MOSAiC as it was the darkest, coldest, and most northerly observational period of the whole project. The leg strongly benefited from the good preparations and routines already introduced in the MOSAiC preparation phase and during Leg 1. These had already installed most of the permanent measurement systems on, under, and above the ice, and had set in place the daily working routines and safety procedures that were just continued to be used during Leg 2, and which are reported about in later chapters of this report. In addition, Leg 2 research strongly relied on helicopter surveys and site visits which posed particular challenges during the polar night and required special aircraft preparation and pilot training.

Other than that measurements were little impacted by darkness and cold, as many observational sites were sufficiently lit by the *Polarstern's* search lights or background illumination, and as the scientists were very well prepared and equipped to work under such harsh conditions. Naturally though, most of our activities were centered on the Central Observatory not farther than 2 km away from the ship. Only the helicopter L-site visits and surveys reached distances of up to 12 nautical miles from the ship, while one snowmobile trip was made to the L2 site approximately 5 miles away.

Work on the ice was significantly aided by the full moon which occurred on December 12, January 10, February 9. During the polar night the moon does not set for between several days and two weeks, depending on latitude. Therefore, in the days surrounding full moon the

moon provides reasonable light conditions easing orientation and navigation, allowing recognition of the structure of the snow surface, and finding of installations.

Tab. 1.1: *Key dates of the expedition PS122/2*

Date	Event
27 Nov 2019	Departure of Kapitan Dranitsyn in Tromsø
13 Dec 2019	Arrival of Kapitan Dranitsyn at the *Polarstern* and ice floe
13-18 Dec 2019	Handover and bunkering activities between both ships
18 Dec 2019	Departure of Kapitan Dranitsyn from ice floe, with crew and scientists of PS122/1
28 Feb 2020	Arrival of Kapitan Dranitsyn at ice floe, with crew and scientists of PS122/3
28 Feb–6 Mar	Handover and bunkering activities between both ships
06 Mar 2020	Departure of Kapitan Dranitsyn from ice floe, with crew and scientists of PS122/2
14-19 Mar 2020	Refuelling of Kapitan Dranitsyn by Admiral Makarov
31 Mar 2020	Arrival of Kapitan Dranitsyn in Tromsø, quarantine
1 Apr 2020	Disembarkation of Kapitan Dranitsyn by crew and scientists of PS122/2, charter flight for all participants from Tromsø to Bremen

1.2 Supply voyages of *Kapitan Dranitsyn* between Tromsø and the *Polarstern*

1.2.1 From Tromsø to the Polarstern, November 27 to December 13, 2019

All leg 2 participants met in Tromsø on November 24, 2019, for fitting of polar clothes and for two days of introductions and trainings organized by AWI's logistics team and held at the Norwegian Polar Institute. All participants boarded *Kapitan Dranitsyn (KD)* in the morning of November 27. The ship cast off from the pier in the early afternoon, however, went to a nearby anchorage for proper lashing of containers, and for waiting for favourable wind conditions for the Barents Sea crossing. Strong winds and waves higher than 3-4 m were expected until December 3, too high for safe passage of the ship and its load of provisionally lashed food containers on the foredeck.

KD left the anchorage early in the morning of December 3, and reached the ice edge east of Svalbard at approximately 77.76°N, 36.15°E in the early evening of December 4 (Figure 1.1), after approximately 38 hours of steaming. From here on there was only very little twilight left, and *KD* sailed mostly in complete darkness of the polar night, only aided by the rising full moon that culminated on December 12 and provided some light when there were no clouds. *KD* circumnavigated Franz Josef Land to the south and east, and crossed the Kara Sea to reach open water and thin ice to the north of Severnaya Zemlya in the evening of December 7. From there the ship took a northerly course to reach the Mosaic floe as directly as possible (Figure 1.1). This route aimed to circumnavigate or avoid completely the zone of older, second-year ice that had survived the previous summer (Figure 1.2) and that had also presented a challenge for Akademik Federov when she returned from her supply of the *Polarstern* during Leg 1 in October 2019.

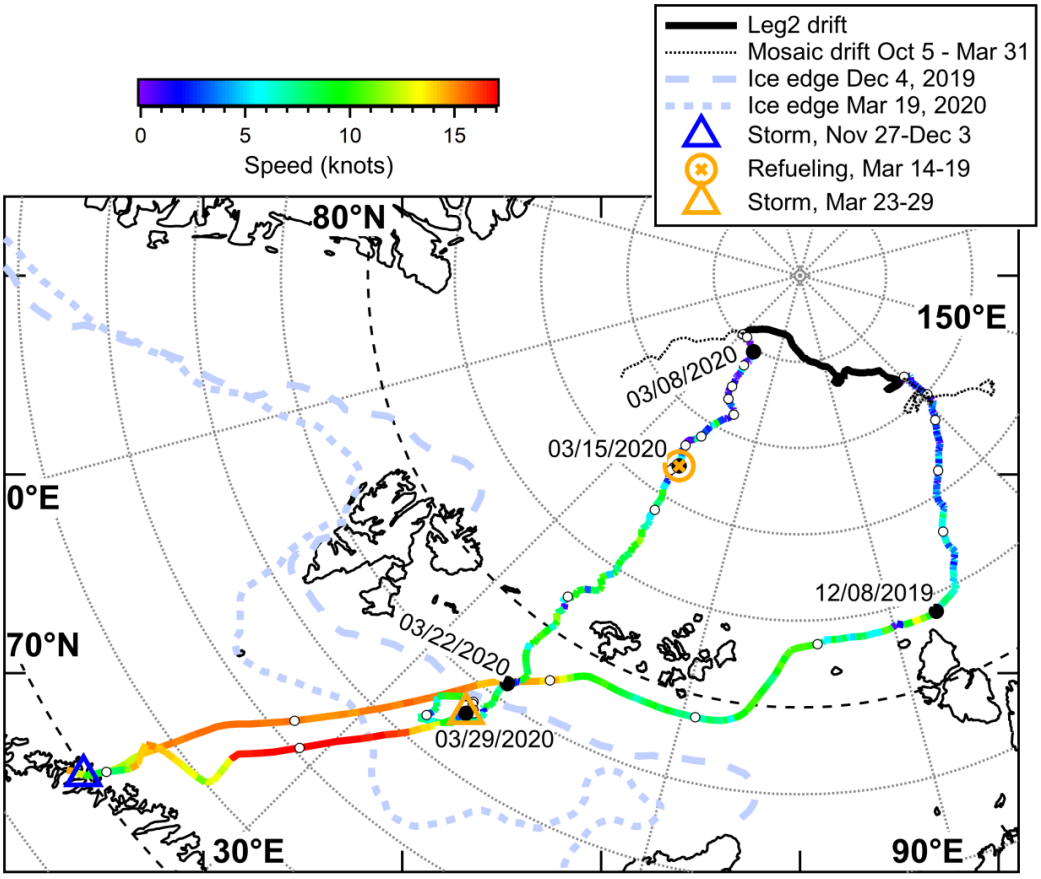


Fig. 1.1: *Overview map of Leg 2 of MOSAiC (PS122/2), including the transit of Kapitan Dranitsyn (KD) in December 2019 and March 2020, colour coded by ship's speed; the Polarstern drift track between December 13, 2019, and March 6, 2020; and the overall MOSAiC drift track from October 5, 2019, to March 31, 2020. Map also shows idle locations of KD while waiting for low wave conditions for the Barents Sea crossing, and the position of the refuelling by icebreaker Admiral Makarov. Note variation of ice edge location between December and March. Axis tick spacing 500 km.*

Passing through the narrow tongue of old ice and pursuing a northerly course provided increasingly difficult, and the average speed decreased significantly, being less than 2 knots on the last day before reaching the *Polarstern* in the morning of December 13, at 86.59°N, 119.25°E (Figure 1.3). In total, the voyage had taken 10.5 days (16 days after casting off in Tromsø) and was 1650 miles long.

During the last day of sailing *KD's* approach took a detour to the north to avoid passing through some of the L- and M-sites where autonomous stations were operated on and under the ice. This was aided by a nautical officer (Felix Lauber) from the *Polarstern* who had been flown to *KD* by helicopter on December 11 when *KD* was approximately 40 miles away from *Polarstern*.

During this first supply voyage ice routing on board *KD* was supported by ice expert Vladimir Bessonov from the Arctic and Antarctic Research Institute (AARI) in St. Petersburg, Russia.

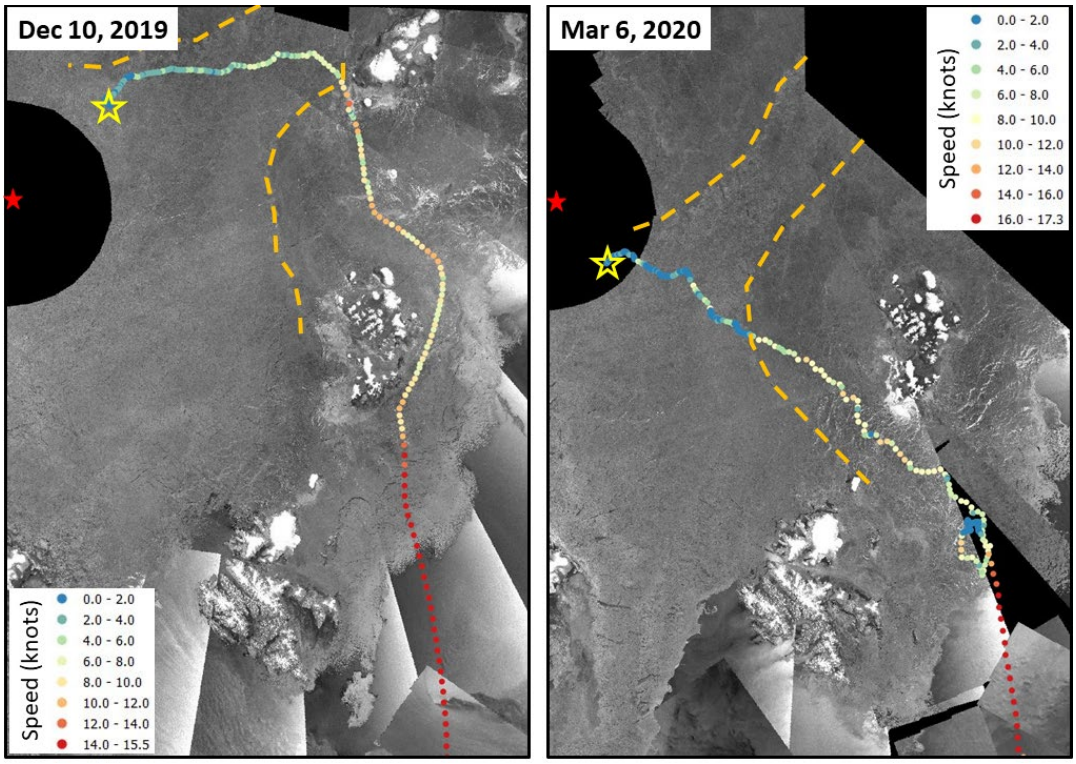


Fig. 1.2: Maps of the Leg 2 supply voyages on board Kapitan Dranitsyn, overlaid on Sentinel 1 radar image mosaics (courtesy DTU), showing ice conditions on December 10, 2019, and March 6, 2020, representative of conditions encountered during both voyages. Stippled orange lines indicate boundaries of old ice region that were advected westwards between December and March, similar to the drift of the Polarstern (yellow stars).

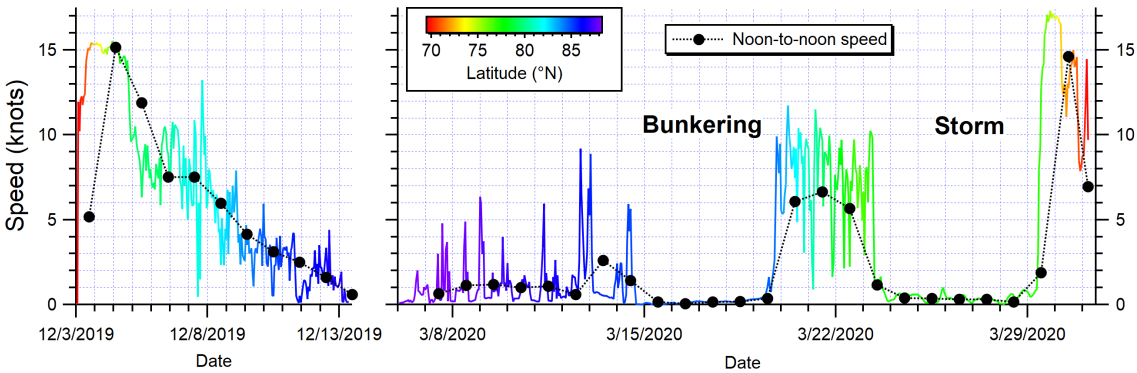


Fig. 1.3: Speed of Kapitan Dranitsyn (KD) during the supply voyages in December 2019 (left) and March 2020 (right). Note decreasing ship speed with increasing latitude (color coded), roughly corresponding to more severe ice conditions farther north. Also note much lower speed and periodic steaming periods in the beginng of March 2020 when prevailing ice thickness was almost twice that in December. KD was stopped for bunkering and when waiting for a passing storm in March. After bunkerung, KD was initially escorted by icebreaker Admiral Makarov.

On December 13 *KD* arrived at *Polarstern* from behind, from the north, roughly following the old floe edge along which *Polarstern* had reached her anchoring position in October. She pulled up to lay alongside *Polarstern's* port side, with her bow reaching just past *Polarstern's* helicopter deck and close enough for the cranes of both ships to reach the other ship, respectively (Fig. 1.4).

Between December 13 and 18, 70 tons of cargo and 900 tons of diesel fuel were transferred from *KD* to *Polarstern*, mostly using both ship's cranes, a hose, and the Argo vehicle with a sledge which transported heavy items from *KD's* helicopter deck over the ice, where they were placed by *KD's* port side aft crane. Special attention had to be given to perishable food that must not have frozen and was therefore reloaded to and lifted in a heated 10 ft container. Personnel could walk over the ice to visit between ships, during times during which polar bear watches were available.

***Fig. 1.4**: Sketch of the anchoring positions of Polarstern and Kapitan Dranitsyn for bunkering in December 2019. Figure courtesy Felix Lauber and officers of Polarstern.*

During the same time, the handover between the scientific teams of legs 1 and 2 took place, including visits of field sites on the ice and in the laboratories. The approximately 2x60 scientists and their extensive luggage swapped ships in the morning of December 16. After more trainings and introductions, including refreshers for snowmobile and firearm usage, Leg 2 fully took over operations in the afternoon of December 17. *KD* left the site in the afternoon of December 18 to head south and to return crew and scientists of Leg 1 back to Tromsø, where they arrived after 14 days on January 1, 2020, following approximately the same route as the northward voyage of Leg 2.

In the last days of the *KD* voyage, six drifting buoys provided by the Arctic and Antarctic Research Institute (AARI) from St. Petersburg were deployed on ice floes along the cruise track. Buoys were deployed during short stops each less than 30 minutes long, when scientist were lifted onto the ice by mummy chair to place the buoys at elevated sites away from the icebreaker channel. An overview of the deployments is given in Table 1.2.

***Tab. 1.2:** Overview of AARI buoy deployments during the KD supply voyage in December 2019.*

Date	Position	Buoy type and name, IMEI
12/9/2019	84°13.8'N 108°27.8'E	SVP-B, 2019P221
12/10/2019	84°56.0'N 114°54.9'E	SVP-B, 2019P222
12/10/2019	85°13.8'N 118°35.9'E	SVP, 2019P112, 300234061161590
12/11/2019	85°33.4'N 119°22.4'E	SVP, 2019P113, 300234061161600
12/11/2019	85°45.8'N 121°48.9'E	SVP, 2019P114, 300234061162590

12/11/2019	85°51.9‘N 121°58.2‘E	SVP, 2019P119, 300234061164580

1.2.2 From the Polarstern to Tromsø, March 6 to April 1, 2020

Kapitan Dranitsyn (KD) had left Tromsø on January 27 and arrived at the MOSAiC ice floe on February 28. For this second exchange of personnel, equipment, and supplies a docking site approximately 1 km from *Polarstern* was chosen, on the port side, past the runway, and at the former edge of the floe which was demarcated of the prominent shear and deformation zone to the East, that was active for much of January and February. It was not planned to bunker any fuel as enough had been exchanged during the first supply voyage in December (Section 1.2.1).

The docking site was initially marked by AIS, however those were not visible on the bridge of *KD*. Therefore battery operated lights were installed on short notice at the site in addition (Figure 1.5), and *KD* had no difficulties to reach the site and to sit there stably without any ice anchors. The site could easily be reached from *Polarstern* by Pistenbully which had prepared a trail over which all heavy loads could be hauled on pontoon sledges. The ice situation between both ships is depicted in Figure 1.5.

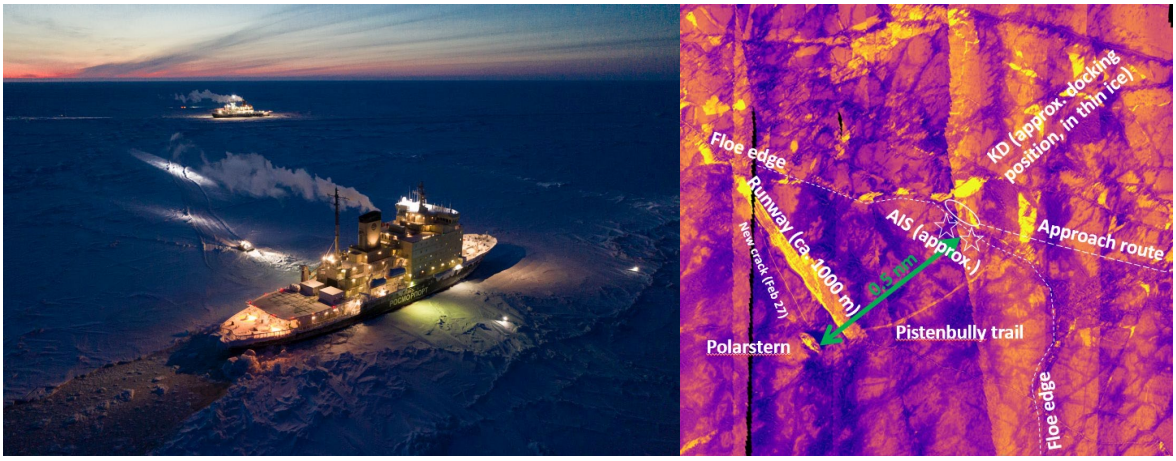


Fig. 1.5: *Docking position of Kapitan Dranitsyn (KD) during the bunkering in Feb/Mar 2020. Photo on left shows situation on Feb 28, just after arrival of KD with nautical twilight conditions (courtesy Steffen Graupner). Pistenbully trail and runway can be seen towards the Polarstern. Right map shows a mosaic of helicopterborne infrared photography, where the Polarstern, thin ice and compacted snow (runway, pistenbully trail) can be seen as brighter features (courtesy Marcus Huntemann).*

Between February 29 and March 5, approximately 40 tons of ship supplies, provisions, and scientific equipment were transported from *KD* to *Polarstern* with the Pistenbullies, for which a second operator had arrived with *KD* (Thomas Sterbenz). The handover period was the coldest period of that duration during the whole MOSAiC project, and therefore many cranes on both ships had difficulties operating. However, *Polarstern’s* portside stern crane was operational most of the time, and being the closest to *KD* all loads were brought there on pontoon sledges and lifted onto the *Polarstern*.

During the same time the scientific handover took place following a carefully composed schedule similar to the handover between Legs 1 and 2. On March 3 the approximately 2x60 scientists were exchanged by snowmobile. Every person took their own luggage and with two snowmobiles each with two Nansen sleds the exchange over the one kilometer long

distance was completed in just over one hour. Most of the *Polarstern* crew swapped berths after completion of the operations on March 5.

KD started engines in the morning or March 6, first turning on the spot and then following the broken channel of late February, which was already well frozen and compacted. The channel was lost in the morning of March 7. Between March 6 and 14 *KD* made very slow progress through the old ice zone, aided by more and more twi- and daylight (Figure 1.1). Civil twilight had commenced on February 29, and the first sunrise occurred on March 10 at a latitude of 86°51'N. Although the ship managed to occasionally find refrozen or open leads in which hourly speeds of 3 to 9 knots could be achieved, overall progress was only 1.2 knots because the ship was stopped for extended periods of time (Figure 1.3). According to *KD's* nautical officers the ship was stopped when there was too much pressure on the ice, but details were difficult to evaluate for the scientific observers.

For nine days, *KD* steamed very slowly from the MOSAiC floe at 88°06'N, 30°49'E to a position of 84°46'N, 42°35'E, with a total distance of 264 nm and an average speed of 1.2 knots. There, still in the old ice zone (Figure 1.2), *KD* rendezvoused with the Russian icebreaker *Admiral Makarov (AM)* for bunkering of fuel. When steaming to the *Polarstern* in February, *KD* had consumed more than 1700 tons of her total of 3000 tons of fuel, i.e. more than half of her supplies. This made a return to Tromsø on her own remaining fuel of 1300 tons questionable, and therefore a refueling operation was organized on short notice. However, due to economic icebreaking including the afore mentioned stops, *KD* did eventually have 800 tons of fuel left at the rendezvous point, theoretically enough to return to Tromsø if she had followed in *AM's* channel for the remainder of the voyage. Good seamanship strongly suggested to use the opportunity to refuel however.

AM had left Murmansk on March 6 and arrived to the north of Franz Josef Land on March 10. There she idled for two days in first year ice, and it was unclear why she did not immediately proceed towards *KD* to assist with ice breaking. However, on March 12 she finally continued her journey and traveled the approximately 186 nm to the *KD* in only two days. Her impressive icebreaking capabilities even in second-year ice conditions were demonstrated when rendezvousing with and anchoring besides *KD*.

Bunkering continued from March 14 to 19, when *KD* took over 1200 tons of heavy fuel. The ships were laid side-by-side in stable ice, with their bows close enough to connect both ships by a gang plank, and a hose laid between both at about mid ships (Figure 1.6).

In the early afternoon of March 19 and after completion of bunkering operations, *KD* followed in the broken channel of *AM* to sail south. *AM* was able to achieve maximum speeds of 9 to 11 knots, only occasionally stopped by heavy and partially pressured ice, resulting in mean speeds between 6 and 7 knots (Figure 1.3). Soon after reaching the first-year ice zone larger regions of open water were encountered, through which fast progress was made. In the evening of March 21 both ships separated just after passing between Nordaustland and Franz Josef Land. From there, *KD* sailed on her own with little reduction in speed, to very near the ice edge which was encountered at midnight of March 22. However, there was heavy swell in the ice, and huge waves in the Barents Sea, and therefore it was decided to sail back into the ice for about 100 nm to wait for calmer conditions (Figures 1.1, 1.2). It is unclear why the ship did not retreat more to the west, more perpendicular to the ice edge where quieter conditions would have been encountered sooner, but there are also restrictions by Svalbard for ships approaching on heavy fuel.

On March 29, after six days of waiting, waves over the Barents Sea were forecast to be low enough so that *KD* began the final section of her voyage. The ice edge was passed at approximately 18:00 local time at approximately 76°02'N, 34°13'E (Figures 1.1, 1.2). In the early morning of March 31, *KD* arrived at the pier in Tromsø, having encountered partially high swells that still required a few course changes along the route (Figure 1.1). Maximum speeds of 17 knots were reached in the open water when waves allowed (Figure 1.3). In Tromsø only Norwegian cruise participants could leave *KD* on the same day, due to the

COVID-19 situation that had emerged during Leg 2's time in the Arctic. All other cruise participants disembarked on April 1 and were transported with private buses to Tromsø airport, from where AWI had organized a charter flight for all remaining scientists and crew. The delay in Tromsø and requirement of a charter flight arose from the COVID-19 situation, that had led to strong international travel restrictions and the cancelation of most commercial passenger flights. In addition, Norway had principally closed their ports to international vessels. However, *KD* was allowed to enter due to tireless negotiations and planning efforts of AWI and the Norwegian Polar Institute.

KD left Tromsø in the night of April 1 and arrived in Murmansk on April 3. In Murmansk the *KD* crew was subjected to a two-week quarantine before they could disembark on April 19.

During this second supply voyage ice routing on board *KD* was supported by ice expert Evgeny Makarov from the Arctic and Antarctic Research Institute (AARI) in St. Petersburg, Russia.

Fig. 1.6: *Bunkering fuel from Admiral Makarov (left) March 14-19. Photo shows gang plank between ships and fuel hose at mid ships (photo courtesy Steffen Graupner).*

1.3. The drift of the *Polarstern* during MOSAiC's Leg 2

Scientists and crew of Leg 2 arrived at the MOSAiC floe on December 13, 2019, and left on March 6, 2020. They were in charge of the scientific program on board *Polarstern* and on the ice for 79 days, from December 16 to March 3. Scientist and crew of Leg 1 left the floe with *Kapitan Dranitsyn* on December 18, and those of Leg 3 arrived on February 28 with the same ship.

Between December 13 (12:00) and March 5 (23:00), *Polarstern* drifted from 88.59°N,119.10°E, to 88.10°N, 30.60°E (Figure 1.7). This was a direct distance of 238 nm. However, the total drifted distance amounted to 386 nm, due to the turns and loops assumed by the drift (Figure 1.7). The average hourly drift speed was 0.19 knots, or 4.6 nm (8.5 km) per day, with a net drift speed of 0.11 knots, or 2.6 nm (4.8 km) per day.

The maximum drift speed of 0.92 knots was observed on February 1, coinciding with the passage of small low pressure systems that brought strong winds and sudden warming events. On February 1, maximum wind speed was 20.8 m/s, the largest observed during Leg 2, and air temperatures increased from -35°C to -11.4°C within 26 hours before the event,

just to decrease to -38.2°C in less than 17 hours afterwards. This was the most rapid temperature swing during Leg 2 and the event is also discussed in Chapters 2 and 3 of this report.

On February 24, 2020, *Polarstern* reached the record northern latitude of 88°36'N, 59°15'E, only 84 nm away from the North Pole (Figure 1.7). Not only was this the northernmost position reached by the MOSAiC project, but also the farthest north position ever reached by a drifting surface vessel in winter as certified by Robert K. Headland from the Scott Polar Research Institute (SPRI) of the University of Cambridge, UK. This broke the previous record of the Tara which had reached 88°32'N on May 28, 2007 (Figure 1.7). The Fram reached only 85°56'N in 1895, however, they were pioneers in many if not most other regards. Leg 2's northern record was also farther north than the drifts of the Jeanette (1879-80 and 1880-81), Karluk (1913-14), Sadko and Malygin (1937-38), and Sedov (1937-38 and 1938-39).

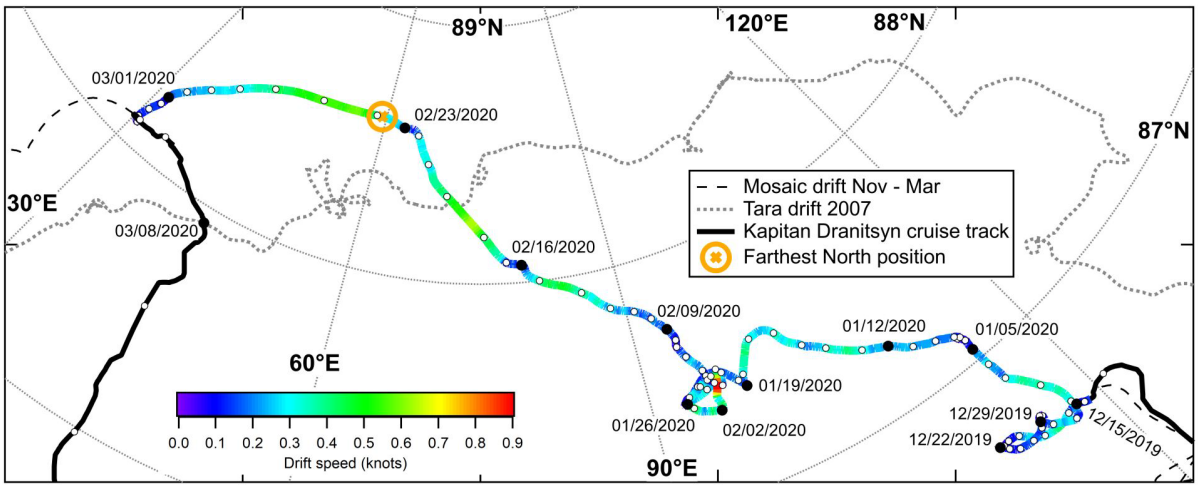


Fig. 1.7: *Overview map of the drift of Polarstern during Leg 2, colour coded by drift speed. Black and white circles show weekly (Sundays) and daily midnight positions, respectively. The drift of the Tara in 2007 that reached slightly lower northern latitudes is shown by stippled grey line. Axis tick spacing 100 km.*

All other events during the 11 week long drift of Leg 2 are described in the following chapters of this cruise report, including weather conditions (Chapter 2 and 3), ice fracture events (Chapter 4), L- and M-site visits (Chapter 1.4), and wildlife sightings (Chapter 4 and 8.1). The only other event to be mentioned here is the preparation of a runway.

Although scientific and logistics flight activities were only planned for the end of Leg 3, already during Leg 2 we felt the need to scout potential runway sites (despite the darkness), and to gain the necessary experience to level out and plough a runway with the Pistenbullies. In addition, a runway was urgently needed for potential cases of medevacs that were statistically likely to be required during so many months away from land. For the most part, Leg 2 was farther away from civilization than e.g. the International Space Station ISS which revolves around Earth in only 400 km altitude, at low or medium latitudes, and from which an evacuation could be carried out within three hours. With a runway *Polarstern* would be reachable by small aircraft if need be, e.g. by Twin Otter. Two potential runway sites were found, one approximately 1.5 to 2 km south of the ship, and one very close to the ship, in the logistics area on the port (east) side (Figure 1.8). Proximity to the ship would minimize the logistical effort to transport men and machines to the landing site. The ship could also support air operations with light and power.

Electromagnetic ice thickness surveys confirmed that the ice was 1 m thick throughout, already in early January, and if a few small rafts and ridges would be removed, the air strip could be 400 m long. Work started on January 6, when the Pistenbully operated by Hannes Lauber moved with ease across the ridged areas ahead of the ship. It then entered the landing strip and cleared a 400 m long, 25 m wide area from snow and ice blocks, leaving just a few pot holes left from previous cracks or ridges (Figure 1.8). Later on, when cracks and new ridges prevented access to the alternative site in the South, the runway was extended to 1000 m to be suitable for large aircraft like Basler BT67 and AN74 which were expected to carry out surveys and crew changes in late March. Work began already during Leg 2 because of the belated arrival of Leg 3. Eventually the long runway was subject to some severe cracking in March which deemed at least half of it unusable and inaccessible for further Pistenbully work. Luckily the air strip did never have to be used for a medevac operation. However, two Twin Otters did land on the runway on April 22 to return a few Leg 3 people to land. In the wake of the COVID-19 situation and the closure of the airport in Longyearbyen unfortunately no other aircraft did ever visit the *Polarstern*.

Despite the close proximity of the runway to the ship, its preparation and use by Pistenbully, snowmobiles, and aircraft would only have caused minimal interference with the aerosol measurements on board *Polarstern*. In fact, major opportunities to study aerosol loads and processes during winter were missed due to the absence of most flight operations.

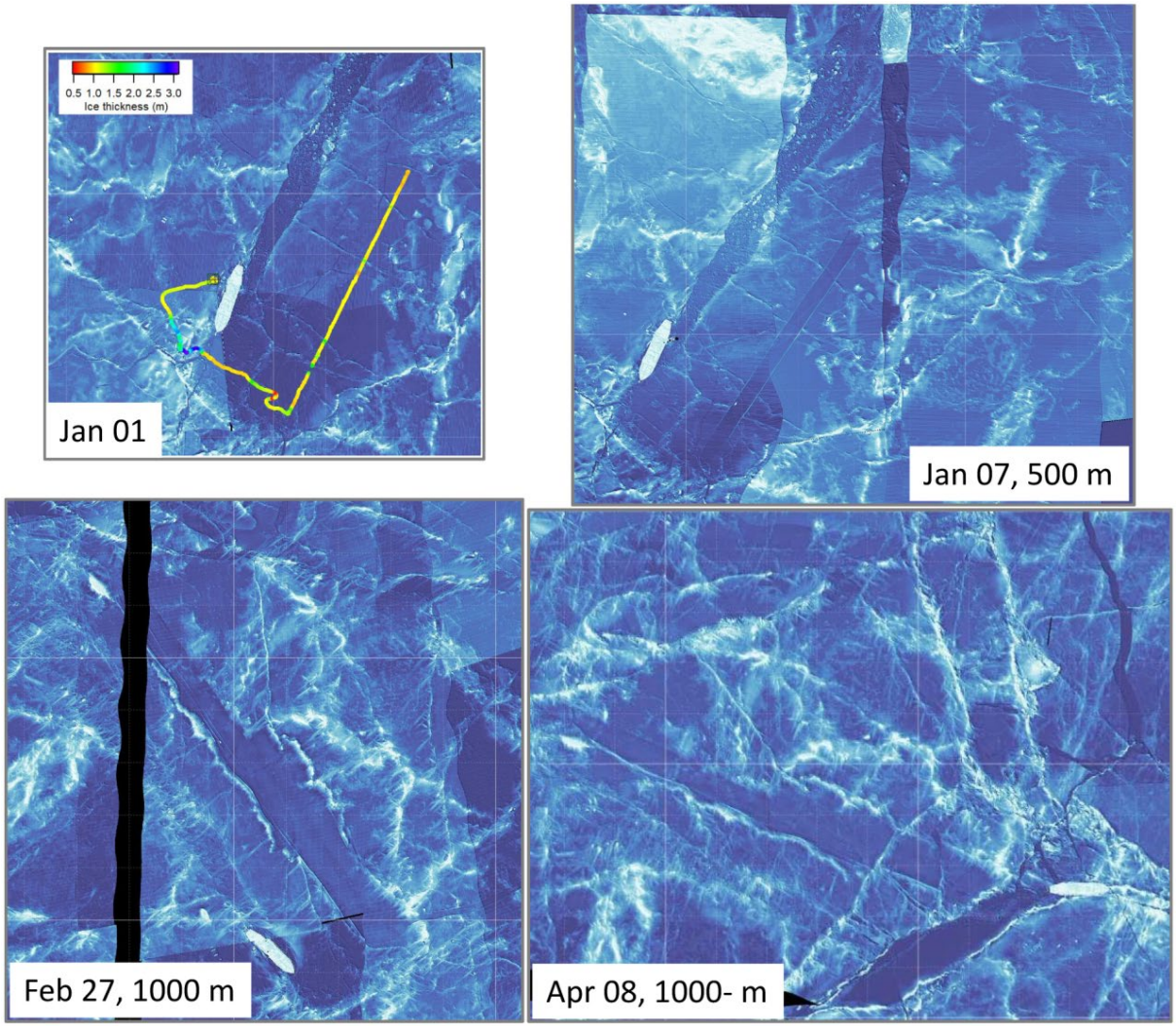


Fig. 1.8: *Airborne laser scanner maps of different stages of the runway. Data show freeboard, with higher elevations shown in brighter tones, e.g. pressure ridges and Polarstern. Runway can be seen*

by its smooth surface and snow banks to the sides. Top left panel shows initial electromagnetic ice thickness survey. Top right shows initial 500 m long medevac runway. Bottom left shows 1000 m extension of runway to welcome BT67 and AN74 aircraft. Bottom right shows situation in April, when runway was cracked and shifted in March deformation events, and only less than 1000 m on the left side remained useable. This was the section on which two Twin Otter aircraft landed on April 22. Note apparent rotation of runway due to the fact that North is up on all graphs, but North turned relatively by at least 100° as the floe drifted from approximately 120°E in early January to approximately 14°E in April.

1.4. State and evolution of ice camp

All installations and sites on the ice on the main floe around Polarstern are called the 'Ice Camp' or 'Central Observatory' (CO). By the end of Leg 1, the ice camp consisted of 5 Cities, 15 dedicated sampling and measurement sites (plots) and some 150 individual instruments and installations. By the end of Leg 2, there were 16 plots (counting overlapping plots) and additional three remote sites outside the CO within 2 km of *Polarstern* (the two Dark Site plots and an area near the old heli pad). These elements were connected through a network of largely flagged walkways and roads, including several km of power and data cables on tripods.

Some care was taken to avoid off-road areas, except the logistics and common leisure area with a diameter of roughly 200 m right next to *Polarstern*. However, dedicated field sampling and measurements; bear guarding and turning skidoos; and scouting to remote sites (e.g. Dark Site plots) necessitated to move across non-dedicated / unflagged areas. Care was taken to avoid moving across flagged plots for any purpose other than local sampling / measurements. This succeeded in most cases, except for Snow 1 (ROV site rescue moved across northernmost part, which was later removed from the plot) and a small part of BGC 1 within about 10 m from the tripwire (prior skidoo turning, now no longer used).

The state of the CO at the time of handover between PS122/1 and PS122/2 in mid-December is shown in Figure 1.9 and the final setup by late February in Figure 1.10. The only major change to the CO was the move of the ROV site at the beginning of PS122/2. A crack had developed right next to the ROV hut and the power hub, running under the ROV tent. Hence the whole installation was moved to thicker ice near the tripwire on the Strength plot, allowing access to different ice types and the Ridge site "Fort Ridge", that was established later.

Parts of the CO were secured by a trip wire installation against polar bears, that was extended during January (see Chapter 8). There was no further extension of the tripwire due to changing ice conditions elsewhere and additional logistics time that would have been necessary for maintenance (regular check of wire and flares). Instead, several locations were equipped with lights, in addition to those already installed: Met City and the tall ridge near Ocean City. Some of the lights were intermittently turned off by bear guards to allow better vision in the dark, depending on background visibility (e.g., moonlight, snow, fog).

The main installation of the power/network lines along the main road connected Polarstern with Ocean City, Balloon Town and Met City. The power line was extended to reach the new ROV site, crossing the main road to Balloon Town and Ocean City. Regular maintenance of the data and power lines was carried out by the Data team and other volunteers, including mobilizing frozen-in tripods (speed of rescue in case of ice-floe breakup), removing snow from spare cable and removing cable from ridges (e.g. between ship and Met City / Remote Sensing).

Skidoos, sleds, pistenbullies, the ARGO and all main logistics components were parked and stored in the logistics area, which remained remarkably stable throughout PS122/2, despite narrow cracks forming and immediately refreezing at times. The fuel station was also located in that area.

By the end of Leg 2, the region in and near the ice camp / CO consisted of

- Five main cities:
    - Met City (MET) with >20 installations for mostly atmospheric observations (Chapter 3)
    - Ocean City (OC) with a tent covering a 1.2 m diameter hole to access the ocean under the sea ice and additional autonomous installations nearby (Chapter 5)
    - Remote Sensing (RS) with several installations of remote sensing instruments observing snow and ice properties (Chapter 8)
    - Balloon Town (BT) with two tents to perform measurements with a tethered balloon (Chapter 3)
    - ROV Oasis (ROV) with installations to operate a Remotely Operated Vehicle under the sea ice (Chapter 4.5)
- Sampling plots for
    - Ice coring on different ice types (Chapter 4)
    - Snow measurements and sampling on different ice types (Chapter 4.2)
    - Ridge observations (Chapter 4)
    - Lead observations (temporary, various chapters)
- Further installations distributed in and around the CO for
    - Ice and snow mass balance measurements (Chapter 4)
    - Sea ice dynamics (Chapter 4)
    - Seismological measurements (Chapter 4)
    - Ocean state, velocity and mixing (Chapter 5)
    - Basic atmospheric measurements (Chapter 4)
- Routes for measurements along transects over the ice (Chapter 4)

Please find more detailed descriptions of all sites and installations in the corresponding chapters.

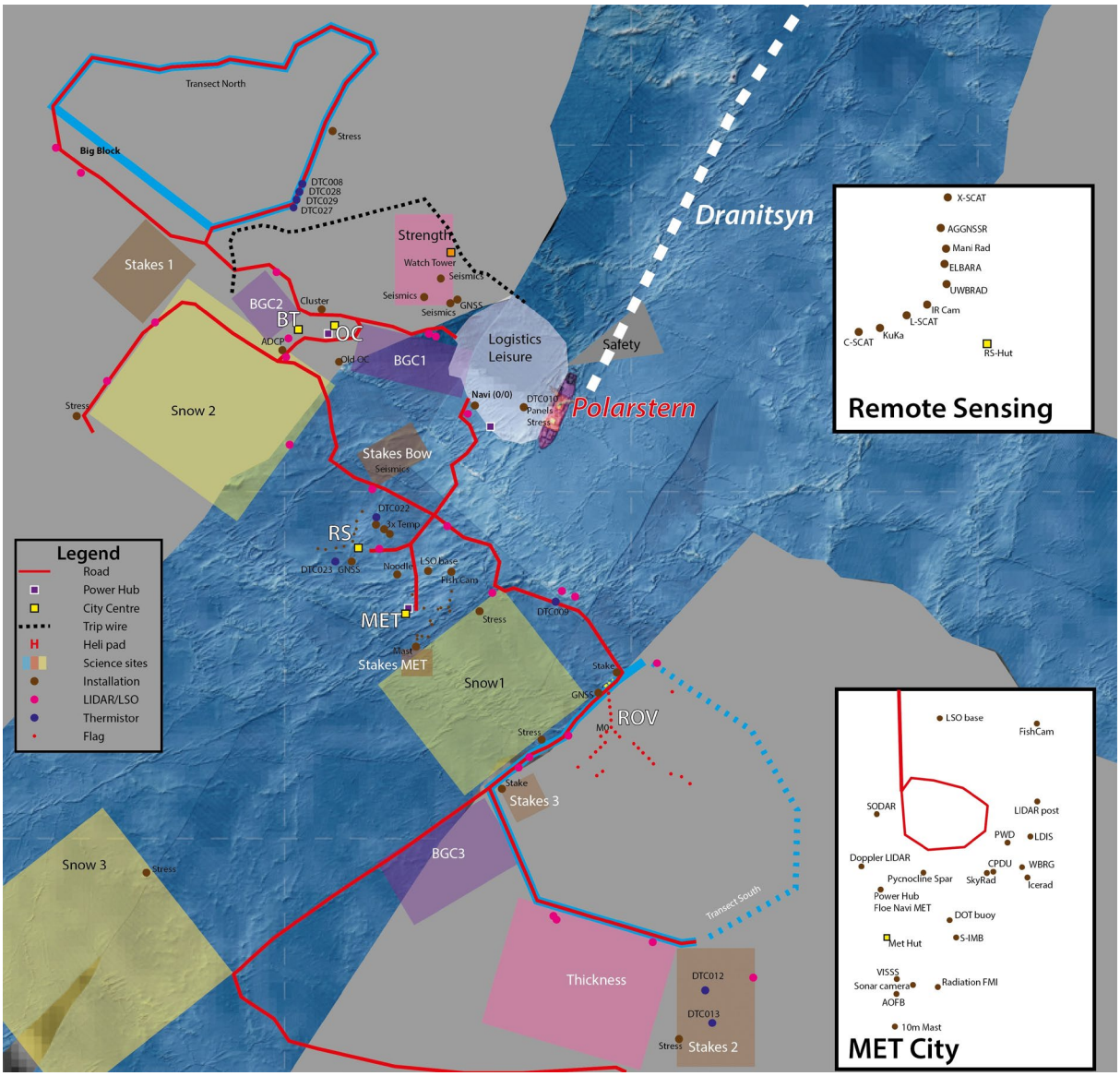


Fig. 1.9: Ice camp map as handed over to PS122/2 on 13 December 2019. The background image shows surface elevation derived from the airborne laser scanner (flight on 06 December 2019, see Section 4.4). This map is a copy of the expedition report from PS122/1 (their Fig. 1.3) to show the status before the ice floe evolved during PS122/2.

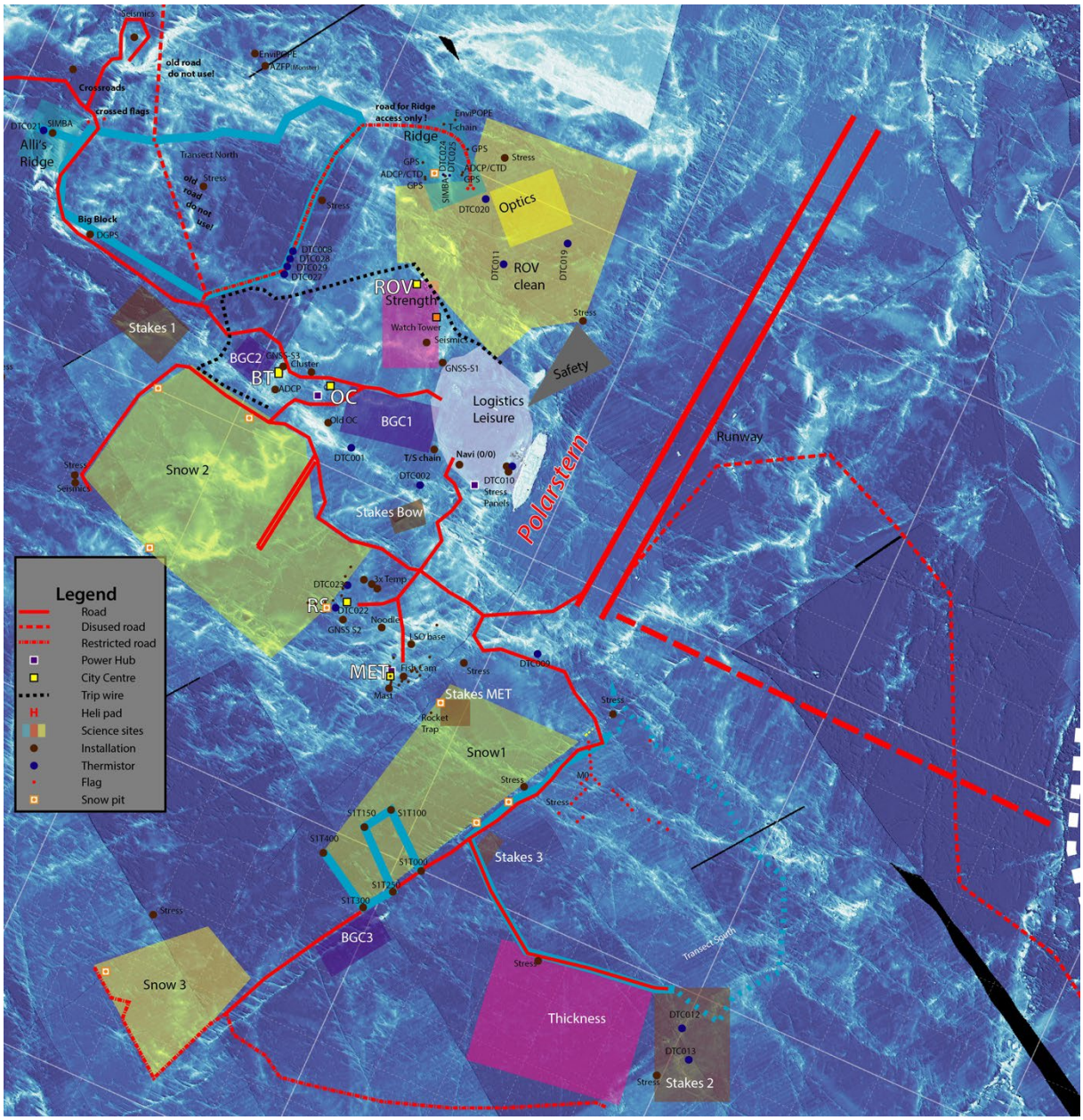
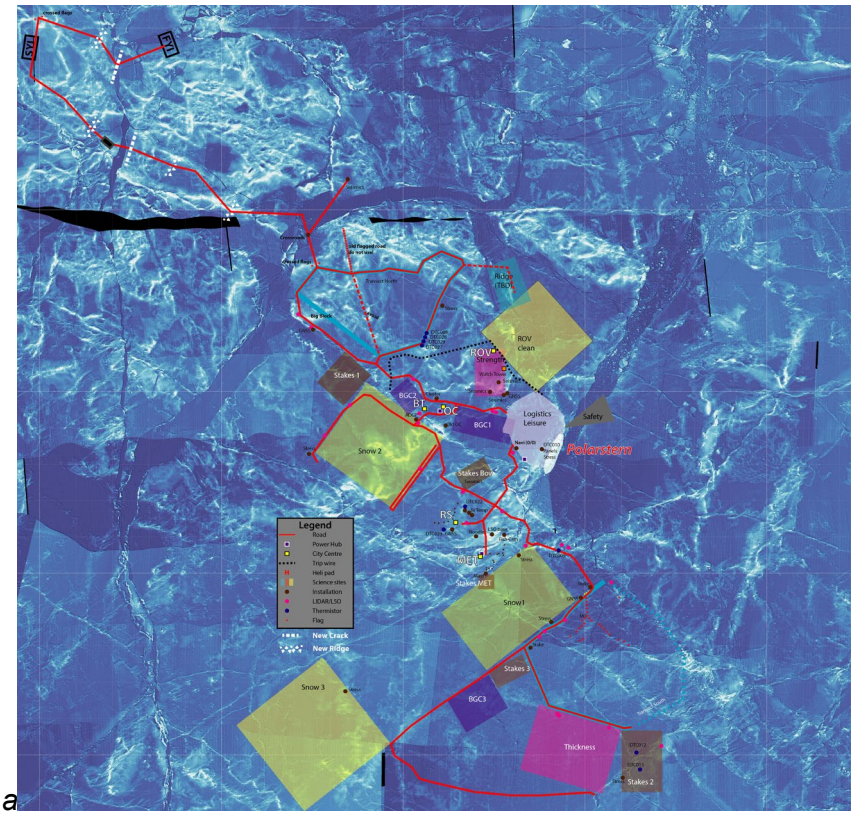
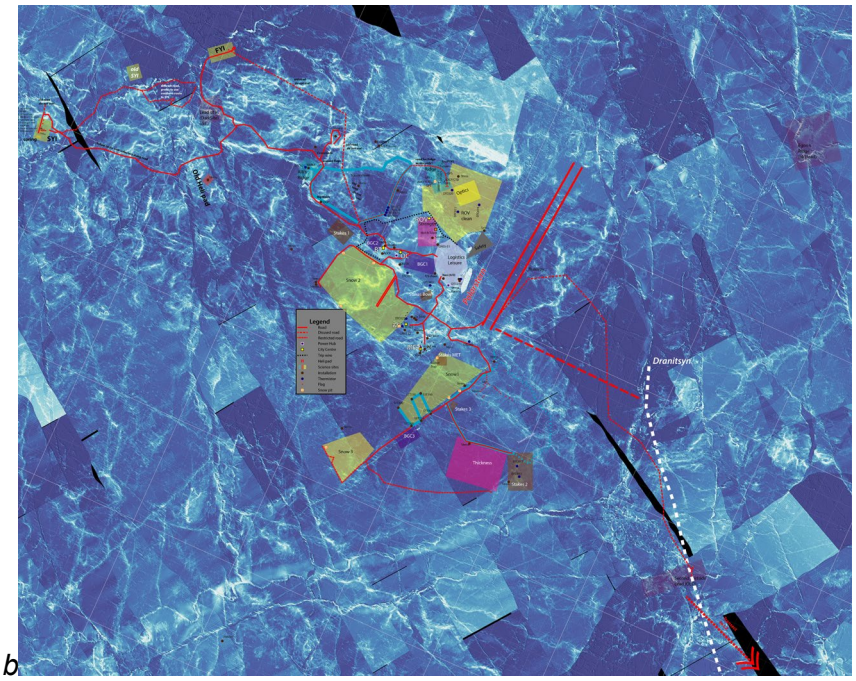


Fig. 1.10: The ice camp shortly after handover to the leg 3 team during PS122/3 on 05 March 2020 (note that the leg in the D-SHIP event and data log started officially in mid February 2020 but the corresponding team arrived only on 28 February). Note that the positions of LIDAR install are not shown on this map. They are further detailed in Section 4.3. The background image shows surface elevation derived from the airborne laser scanner (flight on 17 February 2020; see Section 4.4). The solid-line grid shows mesh sizes of 500 x 500 m^2, the dashed-line mesh size is 100 x 100 m^2.



a



b

Fig. 1.11: Evolution of the larger region around the ice camp / CO, including the Dark Site (FYI and SYI) during PS122/2, including position of the old SYI before a lead/ridging event around the beginning of February (see also Figure 1.13). The maps are from 1 January 2020 (a) and 05 March 2020 (b). The background image shows surface elevations derived from the airborne laser scanner (flights in December 2019 (a) and on 17 February 2020 (b); see Section 4.4). The grid mesh and the legend are the same as in Figure 1.9. Note the docking location of Kapitan Dranitsyn and the path of the dashed access road are only approximate.

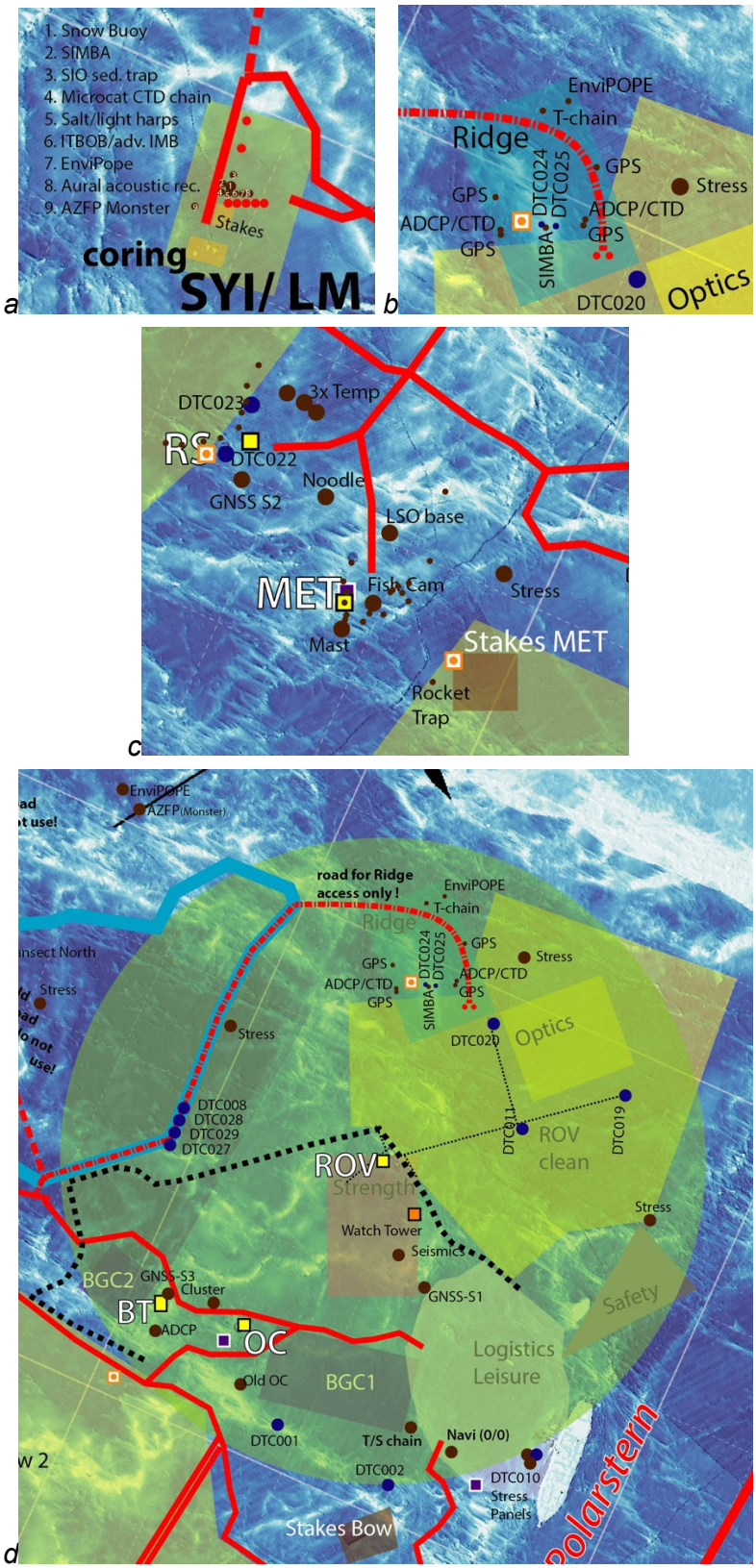


Fig. 1.12: Zoom of selected sites and plots shown in Figure 1.11 b: (a) Dark Site SYI / LM; (b) Fort Ridge site; (c) Met City and Remote Sensing site (positions of install in the latter have not been fully updated); (d) ROV site and survey grid. The grid mesh and the legend are the same as in Figure 1.9.

The layout of the CO changed throughout the leg (see also overview in Figures 1.11 a and b), although the position of the main cities remained unchanged after the relocation of the ROV site at the beginning of the leg (Figures 1.10 and 1.12 d). That included removing the power line to the old ROV site and laying a power line to the new site. Two new plots, the Fort Ridge site and Alli's Ridge were established throughout January (Figures 1.10 and 1.12 b).

Several installs were added during the leg, as detailed in Chapters 4, 5 and 6. All are shown in the map in Figure (1.10 and 1.12), apart from the LIDAR stations. Those are detailed in Chapter 4.

Dimensions of several plots were resurveyed and reshaped, such as Snow 1 and Met City (Figures 1.10 and 1.12 c).

The family of buoys at the Dark Site SYI / LM was extended by an upward-looking AZFP ("Monster"), an EnviPope, an advanced IMB (ITBOB), a salt / light HARP and a vertical chain of CTD (Figure 1.12 a), as detailed in Chapters 4, 5 and 6.

Fort Ridge was equipped with several devices to measure the state of the ridge itself as well as the upper water column below two ADCP and CTD, a SIMBA, a thermistor chain (T-chain), several DTC and an EnviPope (Figure 1.12 b).

Work on the runway commenced on 06 January and continued throughout Leg 2, due to snow drift, cracks and small ridges. It was finally extended to accommodate the small aircraft planned to operate in March and April (see Chapter 123).

Cracks and small ridges lead to power and data cables being buried, that had to be recovered, and installs being relocated. Snow drift repeatedly necessitated to dig out parts of install. However, all those changes had only minor impact on operations in the ice camp, compared to ice dynamics during Leg 1.

Further out ice dynamics significantly reshaped our research landscape, with the Dark Site SYI / LM being separated from the ice camp and FYI for several days around the beginning of February, and shifting almost 1 km away from FYI (see Figure 1.13). Due to lead and ridge formation between the Dark Site and the main ice camp, as well as intermittently heavy snow drift, the road had to be repeatedly scouted. Further significant lead formation and ridging occurred on the portside of the ship (Figures 1.11 a and b).

Temporary sampling and measurement plots, such as a large lead toward the Dark Site and a large lead on the portside, were opportunistically visited before and after lead closure / ridging.

1.5. State and evolution of Distributed Network

The Distributed Network of medium and large buoys deployed during Leg 1a from *Ak Fedorov* was functioning to about 70 % by the end of Leg 2 (43 buoys reporting, 19 not reporting). The network of position tracking (GPS) buoys, such as "SVP", consisted of 43 sites.

We surveyed the L-sites early on during the leg, taking photographs and GPS waypoints to record the state of each buoy.

Regular visits to the L-sites ensured that the remotely operated landing lights were functioning. This was improved by deploying one of the lights with an external (additional) battery pack.

The only M-sites visited during leg 2 were M3 and M5. to install landing lights and carry out calibration CTD casts (M5 only).

In general, sites that no longer had functioning landing lights could be found during full moon and favorable weather conditions; for example, M5.

The snow buoy at L1 that stopped working during Leg 1 due to ridging was replaced during Leg 2. Seismic stations were deployed at both L1 and L2.

The sites experienced significant ice deformation. In particular, the floes with large installations, the L-sites, changed layout throughout leg 2 due to various lead and ridging events. The evolution will later be evaluated using buoy position data.

Whereas L1 experienced deformation during leg 1, L2 and L3 showed a crack running across most of the buoy site. Whereas the buoys at L2 were still in good health by the end of leg 2, subsequent ridging and temporary lead formation at L3 displaced the ASFS, severed the tether on the ITP, buried the AOFB in the ridge and destroyed the SIMBA (see Table 1.3). The ASFS could later be salvaged and all sensor packages were removed. The ASFS shell, including the sledge, is still on-site at L3.

The location of the different sites in the DN relative to Polarstern changed significantly throughout the drift. The status toward the end of leg 2 is shown in Figure 1.13.

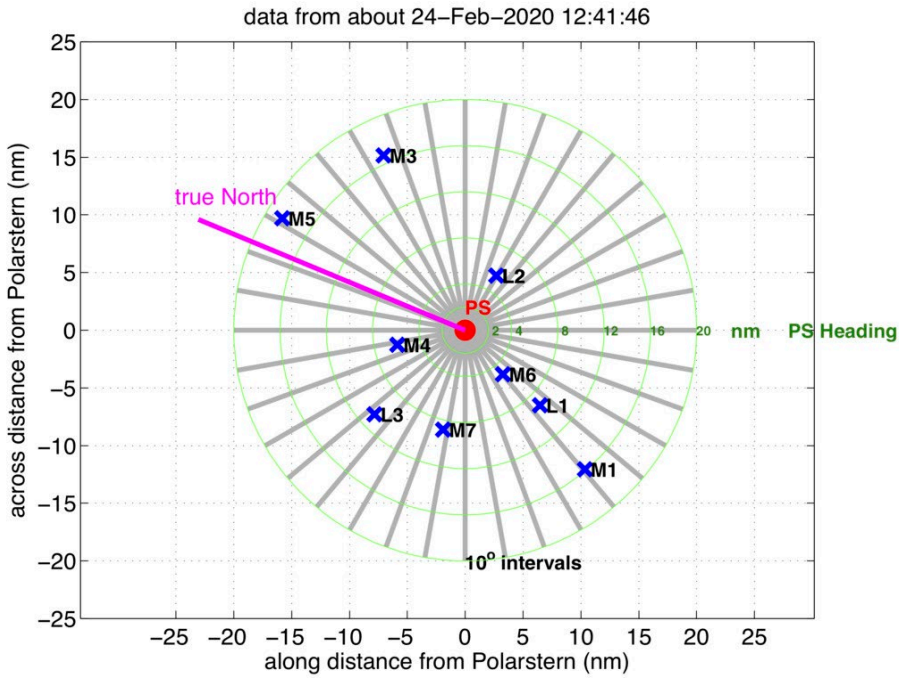


Fig. 1.13 Position of the L- and M-sites in the Distributed Network, relative to Polarstern, on 24 February 2020. Note that M2 and M8 are missing, as LM (Dark Site SYI) was omitted as it is very close to Polarstern.

Tab. 1.3: State of selected buoys at different times with photo documentation (photos by Michael Gallagher, Eric Brossier and Benjamin Rabe).

Site	Buoy	Date	Comment	*Pictures in separate files labelled by row and buoy/date: Table1_X_rowxx_buoydate.jpg*
L1	AOFB	20201222	With wind generator; small ridge nearby	Row 2

	ITP	20200106		3
	SIMBA	20200106		4
	ASFS	20200106		5
	AOFB	20200106		6
	FIO Fixed-layer	20200106	Not reporting	**7**
	ITBOB (radiation/IMB/biooptics/CTD)	20200106		8
L2	Snow	20200106		9
	ITP	20200106		10, 11
	AOFB	20200106		
	ITBOB (radiation/IMB/biooptics/CTD)	20200106		12
	ASFS	20200106		13
L3	Snow	20200106		14
	ASFS	20200106		15
	AOFB	20200106		16
	ITP	20200106		17
	SIMBA	20200106		18
	PRIC Unmanned Ice Station	20200106		19
L1	ASFS, AOFB, Snow, SIMBA	20200111	(full-moon light)	20
L3	AOFB, ASFS	20200117	Crack forming nearby	21
L2	ITP	20200120	Crack forming nearby	22
L3	AOFB, ASFB	20200120	Crack forming nearby	23
	ITP	2020012	Ridge	24

		0	forming nearby	
	AOFB	20200130	Crack forming around buoy	25
	ASFS	20200206 & 20200210	Sensors salvaged; empty buoy remaining at L3	26
	AOFB	20200210	Buoy not reporting; photo shows wind generator only, in ridge.	27
	PRIC Unmanned Ice Station	20200206		28
	ITP	20200209	Tether severed (only surface buoy remaining)	29
L2	Snow buoy	20200215		30