Satellite-based sea ice thickness changes in the Laptev Sea from 2002 to 2017: Comparison to mooring observations

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Abstract. The gridded sea ice thickness (SIT) climate data record (CDR) produced by the European Space Agency (ESA) Sea Ice Climate Change Initiative Phase 2 (CCI-2) is the longest available, Arctic-wide SIT record covering the period from 2002 to 2017. SIT data is based on radar altimetry measurements of sea ice freeboard from the Environmental Satellite (ENVISAT) and CryoSat-2 (CS2). The CCI-2 SIT has previously been validated with in situ observations from drilling, airborne remote sensing and electromagnetic (EM) measurements and Upward-Looking Sonars (ULS) from multiple ice-covered regions of the Arctic. Here we present the Laptev Sea CCI-2 SIT record from 2002 to 2017 and use newly acquired ULS and upward-looking Acoustic Doppler Current Profiler (ADCP) sea ice draft (VAL) data for validation of the gridded CCI-2 and additional satellite SIT products. The ULS and ADCP time series provide the first long-term satellite SIT validation data set from this important source region of sea ice in the Transpolar Drift. The comparison of VAL sea ice draft data with gridded monthly mean and orbit trajectory CCI-2 data, as well as merged CryoSat-2/SMOS (CS2SMOS) sea ice draft shows that the agreement between the satellite and VAL draft data strongly depends on the thickness of the sampled ice. Rather than providing mean sea ice draft the considered satellite products provide modal sea ice draft in the Laptev Sea. Ice drafts thinner than 0.7 m are overestimated, while drafts thicker than approximately 1.3 m are increasingly underestimated by all satellite products investigated for this study. The tendency of the satellite SIT products to better agree with modal sea ice draft and underestimate thicker ice needs to be considered for all past and future investigations into SIT changes in this important region. The performance of the CCI-2 SIT CDR is considered stable over time, however, observed trends in gridded CCI-2 SIT are strongly influenced by the uncertainties of ENVISAT and CS2 and the comparably short investigation period.

Copyright statement.

1 Introduction

Sea ice is one of the most important indicators for climate change in the Earth's polar regions. Two of the primary parameters that are studied in this context are sea ice concentration (SIC) and sea ice thickness (SIT). While knowledge about SIC is widely available it provides limited insight into overall sea ice changes. A joint evaluation of SIC, SIT and sea ice drift is required for the analysis of sea ice mass balance, volume transports and the overall energy balance (Laxon et al., 2013), which comprehensively explain the complex sea ice state.

While in situ measurements of SIC and SIT are limited in time and space, satellite measurements of both parameters provide the means to assess Arctic-wide changes in the sea ice cover. Satellite remote sensing of SIC started in the 1970s with passive microwave sensors (Parkinson et al., 1999) and was further developed, updated and improved by multiple follow-on missions (Comiso and Nishio, 2008; Cavalieri and l. Parkinson, 2012; Lavergne et al., 2019) until today. While these measurements provide about 40 years of continuous SIC records, SIT satellite records of comparable length are not available. The longest existing SIT data record (from 2002 to 2017) was published by the European Space Agency's (ESA) Sea Ice Climate Change Initiative (CCI). The current SIT data record is sufficiently long to achieve the objective of a long-term SIT climate data record (CDR) in the Arctic Ocean and is based on radar altimetry data from the Environmental Satellite (ENVISAT, 2002-2012) and from the CryoSat-2 (CS2) mission that was launched in 2010. SIT remote sensing with radar altimetry relies on retrievals of sea ice freeboard and is therefore an indirect method that is based on certain assumptions and parametrizations that introduce a number of uncertainty factors. These uncertainties can be separated into intrinsic uncertainties that arise from the radar measurements themselves and uncertainties that are induced during the ensuing processing. Processing uncertainties include: the impact of snow on radar backscatter and surface roughness on radar ranging and thus the retrieved elevation of the ice surface, the correct discrimination of sea ice and lead surface types with evolving altimeter footprints, the unknown variability of snow mass and snow and sea ice density that go into the conversion of freeboard to thickness (Wingham et al., 2006; Laxon et al., 2013; Ricker et al., 2014).

The CCI Phase 2 (CCI-2) SIT product was validated with observational data from multiple sources (Kern et al., 2018) including, in situ drill holes from a number of North Pole (NP) drift campaigns (Kern et al., 2018), observations from airborne and ground-based electromagnetic (EM) measurements (Haas, 2004; Haas et al., 2009, 2010), airborne remote sensing measurements from the Operation IceBridge (OIB) (Kurtz et al., 2013) and ice draft measurements from Upward-Looking Sonars (ULS) (Hansen et al., 2013; WHOI, 2014; NPI, 2018). However, these measurements are limited mainly to multi-year ice (MYI) dominated regions of the Arctic. While NP drill holes data is limited to the central Arctic, most airborne EM flights took place in the vicinity of Fram Strait, Lincoln Sea and in the Chukchi and Southern Beaufort Sea. ULS measurements were limited to Fram Strait (Hansen et al., 2013) and the Beaufort Sea (WHOI, 2014).

The Russian Shelf Seas are a region where observational data is very limited and which therefore has not been considered for the validation of the CCI-2 SIT CDR. At the same time the Russian Shelf Seas are also regarded to be the most important source regions of Arctic sea ice with the Laptev Sea being the origin of most of the sea ice passing Fram Strait (Rigor et al., 2002; Hansen et al., 2013; Itkin and Krumpen, 2017). The Laptev Sea is located between the Siberian coast, the New Siberian

Islands to the east and Severnaya Zemlya to the west (Fig. 1). It is ice-covered from October to June (Bareiss and Goergen, 2005) and with water depths between 15 and 200 m very shallow (Timokhov, 1994). The Laptev Sea is dominated by fast ice, flaw polynyas and pack ice (Reimnitz et al., 1994; Bareiss and Goergen, 2005; Krumpen et al., 2013). Sea ice is formed in the polynyas and continuously transported northward by the persistent offshore-directed winds (Timokhov, 1994; Krumpen et al., 2013). Due to the continuous formation and export of ice the Laptev Sea sea ice cover is dominated by first-year ice (FYI).

Recent studies indicate a thinning of Arctic sea ice within the Transpolar Drift (Haas et al., 2008) and in Fram Strait (Krumpen et al., 2019). According to Krumpen et al. (2019) this thinning is a consequence of faster ice transport across the Arctic and leads to more frequent interruptions of the FYI flow from the Russian Shelves towards the Transpolar Drift. Whether fundamental changes of the sea ice cover in the source regions cause the observed thinning of Fram Strait sea ice, needs to be further investigated.

The available CCI-2 SIT CDR has not yet been fully exploited with respect to variability and trends on the Russian Shelves. This is partly due to the lack of validation data but also because the initial aim of the altimtery missions was to measure fluctuations in perennial SIT (Wingham et al., 2006) which is not prevalent in the FYI-dominated Russian Shelf Seas.

In order to close the observational data gap and validate the CCI-2 SIT CDR in this important source region of Arctic sea ice we present a new sonar-based sea ice draft data set from the Laptev Sea. This data set consists of ULS measurements from 2013 to 2015 and upward-looking Acoustic Doppler Current Profiler (ADCP) derived ice draft data that was acquired applying the approach of Belter et al. (2020b). Together with the ADCP-derived ice draft time series the full Laptev Sea validation (VAL) data set covers a period from 2003 to 2016. Since moored sonars are capable of detecting all ice types without a bias towards undeformed ice (Behrendt et al., 2015), this new data set provides comprehensive information about the full thickness range.

The objectives of this study are to examine the gridded monthly mean ESA CCI-2 SIT CDR and use the new in situ data set to evaluate its performance in the Laptev Sea. We will analyse the time dependent stability of the CCI-2 SIT CDR in order to see whether potential trends in Laptev Sea SIT are caused by actual changes in SIT in the region or by a change in the ability of the satellites and the ensuing processing steps to characterize the Laptev Sea sea ice cover over time. In this context, stability is defined as the constancy of the mean difference of the CCI-2 SIT CDR to the Laptev Sea observational data. In addition, we will compare VAL data to satellite products with higher temporal resolution than the gridded monthly mean CCI-2 SIT CDR. Finally, the case study of the 2013/2014 ULS draft time series from the Taymyr mooring (Fig. 1) will highlight and further explain the findings of the presented comparison of satellite and sonar-derived sea ice draft time series.

The presented analysis will assist the interpretation and support future algorithm development of altimetry-based SIT CDR. It is an important addition to the existing validation data sets (Kern et al., 2018) and might provide the means to assess regional differences in the performance of the CCI-2 SIT products in the Arctic. For the Laptev Sea region the presented sonar-based data provides better interpretation and more confidence in the ESA CCI-2 SIT products. After all, this unique satellite-derived SIT record can be an important data set for future investigations into volume transports and will complement previous studies on the changes of the sea ice cover on the Russian Shelves.

2 Data and methods

2.1 Sonar-based ice draft measurements

The Laptev Sea sea ice draft time series were retrieved by two different instruments. The full ice draft time series from upward-looking ADCPs and ULSs (VAL) covers a period from 2003 to 2016 and was taken at water depths between 20 and 60 m. The data set consists of multiple one to two year long sea ice draft time series from a total of nine different locations all over the Laptev Sea (Fig. 1). This inconsistency in the location of the measurements is a considerable limitation for the analysis of sea ice draft variability in this region because we are not sampling a single location over the full period but multiple ones over

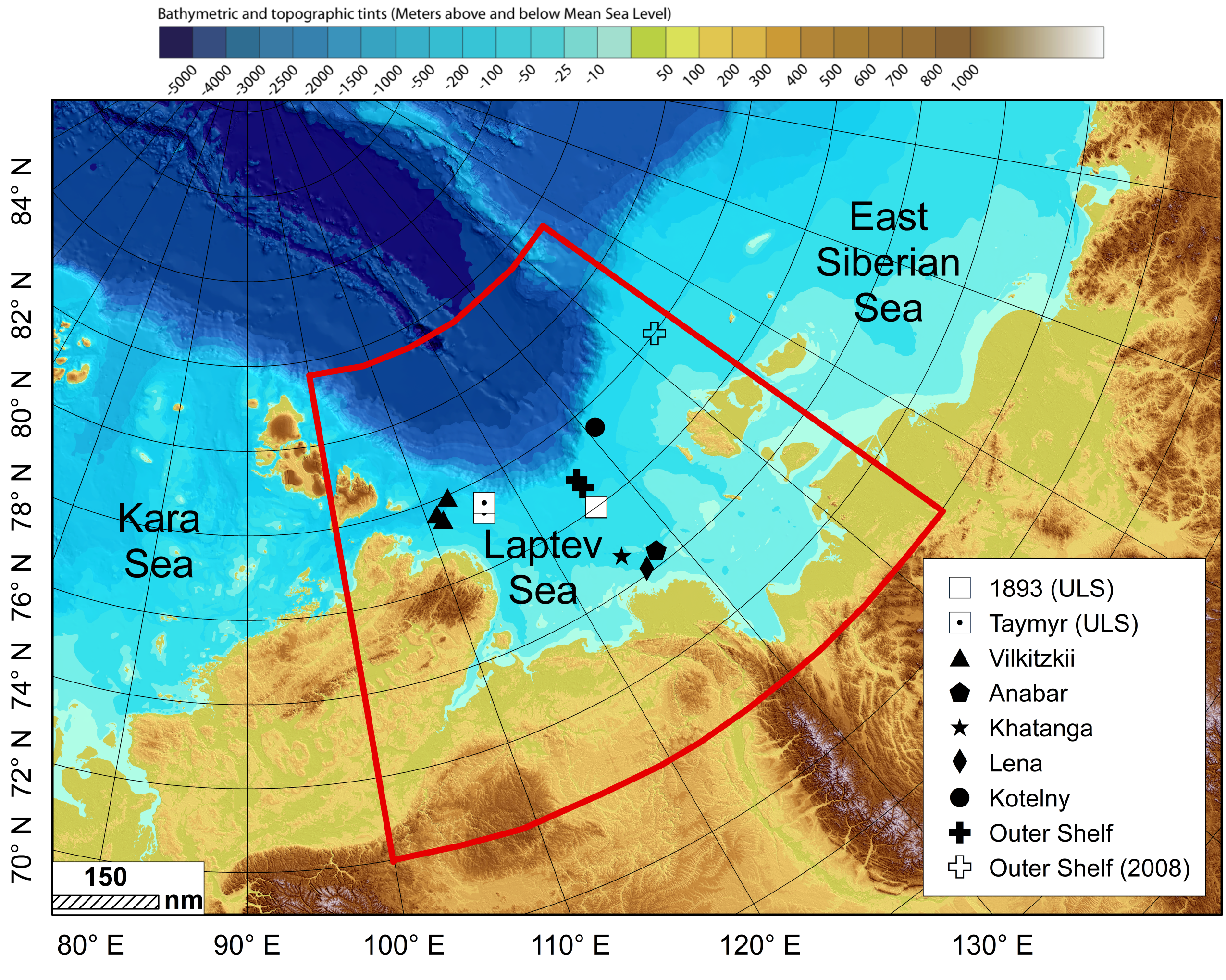

Figure 1. Map of the Laptev Sea showing the validation data (VAL) mooring sites. ESA CCI-2 SIT data from the enclosed area (red) was used for the calculation of satellite SIT anonmaly (Fig. 2). IBCAO basemap provided by Jakobsson et al. (2008).

short periods. Nevertheless, this data set provides important validation data to analyse the performance of satellite-derived sea ice draft over the Laptev Sea region. The proper validation of the satellite SIT products will then allow the targeted analysis of the long-term changes in SIT in this important region of sea ice formation.

2.1.1 Upward-Looking Sonar

ULSs measured from September 2013 to August 2015 at the Taymyr and 1893 stations (Belter et al., 2019). The Laptev Sea ULSs were of the type Ice Profiling Sonar 5 (420 kHz, manufactured by ASL Environmental Sciences Inc.) and operated with a single vertical beam (1.8° beamwidth) at a sampling frequency of 1 Hz. Ice draft was inferred from measured values of range (distance between device and ice-water interface) and auxiliary measurements of instrument tilt, pressure and temperature at instrument depth (sampling frequency 1/60 Hz). Final sea ice draft time series with an approximate precision of $\pm$ 0.05 m were calculated as the difference between instrument depth and range and corrected for instrument tilts and changes in sound speed (Ross et al., 2016; ASL, 2017).

2.1.2 Upward-looking ADCP

The second approach utilized upward-looking ADCPs to derive ice draft time series (Belter et al., 2020a). The available ADCPs were upward-looking Workhorse 300 kHz Sentinel ADCPs manufactured by Teledyne RDI. They measured with four different beams (beamwidth 3.8°) at a default angle of 20° from the vertical. Although ADCPs have been used to derive sea ice draft before (Shcherbina et al., 2005; Banks et al., 2006; Hyatt et al., 2008; Bjoerk et al., 2008), the Laptev Sea ADCPs were not equipped with reliable pressure sensors or lacked them altogether. These additional pressure measurements close to the ADCP proved essential for the determination of instrument depth. In order to determine instrument depth without additional pressure data Belter et al. (2020b) proposed an adaptive approach to derive instrument depth using ADCP bottom track mode measurements of surface and error velocity. Surface and error velocity provide measures for surface inconsistencies in vertical velocity between the four measuring beams. While vertical velocities are similar during ice-covered periods, large velocity differences indicate open water conditions (Belliveau et al., 1990). After determining open water and ice-covered periods the most frequently occurring open water range value was defined as instrument depth for the respective sampling period and mooring (Belter et al., 2020b, a). Ultimately, the approach by Belter et al. (2020b) yielded daily mean sea ice draft time series that are within $\pm$ 0.1 m of the reference draft time series from the coincidental ULS deployments in the Laptev Sea. Following their method we extended the existing Laptev Sea ULS sea ice draft time series with ADCP-derived sea ice draft in this vastly under-sampled source region of Arctic sea ice.

In order to compare daily VAL data to satellite SIT products, VAL data was averaged to weekly and monthly mean values. Open water values (draft values of zero) recorded by ULS and ADCP were excluded prior to weekly and monthly averaging of VAL sea ice draft. In cases where more than 50% of VAL data was missing or considered open water no weekly or monthly average VAL value was calculated.

2.2 Satellite data

2.2.1 ESA CCI-2 monthly mean gridded product

The ESAs CCI-2 SIT Level 3 collated (L3C) gridded product is based on pulse-limited radar altimeter measurements from ENVISAT (2002-2012) and along-track beam-sharpened Synthetic Aperture Interferometric Radar Altimeter measurements from the ongoing CS2 mission (Paul et al., 2018; Hendricks and Ricker, 2019). The CCI-2 SIT data record is available on a 25×25 km EASE2 monthly grid in the Arctic winter season from October through April. The parameters available from the utilized monthly gridded L3C product include: freeboard, freeboard uncertainty, SIT and SIT uncertainty. For simplicity we distinguish between the CCI-2 ENVISAT gridded data (ENVISAT) for the period from 2003-2012 (Hendricks et al., 2018c) and CCI-2 CS2 gridded data (CS2) for the period from 2010-2016 (Hendricks et al., 2018a). The separation of the two data sets that combine for the full CCI-2 SIT CDR is also required because of the different characteristics of the two satellite radar altimeters. Paul et al. (2018) identified differences in freeboard between ENVISAT and CS2 that are based on waveform parameter variations, footprint differences and the fact that ice surface properties are treated differently during the processing. These freeboard differences translate to the gridded monthly mean CCI-2 data presented here. Although Paul et al. (2018) minimized the inter-mission sea ice freeboard biases for the basin average, ENVISAT freeboards in MYI regions are still thinner than CS2 freeboards, while ENVISAT provides thicker freeboards than CS2 in regions that are dominated by FYI (Fig. 13 in Paul et al. (2018)). In the Laptev Sea typical ENVISAT (CS2) SIT uncertainties are 1.5 m (1.1 m).

2.2.2 ESA CCI-2 orbit data

The presented gridded monthly mean CCI-2 data is based on radar altimeter measurements along the orbit trajectories of ENVISAT and CS2 (Hendricks et al., 2018d, b). While the gridded mean data provides Arctic-wide monthly mean values of SIT, the orbital data sets (ENVISATorbit and CS2orbit) provide SIT and freeboard at sensor resolution (2 km in diameter for ENVISATorbit (Connor et al., 2009) and 0.3 km along and 1.5 km across-track for CS2orbit (Wingham et al., 2006)). Typical uncertainties of orbit SIT in the Laptev Sea are about 1.5 (ENVISATorbit) and 1.1 m (CS2orbit). The frequency of the overflights over a predefined 25 km area around the moorings varies between ENVISAT and CS2 due to their different orbit inclinations. However, with an average of about four overflights per month of both satellites orbit trajectory data delivers SIT at a higher frequency than the gridded CCI-2 data sets and allows for a comparison of observational data to a larger number of satellite values.

2.2.3 Merged CryoSat-2/SMOS data

The merged weekly CS2 and Soil Moisture and Ocean Salinity (SMOS) satellite record (CS2SMOS, Ricker et al. (2017)) provides an additional SIT data set with a higher temporal resolution than the gridded monthly mean CCI-2 SIT CDRs. SMOS utilizes 1.4 GHz (L-band) measurements of brightness temperature to retrieve SIT (Tian-Kunze et al., 2014). While the relative uncertainties of the altimetry-based method (CS2) are larger over thin ice regimes (below 1 m thickness), the radiometer-based method (SMOS) shows smaller relative uncertainties over these thin ice regimes (Ricker et al., 2017). Other than gridded CCI-2 and CCI-2 orbit data, CS2SMOS data is only available from 2010 onwards but provides weekly temporal resolution and shows typical uncertainties in the Laptev Sea of approximately 0.15 m. Furthermore, CS2SMOS combines the advantages of observing thick (> 1 m) and thin (< 1 m) ice with CS2 and SMOS, respectively, keeping the relative uncertainties for both ice regimes as small as possible (Ricker et al., 2017).

In order to be consistent with VAL sea ice draft data CCI-2 freeboard was subtracted from CCI-2 SIT to obtain CCI-2 gridded monthly mean and orbit sea ice draft. Since CS2SMOS SIT is derived by an optimal interpolation of two SIT products (Ricker et al., 2017) and thus does not provide freeboard information, sea ice draft was calculated differently than for the CCI-2 products. CS2SMOS SIT was divided by a constant ratio of 1.136 to compute sea ice draft. This ratio between SIT and draft was derived through nearly 400 drillings of sea ice in Fram Strait (Vinje and Finnekasa, 1986) and is in good agreement with Arctic-wide SIT measurements from Russian drillings (Vinje et al., 1998). For the comparison to mooring-based VAL sea ice draft data, all satellite sea ice draft data points from within a predefined 25 km radius around the mooring site were selected and calculated into a weighted mean sea ice draft value. The weighted averaging accounts for the varying distances between the selected satellite data points and the mooring location and was done for each satellite product individually. Since all five data sets are based on radar altimetry data satellite sea ice draft data is only available from October through April.

2.3 Data limitations

2.3.1 VAL data

VAL data is based on sonar-derived ice drafts from two differing instruments. In general, the default setup, with a single narrow vertical beam and a sampling frequency of 1 Hz, makes the ULS the primary instrument for stationary long-term observation of sea ice draft. Although upward-looking ADCPs are based on the the same measurement principles they are build for measurements of currents and ice drift rather than sea ice draft. Consequently, the ADCP-derived sea ice draft time series are less accurate than ULS-derived time series (Belter et al., 2020b). As a result this study compares satellite data to VAL data sets of different quality. This compromise in data quality between ULS and ADCP was taken on because we consider the daily mean sea ice draft time series to be sufficiently accurate for the comparison to weekly and monthly mean sea ice draft from gridded satellite products. Since they are of sufficient quality, the ADCP-derived draft records allow us to significantly extend the available ULS-derived time series. Rather than analysing data from only two consecutive years we are able to investigate a time period of almost 13 years. The increased length of this unique Laptev Sea VAL data set is vital for the evaluation of the stability of the investigated CCI-2 records.

Despite the fact that we were able to extend our Laptev Sea VAL data set it has to be noted that in situ observations of sea ice draft are very limited in the Laptev Sea. The lack of mooring measurements over more than two years at any of the sampled locations prohibits us from comparing satellite data to VAL data from a single mooring location. Instead, the entire VAL data record is composed of one to two year time series from a total of nine different locations all over the Laptev Sea (Fig. 1).

Although this inconsistency is unfavourable for the analysis of long-term variability of sonar-based SIT in this region the VAL data provides a new and unique validation record for the CCI-2 SIT CDR.

2.3.2 ESA CCI-2 gridded monthly mean draft data

Like the VAL data record, gridded and orbit CCI-2 data is based on measurements from two different systems. Inter-mission differences have been analysed previously and indicate that due to the different setups of the ENVISAT and CS2 radar altimeters the final SIT, and therefore draft, records contain residual intermission differences (Guerreiro et al., 2017; Paul et al., 2018). These biases vary regionally and seasonally. The seasonal biases between ENVISAT and CS2 need to be considered for the temporal development of the Laptev Sea SAT-VAL differences between the two periods. For the Laptev Sea the ENVISAT SIT is, on average, approximately 0.22 m thicker than the CS2 SIT for the overlap period from November 2010 to March 2012.

In addition, the biggest limitation for the analysis of the performance of the gridded CCI-2 CDR is its temporal resolution of one month and its limitation to the period from October through April. This significantly limits the number of CCI-2 draft data points for the comparably short validation period from 2003 to 2016.

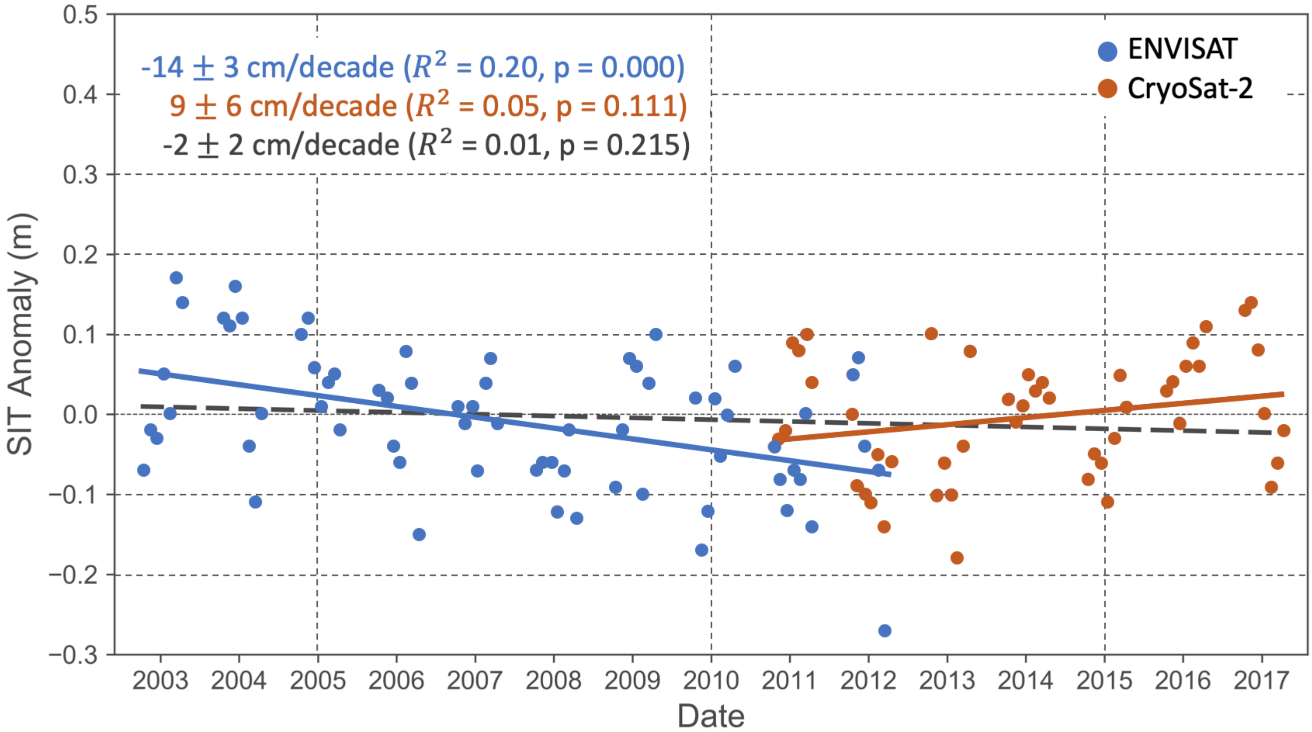

Figure 2. ESA CCI-2 gridded (25 km EASE grid) sea ice thickness (SIT) anomaly in the Laptev Sea. SIT anomaly was calculated for each month compared to the mean of the same month over the full period from 2002 to 2017. Anomalies were calculated for every grid point and averaged over a predefined area in the Laptev Sea (100-145 °E, 70-81.5 °N, enclosed area Fig. 1).

3 Results

3.1 ESA CCI-2 Laptev Sea SIT

The ESA CCI-2 SIT CDR shows no significant change of SIT in the Laptev Sea between 2002 and 2017 (Fig. 2). SIT anomaly was calculated for each month compared to the mean of the same month over the full period from 2002 to 2017. Anomalies were calculated for each grid point and averaged over the Laptev Sea (100-145 °E, 70-81.5 °N, enclosed area Fig. 1). Separating the CCI-2 CDR into the two satellite periods shows that the slightly negative, but highly uncertain, overall trend consists of opposing trends in SIT anomaly from the two CCI-2 data products. While the ENVISAT SIT anomaly (2002-2012) decreases by approximately 14 cm per decade, the trend in CS2 SIT anomaly shows an increase in SIT from 2010 to 2017. In order to investigate the validity of these satellite-derived trends in SIT anomaly the following section provides the results of the statistical analysis of the differences between VAL and satellite-derived sea ice draft data from the Laptev Sea. To determine the agreement between satellite and VAL sea ice draft data, values of root mean square difference (RMSD), mean difference and correlation coefficient (r) were calculated for each of the individual data sets from the stations shown in Fig. 1. For comparison between the ENVISAT and CS2 missions, averages of these three statistical parameters were calculated for all stations during the overlap period from November 2010 to March 2012.

3.2 Validation of CCI-2 products

3.2.1 Gridded monthly CCI-2 sea ice draft

Figure 3a shows the differences between gridded monthly mean CCI-2 and VAL sea ice draft (SAT-VAL difference) for the period from 2003 to 2016. Individual SAT-VAL differences show substantial scatter around zero but the overall trend (black line) indicates an almost constant mean difference of approximately -0.3 m over the full investigation period. The SAT-VAL differences are normally distributed around the mean SAT-VAL difference of approximately -0.3 m (Fig. 3b). Table 1 and 2 provide RMSD, mean difference and correlation coefficients between the gridded ENVISAT and CS2 and VAL draft data from each station, respectively.

For the ENVISAT period RMSD values average 0.70 m, with minimum RMSD of 0.37 m for the Anabar 2007/2008 and maximum RMSD of 1.0 m for the Khatanga 2008/2009 data. The average mean difference is -0.22 m indicating an average underestimation of monthly mean sea ice draft by the ENVISAT data. The ENVISAT underestimation of sea ice draft occurs for all but two data sets. Lena 2003/2004 and Outer Shelf 2011/2012 mean differences are 0.44 and 0.55 m, respectively, indicating a mean overestimation of sea ice draft by the ENVISAT product at these stations. The average correlation coefficient between gridded monthly mean ENVISAT and VAL sea ice draft data is 0.44 for the period from 2003 to 2012. Results from multiple stations show little or almost no correlation, while correlations are significant at the 95% confidence level for data from only three stations.

Compared to ENVISAT, differences between gridded monthly mean CS2 and VAL sea ice draft show a smaller average RMSD (0.48 m) and a higher mean correlation coefficient (0.50). The average mean difference of -0.27 m is slightly more neg-

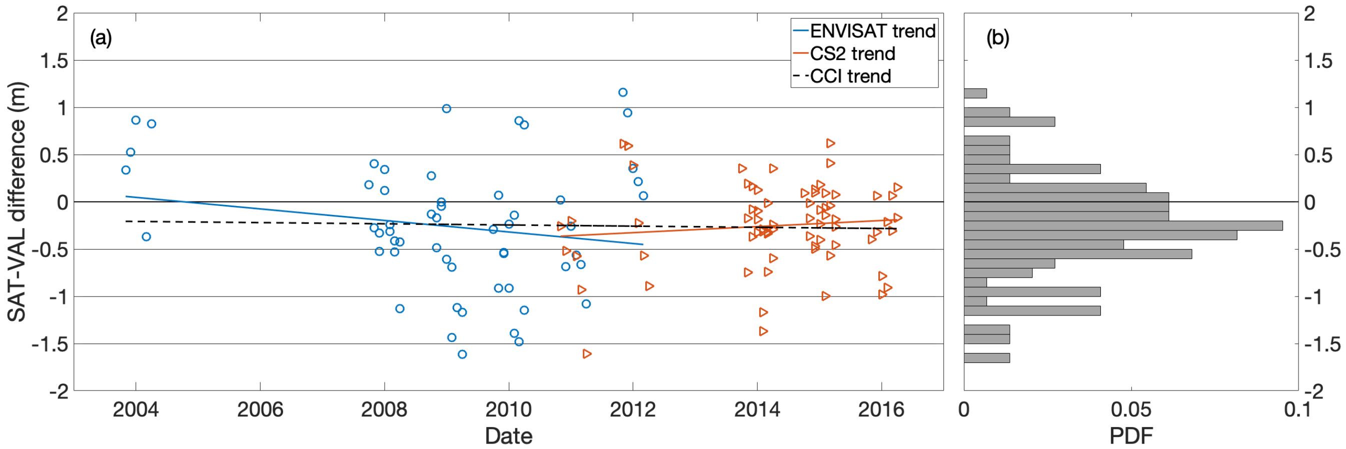

Figure 3. (a) Difference (SAT-VAL difference) between gridded monthly mean ENVISAT/CS2 and VAL ice drafts. VAL data consists of ice draft data derived from upward-looking ADCPs for the ENVISAT period (blue) and a combination of ADCP and ULS data for the CS2 period (orange). (b) Probability density function (PDF) of SAT-VAL differences over the full period from 2003 to 2016.

ative than for ENVISAT. This indicates a stronger mean underestimation of VAL sea ice draft by CS2 compared to ENVISAT. Mean differences are negative for all stations, showing consistent underestimation by CS2 data. Although the mean correlation coefficient is larger compared to the ENVISAT period none of the individual coefficients is significant at the 95% confidence level during the CS2 period.

By grouping VAL sea ice draft values in 0.2 m bins and comparing them to their corresponding monthly mean ENVISAT (2003 to 2012) and CS2 (2010 to 2016) sea ice draft values we are able to examine the agreement between gridded CCI-2 and VAL drafts along the full range of sea ice drafts that were measured by the moorings (Fig. 4). Both scatter plots indicate an overestimation by the gridded CCI-2 products for draft values below approximately 0.7 m. The magnitude of the overestimation decreases with increasing draft. The best agreement occurs for draft values between 0.7 and about 1.2 m, while monthly mean VAL sea ice draft is underestimated for draft values above approximately 1.3 m. The underestimation increases with increasing ice draft values. Additionally, Fig. 4 shows that the variability of the ENVISAT draft values is substantially larger within the selected 0.2 m bins compared to CS2 draft values in the same bins. The difference in the performance of ENVISAT and CS2 data is also revealed for the overlap period between the two satellite missions (2010-2012). While mean differences show the same tendency with -0.54 m (ENVISAT, Table 1) and -0.68 m (CS2, Table 2) for the 2010-2011 Outer Shelf data sets, they disagree considerably for the 2011-2012 period (ENVISAT: 0.55 m, CS2: -0.02 m).

In order to complement the results shown for the comparison between gridded CCI-2 and mean VAL data, we conducted an additional analysis with satellite data products that are based on the measurements from the ENVISAT and CS2 missions and the gridded CS2 data but provide higher temporal resolution of sea ice draft than the gridded CCI-2 record. RMSD, mean

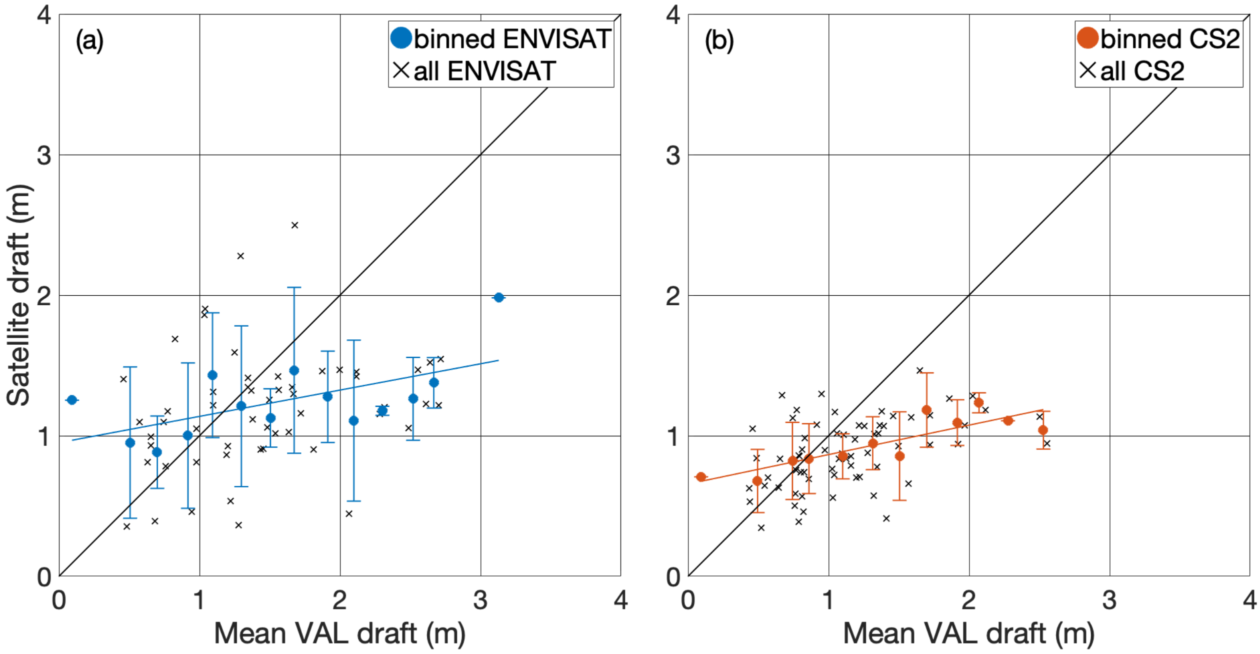

Figure 4. Scatterplot comparing gridded monthly mean CCI-2 sea ice draft to VAL sea ice draft (black crosses). Panel (a) shows the comparison for the ENVISAT period superimposed by the mean ENVISAT draft per 0.2 m VAL data bin, while panel (b) shows the same for CS2 data and period. Error bars indicate ± one standard deviation of the CCI-2 data within the specific 0.2 m bin.

difference and correlation coefficients were calculated for the comparison of sea ice draft from ENVISATorbit (Table 1) and CS2orbit (Table 2) trajectory data and merged CS2SMOS (Table 3) data with VAL sea ice draft data.

3.2.2 Orbit CCI-2 sea ice draft

While the average RMSD, mean difference and correlation coefficients are very similar for the VAL data comparison to gridded CS2 and CS2orbit, almost all stations show significant (at the 95% confidence level) correlations between CS2orbit and VAL sea ice draft (Table 2). ENVISATorbit data shows a higher average RMSD, stronger average underestimation of VAL sea ice draft and much lower average correlation with VAL sea ice drafts compared to the gridded ENVISAT data (Table 1). This suggests that the CS2 component of the CCI-2 CDR is superior to the ENVISAT sea ice draft data. It also confirms the inter-mission biases between ENVISAT and CS2 that were published by Paul et al. (2018).

3.2.3 Intercomparison of CCI-2 and merged CS2SMOS sea ice draft

The comparison of weekly CS2SMOS and VAL sea ice draft data reveals the largest average correlation coefficient. On the other hand, the CS2SMOS and VAL draft comparison also shows the largest average underestimation of any of the presented satellite data products. Figure 5 shows the comparison of the agreement between the gridded and orbit CCI-2 and the CS2SMOS data products with the corresponding VAL sea ice draft data. While the overall tendency of the gridded CCI-2 products to overestimate ice draft for thin ice and increasingly underestimate thickening ice is confirmed by CCI-2 orbit and CS2SMOS data a general offset between the individual satellite products is visible for most of the selected 0.2 m VAL data bins. While both ENVISAT draft data sets indicate thickest drafts over the full thickness range, gridded CS2 and CS2orbit agree rather well. CS2SMOS data shows smallest draft values throughout the entire thickness range compared to the CCI-2 products. The overestimation of sea ice draft values below 0.7 m that is apparent in the gridded and orbit CCI-2 data is minimized by the impact of SMOS on the merged CS2SMOS product. The Laptev Sea is dominated by newly formed and thinner FYI, accordingly the gridded merged product is dominated by SMOS data. Consequently the underestimation of sea ice draft with increasing thickness is largest for CS2SMOS because of the larger influence of SMOS data on the final SIT values in this region.

In summary, the gridded CCI-2 products underestimate monthly mean sea ice draft in the Laptev Sea by an average of -0.22 m (-0.27 m) during the ENVISAT (CS2) period. This underestimation by the monthly mean gridded CCI-2 products is not a constant bias. The agreement between gridded CCI-2 and VAL sea ice drafts is in fact dependent on the thickness of

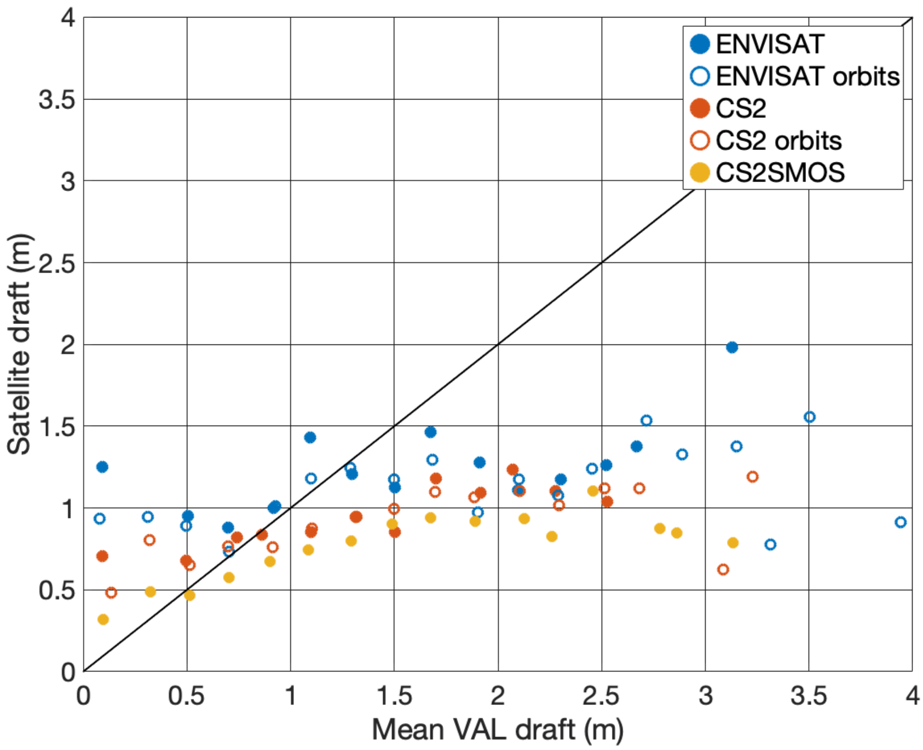

Figure 5. Mean sea ice drafts per 0.2 m VAL data bin from ENVISAT (filled blue circles), ENVISATorbit (blue circles), CS2 (filled orange circles), CS2orbit (orange circles) and CS2SMOS (filled yellow circles) data products.

the observed ice. Thin ice (drafts < 0.7 m) is overestimated by the gridded CCI-2 products and thicker ice (drafts > 1.3 m) is increasingly underestimated with increasing ice draft. The overall spread in SAT-VAL difference values is smaller for the CS2 period. ENVISATorbit and CS2orbit and merged CS2SMOS sea ice draft data, which provide higher temporal resolution than the gridded monthly mean products confirm these results. It has to be noted that sea ice draft values from the four presented satellite products deviate considerably from one another.

4 Discussion

4.1 Comparability of satellite and sonar measurements

ENVISAT and CS2 average mean differences to VAL sea ice draft are of similar magnitude, which indicates a consistent average underestimation of Laptev Sea sea ice draft from the gridded monthly mean CCI-2 CDR between 2003 and 2016. In order to discuss these results and most importantly their meaning for the apparent trends in CCI-2 SIT in the Laptev Sea (Fig. 2) the deficiencies of the VAL and CCI-2 data products have to be examined.

The comparison between gridded satellite products and point measurements from moorings is by default challenging. A significant difference between sonar and altimetry-based measurements are the parameters that are measured. While moored sonars provide sea ice draft data, radar altimeters infer SIT from measurements of freeboard. Altimeter freeboard is converted into SIT based on parametrizations of snow depth and constant densities of snow and sea ice. Snow depth, snow and sea ice density are parameters that are not routinely measured and therefore are based on climatologies: modified Warren snow climatology and Warren snow water equivalent climatology (Warren et al., 1999; Ricker et al., 2014). These assumptions contribute to the uncertainties of the final SIT data records and consequently to the CCI-2 sea ice draft values that are calculated for the presented comparison to VAL sea ice draft. Additionally, both measurements take place on completely different spatial scales. Moored sonars sample a single point throughout the respective sampling period. In contrast, the location of radar altimetry measurements is defined by footprints of the instruments and the trajectories of the satellites. Additionally, the final CCI-2 data product is gridded to achieve Arctic-wide coverage which means that variability within an 25×25 km gird cell is not resolved. These fundamental differences between the compared measurement principles have to be considered when comparing the presented satellite and sonar-based sea ice draft data sets. Additionally, VAL and CCI-2 time series are derived from multiple different instruments during the investigated period from 2003 to 2016. Accordingly, each of these individual records consists of data from different measurement configurations themselves.

4.2 Stability of the CCI-2 SIT CDR

In general, the stability of the satellite records is defined as the constancy of the SAT-VAL differences over time. However, the fact that the full VAL data record consists of multiple one to two year sea ice draft time series from various stations all over the Laptev Sea rather than a single time series from one location inhibits us from assessing an overall trend in sea ice draft over the full VAL period. Therefore, the observed near-consistent average mean differences over the ENVISAT and CS2 periods (Fig. 3)

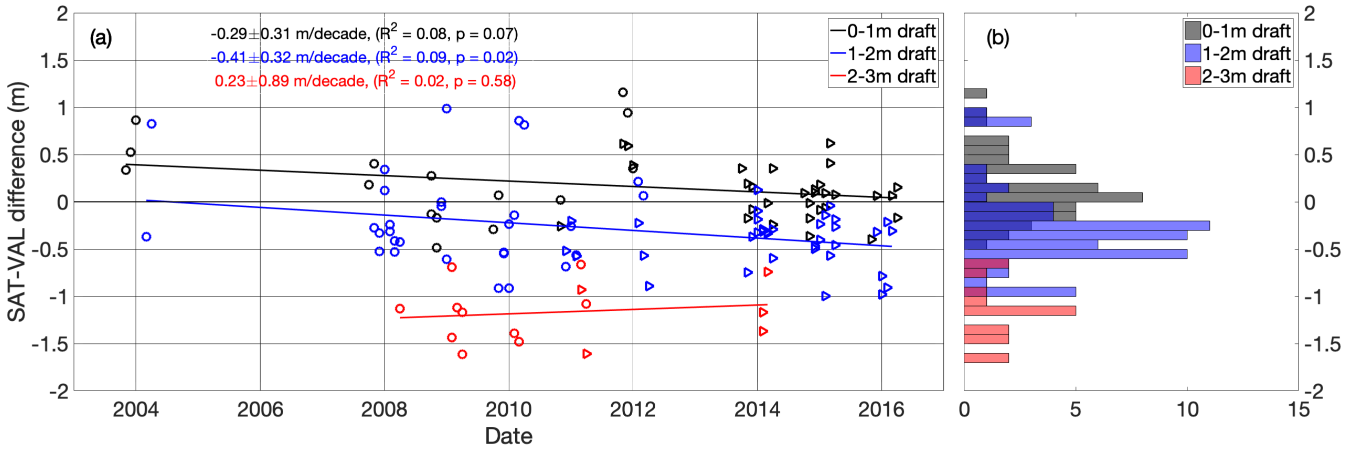

Figure 6. (a) Difference (SAT-VAL difference) between gridded monthly mean ENVISAT (CS2) and VAL ice drafts in circles (triangles) for thickness ranges from 0 to 1 m (black), 1 to 2 m (blue) and 2 to 3 m (red). Linear trends were computed for each of the thickness ranges. (b) Distributions of 0 to 1 m (black), 1 to 2 m (blue) and 2 to 3 m (red) thickness range SAT-VAL differences.

do not provide enough proof of a stable performance of the gridded CCI-2 data. SAT-VAL differences are dependent on the thickness of the ice that is sampled, which means in order to investigate the stability of the gridded CCI-2 records, SAT-VAL differences need to be analysed for different thickness ranges. We therefore consider the presented gridded CCI-2 draft record stable only if the SAT-VAL differences within the selected thickness ranges stay constant over time.

The limiting factor for the analysis of temporal changes in the SAT-VAL difference from different thickness ranges is, again, the small number of data points and the comparably short observational period. The following thickness ranges were selected in order to provide a reasonable number of data points for the analysis of trends: 0 to 1 m, 1 to 2 m and 2 to 3 m. For the thickness ranges between 0 and 1 m and 1 and 2 m negative trends are visible while a positive trend is apparent for the thickness range from 2 to 3 m (Fig. 6). However, the coefficients of determination, R^2, for all three trends are very small indicating that linear trends poorly represent the Laptev Sea SAT-VAL difference and are in fact not suitable to explain the temporal development of SAT-VAL differences over time. Nevertheless they allow us to investigate the stability of the mean difference for different thickness ranges. The trends indicate a decrease (increase) in mean difference for the thickness ranges 0 to 1 m and 1 to 2 m (2 to 3 m). All three trends have large uncertainties and only one is significant at the 95% confidence level (1 to 2 m thickness range, p-values below 0.05). These trends are dependent on the length of the observed time series, the selected thickness ranges and in the presented case on the inter-mission biases between the two CCI-2 products that combine for the full gridded CCI-2 sea ice draft CDR. The above-mentioned ENVISAT overestimation of freeboard in FYI-dominated regions like the Laptev Sea leads to an overestimation of ice draft compared to CS2. SAT-VAL differences during the overlap period (2010 to 2012) show larger differences between satellite and VAL draft for ENVISAT than for CS2 (Fig. 3). This tendency of the ENVISAT data to generally provide thicker ice in FYI regions than CS2 can also be seen in Fig. 4 and might explain the negative trends observed in the 0 to 1 and 1 to 2 m thickness ranges (Fig. 6). The trend for the 2 to 3 m thickness range is less conclusive which is attributed to the small number of data points compared to the other two thickness ranges and the thickness dependency of the SAT-VAL differences that strongly increases for thickness values between 2 and 3 m.

330 Based on this analysis we consider the trends within the three thickness ranges to be caused by the limited number of data points, the selected thickness ranges and the inter-mission bias between ENVISAT and CS2 and the overall gridded CCI-2 CDR to be stable for the investigated period from 2003 to 2016.

4.3 Taymyr 2013/2014 case

In order to support the interpretation and underline the current deficiencies of satellite-derived sea ice draft data in the Laptev Sea we present a case study based on the 2013/2014 ULS deployment at Taymyr station (Fig. 7).

The Taymyr station is located in the western Laptev Sea (Fig. 1). The region is dominated by offshore winds that open coastal polynyas. The ice formed in these polynyas is transported northwards (Itkin and Krumpen, 2017) and passes by the mooring site. Changes in wind direction can lead to temporary closing of the polynyas and convergence towards the coast or fast ice. Sea ice piling up against the south-western coast is deformed and increases in thickness.

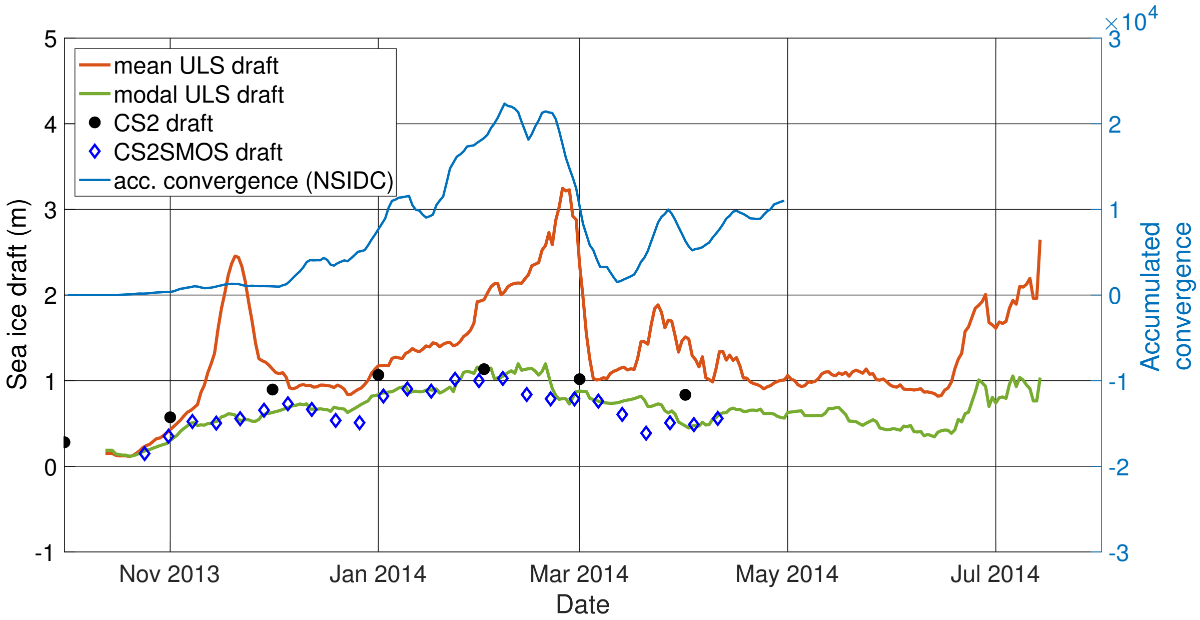

Figure 7. Time series of CS2 (black circles) and CS2SMOS (blue diamonds) sea ice draft compared to ULS-derived mean (orange) and modal (green) sea ice draft from Taymyr station (2013-2014). Sea ice passing the mooring site was tracked using the Lagrangian ice tracking tool ICETrack (Krumpen, 2017). Based on the NSIDC Polar Pathfinder sea ice motion product (Tschudi et al., 2019) accumulated convergence (blue) along the daily sea ice trajectories was calculated.

We utilized a Lagrangian tracking tool, ICETrack (Krumpen, 2017), to determine the trajectories of the ice that was passing by the mooring. ICETrack has been used in multiple studies to determine sea ice source regions, pathways and thickness changes (Damm et al., 2018; Peeken et al., 2018; Krumpen et al., 2019, 2020) and utilizes sea ice motion information from a combination of three different products: motion estimates from scatterometer and radiometer data from the Center for Satellite Exploitation and Research (Girard-Ardhuin and Ezraty, 2012), the OSI-405-c motion product provided by the Ocean and Sea Ice Satellite Application Facility (Lavergne, 2016) and Polar Pathfinder Daily Motion Vectors from the National Snow and Ice Data Center (NSIDC) (Tschudi et al., 2019). The tracking provides us with information about the source regions of the ice measured by the ULS and the atmospheric and oceanic conditions the ice experienced on its trajectory to the mooring location. The NSIDCs Polar Pathfinder sea ice motion product (Tschudi et al., 2019) was used to estimate convergence along the trajectories of the Taymyr sea ice. Analysing daily convergence along the trajectories allowed us to calculate accumulated convergences over each track. Accumulated convergence is a measure for the total amount of deformation the ice that passed by the Taymyr mooring has experienced before it reached the mooring site.

The daily mean ULS draft time series from the Taymyr station indicates a consistent increase in sea ice draft between January and March 2014. Since the Laptev Sea is dominated by newly formed FYI the observed daily mean draft values cannot be explained by thermodynamic growth only. An additional dynamic influence on the ice is confirmed by the increase in accumulated convergence along the trajectories over the same period from January to March 2014. When comparing the daily mean ULS time series to the gridded monthly mean CS2 draft time series it is apparent that the CCI-2 product is not able to reproduce the dynamic increase in sea ice draft. Rather than showing the mean sea ice draft CS2 data shows better agreement with the modal sea ice draft derived from the ULS (Fig. 7). A similar result is visible for the weekly draft values from CS2SMOS.

Table 4 shows RMSD, mean difference and correlation coefficients for the comparison between gridded CS2, CS2orbit and CS2SMOS with modal sea ice draft data from the ULS moorings (Taymyr and 1893) for the 2013/2014 and 2014/2015 periods. Gridded CS2, CS2orbit and CS2SMOS show small mean differences to modal sea ice drafts in the Laptev Sea. Mean correlation coefficients between modal ULS and mean satellite data are between 0.61 and and 0.77 and significant at the 95% confidence level for the higher temporal resolution satellite products (CS2orbit and CS2SMOS). Due to the low temporal resolution of the ADCP measurements reliable modal draft values could not be calculated. Therefore the comparison between mean satellite and modal VAL draft values is limited to the 2013-2015 period when ULS data is available.

Another observation from this case study and the comparison of satellite and VAL sea ice draft in general concerns the differences in length of the time series. While satellite data is only available from October and through April, ULS and ADCP are able to measure sea ice draft even after melt onset. It is known that warm snow and ice as well as the formation of melt ponds prevent CS2 retrieval of Arctic SIT between May and September (Ricker et al., 2017). That means that for investigations into the sea ice cover in the Laptev Sea it is important to be aware that sea ice can persist during the summer melt season when the presented satellites do not provide SIT data.

5 Conclusions

The ESAs CCI-2 gridded SIT CDR covers a period from 2002 to 2017 and has been validated mainly for MYI-dominated regions around the Arctic Ocean. These validation efforts over MYI indicated that CS2 is representing thicker ice rather well, while ENVISAT shows a general tendency towards overestimating thin and underestimating thicker sea ice (Kern et al., 2018). The presented in situ observations of sea ice draft from Laptev Sea ULS and ADCP moorings provide an additional important validation data set from one of the most under-sampled and FYI-dominated regions of Arctic sea ice.

The comparisons between sea ice draft data from ULS and upward-looking ADCPs with gridded monthly mean CCI-2 sea ice draft, higher resolution CCI-2 orbit trajectory and the merged CS2SMOS data in the Laptev Sea indicate:

- The agreement between in situ sonar and satellite data is very sensitive to the thickness of the sampled sea ice.
- Sea ice drafts below 0.7 m are overestimated, while sea ice drafts above approximately 1.3 m are increasingly underestimated by all considered satellite data products.
- The presented satellite products represent the same VAL sea ice drafts differently.

The Taymyr 2013/2014 case study highlights the current deficiencies of the satellite-derived SIT records in the FYI-dominated Laptev Sea region:

- Rather than representing mean sea ice draft, the considered satellite products show better agreement with modal sea ice draft.
- Significant, lasting deformation events that lead to large mean sea ice drafts are not represented in any of the shown satellite data products.

These results indicate distinct differences and deficiencies in the performance of the ESA CCI-2 SIT products over FYI-and MYI-dominated regions that require further investigations. The presented stability analysis of SAT-VAL draft differences in the Laptev Sea reveals that the agreement between gridded monthly mean CCI-2 and VAL sea ice draft data is dependent on the thickness of the ice that is sampled but mean differences are consistent over time for similar thicknesses. Linear changes in mean differences for individual thickness ranges are attributed to inter-mission bias in SIT representation between the two missions (ENVISAT and CS2) composing the gridded CCI-2 record and the comparably small number of data points that were available for the individual thickness ranges.

Applying these results to the presented Laptev Sea CCI-2 SIT anomaly trends (Fig. 2) we conclude that the trends of the ENVISAT and CS2 component are not caused by a change in the performance of the CCI-2 products over time but rather actual changes in SIT in this region. However, due to the high uncertainties of the data products and the comparably short sampling periods these trends need to be investigated further. Although, the stability analysis provides confidence in the CCI-2 SIT CDRs it has to be noted that satellite-derived SIT data is not sufficient to explain overall changes in SIT in the Laptev Sea. In agreement with Haas (2004) we conclude that current satellite SIT data allows examination of changes in modal

SIT and therefore the thermodynamic component of the changes in the Laptev Sea, however, dynamic changes in SIT are not reproduced by the satellite CDRs. Therefore, improvements in the processing of radar altimetry data are required for the estimation of surface roughness but also for the parametrizations of snow depth and densities of snow and ice. Unknown snow properties and depth distribution are a major source for uncertainty in the freeboard retrieval process. Uncertainties in freeboard as well as slight changes in the utilized average ice column densities translate into the final SIT product. As suggested by Wingham et al. (2006) ice type densities should be replaced by thickness dependent ice densities to account for the currently unknown density variations due to deformation processes. Furthermore, continuous long-term SIT measurements in the Laptev Sea are required to provide much needed information on deformation processes. However, with limited access to the vastly under-sampled Russian Shelf regions the satellite-derived SIT CDRs remain a crucial source of long-term SIT data for this region. Their improvement as well as large-scale observations of dynamic changes of SIT redistribution and model simulations are required to investigate the effects governing SIT changes in the Laptev Sea.

Data availability. ULS (Belter et al., 2019) and ADCP-derived daily mean sea ice draft time series (Belter et al., 2020a) are available at the Data Publisher for Earth & Environmental Science PANGAEA.

ESA Sea Ice Climate Change Initiative (Sea_ Ice_ cci): Northern hemisphere sea ice thickness from ENVISAT satellite (Hendricks et al., 2018c) and from CryoSat-2 satellite (Hendricks et al., 2018a) on a monthly grid (L3C), v2.0 are available from the Centre for Environmental Data Analysis data base.

ESA Sea Ice Climate Change Initiative (Sea_ Ice _ cci): Northern hemisphere sea ice thickness from ENVISAT (Hendricks et al., 2018d) and CryoSat-2 (Hendricks et al., 2018b) on satellite swath (L2P), v2.0 are available from the Centre for Environmental Data Analysis data base.

Merged CryoSat-2/SMOS sea ice thickness: A weekly Arctic sea-ice thickness data record from merged CryoSat-2 and SMOS satellite data (2017). The Cryosphere, 11, 1607-1623, https://doi.org/10.5194/tc-11-1607-2017

Author contributions. HJB carried out the analysis, processed ULS and ADCP data and wrote the manuscript. All authors contributed to the discussion and provided input during the writing process. In addition to their input to the manuscript TK conducted the backward-tracking of sea ice from the individual mooring sites, SH provided CCI-2 data and conducted the analysis of CCI-2 SIT changes in the Laptev Sea and RR contributed CS2SMOS SIT data to the analysis. JAH and MAJ deployed and recovered the moorings during numerous expeditions to the Laptev Sea.

Competing interests. Author CH is a member of the editorial board of the The Cryosphere. All other authors declare that they have no conflict of interest.

Acknowledgements. This study was carried out as part of the BMBF-funded Russian-German research cooperation QUARCCS (grant: 03F0777A). Moorings were deployed and recovered within the framework of the Russian-German project CATS/Transdrift (grant: 63A0028B). Special thanks to all the people involved on the various expeditions.

The 2013/2014 ULS data sets were processed by ASL Environmental Sciences Inc., Victoria, BC, Canada. ASL also provided valuable support and the toolboxes for the processing of the 2014/2015 ULS data sets. Additionally, the ECMWF provided ERA-Interim reanalysis surface pressure data (Dee et al., 2011) that was valuable for the ULS processing.

The production of the merged CryoSat-SMOS sea ice thickness data was funded by the ESA project SMOS & CryoSat-2 Sea Ice Data Product Processing and Dissemination Service, and data from 2010 to 2016 were obtained from AWI.

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Table 1. Statistics of the comparison of gridded monthly mean ENVISAT and ENVISATorbit draft data with VAL mean sea ice draft for the period from 2003 to 2012. RMSD and mean difference were calculated for the differences of ENVISAT minus VAL mean sea ice draft. The Pearson correlation coefficient, *r*, was calculated for each station. Bold correlation coefficient values indicate significant correlation at the 95% confidence level. Bottom line values show the averages of RMSD, mean difference and correlation coefficient over all stations.

		ENVISAT			ENVISATorbits		
Period	Station	RMSD [m]	Mean difference [m]	r	RMSD [m]	Mean difference [m]	r
2003-2004	Lena	0.63	0.44	0.25	0.95	0.02	-0.05
2007-2008	Anabar	0.37	-0.17	0.53	0.75	-0.30	-0.01
	Khatanga	0.54	-0.30	0.43	1.20	-0.60	-0.01
2008-2009	Khatanga	1.00	-0.45	-0.14	1.06	-0.61	-0.02
	Outer Shelf	0.73	-0.60	**0.90**	0.92	-0.65	**0.54**
2009-2010	Anabar	0.75	-0.14	0.05	0.84	-0.09	0.20
	Khatanga	0.92	-0.72	**0.81**	1.11	-0.73	0.11
2010-2011	Outer Shelf	0.64	-0.54	**0.86**	0.84	-0.61	**0.60**
2011-2012	Outer Shelf	0.69	0.55	0.29	0.65	0.27	0.12
2003-2012	**Mean**	0.70	-0.22	0.44	0.93	-0.37	0.16

Table 2. Statistics of the comparison of gridded monthly mean CS2 and CS2orbit draft data with VAL mean sea ice draft for the period from 2010 to 2016. RMSD and mean difference were calculated for the differences of CS2 minus VAL mean sea ice draft. The Pearson correlation coefficient, *r*, was calculated for each station. Bold correlation coefficient values indicate significant correlation at the 95% confidence level. Bottom line values show the averages of RMSD, mean difference and correlation coefficient over all stations.

			CS2			CS2orbits	
Period	Station	RMSD [m]	Mean difference [m]	r	RMSD [m]	Mean difference [m]	r
2010-2011	Outer Shelf	0.83	-0.68	0.61	0.94	-0.65	**0.39**
2011-2012	Outer Shelf	0.58	-0.02	0.29	0.71	-0.06	**0.38**
2013-2014	1893	0.23	-0.06	0.71	0.22	-0.02	**0.82**
	Taymyr	0.68	-0.53	0.53	0.71	-0.47	**0.43**
	Kotelnyy	0.61	-0.41	0.74	0.61	-0.46	**0.68**
	Vilkitzkii	0.24	-0.02	0.46	0.44	-0.35	**0.73**
2014-2015	1893	0.55	-0.46	0.46	0.51	-0.39	**0.55**
	Taymyr	0.32	-0.27	0.70	0.41	-0.28	**0.54**
2014-2016	Vilkitzkii1	0.40	-0.02	0.10	0.57	0.02	-0.06
	Vilkitzkii3	0.40	-0.19	0.37	0.58	-0.14	0.21
2010-2016	**Mean**	0.48	-0.27	0.50	0.57	-0.28	0.47

Table 3. Statistics of the comparison of gridded weekly mean CS2SMOS draft data with VAL mean sea ice draft for the period from 2010 to 2016. RMSD and mean difference were calculated for the differences of CS2SMOS minus VAL mean sea ice draft. The Pearson correlation coefficient, *r*, was calculated for each station. Bold correlation coefficient values indicate significant correlation at the 95% confidence level. Bottom line values show the averages of RMSD, mean difference and correlation coefficient over all stations.

Period	Station	RMSD [m]	CS2SMOS Mean difference [m]	r
2010-2011	Outer Shelf	0.88	-0.70	0.41
2011-2012	Outer Shelf	0.48	-0.07	**0.72**
2013-2014	1893	0.32	-0.17	**0.70**
	Taymyr	0.92	-0.76	**0.51**
	Kotelnyy	0.73	-0.64	**0.92**
	Vilkitzkii	0.29	-0.18	**0.78**
2014-2015	1893	0.46	-0.42	**0.80**
	Taymyr	0.40	-0.36	**0.77**
2014-2016	Vilkitzkii1	0.50	-0.24	0.10
	Vilkitzkii3	0.59	-0.41	**0.42**
2010-2016	**Mean**	0.56	-0.39	0.61

Table 4. Statistics for the comparison between gridded CS2, CS2orbit and gridded CS2SMOS mean sea ice draft with modal Taymyr and 1893 ULS sea ice draft from the 2013/2014 and 2014/2015 periods. Due to the low temporal resolution of the ADCP-derived VAL data, modal sea ice draft was only calculated for ULS data. RMSD and mean difference were calculated for the difference between mean satellite minus modal VAL data. The Pearson correlation coefficient, *r*, was calculated for each of the four VAL data sets. The values show the mean of RMSD, mean difference and *r* over the four VAL data sets. Bold mean correlation coefficients indicate significance of all four correlation coefficients at the 95% confidence level. None of the correlations was significant for the CS2 data.

	CS2	CS2orbit	CS2SMOS
RMSD [m]	0.25	0.30	0.21
Mean difference [m]	0.05	0.06	-0.05
r	0.61	**0.63**	**0.77**

Point-by-point response to editor and reviewer concerns by
corresponding author: H. Jakob Belter
March 16, 2020

tc-2019-307:
Satellite-based sea ice thickness changes in the Laptev Sea from 2002 to 2017: Comparison to mooring observations

https://doi.org/10.5194/tc-2019-307:

Belter, H. Jakob, Thomas Krumpen, Stefan Hendricks, Jens A. Hoelemann, Markus A. Janout, Robert Ricker, Christian Haas

Dear anonymous Reviewer #1,

on behalf of all authors, I would like to thank you for your detailed and constructive comments. In the following you can find a point-by-point response to your comments. We really have the feeling that your insights helped improve the manuscript and we hope that all your concerns have been answered to your satisfaction. We would also like to refer you to the responses to the other reviewers for more improvements and changes to the manuscript

General comments:

- *(1) The authors should discuss whether their main results are also applied to other Arctic areas dominated by FYI, like Kara Sea, and point out clearly whether the current CCI-2 CDR can be used to investigate SIT trends over FYI dominated oceans, in Figure 2 only SIT anomaly trend from the CS2 period was statistically significant.*
  -Response:
  This is a really good question that unfortunately can not be answered given the data limitations we are facing in the Russian Shelf Seas. We do not see why the presented results should not be confirmed for similar FYI-dominated shelf seas, however, since we only happen to have moorings in the Laptev Sea we can not provide any proof. Therefore, this study is focused on the region where data is available to us - the Laptev Sea. Our conclusion clearly states that these results only concern the Laptev Sea, however, as we are also providing suggestions and 'to-dos' for further algorithm development we reckon that agreement between satellite and VAL data will be improved across the Arctic. However, without actual in situ observations to validate the satellite products in other regions of the Arctic this remains speculation. In fact, having this newly acquired sonar-based validation data set for the Laptev Sea is already a big step towards analysing regional differences in the performance of the available satellite products. We are certainly hoping for more data sets from other regions but also long-term measurements of similar quality as the unique ULS sea ice draft time series in Fram Strait (NPI and Hansen et al.,2013) for future validation purposes. As for your second comment, longer time series are also the aim for the CCI-2 SIT CDRs, as they will help strengthen the statistical significance of possible satellite-based SIT anomaly trends (Fig. 2).
  -Changes:
  No changes.

- *(2) In Introduction Section you could review what is current understanding on the accuracy/quality of the CCI-2 SIT CDR: it seems this has been investigated at least by Kern et al. 2018. Are there any other studies, especially in peer-reviewed journals? You could also review similar other studies: comparisons between RA SIT records and sonar draft data. What is the typical relationship(s) between sonar and RA drafts over MYI?*
  Response:
  In order to avoid a lengthy introduction we decide to combine this request for an additional review of already existing validation results with your later comment in the 'Conclusion'. Rather than introducing validation results over MYI here we move them to the 'Conclusion'.

Changes:
No changes in the 'Introduction' but a short additional review of previous results and a comparison between MY and FYI results in the 'Conclusion'.

- *(3) A short section describing typical sea ice conditions and typical progress of sea ice season in the Laptev Sea would be good addition to the paper. How much there can be MYI in the Laptev Sea? Can there be large areas of grounded landfast ice for which the used freeboard to SIT conversion is not valid, and thus, could have an effect on your results?*
  -Response:
  Sea ice in the Laptev Sea is mostly FYI, however, fast ice is also present in the coastal regions. As for the influence of fast ice on the satellite SIT thickness: We consider the lack of leads and thus the lack of constraints for the instantaneous sea-surface height the primary issue for SIT retrieval in coastal fast ice regions. Therefore any valid freeboard point in the CCI SIT dataset is discarded if it is further away than 100 km from the next sea-surface height tie points. For the freeboard to thickness conversion we assume that the main sea ice mass is in isostatic compensation with the exception of the grounded anchor points. However, for the satellite SIT data we are comparing to the mooring data this shouldn't be a concern since the mooring locations are far enough away from the fast ice edge. Lena, Anabar and Khatanga stations are the farthest south but rather influenced by the polynyas than the fast ice.
  -Changes:
  We added a short paragraph to introduce the general conditions of the Laptev Sea sea ice cover to the 'Introduction' (**LINES 52-57**).

- *(4) Sections 2-4 should have short introductions about their content and focus.*
  -Response:
  In order to keep this paper as short as possible we tried to clearly distinguish between the different sections. We also made sure to specify our objectives in the 'Introduction' and used multiple subsections in the individual sections so that it is clear what we are presenting and when. We think that with your suggestions for new subsection titles this is even clearer now. We also know that separate introductions into the sections are a personal preference and we hope that you can condone that we prefer to leave these additional introductions out to not interrupt the flow of the text.
  -Changes:
  Title changes in the subsections of the 'Results' section (**LINES 215, 216, 253, 260**).

- *(5) The processing of ADCP data to the sea ice draft is based on reference*

(Belter et al., 2019b), but this is paper under review; so it is possible that it may not ever get published, or at least at time of possible publication of this paper this reference is not available. Is it possible to include this ADCP processing method (summary) as Appendix here? Are there any conference papers, web-pages, etc., you could also have as references?
-Response:
You are quite right, unfortunately, the corresponding method paper is still under review. We hope that the below mentioned changes and additions are sufficient for now and keep our fingers crossed that the method paper will be accepted soon.
-Changes:
For now we published the ADCP-derived sea ice draft time series for all the stations that have been used in this manuscript. We also added a short summary of the processing steps for the derivation of sea ice draft from upward-looking ADCPs in the Laptev Sea to these data sets (Belter et al.,2020a, **LINE 116**) and refer to it in the 'Data and methods' section of this manuscript. In response to Reviewer #3 we extended the subsection on this new method in the manuscript as well **LINES 112-116**.

- *(6) In Section 2 you could have a sub-Section which describes how different datasets are processed to match each other. Now this information is scattered in sub-Sections describing the datasets. Also include a Table which summarizes datasets: spatial and temporal resolutions, accuracies, etc.*
  -Response:
  Thank you for this helpful comment. We summarized how the different data sets are processed to be comparable to the VAL data in a subsection below the introduction of all the satellite data sets ('Data and methods' section). As for the suggested table, we do not think that a table is the right way to go here, although we could certainly summarize the temporal and spatial resolutions, accuracies and uncertainties are a little less clear because they vary on temporal but also spatial scales. Every CCI-2 grid point has its own uncertainty value. Orbit data for example is only available when the trajectory of the satellite coincides with the 25 km area around the mooring, this is something that can happen six or seven times in one month and only 3 times in others. Although we agree that a table supports comparability of the individual products some of them would not fit in or would have unclear values for the selected parameters (spatial, temporal resolution, accuracies, etc.). We would therefore leave the description of the data sets the way they are, clearly mentioned in the individual paragraphs of the different products. We hope you agree.
  -Changes:

Summary paragraph for satellite data processing following the introduction of the satellite data sets **LINES 161-171**).

- *(7) How many pixels there are in the gridded datasets over the Laptev Sea? This is relevant to Figure 2. The gridded (25 km) SIT data were selected from and an area of 25 km radius around a sonar mooring, thus at maximum four pixels were selected? You should give these kind details on the dataset matching Section.*
  -Response:
  We are not quite sure whether adding this information is really necessary. As you rightly mentioned in your comment when selecting gridded data (25 km grid) from within a radius of 25 km around the mooring the maximum number of values is four. This is the case for the gridded CCI-2 data sets ENVISAT and CS2 but also the CS2SMOS one. For the orbit data this number is significantly higher. We therefore would have to mention this detail about the number of data points for each of the presented satellite data sets separately, which is contradicting your previous comment ((6)) about combining the information about the processing into on paragraph rather than scattering it over the individual data set paragraphs. We agree with your previous comment that one summary is the better choice and with the clear information of what the data sets look like in terms of resolution the reader can see how many data points combine for the satellite-derived mean draft value. The same holds for the Fig. 2 data, we added the respective area from which the data was selected to Fig. 1 which helps understand the number of data points that go into the results presented in Fig. 2 the grid resolution was also added to the caption of Fig. 2. We hope you agree with this assessment and the changes that we made.
  -Changes:
  Addition to Fig. 2 caption.

- *(8) The uncertainty of the sea ice draft calculated from the CCI-2 CDR SIT data is estimated with (1)*
  $dunc = d/SIT \cdot SITunc$
  But d = SIT - freeboard, so dunc could be sqrt($SITunc^2 + fbunc^2$)? Well SIT and fb are correlated. How about if you estimate dunc with typical uncertainties of all parameters in the equation $d = SIT - fb$ e.g. snow thickness, would you end up a same figure as with (1)?
  -Response:
  You are right that the CCI-2 draft uncertainty should be calculated differently, however, Reviewer#3 rightly mentioned that we are not really using draft uncertainty anywhere in the paper except Fig. 7. We therefore removed that entire part about draft uncertainty and the uncertainty bars that were

visible in Fig. 7 before. Since uncertainty is an important part of an analysis such as this one we provide typical SIT uncertainty information for each of the discussed satellite products in the respective 'Data and methods' satellite data subsections.
-Changes:
Uncertainty equation and uncertainty bars in Fig. 7 have been removed. Information about uncertainties have been added to the respective 'Data and methods' satellite data subsections.

- *(9) Section 3.3.2 Merged CS2SMOS sea ice draft contains also a summary of all results; this should be in its own sub-Section.*
  -Response:
  We added a free line after the Section 3.3.2. to show that the summary below is the summary for the entire 'Results' chapter rather than the 3.3.2. Section.
  -Changes:
  Addition of extra line after **LINE 272**.

- *(10) Section 4.4, Taymyr 2013/2014 case, is under 'Discussion', but it includes data processing and analyses, these could be under 'Results', also the data processing methods would fit better to Section 2. Why this very important case study which reveals that the CDR SIT correspond modal sea ice draft, and not the mean draft, was not repeated with any ADCP dataset? This would be very important so that we would see consistency of this conclusion. This case study could be also described with more details in Introduction, now only one sentence.*
  -Response:
  Thank you for commenting on this case study, we discussed the question whether this should be part of the 'Results' or 'Discussion' section among the authors as well and found that this case study is not so much a new result at this point but an example that highlights and explains the results we already presented. Rather than leaving the reader with the comment: 'overestimation by the satellites for thicknesses below 0.7 m and underestimation for thicknesses above 1.5 m', we discuss how these results can be explained and what satellite draft values really show. This case study and more specifically the comparison between modal VAL and mean satellite drafts are the means to further explain and interpret the results shown in Section 3. The analysis of ICETrack data is done to determine possible reasons why satellite and VAL draft do not agree well, especially when VAL data suggests large daily mean draft values, like between Jan and Mar 2014 at the Taymyr mooring. We therefore would like to keep the case study subsection at the end of the 'Discussion' as it is right now. As for the repetition of this case study with ADCP data: Due to the low temporal resolution of the ADCP measurements

(mostly hourly and half-hourly values) the number of values per day is not large enough to compute the ADCP ice draft modes reliably. We therefore focused on the four draft time series that are based on high resolution ULS data (2013-2015) and provide reliable modal sea ice draft values. The Taymyr 2013/2014 results showing the better agreement with modal VAL data are confirmed by the other three time series that were analysed.
-Changes:
We added a respective sentence on why the comparison to modal values was only done with ULS data to the text (**LINE 364-366**), however, it is also mentioned in the caption of Tab. 4.

- *(11) Tables 1-3 show averages of statistical parameters from different mooring locations. I am not sure this is meaningful, what an average correlation coefficient really tells us here? I think better would be here to combine all datasets together and then calculate RMSD, mean difference and r.*
  -Response:
  We agree with you, that averages of the correlation coefficients do not tell us anything about how good the agreement is between individual VAL and satellite data, however, we are providing the values of RMSD, mean difference and correlation coefficient for each of the stations individually and add those averages over all stations only for additional information and comparison between the different satellite data sets. With the correlation coefficients available for the individual stations as well we feel that it is clearly displayed what these averages are and it is legitimate to show them here. In case of the mean difference and RMSD these average values actually tells us how different VAL data is from the respective satellite data, on average. While average correlation coefficient might only provide a measure to compare the different satellite eras, combining all data sets to calculate an overall correlation coefficient might not be meaningful either. There are a couple of time series that were recorded simultaneously which means that in order to provide an all data correlation coefficient we either need to leave out time series when more than one is available in some years or we need to combine data that was recorded at the same time which involves more averaging and altering of the data. However, calculating all-data-versions of the statistical parameters would certainly be the right way in cases where the entire time series was recorded at the same position.
  -Changes:
  We hope you agree that we clearly state that the averages of the correlation coefficients are nothing more than averages over all stations and do not provide information about how good the general agreement between VAL and the respective satellite data is. No additional changes have been made here.

Specific comments:

- *(1) line 21: 'While knowledge about SIC is widely available it provides limited insight into overall sea ice changes.'*
  You could include reference(s) to SIC records, like OSI SAF ones.
  26: 'Satellite remote sensing of SIC started in the 1970s with passive microwave sensors (Parkinson et al., 1999) and was further developed, updated and improved by multiple follow-on missions (Comiso and Nishio, 2008; Cavalieri and l. Parkinson, 2012) until today.'
  Some newer references would be nice, like:
  Lavergne et al., Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records, The Cryosphere, 13, 49-78, 2019
  -Response:
  Thank you for this suggestion. We added the recommended reference to provide some more recent publications.
  -Changes:
  Citation added (**LINE 28**).

- *(2) 36: 'the impact of snow radar backscatter'*
  the impact of snow on radar backscatter?
  -Response:
  Changed.
  -Changes:
  LINE 37

- *(3) Explain that both gridded and orbit track SIT CDRs are used in your study.*
  -Response:
  We added a sentence to the objectives paragraph of the 'Introduction' to indicate that we will also compare VAL data to higher temporal resolution satellite products. We do not mention these higher resolution products here since they are properly explained in the 'Data and methods' section right below.
  -Changes:
  LINES 76-77

- *(4) 64: 'Taymyr mooring', at this point a reader does not know what this Taymyr mooring is*
  -Response:
  We added a link to Fig. 1 (the map) so that the reader can find the mooring location here.
  -Changes:
  Reference to Fig. 1 (**LINE 78**).

- *(5) Can you explain why ADCPs where not moored at some locations in different years?*
  -Response:
  There are a number of reasons why some locations weren't visited more often. For one, most of these mooring locations are within the Russian EEZ, which requires a permission for the deployment and recovery of moorings from the Russian government. Secondly, were the expeditions based on multiple different research proposals and therefore varying research questions. While one location might have been interesting for one project it was not for one of the following projects. In the end, none of the available ADCPs were specifically deployed for the purpose of measuring sea ice draft therefore it was not a priority to generate a long-term time series at a specific location.
  -Changes:
  No changes required.

- *(6) Figure 1: you could mask land out; add color scale for the water depth; show boundaries of the Laptev Sea.*
  -Response:
  We kept the land, but added a proper color scale for bathymetry of land and ocean.
  -Changes:
  Colour scale added to Fig. 1.

- *(7) It would be interesting to see what is the typical variation of the sonar draft during a day, week and month. A figure about a time series of sea ice draft from some ADCP location would be nice.*
  -Response:
  We agree that the variation of sea ice draft is very interesting especially since it is not visible from either the daily mean VAL values nor the satellite data, however, since this study is focused on validating the ESA CCI-2 SIT CDR and other satellite SIT products we feel that this extra figure would be outside the scope of this study and simply to much information. An example of the variation on a monthly scale is given in Fig. 7 (the Taymyr case study) and we are happy to provide the high frequency (1 Hz) sea ice draft time series (also for the Taymyr case) below (Fig. 1).
  -Changes:
  No changes to the manuscript.

- *(8) How sonar draft data was processed to a monthly scale, just averaging all datapoints?*
  -Response:
  You are right, sonar draft was simply averaged over the respective month,

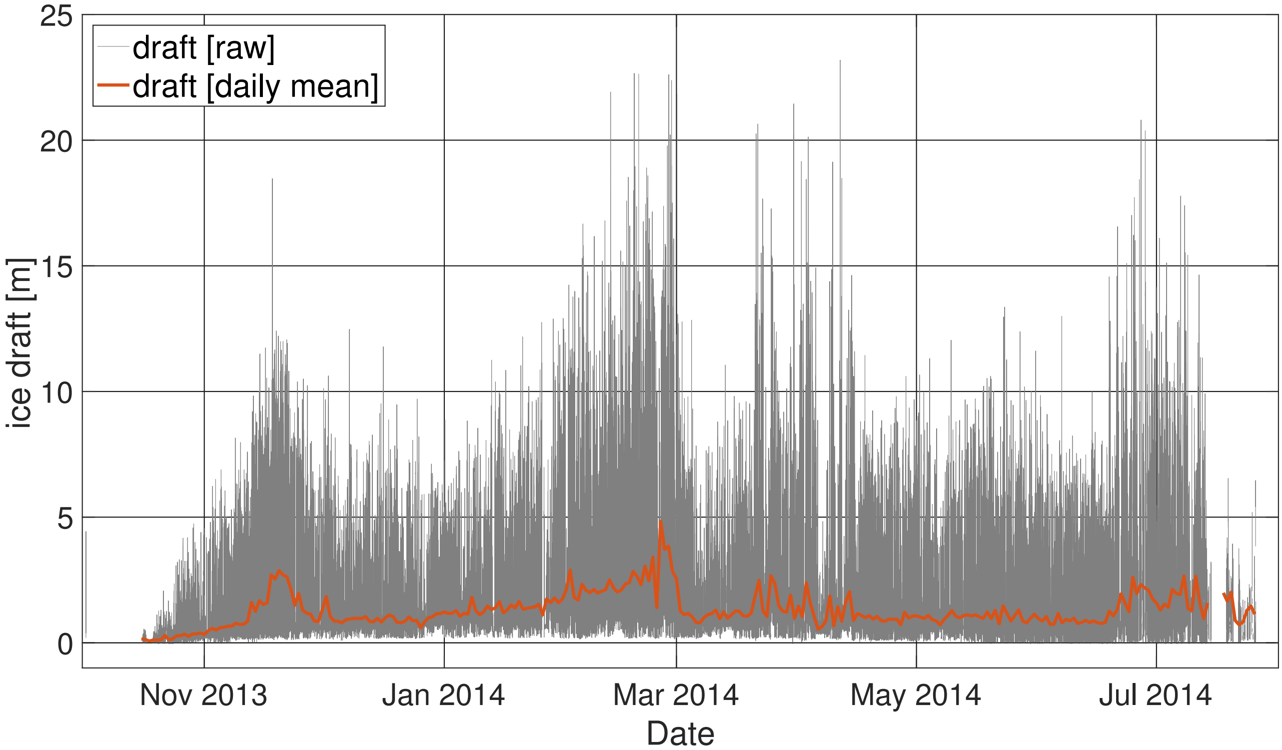

Figure 1: ULS sea ice draft at the Taymyr mooring (2013-2014). Grey line shows raw (1 Hz sampling frequency), orange line shows daily mean sea ice draft data.

however, we only saved a monthly mean value when data was available for at least 50% ('number of data points'-wise) of the month.
-Changes:
An additional paragraph was added to the 'Data and methods' section (**LINES 121-124**, also in response to Reviewer #3)

- *(9) Are there any peer-reviewed journal papers that could be put as reference to CCI-2 SIT CDR in Section 2.2.1? A figure about monthly gridded SIT over the Laptev Sea would be interesting see also what it typical SIT spatial variation over the Laptev Sea in this monthly product? How many pixels there are over the Laptev Sea?*
-Response:
Unfortunately, there are no peer-reviewed publications for the CCI-2 SIT CDRs. Only publications about radar altimetry freeboard are available and have been cited here (Paul et al., 2018). The citation for the data sets themselves are in the Section 2.2.1 text as well.
Arctic-wide sea ice thickness data is available (at least for the CS2 period) on the seaiceportal (https://data.meereisportal.de/gallery/).
-Changes:
No changes to the text required.

- *(10) 118: 'Although Paul et al. (2018) minimized the inter-mission sea ice freeboard biases for the basin average, ENVISAT freeboards in multi-year ice*

(MYI) regions are still thinner than CS2 freeboards, while ENVISAT provides thicker freeboards than CS2 in regions that are dominated by FYI.' Give some figures; how much thinner and thicker.
-Response:
We added a reference to the respective figure from the Paul et al., 2018 paper so that the reader can find the minimized differences between ENVISAT and CS2 freeboard. We also mention the average difference in the 'Data limitations' subsection (see Line 197) that has been moved from the 'Discussion' to the 'Data and methods' section.
-Changes:
Added reference to the figure in Paul et al., 2018 (**LINES 140**).

- *(11) 127: 'a weighted mean sea ice draft value.' What is this weighting?*
  -Response:
  Since multiple satellite data points fall into the 25 km radius around the moorings we did not just calculate an average over all of these values for the comparison to the VAL data but also considered the distances between the individual satellite data points to the mooring location. Closest satellite data points account for a larger fraction of the mean than data points that are further away. The fraction with which each data point is adding to the mean is dependent on its distance to the mooring.
  -Changes:
  Reviewer#3 had a very similar comment and we clarified the weighted mean in the text (**LINES 161-171**).

- *(12) Section 2.2.2: Give typical uncertainty in a single SIT orbit value. How many SIT points are typically averaged within 25 km radius and in a daily scale? What is the uncertainty of this average?*
  -Response:
  As mentioned before, due to the variability in overflights between the months and dependent on the exact path relative to and overlap with the 25 km area around the moorings the number of data points that are averaged for the comparison to VAL data is very different. With the two different approaches (satellite versus mooring-based point measurements) we have to accept the fact that we are not going to be able to measure the exact same thing. Satellite data uncertainties are high for the measurements as well as for the parameters that go into the processing. The selected approach to utilize all available data within the vicinity and calculate a weighted mean is a measure to achieve best possible comparability under the given circumstances. We looked at the numbers of values that go into the weighted mean of one orbit trajectory (over the 25 km area around the mooring) and found numbers between 30 and 60 data points. But as mentioned before these numbers

can be very different from case to case and we made sure to account for these differences by weighting whatever values go into the average depending on how far away they are from the exact mooring location. The same holds for the uncertainty of the averaged values, they depend on the uncertainty of the individual orbit data points and the number and the variance of the values that go into the average themselves. They are very different for each individual data point but due to the noise and variance likely higher than the typical uncertainties of the single SIT orbit values.
-Changes:
We added the typical uncertainty of one SIT orbit value for ENVISATorbit and CS2orbit to the corresponding section in 'Data and methods' (ENVISATorbit: approx. 1.5 m, CS2orbit: approx. 1.1 m, **LINE 146**).

- *(13) Comment correlations shown in Figure 2 in Section 3.1.*
  -Response:
  We are not sure what correlations you are referring to here. We are not showing any correlations in Fig. 2 and therefore do not mention any in the text.
  -Changes:
  No changes.

- *(14) Did you investigate SIT anomalies in different part of the Laptev Sea? I think AARI uses Eastern and Western Laptev Sea regions. Is it possible to compare the SIT anomaly trends to any other study/data source? E.g. based on AARI ice charts? Are the trends related to polynya activity (extent, ice production) in the Laptev Sea?*
  -Response:
  We decided to investigate SIT anomalies for the entire Laptev Sea (as defined in Fig.1) and not divide this into Eastern and Western Laptev Sea mainly due to the fact that our available sonar data originates from moorings that are scattered all over the Laptev Sea. It is certainly possible to compare the SIT anomaly trends to other data sources, however, the focus of this study was on the comparison to high resolution sonar measurements, also for the investigation into stability of the CCI-2 sea ice data. We presented the Laptev Sea SIT anomaly as the basis for our investigation and provide a conclusion on whether the changes are based on satellite performance and how we interpret satellite SIT data in this region. However, as we mention in the 'Conclusion' the presented satellite SIT anomaly needs to be further investigate to understand the observed trends and the reasons behind them. This is beyond the scope of this study and will be tackled in future studies.
  -Changes:
  No changes.

- *(15) Figure 3(b) is not commented/discussed in the text; e.g. symmetry/normality of the pdf?*
  -Response:
  Figure 3b is now described in the text.
  -Changes:
  Short description of Fig. 3b in **LINE 220**.
- *(16) Section 3.2 title could be 'Gridded monthly sea ice draft'.*
  Section 3.3 title 'Higher temporal resolution satellite products' is not good, what is this 'higher'?
  'Daily and weekly sea ice draft products'?
  -Response:
  Apparently, you are not the only one who thought that these titles should be different. Thank you for commenting on this, we followed suggestions from Reviewer #3 to slightly change the structure of this section and accordingly update the titles. We used your suggestion 'Gridded monthly sea ice draft' in the process. We hope you agree with the changes that we made.
  -Changes:
  Changes were made to the structuring of the 'Results' section, including new titles.
- *(17) In Figure 4 it is difficult to see grey crosses. Maybe these single data points can be removed and instead describe in the text how many RA draft data points were typically in each VAL draft interval.*
  -Response:
  Thank you for bringing this up. We think that it is really important to not just show the binned averages but also the data points that combine for those values. However, since the number of data points per bin is very variable it does not really make sense to mention these numbers in the text, we feel that this is better covered by showing the raw data in the figure. In order for the reader to really see those crosses we changed the color to black. We hope this improves readability of the figure.
  -Changes:
  Figure 4 colouring of the raw data (crosses) was changed from grey to black.
- *(18) 214: 'It also confirms the intermission biases between ENVISAT and CS2 that were published by Paul et al. (2018).' Please give out these biases here.*
  -Response:
  Following a comment from Reviewer #2 we moved the 'Data limitations' section from the 'Discussion' to 'Data and methods', there we specifiy the intermission bias for the Laptev Sea. We also added the reference to the respective figure in Paul et al., 2018 to the 'ESA CCI-2 monthly mean gridded

product' section ('Data and methods', your specific comment #10). Therefore, intermission biases have been mentioned and specified leading up to this comment and we think it is not necessary to mention them again here. We hope you agree.
-Changes:
Changes to the general structure were made to account for this comment. No changes were made to this specific sentence though.

- *(19) 227: 'Consequently the underestimation of sea ice draft with increasing thickness is largest for CS2SMOS because of the larger uncertainties of SMOS over thicker sea ice.' But for thicker ice CS2MOS SIT comes only from CS2 data? If so then SMOS uncertainty should have no effect here.*
-Response:
First of all, you are right the uncertainty of SMOS should not be the reason for the larger underestimation of VAL sea ice draft from CS2SMOS. CS2SMOS is based on an optimal interpolation, that means that both data products 'contribute' to the final value. This contribution is dependent on the uncertainty of the individual data points over the area in question. The underestimation observed for the CS2SMOS product is likely a result of local thin ice patches in the region that lead to a larger contribution of SMOS data to the final interpolated merged CS2SMOS SIT value.
-Changes:
We cut 'uncertainty' from the sentence in question and clarified that the underestimation of the CS2SMOS product is based on the influence of SMOS data on the final interpolated SIT product and not its uncertainty (**LINE 271-272**).

- *(20) Figure 6(b) is not discussed in the text.*
-Response:
We discuss Fig. 6 as a whole in the text and feel that this is enough here.
-Changes:
However, we changed the histogram plot in Fig. 6(b). Rather than showing the same PDF as in Fig. 3 we now distinguish between the distributions of the selected thickness ranges (same as in panel (a) of Fig. 6). We accordingly updated the figure caption here.

- *(21) What data is ICETrack using? SAR imagery? Describe in the text.*
-Response:
A short summary of the motion products that are used by ICETrack has been added to the Taymyr case study section.
-Changes:
LINES 341-346

- *(22) 346: 'That means that, for investigations into the sea ice cover in the Laptev Sea it is important to be aware that sea ice can persist some time after the presented satellites stop providing SIT data.'*
  How about before the winter in late summer? Phrasing here: satellites do not provide SIT data, but your data processing methods do, i.e. SIT estimation is not possible (at least currently) for summer/melting season.
  -Response:
  The sentence you are referring to has been changed accordingly.
  -Changes:
  LINES 370-372

- *(23) 350: 'The ESAs CCI-2 gridded SIT CDR covers a period from 2002 to 2017 and has been validated for multiple regions around the Polar regions of the Earth.'*
  A short summary about the results of these validation activities would be good here. Later in Conclusions you could summarize what new insight in the accuracy of the CCI-2 SIT CDR your study resulted.
  -Response:
  Although this study is mainly focused on the validation of satellite SIT data in the Laptev Sea we agree that a short comparison and summary is beneficial to the 'Conclusion' section of this study.
  -Changes:
  Additional sentences on previous efforts (**LINES 374-376**) and the comparison to our results (**LINES 391-392**) were added to the text.

- *(24) 378: 'Therefore, improvements in the processing of radar altimetry data are required for the estimation of surface roughness but also for the parametrizations of snow depth and densities of snow and ice.'*
  How surface roughness would be utilized in the freeboard tracking? How about different freeboard trackers for different ice types, like FYI and MYI?
  -Response:
  Surface roughness widens the leading edge of the radar waveform and this information is used in the Envisat retracker to define the retracking point (Paul et al., 2018). A similar algorithm for CryoSat-2 synthetic aperture waveforms is currently under development and that is what our statement of needed improvements referred to. As for the question about different retracker algorithms for different ice types, this information has to be known on a per-waveform basis. This is currently not the case.
  -Changes:
  No changes.

- *(25) 383: 'Furthermore would continuous long-term SIT measurements in the Laptev Sea provide much needed information on deformation processes.'*

Is this supposed to be an interrogative clause? Or 'Furthermore, continuous long-term SIT measurements in the Laptev Sea would provide.'?
-Response:
-Changes:
Sentence has been revised (**LINE 410-411**).

Additional changes from the authors

- *(1) Due to changes in the review process of the ADCP sea ice draft derivation method paper (previously Belter et al., 2019b, now Belter et al., 2020b, in review at the Journal of Atmospheric and Oceanic Technology) the estimated uncertainty values provided for the daily mean sea ice draft time series have been changed. See changes in* ***LINE 116-117 and LINE 179-181****.*
- *(2) Daily mean sea ice draft time series from the Laptev Sea ADCPs have been published and a reference was added to the 'Data availability' section (****LINE 415****).*

Finally, we would like to thank you again for your efforts to help us improve our manuscript.
Kind regards,
H. Jakob Belter

Point-by-point response to editor and reviewer concerns by
corresponding author: H. Jakob Belter
March 16, 2020

tc-2019-307:
Satellite-based sea ice thickness changes in the Laptev Sea from 2002 to 2017: Comparison to mooring observations
https://doi.org/10.5194/tc-2019-307:
Belter, H. Jakob, Thomas Krumpen, Stefan Hendricks, Jens A. Hoelemann, Markus A. Janout, Robert Ricker, Christian Haas

Dear anonymous Reviewer #2,

on behalf of all authors, I would like to thank you for this extremely helpful review. Below, we provide you with a point-by-point response to your comments. We hope that we were able to answer all your comments sufficiently. We would also like to refer you to the responses to the other reviewers for more improvements and changes to the manuscript.

General comments:

- *(1) The 'Data and method' section lacks important details. The data section only briefly introduces different data sets. It is not clear how many measurements were compared and how the mean Laptev Sea sea ice thickness from gridded data was calculated. Section 4.1. and 4.2 describing data limitations can be moved to the 'Data and methods' to provide the reader with valuable information before introducing the results.*
  -Response:
  We added more information, especially on the processing of ADCP sea ice draft to the respective subsection in the 'Data and methods' section. We also added an additional paragraph to the 'Sonar-based ice draft measurements' subsection to clarify how weekly and monthly VAL draft values have been calculated. Further changes have been made to the 'ESA CCI-2 orbit data' subsection to indicate how many data points are used for the comparison to VAL data (also in response to Reviewer #3). Also in response to the other reviewers we combined the averaging of the satellite SIT values into a single paragraph at the end of the 'Satellite data' subsection. The explanation of how ESA CCI-2 Laptev Sea SIT anomaly was calculated is provided in the first paragraph of the 'Results' section. Thanks to your great suggestion to move the 'Data limitations' subsection to the 'Data and methods' section we also provide additional information before presenting the results, which we agree provides the reader with more information to better follow the rest of this study. We hope you agree that the 'Data and methods' section is more comprehensive now.
  -Changes:
  Changes to the 'Sonar-based ice draft measurements' subsection (**LINES 121-124**). Additional changes to the 'ESA CCI-2 orbit data' subsection (**LINES 146-150**). New paragraph to combine satellite sea ice draft averaging at the end of 'Satellite data' subsection (**LINES 162-171**). 'Data limitations' subsection was moved to the end of 'Data and methods' section (**LINES 172-200**).

- *(2) The discussion can be elaborated. - The Anabar, Khatana and Lena stations a located in the area of polynya formation. Are polynya events taken into account in SAT and VAL data? Do the polynya events affect your comparison between SAT and VAL monthly mean? - One of the main finding shows that SAT data represents modal sea ice thickness rather than mean. What is a possible explanation? - The SAT-VAL difference depend on sea ice thickness. It there a seasonal change in this difference? I suggest that a scatter plot with seasonal cycle might be informative. - Section 4.4 introduces new data, method and results. Would it make more sense to restructure it* *and add a subsection to methods and results? Why other data from ADCP and ULS is not shown? Does it confirm you findings?*

-Response:

Since you are asking a whole bunch of questions here we will divide this response into subtopics:

Polynya influence:

First of all, you are right that Anabar, Khatanga and Lena stations are in the area of possible polynya formation, however, the impact of polynya events on the VAL data is rather limited. In cases of open water (in the polynya) both ADCP and ULS are able to identify the lack of ice. In cases where thin ice is present in the polynya the instruments recognise the ice as well. Daily, weekly and monthly averages of sea ice draft are calculated after open water was exclude from the draft time series and therefore do not impact the final daily, weekly or monthly values. However, daily, weekly and monthly averages of sea ice draft are only calculated in cases where 'enough' data points are available. If for example 20 out of 30 days in October show open water (or no data for that matter), no October mean value is calculated for the respective mooring. The threshold for calculating any of the averages is 50% of the maximum number of data points that are available for that period. If more than 50% of the data is missing or attributed as open water no average is calculated. As for the SAT data, open water is also not included into the SIT values. Thin ice is a little more complicated as it is an issue of ongoing research. The problem here is whether the satellite detects thin ice as ice or as water. Is it detected as water, it does not influence the final SIT value. Thin ice on the other hand is very much overestimated just because of the fact that the algorithm predefines the same amount of snow it would add to thicker ice. For the presented comparison these difficulties from the SAT data side should not be an issue since our VAL data defines whether data points are compared or not. If the sonar detects a long period of polynya induced open water, no daily, weekly or monthly value is calculated. Accordingly there is no VAL data point that could be compared to the SAT data.

Explanation for better agreement with modal sea ice draft:

This issue is also actively discussed right now. The first step to identify reasons for this result would be to figure out whether the initial freeboard measurements already show this tendency. However, the available VAL data is based on draft measurements and no additional information on freeboard is available for comparison here. Possible reasons for this bias are mentioned in this study and include: errors in the retracking, surface type classifications, snow depth, ice density. It is very likely that a combination of all these factors contribute to the overall bias. In order to quantify them future comparisons with ICESat-2 data are planned.

Seasonal changes:
Considering that SIT has a seasonal cycle and SAT-VAL difference is dependent on thickness the SAT-VAL difference will definitely have a seasonal cycle as well. Thick winter ice is underestimated by the satellites (most negative SAT-VAL difference of the respective time series), while thin ice is overestimated (most positive SAT-VAL difference of the respective time series). It would definitely be interesting to look at seasonal changes especially for long-term data sets from one location, however, our data is limited to one year time series from all over the Laptev Sea and this is not possible here. Furthermore do we feel that this is not relevant for the study as it is. The agreement is thickness dependent, independent of when thick or thin ice is observed. The aim, especially of the 'Stability' subsection is to investigate the performance of the satellite data. Answering questions like: Is the SAT-VAL difference the same when 1 m thick ice is measured in 2003 compared to when 1 m thick ice is measured in 2015?
Taymyr 2013/2014 case study:
We thoroughly discussed whether the case study should be part of 'Data and methods' and 'Results', however, we came to the conclusion that it is more of an addition that highlights the results presented before. The introduction of the new method (using ICETrack to calculate accumulated convergence) is an add on here in order to give a first explanation about what possible reasons for the underestimation of thicker ice by the satellites could be. Something similar was commented by Reviewer #1. The analysis on whether the agreement between modal or mean VAL draft is better with satellite draft data was done only for ULS-based draft time series. The temporal resolution of the ADCP-derived drafts was simply not appropriate to calculate meaningful modal ADCP draft values. The result that satellite sea ice drafts agree better with modal VAL drafts was confirmed for all four ULS data sets. We only chose the Taymyr example here since it was the only one of the four ULS data sets that showed a gradual increase in mean sea ice draft (Taymyr 2013/2014 Jan to March). Accordingly the difference between mean and modal VAL draft is larger and our finding could be visualized best.
-Changes:
Polynya influence:
We added the information that open water values were excluded prior to averaging of VAL draft data (**LINES 121-124**).
Taymyr 2013/2014 case study:
We added a sentence on why the comparison to modal values was only done with ULS data (**LINE 364-366**).

Specific comments:

- *(1) Line 160: 'The ESA CCI-2 SIT CDR shows an overall thinning of sea ice in the Laptev Sea between 2002 and 2017.' The sentence about is too strong. The error of the overall trend is as large as trend. Also the significance of the trend is quite low. The black line rather shows that there is no changes in sea ice thickness.*
  -Response:
  Thank you for pointing that out. You are right these first few sentences concerning the overall trend are too strong.
  -Changes:
  We toned down the sentences in question to make sure the reader realizes that although the trend line is slightly negative it is highly uncertain and should rather be interpreted as no significant trend over the period from 2002 to 2017 (**LINES 203**).

- *(2) Lines 161-162: How is the Laptev Sea defined? Please show the region used for SIT anomaly calculation in Figure 1.*
  -Response:
  -Changes:
  The region used to calculate ESA CCI-2 SIT anomaly was added to Fig. 1. Fig. 1 and Fig. 2 captions were updated.

- *(3) Line 210: 'ENVISATorbit data shows a higher average RMSD, stronger average underestimation of VAL sea ice draft and much lower average correlation with VAL sea ice drafts compared to the gridded ENVISAT data' Is there an explanation? Why does the orbit data which supposed to be closer to the VAL measurement shows worse statistical characteristics?*
  -Response:
  This is very likely related to the uncertainty of the individual orbit values and the larger number of data points that go into the weighted mean and the corresponding larger noise compared to the gridded data sets.
  -Changes:
  Also in response to a comment from Reviewer #1 the uncertainties of ENVISAT and CS2 orbit SIT values were added to the respective 'Data and methods' subsection (**LINE 146**).

- *(4) Lines 282-283: 'The seasonal biases between ENVISAT and CS2 need to be considered for the temporal development of the Laptev Sea SAT-VAL differences between the two periods'. Please elaborate. Are those biases considered in this study?*
  -Response:

What that means is that simultaneously measured SIT values from ENVISAT and CS2 are different from one another. This seasonal bias is strongly connected to the different ice thicknesses that can be observed over the course of a 'season' (which is basically late-autumn, winter and early-spring, since CCI-2 SIT data is only available from October through April). These differences are introduced in the 'Data and methods' section (2.2.1). This sentence here serves as a reminder that these inter-mission biases exist and that they are not constant throughout a single season. We consider these biases here, as we compare monthly mean values of sea ice draft from ENVISAT and CS2 rather than annual averages. The offsets between ENVISAT and CS2 to VAL data are shown in Fig. 3, 4 and 5. However they are not declared or displayed as seasonal but thickness dependent offsets. Biases between ENVISAT and CS2 can be specifically seen in Fig. 3 where ENVISAT-VAL and CS2-VAL differences are plotted for the Outer Shelf stations (2010/2011 and 2011/2012). As the focus of this study is on whether satellite products are stable over time we are concerned with thickness rather than seasonal values. We do not want to show whether ENVISAT and CS2 show the same agreement or offset every March but whether they show constant biases for, for example, 1 m thick ice independent of when 1 m thick ice occurs.
-Changes:
No changes.

- *(5) Lines 343-348: It is worth mentioning that ULS provide sea ice draft measurements after the onset of melt. However it is not a real finding that there is sea ice in the Laptev Sea in June-July. Please consider reformulating.*
  -Response:
  We apologize if it seemed like we presented this fact as a new finding. We were merely trying to remind the reader that the temporal limitations of the radar altimeter satellite products should not be mistaken for complete loss of sea ice after April.
  -Changes:
  We reformulated the above-mentioned paragraph (**LINES 367-372**).

- *(5) Line 359: 'The presented satellite products represent similar sea ice drafts differently.' I am not sure the meaning is clear. Do you mean identical sea ice draft or sea ice draft of similar thickness, e.g. within presented bins?*
  -Response:
  Thank you for bringing this up. We are referring to Fig. 5 where it is indicated that the same VAL sea ice draft values are represented very differently by the five investigated SAT data products.
  -Changes:
  We clarified that in the 'Results' section (**LINES 280-281**).

Technical comments:

- *(1) Page 1 line 24: sea ice system - sea ice state?*
  -Response:
  -Changes:
  Changed.

- *(2) Page 2 Line 43: a space after '(ULS)' is missing.*
  -Response:
  -Changes:
  Corrected.

- *(3) Line 132: a space after 'ENVISAT' is missing.*
  -Response:
  In this case we are using the abbreviation ENVISATorbit that was introduced in the line above.
  -Changes:
  No changes required

- *(4) Figure 2: It seems that colors of the legend in the upper left corner are mixed up. The negative trend should be the ENVISAT one.*
  -Response:
  -Changes:
  Corrected.

- *(5) Figure 7: The scale on the sea ice draft axis is missing.*
  -Response:
  We are not sure what you meant with the missing scale. The sea ice draft axis (left) shows sea ice draft values from -1 to 5 m and is labelled with the corresponding unit (m). It is the reference axis for mean, modal, CS2 and CS2SMOS sea ice draft, while the axis to the right corresponds to accumulated convergence from the NSIDC (both the axis and the acc. convergence graph are given in blue).
  -Changes:
  No changes.

Additional changes from the authors

- *(1) Due to changes in the review process of the ADCP sea ice draft derivation method paper (previously Belter et al., 2019b, now Belter et al., 2020b, in review at the Journal of Atmospheric and Oceanic Technology) the estimated uncertainty values provided for the daily mean sea ice draft time series have been changed. See changes in **LINE 116-117 and LINE 179-181**.*
- *(2) Daily mean sea ice draft time series from the Laptev Sea ADCPs have been published and a reference was added to the 'Data availability' section (**LINE 415**).*

Finally, we would like to thank you again for your comments and great suggestions.
We hope you agree that the changes made improve the manuscript.
Kind regards,
H. Jakob Belter

Point-by-point response to editor and reviewer concerns by
corresponding author: H. Jakob Belter
March 16, 2020

tc-2019-307:
Satellite-based sea ice thickness changes in the Laptev Sea from 2002 to 2017: Comparison to mooring observations

https://doi.org/10.5194/tc-2019-307:

Belter, H. Jakob, Thomas Krumpen, Stefan Hendricks, Jens A. Hoelemann, Markus A. Janout, Robert Ricker, Christian Haas

Dear anonymous Reviewer #3,

on behalf of all authors, I would like to thank you for your comments and suggestions to our manuscript. Please find our point-by-point response to your review below. We hope you agree with our changes and feel that your comments have been answered properly. We would also like to refer you to the responses to the other reviewers for more improvements and changes to the manuscript

Specific comments:

- *(1) Line 12: This phrase does not fully correspond to the results presented in the paper. Overestimation (underestimation) of sea ice draft for thin ice below 0.7 m (thick ice above 1.3 m) is indicated from comparison of the mean values, but not with respect to the modal draft.*
  -Response:
  You are right, this sentence was a little misleading we revised it accordingly.
  -Changes:
  LINES 12-14

- *(2) Line 40: Authors could also note that in (Kern et al., 2018) the airborne Operational Ice Bridge data were used for validation of the satellite product as well.*
  -Response:
  Thank you, we added Operation IceBridge to the list of observational data sets that have been used for the validation of the CCI-2 SIT products.
  -Changes:
  LINES 43-44

- *(3) Section 2.1: I guess that open water was excluded from the sonar-based measurements. If so, please, mention it in the text.*
  -Response:
  We added a paragraph on the VAL data averaging and a sentence clarifying that open water values were not included in the calculations of averages.
  -Changes:
  LINES 121-124

- *(4) Line 101: The phrase 'bottom track mode measurements of surface and error velocity' sounds not clear. Although paper by Belter et al. (2019b) will, I guess, describe details of the methodology, some clarifications on what is, e.g., 'error velocity' would be helpful.*
  -Response:
  You are quite right that this description is not sufficient. We therefore added a couple of explaining sentences and the reference to the ADCP sea ice draft data on the PANGAEA data archive where a short summary of the processing steps is provided.
  -Changes:
  Also in response to Reviewer #1, did we add further explanations to the respective section (**LINES 112-116**). Furthermore, did we publish a short summary of the processing steps with the ADCP sea ice draft data sets on PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.912927).

- *(5) Line 125: This way of estimating draft uncertainty is applicable if SIT uncertainty accounts for the sources of freeboard uncertainty. If so, please, mention it in the text. From the other side, since the authors do not use this draft uncertainty further in the analysis, it is not clear what it was estimated for.*
  -Response:
  Thank you for bringing this up. As mentioned in the response to Reviewer#1 the presented draft uncertainty is more complex than what we presented. Following your final comment regarding this issue we removed the draft uncertainty estimation completely and also removed the uncertainty bars from Fig. 7. Since uncertainty is still a very important parameter for the analysis we added information about satellite SIT uncertainty in the respective 'Data and methods sections'.
  -Changes:
  Uncertainty equation and uncertainty bars in Fig. 7 have been removed. Information about uncertainties have been added to the respective 'Data and methods' subsections.

- *(6) Line 127: It is not clear how authors calculate weighted mean values. Possibly this weighting account for the distance between grid center and mooring location? If so, please clarify it.*
  -Response:
  You are completely right, weighted means account for the distances of the selected satellite data points to the mooring location.
  -Changes:
  We clarified that in the text (**LINES 162-171**).

- *(7) Line 133: As a frequency of the orbit tracks that pass over the mooring sites the authors specify 'four overflights'. However Envisat and Cryosat-2 have different orbit inclinations and this frequency should be different for these missions.*
  -Response:
  You are right the number of overflights is different for ENVISAT and CS2. In fact, the number of overflights is occasionally below and some times above four for individual months. We were not accurate enough in the commented sentence. We clarified that the number of overflights is different for the two satellites and also changed 'approximately' to 'about'. On average the number of overflights is even more than four for both satellites. However, the point of the sentence was not to provide a fixed number of overflights per month (which does not exist since it varies) but to indicate that in any case orbit data provides more data points for the comparison to VAL data than the monthly mean gridded CCI-2 data. We hope you agree with the changes

we made to clarify the sentence.
-Changes:
Sentence was changed (**LINES 146-150**).

- *(8) Section 3: I suggest the authors to change structure of this section: to combine sections 3.2 and 3.3 in one section 3.2 with the title, for example, 'Validation of CCI-2 products', and with the subsections '3.2.1 Gridded CCI-2 sea ice draft' (currently section 3.2), '3.2.2 Orbit CCI-2 sea ice draft' (currently section 3.3.1), and '3.3.3 Intercomparison of CCI-2 and merged CS2SMOS drafts' (currently section 3.3.2). Then the accordingly revised text from the first paragraph of the current section 3.3 could be moved to the beginning of new section 3.2*
-Response:
Thank you for this suggestion. Reviewer #1 suggested changes to the titles of this section and we agree that your suggested structure improves the readability of this section. However, we were a little confused by your suggestion to move the first paragraph of the old 3.3 section to the beginning of the new 3.2 section. Since 3.2 is the overarching section for the comparison between all satellite and VAL data we moved the paragraph in question to the end of the new 3.2.1 section. We feel that it fits here since we finish the results part of the monthly mean gridded data and show the reader that we are moving on to the higher temporal resolution products here. We hope you agree with this change. However, calling the last section 'Intercomparison...' is a really good suggestion since the CS2SMOS/VAL comparison is rather short and the paragraph focusses on the results of all presented satellite products.
-Changes:
Changes were made to the structuring of the 'Results' section, including new titles.

- *(9) Line 228: I guess that this enhanced underestimation of thick ice by CS2SMOS data is observed because for some bins corresponding to thick ice the CS2SMOS product is the only available data (as I can see from Figure 5). It means that for these bins CS2SMOS product is generated only from the SMOS measurements. If so, this could be explained in the text.*
-Response:
This is an interesting observation but you have to remember that Fig. 5 shows satellite data from products with different temporal resolutions. Gridded ENVISAT/CS2 data (filled circles) is based on the initial orbit data (empty circles) and CS2SMOS is based on the gridded CS2 and SMOS data. 'Missing' thicker CS2 data could also be caused by missing VAL (when there is no VAL data point available there is no comparison), for example due to a long open water periods that prevented the generation of a monthly mean VAL sea

ice draft value (see new paragraph on open water influence and calculation of VAL daily, weekly and monthly averages, end of section 2.1). However, we agree that reason for this increased underestimation is the influence of SMOS data on the merged product and this could very well be caused by a total lack of CS2 data, resulting in SMOS data being the only product defining an individual data point. In response to a comment from Reviewer #1 we revised the sentence about the SMOS influence to show that the larger impact of SMOS leads to the increased underestimation. We hope that this answers your comment as well.
-Changes:
Additional paragraph at the end of section 2.1 (**LINES 121-124**) and changes to the sentence in the 'Results' section (**LINES 271-272**).

- *(10) Line 285: The reference (Paul et al., 2018) is not appropriate here. Paul et al., 2018 do not provide regional estimates of the differences between SIT derived from ENVISAT and CS2 data.*
  -Response:
  You are right, Paul et al., 2018 provide maps showing the differences between ENVISAT and CS2 freeboard. The value we are presenting here has been calculated from the available SIT data sets.
  -Changes:
  Reference to Paul et al., 2018 was removed from the sentence (**LINE 197**). Please note that the entire 'Data limitations' subsection was moved to the 'Data and methods' section (following a comment from Reviewer #2).

- *(11) Line 315: The indicated trends are small, that supports the conclusion that the gridded CCI-2 CDR is stable over considered period. However Fig.6 shows that these trends might be caused not only by the intermission differences. The trends for thickness ranges 0 to 1 m and 1 to 2 m looks negative even separately for Envisat and CS2 data as well as for combined dataset. For thickness range 2 to 3 m two overlapping points in 2011 shows that Envisat rather overestimate sea ice draft as compared to CS2 as well as for thinner ice.*
  -Response:
  First of all, we agree with your assessment that these trends are small and support the conclusion that the gridded CCI-2 CDR is stable over the considered time period (we mention that in the text as well). You are also right that these trends seem to be there even for each of the two satellite periods individually, however, since the number of data points available for each thickness range is already very small over the full period, looking at both satellite periods separately would decrease this number even further and make those trends even more uncertain. Furthermore, should we consider that these val-

ues are not recorded at the same location, as we see from differences in the agreement between SAT and VAL data in other Arctic regions. This could be simply caused by regional differences in the performance of the satellite products. The reason why we attribute those trends for the three thickness ranges to the inter-mission bias is that fact that it agrees rather well with what Paul et al., (2018) found. The inter-mission bias seems to be dependent on thickness. ENVISAT overestimates (underestimates) thin (thick) ice compared to CS2. For the first two thickness ranges we would expect ENVISAT-VAL differences to be larger compared to CS2-VAL differences. This is the case for the thickness ranges from 0 to 1 and 1 to 2 m (as also suggested by the trend lines). However, we agree that the statement made for the 2 to 3 m thickness range might be a little strong. We revised the sentence to indicate that the small number of data points (even smaller than for the other two thickness ranges) and the underestimation by the satellites that strongly increases within the 2 to 3 m thickness range make this trend rather uncertain and we therefore call it inconclusive. We hope you agree with this change.
-Changes:
Revised sentence (**LINES 327-332**).

- *(12) Line 380: It can be noted here that not only snow depth, but specifically snow properties that influence the location of the main scattering horizon are a major source for uncertainty in the freeboard retrieval process.*
  -Response:
  Thank you for this important addition. We added snow properties to the sentence in question.
  -Changes:
  LINE 407

Technical comments:

- *(1) Line 79: I suggest to replace 'approaches' by 'instruments', otherwise one may interpret it that both ADCP and ULS data are processed by two methods.*
  -Response:
  -Changes:
  Corrected.

- *(2) Line 101: Abbreviation 'BT' is not needed here as it is not used further in the text.*
  -Response:

-Changes:
Corrected.

- *(3) Figure 2: Colours of the first and second lines indicating trend values should be switched*
  -Response:
  -Changes:
  Corrected.

- *(4) Line 231: I suggest to reformulate this sentence: 'While individual stations deviate from this average the overall tendency indicates a dependency of the agreement between monthly mean gridded CCI-2 and VAL sea ice draft on sea ice thickness.'*
  -Response:
  Thank you for pointing this sentence out. It is a little confusing.
  -Changes:
  We changed the entire sentence (**LINE 275-278**).

- *(5) Line 332: In the 'newly formed FYI ice' the word 'ice' is not needed.*
  -Response:
  -Changes:
  Corrected.

- *(6) Line 383: The sentence 'Furthermore...' sounds not clear. Please, consider revising.*
  -Response:
  -Changes:
  Sentence has been revised (**LINE 410-411**).

- *(7) Table 4: In the captions to the Table it is noted that the statistical parameters 'were calculated for the four VAL data sets '. However this table presents the results only for two stations with ULS measurements: Taymyr and 1893.*
  -Response:
  We are looking at Taymyr and 1893 data from the 2013/2014 and 2014/2015 periods which results in a total of four different data sets.
  -Changes:
  We clarified this in the Tab. 4 caption.

Additional changes from the authors

- *(1) Due to changes in the review process of the ADCP sea ice draft derivation method paper (previously Belter et al., 2019b, now Belter et al., 2020b, in review at the Journal of Atmospheric and Oceanic Technology) the estimated uncertainty values provided for the daily mean sea ice draft time series have been changed. See changes in* ***LINE 116-117 and LINE 179-181****.*
- *(2) Daily mean sea ice draft time series from the Laptev Sea ADCPs have been published and a reference was added to the 'Data availability' section (****LINE 415****).*

In the end we want to thank you again. We really appreciate your input and hope you agree that the manuscript has improved.
Kind regards,
H. Jakob Belter