## Sea ice observing systems for Arctic science climate monitoring

by

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### Abstract

Sea ice is an essential climate component which is very sensitive to climate change. In the Arctic, sea ice area and thickness have been reduced during the last three decades affecting the heat flux causing enhanced warming in this region. The reduction of the Arctic sea ice cover in the last decades can only be documented by regular monitoring from satellite passive microwave data. Sea ice observation from satellites has been carried out for more than four decades and is one of the most important applications of satellite data in climate change studies. Regular monitoring of sea ice with passive microwave data has been done continuously since 1979 and these data therefore represent one of the longest satellite data records on climate variables. Several sensors and retrieval methods have been developed and successfully utilized to measure various sea ice variables such as concentration, thickness, albedo, snow cover, surface temperature, duration of melt season, leads/polynyas and ridges. Remote sensing can contribute to retrieve quantitative measurements of most of these parameters, but data from other observing systems are needed to assess the accuracy of the satellite observations. In particular for ice thickness observation, it is necessary to collect data from other platforms and instruments such as airborne surveys, in situ measurements and upward-looking sonars from submarine cruises, anchored moorings and autonomous underwater vehicles. An Arctic Observing System need to include a suite of platforms and sensors to observe the key sea ice variables in order to fill gaps and validate retrievals from satellite data.

## 1.1 Introduction

Sea ice observation from satellites has been carried out for more than four decades and is one of the most important applications of EO data in climate change studies. Several sensors and retrieval methods have been developed and successfully utilized to measure sea ice area, concentration and drift [e.g. *Breivik et al., 2009*]. There are also other sea ice parameters of importance for climate research such as thickness, albedo, snow cover, surface temperature, duration of melt season, leads/polynyas and ridges. [e.g. GCOS, 2010; IGOS, 2007].

The reduction of the Arctic sea ice during the last decades is one of the most significant global warming signals. This reduction could not have been quantified without a time series of homogeneous satellite data that has been systematically collected. Satellite passive microwave data show a decrease of approximately 4.3% per decade for annual mean ice extent and approximately 9.1% per decade for the summer ice [e.g. *Johannessen*, 2008, *Stroeve et al.*, 2007, 2012]. Time series of monthly mean ice extent for March and September is shown in Fig. 1 (a). Ice thickness reduction has been documented by submarine sonar measurements [*e.g. Rothrock et al.*, 2008, *Kwok and Rothrock 2009, Laxon et al.*, 2013]. Several studies suggest that the Arctic Ocean may

become ice-free in summer within 3 to 4 decades [e.g. *Wang and Overland*, 2009], which is much sooner than predicted by the Intergovernmental Panel on Climate Change (IPCC) assessment [*IPCC* 2007]. [*Shepherd et al.*, 2010] showed that decreasing Arctic sea ice area and thickness led to an ice volume reduction by 851±110 km<sup>3</sup>/yr from 1994 to 2007 where the thickness was found to be responsible for 65% of volume loss and area for 35% emphasizing the important role of ice thickness estimates. The disappearance, or strong reduction, of the summer ice will have dramatic impact on the climate, and will also influence Arctic environment, ecosystem and fisheries and human activities such as ship traffic and offshore exploration [e.g. *Johannessen et al.*, 2007; *AMSA*, 2009].

Today operational sea ice monitoring and analysis is fully dependent on use of satellite data. However, new and improved satellite systems, such as multi-polarisation SAR, radar and laser altimeters, require further studies to develop more advanced sea ice remote sensing methods. In climate change studies based on satellite data, it is a major challenge to construct homogeneous time series from a series of consecutive satellite sensors needed for detection of changes over several decades. At the same time there is an evolution in sensors and observation technology, which makes it possible observe new parameters for future monitoring of the Arctic climate system.

# **1.2** Sea ice concentration

The use of thermal microwave data for mapping the sea ice extent and area is perhaps the most successful application of satellite remote sensing for sea ice monitoring. The key elements in climate data series processing is consistency and the quantification of the uncertainties. Both of these elements are achievable for both hemispheres using the microwave radiometer data record from a series of satellites (ESMR, SMMR, SSM/I, AMSR and SSMIS) operating for more than three decades. The fraction of sea ice can be estimated from the microwave radiometer brightness temperatures as a linear combination of the emission from ice and open water. At 18, 36 and near 90 GHz there is a large contrast between the typical signatures of ice and open water. Typical signatures of 100% ice or open water are called tie-points. The tie-points are used in sea ice concentration algorithms as empirical constants for estimating the fraction of sea ice cover called the sea ice concentration.

For climate applications, GCOS requires daily sea-ice concentration products at an accuracy of 5% [e.g. GCOS, 2011]. A number of algorithms have been developed to compute ice concentration from passive microwave data, such as the NORSX algorithm [Svendsen et al., 1983, 1987], the NASA Team [*Cavalieri et al., 1984*], Bootstrap [*Comiso, 1986*] and many others. The accuracy of the algorithms are reported to be in the range of 5 - 10 % in winter [*Steffen and Schweiger, 1991; Emery et al., 1994; Belchansky and Douglas, 2002*] and higher in the summer. The discrepancy between the different algorithms, especially in the summer period, can be as much as 1 mill km2, which is in the order of 25 % of the total ice area in September, when the sea ice extent in the Arctic is at a minimum. This discrepancy makes it difficult to estimate the total summer ice extent with the accuracy required for climate research. The ESA Climate Change Initiative project for sea ice (SICCI project) is presently conducting a systematic comparison of the various algorithms in order to provide consistent and validated time series of ice concentration and ice thickness with known error bars (http://www.esa-cci.org/). The SICCI project is focused on the critical issues related construction of consistent time series of ice concentration data.

(1) Intersensor calibration and choice of tie-points to merge data from a series of satellite sensors. Tie-points are typical signatures of 100% ice and open water that are used in the ice concentration algorithms as a reference. The tie-points are derived by selecting brightness temperatures from regions of known open water and 100% ice. Usually these tie-points are static in time and space,

but they can be adjusted to follow the seasonally changing signatures of ice and open water as it is currently done in the operational OSI SAF ice concentration processing. Static tie-points are prone to be affected by sensor drift, inter sensor calibration differences and climatic trends in surface and atmospheric emission. The data must therefore be carefully calibrated before computing the ice concentrations. The SICCI project will investigate the use dynamic tie-points, a method that minimizes these unwanted effects, with or without prior calibration of the passive microwave data. Such dynamic tiepoints will substantially facilitate the combination of data from different sensors.

(2) Validation and error bars. The complete transfer of uncertainty will be investigated from L1b swath-based brightness temperatures to daily gridded composite. The sensitivity from various sea ice concentration algorithms will be evaluated, with respect to various factors such as atmospheric noise, surface emissivity uncertainty, noise in the observed brightness temperatures, etc. A research effort will be conducted on the gridding and projection algorithms, and will result in a quantitative transfer of uncertainty associated to this step, depending on the FoV size and shape of the instruments. Error bars will be assessed both theoretically and empirically as their consistency is checked against results from an extensive validation exercise. A comparison of ice concentration between 11 algorithms is shown in Fig. 1 b.



Figure 1. (a) Time series of monthly ice extent in the Arctic fro 1979 to 2012. (b) Seasonal variability of Arctic sea ice area during 2010 from 11 different algorithms.

(3) Discrepancies at high ice concentrations (>90%). During winter, in the consolidated ice, well within the ice edge, the ice concentration is very near 100% [Andersen et al., 2007]. This has been established using high resolution SAR data, ship observations and by comparing the estimates from different ice concentration algorithms. The fluxes between the ocean/ice and atmosphere are sensitive to small variations in these ranges of sea ice concentration and thereby these discrepancies are of large importance for coupled climate models. The apparent fluctuations in the derived ice concentration in the near 100% ice regime are primarily attributed to snow/ice surface emissivity variability around the tie-point signature and only secondarily to actual ice concentration fluctuations [Kwok, 2002]. In the marginal ice zone the atmospheric extinction may be significant. The fluctuations due to atmospheric and surface emission are systematic. In fact, different algorithms with different sensitivity to atmospheric extinction and surface emission compute quite

different trends in sea ice area on seasonal and decadal time scales [Andersen et al., 2007]. This means that not only does the sea ice area have a climatic trend, but the atmospheric and surface constituents affecting the microwave emission are also changing. For example, different wind patterns, water vapor and liquid water concentrations in the atmosphere, snow depth, fraction of perennial ice etc.

(4) Discrepancies in summer conditions: melt ponds, wet snow and ice. Reflectances from MODIS channels 1, 3 and 4 can be used to derive the melt-pond cover fraction and a summer-time ice concentration estimate. The melt pond cover fraction is determined using a classification which follows a mixed-pixel approach. It is assumed that the reflectance measured over each MODIS 500 m grid cell comprises contributions from three surface types: melt ponds, open water, sea ice/snow [Roesel et al., 2011]. By using known reflectance values [e.g. Tschudi et al., 2008] a neural network is built, trained, and applied [Roesel et al., 2011]. The resulting surface type class distributions are saved and made available as 500 m, 12.5 km, and 25 km resolution product; melt pond cover fractions are adjusted to the fraction of the sea ice cover per pixel.

(5) Discrepancies between algorithms in the MIZ. The Marginal Ice Zone is the area where the largest discrepancies are observed between the various algorithms. First, the MIZ is the only area where the capability of the algorithm to explore the full-range of ice concentrations fro 0 to 100 %is tested. For an algorithm to perform well in the MIZ, its channel combination must be sensitive to small variations of the surface emissivity, and thus be more than just an ice/no-ice detection algorithm. Second, the MIZ is a region under higher oceanic influence than the ice-pack. In the MIZ, ocean-atmosphere weather effects (e.g. high Cloud Liquid Water and surface winds) are responsible for enhanced noise in the sea ice concentration field. Many of the sea ice concentration algorithms cited above thus embed so called weather filters that limit the occurrence of false-ice detection, but also limit the range of SIC values (and hence the width of the MIZ). Particularly in the Southern Ocean where ocean swell and wind waves are commonly influencing the sea ice in the MIZ causing it to be wet most of the time, ice concentration estimates based solely on passive microwave data may underestimate the actual meridional ice extent by up to a few hundred kilometres [Ozsoy-Cicek et al., 2011a; 2009; Worby et al., 2004]. Andersen et al. [2006] show that atmospheric correction of the brightness temperatures via a Radiative Transfer Model formulation avoids most of the weather contamination yet preserves the full dynamical range of SIC values in the MIZ; see also Kern [2004]. Finally, because rapid variations of sea ice cover take place in both time and space in the MIZ, it is of prime importance to pay close attention to gridding and temporal aggregation of swath data into daily maps of sea ice extent. Indeed, the size of the SSM/I foot-print (15-65 km radius) is comparable to the width of the MIZ and careless gridding of these foot-prints into grid cells might blur the position and sharpness of the ice edge. Challenges specific to the MIZ will be tackled in this project by 1) including MIZ situations in the test/validation data set (e.g. from analyzed ice-charts and from synthetic data), 2) including weather-influenced situations in the test/validation data set, 3) investigating the sensitivity of weather filters to emissivity variations, and 4) thoroughly investigating the effect of various gridding algorithms in the MIZ.

During winter in the Arctic Ocean the ice concentration is very near 100%. This means that the radiometer ice concentration algorithms can be validated over open water and over 100% ice in winter. For the summer season and at intermediate concentrations direct validation is difficult. The fact that sea ice concentration far from the ice edge is very near 100% during winter makes it possible not only to validate but also to calibrate the ice concentration algorithms globally to compensate for inter sensor differences, sensor drift and environmental factors. This calibration method which is very important in climate data processing is called dynamical tie-points. Regional biases may still exist though.

The accuracy of the ice concentration estimates is to some extent degraded by atmospheric constituents, e.g. cloud liquid water and water vapour, and it is thus important to find ice concentration algorithms that are least sensitive to these atmospheric properties [*Andersen et al., 2006; Oelke et al., 1997*]. Other parameters, such as atmospheric water vapor and open ocean surface wind, are quantified rather well by numerical weather prediction models as it is done in the OSISAF [*Andersen et al., 2006*]. It is therefore feasible to correct brightness temperatures for the influence of these effects using radiative transfer models before computing the ice concentration [*Kern, 2001; 2004*]. However, when doing that it is also important to be able to calibrate corrected data afterwards for trends which may be in the NWP data for example using dynamical tie-points. Any use of the data, and particularly in climate modelling, requires estimates of the errors and uncertainties is a important task that has seldom been conducted [*Spreen et al., 2008; Kern, 2001; 2004*] or validated for long time series, especially when sensors with varying calibration (overlapping SSM/I instruments) and/or ground resolution (AMSR-E instrument) are included in the same data record.

Ice concentration retrievals from passive microwave data is a rather mature and robust observing system, but there is a need to establish error bars especially in the melt season and in the marginal ice zone. The discrepancies between the algorithms need to be explained and quantified, and this work is presently undertaken in the SICCI project.

## **1.3** Sea ice thickness

Sea ice thickness and concentration are the major sea ice climate variable in the polar regions. Ice thickness governs the heat flux and influences the radiative balance of the sea ice covered areas, with the highest sensitivity at low ice thickness. While sea ice concentration, and derived ice area, is observed daily with satellite sensors, ice thickness is more difficult to retrieve from spaceborne sensors. Ice thickness is needed to determine long terms trends in ice volume, to compute the ice mass exchanges with the ocean, to verify numerical model simulations as well as to plan operations in the ice. Ice thickness has traditionally been measured by various in situ methods, airborne surveys with electromagnetic induction instruments and upward looking sonars from anchored moorings and submarine cruises. But all these methods are have limited capability to collect enough data to estimate the seasonal and spatial variability of the ice thickness.

Only satellite observations have the possibility to obtain data with sufficient temporal and spatial coverage. One promising method is to use satellites with radar and/or laser altimeters, which can provide ice freeboard data that are inverted to ice thickness, using assumption of isostatic equilibrium and climatological information about snow thickness, snow and ice density *[Giles et al., 2008, Kwok et al., 2009]*. The freeboard method is most useful for the upper part of the thickness spectrum, i.e. ice with thickness > 1.0-1.5 m. This means that it is mainly MY ice and thick FY ice that can be measured by altimeter data. It has been documented that the area of the Arctic sea ice minimum in September is reducing in the last decade much faster than the maximum area in March [*Eisenman et al., 2011*], the area covered with thin ice types including nilas (thickness <0.1 m thick), young ice (0.1-0.3 m) and thin first-year ice (0.3-0.7 m) will increase. If the Arctic ice cover continues to change from mainly multiyear to predominantly firstyear ice, observation of thin ice will become more important.

Validation of the freeboard method is a main issue because the algorithm to transfer freeboard to thickness requires data on snow depth, snow density and ice density, which vary greatly spatially and temporally. The freeboard measurements from radar altimeters also depend on radar reflections which can come from snow layers as well as from the snow-ice interface. Ice with thickness less than about 1.0 m is more difficult to derive by the freeboard method, and therefore other satellite

methods are needed to measure the thin ice. Thin ice is important to observe because its thermodynamic and dynamic properties are considerably different from those of thicker first-year and multiyear ice. The thin ice conducts more heat from the ocean to the atmosphere and has less resistance against deforming forces of wind and currents compared to thicker ice. In order to improve the representation of sea ice in climate and numerical weather prediction models, it is necessary to compare it to observations.

### 1.3.1 Retrieval of ice thickness with radar altimetry

It is possible to measure the thickness of ice thicker than about 1 m through the indirect measurement of sea ice freeboard using radar or laser altimetry, as illustrated in Figure 2. In the case of radar altimetry, freeboard estimation is achieved by discriminating ice floe and open water (or thin ice) echo reflections from which ice elevations are obtained using special retracking algorithms [*Laxon et al., 2003*]. The echo returns from leads are more specular than the diffuse returns from ice floes. The radar altimetry thickness measurement is dependent on the assumption that the radar returns are coming from the snow/ice interface. Useful results are limited to the winter period, when there are no melt ponds or wet snow that disturb the echo return fro the snow-ice interface.



*Figure 2. Measurement principle of a satellite altimeter (modified from Spreen, Ph.D. thesis, 2008). Green and purple lines denote a radar and a laser altimeter shot, respectively.* 

In the last 20 years radar altimeter data from ERS and ENVISAT have been used to determine inter-annual changes in sea ice thickness through direct measurements of sea ice freeboard [*Giles et al., 2008; Laxon et al., 2003*]. From 2010, CryoSat radar altimeter data with higher spatial resolution than the previous ERS and ENVISAT data has been available and the first results of CryoSat ice thickness retrievals have been published (Laxon et al., 2013). From 2014, Sentinel -3 will continue to provide similar high-resolution radar altimeter data. From comparison with co-incident submarine data the accuracy of the ERS thickness data are estimated at ~0.5m on scales of order one month/100 km [*Laxon et al., 2003*]. However the actual error on any specific sea ice thickness metric are far more complex due to the variable spatial and temporal sampling provided by the satellite orbit and the variable frequency of floe sampling. A further complexity arises from

the error covariance or sea surface height determination, tides and other ancillary data required to obtain thickness [*Wingham et al.*, 2006].

Laser altimeter data from ICESat have been used to measure sea ice freeboard plus snow thickness to estimate ice thickness [*Forsberg and Skourup*, 2005; *Forsberg et al.*, 2007; *Kwok et al.*, 2009]. ICESat has collected elevation data over the Arctic Ocean up to 86N with its laser altimeter which has a \_70 m footprint [Zwally et al., 2002], the mission has completed 14 operational campaigns of global observations from 2003 to 2008. Analysis of ice thickness retrievals from IceSat showed a significant decrease in ice thickness of MY ice in this period [Kwok et al., 2009]. The IceSat mission demonstrated a powerful capacity to measure freeboard and retrieve ice thickness (Fig. 3).

A follow-up mission (IceSat2) is planned to be launched in 2016, when also Sentinel-3 with radar altimeter will be in operation. Combined use of radar and laser altimeters will improve the retrievals of ice thickness as well as snow thickness. Promising new sources of altimeter data include the NASA Icebridge snow radar data that has the potential to provide wide-area multi-year coverage, as well as the laser/Ku-band radar combination data from the ESA CryoVex campaigns. *Kurtz et al [2012]* have demonstrated that the IceBridge products are capable of providing a reliable record of snow depth and sea ice thickness.

Studies of ice thickness from radar altimeters have focused on estimating changes or anomalies in ice thickness [*Giles et al., 2008; Laxon et al., 2003*] from a single satellite mission. To determine absolute ice thickness time-series from several satellites is a new task requiring careful cross-calibration between sensors and a relative calibration of the ice and ocean retracking algorithms for each mission. The estimation of errors required by the modelling community is therefore complex with error invariably varying in both time and space.



Figure 3. Maps of sea ice thickness in the Arctic retrieved from IceSat data for February-March 2004, 2006 and 2008. [Kwok et al., 2009].

There is a number of critical issues related to ice thickness retrievals from radar altimetry. These include:

(1) Penetration issues. A fundamental assumption of sea ice thickness retrieval using radar altimeters is that the radar return originates from the snow/ice interface. There is evidence from airborne laser/radar altimetry to support this view [Connor et al., 2009; Giles et al., 2007] but the data on which this is based are limited spatially, and work carried out by Willatt et al. [2011] in the Arctic. The use of theoretical modelling of penetration [e.g. Tonboe et al., 2006] is hampered by

the lack of knowledge of the detailed physical properties, and suitable scattering models, relevant to the understanding the return from a 13 GHz nadir looking radar. For this reason a strong focus of the ongoing CryoSat Cal/Val campaign is to gather far more detailed field data on this aspect that will be equally informative for the historical radar altimeters operating at the same 13 GHz frequency.

(2) Discrimination of surface types and waveform retracker. The determination of ice freeboard requires discrimination of echo returns from ice and water. Schemes have been developed to perform this task for ERS and ENVISAT radar altimeters [e.g. *Peacock and Laxon, 2004*], but improvements are needed for the new generation of Delay-Doppler altimeters on CryoSat and Sentinel-3. The determination of sea ice freeboard by radar altimetry requires precise measurements of both ice and surface elevation. The effects of different retrackers on the processing retrievals need to be further investigated.

(3) Snow Depth. Snow depth presents potentially a significant uncertainty for ice thickness retrieval from altimetry [Giles et al., 2007]. Knowledge of snow depth is limited with the most comprehensive compilation from in-situ measurements over multi year ice over many years [Warren et al., 1999]. This data does not however account for potential changes in snow depth in recent years and excludes marginal regions and first-year ice.

(4) Water/Ice density. The calculation of ice thickness from freeboard measurements using the hydrostatic assumption requires data on ice and water density as well as snow depth and density. Data on these parameters are literature surveys and recent field observations [e.g. Laxon et al., 2003; Giles et al., 2008, Alexandrov et al., 2010]. The loosely consolidated state of the ice within first-year pressure ridges, and the very different nature of the ice in multi-year ridges, implies that special attention should be paid to deriving an equivalent ice density for ridged areas; ridges make up some 50% of the ice volume in the Arctic. Experiments on individual ridges in which AUV maps of the underside are compared with laser maps of the topside are vital in this respect [e.g. Doble et al., 2011].

(5) Inter sensor calibration. To generate consistent timeseries of sea ice thickness data over the last 20 years requires merging of radar altimetry data from ERS-1, ERS-2 and ENVISAT with several corrections since the three altimeter instruments differ in detail in the echo recording, on-board tracking algorithms and different biases for the retracking algorithms. Also the range corrections (tides, atmospheric propagation, etc.) differ between the missions. To ensure a consistent data record therefore requires cross-calibration of the freeboard retrieval from the three missions.

(6) Validation and error bars. In order to determine the errors of the ice thickness retrievals from altimeters data, comparison with against available in-situ measurements and other independent ice thickness data is required. The availability of in-situ data is insufficient to fully characterize error bars on a regional/seasonal basis. Therefore, theoretical estimations of the errors can be an alternative approach. Up to now detailed comparisons with ice draft data from submarine cruises have been done to validate the ERS ice thickness retrievals [Laxon et al., 2003]. Other ice draft data from upward looking and multi-beam sonars in areas such as the Fram Strait and Beaufort Sea are used for validation. In addition to the comparisons of mean thickness the ice thickness distribution over various space/time windows should also be compared. This is particularly important in understanding the under-sampling of thin/new ice by the altimeter and in estimating the contribution of ridged ice to the altimeter signal.

# **1.3.2** Thin ice thickness retrieval from L-band passive microwave data

The L-band radiometer SMOS mission (Soil Moisture and Ocean Salinity), launched in 2009, has the potential to measure sea-ice thickness up to values of about 0.5 m [*Heygster et al., 2009;* 

*Kaleschke et al., 2010; 2011*]. Currently, the retrieval algorithm for sea ice thickness is under development in the ESA project SMOSIce (<u>https://wiki.zmaw.de/ifm/SMOSIce</u>). Kaleschke et al (2012) have demonstrated retrieval of thickness of thin sea ice for the Arctic freeze-up period based on Level 1C brightness temperatures from SMOS data. The SMOS ice thickness product has been compared with independent sea ice thickness estimates from MODIS thermal infrared imagery and modeled ice growth. The results confirm that SMOS can be used to retrieve sea ice thickness up to half a meter under ideal cold conditions with surface air temperatures below -10°C and high concentration sea ice coverage (Fig. 4). If the Arctic sea ice continues to change from multiyear to predominantly firstyear ice, data on seasonal ice growth of sea ice will be needed by ice modelers and other users of ice data in the Arctic.



Figure 4. (a) Comparison between ERS satellite altimeter and submarine derived ice thickness in the Beaufort Sea during the 1990s. Submarine thicknesses are shown for each of the 50 km segments gathered during the four missions during the 1990s. Altimeter thickness estimates are generated from observations within 15 days and 100 km of the submarine draft sections [Laxon et al., 2003]; (b) Thickness of thin ice retrieved from SMOS data on 01 October 2010. Colour code shows thickness from 0 to 50 cm. Black is ice thicker than 50 cm.

### **1.3.3** Non-satellite ice thickness observing systems

Use of electromagnetic sounding from aircraft flights has become a well-established technique for measuring ice thickness on local and regional scale. Measurements are based on an electromagnetic induction sensor, the so-called EM-Bird, which is towed underneath an aircraft (helicopter or airplane) in a height of 40 to 50 ft above the sea ice surface. This method allows individual sea ice thickness profiles with a length of 200 km (helicopter) and up to 500 km (airplane).

AWI has been conducting aircraft expeditions to the Arctic Ocean on a regular basis where measurement of sea ice thickness is one of the main tasks. In spring 2011, airborne sea ice thickness and surface roughness data were obtained during the PAMARCMIP campaign over sea ice in the Lincoln, Beaufort and Chukchi Seas. Figure 5 shows a map with flight tracks (red)



performed during this campaign as well as histograms of the sea ice thickness distribution for the individual regions.

Figure 5. Map of flight surveys and ice thickness measurements performed by AWI in 2009. The greyscale image is backscatter from Quikscat showing areas of multiyear ice as bright and first grear ice as dark (Haas et 1., 2010)

To convert the instrument output to ice thickness, the EM response is routinely converted at AWI by a semi empirical method called EMPEX [*Pfaffling et al., 2007*]. A theoretical relation between the measured magnetic field and the distance to the ice-water interface is approximated with an exponential equation, with five constants that are determined by exponential curve fitting used on measured magnetic field and height above surface over open water. Once the algorithm is tuned, the total thickness (snow + ice thickness) is determined by calculating the difference between the height above ice-water interface from the conductivity meter and the height above the air-snow/ice interface from the laser altimeter. The accuracy of the EM-Bird ice thickness measurements are within  $\pm 0.1$  m over level ice, over ridges however, the accuracy is lower since the footprint size is larger than the spatial scale of ridges. Therefore, the EM-bird can underestimate the thickness of ridges by as much as 50-60% [*Wadhams et al., 2006*].

The electromagnetic induction instrument EM-31 is used to measure in situ ice thickness. It works according to the same measurement principle as described for the EM-Bird system above. For example, the EM-31 is mounted on a sledge and pulled along on two metres thick ice, the footprint and hence the spatial resolution of the thickness measurements is about 9 metres. To convert the instrument output of apparent conductivity to ice thickness, the EM response needs to be modelled. To do this the conductivity of both ice and water needs to be known [Tateyama et al., 2006]. An alternative when working on ice without big changes in thickness, is to use a standard formula developed by *Haas et al.* [2009] and adjust its constants to the conditions at the measurement site

by calibration. The calibration is done by drilling holes in the ice and measuring ice thickness, and then to measure the apparent conductivity at the same spot with the EM-31.

### Under ice measurement of ice draft with submarines and AUVs

The only method available to measure both the full probability density function of ice thickness and the actual three-dimensional shape of the ice underside is sonic profiling from below, notably with 3-D multibeam sonar. Two-dimensional profiling of the ice underside using single-beam sonar has been done since 1958 from US submarines, and in Europe since 1971 using UK submarines. The most important statistic is the probability density function g(h) of ice draft, but we also derive the distributions of (i) pressure ridge depths and spacing; (ii) lead widths, lead spacings and ice thicknesses in leads; (iii) separated distributions of deformed and undeformed ice drafts; (iv) ice floe lengths; (v) fractal dimensions and (vi) pressure ridge shapes and along-track slope angles. Each of these distributions has specific statistical characteristics indicative of the nature and state of deformation of the ice (Wadhams, 2000). In its simplest form, the mean drafts from 50 km sections can be used to validate ice thickness retrievals from altimetry sensors such as ICESat and CryoSat.

Several calibration/validation campaigns for the Cryosat-2 satellite have been conducted, flying airborne laser and radar instruments under the track of the satellite. Recent investigations have shown that the relation between freeboard and ice thickness is highly variable. Any sensible validation of freeboard-based ice thickness retrievals therefore requires co-incident acquisition of draft data. The three-dimensional mapping of ice draft by AUV is also highly valuable to understand the response of EM methods (Fig. 6) to deformed ice.



Figure 6. (a) Mapping the underside of the ice using multibeam sonar from the submarine Tireless; (b) Comparison of ice thickness data from IceSat and submarine sonar profile taken in the same period in winter 2004;

### **1.4** Requirements for sea ice data in the coming years

Sea ice climate data plays an important role to assess the performance of climate models in the Coupled Model Intercomparison Project (CMIP). CMIP provides a standard experimental protocol

for studying the output of coupled atmosphere-ocean general circulation models (AOGCMs) and provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. This framework enables a diverse community of scientists to analyze GCMs in a systematic fashion, a process which serves to facilitate model improvement.

The three decades of sea ice extent data is a key data set to validate the climate models in the polar regions. The recent CMIP5 studies have shown that climate models in general predict that the summer sea ice in the Arctic will disappear in this century, but there is large discrepancies between the models when this will happen *[e.g. Stroeve et al., 2012]*. It is also noteworthy that the observed decrease in summer ice extent is faster than most of the model predictions. This suggests that there are important processes that are nor adequately represented in the climate models.

Future observations of Arctic sea ice will require data with higher spatial resolution and more parameters in order to improve the sea ice models. Also modeling of air-ice-ocean interaction will need higher resolution and climate models will become more regional with capability to resolve mesoscale processes. This implies that sea ice observations must be developed in parallel with atmospheric and ocean observations through integrated systems providing data with adequate resolution and coverage.

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