Annual Progress Report Year 2 (3 June 2009- 2 June 2010)

Project Title: **Antarctic sea ice thickness from space: validating estimates from the laser and radar satellite altimeters with ship-based measurements**
(a three year project to The University of Texas at San Antonio funded by the NASA Cryosphere Program from 6/3/2008-6/2/2011)

Investigators: PI: S.F. Ackley (UTSA) CoPI's: Hongjie Xie (UTSA), Anthony Worby (Antarctic CRC, Australia), Thorsten Markus (NASA Goddard)

NASA Grant # NNX08AQ87G

Summary Accomplishments

- Calibration/Validation of the IceSAT estimated Antarctic sea ice thickness. Data obtained during the SIMBA and SIPEX 2007 International Polar Year Antarctic Sea Ice cruises relating surface elevation and sea ice thickness have been used to develop predictive relationships and then applied to the only concurrent ICESat data ever obtained over Antarctic sea ice (Xie et al., DSR, in press; Worby et al., DSR, in press) and have given a fully confirmed estimate of sea ice thickness from space.

-Data on several hundred surface elevation and ice thickness profiles from 15 ship-based experiments were recovered from their multiple sources, covering most seasons and regions of circumpolar Antarctic sea ice from 20 years of cruises. Careful examination and data analysis have been conducted. Preliminary results of empirical relations between sea ice thickness and snow freeboard for different sectors and for the entire Antarctic sea ice zone were presented at the 2009 AGU Fall conference and a paper is in preparation to be submitted to JGR. The empirical equations derived are being directly applied to ICESat snow freeboard data for deriving sea ice thickness in its footprint scale from 2003-2009 for the Bellingshausen-Amundsen and Ross Seas and will be presented at a meeting in June 2010.

- Modeling ICESat altimetry data based on SIMBA field data. We modeled the elevation, snow depth, ice freeboard and thickness distribution based on field measurements on the Belgica floe (5 km2) of mixed first year and multiyear ice and simulated the number of ICESat "hits" required to represent the ice thickness distribution (Weissling and Ackley, IGS, submitted). For any Arctic or Antarctic region's distribution of sea ice thickness, the UTSA IceSAT Simulator can now calculate the line track length of IceSAT altimetry that is required to effectively characterize that region to a designated statistical accuracy. For the Bellingshausen Sea region of mixed multiyear-first year ice that we characterized, this was determined to be a track length minimum of 19.5km, while an adjacent first year ice region could be characterized by a shorter track, 14.5km.

-Workshop on "Monitoring Arctic and Antarctic sea ice from various satellite products" co-sponsored by International Space Science Institute (ISSI) and this NASA grant The workshop was held in Bern, Switzerland, from March 15-19, 2010. This workshop brought 6 senior and 8 young scientists from all over the world to discuss the current issues of remote sensing of Arctic and Antarctic sea ice for its extent, thickness, type, roughness, changes and their climate connection (co-chaired by H. Xie and B. Ozsoy-Cicek (a PhD student of PIs)).

-Publication of eight journal articles related to Antarctic Sea Ice processes and IceSAT, AMSR-E and MODIS-based satellite remote sensing in polar or mountainous regions

-Conference Presentations were made, two at Fall AGU and six at other conferences, related to Antarctic Sea Ice or IceSAT, AMSR-E and MODIS-based satellite remote sensing in polar or mountainous regions.

-ESA Category 1 proposal submitted and approved. This approval allows access to ESA Cryosat 2 data for Antarctic sea ice study.

Introduction

The report, in three Parts and one Appendix, relates the activities under the NASA Grant performed in the second year of activity 3 June 2009-2 June 2010. The first section describes the activities of the grant performed at the Univ of Texas San Antonio, under the direction of the Principal Investigator Stephen F. Ackley and Co PI Hongjie Xie. Those activities comprise the main funded efforts of the grant. Sections 2 and 3 are reports on the activities from the two CoI's not at UTSA: Anthony Worby (unfunded CoI) Antarctic CRC, Hobart Tasmania Australia and Thorsten Markus (funded CoI) of NASA GSFC. The Appendix contains the draft summaries and full list of attendees of the Workshop "Monitoring Arctic and Antarctic sea ice from various satellite products" held in Bern, Switzerland, from March 15-19, 2010. These sessions were participated in by the Co-PI H. Xie, one UTSA graduate student (B.Cicek) and one UTSA postdoc (A. Tekeli), the CoI T. Markus and and CoI A. Worby's student (N. Galin), and Grant Collaborators Donghui Yi (NASA Goddard) and Collaborator Seymour Laxon's student (R. Willatt) (CPOM, Univ College London, UK). A second workshop of the type was discussed in the workshop and will be held in summer 2011. The theme of the second workshop will be "Scaling and Error Issues in Sea Ice Remote Sensing".

Part 1. Activities of the Laboratory for Remote Sensing and Geoinformatics UTSA (S.F. Ackley PI and Hongjie Xie CoI).

Administrative Activities
During this second year of activity, two PhD students, Burcu Ozsoy-Cicek and Michael Lewis, have fully committed to their research. B. Ozsoy-Cicek submitted a paper to DSR

special issue that has been accepted for publication (2010). This paper conducts intercomparison of sea ice types based on ship observations, RADARSAT, Envisat, QuickSCAT, and AMSR-E measurements during the SIMBA 2007 period. The primary study of B. Ozsoy-Cicek is, however, analyzing profile data from Antarctic sea ice to develop better algorithms for converting IceSAT elevations in sea ice thickness. Results are very promising and was first presented in the 2009 fall AGU meeting and a paper is in preparation for submission to JGR. M. Lewis submitted a paper to DSR special issue and has been accepted for publication (2010). This paper summarizes the sea ice and snow cover characteristics during the winter-spring transition in the Bellingshausen Sea: an overview of SIMBA 2007. This study prepared him of snow and ice properties, which is greatly helping him in focussing on the modeling part of his dissertation study. Both PhD students are scheduled to defend their dissertations by the end of 2010. A postdoc, Ahmet Tekeli, has worked on two parts. One is studying sea ice properties from EnviSat and AMSR and validating those with ship-based observations. This study will be presented at IGS (Tromso Norway, June 2010) and is submitted for publication by IGS. The second study is analyzing the ICESat freeboard and ice thickness for the BA sector of Antarctic from 2003-2009 for its spatial and temporal variations, currently under analysis for publication in the latter part of 2010. Due to the effort of Co-I H. Xie in meeting with the Pacific Arctic Group (PAG) in Bergen Norway 20-21 March 2009, the UTSA group is invited to participate in the 4th Chinese Arctic Expedition from July to September 2010 on their icebreaker Xuelong in the Arctic Ocean. Planning activities are underway for two cruises to the Antarctic sea ice zone for the end of 2010. We have three designated berths on the Icebreaker Oden into the Amundsen Sea in December 2010 and, depending on pending support, either two or three berths on the UK's research vessel James Clark Ross, going into the Bellingshausen Sea in November 2010. Remote sensing activities are being coordinated with these opportunities for Calibration/Validation. These include IceBridge airborne lidar and photography flights (Nov 2010), CryoSAT radar altimetry (launch scheduled in April 2010), EnviSAT active radar imagery (ongoing), and AMSR-E passive microwave (ongoing).

At the PAG, future participation in both Arctic and Antarctic cruises for ground validation of satellite data was discussed. Vessels from China and South Korea as well as US and Australian vessels used (as described below) are possible future venues and initial queries were made for participation in these vessels' cruises. S.F. Ackley gave an Invited Presentation at the symposium and workshop marking the launch of the South Korean icebreaker in Incheon Korea on June 10 2009, where these plans were further developed for future participation with the South Korean vessel. Advisory activities are being conducted with the South Koreans on their upcoming Antarctic cruise, tentatively scheduled for late 2010 into the Amundsen Sea. A European Space Agency (ESA) Category 1 proposal was submitted and approved. This acceptance allows access to ESA Envisat and other data from the ESA Rolling Archive, and was used to monitor imagery during Oden 2008 and NB Palmer 2009 cruises and will be used for joint radar altimeter and active microwave imagery for upcoming IceBridge missions at the end of 2010 and the ship-based activities described above on JC Ross and Oden. The Australian cruise has been rescheduled for 2012 so planning activities are postponed until 2011 when they will be resumed.

Lists of papers and conference presentations are also given in the Publications section. A website for the project is now established at:
http://129.115.102.107/lrsg/SeaIceThickness/

Science Activities

A major effort of the second year was analyzing the IceSAT data during the SIMBA period (Oct 2007). This is the only ICESat campaign with concurrent field based observations and measurements for the Antarctic sea ice during the 2003-2009 operation period of ICESat.
A snow freeboard and ice thickness model generated from *in situ* measurements was then applied to contemporaneous ICESat (satellite laser altimetry) measured freeboard to derive ice thickness at the ICESat footprint scale (Figures 1 and 2). Errors from *in situ* measurements and from ICESat freeboard estimations were incorporated into the model, so a thorough evaluation of the model and uncertainty of the ice thickness estimation from ICESat were made. Our results indicate that ICESat derived snow freeboard and ice thickness distributions (asymmetrical unimodal tailing to right) for first year ice (0.29±0.14 m for mean snow freeboard and 1.06±0.40 m for mean ice thickness), multi-year ice (0.48±0.26m and 1.59±0.75m, respectively), and all ice together (0.42±0.24m and 1.38±0.70m, respectively) for the study area seem reasonable compared with those values from the *in situ* measurements, ASPeCt observations, and EM measurements. Our approaches: (1) of using empirical equations relating snow freeboard to ice thickness based on *in situ* measurements and (2) of using isostatic equations that replace snow depth with snow freeboard (or empirical equations that convert freeboard to snow depth), are efficient and important ways to derive ice thickness from ICESat altimetry at the footprint scale for Antarctic sea ice. (Paper has been Accepted for publication in Deep Sea Research II, Xie et al, 2010 in the publication list below). Spatial and temporal snow and ice thickness from satellite altimetry for the BA sector and for the entire Southern Ocean is therefore possible. These analyses are now being conducted with preliminary results for the BA sector and the Ross Sea presented in June 2010 at the IGS Sea Ice Conference in Tromso Norway.

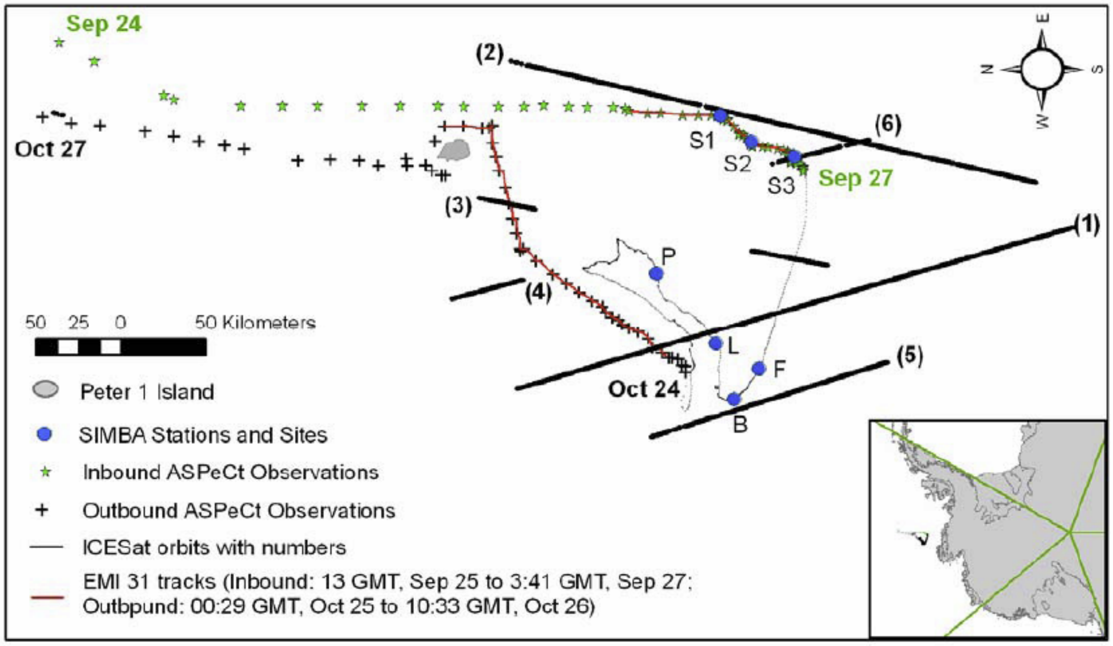

Figure 1. ASPeCt observations, EMI 31 and ICESat tracks of the SIMBA 2007 experiment. Inbound track from Sep 24 to Sep 27; outbound track from Oct 24 to Oct 27; ICESat tracks (1) 1299 (Oct 4), (2) 0011 (Oct 8), (3) 0145 (Oct 17), (4) 0183 (Oct 20), (5) 0198 (Oct 21), and (6) 0302 (Oct 28); Tracks 2 and 3 are polewards, Tracks 1, 4, 5, 6 are away from the pole; S1, S2, S3 SIMBA ice stations; F, B, L, and P respectively SIMBA's Fabra site, Brussels site, Liege site, and Patria site.

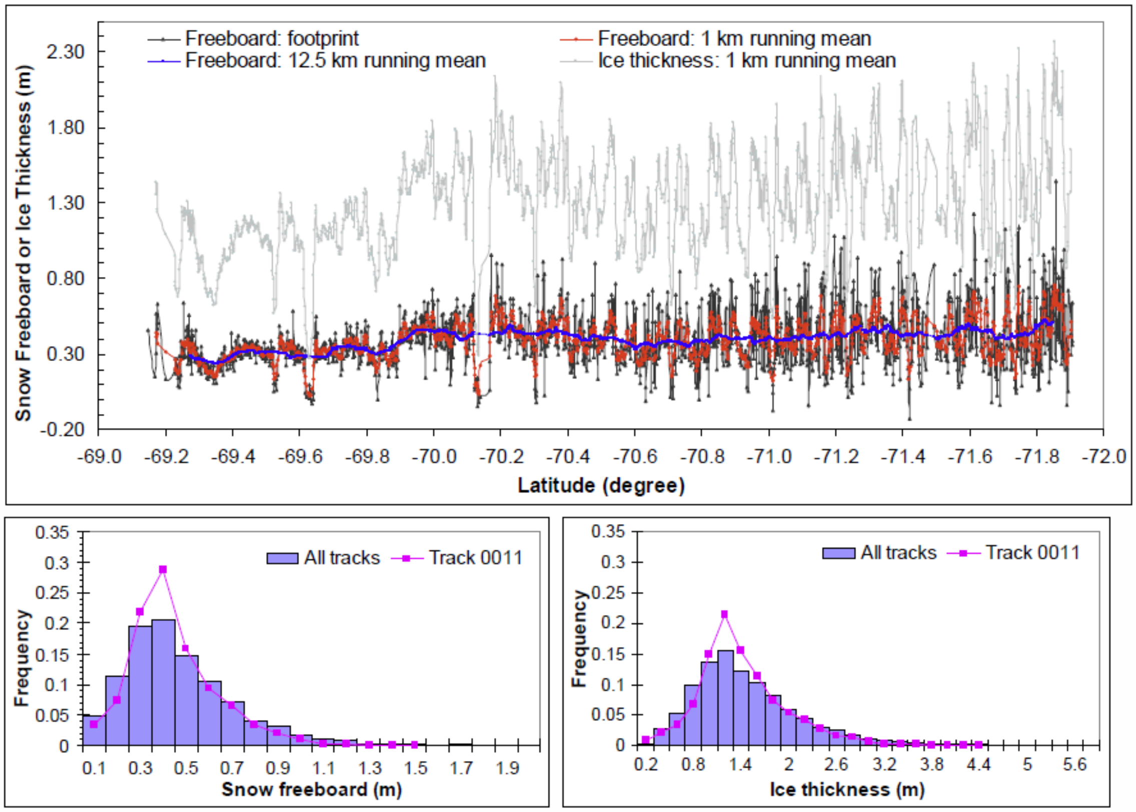

Figure2. ICESat snow freeboard and ice thickness profile from track 0011 (Oct 8, 2007, top panel) and frequency distributions of snow freeboard for track 0011 and all tracks (bottom left) and ice thickness for track 0011 and all tracks (bottom right)

The second effort of the second year was analyzing the field-measured profile data of the past 20 years for the Antactic sea ice to derive equations of sea ice thickness from snow freeboard. Profile data from sixteen Antarctic cruises: five cruises for Weddell Sea Sector, four cruises for Bellingshausen and Amundsen Seas sector, one cruise for Ross sea sector, and six cruises for Indian Ocean and Western Pacific Ocean sector, that had measurements of snow depth, ice freeboard (height above or below sea level of the ice surface), and ice thickness were compiled and standardized. Typically these data were measured by using ice augers usually at 1 meter intervals for distances nominally from 50m to 100m profiles. The relations between snow depth, snow freeboard and ice thickness for each cruise were derived and analyzed. Those relations were separated in sectors as well as for the entire Antarctic. Figure 3 shows the relationship between mean snow depth and mean snow freeboard (elevation above sea level of the snow surface) for all profiles and for the individual sectors. Single mean values for each of the profiles (tens to hundred meters) of ice thickness, snow depth, and ice freeboard were also computed. The estimate of ice thickness took into account the increased density of flooded snow, if the ice freeboard was negative (below sea level). We found that errors in thickness prediction compared to measured values were excessive if the flooded condition of the surface was not taken into account. Figure 4 shows the relationship

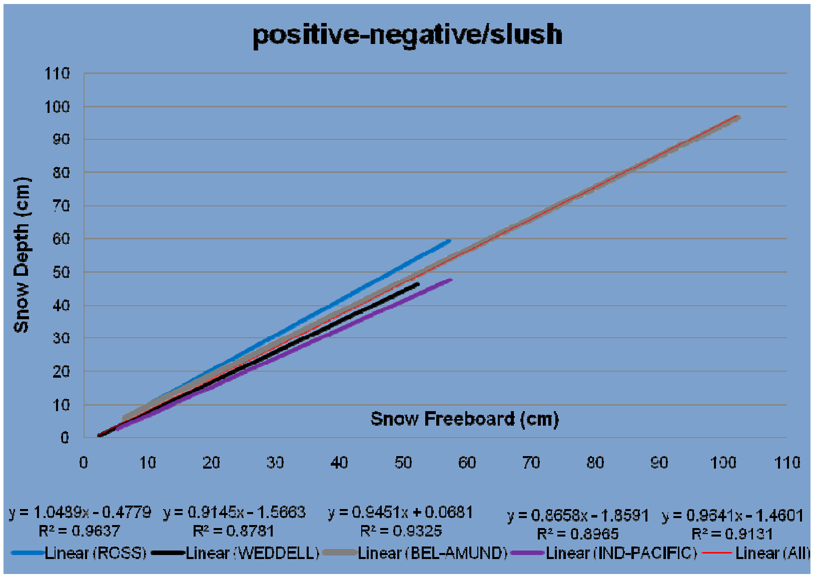

Figure 3, Relationship between Snow Freeboard and Snow Depth for all 15 measured profiles, separated into sectors and with all the profiles grouped.

between Ice thickness and Snow Depth based on these assumptions for the sectors and for all data. Here we see that the Indian Ocean sector is the apparently differently behaving sector in this prediction, relative to either the grand mean or the other sectors. Our results both confirm more complex relationship between elevation and ice thickness than that predicted by simple isostasy from satellite laser altimetry and that the behavior around Antarctica is generally consistent, with the exception of the Indian Ocean sector. In the Indian Ocean sector, observations generally show relatively thin snow covers and a redistribution of snow into deformed ice areas (see report by T. Markus below). These observations are therefore also consistent with the prediction of Figure 4, where relatively thinner snow correlates with thicker ice in the Indian Ocean sector than for other regions.

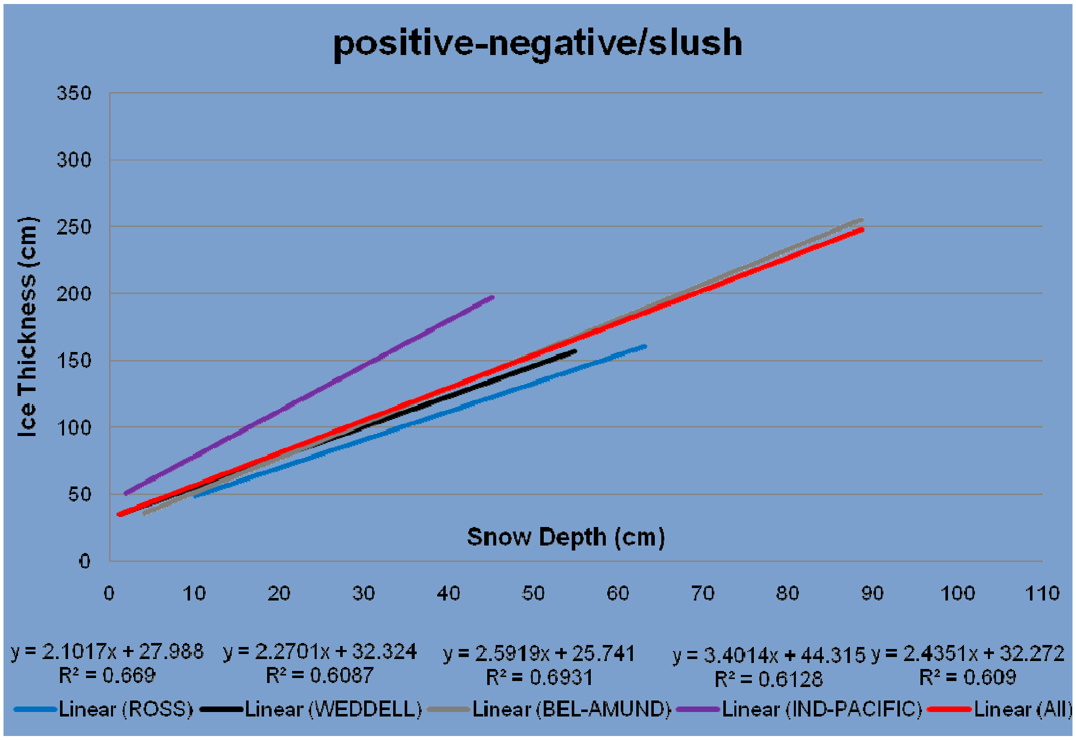

Figure 4. Mean Ice thickness for all profiles predicted from Snow Depth, separated into sectors and for all profiles grouped (brown line). The Indian-Pacific Ocean sector (purple line) deviates significantly in this relation from other sectors and All data grouped.

The third effort of the second year was conducting intercomparison of sea ice types based on ship observations, RADARSAT, Envisat, QuickSCAT, and AMSR-E measurements during the SIMBA 2007 period. Some results are summarized here and shown in Figure 5 and 6. The C-Band backscatter (NRCS) permits distinction between first-year, MIZ, and undeformed young ice. However, NRCS of the multiyear ice zone overlaps with that of the other ice zones and types. Ku-Band NRCS obtained for the same ice types permits discrimination of the first-year ice zone only. Obtained NRCS agree with those of previous studies and suggest a high degree of deformation and considerable potential for flooding for the first-year ice case. In comparison to large scale NRCS, AMSR-E snow depth values form two clearly separated clusters, one for 0.24-0.35 m depth (first-year ice zone) and one for 0.36-0.54 m depth (multiyear ice zone). However, a comparison to ASPeCt observations suggests a remarkable underestimation of the snow depth by AMSR-E in the multiyear ice and for first-year cake ice, even though the trend, of thinner snow on first year ice, is shown by the AMSR-E distinction

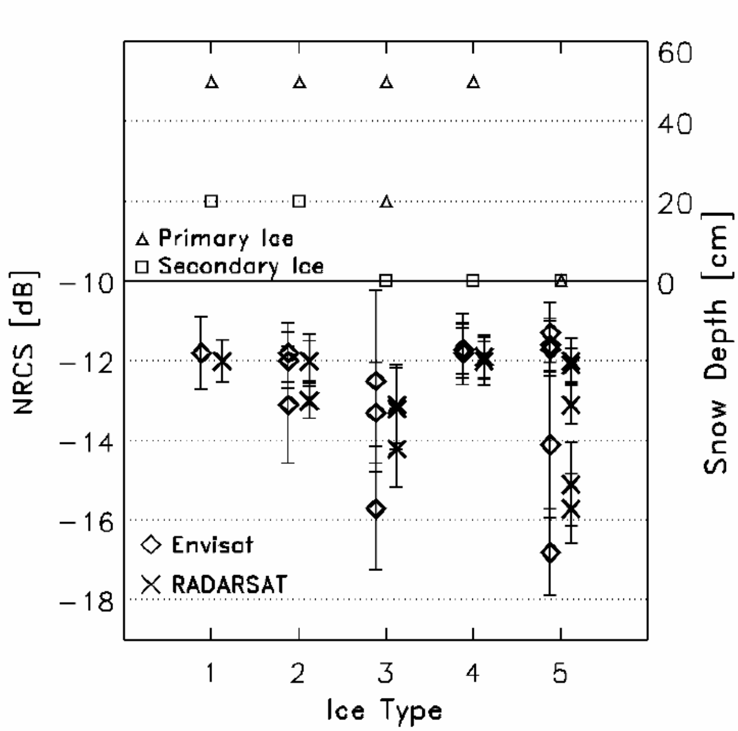

Figure 5. Mean Envisat (AT 06:26 UTC) and RADARSAT-1(AT 09:33 UTC) backscatter (NRCS values) obtained for ASPeCt observation boxes (see Figure 2) for Oct. 26, 2007, grouped from thick to thin ice. The ice types (mixtures) are: **1:** TFY, FY; **2:** TFY, FY, Nilas; **3:** TFY, Young Grey-White; **4:** TFY, Nilas; **5:** Young Grey, Pancake, Nilas, and Grease. Error bars annotated to each NRCS value denote one standard deviation based on 6400 and 256 values for RADARSAT-1 (pixel size: 25 m) and Envisat (pixel size: 125 m) data, respectively. ASPeCt based snow depth is given for the primary and secondary ice types (right y-axis) on top part.

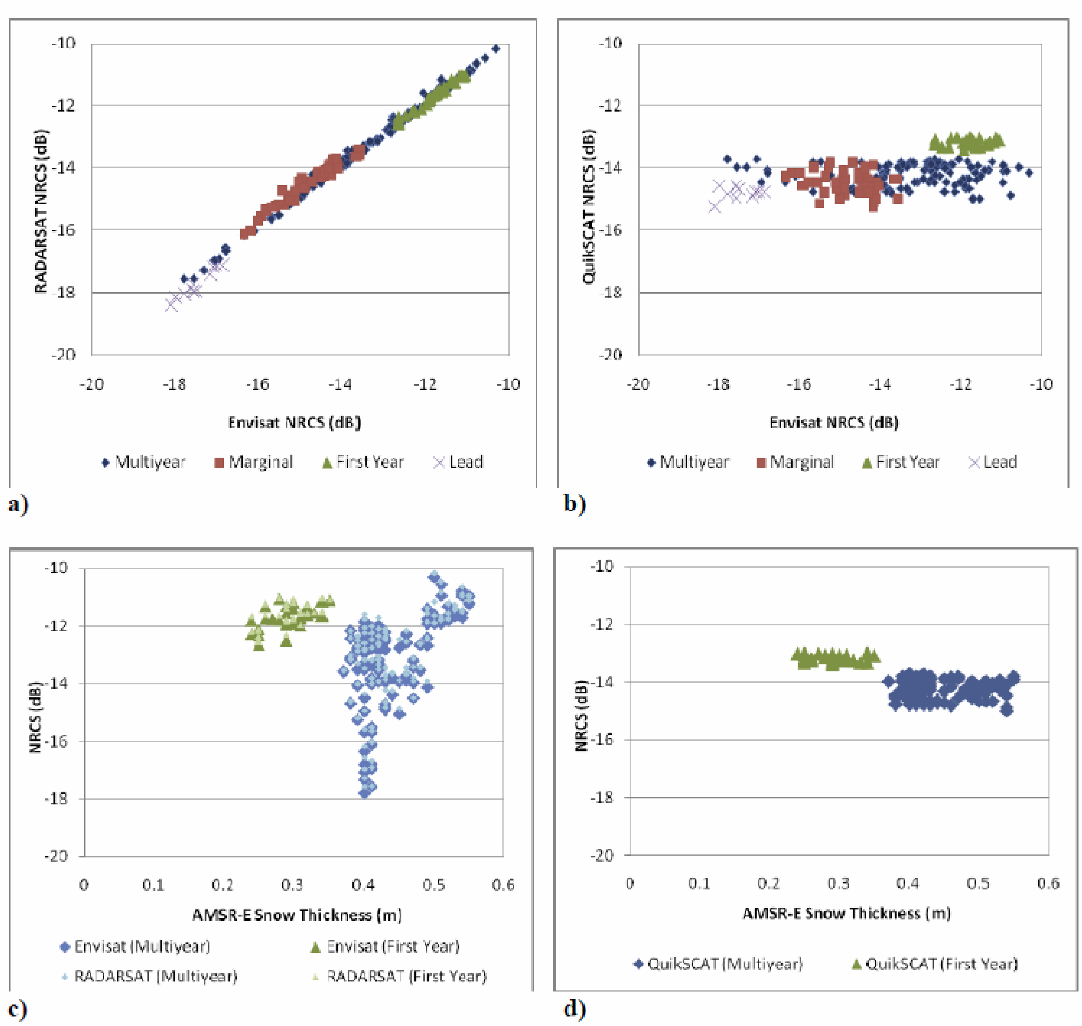

Figure xx. Scatter plots comparing values at 12.5km x 12.5km grid cell sizes. a) NRCS values from RADARSAT-1 for each of the four regions selected in Figure 5 in comparison to NRCS values from Envisat b) NRCS values from Envisat vs. QuikSCAT backscatter c) Comparison between NRCS values at C-Band, HH-polarization (RADARSAT-1 and Envisat) and AMSR-E snow depth data of the FY and MY ice regions (d) Comparison between NRCS values at Ku-Band, VV-polarization (QuikSCAT) and AMSR-E snow depth data for FY and MY ice regions. All data shown are from Oct. 12, 2007. See Table 4 for an overview of the mean NRCS values.

The fourth effort of the second year was modeling ICESat altimetry hits based on field measurements on the Belgica floe (5 km2) of mixed first year and multiyear ice shown in Figure 7. The question we posed is: What is the required ICESat sampling density for seasonally accurate estimation of snow surface elevation (snow freeboard) and ultimately, the derived ice thickness, given inherent spatial averaging? Random simulated ICESat altimeter tracks with spot size of ~ 70 m and spacing of ~ 170 m sampled the floe's three regions or "ice towns"(Figure 8). This sampling was used to generate a buoyancy-derived ice thickness distribution from altimeter elevation, and each town's known freeboard characteristics. Figure 9 shows that the minimum number of altimeter hits to statistically recreate the regional thickness mean, compared to observed ground measurements of thickness, and giving the correct distribution was 115 hits for the three-town assemblage of mixed first and multi-year ice, and 85 hits for a two-town assemblage of first year ice types only. This number of samples for representative ice thickness distributions would be equivalent to 19.5 km and 14.5 km respectively of continuous altimeter line track over a region composed of floes of similar structure., Results from this study have significant implications toward development of a statistical model of sea ice sampling performance of the IceSat laser altimeter record as well as maximizing sampling characteristics of satellite and airborne laser and, perhaps radar-altimetry missions, for sea ice thickness.

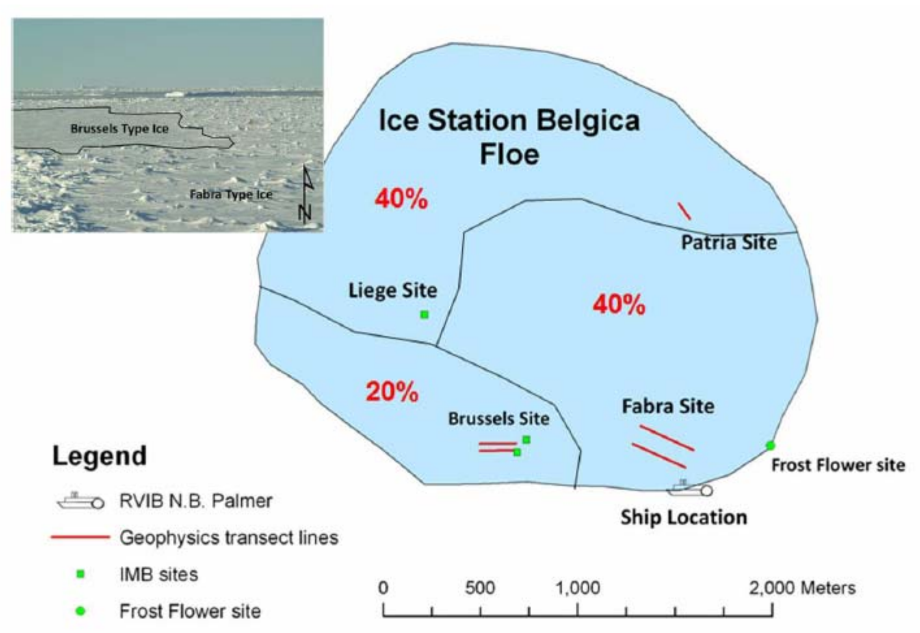

Figure 7. Generalized map of the ISB floe depicting geophysical study site locations and ice towns Brussels (lower left), Patria/Liege (upper section), and Fabra (lower right). Percentages of ice town areas are approximate. Photograph was taken from the ship looking NW across floe toward the open lead. Brussels ice (flat) can be visually distinguished from Fabra ice(rougher) by surface texture in the photograph.

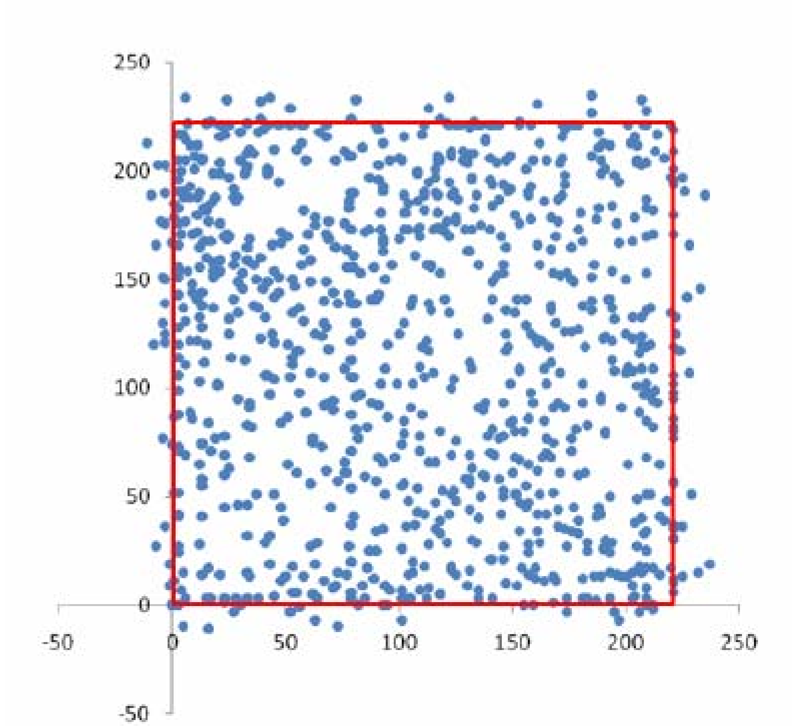

Figure 8. Map of simulated ICESat altimeter sampling locations for 100 randomly oriented tracks over the model 1 floe (red square). Scales are in pixels (1 pixel = 10 m).

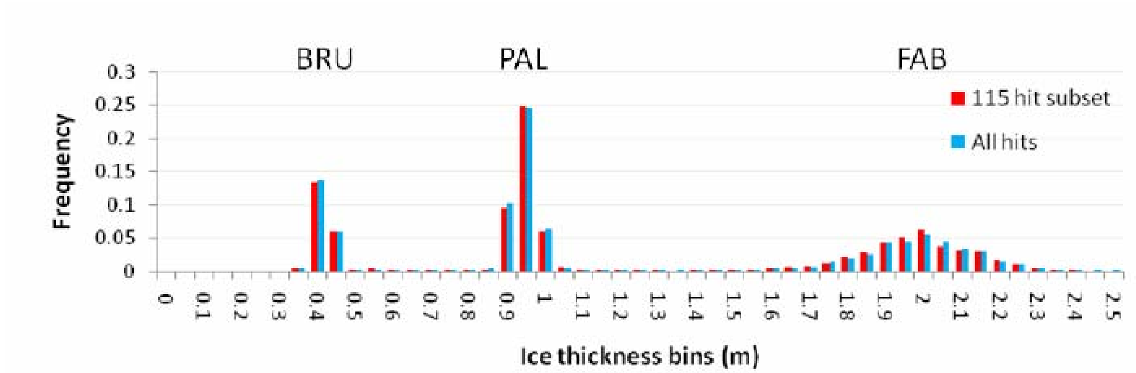

Figure 9. Ice thickness probability distributions for BRU, PAL, and FAB ice towns for a 115 sample subset compare to all data for 25 replicate transits of the model 1 floe.

Publications

Gao, Y., H. Xie, N. Lu, T. Yao, and T. Liang, 2010. Toward advanced daily cloud-free snow cover and snow water equivalent products from Terra-Aqua MODIS & Aqua AMSR-E measurements. Journal of Hydrology, doi:10.1016/j.jhydrol.2010.01.022.

Gao, Y., H. Xie, T. Yao, and C. Xue, 2010. Integrated assessment on multi-temporal and multi-sensor combination for reducing cloud obscuration of MODIS snow cover products at the Pacific Northwestern USA. Remote Sensing of Environment, doi:10.1016/j.rse.2010.02.017

Fan, C., H. Xie, D. Schulze-Makuch, S.F. Ackley, 2010. *A formation mechanism for hematite-rich spherules on Mars*. Planetary and Space Science 58(3):401-410, doi:10.1016/j.pss.2009.11.001

Worby, A., A. Steer, J. Lieser, N. Galin, D. Yi, I. Allison, P. Heil, R.A. Massom, and J. Zwally, 2010. Regional-scale sea ice and snow thickness distributions from in situ and satellite measurements over East Antarctica during SIPEX. Deep Sea Research, Accepted

Xie,H., S.F. Ackley, D. Yi, H.J. Zwally, P. Wagner, B. Weissling, M. Lewis, K. Ye 2010, Sea ice thickness distribution of the Bellingshausen Sea from surface measurements and ICESat altimetry, Deep Sea Research, Accepted

Ozsoy-Cicek, B., Kern, S., Ackley, S.F., **Xie, H.**, Tekeli, A.E., 2010. Intercomparisons of Antarctic sea ice properties from ship observations, active and passive microwave satellite observations in the Bellingshausen Sea. Deep Sea Research II, Accepted

Lewis, M. J., Tison, J. L., Weissling, B., Delille, B., Ackley, S. F., Brabant, F., **Xie, H.**, 2010. Sea ice and snow cover characteristics during the winter-spring transition in the Bellingshausen Sea: an overview of SIMBA 2007, Deep Sea Research II (accepted)

Weissling, B. and S.F. Ackley, Antarctic sea ice altimetry: scale and resolution effects on derived ice thickness distribution, IGS, Submitted, (presented at IGS Tromso Norway, June 2010)

List of Presentations

Ozsoy-Cicek, B., S.F. Ackley, H. Xie and A. Tekeli, 2009. Antarctic sea ice thickness predicted from surface elevation: a comparison to measured values. AGU Fall meeting, San Francisco, CA, December 14-18

Xie, H. Y. Gao, T. Yao, T. Liang, 2009. Estimating snow cover onset date, end date, and duration from MODIS, AMSR-E, and blended snow cover products. AGU Fall meeting, San Francisco, CA, December 14-18

Ozsoy-Cicek, B., S. Kern, S. Ackley, H. Xie, A. Tekeli, 2009. Intercomparisons of Antarctic sea ice properties from ship observations, active and passive microwave satellite observations in the Bellingshausen Sea. ASPRS/MAPPS Fall Conference, Nov 16-19, San Antonio, TX

Tekeli, A.E., H. Xie, S. Ackley, B. Cieck, 2009. Monitoring sea ice by Envisat ASAR and validating with the Palmer 2009 cruise field data for Antarctica. ASPRS/MAPPS Fall Conference, Nov 16-19, San Antonio, TX

Xie, H. and Y. Gao, 2009. Multi-temporal and multi-sensor combined approaches for snow cover mapping. ASPRS/MAPPS Fall Conference, Nov 16-19, San Antonio, TX

Xie, H., Y. Gao, X. Huang, and T. Liang, 2009. MODIS and ICESat-based snow cover and glacier changes across three rivers headstream region of Tibetan Plateau International Workshop on Environmental Change, Glacial and Hydrological Processes, and Related Consequence in the Third Pole Region, August 15-20, 2009, Beijing-Lhasa, China

Xie, H., X. Wang, and T. Liang, 2009. MODIS/Terra-Aqua snow cover products, validation, and applications (invited), SPIE Optics+Photonics: Remote Sensing and Modeling of Ecosystems for Sustainability 2-6 August 2009. San Diego, CA

Xie, H., X. Huang, T. Laing, D. Yi, 2009. Estimating vertical error of SRTM and map-based DEMs using ICESat data in Tibetan Plateau, SPIE Optics+Photonics: Remote Sensing and Modeling of Ecosystems for Sustainability 2-6 August 2009. San Diego, CA

In addition, S.F. Ackley presented two papers at the Ocean Sciences Meeting in Portland, OR, Feb, 2010 and two papers at the IACS Symposium (MOCA 09) in Montreal Que, July 2009. He has presented Invited Seminars to Los Alamos National Lab, Southwest Research Inst and Texas A&M-Galveston as well as several at UTSA.

Part 2 Activites of the Antarctic CRC, Hobart Tas, Austalia (A. Worby, CoI)

A major effort of the second year was analyzing the IceSAT data during the SIPEX and SIMBA period. This is the only ICESat campaign with concurrent field based observations and measurements for the Antarctic sea ice during the 2003-2009 operation period of ICESat. Figure 1 shows the L3I ICESat tracks and snow freeboard in the SPIEX study region. The equation below

$$h_i = \frac{\rho_w}{\rho_w - \rho_i} F - \frac{\rho_w - \rho_s}{\rho_w - \rho_i} h_s \quad (1)$$

is then used to derive the sea ice thickness using ICESat freeboard, actual snow depths, snow and ice density data from the SIPEX measurements. The ice thickness distribution of the 6 tracks highlighted in yellow of Figure 1 is shown in Figure 2 and is in quite reasonable agreement with field data.

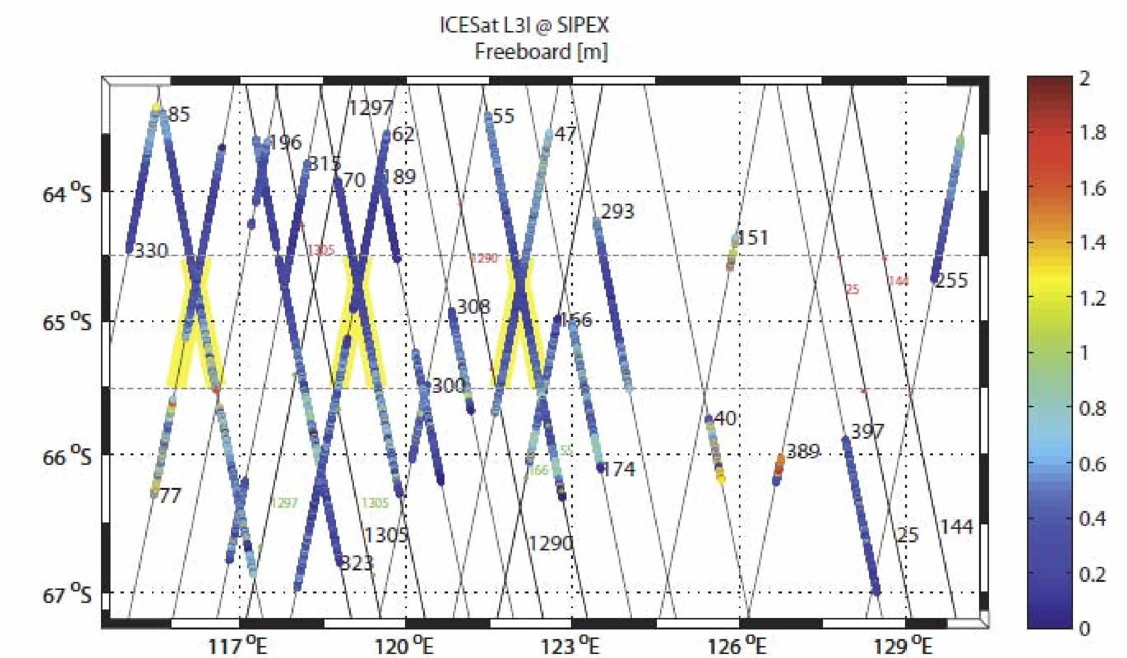

Figure 1. Map showing ICESat L3I tracks over the SIPEX study region, and the areas where data were collected. Freeboard is shown in metres. The 6 tracks highlighted in yellow have been used to generate the PDFs of ice thickness shown in the Figure below, for the 1 degree latitude band between 64º30’ – 65º30’S.

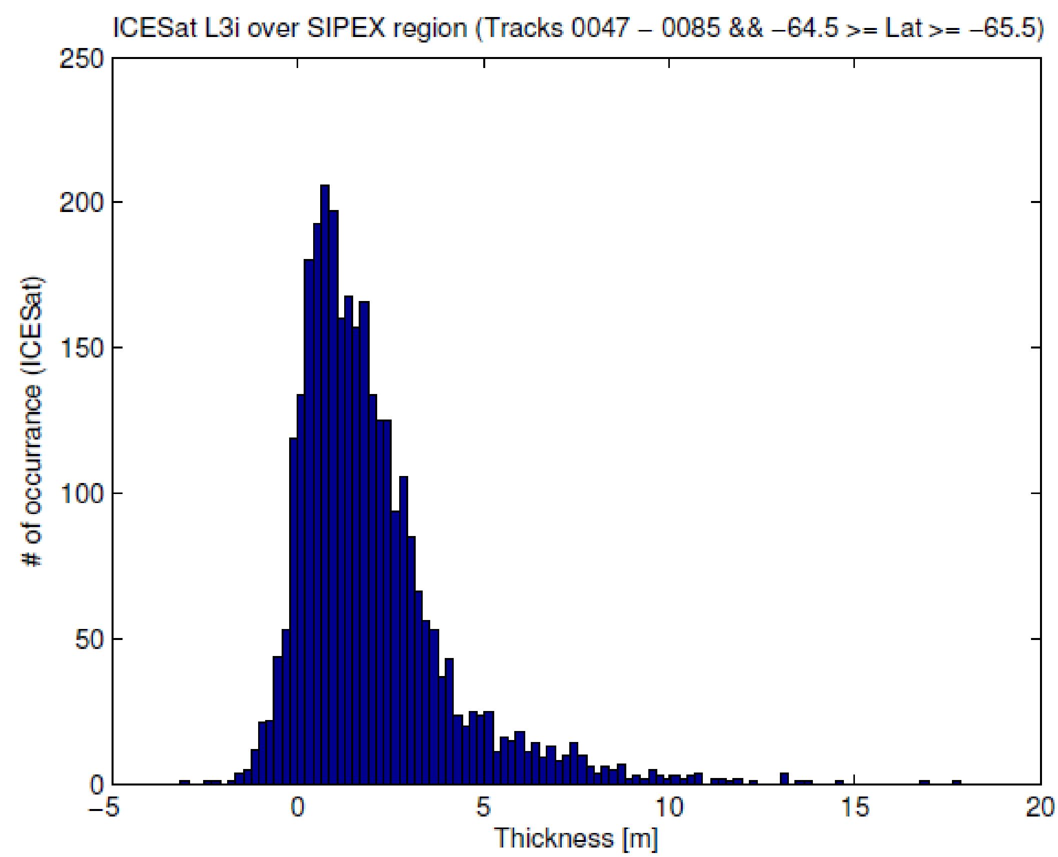

Figure 2. PDF of ice thickness calculated from ICESat data for the six sections of track highlighted in yellow in Figure 6.

Part 3 Combination of ICESat and AMSR-E data for improved snow depth retrievals (T. Markus, Goddard Space Flight Center, Greenbelt MD)

Previous studies have suggested that AMSR-E underestimates snow depth in areas with a high fraction of rough sea ice [Maslanik et al., 2006; Markus et al., 2006; Worby et al., 2008b]. The following comparison will attempt to utilize ICESat data to account for sea ice roughness in the AMSR-E snow depth algorithm. ICESat variability is used for this comparison because the QuikSCAT backscatter may be also be influenced by changes in snow and ice physical properties rather than solely roughness. Further study is required to better interpret the QuikSCAT signal, especially when applied automatically. A comparison of AMSR-E snow depth and Station snow depth from the ARISE experiment (see last year's report) shows two clusters: one with data points close to the diagonal and one with data points where the Station snow depths are considerably larger (Figure 1). Coincident ICESat variability data show correspondingly low values for the data close to the diagonal (ICESat variability <15 cm; blue and green dots) and high values where the Station data are greater (ICESat variability > 15 cm, brown and purple dots). This suggests that ICESat variability may be used to adjust the coefficients of snow depth algorithm accounting of sea ice roughness or variability.

Using multiple linear regression we get a relationship for snow depth, h_s of

$$h_s = -5.45 - 638.67\, GR_{Ice} + 1.21\, Var_{ICESat}$$

where GR_{Ice} is the AMSR-E spectral gradient ratio corrected for sea ice concentration variations as used in the current AMSR-E routine and Var_{ICESat} is the ICESat variability. A comparison with in-situ snow depth gives a correlation coefficient of 0.84 with a mean difference of 2.3 cm and a negligible bias (Figure 2). While the results look encouraging it is important to note that the data are from a limited region and a limited period so the results cannot necessarily be directly transferred to others areas and to other seasons.

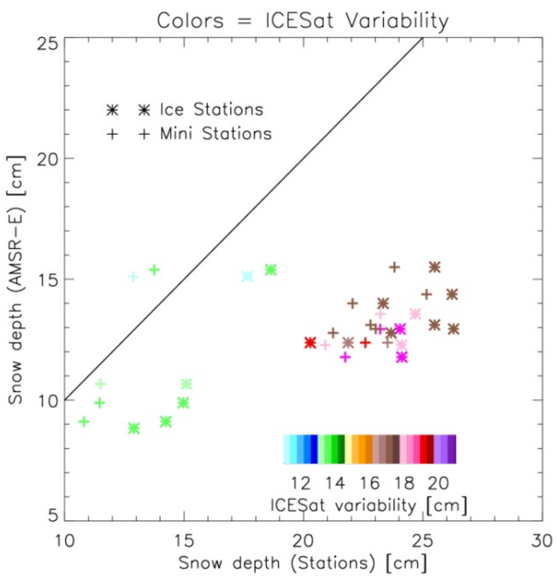

Figure 1: AMSR-E snow depth vs Ice Station and Mini Station snow depth. ICESat variability is indicated in colors.

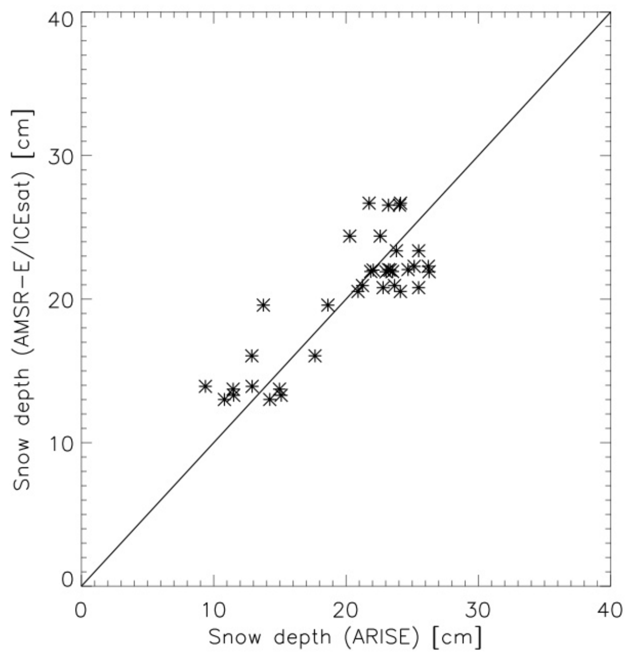

Figure 2: Combined ICESat-AMSR-E snow depth vs Ice Station and Mini Station snow depth.

APPENDIX

Draft reports from Workshop on “Monitoring Arctic and Antarctic sea ice from various satellite products” co-sponsored by International Space Science Institute (ISSI) and this NASA grant were held at Bern, Switzerland, from March 15-19, 2010. (co-chaired by H. Xie and B. Ozsoy-Cicek (a PhD student of PIs))

Workshop goals:

- A primary goal was to provide young scientists (PhD candidates and PostDocs) with the opportunity to work closely with experts/senior scientists on their own specific science problems.
- The second goal of the workshop was to explore/examine data fusion techniques and provide a “road map” of analyses to optimize the data from multiple sources.

List of Outputs:

The anticipated outcome of the meeting was to bring senior scientists, students and early career scientists together to discuss the current issues and challenges in remote sensing of sea ice. We believe we have reached our expectation and the workshop was fruitful. Younger scientists were able to network with peers on various scientific and technical issues, refining and optimizing the use of remote sensing tools in studying the polar sea ice environment. The meeting provided a dynamic environment for the presentation of these problems and was highly productive towards their solution. The network will continue to act as an effective conduit for collaboration and solution for many questions and problems that we are facing.

DAY-1 - INTRODUCTION

Introduction into the characteristics and physics of sea ice

1. Measuring properties – inferring processes
2. Problem is that there are different scales of properties and processes, and not same
3. Contrast between the Antarctic and Arctic sea ice cover, which needs to be

acknowledged

4. Question: depending on the origins of formation (rough or smooth ocean), the ice sheet/floe bottom/undersea is rough or smooth – how proven? Remotely sensed? Confirmed – ice cores?

   (1) Underside roughness affects low frequency (L-band) backscattering signature
5. Frost flowers characteristics, growth
6. 'Sea ice thickness' – holy grail of remote sensing :

   (1) what is the required accuracy and precision

   (2) given the small scale roughness present, what would be the meaning of 1m of ice thickness over a 10km x 10km pixel scale
7. Saline ice – increasing heat capacity with increasing salinity, and increasing temperatures divergent profiles, hence could AMSR-E have increased sensitivity to salty ice?
8. Snow – how good is the approximation that snow is the 'freeboard' in the Antarctic?
9. Albedo cycle of snow can identify the snow type, and albedo parameterization is highly affected by the melt ponds fraction per pixel, important study parameter
10. Snow ice formation, and superimposed ice formation (due to melt within the snow pack), both important, and need to be sensed?
11. Important snow and sea ice properties for microwave remote sensing: scattering and emissivity: salinity, internal roughness, surface roughness and wetness: what models allow for understanding the dependence of microwave signature on these properties? And is there a one-to-one correspondence between the microwave signature and specific snow properties? Forward and emission scattering models needed.
12. Have done atmospherics already – Matthew Sturm, has done scaling studies

Introduction to sea ice remote sensing: Introduction of basics of sensing with EM waves

1. Atmospheric transparency
2. Basic laws for reflection/transmission/interaction
3. Active and passive definitions: however, if active sensor is in the same spectrum as is already normally emitted by material, how does this affect the signature? Is it distinguishable? Is it done? Or is this why most active instruments stay away from normally emitted wavelengths?

   (1) RADARSAT and ENVISAT – comparable frequencies, but a lot less in power, hence not necessarily a noise
4. Definition: radar/laser pulse? What is the difference?
5. Profiling- altimeter, imagining – scanning ability,
6. In microwave region, dependence of spatial resolution, and size of antenna
7. SAR processing – coherent signal processing – available now in radiometry – hence coherence not required? - non-coherent SAR processing, applicable to passive
8. SSM/I scanning – important point, that single pixel value is actually an integrated field of view, of a few microseconds, which necessarily means that the pixel is moving slightly during this time, i.e. integration in space, and time (i.e. 2D integration)
9. Swath definition – scanning ability of the instrument
10. Elliptical orbits would achieve pseudo-stationary orbits over the poles, on the technical 'to do' list
11. Scatterometer vs altimeter, what is the difference, just the processing of the data?

    (1) Scatterometer – good resolution of time/backscatter *within* the pulse

    (2) altimeter – good resolution of time *between* pulses

SUMMARY:

1. Overview: what is sea ice and its physical properties, how they relate to EM sensitive parameters?

2. How can the physical properties be best parameterized (their sensitivity) and extended from theory (in-situ) measurements to satellite footprint?

3. Found that even within a single instrument there are differences in the frequencies that play an important role and must be considered when comparing the data sets
4. Background into radiative transfer theory and how we can use radiometers?
5. Using a mathematical LSE model for ice concentration – have considered MMSE?

DAY-2

SUMMARY:

1. Snow is an error in ICESat for ice thickness estimation – how acceptable are the models used for Arctic (climatologically), and Antarctic (AMSR-E)
2. Why is constant density values used for the sea ice thickness estimates across the board?
3. Need to have a 1/2/3 layer model for sea ice retrieval – changes with season/region, how to standardize?
4. Negative freeboard obviously an issue in Antarctica, should not be ignored. Could perhaps discuss a rational standardized approach to regional values?
5. More studies needed to judge the penetration of Ku band radar into snow pack, both in the Arctic and Antarctic. What is the effect of wetness and salinity? Is Arctic snow less subject to flooding? Can comparison between ICESat and ENVISAT provide some indication affect?
6. Multi-year ice studies show that Ku band radar penetrates the snow, but multi-year ice is in short demand.

DAY-3

SUMMARY:

1. Snow spoils sea-ice surface signals? But, can we derive snow properties?
2. Can the backscatter be an indication not only of roughness features, but density changes
3. All instruments have difference footprints, swaths, and also the sensor type determines the level of 'averaging' i.e. the weighting window applied to the contents within the pixel which contribute to the single pixel value

DAY-4

SUMMARY:

1. Our *measurements* are all valid, but comparisons should be done when they are qualified by the scale at which they were made.

2. Would be interesting to conduct a study into the 'type' of *averaging* that is made by the satellite sensor to provide a pixel value – what sub pixel conditions are most important.

3. How can local observations be extrapolated into general laws? Is this possible/feasible?

4. Polynyas are important contributors for sea ice production, but what is their size/distribution/contribution?

PLANNING OF SECOND MEETING (Anticipated time frame: 2011 Summer)

In summary, the participants of the workshop have found that a common drawback was present throughout their work. After much discussion, this was summarized as:

1. Sea ice product error analysis, (accuracy and precision): where this refers to efforts in providing all reported figures (e.g. physical parameters - density, thickness etc) with their expected accuracy and precision, or qualified by the appropriate statistical distribution values.

2. Sea ice product scaling, (necessary and sufficient conditions): where this refers to efforts and consideration necessary in comparing datasets which differ on spatial or temporal scales.

It is anticipated that the current participants will at the next workshop present their work in this context.

Agenda of the First Meeting

Monday, Overall perspective of Satellite products on Polar Sea Ice - 15 March 2010

0900-0930 Ozsoy-Cicek Welcome, Introduction, and workshop goals

0930-1030 **Hongjie Xie**, **Introduction to sea ice monitoring activities at UTSA**

1030-1115 **Sascha Willmes, Introduction into the characteristics and physics of sea ice**

1115-1130 Break

1130-1200 **Leif Toudal Pedersen, Introduction to sea ice remote sensing**

1200-1400 Lunch

1400-1430 **Leif Toudal Pedersen, Ice concentration**

1430-1500 **Leif Toudal Pedersen, Ice type**

1500-1515 Break

1515-1545 **Leif Toudal Pedersen, Ice drift**

1545-1630 All - Discussion of the of key science questions and roadmap

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Tuesday, Satellite Laser and Radar Altimeter on Polar Sea Ice - 16 March 2010

0900-0910 Ozsoy-Cicek Review workshop roadmap.

0910-0930 **Donghui Yi, Overall ICESat Mission**

0930-1030 **Donghui Yi, Applications and case studies of ICESat**

1030-1100 **Thorsten Markus, future ICESat -2 mission**

1100-1130 Break

1130-1200 **Hongjie Xie, SIMBA – ICESat study (DSR Paper)**

1200-1230 **Ahmet E. Tekeli**, **Ice thickness drived from ICESat freeboard**

1230-1400 Lunch

1400-1430 **Burcu Ozsoy-Cicek, Overall ice thickness profiles from different Antarctic cruises**

1430-1500 **Rosemary Willatt, Cryosat-2 mission**

1500-1515 Break

1515-1545 **Rosemary Willatt, Ice thickness retrieval from radar altimetry**

1545-1630 **Rosemary Willatt, Observations of radar penetration into snow in support of sea ice thickness estimates from satellite radar altimetry**

1630-1700 All - Discussion of the of key science questions and roadmap

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Wednesday, Satellite Active Microwave on Polar Sea Ice - 17 March 2010

0900-0910 Ozsoy-Cicek Review workshop roadmap.

0910-1000 **Sascha Willmes, Snowmelt monitoring from passive microwaves / hemispheric contrasts, Quikscat surface backscatter from Antarctic sea ice.**

1000-1100 **Natalia Galin, SIPEX expedition and collecting radar data -results**

1100-1130 Break

1130-1200 **Burcu Ozsoy-Cicek, Sea ice type retrieval using Radarsat-Envisat-Quikscat -SIMBA 2007 cruise**

1200-1230 **Ahmet E. Tekeli, Sea ice type retrieval from Envisat for ODEN-PALMER cruise**

1230-1400 Lunch

1400-1445 **Stefan Kern, About sea ice radar backscatter estimation and interpretation**

1445-1515 **Matilde Marie Brandt Jensen**, **Satellite data for sea ice mapping**

1515-1530 Break

1530-1600 **Leif Toudal Pedersen, PolarView providing the processed data for both Arctic and Antarctic**

1600-1630 All - Discussion of the of key science questions and roadmap

1630 Group picture

Thursday, Satellite Passive Microwave on Polar Sea Ice - 18 March 2010

0900-0910 Ozsoy-Cicek Review workshop roadmap.

0910-1000 **Thorsten Markus, Extracting sea ice information from satellite passive microwave data**

1000-1045	**Stefan Kern**, **Remote Sensing of polynyas**
1045-1115	Break
1115-1200	**Susanne Adams, Thin ice thickness retrieval within the Laptev Sea Polynya from high-resolution ice surface temperatures**.
1200-1230	**Burcu Ozsoy-Cicek, ODEN cruise 2006, comparison of ASPeCt ice observations with AMSR-E ice concentration**
1230-1400	Lunch
1400-1430	**Jiaqiang Hou - Analysis of Characteristic of Polynya at Front of the Amery Ice Shelf Based on Remote sensing**
1430-1500	**Matilde Marie Brandt Jensen, Sea ice thermal infrared brightness temperature - field campaign measurements**
1500-1530	Break
1530-1600	**Giuseppe Aulicino, Sea-ice thickness estimation in Antarctic region from SSM/I brightness temperatures**
1600-1645	All - Discussion of the of key science questions and roadmap
1645-1700	Xie Closing remarks and map towards next workshop

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