AMSR-E Geolocation and Validation of Sea Ice Concentrations Based on 89 GHz Data

Georg Heygster*1, Heidrun Wiebe*1, Gunnar Spreen*2 and Lars Kaleschke*2

Abstract

Sea ice concentrations based on AMSR-E 89 GHz data are unprecedented in combining data timeliness (about 6 hours after overflight), horizontal resolution (about 5 km) and daily global coverage. Here the geolocation of the AMSR-E Level 1 data (required to use due to the time constraints) is corrected and the sea ice concentrations are validated. The geolocation adjusts the cone angle and scan angle of AMSR-E's conical scanning scheme based on the comparisons of the jump of the AMSR-E brightness temperature at the global coastlines with a global landmask. The average residual error increasing from 250 m for the 89 GHz channels to 1425 m in the 6 GHz channels. The ice concentrations are based on the ARTIST (Arctic Radiation and Turbulence Interaction STudy) Sea Ice (ASI) retrieval algorithm which is an enhancement of the Svendsen 85 GHz algorithm. Here we review the results of four types of comparisons of the ASI/AMSR-E ice concentrations, namely with (1) Arctic ship based bridge observations of RV Polarstern, (2) optical images of the multispectral imager ETM+ operating on Landsat-7, (3) Envisat and Radarsat-1 SAR images and (4) two other AMSR-E sea ice concentration algorithms (Bootstrap and NASA Team 2) which use the 19/37 GHz channels. In spite of the different sensor types, wavelengths and interaction principles of the electromagnetic radiation the four comparisons yield a rather consistent picture. On average the ASI ice concentrations range between those from Landsat and SAR. Both the bias intervals (−2.9...2.6%) and the rms errors are slightly higher than those of the NT2 algorithm, applied to the same scenes. In the hemispherical (Arctic and Antarctic) comparisons of the ASI results with the widely used NASA Team 2 and Bootstrap concentrations, the biases do not exceed 2%, the rms error ranges between 7 and 11% ice concentration.

Keywords: AMSR-E, Microwave, Geolocation, Sea ice, Validation

1. Introduction

Spaceborne passive microwave sensors on polar orbits belong to the most important tools for global sea ice observations as they have been observing the complete earth surface daily since over 30 years. The launch of ADEOS-2 and AQUA in 2002 with the sensors AMSR and AMSR-E has increased the horizontal resolution of the observations by a factor of about three, compared to the resolution of the sensors SSM/I mainly used before. Together with the shift of the used frequencies for sea ice concentration retrievals from the 18/37 GHz channels to the 89 GHz channels, a resolution improvement of a factor of about 10 from 50 to 5 km can be achieved. However, at 89 GHz the atmospheric influence from water vapor and clouds is considerably higher than at 18 and 37 GHz so that a careful validation of the retrieved sea ice concentrations is required. Here we give a synopsis of the validation efforts which have been undertaken for the 89 GHz ASI (ARTIST Sea Ice) algorithm. Such data are daily calculated hemispherically in a 6.25 km grid, and for some regions of interest in a 3.125 km grid.

For any validation (as well as for any other application) the exact geolocation of the satellite observed data is important for the correct mapping of retrievals during the comparison. At the same time, any retrieval method using several frequencies or data from different sensors requires an exact geolocation. Here, the geolocation of the data is especially needed during the near-real time calculation of global and regional sea ice maps at the University of Bremen in the framework of the GMES (Global Monitoring for Environment and Security) service Polar View.

2. Geolocation of AMSR-E Data

The geolocation of the AMSR-E Level 1 data is currently not optimal, which can in particular be seen along coastlines due to the high land-sea contrast in brightness temperatures.
Fig. 1 Brightness temperatures at 89 GHz (map of Denmark), October 01, 2004, a) JAXA geolocation, b) IUP geolocation.

Observations of the geolocation error show that the projected footprints are shifted in the satellite flight direction, i.e. footprints of ascending swaths are shifted towards north-west, those of descending swaths towards south-west (see Figure 1 (a)). Consequently, the brightness temperature differences between ascending and descending swaths of one day are expected to be quite high along coastlines. The top image of Figure 2 shows those differences at 89 GHz (map of Scandinavia and Baltic States), where we have positive differences (yellow and red colors) along north coasts, and negative differences (blue and violet colors) along south coasts. The approach of improving the geolocation of AMSR-E data is finding optimal values for the nadir (nominal : 47.5°) and the scan angle (nominal : 75°) of the AMSR-E instrument by minimizing the sum over all absolute values of brightness temperature differences between ascending and descending swaths. The procedure is applied to data of 16 days (the first day of each quarter year from January 2003 to October 2006) using globally all data within a distance of 20 km or less from coastlines. The averages of those 16 days are taken as the global optimal viewing angles.

After adjusting the viewing angles there is a considerable improvement in the geolocation of the data (Figure 1). In the JAXA geolocation (top image) some areas that correspond to land (reddish color) are located on water (seas and lakes), and some areas that refer to water (bluish color) are placed
on land. In the IUP geolocation (bottom image) in contrast, the geolocation is much more accurate, that means all reddish areas are on land and all bluish areas on water.

The brightness temperature differences between ascending and descending swaths show the improvements in geolocation even more impressively (Figure 2). The numerical values of mean differences per pixel for one typical of the 16 days are between 8.75 K and 15.74 K for JAXA geolocation, and between 4.94 K and 7.87 K for IUP geolocation. That means the mean differences have been reduced by factors between 1.6 and 2.7. Remaining differences refer to different surface temperatures at the acquisition time of ascending and descending overpasses (which typically are several hours apart), and to different atmospheric influences, i.e. weather effects (especially in higher frequency channels).

The results for the viewing angles obtained from the geolocation optimization are given in Table 1. Note the small remaining uncertainty in the angles. There was no time trend observed in the series of the 16 selected days from January 2003 to October 2006\(^1\).

The average residual error in the here calculated geolocation ranges from 245 m for the 89 GHz channels to 1425 m for the 6 GHz channel. This corresponds to 5% of the footprint size for 89 GHz and between 2% to 3% for the lower frequencies. There was no trend in time observed\(^1\).

3. Sea Ice Concentration

The ARTIST sea ice (ASI) algorithm, which bases on ideas of Svendsen et al. (1987)\(^1\) was adapted and validated for AMSR-E data\(^1\). The ASI algorithm is based on the brightness temperature polarization difference at 89 GHz (\(T_{\text{bVV}} - T_{\text{bHH}}\)) to calculate sea ice concentrations. The polarization difference is high over open ocean and low over sea ice, rather independent of the ice type. The algorithm has two adjustable parameters, called tie points. These are the polarization differences over open water, P0, and over 100% ice cover, P1. With 4 km × 6 km IFOV the 89 GHz channels offer the sensor’s highest spatial resolution, and ice maps are calculated operationally in 6.25 s and 3.125 km grids. Unfavorable is the enhanced atmospheric influence at this frequency in comparison to the lower frequency channels. A standard polar atmosphere is used to model the atmospheric influence on the brightness temperature difference in dependence of the ice concentration but independent (constant) of space and time. The lower frequency channels 19, 22, and 37 GHz, which are less influenced by the atmosphere, and additionally Bootstrap BBA (hereafter referred to as BT) ice concentrations\(^4\) are used to eliminate spurious ice in the open ocean. The quality of the ASI algorithm using SSM/I data was evaluated in several studies\(^3\)\(^-\)\(^7\), where it showed a performance equal to or better than other passive microwave remote sensing sea ice concentration algorithms.

Here we show how the AMSR-E ASI algorithm compares (1) to ship based observations and (2) to two other AMSR-E sea ice concentration algorithms which use the 19/37 GHz channels, (3) to optical images of the multispectral imager ETM + operating on Landsat-7 and (4) to Envisat and Radarsat-1 SAR images.

3.1 Comparison to Ship Based Observations

During the research vessel R/V Polarstern cruises ARK-XIX/1 (28 February to 24 April 2003), ARK-XX/2 (16 July to 29 August 2004), and ARK-XXII/2 (28 July to 7 October 2007) sea ice conditions around the vessel were routinely observed from the bridge by the on board scientist by visual surveillance. The winter/spring cruise ARK/XIX/1 started in the Storfjorden and Barents Sea and continued along the west coast of Spitzbergen up to 82° N in the Fram Strait. Sea ice observations were conducted between 2003–03–06, 09 : 00 UTC and 2003–04–21, 11 : 00 UTC. The summer cruise ARK-XX/2 started in Longyearbyen and went through the Greenland Sea through Fram Strait up to 85° N. Sea ice observations were conducted between 2004–07–24, 15 : 00 UTC and 2004–08–18, 13 : 00 UTC. The summer to fall cruise ARK-XXII/2 started in Tromso, Polarstern steamed through the Barents Sea passing East of Svalbard up to 84.5° N. From there the cruise continued to the East covering almost the complete part of the Eurasian and Russian Arctic Ocean. The northern most point was 88.4° N and the eastern most 135° W. Sea ice observations were conducted between 2007–08–01, 17 : 00 UTC and 2007–09–25, 12 : 20 UTC. Plots of the cruise track of the three expeditions are shown on the right side of Figure 3.

One of the several observed quantities is the total sea ice concentration, which is shown as gray lines in Figure 3 for ARK-XIX/1 (top), ARK-XX/2 (middle), and ARK-XXII/2 (bottom), respectively. As the observations were conducted by up to 16 different persons, errors may be introduced due to different subjective estimates of the ice concentration around the ship. The ice concentration estimates represent the area

<table>
<thead>
<tr>
<th>Channel</th>
<th>Nadir Angle [°]</th>
<th>Scan Angle [°]</th>
</tr>
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<tbody>
<tr>
<td>6 GHz</td>
<td>47.664 ± 0.0053 (± 183 m)</td>
<td>74.848 ± 0.0034 (± 49 m)</td>
</tr>
<tr>
<td>10 GHz</td>
<td>47.638 ± 0.0046 (± 156 m)</td>
<td>74.930 ± 0.0052 (± 75 m)</td>
</tr>
<tr>
<td>18 GHz</td>
<td>47.580 ± 0.0047 (± 160 m)</td>
<td>74.936 ± 0.0064 (± 93 m)</td>
</tr>
<tr>
<td>23 GHz</td>
<td>47.572 ± 0.0056 (± 192 m)</td>
<td>74.928 ± 0.0055 (± 84 m)</td>
</tr>
<tr>
<td>36 GHz</td>
<td>47.586 ± 0.0050 (± 170 m)</td>
<td>74.952 ± 0.0070 (± 101 m)</td>
</tr>
<tr>
<td>99 GHz A</td>
<td>47.574 ± 0.0048 (± 163 m)</td>
<td>75.142 ± 0.0026 (± 37 m)</td>
</tr>
<tr>
<td>99 GHz B</td>
<td>47.082 ± 0.0063 (± 217 m)</td>
<td>75.410 ± 0.0048 (± 76 m)</td>
</tr>
<tr>
<td>Mean</td>
<td>± 0.0052 (± 177 m)</td>
<td>± 0.0050 (± 73 m)</td>
</tr>
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</table>
Fig. 3 Comparison of ice concentrations from R/V Polarstern with those of three AMSR-E algorithms. Expedition a) ARK-XIX/1 (March/April 2003), b) ARK-XX/2 (July/August 2004), and c) ARK-XXII/2 (August/September 2007). In gray the visual Polarstern ice concentrations are plotted. The Differences between these and the ASI, NASA-Team 2, and Bootstrap algorithm ice concentration are shown in black, green, and red, respectively. X-axes give data point numbers (bottom) and the corresponding dates (top). d-f) respective cruise plots.
visible from the vessels bridge, mostly in a radius of 1 km. However, the observed area depends on the overall visibility (fog, haze etc.) and thus is often considerably smaller than the AMSR-E 89 GHz footprint and certainly smaller than the 37 GHz and 19 GHz footprints. Still these are valuable in-situ data for validation of sea ice concentration algorithms. These in-situ observations are compared to three different AMSR-E sea ice concentration data sets: (1) ASI ice concentrations on a 6.25 km grid using the tie-points P0 = 47 K and P1 = 11.7 K, (2) NASA-Team 2 (hereafter referred to as NT2) ice concentrations on a 12.5 km grid\(^1\), which is the standard AMSR-E ice concentration data available from NSIDC (National Snow and Ice Data Center, Boulder, US), and (3) ice concentrations from the Basic Bootstrap algorithm\(^1\) on a 12.5 km grid, which are provided as differences to NT2 concentrations in the NSIDC data set, too. The differences between these three algorithms and the Polarstern data are shown in Figure 3.

Table 2 summarizes the statistical analyses. During the three Polarstern campaigns all three ice concentration algorithms are performing quite similar. During the winter campaign ARK-XIX/1 all algorithms reproduce the Polarstern ice concentration estimates quite well with a small overall underestimation, which is small compared to the rms error (standard deviation) and caused by outliers in only short periods, where Polarstern mostly operated in the marginal ice zone and the total ice concentration was low (Figure 3). For low ice concentrations the expected error for all algorithms is larger than for high ice concentrations. But here the main reason for the large differences at low ice concentrations can be attributed to the different spatial resolution and time sampling of the Polarstern and AMSR-E ice concentrations. Polarstern ice concentrations are collected hourly while the AMSR-E ice concentrations are calculated from a mean of Polarstern ice concentrations are collected hourly while the chosen tie-point P has to be lower than the winter tie-point. Thus for the ASI algorithm a summer tie-point is applied. During the summer campaigns ARK-XX/2 and ARK-XXII/2 all three algorithms on average underestimated the Polarstern observations between 4 and 12%. During ARK-XX/2 the bias (mean difference) is positive for almost the complete time series and all three algorithms are well correlated. This is in agreement with the experience made during the cruise ARK-XX/2, where different tie-points (P0 = 50.0 K, P1 = 9.0 K) were used to better represent the visual inspections from the helicopter. During ARK-XXII/2 until end of August the bias is positive and of the same order as during ARK-XIX/1 for all algorithms. Later that the biases for ASI and BT drop down to near zero and even goes negative towards the end of the cruise where low ice concentrations were encountered. The second part therefore is more similar to the winter cruise ARK-XIX/1 and the transition of the differences can be explained by the change from summer melting conditions to the start of freeze up in fall. During this second part of the cruise, the NT2 results are quite different from and often much lower than the other two algorithms. Especially at start of September NT2 is heavily underestimating the observed ice concentrations. The reasons for that are not known so far. In total this underestimation causes the small bias of 4% for the NT2 algorithm but it can be stated that for the ARK-XXII/2 cruise ASI and BT perform best out of the three algorithms, as the rms error of NT2 is largest and its correlation is smallest.

Why are all three algorithms overestimating the observed sea ice concentrations during summer? Wet snow and melt ponds should cause an underestimation of sea ice concentration. For the ASI algorithm one main cause is the atmospheric influence. High cloud liquid water and water vapor values in the atmosphere will cause a positive bias for the ice concentrations, if this is not corrected by adapted tie-points. The study of Spreen et al. (2008)\(^2\) of automatically matching AMSR-E ASI ice concentration to SSM/I ice concentrations derived with NT2 showed that for the ASI algorithm in the Arctic at least two different sets of tie-points would be necessary to imitate the SSM/I NT2 ice concentrations. Especially the summer ice tie-point P1 has to be lower than the winter tie-point. Thus for the ASI algorithm a summer tie-point for melting conditions of about P1 = 9 K should be a better choice than the here all year around used tie-point P1 = 11.7 K. Another reason for the positive bias might be caused by the in situ observations itself, as Polarstern’s cruise track is biased to easy navigable ice conditions. During the winter cruise, where the ice concentrations mostly were near or at 100%, this fact makes no much difference for the ice concentration differences, as the vessel’s captain might prefer leads,
but which are mostly refrozen and 100% ice covered. In contrast to the winter cruise, in summer the observed ice concentration seldom exceeds 90%. Now the choice of the vessel’s route through the ice also influences the ice concentration differences, as the ship route might be biased to lower ice concentration compared to the general ice conditions in the AMSR-E footprints. On the other hand, the better representation of the small field of view from the bridge of Polarstern by the higher spatial resolution of the ASI algorithm is not attaining any advantage in comparison to the other two algorithms. Rms errors and correlations are insignificantly different for all three algorithms (beside the one already discussed NT2 case). This is again presumably caused by the enhanced sensitivity of the 89 GHz channels to atmospheric water vapor and cloud liquid water.

### 3.2 Comparison to ETM+/Landsat-7

The Landsat ETM+ images were acquired during March 2003 in the area of the Bering Sea and the Bering Strait. The four scenes, provided by Thorsten Markus, NASA Goddard Space Flight Center, cover various ice conditions (e.g. ice edges, polynyas, closed ice cover) and ice types (new ice, young ice, first-year ice), having mostly clear sky conditions. The physical quantity of the data is the albedo, which is calculated from the spectral radiance of the panchromatic band of the ETM+. Here we only present the comparison of one scene, the three others ones show similar behaviour.

Comparing two different data sets requires a co-location and a resolution matching. In the ASI data set we have ice concentrations on a 12.5 km grid, in the Landsat data set we have albedos on a 15 m grid which were reduced by averaging to a 150 m grid for ease of handling ; both grids are polar stereographic. The data are prepared for the comparison in two steps:

1. An ice-water albedo threshold of 0.1 is applied to the Landsat data, setting all Landsat pixels with albedo below 0.1 to 0% ice concentrations and all above 0.1 to 100% ice concentration.

2. The Gaussian weighted mean is taken from the Landsat pixels within a neighborhood of 83×83. This is how often 150 m fits into one ASI pixel of 12.5 km.

The tie points of the ASI data is adapted according the method described in Spreen et al. (2008), the resulting tie points are P0=80 K and P1=20 K. Here we only show the results of Scene 1, the other three scenes show similar behavior. Figure 4 shows the ice concentrations of (a) ASI, (b) Landsat, and (c) the differences between ASI and Landsat. Clearly the ASI algorithm underestimates the ice concentrations in the polynya area south of St. Lawrence Island (blue color in the difference image), and overestimates ice concentrations along the ice edge (red color in the difference image).

The bias and rms errors of the ice concentrations in all four scenes are analyzed for different ice types. The bias of first-year ice lies between −0.2% and −0.8%, the rms error between 1.2% and 4.0%. These are values very similar to results of the NT2-Landsat comparison, that had rms errors between 1.2% and 4.7%. The bias of young ice ranges from −0.3% to −3.9%, the rms error from 3.3% to 9.1%. These are still acceptable ranges. New ice is recognized with less reliability. It mainly occurs at the ice edge and in and an rms error of 18.3% to 26.2%. Summarized over all ice types and open water we have bias of −8.4% to 4.5% and rms errors of 2.0% to 17.4%.

The overestimation of ASI ice concentrations mainly occurs at the ice edge. Time shift between the data takes of the two sensors and geolocation errors can be ruled out as sources for the discrepancy : time differences are between ½ and 2 hours, the geolocation errors are below 4 km for March 2003 so that these cannot cause errors on a 12.5 km grid. The remaining explanation is the relatively high tie point P0=80 K, which causes ASI to recognize some water pixels as ice, leading the overestimation at the ice edge. The optimization procedure did lead to P0=80 K because with a lower tie point P0, most of the new ice would be recognized as water.

The underestimation of ASI ice concentrations mainly occurs in polynya areas where we have new ice. The ASI ice concentrations range between 60% and 80%, corresponding to a polarization difference of 40 K to 50 K. This means that ‘older ice’ (young ice and first-year ice) causes higher polarization differences than ‘younger ice’ (new ice, nilas and young ice) (≈10 K-20 K). Ice concentrations based on Landsat images are generally higher for new ice (≈ 80%-100%). This is mainly due to the deep step in ice concentration near the albedo threshold of 0.1 because Landsat pixels with an albedo slightly above the threshold of 0.1 are mapped to 100% ice concentration. Although we consider the Landsat data as ground truth, the threshold method has its drawbacks. Particularly the influence of snow leads to errors in the Landsat ice concentrations. When there is snow on top of the ice it may look brighter in the visible image. The older ice already looks quite bright, but new ice generally appears darker. Snow on top of new ice will then lead to ice concentrations that are too high. This phenomenon was examined by Cavalieri et al. (2006) who indeed found snow layers of 30 cm to 40 cm thickness in the area of the Landsat scenes. Wiebe (2007) concluded that the ASI algorithm tends to underestimate the ice concentration in polynya areas and to overestimate it near the ice edge.

### 3.3 Comparison : ASI-SAR Ice Concentrations

The SAR data set consists of several scenes from either
Radarsat-1 (ScanSAR wide mode data) or Envisat (Wide Swath mode data), taken in the Arctic between May 2003 and November 2004. The sizes range between 425 km x 445 km to 560 km x 565 km. The data is gridded on a polar stereographic grid with grid sizes of 100 m for Radarsat-1 scenes, and 75 m for Envisat scenes.

The classification method of the original single-polarized SAR images is based on a supervised neural network classification of second-order gray level statistics features. Four different classes are distinguished: calm water, rough water, low backscatter ice (smooth surface), and high backscatter ice (rough surface). The method to map the classified SAR pixels to ice concentrations on the low resolution 12.5 km ASI grid is as follows: In the classified SAR image all calm and rough water pixels are set to 0% ice concentration, all low backscatter and high backscatter ice pixels are set to 100% ice concentration. Finally, the mean is taken over those SAR pixels that correspond to a given ASI pixel on the polar stereographic 12.5 km grid. For the ASI ice concentrations the same tie points as for the Landsat comparison are used (P0 = 80 K, P1 = 20 K).

For the comparison of ice concentrations between ASI and SAR, four scenes are selected from a total of 39 scenes that cover the ice edge (Scene 1: Jun 06, 2004, Scene 2: Jun 30, 2004, Scene 3: Oct 03, 2003, Scene 4: Aug 26, 2003). In Figure 5 we only show the results for Scene 3, the other three scenes displaying a similar behavior. In the SAR ice concentration image (Fig. 5a) the pixels where the SAR classification scheme did not work (the method is not able to distinguish between high backscatter sea ice and high backscatter sea water) are excluded, as well as in the ASI-SAR difference image (Fig. 5b) from which we see that we have mainly underestimation of ASI ice concentrations along the ice edge (blue), and in some interior areas overestimation of ASI ice concentrations (red) with respect to the SAR ice concentrations. The errors mainly occur at lower ice concentrations. All biases are low, they range between −2.9% and 2.6%, the rms errors are quite large, ranging from 16.9% to 20.1%.

3.4 Comparison to other Passive Microwave Algorithms

To further evaluate the performance of the ASI algorithm in comparison to the BT and NT2 ice concentrations (same data sets as in last section) the complete AMSR-E time series from 19 June 2002 to 31 August 2006 is considered. Days with large areas of missing data or with spurious ice caused by strong atmospheric influence in at least one of the datasets were discarded. In total 95% of the 1534 days are considered in the Arctic and 96% in the Antarctic. The sea ice area and sea ice extent are often taken as climate change indicators.

To compare the three data sets with a matched resolution the ASI data are convolved with a Gaussian function with the full width at half maximum set to 21 km, the resolution of the AMSR-E 18.7 GHz channels, and then interpolated on the 12.5 km grid. The spatial distribution of the biases during the 2002-06-19 to 2006-08-31 AMSR-E period for ASI minus BT, ASI minus NT2 and the time series of these differences are shown for both hemispheres in Spreen et al. (2008). The spatial patterns in the maps of both differences show a lot of similarities. They are high in regions of high ice dynamics and near the ice edge.

The quantitative main findings are summarized in Table 3. The absolute value of the biases is not exceeding 2% for any of the four cases. This is within the error estimates of all three algorithms. The rms errors reach 10% but the larger differences mainly occur along the coast and in the marginal ice zone. For three out of the four cases the bias is negative and for one it is positive with a similar absolute value. In the Arctic the ASI algorithm seems to slightly underestimate the ice concentration in comparison to the two standard AMSR-E algorithms. In the Antarctic ASI lies well in between the two algorithms.

The analyses of this section allow to find tie points for the ASI algorithm which result in ice concentrations best matched the results of another algorithm, here BT and NT2. But as we do not know which of the three algorithms best
Fig. 5  Sea ice concentration maps of a) ASI and b) SAR, and c) the differences in ice concentration: ASI minus SAR, from October 03, 2003

Table 3  Biases D (%) and rms errors σ (%) and correlations r of the differences ASI-Bootstrap and ASI-NT2 algorithms for the Northern (NH) and Southern (SH) hemispheres.

<table>
<thead>
<tr>
<th></th>
<th>ASI - BT</th>
<th></th>
<th>ASI - NT2</th>
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<tbody>
<tr>
<td></td>
<td>D ± σ</td>
<td>r</td>
<td>D ± σ</td>
</tr>
<tr>
<td>NH</td>
<td>-1.4 ± 8.2</td>
<td>.95</td>
<td>-2.0 ± 8.8</td>
</tr>
<tr>
<td>SH</td>
<td>1.7 ± 10.8</td>
<td>.92</td>
<td>-1.6 ± 7.2</td>
</tr>
</tbody>
</table>

represents the truth, an adaptation based only on differences is questionable. Nevertheless, for applications where not the best representation of the truth but minimal differences between two algorithms is worthwhile, an adaptation of the tie-points like the one described in Spreen et al. (2008) should be used.

4. Conclusions

Validation requires independent data. Here we have presented validation efforts by comparing ASI ice concentrations with four different types of data: ship borne observations, optical Landsat TM images, lower frequency (ν<80 GHz) microwave observations, and SAR. Each data type has its own strengths and shortcomings: ship borne observations are most detailed, but biased towards lower ice concentrations and thicknesses, and cover only a small fraction of the footprint of satellite passive microwave sensors, optical data need daylight and are biased towards clear-sky cases, from SAR data ice concentrations are difficult to derive, and lower-frequency ice concentrations have less resolution than the data to be tested.

The comparisons in section 3.1 of the ASI, NT2 and BT results with ship observations from cruises in three different years give a rather consistent picture: with one exception (NT2 during ARK XXII), the biases of all three algorithms coincide within 3% bias and 2% rms error (Table 2).

Consistently over all considered Landsat scenes (section 3.3), the ASI algorithm detects first-year ice with an accuracy very similar to that of the NT2 algorithm (bias below 1%, rms errors 1...4%). For young and even more for new ice (which cover much less area) the bias and rms error increase, for new ice up to 26%. The contrasting results of the comparisons of ASI ice concentrations with Landsat and SAR (section 3.4) scenes show that the data considered as ground truth (Landsat and SAR data) may detect different ice types differently. Areas that are identified as new ice by the optical sensor have higher ice concentrations compared to those indicated by the ASI algorithm.

On average the ASI ice concentrations range between those from Landsat and SAR. Both the bias intervals (−2.9...2.6%) and the rms errors are slightly higher than those of the NT2 algorithm, applied to the same scenes.

In order to overcome the limitations of regionally and seasonally limited case studies, the differences between the ASI and the NT2 and BT results, respectively, have been determined in sections 3.4 independently for both hemispheres and over the years 2002 to 2006. The biases of the four cases do not exceed 2%, the rms error ranges between 7 and 11% ice concentration. At first glance, these rms errors may appear relatively high. However, here none of the three involved ice concentrations can be regarded as ‘ground’ truth. Rather, they all three carry their own errors.

The fast delivery within few hours after observation and higher horizontal resolution, compared to other ice concentration products based on passive microwave data, have created a high request on the operational ASI products (www.iup.uni-bremen.de) for ship navigation and other operational applications. Over SAR images the ASI data have the advantage of daily global coverage with quantitative sea ice concentrations. For climate studies, e.g. as input for climate models with less critical constraints on fast delivery, the users may
adjust according to their specific needs. the tradeoff between the higher horizontal resolution of the here presented near-90 GHz products and ice concentrations based on more traditional 19/37 GHz algorithms with slightly lower rms errors.

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References

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