Sea Ice CCI+

ESA CCI+ CLIMATE CHANGE INITIATIVE

PHASE 1: NEW R&D ON CCI ECVS

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CCI+ Sea Ice ECV
SEA ICE THICKNESS
END 2 END UNCERTAINTY BUDGET
(E3UB)

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Contents

1 INTRODUCTION

1.1 Purpose

This document is the End 2 End Uncertainty Budget for sea ice thickness for the Sea Ice ECV within CCI+ PHASE 1 - NEW R&D ON CCI ECVs, which is being undertaken by a METNO-led consortium. Its purpose is to provide an overview for the user of error components that contribute to the total SIT uncertainty, their relevance and implementation in the SIT uncertainty computation.

1.2 Scope

The E3UB describes the main error contributions and their impact on the final sea-ice thickness product. It contains only a brief overview of the algorithm itself as this information is available in the Algorithm Theoretical Baseline Document [ATBD].

1.3 Document Status

This is the second version of the E3UB for Sea Ice Thickness within this project. It has been changed significantly after feedback from ESA to the first version.

1.4 Applicable Documents

Table 1 below lists the Applicable Documents referred to in this document.

Table 1: Applicable Documents

Document ID	Document referred to
[ATBD]	D2.1: Sea Ice Thickness Algorithm Theoretical Basis Document (ATBD)

1.5 Acronyms and Abbreviations

The table below lists the acronyms and abbreviations used in this volume.

Table 2: Acronyms and Abbreviations.

Acronym	Meaning
CCI	Climate Change Initiative
CDR	Climate Data Record
CS-2	ESA’s CryoSat-2

ENVISAT	ESA's Environmental Satellite
EO	Earth Observation
ERS	European Remote Sensing Satellite
ESA	European Space Agency
FYI	First Year Ice
GCOS	Global Climate Observing System
L1b, L2, L3C, ...	Satellite data processing Level (Level-1b, …)
MYI	Multi-Year Ice
RA	Radar Altimeter
SIT	Sea Ice Thickness
SAR	Synthetic Aperture Radar
SIRAL	Synthetic Aperture Radar (SAR) Interferometer Radar Altimeter

1.6 Executive Summary

The error budget of sea-ice thickness (SIT) depends on several components, some of them are not fully quantified and their error covariance is mostly unknown. The reason for this is the lack of observational capability for auxiliary information on which the SIT algorithm relies to a significant degree. In the retrieval algorithm these error contributions are based on either climatologies or values from scientific literature.

In general the error budget can thus be divided in two parts: a) errors arising from the limitation of the radar altimeter sensors; and b) uncertainties of the auxiliary data. In addition, a distinction needs to be made between the uncertainty of L2 data that is dominated by noise at the full resolution and gridded L3 data, which is uncertainty is dominated by auxiliary data uncertainty.

For the L2 orbit data and at 25 km scales and in the absence of auxiliary data uncertainty, the radar altimeter from Envisat is technically able to reach a SIT uncertainty of 0.51 m and CryoSat-2 of 0.36 m.

For the gridded L3 data, the dominating error contribution is sea ice density, followed by snow depth and density, based on the uncertainty ranges of the respective auxiliary variables.

2 HIGH-LEVEL DESCRIPTION OF THE UNCERTAINTY BUDGET

The section provides a general overview of all error contributions, their specific relevance and impact on sea-ice thickness as well as the respective representation in the uncertainty variables of the L2 and L3 data products. For the specific implementation of the algorithm, the reader is directed to the [ATBD] and only a brief overview is given here.

In general, quantifying the end-to-end uncertainty budget of sea-ice thickness (SIT) is a challenging task that is still an field of active research. The main challenges can be summarized as:

1. Sea-ice thickness is not a direct observation from the point of remote sensing, but a geophysical parameter that is derived from the actual observation (radar range) by an algorithm that is heavily dependent on auxiliary data and assumptions in the absence of suitable auxiliary data.
2. Due to the remoteness of the ice-covered oceans, reliable and extensive ground truth to verify the estimated uncertainty bounds, especially for intermediate parameters such as sea-ice freeboard.
3. The partly inadequacy of the observational capability with respect to certain auxiliary parameters, both from remote sensing and in-situ, results in unknown error covariances between the different components of the end-to-end uncertainty budget.

Due to the heavy reliance of the SIT retrieval on auxiliary data that is in part based on climatologies in the absence of actual observations, the contribution of auxiliary data to the total SIT error is as important, if not more, as the contribution associated with the radar altimeter data and its direct evaluation. The strategy of estimating sea-ice thickness uncertainty therefore depends on using observations or magnitudes from scientific literature where possible and parametrizations or assumptions when necessary. The result is a SIT uncertainty magnitude that does not meet the GCOS ECV requirements and is not expected to do so in the near future.

2.1 Algorithm Overview

The SIT retrieval algorithm uses L-2 orbit data and is implemented at the full sensor resolution. Practically, one thickness estimate is compute per radar waveform using the following processing steps:

1. Surface type classification using waveform properties
2. Estimation of surface elevation by a waveform retracking algorithm
3. Interpolating SSH tie points at lead waveforms to estimate along-track SSH
4. Estimation of radar freeboard by subtracting along-track SSH from surface elevation of ice waveforms
5. Converting radar freeboard to sea-ice freeboard by applying corrections of the slower EM wave propagation speed in the snow layer
6. Computation of sea-ice thickness from sea-ice freeboard with information of the snow load and density of the sea-ice layer

The uncertainty computation for the L2 geophysical variables is realised using error propagation through the steps listed above, assuming that error contributions are uncorrelated. The magnitude of the uncertainties can exceed the geophysical variables at L2 as a result of large uncertainties and sensor noise at individual waveform levels.

For the L3 gridded data the error computation using the error propagation, but the error contributions are separated in random and systematic contributions. An error contribution is classified as systematic, if the uncertainty of a parameter is highly correlated for all L2 data points within a grid cell and as random in the opposite case. Examples for systematic uncertainties are usually auxiliary data fields such as snow depth, which are almost identical for the grid cell area. Systematic uncertainties are not reduced by averaging and thus remain at the L2 magnitude while the contribution of random error components to the total error budget is reduced depending on the number of L2 points per grid cell.

The main limit for the error budget of gridded SIT are therefore the systematic error components that are usually associated with auxiliary information.

2.2 List of Error Contributions

This section lists all error contributions for the L2 and L3 uncertainties, their status of implementation in the estimated uncertainty variables, impact and estimated severity. The components include components of the algorithm and in addition factors like temporal and spatial data coverage, which are relevant for the uncertainty of gridded L3 SIT.

Table 3: List of all known error components contributing to the SIT error budget.

Component (Type)	State of Knowledge	Implementation in Uncertainty Budget	Data Level	Severity	Impact
Sensor Limitations (R)	Robust evaluation by space agencies	Platform-specific fixed range noise	L2	Critical	SNR <= 1 at full sensor resolution, averaging required
			L3	Minor	Insignificant for 25/50km grids
Surface Type Classification	Well established methods in scientific literature	no direct implementation, statistics included in quality flag	all levels	Minor	Observation in heterogeneous sea ice regions (ice edge) are underrepresented
Surface Roughness Statistics (S)	Robust knowledge of sea ice height distribution, full utilization requires advanced waveform interpretation	Included in fixed range noise	all levels	Major	Systematic and potentially regional SIT bias with unknown sign
Snow-Radar Interaction - Snow Backscatter (S)	Case studies in scientific literature, no direct observations of temporal/spatial pattern	Not implemented, snow assumed to be transparent in absence of parametrization	all levels	Major	SIT biased high
Snow-Radar Interaction - EM propagation speed (S)	Robust knowledge of radiation transfer theory but no direct observation of snow stratigraphy	Not implemented	all levels	Minor	Seasonally evolving SIT bias
Geophysical Range and Tide Corrections (R)	Known uncertainties; only relevant in areas with no SSH tie points (leads in sea ice)	Part of parametrized SSH uncertainty	all levels	Minor	Random impact in areas with sufficient coverage of leads.
Sea Surface Height Interpolation (R)	Mitigating full impact by use of mean sea surfaces, few regions with sparse lead observations	Parameterized uncertainty based in distance to closest SSH tiepoint	L2	Minor	Localized in areas with few leads, random impact on SIT
			L3	Minor	Impact reduced by regional averaging
Wave penetration in sea ice (S)	Frequent in marginal ice zones, especially southern hemisphere	Not implemented	all levels	Minor	SIT biased high or excluded due to failed surface type classification
Sea Ice Type (S)	Climate data records available	Indirect implementation in	all levels	Minor	Systematic SIT bias indirectly enacted by snow depth and sea ice density parametrization
Snow depth (S)	Evolving. Few remote	Monthly fixed	all levels	Critical	Systematic and

	sensed data sets with varying maturity and coverage. SIT CDR based in climatology.	uncertainty depending on ice type			significant bias with unknown direction. Potentially incorrect interannual variability.
Snow density (S)	Not directly observed but well established seasonal cycle	Monthly fixed uncertainty	all levels	Minor	Systematic bias with unknown direction.
Sea Ice Density (S)	Sparse observations mostly from	uncertainty values from literature depending on ice type	all levels	Critical	Systematic and significant bias with unknown direction
Sea Water Density (S)	Well known parameter with negligible variation in nature	Uncertainty set to negligible	all levels	Minor	Negligible
Orbit Coverage (R)	Data coverage exactly known	Not implemented, quality flag only	L3	Minor	potential phase bias in grid cells for monthly periods
Sea Ice Drift (R)	Observed by remote sensing	Not implemented	L3	Minor	Smearing uncertainty not quantified in monthly grids

3 ANALYSIS OF THE UNCERTAINTY BUDGET

In this section we evaluate the impact of individual error components on the SIT result. This is not done for all error componentes in Table 3, instead we focus on selected issues that illustrate the main challenges in the SIT retrieval algorithm. The challenges are grouped in two main categories: a) the capabilities of the radar altimeters and b) the uncertainty range of auxiliary data required for the estimation of sea-ice freeboard and the freeboard to thickness conversion.

3.1 Radar Altimeter Sensor Limitations

The limits of a radar altimeter sensor are defined by sensor noise, footprint size and waveform range resolution as these parameters control the fidelity of the surface type classification and range retrieval algorithm. The contribution to the SIT error budget by altimeter sensor limits is the theoretical limit of SIT uncertainty in the hypothetical case that auxiliary data or any assumptions would only contribute negligible to the total error budget.

To estimate the sensor limit contribution to the SIT error budget we conduct an analysis of SIT differences at orbit crossovers with close temporal proximity. Specifically, we use SIT orbit data within 12.5 km of all orbit cross-over points occurring in the same UTC calendar day. The location of these cross-over points are defined by the specific orbit and thus spatially limited and not representative for the entire sea-ice cover in one hemisphere. However, it is a reasonable assumption that sea-ice conditions within the scale of 25 km are unchanged between the two orbits that are often only a few hours apart. The SIT difference between the two orbits are thus mainly due to radar range noise and along-track interpolation errors caused by potentially inconsistent lead detections. Minor contributions to

SIT difference can be caused by a sampling bias of the orbit location and actual SIT change between the two orbits.

The SIT cross-over analysis is done for Envisat and CryoSat-2 L2 orbit data and aggregated for all months of the Arctic winter season (Figure 1). Both the mean of the SIT differences and the standard deviation show little variation between months and thus provide confidence that this approach provides information on the uncertainty caused by the sensor limits and not factors controlled by actual sea ice conditions.

Table 4 therefore provides aggregated SIT difference statistics of all crossovers for the Envisat and CryoSat-2 radar altimeters. As expected, the improved sensor resolution of the CryoSat-2 SAR altimeter results in lower thickness differences compared to Envisat's pulse-limited altimeter. The mean total difference, computed as the mean of absolute differences, is 15 cm lower for CryoSat-2 (36 cm) compared to Envisat (51 cm). Similarly, the standard deviation of thickness difference is also lower for CryoSat-2 (48 cm) compared to Envisat (78 cm). The mean of SIT differences, which are computed as first orbit minus last, is slightly negative and in the magnitude of the expected sea-ice growth rate for an Arctic winter season per day, though the respective values for Envisat and CryoSat-2 however cannot be compared directly as the orbit crossover points are located in different regions.

These results indicate a remarkable precision of radar altimeter to map SIT changes even at short time scales, given that a significant amount of data is available to stand out of the sensor noise. The main conclusion however is that at scales of 25 km the SIT precision is 36 cm for CryoSat-2 and 51 cm for Envisat. Overcoming this threshold requires improvements of radar altimeter sensor technology or averaging larger data sets. It also must be noted that this analysis is valid for L2 orbit data only. Gridded L3 SIT usually contains data from several orbits per grid cell and thus this uncertainty computed is reduced by averaging due to the random nature of this error component and the magnitude depends on the number of orbits that are included in the individual grid cells.

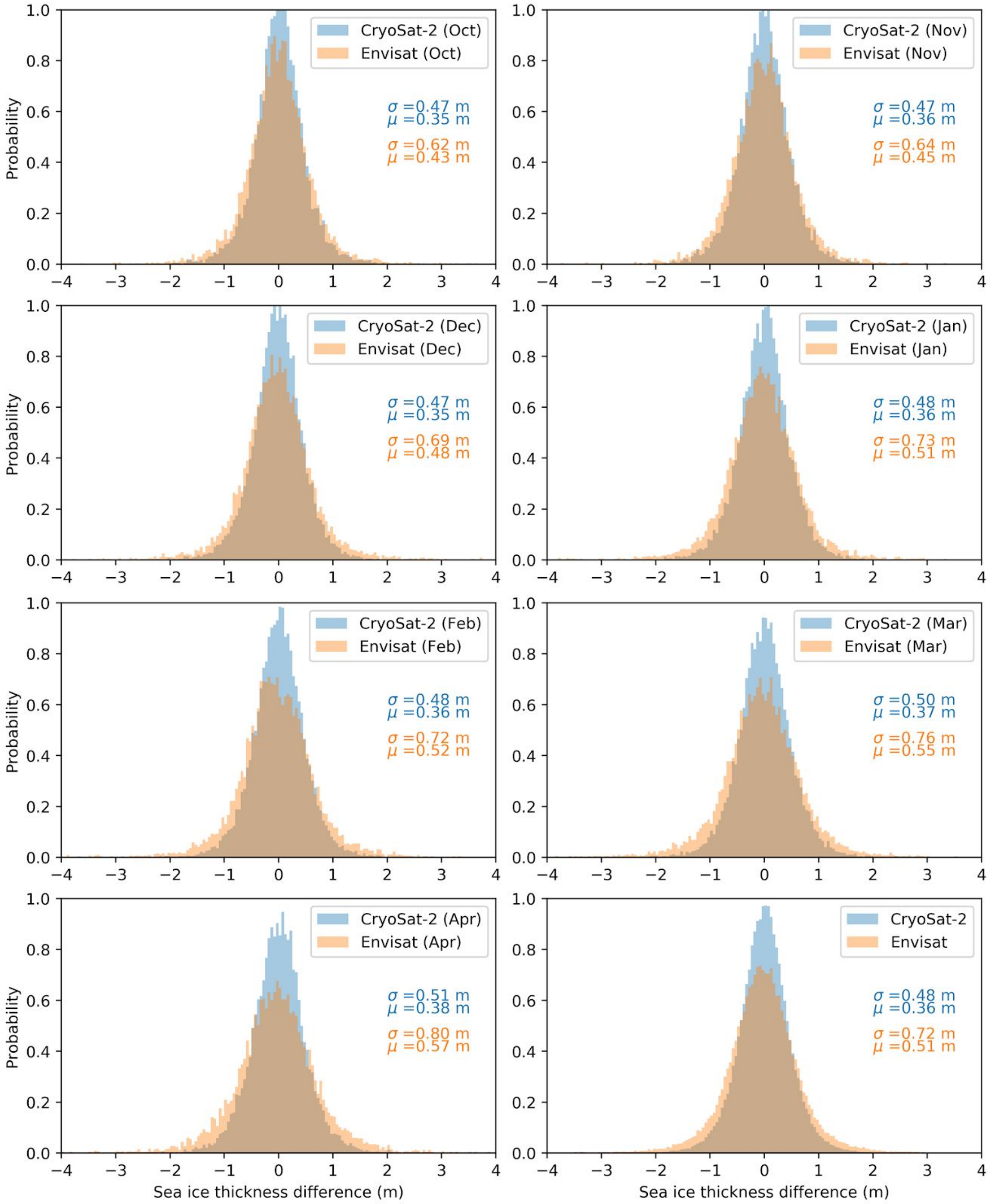


Figure 1: SIT differences statistics aggregated for all Arctic winter months within 12.5 km of across-over point in a UTC calendar day from Envisat and CryoSat-2 L2 trajectory data

Table 4: Aggregated statistics of SIT difference (first orbit minus second) within 12.5 km of across-over point in a UTC calendar day from Envisat and CryoSat-2 L2 trajectory data.

Platform	**Standard Deviation (m)**	**Mean Difference (m)**	**Mean Absolute Difference (m)**
Envisat	0.72	-0.03	0.51
CryoSat-2	0.48	< -0.01	0.36

3.2 Auxiliary Data Uncertainty

Auxiliary information such as snow depth, density and sea ice density in the SIT retrieval algorithms are not based on direct observations that match the coverage of the radar altimeter data. Instead, parametrization based on climatological values, such as for snow depth and density, or fixed literature values in the case of sea-ice density are used. To approximate the interannual variability and changing ice cover, these values are modified by ice type. However, the lack of knowledge of the actual spatial and temporal variability of these parameters leads to a large uncertainty which significantly contributes to the SIT uncertainty.

To assess this uncertainty contribution of the auxiliary data components separately, we conduct an impact analysis in which we recompute SIT with changed values of the individual auxiliary data and compare this to the actual SIT field in the product. We modify each auxiliary variable twice, once by subtracting the uncertainty range to the variable and once by adding it. The difference to the SIT field in the product and the range between the two uncertainty bounds are then used to assess how SIT depends on the auxiliary information uncertainty, both in direction as well as magnitude.

The impact analysis is in principle independent from the chosen platform, however we use one winter in the CryoSat-2 period from October 2018 to April 2019 as scenario. The impact analysis is implemented using L3 gridded data in the northern hemisphere, but the results can in principle be transferred to the southern hemisphere as well.

3.2.1 Snow Depth

Snow depth on sea ice has a two-fold impact in the SIT algorithm: 1) The geometric correction for slower wave propagation speed of EM waves in snow in the radar freeboard to sea-ice freeboard conversion and 2) as snow mass in the sea-ice freeboard to thickness conversion. Its role in the uncertainty budget has been evaluated early on, e.g. Giles et al., 2007, and the common understanding is that the lacking knowledge of snow on sea ice is one of the most fundamental challenges for the observation of sea-ice thickness with satellite altimeters.

SIT is underestimated when snow depth is underestimated and vice versa. With the current implementation of the snow climatology in the SIT CDR the impact is higher on MYI than FYI due to the higher uncertainties in the thicker snow regime on older sea ice. As previously known the impact of snow uncertainty is significant for the average hemisphere-wide change of SIT of 0.74 m (0.85 m) in October (April) if snow depth within the uncertainty range (Figure 2). The comparable small regional variation of the SIT bias of 0.14 m (0.22 m) in October (April) is a consequence of the smooth snow climatology.

3.2.2 Snow Density

Similarly to snow depth, the density of the snow layer also affects both freeboard via the geometric range correction and thickness via its role on snow mass in the hydrostatic equilibrium. The uncertainty range of snow density is lower though and comparisons to the Warren 99 climatology showed that bias and variability in field data are “insufficient to drive strong uncertainty in radar derived freeboard” (King et al., 2020).

As a consequence the impact on SIT is much lower than snow depth and follows the same direction, such as that overestimating snow density results in overestimating SIT and vice versa. The impact of snow density uncertainty in SIT is roughly a third of the impact of snow depth uncertainty (Figure 3) with a range SIT changes of 0.23 m (0.29 m) in October (April) within the full uncertainty range.

3.2.3 Sea Ice Density

The density of the sea ice layer in the CCI SIT algorithm depends on fixed values for FYI and MYI based on field observations that also provide an uncertainty range (Alexandrov et al., 2010). The field observations often only comprise data from level ice and Alexandrov et al., 2010 caution that these values might not be valid for deformed FYI. Observations of bulk sea-ice density over areas comparable to a radar altimeter footprint by non-sampling methods are difficult to obtain, as they require colocated observations of thickness/draft, freeboard and snow mass. The uncertainty range used in the SIT uncertainty budget might therefore even underestimate the actual variability.

Nevertheless, modifying sea-ice density by its uncertainty in the SIT computation has a higher impact than either snow depth or snow density (Figure 4). This is in part because the impact also scales with the observed freeboard and thus increases significantly with the progression of the sea ice growth season. The impact of the full uncertainty range progresses from 0.59 m in October to 1.30 m in April. The highest values are located in the FYI region, caused by the higher uncertainty range for FYI.

3.3 Unquantified Error Components

Several known error components are not included in the computation of SIT uncertainty in the current CDR.

3.3.1 Surface Roughness

Empirical retracker thresholds used in the SIT CDR are susceptible to biases for different surface roughness conditions. Though we assume a relatively high uncertainty for each range value, quantifying this error component and its regional variability requires a fundamental change to physical retrackers that are currently not planned for v3.0 of the SIT CDR.

3.3.2 Snow-Radar Interaction

Numerous studies have demonstrated a range bias for Ku-Band radar when volume/interface backscatter or extinction in the snow layer becomes relevant under certain physical conditions. Similar to surface roughness this effect cannot be quantified in the SIT CDR in the absence of significantly improved knowledge of the internal conditions of snow on sea ice on a global scale.

3.3.3 Temporal Coverage and Smearing Uncertainty

L3 SIT data in the monthly grids does not have the same temporal coverage for each grid cell due to the orbit coverage. This is likely to lead to a phase bias between individual grid cells, especially in periods of rapid ice growth. This issue is superpositioned with the fact that ice is advected by distances far larger than the grid resolution. While the temporal coverage for each grid cell is fully known, sea-ice drift is currently not included in the gridding process.

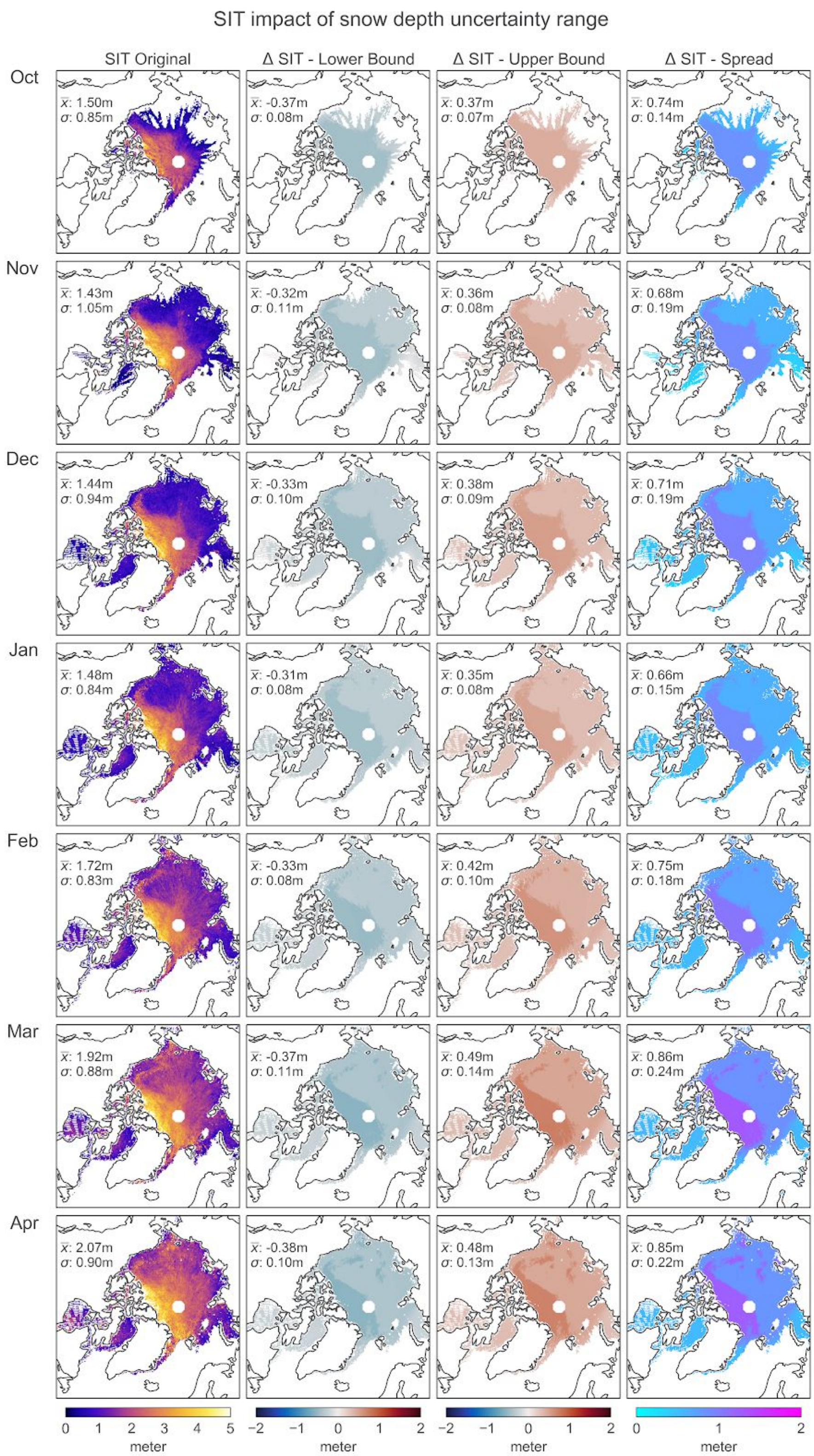
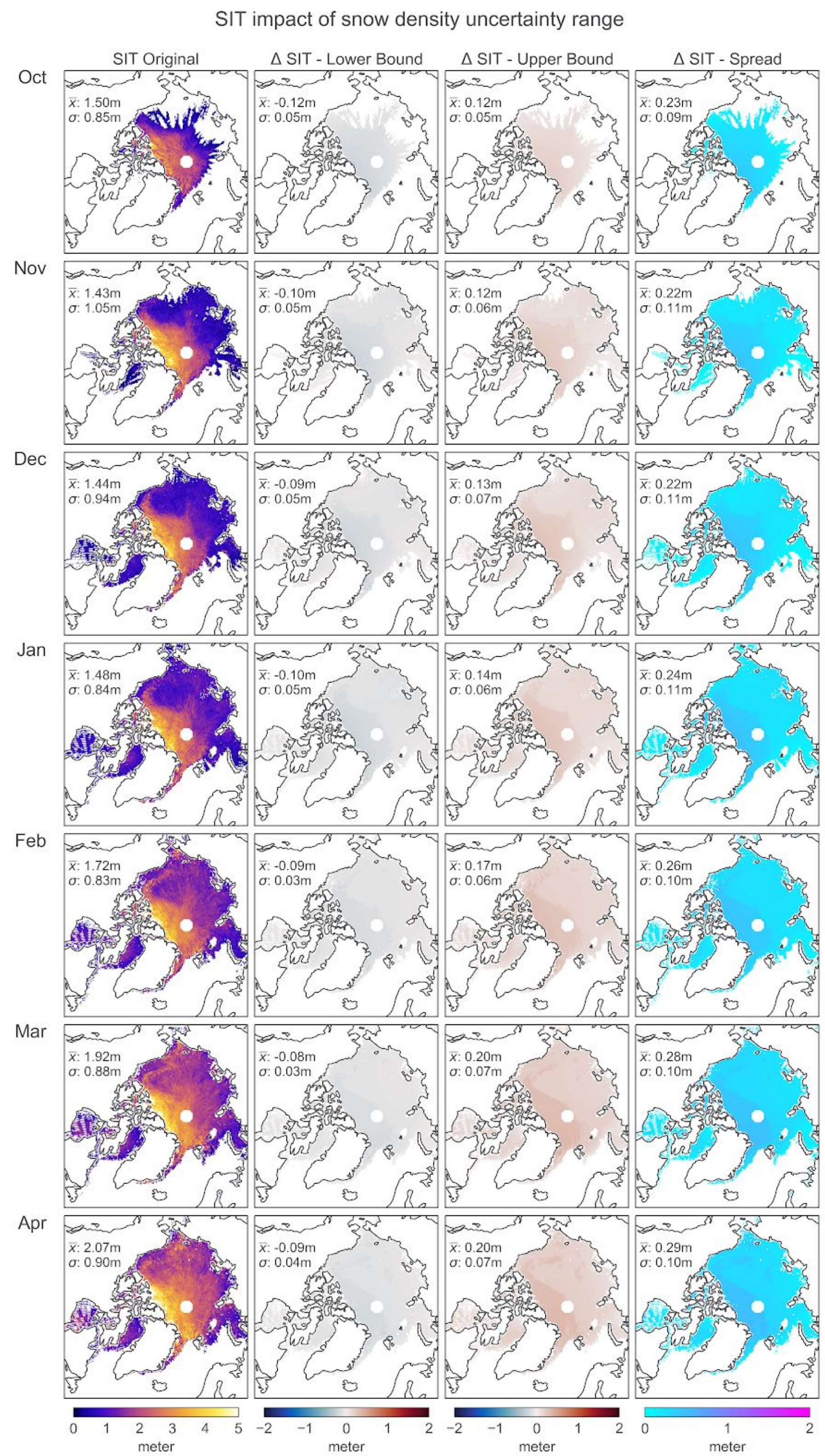


Figure 2: SIT Impact analysis of auxiliary uncertainty bounds for an Arctic Winter Season, in this case October 2018 through April 2019. First column: Original SIT fields; Second column: SIT difference if snow depth would be reduced by uncertainty; Third column: SIT difference if snow depth would be increased by uncertainty; Fourth column: Spread of SIT solutions with between snow depth uncertainty bounds.



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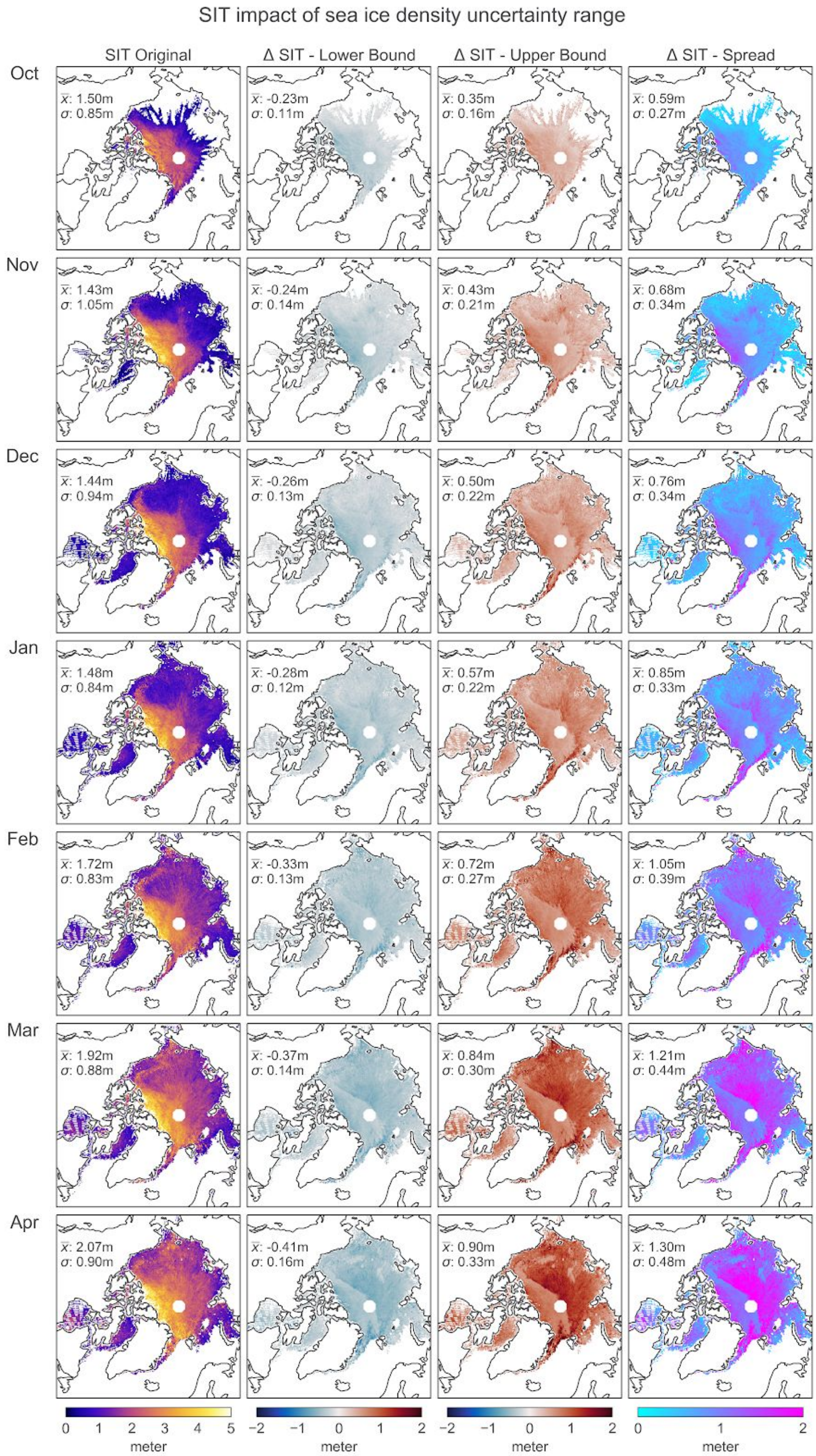

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4 SUMMARY AND CONCLUSION

The breakdown of the full error budget of the SIT algorithm is complicated by an observational gap for the required auxiliary information and as a result, the unknown error covariances. Even with improvements in remote sensing data analysis, most of the required parameters such as snow depth and density will not be available for the past data of the SIT CDR.

Breakthroughs for improving SIT accuracy can therefore be made with numerical modelling of snow on sea ice. In addition, recent developments of forward models for altimeter waveforms over sea ice surface hold the prospect to reduce the uncertainty caused by varying surface roughness conditions. Efforts for improved estimation of sea-ice density larger scales are also indicated.

The current SIT CDR uncertainty computation uses parametrizations and a modified approach for L2 and L3 data to take these limitations into account. Though improvements in auxiliary information can be expected, which will bring improved and reduced uncertainties, it is highly unlikely that the GCOS uncertainty requirement will be met in the near future.

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