Sea Ice Climate Change Initiative:
Phase 1

ANT D1.1 Passive Microwave Snow Depth on Antarctic sea ice assessment

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1 Introduction

1.1 Purpose and Scope

This document summarises the results of Work Package WP 1100 of the ESA Sea Ice ECV Project Option: Antarctic sea ice thickness distribution. This work package had two main objectives:

(1) The comparison of the AMSR-E snow depth retrieval provided by the NSIDC [RD-01] retrieved using the method introduced by Markus and Cavalieri [RD-02] for the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) with ship-based snow depth estimates using the ASPeCt protocol [RD-03, RD-04] and in situ measurements from the ASPeCt-Bio [RD-05] and ISPOL datasets [RD-06].

(2) To derive AMSR-E specific regression coefficients to set up a new snow depth retrieval for AMSR-E including sophisticated error estimation.

1.2 Document Structure

This report is structured as follows: this Section will provide a short overview of the role of Antarctic snow on the formation of Antarctic sea ice, the typical properties of Antarctic snow and existing detection methods. The second Section will briefly review the SSM/I- and AMSR-E snow depth retrieval and provide the main equations used in the uncertainty estimation of the final snow depth product. The third Section provides an overview of the data products used in this work package. In the fourth Section the results of the comparison of the SSM/I and AMSR-E snow depth product with ASPeCt snow depth observations and ASPeCt-Bio and ISPOL in situ measurements are presented and discussed. The fifth Section describes the route to the new snow depth retrieval and the sixth Section provides a short summary and an outlook on future work.

1.3 Applicable Documents

The following table lists the Applicable Documents that have a direct impact on the contents of this document and should be read in concert with it.

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<th>Reference</th>
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<td>ESA-CCI Scientific user consultation and detailed specification: Statement of Work (SoW)</td>
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Table 1.1: Applicable Documents
## 1.4 Reference Documents

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<tr>
<td>RD-13</td>
<td>Summer Antarctic sea ice as seen by ASAR and AMSR-E and observed during two IPY field cruises</td>
<td>Tekeli, A. E., S. Kern, S. F. Ackley, B. Ozsoy-Cicek, and H. Xie, Annals of Glaciology, 52(57), 327 - 336, 2011.</td>
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### Passive Microwave Snow Depth on Antarctic sea ice assessment

Ref. SICCI-ANT-PMW-SDASS-11-14  
Version 1.0 / 28 Nov 2014

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1.5 Acronyms and Abbreviations

<table>
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<tr>
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<tr>
<td>ACDD</td>
<td>Attribute Convention for Dataset Discovery</td>
</tr>
<tr>
<td>ATBD</td>
<td>Algorithm Theoretical Basis Document</td>
</tr>
<tr>
<td>CCI</td>
<td>Climate Change Initiative</td>
</tr>
<tr>
<td>CF</td>
<td>Climate and Forecasting</td>
</tr>
<tr>
<td>DMSP</td>
<td>Defence Meteorological Satellite Program</td>
</tr>
<tr>
<td>EASE</td>
<td>Equal Area Scalable Earth-Grid</td>
</tr>
<tr>
<td>ECV</td>
<td>Essential Climate Variable</td>
</tr>
<tr>
<td>Envisat</td>
<td>Environmental Satellite</td>
</tr>
<tr>
<td>EO</td>
<td>Earth Observation</td>
</tr>
<tr>
<td>GCOS</td>
<td>Global Climate Observing system</td>
</tr>
<tr>
<td>GHRSSST</td>
<td>Group for High Resolution Sea Surface Temperature</td>
</tr>
<tr>
<td>IDL</td>
<td>Interactive Data Language</td>
</tr>
<tr>
<td>Matlab</td>
<td>Matrix Laboratory</td>
</tr>
<tr>
<td>MIZ</td>
<td>Marginal ice zone</td>
</tr>
<tr>
<td>n.a.</td>
<td>Not applicable</td>
</tr>
<tr>
<td>netCDF</td>
<td>Network Common Data Format</td>
</tr>
<tr>
<td>Acronym</td>
<td>Meaning</td>
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<tr>
<td>---------</td>
<td>----------------------------------------------</td>
</tr>
<tr>
<td>NH</td>
<td>Northern hemisphere</td>
</tr>
<tr>
<td>NSIDC</td>
<td>National Snow and Ice Data Centre</td>
</tr>
<tr>
<td>OSI-SAF</td>
<td>Ocean and Sea Ice Satellite Application Facility</td>
</tr>
<tr>
<td>PDGS</td>
<td>Payload Data Ground System</td>
</tr>
<tr>
<td>RA</td>
<td>Radar altimeter</td>
</tr>
<tr>
<td>SH</td>
<td>Southern hemisphere</td>
</tr>
<tr>
<td>SIC</td>
<td>Sea Ice Concentration</td>
</tr>
<tr>
<td>SICCI</td>
<td>Sea Ice Climate Change Initiative</td>
</tr>
<tr>
<td>SIT</td>
<td>Sea Ice Thickness</td>
</tr>
<tr>
<td>SMMR</td>
<td>Scanning Multichannel Microwave Radiometer</td>
</tr>
<tr>
<td>SMOS</td>
<td>Soil Moisture and Ocean Salinity</td>
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<tr>
<td>SSM/I</td>
<td>Special Sensor Microwave / Imager</td>
</tr>
<tr>
<td>TBD</td>
<td>To be defined</td>
</tr>
<tr>
<td>URD</td>
<td>User Requirements Document</td>
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Table 1.3: Acronyms

### 1.6 Introduction to Snow Depth on Antarctic Sea Ice

Snow plays an important role in the global climate system. It has a high albedo up to 0.9 [e.g. RD-07] in the visible spectral range and reflects high amounts of incoming solar light back into space. In the polar regions sea ice with varying extend covers the open ocean nearly the whole year and snow accumulating on the ice surface especially during winter can, due to its heat conductivity being about one magnitude smaller than that of sea ice, reduce the heat conduction through the ice-snow layer [RD-08]. However, the seasonal amplitude of the sea ice extent is considerably larger in the Antarctic than in the Arctic where substantially more sea ice survives summer melt and becomes second-year and eventually multiyear ice. The smaller amount of multiyear ice in the Antarctic is not only caused by the stronger melt but also a result of the general sea ice motion. While sea ice can accumulate in the Arctic Ocean because it is surrounded by land, in the Antarctic the equator-ward motion of the sea ice is not limited by land. Hence it drifts into warmer water and melts. Therefore Antarctic multiyear ice is confined mainly to the Weddell Sea and a few small isolated regions around Antarctica. In the Antarctic multiyear ice is rarely older than 2 or 3 years. Besides the smaller amount of multi-year ice the processes playing a role in the formation of sea ice differing strongly from those in the Arctic. The dynamical and hydrological conditions in the Antarctic can lead to heavy snowfalls leading to snow layers more rapidly accumulating and much thicker than found in the Arctic. In the case the insulation by the ice and snow layers is high enough it prevents further basal freezing and therefore thickening of the sea ice.

If the gravitational pressure exerted by the snow on the ice exceeds the buoyancy pressure exerted by the underlying water on the ice, the snow-ice interface is submerged and salty sea water intrudes into the snow layer. Subsequent refreezing then can lead to the formation of a snow-ice layer having different thermal, radiative and optical properties than sea ice formed from ocean water. If the snow layer on top of the ice is not thick enough to submerge the snow-ice-interface but the heat conduction through the ice is higher than through the snow layer the excess energy can lead to
internal melting in the snow layer. Refreezing of the molten snow can alter the optical and radiative properties of the snow layer, e.g. by the formation of ice layers in the snow. Furthermore, especially in regions with heavy snowfalls snow to ice conversion contributes to ice growth on top of the sea ice.

1.7 Introduction to Snow Depth Observation in the Antarctic

Due to the different processes discussed in the last paragraphs the radiative properties of Antarctic sea ice are significantly different from those of Arctic sea ice. Due to its thermal and radiative properties snow depth, not only on sea ice, represents an important input variable for global climate models. However, in the Antarctic the large annual amplitude in sea ice extent and the small amount of sea ice surviving summer melt makes the continuous observation of snow depth and properties difficult. While in the Arctic fixed stations can be operated continuously for several years [e.g. RD-09], fixed stations would rarely survive more than one winter in the Antarctic. Therefore, on Antarctic sea ice in-situ measurements of snow depth and snow properties can only be conducted during ship-based research cruises, while remote measurements or observations can also be conducted from air- or spaceborne platforms. However, although in-situ and airborne measurements provide the possibility to analyse the small-scale structure of snow and potentially result in a high accuracy, besides being labour and cost intensive, they offer only a limited spatial and temporal cover. Spaceborne spectro- or radiometers on the other hand are either limited to the periods of the day where sunlight is available (passive optical sensors) or require an internal energy source at the cost of the duration of the observation period (active optical sensors). Further, especially for the retrieval of snow depth they need external a-priori information. For the Antarctic snow depth products are available from a variety of different sources. The Antarctic Sea Ice Processes and Climate (ASPeCt) protocol dataset (http://aspect.antarctica.gov.au) [RD-03; RD-04] provides ship-based snow depth observations for the period between 1981-2005 and, including observations using the protocol but not being included in the official dataset, can be extended until early 2011 [RD-10; RD-11; RD-12; RD-13; RD-14; RD-15]. Compared to in-situ measurements the ASPeCt-dataset has a relatively large spatial cover, however, also a relatively large uncertainty. Compared to ship-based observations in-situ measurements conducted during research cruises offer an even lower spatial resolution but have a high accuracy [RD-06, RD-05, RD-16].

Operation IceBridge (see Panzer et al. [RD-17] for description of the sensor suite and for results see Kurtz and Farrell [RD-18], Kwok et al. [RD-19], Farrell et al. [RD-20], Kurtz et al., [RD-21]) conducts snow and ice observations using a snow-penetrating radar in combination with a laser scanner to provide information about ice and snow thickness along the flight track. However, although recently a method to separate snow and ice layers was introduced [RD-22], currently for the Antarctic no snow depth products from Operation IceBridge measurements are available.

Contrary to airborne and ship-based instruments satellite sensors offer only a comparatively coarse spatial resolution of about 12.5 km (AMSR-E) to 25 km (SSM/I). Since during polar winter no sunlight is available passive microwave sensors offer the best potential to retrieve snow depth on sea ice the whole year round. However, so far only one algorithm has been developed to retrieve snow depth on sea ice from passive microwave sensors [RD-02; RD-23; RD-24], and later adapted to potentially improve

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the retrieval of snow depth over rough sea ice by using complementary ICESat LIDAR data [RD-25].
The algorithm was introduced by Markus and Cavalieri [RD-02] for the Special Sensor Microwave/Imager (SSM/I) and later adapted for the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) [RD-23; RD-24].
The algorithm is based on an empirical regression of the gradient ratio of the vertically polarised brightness temperatures at 19.35 and 37.0 GHz (18.7 and 36.5 GHz for AMSR-E) with ship-based and in-situ snow depth measurements in the Weddell Sea and the Bellingshausen and Amundsen Seas ([RD-02] and references therein) and can be applied to retrieve snow depths up to about 50 cm. It is limited to seasonal ice with dry snow cover and is currently applied to retrieve snow depth on sea ice in the Arctic as well as in the Antarctic.
Accurate snow depth on sea ice products are necessary for various other purposes: estimation of freeboard from ICESat measurements (e.g. [RD-26; RD-27]), improvement of parameterisation in global climate models, as well as for the understanding of physical processes involving ice formation in the Antarctic. Therefore, passive microwave instruments offer the highest potential for long term observations of snow depth on sea ice.
2 Passive Microwave Snow Depth Retrievals for SSM/I and AMSR-E

2.1 Algorithm Theoretical Basics

This Section will shortly introduce the theoretical basics of the snow depth retrieval algorithm for SSM/I and AMSR-E and provide an overview of the snow depth and sea ice concentration datasets used in this workpackage. A full overview of the snow depth and NASA Team-2 sea ice concentration algorithm can be found in Markus et al. [RD-31].

2.1.1 Retrieval Algorithm

The retrieval method used to derive snow depth on sea ice using daily gridded passive microwave data was first introduced by Markus and Cavalieri [RD-02]. They compared the sea ice concentration corrected gradient ratio of the vertically polarised brightness temperatures of the 19.35 and 37.0 GHz SSM/I channels with snow depths from in-situ measurements and ship-based observations. Here, the sea ice concentration corrected gradient ratio is given by:

$$ GR_{\text{ice}}^V = \frac{T_B(37V) - T_B(19V) - k_1(1 - C_{\text{ice}})}{T_B(37V) + T_B(19V) - k_2(1 - C_{\text{ice}})} $$ (2.1)

Where $T_B(19V)$ and $T_B(37V)$ are the vertically polarised brightness temperatures at 19.35 and 37.0 GHz, $C_{\text{ice}}$ is the sea ice concentration for the given grid cell (or pixel), and $k_1$ and $k_2$ are constants derived from the vertically polarised brightness temperatures of open water at 19.35 and 37.0 GHz ($T_{B,\text{OW}}(19V)$ and $T_{B,\text{OW}}(37V)$):

$$ k_1 = T_{B,\text{OW}}(37V) - T_{B,\text{OW}}(19V) $$ (2.2)

$$ k_2 = T_{B,\text{OW}}(37V) + T_{B,\text{OW}}(19V) $$ (2.3)

Markus and Cavalieri [RD-02] used the linear regression between the calculated SSM/I gradient ratios and in-situ and ship-based snow depth observations to obtain an empirical relationship for the retrieval of snow depth on sea ice. This empirical relation is given by:

$$ S = a + bGR_{\text{ice}}^V $$ (2.4)

Where $a$ and $b$ are constants. For SSM/I these constants are $a = -2.34$ cm and $b = -771$ cm. For AMSR-E and its successor AMSR-2 the snow depth retrieval uses modified coefficients derived from inter-comparisons between SSM/I and AMSR-E brightness temperatures at 19.35/18.7 GHz and 37.0/36.5 GHz [RD-28], however, the basic relation between the gradient ratio and snow depth remains the same (Eq. 2.4). The only difference is that the SSM/I brightness temperatures are replaced by their AMSR-E equivalents. Here, the coefficients of the linear regression are given by $a = 2.9$ cm and $b = -782/783$ cm [RD-28; RD-24; RD-29; RD-30; RD-31]. The retrieval is limited to dry snow conditions on first-year ice with maximum snow depths up to about 50 cm [RD-02].
### 2.1.2 Error Propagation Formula

The error propagation of Eqs. 2.1 and 2.4 is straightforward and, although the terms of the single components are quite complex, easy to derive. Since the uncertainties provided in Section 5.2 are all originating from some kind of statistical analysis only the Gaussian error propagation will be derived here, however, the error propagation for the estimation of the maximum error can be derived in a similar way. In general the statistical error $\sigma_f$ from the Gaussian error propagation of a function $f(x_i)$ depending on the independent variables $x_i$ is given by:

$$\sigma_f = \pm \sqrt{\sum_i \left( \frac{\partial f}{\partial x_i} \sigma_{x_i} \right)^2}$$  \hspace{1cm} (2.5)

Applying the error propagation to Eq. 2.4 gives for the Gaussian error:

$$\sigma_s = \pm \sqrt{(\sigma_0)^2 + (\Gamma R_{ic}^b \sigma_b)^2 + \left( b \sigma_{GR_{ic}} \right)^2}$$  \hspace{1cm} (2.6)

Here, $\sigma_{GR_{ic}}$ is composed of five terms: $\sigma_{R_{ic}}$, $\sigma_{R_{ic}}$, $\sigma_{C_{ic}}$, $\sigma_{k_1}$, and $\sigma_{k_2}$ as well as the variables themselves. Since $\sigma_{k_1}$ and $\sigma_{k_2}$ contain only additive terms and due to the square the minus in the derivative of Eq. 2.2 can be neglected, they can both be calculated using the same equation:

$$\sigma_{k_1} = \sigma_{k_2} = \pm \sqrt{(\sigma_{b_{0_{ic}}})^2 + (\sigma_{b_{1_{ic}}})^2}$$  \hspace{1cm} (2.7)

Thus the Gaussian error of $\sigma_{GR_{ic}}$ is given by:

$$\sigma_{GR_{ic}} = \pm \sqrt{(G_1 \sigma_{R_{ic}})^2 + (G_2 \sigma_{R_{ic}})^2 + (G_3 \sigma_{C_{ic}})^2 + (G_4 \sigma_{k_1})^2 + (G_5 \sigma_{k_2})^2}$$ \hspace{1cm} (2.8)

Where the terms $G_i$ ($i = 1, 2, 3, 4, 5$) are given by the following equations:

$$G_1 = \frac{(k_1 + k_2)(1 - C_{ic}) - 2T_b(37V)}{(T_b(37V) + T_b(19V) - k_2(1 - C_{ic}))^2}$$  \hspace{1cm} (2.9)

$$G_2 = \frac{(k_1 - k_2)(1 - C_{ic}) + 2T_b(19V)}{(T_b(37V) + T_b(19V) - k_2(1 - C_{ic}))^2}$$  \hspace{1cm} (2.10)

$$G_3 = \frac{(k_1 - k_2)T_b(37V) + (k_1 + k_2)T_b(19V)}{(T_b(37V) + T_b(19V) - k_2(1 - C_{ic}))^2}$$  \hspace{1cm} (2.11)

$$G_4 = \frac{C_{ic} - 1}{T_b(37V) + T_b(19V) - k_2(1 - C_{ic})}$$  \hspace{1cm} (2.12)

$$G_5 = \frac{(T_b(37V) - T_b(19V) - k_2(1 - C_{ic}))(1 - C_{ic})}{(T_b(37V) + T_b(19V) - k_2(1 - C_{ic}))^2}$$  \hspace{1cm} (2.13)

Eq. 2.8 can then be inserted into Eq. 2.6 to obtain the error of the retrieved snow depth.
2.2 The SSM/I Sea Ice Concentration and Snow Depth Product

SSM/I snow depth and sea ice concentration products retrieved using the algorithm of Markus and Cavalieri [RD-02], [RD-23] and the enhanced NASA Team sea ice concentration algorithm (NT2) [RD-32] were downloaded from the webpage of NASA’s Cryosphere Science Research Portal (http://neptune.gsfc.nasa.gov/csb/index.php?section=52). Both products are provided in the National Snow and Ice Data Center (NSIDC) grid with a grid resolution of 25 km and cover the period between January 1, 1992 and April 2, 2008. The snow depth product contains three different classifiers to mark areas of open water (value: 0), snow depth in cm (values: 1 - 100) and land (value: 200) and the sea ice concentration product contains four different classifiers to mark open water (value: 0), sea ice concentration in % (values: 1 - 100), land (value: 117) and missing data (value: 130).

2.3 The NSIDC AMSR-E Sea Ice Concentration and Snow Depth Product

The NSIDC provides AMSR-E snow depth and sea ice concentrations together with the brightness temperatures of the AMSR-E 18.7 - 89 GHz channels in one single product [RD-01]. At the beginning of this project the current data version was version 12/13, however, recently the dataset was updated to version 15 which is used in this project. The dataset covers the period between June 1, 2002 and October 4, 2011 and is provided in the NSIDC grid with 12.5 km grid resolution.

The snow depth on sea ice product [RD-02] is a five day running average including the current and the four previous days. Similar to the SSM/I dataset the AMSR-E snow depth product is classified with different markers. Valid snow depths have values between 0 and 100 in cm, the value 110 indicates missing data, 120 land, 130 open water, 140 multi-year ice areas, 150 areas of highly variable snow depths and 160 areas affected by snow melt.

In addition, to the snow depth the dataset contains sea ice concentrations retrieved by using the NASA Team-2 algorithm [RD-32]. Similarly to the snow depth product the NT2 sea ice concentration datasets contain different classifiers with values between 0 and 100 indicating sea ice concentrations in % (0: open water, values >0: sea ice concentrations) and 120 indicating land covered areas.
3 In-Situ, Ship-based and Airborne Snow Depth Observations

3.1 Snow Depth from the ASPeCt Protocol


In addition to the official ASPeCt dataset in this project snow depths from another nine cruises between 2006 and 2011, all recorded using the ASPeCt protocol, collected by S. Kern and A. Beitsch [2013, pers. communication] were used; see also [RD-33]. A full overview of all cruises, their duration and the Antarctic sectors visited (see [RD-02] for a map of all sectors) can be found in Tab. 3.1. Additionally for the cruises in the extended ASPeCt dataset, if available, references and data sources are given.

Besides snow depth estimates the dataset also contains information on snow and sea ice properties and types, and sea ice concentration. Here, observations are noted for primary, secondary and tertiary sea ice (ordered by sea ice thickness) and average values are calculated from observations of the single ice types weighting the contributions of each ice type by its partial sea ice concentration. The uncertainty of the snow depth estimates are assumed to be about ±50% for snow depths < 10 cm, about ±30% for snow depths 10 cm < snow depth < 30 cm, about ±20% for snow depths > 30 cm on level sea ice and higher for ridged sea ice [RD-04]. Observations are generally made within a radius of 1 km around the ship and thus with approximately 3 km² the areal cover is much lower than for satellite sensors.

3.2 In-Situ Datasets

3.2.1 ASPeCt-Bio

The ASPeCt-Bio dataset consists of ice core data from about 32 cruises in the period between 1983 and 2008 [RD-05]. Of these 32 cruises seven cruises between 2002 and 2007 coincide with the observation period of AMSR-E. All those cruises are listed together with the cruises using the ASPeCt protocol in Tab. 3.1. Besides information on biological parameters this dataset also contains information on snow depth, sea ice thickness and freeboard. However, in this work package only the snow depth data are used and thus the other parameters will not be considered any further. The in situ snow depths were measured using a ruler stick allowing to measure snow depths with a precision of about ±1 cm, however, in cases the snow-ice interface is difficult to distinguish the accuracy of the measurements is lower than the precision [RD-16]. Single ASPeCt-Bio measurements have roughly an aerial cover of about 1 m². The ASPeCt-Bio data used in this work package were prepared and provided by S. Kern [2013, pers. communication]. Since for the time being only the data collected during the AMSR-E operation period were prepared the comparison of ASPeCt-Bio snow depths will be conducted for AMSR-E only and a comparison with SSM/I snow depth retrievals may be part of future studies.
3.2.2 Ice Station Polarstern (ISPOL)

The Ice Station Polarstern (ISPOL) is an independent research cruise not associated with the ASPeCt dataset. ISPOL was conducted between November 28, 2004 and January 2, 2005 in the western Weddell Sea. During this time the German research vessel Polarstern was anchored to an ice floe with a size of approximately 100 km$^2$ consisting of first- and second-year ice. Four measurement sites (two with first year snow and two with second year snow) were set up to measure snow and ice properties. For a full description of the ISPOL drift see Nicolaus et al. [RD-06]. Among the measured parameters only snow depth is of interest for this work package. During the ISPOL drift snow depth was measured along a 50 m profile with a separation of about 1 m between the measurements using a ruler stick [RD-06]. The measured snow depth is assumed to have an accuracy about 2 cm or better, however, the dataset provided by the Pangaea database (http://www.pangaea.de) does only provide mean values and their standard deviation (supplement to RD-06)) and thus the standard deviation is used as an estimate of the uncertainty instead of a classical error propagation.

3.3 Operation IceBridge Airborne Radar Measurements

Operation IceBridge generally conducts airborne radar measurements in the Arctic and the Antarctic [RD-20; RD-21; RD-22]. The snow depth is determined from the backscatter at the air-snow interface and the ice-snow interface [RD-21]. While this generally works well in the Arctic, however, due to different snow and ice properties and the processes governing snow and ice formation the snow-ice interface is more difficult to detect on Antarctic sea ice. Although recently a method to retrieve snow depth on Weddell and Bellingshausen Seas sea ice was suggested by [RD-22], the dataset is currently not publicly available and thus cannot be used in this work package, however, it will offer another option for the comparison of AMSR-E snow depths later in the project.

Table 3.1: List of all ASPeCt - cruises and in situ measurement operations in the SSM/I (1992 - 2008) and AMSR-E (2002-2011) observation periods. The cruise names are as provided in the datasets. The columns “Duration” and “Antarctic Sectors” provide information about the first and last days of the observation record provided in the datasets and the Antarctic sectors visited during the cruise. ASPeCt: all cruises provided in the online ASPeCt dataset. ASPeCt-2011: cruises added in the extended ASPeCt dataset gathered and provided by A. Beitsch and S. Kern (2013, personal communication, also [RD-33]). ASPeCt-Bio: drill core measurements taken during ASPeCt-cruises, provided by S. Kern [2014, personal communication]. If available for the extended ASPeCt and the ASPeCt-Bio dataset reference publication and/or name of the contact are given along with the dataset. ISPOL data are taken from the Pangaea database (supplement to [RD-06]). Sector abbreviations: Weddell Sea: Wed, Bellingshausen and Amundsen Seas: Bel, Ross Sea: Ros, Indian Ocean: Ind, Western Pacific Ocean: WeP.

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<td>ASPeCt-2011, provided by: S. F. Ackley</td>
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<td>Bel, Ros</td>
</tr>
</tbody>
</table>
4 Comparison of SSM/I and AMSR-E Snow Depth Retrieval Products with ASPeCt and In-Situ Observations

4.1 Collocation Method

Generally the same collocation method is applied for the ASPeCt, the ASPeCt-Bio and the ISPOL dataset. First all observations for the current day and year are selected. Then for every day the ASPeCt-coordinates are selected as reference points and all AMSR-E or SSM/I-pixels within a 12.5 km x 12.5 km (AMSR-E) or a 25 km x 25 km (SSM/I) box with the ASPeCt or in-situ observation coordinates in the centre are searched. Then the closest pixel is assigned as collocation partner to the ASPeCt observation or in-situ measurement. In the rare case that the ASPeCt-observation or in-situ measurement is located exactly between two pixels both pixels are assigned as two collocation pairs. In general this introduces a small bias; however, since this is a very rare case this does not affect the comparison strongly.

To allow a comparison on the basis of pixel and daily averages the pixels were separated for the Antarctic sectors using the longitude borders given in Tab. 4.1. The snow depth pairs for the West Antarctic (Weddell Sea, Bellingshausen and Amundsen Seas and Ross Sea Sectors), the East Antarctic (Indian Ocean and Western Pacific Ocean Sectors) and the Antarctic (all sectors) are then obtained from the averages from the single sectors without any further averaging.

Table 4.1: Borders of the Antarctic Sectors. Longitudes are given in 0 to 360°-range.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Longitude range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weddell Sea</td>
<td>300° ≤ Lon &lt; 20°</td>
</tr>
<tr>
<td>Bellingshausen and Amundsen Seas</td>
<td>230° ≤ Lon &lt; 300°</td>
</tr>
<tr>
<td>Ross Sea</td>
<td>160° ≤ Lon &lt; 230°</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td>20° ≤ Lon &lt; 90°</td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>90° ≤ Lon &lt; 160°</td>
</tr>
</tbody>
</table>

Then from the single pairs, pixel averages are calculated. Here, first all ASPeCt or in-situ observations at the same position are averaged. Then the snow depth observations with different positions in one pixel are averaged into one pixel average. Since for the SSM/I and AMSR-E snow depth retrievals no pixel-based uncertainty estimates are available, no error is assigned to the satellite snow depth retrievals. Rather, to estimate the uncertainties of the ASPeCt and in-situ values the standard deviation of all ship-/ground-based observations are calculated. However, it has to be noted that this represents the variability of the snow depth rather than a real error.

Then from the pixel averages, daily averages and their standard deviations, now for both, pixel as well as pixel-averaged snow depths, have been calculated following the method of Beitsch et al. [RD-33]. Here, again the standard deviation of all pixel averages is calculated since the standard deviations of the pixel averages represent a variability of the averaged snow depth and thus it is questionable if Gaussian error propagation is suitable for the estimation of the uncertainty of the daily averaged snow depths. Finally for both, the pixel and the daily averages, satellite retrievals and ground-
/ship-based snow depth observations are compared in scatter plots and linear regressions are performed. Sections 4.2 and 4.3 provide detailed information on each comparison, while the main results are shortly summarised and discussed in Section 4.4.

4.2 SSM/I
The SSM/I snow depth retrievals were compared with ASPeCt snow depth observations for the period between January 1992 and early April 2008. To investigate the influence of the sea ice concentration on the retrieved snow depth this comparison was done for snow depths on sea ice with concentrations ≥ 20% and ≥ 80%. However, since the results of both comparisons are not substantially different, only the results of the comparison for sea ice concentrations ≥ 20% are shown here, while for sea ice concentrations ≥ 80% only the regression coefficients are given (Tabs. A.2 and A.4, Appendix A).

4.2.1 Pixel Averages
The comparison of the snow depths retrieved from SSM/I passive microwave data with pixel-averaged ASPeCt observations are shown in Figs. A.1 - A.12 following the annual cycle (January - December) and in Figs. 4.2 and 4.3 for the period between April and October and all data for the whole period, respectively. The correlation coefficients of the regressions and the RMSDs for the single months can be found in Tab. A.1 for the comparison for snow on sea ice with concentrations ≥ 20% and in Tab. A.2 for the comparison of snow on sea ice with concentrations ≥ 80%.

Fig. 4.1 concludes the monthly values of the regression coefficients (slope, y-intercept and correlation coefficient), RMSD and the number of snow depth pairs used for each comparison, for each of the Antarctic sectors, for their combinations the West Antarctic (Weddell Sea, Bellingshausen and Amundsen Seas, and Ross Sea Sectors), the East Antarctic (Indian Ocean and Western Pacific Ocean Sectors) and the whole Antarctic.

Summer Period: November-March
Figs. A.1-A.3 and A.11, and A.12 (Appendix A) show the Antarctic summer months (November - March). In the summer months the snow depth in Antarctica is generally very variable and the snow depth retrieval is affected by varying weather conditions, and melt-refreeze-cycles. For the Weddell Sea the comparisons show a relatively strong scatter especially for January, February and November (correlation coefficients < 0.3) while for March and December the scatter is less strong (correlation coefficients ≈ 0.35). The RMSD increases from approximately 13 cm in November to about 21 cm in January and decreases again to approximately 11 cm in March. While the comparison shows the tendency that ASPeCt snow depths are underestimated by the retrieved SSM/I snow depths for snow depths below approximately 15 cm, the opposite is the case for snow depths above approximately 30 cm. Furthermore, the y-intercept and the RMSD show maxima of about 10-20 cm and 20 cm, respectively, for January and February. In the following months intercept and RMSD decrease and remain constant between roughly 5 to 10 cm and 10 to 15 cm respectively.
Figure 4.1: Slope, y-Intercept, correlation coefficient, RMSD and number of snow depth pairs of the comparisons of SSM/I snow depth retrievals with ASPeCt ship-based snow depth estimations for single months, the whole winter period (April–October) and the whole dataset. SSM/I observation period: 1992–2008, SSM/I and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.1.

In the Bellingshausen and Amundsen Seas Sector only few snow depth pairs are available for the summer months and thus the single comparison are not necessarily representative. However, for SSM/I the tendency to underestimate ASPeCt snow depths for snow depths above approximately 30 cm still seems to hold, however, due to a lack of comparison data for snow depths below 15 cm no conclusion can be drawn. This tendency is also reflected by the RMSD which varies between approximately 15 cm in February and 28 cm in January. As found for the Weddell Sea Sector the y-intercept reaches a maximum of about 25-30 cm for January and February and decreases for the following months. Similarly to the Weddell Sea Sector the comparison for the Ross Sea Sector shows a strong scatter of the snow depth pairs. For all summer months the correlation coefficients are usually below 0.3. The RMSD increases from approximately 16 cm in December to 28 cm in January and then decreases to approximately 10 cm in March. The maximum of the y-intercept in
January and February is with 10-20 cm less pronounced than for the Weddell Sea and Bellingshausen and Amundsen Seas Sectors. However, the overall pattern is the same as found for the Weddell Sea.

The Indian and Western Pacific Ocean Sectors show generally a very similar pattern and thus they are discussed together. In November and March the snow depth observed using the ASPeCt protocol varies between 0 and approximately 70 cm while the snow depth from the SSM/I snow depth retrieval remains mainly below 40 cm and no values higher than roughly 20 cm can be found for ASPeCt snow depth estimates higher than about 25 cm. The absolute value of the correlation coefficient is always lower than 0.3. While the correlation coefficient is negative for November, it is positive for March. From December to February the scatter of the snow depth pairs strongly increases (February: only Indian Ocean Sector) but it usually remains below 0.3. However, for the Indian Ocean with 0.43 the correlation coefficient is high compared to the other sectors and months. Comparing this comparison to the other months and sectors indicates that this rather seems to be an effect of the data sampling than a better performance of the algorithm. Similarly to the West Antarctic sectors the RMSD increases for both sectors from November to January and decreases again towards March. Similar to the West Antarctic sectors for the Indian Ocean and Western Pacific Ocean Sectors the y-intercept shows a distinguishable maximum between 20 to 30 cm for January and February.

The comparisons for the West Antarctic, the East Antarctic and the Antarctic are a combination of all snow depth pairs of their respective sectors. The overall pattern found for the comparison of SSM/I snow depth retrievals in the single sectors remains the same for the West Antarctic, the East Antarctic and the whole Antarctic (underestimation of snow depth below approximately 15 cm and overestimation of snow depth above approximately 30 cm by the SSM/I snow depth retrieval, increase of the RMSD from November to January and then decrease from January to March) and thus they are not discussed here in addition to the single sectors.

**Winter Period: April-October**

The months from April to October roughly mark the winter period in the Antarctic. The comparisons for those months are shown in Figs. A.4 - A.10 (Appendix A).

In the Weddell Sea for April until August the comparison of SSM/I snow depth retrievals with ASPeCt snow depth observations show a strong clustering below snow depths of approximately 20 cm. However, while the comparisons for April and July show only the cluster in this region, the comparisons for May, June, and August show also snow depth pairs at higher snow depths but with stronger scatter. Here, especially the months May and June are of particular interest since the correlation coefficients are with 0.71 and 0.9 much higher than for all other sectors and comparisons. While for both comparisons overestimations of low ASPeCt snow depths can be found they are close to the one-to-one line and thus the slope of the comparisons is close to one. However, for May the effect of the snow depth pairs with ASPeCt snow depth estimates being overestimated by the SSM/I retrieval is reduced by snow depth pairs with ASPeCt snow depth estimates being underestimated by the SSM/I retrieval and thus the slope of the regression line is closer to one than that for June. Although the comparison does not contain data which were used in the setup of the original snow depth retrieval algorithm [RD-02], they were partly collected in the Weddell Sea during the same period (ISW [RD-40]) and thus most likely represent the snow conditions in the Weddell Sea better for the winter months May
and June than for the rest of the year. Here, it is interesting to note that for July, where also observations from one Polarstern cruise were used in the setup of the retrieval algorithm [RD-02], the ASPeCt snow depth estimates are less well correlated with the SSM/I snow depth retrievals. However, since the RMSD is only about 4 cm, this may be caused by the fact that only snow depths lower than about 20 cm contribute to the comparison and thus even small deviations at lower and higher snow depths may strongly affect the regression.

For the months August to October the snow depth pairs above 20 cm are generally stronger scattered than for April and July, however, while the comparison still shows a strong clustering for snow depths below 20 cm in August this clustering disappears for September and October. During the whole winter period the RMSD remains below 15 cm. However, it becomes especially low for those months in which the SSM/I-ASPeCt snow depth pairs build a cluster below 20 cm (April, July, and August). The y-intercept is usually below 10 cm and shows a slight decrease from about 5 cm in April to 10 cm in October. During the winter period in the Bellingshausen and Amundsen Seas Sector, no data are available for April and May. However, for June and July the comparisons show a similarly strong clustering as found for April and July in the Weddell Sea. For both months the RMSD lies between 6 and 8 cm. For the period between August and October the scatter found in the data is much stronger and similar to that found in the Weddell Sea, however, compared to the same months in the Weddell Sea the correlation is with about 0.5 for August and September and about 0.8 for October much higher than found for the Weddell Sea and the RMSDs for all three months lie between 10 cm and 15 cm. Here, a part of the data used for the setup of the original snow depth retrieval algorithm came from the R/V Nathaniel Palmer cruise during August and September 1993 [RD-02]. Since these data are also used in this comparison they may contribute to the high correlation between ASPeCt snow depth observations and SSM/I retrievals. However, it is interesting to note that the correlation is lower and the regression line is further away from the one-to-one line than for the Weddell Sea although the majority of the setup data came from the Bellingshausen and Amundsen Seas Sector. This indicates that the current retrieval is of limited use in the Bellingshausen and Amundsen Seas Sector even in the winter months. In addition, the y-intercept shows a similar behavior as found for the Weddell Sea Sector.

For the Ross Sea Sector the comparison shows a similar pattern as found for the Bellingshausen and Amundsen Seas Sector. For the period between April and June the comparison shows a strong clustering for snow depths below 20 cm with RMSDs between 5 and 8 cm. For the period between August and October the comparison shows a strong scatter with RMSDs between 11 and 18 cm. In July no data are present. While for the rest of the year the y-intercept is below 10 cm in September it is about 25 cm, however, considering that the slope is negative and only four snow depth pairs are present this most likely is only an effect of the snow depth pair distribution. The comparisons for the Indian Ocean Sector again show a strong clustering for snow depths below 20 cm. While for April and May only a few snow depth pairs with either of the both snow depths above 20 cm can be found and the RMSD is below 9 cm, the number of snow depth pairs especially with ASPeCt snow depth averages above 20 cm increases. Here, for both months the correlation coefficient is either negative or close to zero. While during the whole period from April to October the RMSDs lie between 8 and 12 cm, the correlation coefficient is usually close to zero (August/October)
or positive. However, although for September the correlation coefficient is about 0.45 this only implies that both datasets are stronger positively correlated than for the other months but the slope of the regression line is with approximately 0.2 still relatively low.

For the Western Pacific Ocean the comparison shows a similar structure as found for the Indian Ocean Sector. However, while the SSM/I snow depth retrieval gives usually snow depths less than 20 cm the ASPeCt averages are much more variable with a relatively strong scatter. Usually the RMSD lies between approximately 9 and 14 cm. However, in June and July the snow depth pairs show a much stronger scatter with RMSDs of approximately 24 cm and 28 cm, respectively.

As for the West Antarctic Sectors for both, the Indian Ocean Sector and the Western Pacific Sector the y-intercept is usually smaller than 10 cm.

Figure 4.2: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for the period between April and October. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are pixel averages. For full set of correlation coefficients see Tab. A.1.
Just as for the summer period the results for the West Antarctic, the East Antarctic and the whole Antarctic are similar to the single sectors and thus will not be discussed here separately. However it has to be noted that especially for May and June (Figs. A.5 and A.6, Appendix A) the overall comparison for the West Antarctic and the whole Antarctic are strongly affected by the comparisons from the Weddell Sea (especially by those with SSM/I snow depth retrievals larger than 20 cm) and thus the regression line lies close to the one-to-one line.

**Period April-October and whole Dataset**

The comparisons for the period between April and October as well as the whole period, for which data are available, are shown in Figs. 4.2 and 4.3. Generally both comparisons show a very strong influence from salient comparisons from the single months.

For the Weddell Sea Sector the comparison is mainly dominated by a cluster of snow depths below 20 cm. However, due to the high snow depths discussed for May and June the regression line is still very close to the one-to-one line with a slope of about 0.8 and a correlation coefficient of about 0.66 for the period between April and October. For the whole year the situation is very similar and the only difference is that with about 0.55 and 0.46 the slope and the correlation coefficient are lower. With about 10 cm (April-October) and 14 cm (whole year) the RMSDs of both comparisons show only a slight increase when including the months November to March. In addition, the y-intercept increases from approximately 5 cm to 9 cm when the period November to March is included.

For the Bellingshausen and Amundsen Seas Sector the situation is very similar. One can find a cluster of snow depth pairs at snow depths below 20 cm (mainly originating from observations in June, July and October) however, for snow depths above 20 cm the snow depth pairs from August, September, and partly October have a very strong influence on the regression line. Thus, despite being lower, with 0.42 and 0.57 for the period between April and October and 0.42 and 0.64 for the whole year the slope of the regression line and the correlation coefficient of both comparisons show that both datasets are relatively well correlated and the underestimation especially of snow depths above 20 cm is not as strong as for the East Antarctic. As for the Weddell Sea Sector the RMSD only increases slightly from approximately 10 cm to approximately 12 cm when including the months November to March. Contrary to the RMSD the y-intercept remains with about 9 cm relatively constant.

For the Ross Sea Sector the comparisons for the period between April and October and for the whole year show significant differences. While for the period between April and October the ASPeCt pixel averages are always below 40 cm while for the whole year ASPeCt pixel averages cover the whole range between 0 and 70 cm. However, while the correlation coefficient remains approximately constant, the slope of the regression line decreases from approximately 0.65 to 0.27, the RMSD increases from approximately 10 cm to approximately 18 cm, and the y-intercept from approximately 5 to 10 cm, when the months between November and March are included.

As for the single months the comparisons for the Indian Ocean and Western Pacific Ocean Sectors show nearly no correlation between the pixel averaged ASPeCt snow depths and the SSM/I retrieval result (R<0.1) for the period between April and October. However, when the period between November and March is included the slope of the regression line and the correlation coefficient increase from 0.05 to 0.26 and 0.08 to 0.28 for the Indian Ocean
Sector. This increase is predominantly caused by the presence of SSM/I pixels with snow depths above 20 cm. In addition for both the Indian Ocean Sector and the Western Pacific Ocean Sector the RMSD increases from 9.5 cm (Indian Ocean) and 13.7 cm (Western Pacific Ocean) to 11.5 cm (Indian Ocean) and 16.5 cm (Western Pacific Ocean). For both comparisons the y-intercept remains approximately constant (Indian Ocean Sector: ~5-6 cm, Western Pacific Ocean: ~9 cm).

The effects discussed above for the single sectors are also reflected in the comparisons for the West Antarctic, the East Antarctic and the whole Antarctic. For the West Antarctic the influence of the high correlation and slope near one in May and June from the Weddell Sea Sector and August and September from the Bellingshausen and Amundsen Seas Sectors is still present. However, the slope of the regression line and the correlation coefficient decrease from 0.6 to 0.36 and from 0.57 to 0.43, respectively.

**Figure 4.3:** Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic. SSM/I observation period: 1992-2008, SSM/I and ASPeCt observations are pixel averages. For full set of regression coefficients see Tab. A.1.
The RMSD increases from 10 cm to 15.1 cm and the y-intercept from 6.3 to 10.1 cm when the months from November to March are included in the comparison.

In the East Antarctic due to the influence of the snow depth pairs with retrieved SSM/I snow depths larger than 40 cm from the Indian Ocean Sector the slope of the regression line, the correlation coefficient and the root RMSD increase slightly from 0.07 to 0.13, from 0.1 to 0.18 and from 11.7 cm to 14.1 cm, respectively, when the months from November to March are included. The y-intercept remains roughly constant (~7 cm).

While being less strong the behavior found for the West Antarctic can also be found for the whole Antarctic. The slope of the regression line slightly decreases from 0.38 to 0.32, while the correlation coefficient is with 0.4 approximately constant for both comparisons and the RMSD deviation increases from 10.8 cm to 14.7 cm. Further, the y-intercept increases from 6.6 to 8.3 cm.

**Influence of Sea Ice Concentration**

The results change only slightly, when in the comparison instead of sea ice concentrations (SIC) ≥ 20% only SICs ≥ 80% are considered (for slope, y-intercept, correlation coefficient and number of data pairs included see Tabs. A.3 and A.4). Usually the variation of the slope and the correlation coefficient is within ± 0.1 and the change of the RMSD within approximately ± 2 cm. Therefore, no additional figures are shown here for the regressions with SICs ≥ 80%. Instead the few cases with notable changes are described in the following text. The changes in slope and correlation coefficient rather depend on the distribution of the snow depth pairs than on the absolute values of the corresponding snow depths. The opposite is the case for the RMSD, thus, changes in the RMSD can be larger.

Although, for most of the presented comparisons the change of the regression coefficients and the RMSD is comparatively low, in some cases extreme changes caused by the distribution of the snow depth pairs can be found. Especially when snow depth pairs with snow depths below 20-30 cm are removed slope and intercept can show a salient change. This feature only occurs for the summer months. For December removal of snow depth pairs with snow depths below 20-30 cm leads to salient changes of the regression coefficients for the Bellingshausen and Amundsen Seas Sector, the Indian Ocean Sector, the Western Pacific Ocean Sector and as a consequence of the regression coefficients in the West and East Antarctic, while the comparison for the whole Antarctic is not that strongly affected. A similar effect can be found when snow depth pairs with high snow depths are removed. As an example for the comparison in the Bellingshausen and Amundsen Seas Sector (Fig. A.1) the line with constant ASPeCt snow depth along the SSM/I axis and except one snow depth pair the whole Western Pacific Ocean Sector’s snow depth pairs are removed. As a result the y-intercept reduces from approximately 30 to 20 cm and the slope increases from 0.15 to 0.43 for the Bellingshausen and Amundsen Seas, and the reduction of the Western Pacific Ocean Sector snow depth comparison to one snow depth pair leads to the removal of all except one snow depth pairs below the one-to-one line which drags the regression line down. Other months with salient changes of the regression line can be found for the month February for the Ross Sea and Indian Ocean Sectors and as a result for the West and East Antarctic.
4.2.2 Daily Averages

Figure 4.4: Slope, y-Intercept, correlation coefficient, RMSD and number of snow depth pairs of the comparisons of SSM/I snow depth retrievals with ASPeCt ship-based snow depth estimations for single months, the whole winter period (April-October) and the whole dataset. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are daily averages. For full set of regression coefficients see Tab. A.1.

The comparison of the daily averaged snow depths retrieved from SSM/I passive microwave data with daily-averaged ASPeCt observations are shown in Figs. A.13 - A.24 (Appendix A) following the annual cycle (January - December) and in Figs. 4.5 and 4.6 for the period between April and October and the whole dataset, respectively. The correlation coefficients of the regressions and the RMSDs for the single months can be found in Tab. A.3 for the comparison for snow on sea ice with concentrations ≥ 20% and in Tab. A.4 for the comparison of snow on sea ice with concentrations ≥ 80%.

Fig. 4.4 concludes the monthly values of the regression coefficients (slope, y-intercept and correlation coefficient), RMSD and the number of snow depth pairs used for each comparison, for each of the Antarctic sectors, for
their combinations the West Antarctic (Weddell Sea, Bellingshausen and Amundsen Seas, and Ross Sea Sectors), the East Antarctic (Indian Ocean and Western Pacific Ocean Sectors) and the whole Antarctic. Despite a reduction of snow depth pairs the basic features observed in the comparison of daily averaged SSM/I snow depth retrievals with daily averaged ASPeCt snow depth observations commonly maintain the same features as already discussed for the pixel averages. Thus here only the most significant changes will be discussed.

**Summer Period: November-March**

When switching from pixel averages to daily averages for the summer period the RMSD generally either remains roughly constant or reduces by up to approximately 5 cm. However, for December in the Bellingshausen and Amundsen Seas Sector and for January the Indian Ocean Sector and the East Antarctic the comparisons show an increase of the RMSD by approximately 1-2 cm. This is caused by the decrease of the number of the snow depth pairs compared to the pixel averages and the associated change in the distribution of the pixel snow depth pairs.

In November the most drastic change can be observed for the Weddell Sea Sector. The slope as well as the correlation coefficient increase from 0.3 to 0.57 and from 0.27 to 0.5 and the y-intercept decreases from 12.6 cm to 4.7 cm. Here, the reduction in the y-intercept is mainly caused by the snow depth pairs with SSM/I snow depths around 40 cm in Fig. A.1 being averaged into fewer pixels closer to the regression line. This is also one cause for the increase of the slope. The other contribution to the increase of the slope is that the number of snow depth pairs, with averaged ASPeCt snow depths between 20 and 40 cm and being underestimated by the SSM/I snow depth retrieval, are averaged into fewer snow depth pairs closer to the regression line.

A similar effect occurs for the December comparison in the Indian Ocean Sector. Especially above the one-to-one line snow depth pairs are averaged into fewer points and as a result the slope of the regression line increases from 0.52 to 0.76 and the correlation coefficient from 0.43 to 0.63 while the RMSD decreases from 13.8 cm to 10.6 cm and the y-intercept from 14.9 cm to 9.3 cm. However, in some cases, such as found for the March comparison in the Western Pacific Ocean Sector, the averaging may only cause a significant increase of the correlation coefficient compared to the change of the slope (March - Western Pacific Ocean Sector: 0.08 to 0.25), y-intercept (March - Western Pacific Ocean Sector: 3.2 to 0.4) and RMSD (March - Western Pacific Ocean Sector: < 1 cm).

In other cases, especially when low snow depths average out in the averaging process (e.g. January-comparison for the Bellingshausen and Amundsen Seas Sector, Figs. A.1 and A.13) the sign of the slope can also reverse. A similar case occurs for the February-comparison in the West Antarctic and whole Antarctic. The slopes for the West Antarctic and the Antarctic improve from nearly zero to about 0.2 and to about 0.14 for the Antarctic, the correlation coefficient increases from close to zero to 0.21 and 0.13, respectively, while the y-intercept and the RMSD reduce only slightly by approximately 2 to 4 cm for both comparisons.

**Winter Period**

For the winter months the effects occurring due to the averaging process are similar as for the summer months and therefore they will not be
discussed here again. The changes in slope, $\gamma$-intercept, correlation coefficient and RMSD are generally comparable to those found for the summer months.

**Figure 4.5:** Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for the period between April and October. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.

**Period April-October and whole Dataset**

For the period between April and October as well as the whole year the comparisons show only very small differences, with the largest differences occurring for the Weddell Sea Sector, the West Antarctic and the whole Antarctic. For these comparisons the course of the regression line is mainly determined by the distribution of the single snow depth pairs as well as the effects occurring due to the averaging procedure. Here, especially snow depth pairs with ASPeCt snow depth pixel averages above 25 cm are averaged into fewer daily averages and due to the presence of higher SSM/I snow depth averages above 25 cm when switching from pixel averages to
daily averages the slope of the regression line and the correlation coefficient increases, while the RMSD and the y-intercept decrease. For the remaining comparisons the slope, the y-intercept, the correlation coefficient and the RMSD are comparable to those from the pixel averages.

**Influence of Sea Ice Concentration**

Switching from 20% sea ice concentration to 80% sea ice concentration the results are generally similar as for the pixel averages, only that in those cases for which only few snow depth pairs are present the change in slope, y-intercept, correlation coefficient and RMSD are slightly more extreme. The same is valid when comparing the daily averages for 20% and 80% sea ice concentration.

**Figure 4.6:** Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
4.3 AMSR-E

Contrary to the SSM/I period data cover of the AMSR-E period is relatively low and thus strongly affects the quality of the comparison. For example in particular for the two winter months May and June no data are available and for April and July the data cover is quite sparse (see also Fig. 5 in [RD-33]). Although the data cover is limited an attempt was made to compare AMSR-E snow depth retrievals for the Antarctic sectors and single months separately. However, the results have to be treated with utmost care and are most likely not representative. The comparison for the winter and spring period between April and October is most likely more representative and thus the focus of the discussion will be set on this comparison and a comparison in which data from all months are included. Besides the comparison with the ASPeCt dataset also a comparison with data from the ASPeCt-Bio dataset as well as from ISPOL are presented. Since in situ data are more sparse than the ASPeCt observations a comparison was only made for the winter and spring period (ASPeCt-Bio only) and for all months (ASPeCt-Bio and ISPOL). Similarly to the comparison of the SSM/I snow depth dataset with ASPeCt ship observations the influence of the sea ice concentration on the retrieved snow depth is investigated by comparing the comparisons for snow depths on sea ice with concentrations ≥ 20% and ≥ 80%. However, similarly to the comparison for SSM/I the results of both comparisons are not substantially different and thus the comparison for sea ice concentrations ≥ 20% are shown here, while for sea ice concentrations ≥ 80% only the regression coefficients are given.

4.3.1 ASPeCt

4.3.1.1 Pixel Averages

The comparison of the snow depths retrieved from AMSR-E passive microwave data with pixel-averaged ASPeCt observations are shown in Figs. A.25 - A.34 following the annual cycle (January - December) and in Figs. 4.8 and 4.9 for the period between April and October and all data for the whole period, respectively. The correlation coefficients of the regressions and the RMSDs for the single months can be found in Tab. A.5 for the comparison for snow on sea ice with concentrations ≥ 20% and in Tab. A.6 for the comparison of snow on sea ice with concentrations ≥ 80%.

Fig. 4.7 concludes the monthly values of the regression coefficients (slope, y-intercept and correlation coefficient), RMSD and the number of snow depth pairs used for each comparison, for each of the Antarctic sectors, for their combinations the West Antarctic (Weddell Sea, Bellingshausen and Amundsen Seas, and Ross Sea Sectors), the East Antarctic (Indian Ocean and Western Pacific Ocean Sectors) and the whole Antarctic.

Summer Period: November-March

In the summer period for the comparison between the retrieved snow depth from AMSR-E passive microwave brightness temperatures with ASPeCt pixel averages generally only few (<30) snow depth pairs per sector could be found. The only exceptions are the Weddell Sea Sector (48 pixels) in December, the Ross Sea Sector in March (396 pixels) and December (159 pixels) and the Bellingshausen and Amundsen Seas Sector in December (101 pixel). Besides January and February, where for the Weddell Sea Sector slope and correlation coefficient are 0.48 and 0.67, and 0.4 and 0.55,
respectively, the slope of the regression line as well as the correlation coefficient is always close to zero or even negative. However, for the Weddell Sea Sector in January and March only few pixels (6 and 5, respectively) are available and thus it is most likely that the relatively good regression is due to the distribution of the snow depth pairs and not necessarily due to an overall agreement of the pairs with the regression line since the estimated uncertainty of the 1σ-standard deviation is about ±1. Furthermore, the y-intercepts vary between about 2 cm (Weddell Sea Sector, March) and 16 cm (Ross Sea Sector, January). The RMSD is relatively low for the months January to March (5-15 cm) as well as for the Weddell Sea Sector in December, however, for November and December it increases up to 27 cm (Weddell Sea Sector, November).

In the East Antarctic data are only available for the Western Pacific Ocean in November and for the Indian Ocean Sector in December. Similar to the West Antarctic sectors the slope of the regression lines is always close to zero, and the y-intercept is lower than 2 cm. However, while for the Indian Ocean Sector the correlation coefficient is zero, it is about 0.5 for the Western Pacific Ocean Sector. A comparison with Fig. A. 33 shows that all snow depth pairs lie closely around the regression line. Therefore, although the slope of the regression line is close to zero (about 0.05) it results in a high correlation. The results for the comparisons for West Antarctic, the East Antarctic and the whole Antarctic are similar to those already described for the single sectors, in fact for the East Antarctic they are identical, and thus they will not be discussed here again.

**Winter Period: April-October**

For the winter period between April and October the situation is much more variable. For April and July (no data are available for May and June) the snow depth pairs can only be found for AMSR-E snow depth retrievals below 10 cm. On the other hand the ASPeCt pixel averages vary between 0 and 30 cm and thus the RMSD is relatively high: about 12 cm. However, while for April the regression lines of those sectors for which data are available have a slope close to zero, the slope of the regression line for the comparison in July is approximately 0.35 (only data for Weddell Sea available) but the variation along the x-axis is confined for snow depths between 0 and 10 cm and consequently the RMSD is relatively low.

Similarly to April in August the comparisons for the Weddell Sea and the Bellingshausen and Amundsen Seas have slopes and correlation coefficients close to zero. For the West Antarctic and the whole Antarctic the slope as well as the correlation coefficient are approximately 0.2. Here, the snow depth pairs with AMSR-E snow depth retrievals of approximately 20 cm from the Bellingshausen and Amundsen Seas Sector lifts the upper end of the regression line up. However, because especially for high snow depth >20 cm no snow depth pairs are available it is not sure how representative this comparison is and how it would look in the case a larger amount of data could be included.

For September and October all comparisons have slopes and correlation coefficients larger than zero, however, the scatter of the ASPeCt snow depth usually shows a larger variability than the corresponding AMSR-E retrievals. Here, the positive correlation coefficients indicate that although the pixel-averaged ASPeCt observations tend to be underestimated by the AMSR-E retrieval AMSR-E tends to observe increasing snow depth when ASPeCt observations also indicate increasing snow depths for late winter.
Further, Fig. 4.7 shows that in the West Antarctic the RMSD increases from below 5 cm in the Weddell Sea Sector (July) to about 20 cm in October (and even further if November and December are considered as well). Figures A.29-A.32 show that the increase of the RMSD is mainly caused by increasing scatter and partly also by a reduction of the amount of data included in the comparison.

In the East Antarctic only data for the Western Pacific Ocean Sector are available (April, September and October). The slope of the regression line is usually below 0.2. While the retrieved AMSR-E snow depths are usually below 20 cm, the ASPeCt pixel-averages lie between 0 and 70 cm and show a relatively strong scatter. Here, for September and October the snow depth pairs lie relatively close to the regression line. Hence the correlation coefficients are about 0.4 and 0.5, respectively.

For the West Antarctic, the East Antarctic and the whole Antarctic the features are basically the same as already discussed for the single sectors and thus the comparisons will not be discussed here.

Figure 4.7: Slope, y-Intercept, correlation coefficient, RMSD and number of snow depth pairs of the comparisons of SSM/I snow depth retrievals with ASPeCt ship-based snow depth estimations for single months, the whole winter period (April-October) and the whole dataset. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.5.
Period April-October and whole Dataset

The results discussed in the last passage are also indicated by the comparison for the period between April and October (Fig. 4.8). However, for the whole year, different to the comparison of SSM/I snow depth retrievals, the comparisons gave regression lines with slopes close to zero except for the Weddell Sea Sector.

Figure 4.8: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for the period between April and October. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.5.
Figure 4.9: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.5.

Influence of Sea Ice Concentration

The results of the comparisons also do not change significantly when the included snow depths are confined to sea ice concentrations of 80% or higher. The only salient changes here occur in January for the Bellingshausen and Amundsen Seas Sectors, in February for the Ross Sea Sector, and in December for the Weddell Sea Sector. However, since for those sectors only three pixels remain after the confinement of the snow depth to sea ice concentrations of 80% and above these changes are most likely not significant for the whole sector. Thus they are not discussed here.
4.3.1.2. Daily Averages

Figure 4.10: Slope, y-Intercept, correlation coefficient, RMSD and number of snow depth pairs of the comparisons of SSM/I snow depth retrievals with ASPeCt ship-based snow depth estimations for single months, the whole winter period (April-October) and the whole dataset. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are daily averages. For full set of regression coefficients see Tab. A.7.

The comparison of daily averaged AMSR-E passive microwave snow depth retrievals with daily-averaged ASPeCt observations are shown in Figs. A.35 - A.43 following the annual cycle (January - December) and in Figs. 4.11 and 4.12 for the period between April and October and all data for the whole period, respectively. The correlation coefficients of the regressions and the RMSDs for the single months can be found in Tab. A.7 for the comparison for snow on sea ice with concentrations ≥ 20% and in Tab. A.8 for the comparison of snow on sea ice with concentrations ≥ 80%.

For the daily averages the results of the comparison are generally similar to for the pixel averages, however, with fewer snow depth pairs. Here, this decrease of snow depth pairs mostly affects the comparison for the Weddell Sea and Ross Sea Sector in January where the slope strongly increases for
the first and strongly decreases for the latter. Further, for the comparison in July and for the Western Pacific in April less than three snow depth pairs remain and thus those days are only included in the comparison for the next higher level (sector or period).

Figure 4.11: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for the period between April and October. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.7.
Figure 4.12: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.7.

Influence of Sea Ice Concentration

When the sea ice concentration is limited to 80% and higher the results of the comparisons basically do not change. The number of the snow depth pairs in the Indian Ocean Sector, however, is now smaller than three and thus the sector is excluded from the comparison and thus only occurs in the comparison for the East Antarctic (if enough data are available) and the whole Antarctic. Further, for the Bellingshausen and Amundsen Seas in January one snow depth pair is removed and for the remaining pixel the AMSR-E daily averages are below 20 cm while the ASPeCt daily snow depth averages are all above 60 cm and thus this result is not representative for the whole sector.
4.3.2 ASPeCt-Bio and ISPOL

For the AMSR-E observation period ASPeCt-Bio data were only available for the Weddell Sea, the Bellingshausen and Amundsen Seas, and the Western Pacific Ocean Sectors. As for the comparison of AMSR-E snow depths with ASPeCt data the comparison was done for pixel and daily averages separately. Since contrary to the ASPeCt dataset only about 70 pixel averages for the winter period and 80 for the whole year were available, the comparison was not done for single months separately but only for the period from April to October as well as the whole year. The difference of the latter to the first is that here the ISPOL data were added. For both datasets the influence of the sea ice concentration was not investigated since the NSIDC NT2 sea ice concentration always indicate sea ice concentrations above 80%.

4.3.2.1 Pixel Averages

Fig. 4.13 shows the pixel-based comparison of ASPeCt-Bio snow depth data with NSIDC AMSR-E snow depth retrievals. In total there are 11 snow depth pairs for the Weddell Sea sector, 20 snow depth pairs for the Bellingshausen and Amundsen Seas Sector, and 38 snow depth pairs for the Western Pacific Ocean Sector. A full list of all correlation coefficients and RMSDs can be found in Tab. 4.1. While for the Weddell Sea Sector the regression line indicates a positive correlation between the retrieved snow depth and in-situ measurements the correlation shows a negative tendency for the Bellingshausen and Amundsen Seas Sector as well as for the Western Pacific Ocean Sector with correlation coefficients of about -0.1. However, since especially for the Weddell Sea Sector only very few measurements are available it remains an open question if this correlation still holds if a larger number of pixels were included in the comparison. The comparisons for the West Antarctic and the whole Antarctic (since for the Indian Ocean Sector no data is available the comparison for the East Antarctic has the same results as the comparison for the Western Pacific Ocean Sector) are a combination of the single sectors. Thus for the West Antarctic data distribution within the scatter plot is an overlap of the distributions for the Weddell Sea Sector and the Bellingshausen and Amundsen Seas Sector. The low snow depths (< 15 cm) influence the regression line such that although the Bellingshausen and Amundsen Seas Sector has nearly no correlation an overall tendency of increasing snow depths retrieved by AMSR-E with increasing snow depths from in-situ measurements can be observed. The same effect occurs for the whole Antarctic, only that the large cluster of low snow depths (< 15 cm) gives these values even more weight than those in the West Antarctic had and thus the correlation is higher than for the West Antarctic. However, although the different sectors show a different snow depth pair distribution the RMSD of the snow depth is with values between 10 cm and 15 cm relatively constant.

Similar to the comparison of the SSM/I and NSIDC AMSR-E snow depth retrievals with ASPeCt ship-based observations, the comparison shows that the snow depth retrieved by AMSR-E tends to underestimate the snow depth from in-situ measurements for snow depths below approximately 15 cm and to overestimate snow depths from in-situ measurements for snow depths above approximately 30 cm.
Figure 4.13: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for the period between April and October. AMSR-E observation period: 2002-2007, AMSR-E and ASPeCt-Bio data are pixel averages. For full set of regression coefficients see Tab. 4.2.
Figure 4.14: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic. AMSR-E observation period: 2002-2007, AMSR-E, ASPeCt-Bio, and ISPOL data are pixel averages. For full set of regression coefficients see Tab. 4.2.

Fig. 4.14 shows the same comparison as Fig. 4.13 but for the entire year. The regression coefficients and RMSDs can be found in Tab. 4.2. The only difference to Fig. 4.13 is that due to the extended time period the ISPOL dataset was added in the Weddell Sea Sector. The overall pattern is similar to the comparison of the period between April and October, only that the correlation coefficient for the Weddell Sea is lower and the RMSD for the Weddell Sea Sector, the West Antarctic as well as the Antarctic are approximately 5, 3 and 2 cm higher than before. This is caused by the high snow depths contained in the ISPOL dataset.
Table 4.2: Regression coefficients for the comparison of in-situ measurements from the ASPeCt-Bio and ISPOL dataset with NSIDC AMSR-E snow depth retrievals, pixel averages.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Slope</th>
<th>Intercept(cm)</th>
<th>R</th>
<th>RMSD(cm)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weddell Sea</td>
<td>0.26±0.12</td>
<td>8±2.7</td>
<td>0.65</td>
<td>12.6</td>
<td>11</td>
</tr>
<tr>
<td>Bellingshausen and Amundsen Seas</td>
<td>-0.05±0.21</td>
<td>20±5.2</td>
<td>-0.06</td>
<td>13.6</td>
<td>20</td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>-0.04±0.05</td>
<td>7±0.7</td>
<td>-0.12</td>
<td>10.6</td>
<td>38</td>
</tr>
<tr>
<td>West Antarctic</td>
<td>0.17±0.13</td>
<td>13.1±3</td>
<td>0.26</td>
<td>13.3</td>
<td>31</td>
</tr>
<tr>
<td>East Antarctic</td>
<td>-0.04±0.05</td>
<td>7±0.7</td>
<td>-0.12</td>
<td>10.6</td>
<td>38</td>
</tr>
<tr>
<td>Antarctic</td>
<td>0.25±0.07</td>
<td>7.5±1.4</td>
<td>0.39</td>
<td>11.9</td>
<td>69</td>
</tr>
</tbody>
</table>

Period: April-October

<table>
<thead>
<tr>
<th>Sector</th>
<th>Slope</th>
<th>Intercept(cm)</th>
<th>R</th>
<th>RMSD(cm)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weddell Sea</td>
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<td>9±2.7</td>
<td>0.52</td>
<td>17.3</td>
<td>22</td>
</tr>
<tr>
<td>Bellingshausen and Amundsen Seas</td>
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<td>20±5.2</td>
<td>-0.06</td>
<td>13.6</td>
<td>20</td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>-0.04±0.05</td>
<td>7±0.7</td>
<td>-0.12</td>
<td>10.6</td>
<td>38</td>
</tr>
<tr>
<td>West Antarctic</td>
<td>0.16±0.09</td>
<td>12.9±2.5</td>
<td>0.28</td>
<td>15.6</td>
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</tr>
<tr>
<td>East Antarctic</td>
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<td>7±0.7</td>
<td>-0.12</td>
<td>10.6</td>
<td>38</td>
</tr>
<tr>
<td>Antarctic</td>
<td>0.25±0.06</td>
<td>7.7±1.3</td>
<td>0.44</td>
<td>13.5</td>
<td>80</td>
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</table>
4.3.2.1 Daily Averages

Figure 4.15: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for the period between April and October. AMSR-E observation period: 2002-2007, AMSR-E and ASPeCt-Bio data are daily averages. For full set of regression coefficients see Tab. 4.3.

Figs. 4.15 and 4.16 show the same comparisons as Figs. 4.13 and 4.14. The regression coefficients can be found in Tab. 4.3. The only difference is that here daily averages instead of pixel averages are compared. Since usually most in-situ measurements were only conducted within one pixel the pattern of the scatter plots for the daily averages are very similar to the scatter plots obtained for the pixel averages. Thus the discussion would be the same as for the pixel averages and thus is not repeated here.
Figure 4.16: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic. AMSR-E observation period: 2002-2007, AMSR-E, ASPeCt-Bio, and ISPOL data are daily averages. For full set of regression coefficients see Tab. 4.3.
### Table 4.3: Regression coefficients for the comparison of in-situ measurements from the ASPeCt-Bio and ISPOL dataset with NSIDC AMSR-E snow depth retrievals, daily averages.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Slope</th>
<th>Intercept[cm]</th>
<th>R</th>
<th>RMSD[cm]</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weddell Sea</td>
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<td>8±2.7</td>
<td>0.65</td>
<td>12.6</td>
<td>11</td>
</tr>
<tr>
<td>Bellingshausen and Amundsen Seas</td>
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<td>20±5.2</td>
<td>-0.06</td>
<td>13.6</td>
<td>20</td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>0.02±0.06</td>
<td>6.5±0.8</td>
<td>0.05</td>
<td>9</td>
<td>31</td>
</tr>
<tr>
<td>West Antarctic</td>
<td>0.17±0.13</td>
<td>13.1±3</td>
<td>0.26</td>
<td>13.3</td>
<td>31</td>
</tr>
<tr>
<td>East Antarctic</td>
<td>0.02±0.06</td>
<td>6.5±0.8</td>
<td>0.05</td>
<td>9</td>
<td>31</td>
</tr>
<tr>
<td>Antarctic</td>
<td>0.29±0.08</td>
<td>7.3±1.5</td>
<td>0.43</td>
<td>11.4</td>
<td>62</td>
</tr>
</tbody>
</table>

#### 4.4 Summary and Discussion

SSM/I and AMSR-E snow depth retrievals were compared with snow depth estimates and in-situ measurements from the ASPeCt protocol (official ASPeCt dataset until 2005 and the extended dataset for the period from 2002 to 2006) and the ASPeCt-Bio dataset (2002-2007) for the periods between January 1st, 1992 and April 2nd 2008 and June 1st, 2002 and October 4th 2011, respectively. These comparisons were made for pixel-based as well as daily sector averages (i.e. all pixels averaged on one day in one sector) for (1) the five Antarctic sectors, (2) the West and East Antarctic, as well as (3) the whole Antarctic. The comparisons were done for (1) all months separately, (2) only the Antarctic winter period from April to October as well as (3) the whole dataset. The influence of the sea ice concentration was investigated by comparing the retrieved snow depths for sea ice concentrations ≥ 20% and ≥ 80%.

**SSM/I Results Summary**

In general the comparison of ASPeCt and ASPeCt-Bio snow depth averages with SSM/I and AMSR-E snow depths (averages) shows an overestimation of ASPeCt/ASPeCt-Bio snow depth averages by SSM/I and AMSR-E snow depth retrievals for snow depths below about 15 cm, and an underestimation for snow depths above about 30 cm.

For SSM/I, in the West Antarctic sectors the comparisons showed a relatively high correlation for winter months, and here in particular in May and June for the Weddell Sea Sector, in the period August to October for the Bellingshausen and Amundsen Seas Sector and in October for the Ross Sea Sector. For the Ross Sea Sector the slope, 0.64, is relatively high, and the
correlation coefficient, 0.3, is relatively low, which is caused by relatively strong scatter of the snow depth pairs. In contrast, for the Weddell Sea Sector the slopes are close to one and the correlation coefficients are 0.71 for May and 0.9 for June. For the Ross Sea Sector the slope varies between 0.37 in September and 0.51 in October, while the correlation coefficient varies between about 0.5 in August and September and 0.82 in October. Furthermore, for the months April to August the RMSD (root mean square difference) usually is below 10 cm. It increases towards the summer months and reaches its maximum in January and February.

For the East Antarctic sectors the comparison usually yields slopes below approximately 0.2. The correlation coefficient and the RMSD show a relatively random variation and, in contrary to the West Antarctic, no annual pattern is visible.

The comparisons for the West Antarctic, the East Antarctic and the whole Antarctic still showed that results from the single sectors can dominate the results of the larger region, e.g. the West Antarctic. In the West Antarctic this influence especially came from the Weddell Sea Sector in May and June and from the Bellingshausen and Amundsen Seas Sector in August-October. The same effects were also observed in the comparisons for the winter period (April-October) and for the whole dataset, but they are weaker because of the larger number of snow depth pairs.

**AMSR-E Results Summary**

For AMSR-E the comparisons show a higher variability in slope and correlation coefficient as well as RMSD. Here, the strong variations for January-March were caused either by only very few (<10) snow depth pairs, or by the dominance of snow depth pairs with very high differences between ASPeCt snow depth averages and AMSR-E snow depth averages (>20 cm), accompanied by an underestimation of ASPeCt snow depth observations by AMSR-E snow depth retrievals, and snow depth differences >10 cm accompanied by an overestimation of ASPeCt snow depth observations by the AMSR-E snow depth retrievals. Furthermore, relatively good correlations (>0.45) and slopes (>0.3) were found for July, September and October. However, while for the Weddell Sea Sector this was only caused by low snow depths (<10 cm), in the comparisons for September and October in the Bellingshausen and Amundsen Seas Sector this was caused by the presence of a large number of snow depth pairs with ASPeCt snow depth averages below 30 cm and few snow depth pairs with ASPeCt snow depth values above 30 cm (September) to 40 cm (October).

For the East Antarctic sectors the comparison showed the same results as for SSM/I. For the comparisons for the West Antarctic, the East Antarctic and the whole Antarctic, as well as for the period from April to October and the whole year, the single sectors have a similarly high influence as the monthly comparisons for SSM/I.

Similarly to the comparison of SSM/I snow depth retrievals with ASPeCt ship-based snow depth observations, the results from comparing AMSR-E snow depth retrievals with ASPeCt-Bio and ISPOL in situ measurements did not show a significant difference. Here, for the Weddell Sea Sector the slope and the correlation were positive and negative or close to zero for the Bellingshausen and Amundsen Seas and the Western Pacific Ocean Sectors. In the comparison the main result was that passive microwave snow depth retrievals overestimate ASPeCt observations and in situ measurements below about 15 cm and underestimate them for snow depths above about 30 cm.
General Main Outcome

In general the comparison of ASPeCt, ASPeCt-Bio and ISPOL data with the SSM/I and AMSR-E snow depth product had the tendency to show a better agreement between ship-based and in situ reference data for the West Antarctic than for the East Antarctic. Furthermore, the comparisons showed the tendency of the snow depth retrievals to better agree with ship-based and in situ measurements for the winter period (April-October) than for the summer period (November-March).

Discussion of the Limitations

In their original publication Markus and Cavalieri [RD-02] discussed several influences originating from weather effects and changes in snow properties such as snow wetness and snow grain size on the retrieved snow depth. The key points will be summarised here. While it is mainly referred to the paper of Markus and Cavalieri [RD-02], all additionally references provided in the text are the papers listed by Markus and Cavalieri [RD-02] as references.

Markus and Cavalieri [RD-02] noted that in particular for high sea ice concentrations weather effects increase the gradient ratio which can lead to an underestimation of snow depth [RD-34; RD-35]. Furthermore, Markus and Cavalieri [RD-02] describe that an under-/overestimation of the sea ice concentration itself can lead to an over-/underestimation of snow depth. Besides weather effects, snow wetness and grain size have a strong influence on snow properties. Formerly dry snow can be transformed into wet snow in three ways. Firstly, the snow cover is so heavy that the buoyancy of the underlying water cannot balance the gravitational force on the ice sheet and thus the snow-ice interface sinks below the waterline and is flooded. Then due to capillary entrainment the water can also penetrate into snow layers lying above the water level. Due to the high salinity of the intruding sea water compared to dry snow, the dielectric properties of the snow layer are altered. Secondly, if the energy flux through the ice is higher than the flux through the snow layer, the snow begins to melt internally resulting in a change of the dielectric properties for the wet state as well as in the case of refreezing. Thirdly, snow can also melt at the surface due to exposure to solar radiation. Here, Markus and Cavalieri [RD-02] noted that wet snow on land results to a gradient ratio close to zero [RD-36; RD-37] and an underestimation of snow depth.

In addition to the change in dielectric properties the snow grain size changes as well when refreezing occurs. Here, the larger snow grain size results in stronger scattering and because the effect is stronger at 37 GHz than at 19 GHz this can result in a decrease of the gradient ratio and an overestimation of snow depth [RD-02; RD-38]. Further, refreezing of molten surface snow can result in a thin snow-ice layer on top of the snow leading having the same effect [RD-02; RD-39]. However, Markus and Cavalieri [RD-02] note that for satellite observations extreme grain sizes will average out and thus the effects from scattering will be reduced. Among the effects listed by Markus and Cavalieri [RD-02] weather effects, an overestimation of sea ice concentration, and the presence of wet snow could be one cause for the observed underestimation of ASPeCt observations and in situ measurements by SSM/I and AMSR-E snow depth retrievals for snow depths above 30 cm, while the observed overestimation for snow depths below 15 cm can be caused by snow with large grain sizes due to e.g. refreezing of molten snow, underestimation of sea ice concentration, or the formation of a thin ice layer on top of the snow layer.
Besides weather effects and ice and snow properties, the observation geometry may also have a strong influence on the comparison. SSM/I and AMSR-E pixel cover roughly areas of about 625 km$^2$ and 156 km$^2$, respectively, while one ASPeCt observation covers only about 3 km$^2$ and one in situ measurement might not be representative even for 1 m$^2$. Although for the comparison several ship-based or in situ measurements were averaged into one ASPeCt pixel average usually less than about 10 (more commonly less than five) ASPeCt or in situ measurements were available for one pixel and thus commonly less than about 20% of the pixel area is covered. Furthermore, research vessels commonly follow channels of open water and paths of thin ice through the ice cover. Along channels of thin ice or open water sea ice is usually only covered by thin snow layers. In addition, ASPeCt observations are only irregularly spaced within one pixel and thus, the pixel average does not necessarily represent an average snow depth for the entire pixel and in particular for pixels where only observations for thin sea ice were made this can lead to an underestimation of the snow depth for the entire pixel and an overestimation of ASPeCt and in situ measurements by SSM/I and AMSR-E snow depth retrievals. However, due to its large pixel size in particular for SSM/I the variability of snow depth within one pixel can affect the retrieval. But this effect can also not be excluded for AMSR-E. If within one pixels the snow depth exceeds 50 cm this may lead to an underestimation of snow depth because SSM/I and AMSR-E only measure the emission of the upper 50 cm and nothing below. Although this effect may to an unknown degree affect the comparison it should not have a strong effect because pixel averages with ASPeCt or AMSR-E snow depth above 70 cm are filtered out. Furthermore, the better agreement between ship-based snow depth observations and in situ measurements for winter than for summer is most likely caused by surface melt as well as sea ice flooding. While previous analyses from ship-based expeditions and ICESat ice freeboard retrievals generally show a tendency for flooding events to occur in the whole Antarctic [RD-40; RD-41; RD-42; RD-12; RD-16], the analysis of Yi et al. [RD-43] of ICESat freeboard retrievals for the ICESat observation periods from 2003 to 2009 showed that in the Weddell sea flooding mainly occurs for February and March (roughly 20% - 43% of the investigated area) and decreases thereafter (March and April: roughly 20%, May and June: 10-20%, October to December: 0-10%).
5 Derivation of a New Set of Empirical Regression Coefficients for AMSR-E

5.1 Input Data

The re-derivation of the linear regression coefficients is done using the AMSR-E L1A Raw Observation Count data (Version 3), provided by the NSIDC ([http://nsidc.org/data/amsrel1a](http://nsidc.org/data/amsrel1a), [RD-44]). To derive the gradient ratio three different variables were derived from the raw data: the brightness temperatures of the vertically polarized channels at 18.7 and 36.5 GHz, and sea ice concentrations derived from the 89 GHz channels using the ARTIST (ASI) algorithm described by Spreen et al. [RD-45]; see also Kaleschke et al. [RD-46].

From the obtained swath data then daily averages of the sea ice concentration and the brightness temperature were calculated and projected onto a 6.25 km, 12.5 km, and 25 km grid for the sea ice concentration, the 36.5 GHz (only vertical polarisation) and the 18.7 GHz (vertical and horizontal polarization) brightness temperatures, respectively. However, before the gradient ratio can be calculated two important steps have to be done. Firstly, new open water tie points have to be calculated since the old tie points of the retrieval were only provided for SSM/I, and for all other tie points error estimates are not available. Secondly, the uncertainties used for the calculation of the errors of the gradient ratio have to be quantified.

The calculation of the new open water tie points will be discussed in the next Section while the uncertainties of all variables will be discussed in Section 5.3.

5.2 Calculation of Open Water Tie Points at 18.7 and 36.5 GHz

The open water tie points were calculated in three steps. In the first step for the sea ice concentration product and the vertically polarised brightness temperatures of the 36.5 GHz channel the grid resolution was reduced from 6.25 km and 12.5 km to 25 km.

In the next step the ASI sea ice concentration product and the land mask used in ASI were used to filter out areas covered by land and sea ice. In addition from the 18.7 GHz channels the polarisation ratio was calculated:

\[ PR = \frac{T_B(19v) - T_B(19h)}{T_B(19v) + T_B(19h)} \]  

(Spren [RD-47] used the polarisation ratio as weather filter. Similarly, here the polarisation ratio is used to filter out remaining sea ice effects as well as possible cloud and water vapour effects.

After applying these filters to the vertically polarised brightness temperatures of the 18.7 and 36.5 GHz channels a two pixel security belt was laid around the filtered areas by applying a region growing operator to ensure that all sea ice effects are securely excluded.

In the last step for the 18.7 and 36.5 GHz channels the averaged brightness temperatures over open water and their standard deviations were calculated for each day. This was done separately for all Antarctic sectors as well as the West Antarctic, the East Antarctic and the whole Antarctic. From the daily averaged brightness temperatures annual averages as well as the averaged brightness temperature for the period from June 2002 to October
2011 and their standard deviations were calculated to estimate the variability of the brightness temperatures of open water and their errors. To assess the influence of different water masses with their varying temperatures these calculations were performed for all pixels south of a certain latitude limit, which was varied in 5° latitude steps from 50°S to 70°S. Here, the latitude steps represent the upper limit of the area for which the calculations were performed. The results for the Weddell Sea Sector, the Bellingshausen und Amundsen Seas Sector, the Ross Sea Sector, the Indian Ocean Sector, the West Antarctic, the East Antarctic, and the Antarctic are provided in Tabs. 5.1 - 5.8 in the same order. Note that data from the years 2002 and 2011 are not complete.

**Table 5.1: Annual and overall averaged brightness temperatures for the vertically polarised channels at 18.7 and 36.5 GHz over open water for the Weddell Sea Sector.** For 2002 and 2011 only the period for which data is available is considered. Upper latitude steps in 5° from 70°S to 50°S.

<table>
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<th>Year</th>
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<th>≤65°S</th>
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<td>184.9 ± 1.64</td>
<td>184.6 ± 2.09</td>
<td>186.1 ± 2.6</td>
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<tr>
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</tr>
<tr>
<td>2005</td>
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<td>184.6 ± 1.08</td>
<td>184.3 ± 1.46</td>
<td>183.9 ± 1.47</td>
<td>183.5 ± 1.65</td>
</tr>
<tr>
<td>2006</td>
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<td>184.9 ± 1.15</td>
<td>184.4 ± 1.64</td>
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<td>183.7 ± 1.67</td>
</tr>
<tr>
<td>2007</td>
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<td>184.6 ± 1.03</td>
<td>184 ± 1.69</td>
<td>183.7 ± 1.04</td>
<td>183.8 ± 1.62</td>
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<tr>
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<td>184.7 ± 1.39</td>
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<td>183.9 ± 1.77</td>
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Table 5.2: Annual and overall averaged brightness temperatures for the vertically polarised channels at 18.7 and 36.5 GHz over open water for the Bellingshausen and Amundsen Seas Sector. For 2002 and 2011 only the period for which data is available is considered. Upper latitude steps in 5° from 70°S to 50°S.

<table>
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<tr>
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<td>( T_g ) [K]</td>
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<td>185.6 ± 0.95</td>
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<td>185.1 ± 1.18</td>
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<td>( T_g ) [K]</td>
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Table 5.3: Annual and overall averaged brightness temperatures for the vertically polarised channels at 18.7 and 36.5 GHz over open water for the Ross Sea Sector. For 2002 and 2011 only the period for which data is available is considered. Upper latitude steps in 5° from 70°S to 50°S.

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<td>(T_B) [K]</td>
<td>(T_b) [K]</td>
<td>(T_B) [K]</td>
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<td>210.7 ± 1.84</td>
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Table 5.4: Annual and overall averaged brightness temperatures for the vertically polarised channels at 18.7 and 36.5 GHz over open water for the Indian Ocean Sector. For 2002 and 2011 only the period for which data is available is considered. Upper latitude steps in 5° from 70°S to 50°S.

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<tr>
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<td>2003</td>
<td>185.2 ± 1</td>
<td>209.7 ± 1.07</td>
</tr>
<tr>
<td>2004</td>
<td>185.2 ± 0.95</td>
<td>210.7 ± 1.07</td>
</tr>
<tr>
<td>2005</td>
<td>185 ± 0.88</td>
<td>210.7 ± 1.22</td>
</tr>
<tr>
<td>2006</td>
<td>185.1 ± 1.19</td>
<td>210.7 ± 1.22</td>
</tr>
<tr>
<td>2007</td>
<td>184.9 ± 0.98</td>
<td>210.7 ± 1.22</td>
</tr>
<tr>
<td>2008</td>
<td>185.2 ± 1.04</td>
<td>210.7 ± 1.22</td>
</tr>
<tr>
<td>2009</td>
<td>185.3 ± 1.06</td>
<td>210.7 ± 1.22</td>
</tr>
<tr>
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</tr>
<tr>
<td>2011</td>
<td>185.5 ± 0.94</td>
<td>210.7 ± 1.22</td>
</tr>
<tr>
<td>2002-2011</td>
<td>185.2 ± 1.05</td>
<td>210.7 ± 1.22</td>
</tr>
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</table>

For 2002 and 2011 only the period for which data is available is considered.
Table 5.5: Annual and overall averaged brightness temperatures for the vertically polarised channels at 18.7 and 36.5 GHz over open water for the Western Pacific Ocean Sector. For 2002 and 2011 only the period for which data is available is considered. Upper latitude steps in 5° from 70°S to 50°S.

<table>
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<th>≤65°S</th>
<th>≤70°S</th>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>185.2 ± 1.46</td>
<td>184.7 ± 1.49</td>
<td>184.4 ± 1.74</td>
<td>182.8 ± 2.48</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>185.7 ± 1</td>
<td>185.2 ± 1.07</td>
<td>184.6 ± 1.36</td>
<td>184.5 ± 2.25</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>185.4 ± 1.01</td>
<td>184.9 ± 1.07</td>
<td>184.5 ± 1.23</td>
<td>184.5 ± 2.88</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>185.4 ± 1.08</td>
<td>184.9 ± 1.16</td>
<td>184.5 ± 1.33</td>
<td>184.2 ± 2.78</td>
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</tr>
<tr>
<td>2006</td>
<td>185.4 ± 0.98</td>
<td>184.9 ± 1.12</td>
<td>184.5 ± 1.34</td>
<td>184.3 ± 2.67</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>185.4 ± 1.07</td>
<td>184.9 ± 1.18</td>
<td>184.3 ± 1.35</td>
<td>183.8 ± 1.89</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>185.4 ± 0.96</td>
<td>184.9 ± 1.06</td>
<td>184.3 ± 1.25</td>
<td>182.9 ± 2.33</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>185.2 ± 1.1</td>
<td>184.7 ± 1.21</td>
<td>184.3 ± 1.33</td>
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</tr>
<tr>
<td>2010</td>
<td>185.6 ± 0.98</td>
<td>185.1 ± 1.11</td>
<td>184.6 ± 1.3</td>
<td>184.8 ± 3.07</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>185.6 ± 1.04</td>
<td>185.1 ± 1.19</td>
<td>184.6 ± 1.3</td>
<td>183.9 ± 2.07</td>
<td></td>
</tr>
<tr>
<td>2002-2011</td>
<td>185.4 ± 1.06</td>
<td>184.9 ± 1.16</td>
<td>184.5 ± 1.34</td>
<td>184.1 ± 2.59</td>
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</tr>
<tr>
<td>36.5 GHz</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>210.5 ± 1.84</td>
<td>210.5 ± 2.07</td>
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</tr>
<tr>
<td>2003</td>
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<td>210.5 ± 1.5</td>
<td>210.5 ± 2.84</td>
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</tr>
<tr>
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<td>210.2 ± 3.57</td>
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</tr>
<tr>
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<td>210.6 ± 1.39</td>
<td>210.5 ± 1.58</td>
<td>210.2 ± 3.46</td>
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</tr>
<tr>
<td>2006</td>
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<td>210.4 ± 1.28</td>
<td>210.2 ± 1.48</td>
<td>210.2 ± 3.14</td>
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</tr>
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<td>2007</td>
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<td>210.6 ± 1.31</td>
<td>210.3 ± 1.53</td>
<td>209.7 ± 2.4</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>210.7 ± 1.15</td>
<td>210.5 ± 1.29</td>
<td>210.1 ± 1.53</td>
<td>208.5 ± 2.9</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>210.6 ± 1.3</td>
<td>210.4 ± 1.36</td>
<td>210.4 ± 1.47</td>
<td>209.9 ± 3.18</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>210.9 ± 1.22</td>
<td>210.7 ± 1.35</td>
<td>210.4 ± 1.53</td>
<td>211 ± 3.84</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>211 ± 1.21</td>
<td>210.7 ± 1.36</td>
<td>210.5 ± 1.55</td>
<td>210 ± 2.52</td>
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</tr>
<tr>
<td>2002-2011</td>
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<td>210.6 ± 1.36</td>
<td>210.4 ± 1.56</td>
<td>210 ± 3.19</td>
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</tbody>
</table>
Table 5.6: Annual and overall averaged brightness temperatures for the vertically polarised channels at 18.7 and 36.5 GHz over open water for the West Antarctic. For 2002 and 2011 only the period for which data is available is considered. Upper latitude steps in 5° from 70°S to 50°S.

<table>
<thead>
<tr>
<th>Year</th>
<th>18.7 GHz</th>
<th>36.5 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_\text{B}$ [K]</td>
<td>$T_\text{B}$ [K]</td>
</tr>
<tr>
<td>2002</td>
<td>185.3 ± 1.19</td>
<td>210.9 ± 1.39</td>
</tr>
<tr>
<td>2003</td>
<td>185.6 ± 0.58</td>
<td>211.1 ± 0.74</td>
</tr>
<tr>
<td>2004</td>
<td>185.6 ± 0.57</td>
<td>211.2 ± 0.7</td>
</tr>
<tr>
<td>2005</td>
<td>185.5 ± 0.57</td>
<td>211.1 ± 0.72</td>
</tr>
<tr>
<td>2006</td>
<td>185.5 ± 0.59</td>
<td>211 ± 0.75</td>
</tr>
<tr>
<td>2007</td>
<td>185.5 ± 0.6</td>
<td>211.1 ± 0.76</td>
</tr>
<tr>
<td>2008</td>
<td>185.6 ± 0.6</td>
<td>211.1 ± 0.76</td>
</tr>
<tr>
<td>2009</td>
<td>185.5 ± 0.64</td>
<td>211.1 ± 0.76</td>
</tr>
<tr>
<td>2010</td>
<td>185.7 ± 0.55</td>
<td>211.1 ± 0.76</td>
</tr>
<tr>
<td>2011</td>
<td>185.4 ± 0.63</td>
<td>211.1 ± 0.76</td>
</tr>
<tr>
<td>2002-2011</td>
<td>185.5 ± 0.65</td>
<td>211.1 ± 0.76</td>
</tr>
</tbody>
</table>

Note: $T_\text{B}$ denotes the averaged brightness temperature (in K).
Table 5.7: Annual and overall averaged brightness temperatures for the vertically polarised channels at 18.7 and 36.5 GHz over open water for the East Antarctic. For 2002 and 2011 only the period for which data is available is considered. Upper latitude steps in 5° from 70°S to 50°S.

<table>
<thead>
<tr>
<th>Year</th>
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<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T_B ) [K]</td>
<td>( T_B ) [K]</td>
<td>( T_B ) [K]</td>
<td>( T_B ) [K]</td>
<td>( T_B ) [K]</td>
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<td>185.2 ± 1.06</td>
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</tr>
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<td>2004</td>
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<td>183.6 ± 1.75</td>
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</tr>
<tr>
<td>2005</td>
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<tr>
<td>2006</td>
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<td>184.3 ± 1.23</td>
<td>183.5 ± 1.99</td>
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</tr>
<tr>
<td>2007</td>
<td>185.1 ± 0.71</td>
<td>184.7 ± 0.77</td>
<td>184.1 ± 1.05</td>
<td>183.3 ± 1.47</td>
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<tr>
<td>2008</td>
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<tr>
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</tr>
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</tr>
<tr>
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<td>183.8 ± 1.92</td>
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</tr>
<tr>
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<td>184.3 ± 1.12</td>
<td>183.5 ± 1.73</td>
<td></td>
</tr>
<tr>
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<td>( T_B ) [K]</td>
<td>( T_B ) [K]</td>
<td>( T_B ) [K]</td>
<td>( T_B ) [K]</td>
</tr>
<tr>
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<td>210.7 ± 1.37</td>
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<td>210.4 ± 1.73</td>
<td>209.7 ± 2.34</td>
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<td>2003</td>
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<td>210.2 ± 1.32</td>
<td>209.2 ± 1.72</td>
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</tr>
<tr>
<td>2004</td>
<td>210.7 ± 0.8</td>
<td>210.3 ± 0.92</td>
<td>210.1 ± 1.22</td>
<td>209.4 ± 1.99</td>
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</tr>
<tr>
<td>2005</td>
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<td>210.4 ± 0.98</td>
<td>210.2 ± 1.32</td>
<td>209.4 ± 2.23</td>
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<td>2006</td>
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<tr>
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<td>210.1 ± 1.17</td>
<td>209 ± 1.77</td>
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<tr>
<td>2010</td>
<td>210.9 ± 0.86</td>
<td>210.6 ± 0.96</td>
<td>210.2 ± 1.25</td>
<td>209.8 ± 2.19</td>
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</tr>
<tr>
<td>2011</td>
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<td>209.9 ± 2.14</td>
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<td>2002-2011</td>
<td>210.8 ± 0.89</td>
<td>210.5 ± 0.97</td>
<td>210.2 ± 1.29</td>
<td>209.4 ± 1.99</td>
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</table>
Table 5.8: Annual and overall averaged brightness temperatures for the vertically polarised channels at 18.7 and 36.5 GHz over open water for the Antarctic. For 2002 and 2011 only the period for which data is available is considered. Upper latitude steps in 5° from 70°S to 50°S.

<table>
<thead>
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<th>Year</th>
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<th></th>
<th>36.5 GHz</th>
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<th></th>
<th></th>
</tr>
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<tbody>
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<td></td>
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<td>≤55°S</td>
<td>≤60°S</td>
<td>≤65°S</td>
<td>≤70°S</td>
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</tr>
<tr>
<td>2002</td>
<td>185.2 ± 1</td>
<td>184.9 ± 1.01</td>
<td>184.5 ± 1.08</td>
<td>184.4 ± 1.49</td>
<td>182.2 ± 2.33</td>
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</tr>
<tr>
<td>2003</td>
<td>185.5 ± 0.45</td>
<td>185.2 ± 0.49</td>
<td>184.8 ± 0.65</td>
<td>184.3 ± 1.2</td>
<td>183.5 ± 1.57</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>185.5 ± 0.47</td>
<td>185.2 ± 0.52</td>
<td>184.8 ± 0.74</td>
<td>184.5 ± 1.39</td>
<td>183.6 ± 1.75</td>
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</tr>
<tr>
<td>2005</td>
<td>185.3 ± 0.47</td>
<td>185.1 ± 0.49</td>
<td>184.7 ± 0.71</td>
<td>184.4 ± 1.27</td>
<td>183.4 ± 1.52</td>
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</tr>
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<td>185.4 ± 0.48</td>
<td>185.1 ± 0.53</td>
<td>184.7 ± 0.71</td>
<td>184.3 ± 1.18</td>
<td>183.2 ± 1.69</td>
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<tr>
<td>2007</td>
<td>185.3 ± 0.46</td>
<td>185.0 ± 0.47</td>
<td>184.6 ± 0.71</td>
<td>184.2 ± 1.2</td>
<td>183.4 ± 1.91</td>
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<tr>
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<td>185.2 ± 0.5</td>
<td>184.7 ± 0.67</td>
<td>184.2 ± 1.43</td>
<td>183.1 ± 1.69</td>
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</tr>
<tr>
<td>2009</td>
<td>185.4 ± 0.51</td>
<td>185.1 ± 0.55</td>
<td>184.7 ± 0.72</td>
<td>184.4 ± 1.4</td>
<td>183.1 ± 1.51</td>
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</tr>
<tr>
<td>2010</td>
<td>185.6 ± 0.45</td>
<td>185.3 ± 0.5</td>
<td>184.9 ± 0.62</td>
<td>184.2 ± 1.45</td>
<td>183.8 ± 1.53</td>
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<tr>
<td>2011</td>
<td>185.4 ± 0.48</td>
<td>185.1 ± 0.53</td>
<td>184.6 ± 0.72</td>
<td>184.2 ± 1.23</td>
<td>183.6 ± 1.29</td>
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</tr>
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<td>2002-2011</td>
<td>185.4 ± 0.52</td>
<td>185.1 ± 0.56</td>
<td>184.7 ± 0.73</td>
<td>184.3 ± 1.32</td>
<td>183.4 ± 1.65</td>
<td></td>
</tr>
</tbody>
</table>

The calculated averages of the single years as well as for the period from June 2002 to October 2011 show a variation between 183 and 186 K for the 18.7 GHz channel and a variation between 209 and 211 K for the 36.5 GHz channel. However, especially for the East Antarctic land and ice cover extends relatively far north up to about 60-65°S and thus no open water tie points can be calculated especially during winter. For the averages calculated from data ranging north up to 50°S, however, influences from warmer water masses may increasingly affect the calculated open water tie points and, therefore, it was decided to use the calculated tie points for latitudes ≤ 60°S. However, since the variation of the tie points in the single sectors is relatively constant the averaged open water brightness temperatures for the whole period are used as open water tie points for the calculation of the vertically polarised gradient ratio and the new snow depth retrieval algorithm for the entire Antarctic. These tie points are given by 184.7 K and 210.5 K for the 18.7 and 36.5 GHz channels, respectively. The tie points were kept fixed for the entire year.

5.3 Quantification of Errors

As discussed above to obtain a new snow depth retrieval with error estimates an error propagation is needed to distinguish between uncertainties coming from the input variables and systematic errors due to
e.g. snow melt, snow accumulation, etc. For this purpose the standard error
propagation formula given by Eqs. 2.6 and 2.8 will be used.
Since the error of the snow depth (Eq. 2.6) requires uncertainty estimates
of the regression coefficients the error of the snow depth will be discussed in
Section 5.4. However, an error estimate of the gradient ratio can already be
provided.
Here, the uncertainty of the gradient ratio comes from five different
variables: the tie points of open water at 18.7 and 36.5 GHz, the
uncertainty of the brightness temperatures at the same frequencies, and the
uncertainty of the sea ice concentration. While the uncertainty estimates of
the open water tie points originate from the calculation of the open water tie
points, the uncertainty estimates for the brightness temperatures and the
sea ice concentration had to be taken from the literature.
Since the snow depth product provided in this work package shall be
provided with a pixel-based uncertainty estimate a pixelwise error of the sea
ice concentration is needed as well. Here, [RD-47; RD-45] estimated the
uncertainty of the retrieved sea ice concentration based on in-situ measurements from ship campaigns and obtained a sea ice concentration
dependent error estimate of the retrieved sea ice concentration (Fig. 9 in
[RD-45]). However, [RD-47] noted that these coefficients only represent
Arctic summer conditions and even there only a short period of time.
Another, problem for the estimation of the uncertainty of the retrieved snow
depth is that although the uncertainty estimates are calculated using the
Gaussian error propagation the sea ice uncertainties can only be roughly
estimated from Fig. 4.17 in [RD-47]. Therefore, within an interval of 10%
sea ice concentration change always the maximum error will be taken as
rough error. However, an exception is made for 100% sea ice concentration.
Here, the sea ice concentration uncertainty is estimated from the same
figure to be about 6%. Considering that all uncertainty estimates read from
the figure are estimates of the maximum error for a sea ice concentration
interval one has to consider whether the absolute error or the Gaussian
error propagation should be used. However, within an interval of 10% sea
ice concentration change the error changes only by about 2-3%. In addition
even the maximum estimated maximum error is a statistical error.
Therefore it appears to be more suitable to use the Gaussian error
propagation instead of the absolute error and it will be used to estimate the
error of the gradient ratio.
Similarly the uncertainty of the open water tie points are estimated from the
standard deviation of the daily averaged tie points of the Antarctic for the
whole AMSR-E observation period. In the case that an algorithm with
regionally or temporally (e.g. seasons) independent regression coefficients
shall be implemented in the future, open water tie points can be calculated
for all Antarctic sectors as well as the West and East Antarctic.
The only remaining error is the uncertainty of the brightness temperatures
at 18.7 and 36.5 GHz. The instrument description
(http://nsidc.org/data/docs/daac/amsr_instrument.gd.html) provides the
noise equivalent temperature of about one Kelvin and thus the noise
equivalent temperature will be used as uncertainty estimate for the
brightness temperatures. Since similarly to the sea ice concentration the
noise equivalent temperature is derived from a statistical analysis it will be
taken as a statistical error. A complete overview of all uncertainties used in
the calculation of the uncertainty of the gradient ratio can be found in Tab.
5.9.
Table 5.9: Uncertainty estimates for the vertically polarised brightness temperatures and open water tie points at 18.7 and 36.5 GHz, and for the ASI sea ice concentration.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Uncertainty</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{B,OW}(19\nu)$</td>
<td>0.73 K</td>
<td>Section 5.2, Tab. 5.8</td>
</tr>
<tr>
<td>$T_{B,OW}(37\nu)$</td>
<td>0.84 K</td>
<td>Section 5.2, Tab. 5.8</td>
</tr>
<tr>
<td>$T_B(19\nu)$</td>
<td>1 K</td>
<td><a href="http://nsidc.org/data/docs/daac/amsr_i">http://nsidc.org/data/docs/daac/amsr_i</a></td>
</tr>
<tr>
<td>$T_B(37\nu)$</td>
<td>1 K</td>
<td>instrument.gd.html, accessed: 8.9.2014</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$C_{ice}$</th>
<th></th>
<th>[RD-45; RD-47]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%-29%</td>
<td>21%</td>
<td></td>
</tr>
<tr>
<td>30%-39%</td>
<td>19%</td>
<td></td>
</tr>
<tr>
<td>40%-49%</td>
<td>16%</td>
<td></td>
</tr>
<tr>
<td>50%-59%</td>
<td>13%</td>
<td></td>
</tr>
<tr>
<td>60%-69%</td>
<td>11%</td>
<td></td>
</tr>
<tr>
<td>70%-79%</td>
<td>9%</td>
<td></td>
</tr>
<tr>
<td>80%-89%</td>
<td>7.5%</td>
<td></td>
</tr>
<tr>
<td>90%-99%</td>
<td>7%</td>
<td></td>
</tr>
<tr>
<td>100%</td>
<td>6%</td>
<td></td>
</tr>
</tbody>
</table>

5.4 Derivation of the New Set of Regression Coefficients

The basic procedure is similar to the comparison of the NSIDC AMSR-E and the SSM/I snow depths with ASPeCt and in situ snow depths. So here only the differences will be described. In the first step the AMSR-E vertically polarised brightness temperatures at 18.7 GHz and the ASI sea ice concentration are re-gridded to a 12.5 km x 12.5 km grid by splitting each grid cell into four separate cells (brightness temperature at 18.7 GHz) or average four grid cells to one 12.5 km grid cell (ASI sea ice concentration). Then the vertically polarised gradient ratio and its uncertainty are calculated using Eqs. 2.1 and 2.8, the calculated tie points from Section 5.1 and the uncertainties presented in Tab. 5.9 in Section 5.3. Then the calculated gradient ratios are collocated with ASPeCt snow depth observations. Because the comparison in Section 4 showed that the summer months (November - March) have a rather low correlation the new regression coefficients are derived from daily averages for the period between April and October (winter period).

To calculate the new AMSR-E coefficients pixel as well as daily averages are calculated for each Antarctic sector. Then a linear regression was performed with the gradient ratio as reference value. The regression coefficients and their uncertainties were obtained from the output of the regression.
Figure 5.1: Comparison of the vertically polarised gradient ratio (GRV) derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for the period between April and October. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt data are pixel averages. For full set of regression coefficients see Tab. 5.10.

Fig. 5.1 shows the comparison of the vertically polarised gradient ratio derived from the AMSR-E 18.7 and 36.5 GHz channels with ASPeCt-observations for the Weddell Sea, the Bellingshausen and Amundsen Seas, the Ross Sea, and the Western Pacific, the sectors combined as West and East Antarctic and for the whole Antarctic based on pixel averages. The full set of all regression coefficients can be found in Tab. 5.10. The slope of the regression line varies between about -200 cm and -85 cm with uncertainties between about ±30 cm and ±128 cm. The y-intercept of the regressions is usually between 10 and 15 cm with uncertainties of about ±1 and ±2 cm. Compared to the original AMSR-E regression coefficients (slope: -782 cm, intercept: 2.9 cm) provided in the literature [RD-28; RD24; RD-29; RD-30; RD-25] the newly derived coefficients are much lower. Moreover, the comparison of the AMSR-E as well as the SSM/I snow depth retrieval products in Section 4 indicated that especially for high snow depths the
retrieval shows an underestimation of ship-based as well as in-situ observation. Therefore, to correct this underestimation the slope has to be steeper for the new retrieval. Since for the daily averages the comparison of the snow depth data with the ASPeCt and in situ data was usually slightly better, the same comparison as in Fig. 5.1 is shown in Fig. 5.2 but for daily averages instead of pixel averages.

Figure 5.2: Comparison of the vertically polarised gradient ratio (GRV) derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for the period between April and October. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt data are daily averages. For full set of regression coefficients see Tab. 5.10.

For the comparisons with daily averages the regression coefficients can be found in Tab. 5.10. For the comparison using daily averages with about -530 the steepest slope can be found for the Ross Sea Sector, while the slope for the whole Antarctic is about -252. Thus, even for daily averages the obtained slope of the linear fit is still too flat to compensate for the underestimation of high snow depths as observed using the ASPeCt protocol. Therefore, these regressions cannot be used to obtain a new
retrieval as well. Since besides the snow and sea ice properties provided by the ASPeCt protocol no further information are available, a first attempt would be to use those properties to identify possible outliers. However, since the ASPeCt observations are ship-based observations only and do not contain in situ measurements, to the authors of this report the accuracy of the snow and sea ice type identification is unclear. It has to be assumed that discrimination between different snow and sea ice types requires more experience from an observer than the estimation of the total sea ice concentration.

Table 5.10: Regression coefficients for the comparison of pixel (Fig. 5.1) and daily (Fig. 5.2) with AMSR-E pixel-based and daily-averaged vertically polarised gradient ratios (GRV) for all Antarctic sectors, the West Antarctic, the East Antarctic (only Western Pacific Ocean Sector), and the whole Antarctic.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Slope [cm]</th>
<th>Intercept [cm]</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Averages</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weddell Sea</td>
<td>-157±32</td>
<td>10.5±0.7</td>
<td>-0.22</td>
<td>478</td>
</tr>
<tr>
<td>Bellingshauen and Amundsen Seas</td>
<td>-202±60</td>
<td>13.1±1.7</td>
<td>-0.27</td>
<td>149</td>
</tr>
<tr>
<td>Ross Sea</td>
<td>-85±128</td>
<td>9.8±1.6</td>
<td>-0.11</td>
<td>40</td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>-13±46</td>
<td>11.1±0.7</td>
<td>-0.02</td>
<td>306</td>
</tr>
<tr>
<td>West Antarctic</td>
<td>-191±27</td>
<td>10.7±0.6</td>
<td>-0.27</td>
<td>667</td>
</tr>
<tr>
<td>East Antarctic</td>
<td>-13±46</td>
<td>10.7±0.7</td>
<td>-0.02</td>
<td>306</td>
</tr>
<tr>
<td>Antarctic</td>
<td>-157±23</td>
<td>10.8±0.5</td>
<td>-0.22</td>
<td>973</td>
</tr>
<tr>
<td>Daily Averages</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weddell Sea</td>
<td>-199±88</td>
<td>12.5±1.8</td>
<td>-0.27</td>
<td>69</td>
</tr>
<tr>
<td>Bellingshauen and Amundsen Seas</td>
<td>-495±136</td>
<td>8.5±3.7</td>
<td>-0.66</td>
<td>22</td>
</tr>
<tr>
<td>Ross Sea</td>
<td>-530±1053</td>
<td>7.3±9.1</td>
<td>-0.62</td>
<td>4</td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>-121±122</td>
<td>13.4±1.9</td>
<td>-0.13</td>
<td>60</td>
</tr>
<tr>
<td>West Antarctic</td>
<td>-312±70</td>
<td>11.2±1.5</td>
<td>-0.43</td>
<td>95</td>
</tr>
<tr>
<td>East Antarctic</td>
<td>-121±122</td>
<td>11.2±1.9</td>
<td>-0.13</td>
<td>60</td>
</tr>
<tr>
<td>Antarctic</td>
<td>-252±60</td>
<td>12.1±1.2</td>
<td>-0.33</td>
<td>155</td>
</tr>
</tbody>
</table>

Therefore, the filtering of possibly unreliable data will be done mainly using the uncertainty of the collocated GRVs and ASPeCt snow depths. The assumption behind this procedure is that daily averages of GRV and ASPeCt snow depth with high uncertainties have a high probability of not being representative for the actual snow depth. Thus, although they may also contain reliable information, in particular in the case of the GRV they have a high probability to exceed the value of the GRV itself and thus one cannot say how reliable those data are.

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**Table 5.10: Regression coefficients for the comparison of pixel (Fig. 5.1) and daily (Fig. 5.2) with AMSR-E pixel-based and daily-averaged vertically polarised gradient ratios (GRV) for all Antarctic sectors, the West Antarctic, the East Antarctic (only Western Pacific Ocean Sector), and the whole Antarctic.**
Figure 5.3: Frequency distribution of the uncertainty of the vertically polarised gradient ratio of the 18.7 and 36.5 GHz channels.

Fig. 5.3 shows a histogram of the frequency distribution of the uncertainty of the gradient ratio. The histogram shows that the uncertainty obtained via error propagation $\sigma_{GRV}$ is usually smaller than about 0.005 (102 of 122 day pairs). Here, it was decided to take the bin centre, which is 0.004 as upper limit for the uncertainty of the GRV to be used in the next iteration to derive a regression between snow depth and GRV. The number of pairs is roughly the same for $\sigma_{GRV} = 0.004$ (99 of 122 day pairs).

A similar attempt was made for the ratio of snow depth standard deviation to mean snow depth for the ASPeCt daily snow depth averages. The main assumption behind this step is that for daily snow depth averages with a relatively low uncertainty the snow conditions and the snow depth distribution can be assumed to be more homogeneous along the ships track and thus are more likely to represent the actual snow conditions. The obtained histogram is shown in Fig. 5.4.

As one can see the ratio of standard deviation to mean snow depth forms a Gaussian-shaped curve with asymmetry to ratios larger than 1.0. However, the histogram does not present a clear upper cut off limit. Thus the histogram allows to filter out snow depth pairs with standard deviation to mean ratios larger than 1.0 but below this value it does not allow any separation and one has to look for another filter criterion.

To find this criterion, the upper limit of the ratio of standard deviation and mean (from here on called $r$) was varied between 1.0 and 0.3 and the comparisons were separately plotted for all four ratios. This is shown in Fig. 5.5 and the corresponding regression coefficients can be found in Tab. 5.11. As one can see for ratios of standard deviation to mean of 0.5, 0.7 and 1.0 the slope of the regression lines does not increase compared to the comparison for which no filters are applied (Fig. 5.2 and Tab. 5.10). Only for
the ratio of standard deviation to mean of \( r = 0.3 \) the slope increases to a value comparably high as that applied in the standard snow depth retrieval algorithm (slope: -782). Therefore, the comparison shown in Fig. 5.5 indicates that \( r = 0.3 \) should be used to find the coefficients for the new snow depth retrieval. Furthermore, the use of the 0.3 standard deviation to mean ratio has also another advantage: while for ratios of 0.5, 0.7 and 1.0 additionally possible outliers have to be identified and removed this has not to be done for a ratio \( r \) of 0.3. The problem of removing outliers becomes immediately clear when one closely looks at Fig. 5.5 again. Except for \( r = 0.3 \) all other three comparisons show a strong scatter and thus it is difficult to clearly identify outliers.

![Figure 5.4: Frequency distribution of the ratio of standard deviation and snow depth for ASPeCt daily snow depth averages.](image)

**Table 5.11: Regression coefficients for the comparison of daily averaged ASPeCt snow depth observations with AMSR-E pixel-based and daily-averaged vertically polarised gradient ratios (GRV) for the whole Antarctic for ratios \( r \) between standard deviation and mean of \( r = 0.3, 0.5, 0.7, 1.0 \).**

<table>
<thead>
<tr>
<th>( R )</th>
<th>Slope [cm]</th>
<th>Intercept [cm]</th>
<th>( R )</th>
<th>( N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>-798\pm 211</td>
<td>6.5\pm 3.6</td>
<td>-0.74</td>
<td>16</td>
</tr>
<tr>
<td>0.5</td>
<td>-248\pm 113</td>
<td>11\pm 1.9</td>
<td>-0.29</td>
<td>56</td>
</tr>
<tr>
<td>0.7</td>
<td>-249\pm 99</td>
<td>11.1\pm 1.7</td>
<td>-0.28</td>
<td>80</td>
</tr>
<tr>
<td>1.0</td>
<td>-271\pm 85</td>
<td>10.3\pm 1.4</td>
<td>-0.32</td>
<td>93</td>
</tr>
</tbody>
</table>
Figure 5.5: Comparison of the vertically polarised gradient ratio (GRV) derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for ratios $r$ between standard deviation and mean for $r = 0.3, 0.5, 0.7, \text{ and } 1.0$. Whole Antarctic for the period from April to October. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt data are daily averages. For full set of regression coefficients see Tab. 5.11.

To identify possible outliers it is important to identify for which snow depths which GRVs occur. For this purpose Fig. 5.6 shows the vertically polarised gradient ratio of the 18.7 and 36.5 GHz channels from numerically modeled microwave emissions of sea ice. One can see that for around 20 cm thick sea ice without snow cover the GRV is around 0.005. Considering that for snow depths below 50 cm the vertically polarised gradient ratio decreases linearly (e.g. Fig 4 in [RD-29]) with increasing snow depth to about -0.06 for a snow depth of about 50 cm one can try to identify possible outliers in Fig. 5.5, however, due to the strong scatter only few GRV-snow depth pairs could be identified as outliers when using this criterion. Thus, only the snow depth-GRV pairs for $S_{\text{ASPeCt}} = 30-40 \text{ cm}$ and $\text{GRV} \approx 0$ and $S_{\text{ASPeCt}} = 10 \text{ cm}$ and $\text{GRV} \approx -0.04$ could be identified using the physical criteria from numerical microwave radiative transfer calculations. However, although this physical behaviour can help to identify outliers, the real snow depth conditions for these snow depth-GRV pairs are not known and since, in the case one
Passive Microwave Snow Depth on Antarctic sea ice assessment

Ref. SICCI-ANT-PMW-SDASS-11-14  Version 1.0 / 28 Nov 2014

considers the scatter of the snow depth-GRV, they are not too far away from the main cluster, in particular for \( r = 1.0 \), it is still not impossible that they are no outliers and thus it is appears artificial to just remove them from the regression.

Figure 5.6: Dependence of the vertically polarised gradient ratio at 19 and 37 GHz on sea ice thickness from SMOS without snow cover. Sea ice can be snow covered from about 20 cm (0.2 m) thickness on. Image produced within the ESA Sea Ice CCI [L. T. Pedersen, personnel communication, 2014].

Hence, the regression with \( r = 0.3 \) will be used since it has the advantage that no outliers have to be removed, however, on the other hand it has the disadvantage that only 16 daily averages remain. However, Markus and Cavalieri [RD-02] did only use about 100 pixel averages from three different datasets to set up the original snow depth retrieval algorithm and thus, if daily averages were calculated from those averages most likely only 20-30 averages would remain, roughly the same number as used in the comparison for \( r = 0.3 \) in Fig. 5.7. However, no snow depth values are available for bare sea ice. To compensate for this in three artificial points were introduced for \( S_{\text{ASPECT}} = 0 \) cm (GRV = 0.004, 0.005, 0.006). Here, the three points were chosen based on the dependence of the GRV on sea ice thickness derived from SMOS L-Band brightness temperatures shown in Fig. 5.6. Snow begins to accumulate on sea ice when it is roughly 20 cm (0.2 m) thick. This corresponds to a GRV of roughly 0.005. In the regression three values were
used to be able to imitate the natural variability of the gradient ratio at one sea ice thickness shown in Fig. 5.6.

Figure 5.7: Comparison of the vertically polarized gradient ratio (GRV) derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for $r = 0.3$. Whole Antarctic for the period from April to October. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt data are daily averages. The full set of the regression coefficients is given in the text.

Fig. 5.7 shows the result of the regression using the remaining 16 snow depth-GRV pairs from Fig. 5.5 ($r = 0.3$) and the three artificial points for bare sea ice. The equation of the regression line in Fig. 5.7 is given by:

$$S_{ASPeCt} = (-864 \pm 131) \text{ cm} \cdot \text{GRV} + (5.4 \pm 2.1) \text{ cm}$$  \hspace{1cm} (5.1)

The calculated uncertainties represent the $1\sigma$-standard deviation of the fit. The correlation coefficient is -0.87. Compared to the old regression coefficients for AMSR-E (slope: -782 cm, y-intercept: 2.9 cm) the slope is only slightly lower but the y-intercept did significantly increase thus one can expect that the for the new snow depth retrieval the overestimation of ASPeCt snow depth averages for snow depths below about 15 cm will most likely increase, however, the steeper slope will most likely correct in
particular snow depths above 30 cm, for which in Section 4 an underestimation of the ASPeCt snow depth averages was found, to higher snow depths.

To estimate which effect the new coefficients have on the snow depth retrieval the new coefficients were applied to AMSR-E data to compute a new snow depth data set and a new comparison performed. Furthermore, maps of the new snow depth retrieval will be compared to maps of the NSIDC snow depth product. This will be described in the next subsection.

5.5 The New Snow Depth Retrieval

Using the results of the linear regression from the last paragraph a new snow depth retrieval algorithm was set up. Here, the open water tie points from Section 5.2 and the empirical coefficients from the previous subsection are used. An overview of fixed coefficients and their uncertainties used in the retrieval can be found in Tab. 5.12.

Table 5.12: Constant parameters used for the calculation of the new snow depth on sea ice product.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant of empirical regression</td>
<td>864 cm ± 131 cm</td>
</tr>
<tr>
<td>slope of linear regression</td>
<td>5.4 cm ± 2.1 cm</td>
</tr>
<tr>
<td>open water tie point at 18.7 GHz</td>
<td>184.7 K ± 0.73 K</td>
</tr>
<tr>
<td>open water tie point at 36.5 GHz</td>
<td>210.5 K ± 0.84 K</td>
</tr>
</tbody>
</table>

Besides the open water tie points and the empirical regression coefficients two data products are used for the calculation of the AMSR-E snow depth product and its uncertainty three different variables derived from the AMSR-E L1A Raw Observation Count data (Version 3), provided by the NSIDC (http://nsidc.org/data/amsrel1a, [RD-44]) were used:

1) the brightness temperature of the vertically polarised channel at 18.7 GHz,
2) the brightness temperature of the vertically polarised channel at 36.5 GHz,
3) the sea ice concentrations derived from the 89 GHz channels using the ARTIST (ASI) algorithm described by [RD-45]; see also [RD-46]. Note that the implementation of the ASI algorithm at University of Bremen is used.

The uncertainties for the sea ice concentration and the brightness temperatures not listed in Tab 5.12 can be found in Tab. 5.9. As for the NSIDC product the snow depth retrieval is limited to sea ice concentrations ≥ 20%. In the processing first snow depth and snow depth uncertainty swath data are derived. Then from the swath data daily averages are calculated and gridded into the 12.5 km x 12.5 km NSIDC grid.

5.5.1 Example Snow Depth Maps

Figs. 5.8 and 5.9 show the annual development of the snow depth on Antarctic sea ice for the year 2009. These daily maps are produced for the 15th of every month and salient features for summer months (November - March) as well for winter months (April - December).
In Fig. 5.8 black pixels indicate negative snow depths retrievals and white pixels indicate snow depths above 50 cm. From November on the sea ice covered area in the Antarctic significantly decreases due to melting processes and reduces to small areas close to the Antarctic continent and larger areas in the Weddell Gyre as well as in the Ross Sea. This is also shown by the snow depth retrieval. First from September to October the area covered by pixels with negative snow depth retrievals along the ice edge increases further pole-ward while the area covered by sea ice with sea ice concentrations of 20% and higher remain nearly constant. These negative snow depth values are unphysical since by definition snow depth cannot be negative. Because negative snow depth retrievals mainly occur along the ice edge this may indicate that here melting or flooding may play an important role. Furthermore, areas along the ice edge might be covered by different ice types than the main sheets and might have different radiometric properties (e.g. pancake ice with open water leads between the ice). However, the algorithm was set up for solid first year ice and thus might not work in these areas.

From October to January the sea ice retreats further and the snow cover decreases as well, however, the areal fraction of negative snow depth retrievals seems to increase. In January the ratio of negative snow depth retrievals to snow depth retrievals with positive values increases to nearly 50%. The sea ice and snow covered area reaches a minimum for February - with the areal fraction of negative snow depth retrievals being significantly reduced compared to January - and begins to increase again thereafter until it reaches the maximum extent in September.

Overall the monthly plots show a very consistent annual evolution of the snow thickness. Snow depths below approximately 20 cm can mainly be found for sea ice covered areas where seasonal ice is formed. Maximum snow depths occur in the Weddell Gyre where sea ice can survive at least one winter, the Bellingshausen and Amundsen Seas, the Ross Sea, and in the western part of the Western Pacific Ocean. Here, in these areas the retrieved snow depth also exceeds the theoretical limit of about 50 cm, however, the data are not excluded since they may provide a rough idea of the general snow depth distribution.

Besides the regular snow depth cover around Antarctica the product also shows single spots of snow depth in the open ocean especially also for areas north of 50°S. Here, usually no sea ice and thus snow depth can be found and it is most likely that these spots result from missed weather effects.

Fig. 5.9 shows a similar structure for the snow depth uncertainty as found for the retrieved snow depth. Usually the uncertainty lies between 4 and 8 cm, however, in areas where the snow depth retrieval exceeds the theoretical 50 cm limit the uncertainty increases to about 10 to 14 cm. Very high uncertainties (> 20 cm) can also be found along the ice edge, predominantly where negative snow depths retrievals occurred (e.g. March 15th 2009 in Fig. 5.8).

The uncertainty of the sea ice concentration has a high influence on the uncertainty of the snow depth retrieval in particular for low sea ice concentrations. At the ice edge the uncertainty of the sea ice concentration easily exceeds 15-20% for sea ice concentrations < 50% and due to their strong contribution in the error propagation the snow depth uncertainty in these regions is very high.
Figure 5.8: Maps of the annual development of the daily snow depth from the new retrieval. Every map is taken at the 15\textsuperscript{th} of the respective month. Black areas: negative snow depths. White areas: snow depths larger than 50 cm. Sea ice concentration cut off limit: 20\%. Grey areas: open water.
Figure 5.9: As for Fig. 5.8 but for snow depth uncertainty. White areas: uncertainty higher than 20 cm.
5.5.2 Comparison with ASPeCt and In-Situ Data

To assess how the snow depth changed when using the newly derived regression coefficients the same comparison as done in Section 4 was repeated. The collocation method and the procedure to derive pixel and daily averages is the same as described in Section 4 only that the sea ice criterion was not applied. Furthermore, negative snow depth retrievals were not included.

ASPeCt

![Graphs showing comparison of new snow depth product derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for the period between April and October. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt observations are pixel averages. For full set of regression coefficients see Tab. 5.13.]

Figs. 5.10-5.11 show the comparison of pixel-based AMSR-E snow depth averages and Figs. 5.12-5.13 show the comparison of AMSR-E daily snow depth averages retrieved using the new regression coefficients with pixel
and daily ASPeCt snow depth averages. A full list of the regression coefficients can be found in Tabs. 5.13 and 5.14.

Figure 5.11: Comparison of new snow depth product derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for the whole year. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt observations are pixel averages. For full set of regression coefficients see Tab. 5.13.

Compared to Figs. 4.8 and 4.9 (pixel-based comparisons) and Figs. 4.11 and 4.12 (daily averages) the comparisons show basically the same structure but slightly shifted to higher snow depths and, partially, higher slopes. Furthermore, for some comparisons (e.g. for the Bellingshausen and Amundsen Seas) the number of the pixel contributing to the comparison significantly increased, however, overall, less pixels contribute to the comparison.

For the comparison of the pixel averages the changes of the RMSD are between about -6 cm for the Bellingshausen and Amundsen Seas Sector and about 4 cm for the Ross Sea Sector. For the comparison of the daily averages changes of the RMSD lie between about -7 cm for the Bellingshausen and Amundsen Seas Sector and about 1 cm for the Weddell Sea Sector.
In comparison to the NSIDC snow depth product the snow depth from the new retrieval did not use any multiyear ice, snow variability and snow melt filters. Moreover, instead of the NASA-Team 2 algorithm the ARTIST sea ice algorithm was used, and since the NASA-Team 2 algorithm retrieves sea ice concentration from the 18.7, 36.5 and 89.0 GHz channels the ASI algorithm from the 89 GHz channels especially at the ice edge differences can occur, however, in the Antarctic also “pseudo” open water areas- areas covered by 100% sea ice but wrongly classified as open water- have been found [C. Melsheimer, personal communication, 2014]. Thus, the difference in the number of snow depth data pairs most likely comes from the missing filters as well as the use of different sea ice concentrations.

Figure 5.12: Comparison of new snow depth product derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for the period between April and October. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are daily averages. For full set of regression coefficients see Tab. 5.14.
Figure 5.13: Comparison of new snow depth product derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for the whole observation period. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are daily averages. For full set of regression coefficients see Tab. 5.14.

A particularly strong improvement was found for the Indian Ocean Sector (Fig. 5.11). The slope of the regression line as well as the regression coefficient increased from about 0 to about 1.2 and 0.85, respectively. However, due to the low number of snow depth pairs contributing to this comparison no conclusion can be drawn if this is only a quantitative effect caused by the low number of pixels, or an effect from the use of the new coefficients. Because for the other sectors the regression coefficients do not significantly change, this suggests that it is a rather quantitative effect.
Table 5.13: Slope, Intercept, correlation coefficient $R$, RMSD and number of pixels included in the comparison of the new AMSR-E passive microwave snow depth retrieval product with pixel by pixel averaged ASPeCt observations for the period 2002 – 2011.

<table>
<thead>
<tr>
<th>Period: April-October</th>
<th>Sector</th>
<th>Slope $\pm$ [cm]</th>
<th>Intercept [cm]</th>
<th>$R$</th>
<th>RMSD [cm]</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weddell Sea</td>
<td>0.25±0.03</td>
<td>11.4±0.6</td>
<td>0.34</td>
<td>11.1</td>
<td>408</td>
<td></td>
</tr>
<tr>
<td>Bellingshausen and Amundsen Seas</td>
<td>0.15±0.07</td>
<td>21.3±1.6</td>
<td>0.19</td>
<td>16.3</td>
<td>133</td>
<td></td>
</tr>
<tr>
<td>Indian Ocean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ross Sea</td>
<td>0.28±0.16</td>
<td>5.6±2</td>
<td>0.33</td>
<td>7.9</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>0.08±0.03</td>
<td>9.6±0.5</td>
<td>0.19</td>
<td>11.6</td>
<td>221</td>
<td></td>
</tr>
<tr>
<td>West Antarctic</td>
<td>0.3±0.03</td>
<td>12.3±0.6</td>
<td>0.36</td>
<td>12.4</td>
<td>570</td>
<td></td>
</tr>
<tr>
<td>East Antarctic</td>
<td>0.08±0.03</td>
<td>9.6±0.5</td>
<td>0.19</td>
<td>11.6</td>
<td>221</td>
<td></td>
</tr>
<tr>
<td>Antarctic</td>
<td>0.25±0.03</td>
<td>11.5±0.5</td>
<td>0.32</td>
<td>12.2</td>
<td>791</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Period: January-December</th>
<th>Sector</th>
<th>Slope $\pm$ [cm]</th>
<th>Intercept [cm]</th>
<th>$R$</th>
<th>RMSD [cm]</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weddell Sea</td>
<td>0.33±0.03</td>
<td>12.8±0.7</td>
<td>0.41</td>
<td>13.5</td>
<td>570</td>
<td></td>
</tr>
<tr>
<td>Bellingshausen and Amundsen Seas</td>
<td>-0.01±0.04</td>
<td>21.8±1.4</td>
<td>-0.02</td>
<td>22.5</td>
<td>261</td>
<td></td>
</tr>
<tr>
<td>Indian Ocean</td>
<td>1.2±0.44</td>
<td>-0.5±12.1</td>
<td>0.85</td>
<td>8.3</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Ross Sea</td>
<td>-0.01±0.04</td>
<td>14.1±0.7</td>
<td>-0.02</td>
<td>15.2</td>
<td>449</td>
<td></td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>0.05±0.03</td>
<td>9.7±0.5</td>
<td>0.12</td>
<td>12.5</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>West Antarctic</td>
<td>0.17±0.02</td>
<td>14.2±0.5</td>
<td>0.23</td>
<td>16.3</td>
<td>1280</td>
<td></td>
</tr>
<tr>
<td>East Antarctic</td>
<td>0.12±0.03</td>
<td>9.3±0.6</td>
<td>0.22</td>
<td>12.4</td>
<td>237</td>
<td></td>
</tr>
<tr>
<td>Antarctic</td>
<td>0.18±0.02</td>
<td>13.2±0.4</td>
<td>0.24</td>
<td>15.7</td>
<td>1517</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.14: Slope, Intercept, correlation coefficient R, RMSD and number of days included in the comparison of the new AMSR-E passive microwave snow depth retrieval product with daily averaged ASPeCt observations for the period 2002 – 2011.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Slope</th>
<th>Intercept [cm]</th>
<th>R</th>
<th>RMSD[cm]</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weddell Sea</td>
<td>0.21±0.09</td>
<td>11.3±1.6</td>
<td>0.3</td>
<td>10.6</td>
<td>62</td>
</tr>
<tr>
<td>Bellingshausen and Amundsen Seas</td>
<td>0.31±0.16</td>
<td>16.1±3.9</td>
<td>0.42</td>
<td>12.7</td>
<td>21</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ross Sea</td>
<td>0.66±0.8</td>
<td>1.3±9.1</td>
<td>0.79</td>
<td>3.6</td>
<td>4</td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>0.07±0.05</td>
<td>10.4±1</td>
<td>0.2</td>
<td>12.4</td>
<td>52</td>
</tr>
<tr>
<td>West Antarctic</td>
<td>0.31±0.08</td>
<td>11±1.6</td>
<td>0.4</td>
<td>10.9</td>
<td>87</td>
</tr>
<tr>
<td>East Antarctic</td>
<td>0.07±0.05</td>
<td>10.4±1</td>
<td>0.2</td>
<td>12.4</td>
<td>52</td>
</tr>
<tr>
<td>Antarctic</td>
<td>0.22±0.06</td>
<td>10.9±1.1</td>
<td>0.32</td>
<td>11.5</td>
<td>139</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sector</th>
<th>Slope</th>
<th>Intercept [cm]</th>
<th>R</th>
<th>RMSD[cm]</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weddell Sea</td>
<td>0.34±0.08</td>
<td>11.1±1.8</td>
<td>0.43</td>
<td>13.3</td>
<td>92</td>
</tr>
<tr>
<td>Bellingshausen and Amundsen Seas</td>
<td>-0.04±0.08</td>
<td>20.1±3</td>
<td>-0.07</td>
<td>25.3</td>
<td>55</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td>-0.11±0.1</td>
<td>15.4±1.9</td>
<td>-0.14</td>
<td>15.5</td>
<td>68</td>
</tr>
<tr>
<td>Ross Sea</td>
<td>0.04±0.05</td>
<td>10.3±1.1</td>
<td>0.09</td>
<td>13.7</td>
<td>57</td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West Antarctic</td>
<td>0.12±0.04</td>
<td>14±1.2</td>
<td>0.19</td>
<td>17.8</td>
<td>215</td>
</tr>
<tr>
<td>East Antarctic</td>
<td>0.06±0.06</td>
<td>10.4±1.3</td>
<td>0.13</td>
<td>13.5</td>
<td>59</td>
</tr>
<tr>
<td>Antarctic</td>
<td>0.13±0.04</td>
<td>12.8±1</td>
<td>0.21</td>
<td>17</td>
<td>274</td>
</tr>
</tbody>
</table>
In Situ Data

Figure 5.14: Comparison of new snow depth product derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for the period between April and October. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-Bio observations are pixel averages. For full set of regression coefficients see Tab. 5.15.

Figs. 5.14 and 5.15 show the comparison of pixel-based AMSR-E snow depth averages and Figs. 5.16 and 5.17 show the comparison of AMSR-E daily snow depth averages retrieved using the new regression coefficients with pixel and daily ASPeCt-Bio and ISPOL snow depth averages. A full list of the regression coefficients can be found in Tabs. 5.15 and 5.16. Similarly to the comparison of the snow depth from the new snow depth product with ASPeCt ship-based observations the comparison with ASPeCt-Bio and ISPOL in situ data the AMSR-E snow depth increased, however, contrary to the comparison with ASPeCt data the slope of the regression lines decreased in comparison to the comparisons of the NSIDC snow depth product with the in situ data. The number of snow depth pairs is roughly the same as for the comparison of the NSIDC snow depth product.
Figure 5.15: Comparison of new snow depth product derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for the whole year. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-Bio observations are pixel averages. For full set of regression coefficients see Tab. 5.15.

For the comparison of the pixel averages the changes of the RMSD are between about 0 cm and about 6 cm for the Weddell Sea Sector. For the comparison of the daily averages changes of the RMSD lie between about 0 cm and about 5 cm for the Weddell Sea Sector.
Figure 5.16: Comparison of new snow depth product derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for the period between April and October. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-Bio and ISPOL observations are daily averages. For full set of regression coefficients see Tab. 5.16.
Figure 5.17: Comparison of new snow depth product derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for the whole year. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-Bio and ISPOL observations are daily averages. For full set of regression coefficients see Tab. 5.16.
Table 5.15: Slope, Intercept, correlation coefficient R, RMSD and number of pixels included in the comparison of the new AMSR-E passive microwave snow depth retrieval product with pixel-by-pixel averaged ASPeCt-Bio and ISPOL in situ measurements observations for the period 2002 – 2011.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Slope</th>
<th>Intercept [cm]</th>
<th>R</th>
<th>RMSD[cm]</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weddell Sea</td>
<td>0.04±0.17</td>
<td>14.1±4.7</td>
<td>0.1</td>
<td>18.5</td>
<td>10</td>
</tr>
<tr>
<td>Bellingshausen and Amundsen Seas</td>
<td>-0.31±0.19</td>
<td>30.2±4.5</td>
<td>-0.35</td>
<td>15.2</td>
<td>24</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ross Sea</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>-0.08±0.05</td>
<td>12.9±0.7</td>
<td>-0.26</td>
<td>10.8</td>
<td>36</td>
</tr>
<tr>
<td>West Antarctic</td>
<td>-0.11±0.13</td>
<td>23.2±3.3</td>
<td>-0.14</td>
<td>16.2</td>
<td>34</td>
</tr>
<tr>
<td>East Antarctic</td>
<td>-0.08±0.05</td>
<td>12.9±0.7</td>
<td>-0.26</td>
<td>10.8</td>
<td>36</td>
</tr>
<tr>
<td>Antarctic</td>
<td>0.09±0.08</td>
<td>14.9±1.6</td>
<td>0.14</td>
<td>13.7</td>
<td>70</td>
</tr>
</tbody>
</table>

Period: April-October

<table>
<thead>
<tr>
<th>Sector</th>
<th>Slope</th>
<th>Intercept [cm]</th>
<th>R</th>
<th>RMSD[cm]</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weddell Sea</td>
<td>0.16±0.12</td>
<td>14.9±3.6</td>
<td>0.29</td>
<td>17.7</td>
<td>23</td>
</tr>
<tr>
<td>Bellingshausen and Amundsen Seas</td>
<td>-0.31±0.19</td>
<td>30.2±4.5</td>
<td>-0.35</td>
<td>15.2</td>
<td>24</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ross Sea</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>-0.08±0.05</td>
<td>12.9±0.7</td>
<td>-0.26</td>
<td>10.8</td>
<td>36</td>
</tr>
<tr>
<td>West Antarctic</td>
<td>0.01±0.1</td>
<td>20.8±2.7</td>
<td>0.02</td>
<td>16.4</td>
<td>47</td>
</tr>
<tr>
<td>East Antarctic</td>
<td>-0.08±0.05</td>
<td>12.9±0.7</td>
<td>-0.26</td>
<td>10.8</td>
<td>36</td>
</tr>
<tr>
<td>Antarctic</td>
<td>0.15±0.07</td>
<td>14.6±1.5</td>
<td>0.25</td>
<td>14.3</td>
<td>83</td>
</tr>
</tbody>
</table>
Table 5.16: Slope, Intercept, correlation coefficient R, RMSD and number of days included in the comparison of the new AMSR-E passive microwave snow depth retrieval product with daily averaged ASPeCt-Bio and ISPOL in situ measurements observations for the period 2002 – 2011.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Slope</th>
<th>Intercept [cm]</th>
<th>R</th>
<th>RMSD [cm]</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weddell Sea</td>
<td>0.04±0.17</td>
<td>14.1±4.7</td>
<td>0.1</td>
<td>18.5</td>
<td>10</td>
</tr>
<tr>
<td>Bellingshausen and Amundsen Seas</td>
<td>-0.31±0.19</td>
<td>30.2±4.5</td>
<td>-0.35</td>
<td>15.2</td>
<td>24</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ross Sea</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>-0.07±0.07</td>
<td>12.9±0.9</td>
<td>-0.2</td>
<td>9.6</td>
<td>30</td>
</tr>
<tr>
<td>West Antarctic</td>
<td>-0.11±0.13</td>
<td>23.2±3.3</td>
<td>-0.14</td>
<td>16.2</td>
<td>34</td>
</tr>
<tr>
<td>East Antarctic</td>
<td>-0.07±0.07</td>
<td>12.9±0.9</td>
<td>-0.2</td>
<td>9.6</td>
<td>30</td>
</tr>
<tr>
<td>Antarctic</td>
<td>0.1±0.09</td>
<td>15.1±1.7</td>
<td>0.15</td>
<td>13.5</td>
<td>64</td>
</tr>
<tr>
<td>Period: January-December</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weddell Sea</td>
<td>0.16±0.12</td>
<td>14.9±3.6</td>
<td>0.29</td>
<td>17.7</td>
<td>23</td>
</tr>
<tr>
<td>Bellingshausen and Amundsen Seas</td>
<td>-0.31±0.19</td>
<td>30.2±4.5</td>
<td>-0.35</td>
<td>15.2</td>
<td>24</td>
</tr>
<tr>
<td>Indian Ocean</td>
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<td></td>
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<tr>
<td>Ross Sea</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western Pacific Ocean</td>
<td>-0.07±0.07</td>
<td>12.9±0.9</td>
<td>-0.2</td>
<td>9.6</td>
<td>30</td>
</tr>
<tr>
<td>West Antarctic</td>
<td>0.01±0.1</td>
<td>20.8±2.7</td>
<td>0.02</td>
<td>16.4</td>
<td>47</td>
</tr>
<tr>
<td>East Antarctic</td>
<td>-0.07±0.07</td>
<td>12.9±0.9</td>
<td>-0.2</td>
<td>9.6</td>
<td>30</td>
</tr>
<tr>
<td>Antarctic</td>
<td>0.15±0.07</td>
<td>14.8±1.6</td>
<td>0.25</td>
<td>14.2</td>
<td>77</td>
</tr>
</tbody>
</table>
5.6 Summary

In this Section new regression coefficients were derived to set up a new snow depth on sea ice retrieval algorithm with uncertainty estimation. For this purpose first new static open water tie points for the 18.7 GHz and 36.5 GHz channels and their uncertainties were calculated. Then using these tie points and sea ice concentrations from the ASI sea ice algorithm the vertically polarised gradient ratio, GRV, and its uncertainties were calculated. The calculated GRVs were then compared to ship-based snow depth observations from ASPeCt. Under the condition of the homogeneity of the ASPeCt observations along the daily ship passage and the GRV, and the consideration that for snow free sea ice SMOS sea ice thicknesses of about 20 cm correspond to a GRV of about 0.005 a new linear regression between daily AMSR-E GRV averages and ASPeCt snow depth averages was performed. The slope, y-intercept and their uncertainties were taken as new regression coefficients to set up a new snow depth algorithm:

\[ S_{\text{ASPeCt}} = (-864 \pm 131) \text{ cm} \cdot \text{GRV} + (5.4 \pm 2.1) \text{ cm} \] (5.2)

Using these coefficients a new daily averaged snow depth product was produced and compared to the ASPeCt ship-based observations and in situ measurements. The comparisons were compared to the comparisons for the NSIDC AMSR-E snow depth product with the same datasets. Here, the snow depths generally showed a shift to higher snow depths, however, while the comparisons showed a slight improvement for the ASPeCt dataset this could not be found for the in situ data. Altogether the new snow depth product did not show a significant improvement to the NSIDC product except that for the new data set now a pixel-based uncertainty estimation from the Gaussian error propagation is available.

Here, it is important to note that it is not surprising, that the new snow depth retrieval algorithm does not provide a breakthrough in snow depth retrieval. The method used, a linear regression between coarse scale satellite observations and small scale in situ estimates of the snow depth which has its limitations per se, is still the same as used before - except that it has now been derived carefully solely from AMSR-E brightness temperatures. This was one of the main goals of this work package. More innovative approaches, such as testing other than linear empirical relationships or involving a more physically based retrieval by using radiative transfer modeling would have gone beyond the projects’ scope. Instead it was more important to come also up with per-grid cell uncertainty estimation - the second main goal.

However, although they may contain relevant information for future snow depth operations the unphysical snow depth values may cause problems for data users. Here, three different options exist to circumvent this problem: (1) the negative snow depths can be set to 0, (2) the area under investigation can be limited to sea ice concentration of 80% or larger since here the probability of having negative snow depths is reduced, or (3) a weighting using the snow depth uncertainty could be applied and those snow depth values for which the ratio of snow depth uncertainty to snow depth exceed a certain threshold removed. The final decision how to deal with negative snow depth will be left to the data users since different users may have different preferences.
6 Conclusions and Remarks

In this document the results of Work Package WP 1100 of the ESA Sea Ice ECV Project Option: Antarctic sea ice thickness were summarised. In the first part of WP1100 SSM/I (years 1992 - 2008) and AMSR-E (years 2002 - 2011) snow depth retrieval products from the National Snow and Ice Data Center were compared with ship-based snow depth observations recorded using the ASPeCt protocol, and in situ measurements from the ASPeCt-Bio and ISPOL datasets. The results showed that the satellite retrievals have the tendency to overestimate the reference snow depths from ASPeCt and in situ measurements for snow depths below approximately 15 cm, while they have the tendency to underestimate the reference snow depths for snow depths above approximately 30 cm. In particular for SSM/I the comparisons indicated that the NSIDC snow depth data product agrees better with ship-based and in situ measurements for the West Antarctic Sectors (Weddell Sea Sector, Bellingshausen and Amundsen Seas Sector, and Ross Sea Sector), and during winter months (period April-October) than for the East Antarctic Sectors (Indian Ocean Sector and Western Pacific Ocean Sector) and summer months (November-March).

In the second part of the Work Package new regression coefficients for the empirical relation between the vertically polarised gradient ratio (GRV) at 18.7 and 36.5 GHz were derived and uncertainty estimation for the retrieved snow depth product was implemented. Here, first new static open water tie points were derived. They are 184.7 K ± 0.73 K for the 18.7 GHz channel and 184.7 K ± 0.73 K for the 36.5 GHz channel. The resulting GRVs were compared with snow depths with ASPeCt ship-based observations from winter months. However, since regression coefficients obtained from the comparisons were much lower than those given by e.g. Brucker and Markus [RD-28] and the comparisons from Section 4 showed that in particular steeper slopes are needed to correct the underestimation of snow depth, found in particular for snow depths above 30 cm, for the final derivation of the new regression coefficients three constraints were applied:

1. The uncertainty of the gradient ratio (GRV) - snow depth pairs had to be smaller than 0.004 for GRV.
2. The snow depth mean to standard deviation ratio for the daily averaged ASPeCt snow depths had to be smaller than 0.3.
3. Three artificial regression points were added to consider the GRV for thin bare sea ice.

The first two criteria are homogeneity criteria which can be justified if one considers that in general the variability of the brightness temperatures as well as the representativeness and variability of ASPeCt snow depth observations within one satellite pixel and along the daily ship track are not known. The application of criteria 1. and 2. ensure that only those days are included where the snow and ice conditions are very homogeneous and thus the representativeness, although still unknown, can be assured to a higher degree than for days with higher variations and thus the uncertainty of the coefficients obtained are more representative. Here, it has to be noted that by doing this the natural variability of the snow depth within a satellite grid cell is partly excluded. The criterion for the GRV of bare thin sea ice was added since the comparison did not contain any pairs with ASPeCt snow depth averages close to zero.
Using these criteria the new empirical regression coefficients derived for AMSR-E are $a = (-864 \pm 131)$ cm and $b = (5.4 \pm 2.1)$ cm.

With the new empirical coefficients a new AMSR-E snow depth and snow depth uncertainty dataset was derived for sea ice concentrations ≥20%. The dataset shows reasonable snow depth and snow depth uncertainty distributions for the Antarctic, however, in particular at the ice edge negative snow depths can be found. The negative snow depths coincide with high snow depth uncertainties. These can be assumed to be caused by the high uncertainty of the sea ice concentration which can easily exceed 15-20% for sea ice concentrations below 50%. Furthermore, high snow depth uncertainties were found for areas with possibly perennial sea ice or sea ice which exhibits a radiometric signature similar to the one of perennial sea ice. Here, the retrieved snow depths can exceed the theoretical limit of about 50 cm for the snow depth retrieval algorithm and thus due to the variations of the parameters influencing surface emission validity of the snow depth cannot be assured. Furthermore, a remaining task for future work is to implement a more effective cloud filter to remove false snow depth retrievals at positions where no sea ice is present. While this task is relatively easy for areas at latitudes lower than 50°S it is more challenging for false retrievals close to ice and snow covered areas. Furthermore, to get an idea about the differences between the old and the new retrieval the new snow depth product was compared with the ASPeCt, ASPeCt-Bio and ISPOL datasets for the period between 2002 and 2011. Although, the new coefficients are AMSR-E specific in the comparison with ASPeCt ship-based snow depth observations only slight corrections to higher snow depth (as well as a shift to higher snow depths in general) and for the comparison with ASPeCt-Bio and ISPOL in situ data even a diminishment were found. Thus the new snow depth product did not improve much compared to the NSIDC snow depth product. However, in comparison to the NSIDC snow depth product it has the advantage that an pixelwise uncertainty estimation is included, providing data users with information about the snow depth uncertainty originating from the input parameters.

**Outlook on Future Work**

As shown in this Work Package the retrieval of snow depth needs more in depth investigation. The comparison of NSIDC SSM/I and AMSR-E snow depth retrieval products with ASPeCt ship-based observations showed strong territorial variations between the Antarctic Sectors. Furthermore, a strong variation could only be found between Antarctic summer and winter. This is also illustrated in the new snow depth product where the fraction of negative and hence unphysical snow depth data is unacceptable large. Thus, the comparisons suggest, that a combination of sector-wise and seasonal retrieval could improve the algorithms’ skill to completely include different snow and ice conditions in each sector. This, however, would need a much larger areal cover of snow depth observations from ship-based, in situ and airborne measurements - if the same methodology to derive retrieval coefficients would be used. Because ship-based and in situ observations are very time intensive and thus very challenging, airborne observations would provide a better opportunity to collect snow depth data for comparatively large areas with high temporal (if the flights are conducted regularly) and spatial resolution. Although Operation IceBridge (OIB) already conducted snow depth measurements the indistinguishability of the snow ice interface in the data made it until recently impossible to derive snow depth from the
recorded measurements. However, [RD-22] suggested a method to distinguish the snow ice interface on Antarctic sea ice. Thus extension of the radar measurements to the whole Antarctic would provide a useful dataset to derive and validate a new snow depth retrieval for future satellite missions, in particular for AMSR-2 the successor of AMSR-E. Because the comparison performed in this work indicates that the retrieved snow depth is also strongly influenced by other parameters such as e.g. snow wetness, snow grain size, surface roughness (in particular due to ice ridges), an approach which enhances the new empirical retrieval algorithm with results from radiative transfer modeling of snow on sea ice emission under adverse weather conditions and sea-ice growth histories seems to be a more promising way to follow. The comparison of brightness temperatures or GRVs with snow depth measurements, and modeling of the brightness temperatures for the snow and ice conditions in the pixel could be used to set up Look-Up-Tables for different ice conditions such as wet snow, flooding, perennial sea ice, different snow grain sizes, etc. Here, the basic idea is that these Look-Up-Tables contain information about the emissivity of different microwave frequencies for the prevalent snow conditions and thus the snow depth can easily related to snow depth. However, this requires that for the microwave channels characteristic relations between microwave emission and snow depths can be found but it would give more sophisticated and more generally applicable retrieval than the current approach. Moreover, if realisable also a linear mixing model could be applied to obtain snow depth for pixels with mixed surface conditions. While the two suggestions for future work made above, if carried out, will require large efforts from the experimental as well as the theoretical side and thus are very time and work intensive and most likely will require several years of intensive research, a short-term approach could be to implement the snow depth retrieval for the 10 and 18.7 GHz channels suggested by Markus et al. [RD-29] to increase the upper retrieval limit of the retrievable snow depth from about 50 cm to about 100 cm.
Appendix A Snow Depth Comparisons for SSM/I and AMSR-E

A.1 SSM/I: Pixel Averages

Figure A.1: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for January. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.1.
Figure A.2: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for February. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.1.
Figure A.3: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for March. SSM/I observation period: 1992-2008, SSM/I and ASPeCt observations are pixel averages. For full set of regression coefficients see Tab. A.1.
Figure A.4: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for April. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.1.
Figure A.5: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for May. SSM/I observation period: 1992-2008, SSM/I and ASPeCt observations are pixel averages. For full set of regression coefficients see Tab. A.1.
Figure A.6: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for June. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.1.
Figure A.7: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for July. SSM/I observation period: 1992-2008, SSM/I and ASPeCt observations are pixel averages. For full set of regression coefficients see Tab. A.1.
Figure A.8: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for August. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.1.
Figure A.9: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for September. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.1.
Figure A.10: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for October. SSM/I observation period: 1992-2008, SSM/I and ASPeCt observations are pixel averages. For full set of regression coefficients see Tab. A.1.
Figure A.11: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for November. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.1.
Figure A.12: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for December. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.1.
### Table A.1: Slope, Intercept, correlation coefficient R, RMSD and number of pixels included in the comparison of SSM/I passive microwave snow depth retrievals with pixel by pixel averaged ASPeCt observations for the period 1992 – 2008. The uncertainties of the slope and intercept give the 1σ-standard deviation. The sea ice concentration filter is set to 20%.

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<tr>
<th>Months</th>
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<th>R</th>
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Table A.2: Slope, Intercept, correlation coefficient R, RMSD and number of pixels included in the comparison of SSM/I passive microwave snow depth retrievals with pixel by pixel averaged ASPeCt observations for the period 1992 – 2008. The uncertainties of the slope and intercept give the 1σ-standard deviation. The sea ice concentration filter is set to 80%.

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<th>R</th>
<th>RMSD [cm]</th>
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A.2 SSM/I: Daily Averages

Figure A.13: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for January. SSM/I observation period: 1992-2008, SSM/I and ASPeCt observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
Figure A.14: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for February. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
Figure A.15: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for March. SSM/I observation period: 1992–2008, SSM/I and ASPeCt observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
Figure A.16: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for April. SSM/I observation period: 1992-2008, SSM/I and ASPeCt observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
Figure A.17: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for May. SSM/I observation period: 1992-2008, SSM/I and ASPeCt observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
Figure A.18: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for June. SSM/I observation period: 1992-2008, SSM/I and ASPeCt observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
Figure A.19: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for July. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
Figure A.20: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for August. SSM/I observation period: 1992-2008, SSM/I and ASPeCt observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
Figure A.21: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for September. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
Figure A.22: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for October. SSM/I observation period: 1992-2008, SSM/I and ASPeCt observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
Figure A.23: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for November. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
Figure A.24: Comparison of snow depth derived from SSM/I brightness temperatures at 19 and 37 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for December. SSM/I observation period: 1992-2008, SSM/I and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.3.
Table A.3: Slope, Intercept, correlation coefficient R, RMSD and number of days included in the comparison of daily averaged SSM/I passive microwave snow depth retrievals with daily averaged ASPeCt observations for the period 1992 – 2008. The uncertainties of the slope and intercept give the 1σ-standard deviation. The sea ice concentration filter is set to 20%.

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## Passive Microwave Snow Depth on Antarctic sea ice assessment

Ref. SICCI-ANT-PMW-SDASS-11-14  
Version 1.0 / 28 Nov 2014

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Table A.4: Slope, Intercept, correlation coefficient R, RMSD and number of days included in the comparison of daily averaged SSM/I passive microwave snow depth retrievals with daily averaged ASPeCt observations for the period 1992 – 2008. The uncertainties of the slope and intercept give the 1σ-standard deviation. The sea ice concentration filter is set to 80%.

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<th>RMSD [cm]</th>
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A.3 AMSR-E: Pixel Averages

Figure A.25: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for January. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.5.
Figure A.26: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for February. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.5.
Figure A.27: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for March. AMSR-E observation period: 2002-2011, AMSR-E and ASPerCt-observations are pixel averages. For full set of regression coefficients see Tab. A.5.
Figure A.28: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for April. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.5.
Figure A.29: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for July. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.5.
Figure A.30: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for August. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.5.
Figure A.31: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for September. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.5.
Figure A.32: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for October. AMSR-E observation period: 2002-2011. AMSR-E and ASPeCt observations are pixel averages. For full set of regression coefficients see Tab. A.5.
Figure A.33: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for November. AMSR-E observation period: 2002-2011. AMSR-E and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.5.
Figure A.34: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic, and the whole Antarctic for December. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are pixel averages. For full set of regression coefficients see Tab. A.5.
Table A.5: Slope, Intercept, correlation coefficient R, RMSD and number of pixels included in the comparison of NSIDC AMSR-E passive microwave snow depth retrievals with pixel by pixel averaged ASPeCt observations for the period 2002 – 2011. The uncertainties of the slope and intercept give the 1σ-standard deviation. The sea ice concentration filter is set to 20%. Months and Antarctic sectors without comparison are not listed.

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Table A.6: Slope, Intercept, correlation coefficient R, RMSD and number of pixels included in the comparison of NSIDC AMSR-E passive microwave snow depth retrievals with pixel by pixel averaged ASPeCt observations for the period 2002 – 2011. The uncertainties of the slope and intercept give the 1 σ-standard deviation. The sea ice concentration filter is set to 80%. Months and Antarctic sectors without comparison are not listed.

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A.4 AMSR-E: Daily Averages

Figure A.35: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for January. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.7.
Figure A.36: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for February. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.7.
Figure A.37: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for March. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.7.
Figure A.38: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for April. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.7.
Figure A.39: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for August. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.7.
Figure A.40: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for September. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.7.
Figure A.41: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for October. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.7.
Figure A.42: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for November. AMSR-E observation period: 2002-2011, AMSR-E and ASPeCt observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.7.
Figure A.43: Comparison of snow depth derived from AMSR-E brightness temperatures at 18.7 and 36.5 GHz for all Antarctic sectors, the West Antarctic, the East Antarctic and the whole Antarctic for December. AMSR-E observation period: 2002-2011. AMSR-E and ASPeCt-observations are daily averages over all pixels. For full set of regression coefficients see Tab. A.7.
Table A.7: Slope, Intercept, correlation coefficient R, RMSD and number of pixels included in the comparison of NSIDC AMSR-E passive microwave snow depth retrievals with daily averaged ASPeCt observations for the period 2002 – 2011. The uncertainties of the slope and intercept give the 1σ-standard deviation. The sea ice concentration filter is set to 20%. Months and Antarctic sectors without comparison are not listed.

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<th>RMSD [cm]</th>
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Table A.8: Slope, Intercept, correlation coefficient R, RMSD and number of pixels included in the comparison of NSIDC AMSR-E passive microwave snow depth retrievals with daily averaged ASPeCt observations for the period 2002 – 2011. The uncertainties of the slope and intercept give the 1σ-standard deviation. The sea ice concentration filter is set to 80%. Months and Antarctic sectors without comparison are not listed.

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