ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

ESTABLISH A DATASET OF CO-LOCATED IN-SITU AND SATELLITE DATA FOR SEA ICE IN THE SOUTHERN OCEAN

M.Sc. THESIS

Özgün OKTAR

Maritime Transportation Engineering Department

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Özgün Oktar, a M.Sc. student of ITU Graduate School of Science Engineering and Technology student ID 512151005 successfully defended the thesis/dissertation entitled "ESTABLISH A DATASET OF CO-LOCATED IN-SITU AND SATELLITE DATA FOR SEA ICE IN THE SOUTHERN OCEAN", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To Assoc. Prof. Dr. Burcu Özsoy who persuaded Turkey to research Antarctica

FOREWORD

This thesis was written for my Master degree in Maritime Transportation Engineering Department, Maritime Transportation Engineering Master Program at Istanbul Technical University. The research was part of "SPICES - Space-borne observations for detecting and forecasting sea ice cover extremes" Horizon 2020 project. The purpose of SPICES project was developing new methods to retrieve sea ice parameters in order to provide enhanced products for polar operators and prediction systems, specifically addressing extreme and unexpected conditions.

I would like to thank the following people, without whose help and support this thesis would not have been possible. First, I like to show my gratitude to ITU Polar Research Center (PolReC) and my supervisor Dr. Burcu Ozsoy for her suggestions, encouragements and guidance in writing the thesis and approaching the different challenges during the thesis with her positive energy. I would like to thank Dr. Stefan Kern for his inputs and thoughts about the subject, guidance and motivation taught me a lot. I want to thank jury members for their time and support. Finally, I would like to thank my parents for their constant support during the time I studied.

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Özgün OKTAR
(Oceangoing Watchkeeping
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ABBREVIATIONS

AMSR : The Advanced Microwave Scanning Radiometer
AMSR-E : The Advanced Microwave Scanning Radiometer for EOS
ASCAT : The Advanced Scatterometer
ASPeCt : Antarctic Sea Ice Processes & Climate
DJF : December - January - February
ECMWF : The European Centre for Medium-Range Weather Forecasts
ENVISAT : Environmental Satellite
EUMETSAT : The European Organisation for the Exploitation of Meteorological Satellites
FYI : First Year Ice
GLAS : Geoscience Laser Altimeter System
ICESat : Ice, Cloud, and land Elevation Satellite
IPCC : Intergovernmental Panel on Climate Change
JAXA : Japan Aerospace Exploration Agency
JJA : June - July - August
LIDAR : Light Detection and Ranging - Laser Imaging Detection and Ranging
MAM : March - April - May
MetOp B : Meteorological operational satellite - B
MYI : Multiyear Ice
NASA : National Aeronautics and Space Administration
NERSC : Nansen Environmental and Remote Sensing Center
NSR : Russian Arctic
QUIKSAT : Quick Scatterometer
RA : Radar Altimeter
SAR : Synthetic Aperture Radar
SIC : Sea Ice Concentration
SICCI-UB : Sea Ice Climate Change Initiative - University of Bremen
SIT : Sea Ice Thickness
SMOS : The Soil Moisture and Ocean Salinity
SMV : Support Vector Machines
SON : September - October - November
SYI : Second Year Ice
Tb : Brightness Temperature
WMO : World Meteorological Organization

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ESTABLISH A DATASET OF CO-LOCATED IN-SITU AND SATELLITE DATA FOR SEA ICE IN THE SOUTHERN OCEAN

SUMMARY

Sea ice is simply frozen seawater. Remote sensing of sea ice properties has always been a challenging task. This thesis is part of HORIZON 2020 SPICES "Space-borne observations for detecting and forecasting sea ice cover extremes" project as of to establish a dataset of co-located in-situ and satellite data for sea ice in the Southern Ocean. In order to response needs of increase polar activities, SPICES is focusing on detection of sea ice extremes and in particular, it aims for detection of heavily ridged ice regions from SAR, detection of MYI floes in a area composed mostly FY from SAR, detection of most thickest ice from RA thickness profiles, detection of regionally anomalous thick or thin ice via SMOS data, detection of sea ice areas vulnerable for the wave action, detection of early/late melting season and improving capabilities to forecast seasonal sea ice extremes. Remote sensing products traditionally provide overall information on sea ice conditions such as ice extent and concentration. However, this information stays limited for ice charting, tactical navigation and management of offshore activities since the sea ice hazards are related to sea ice thickness. Therefore, the thesis provided the basis to obtain sea ice thickness information by establishing the datasets.

For the purpose of this thesis, Chapter 1 included the introduction of sea ice related satellite technology and the main purpose of the thesis. Chapter 2 provided the information on "Study Area: Antarctic Sea Ice" and "Data description: Satellite Remote Sensing Detecting Sea Ice". Chapter 3 followed with methodology. Chapter 4 included the results and discussion, for the overall purpose of this thesis, to construct a dataset of in-situ reference snow/ice data co-located with all relevant satellite data. Chapter 5 suggested the conclusion with necessary steps to have more elaborating the idea of the Space-borne Observations for Detecting and Forecasting Sea Ice Cover Extremes.

GÜNEY OKYANUSUNDA BULUNAN DENİZ BUZU İÇİN EŞ-KONUMLANDIRILMIŞ UYDU VE YERSEL GÖZLEM VERİ SETİ OLUŞTURMA

ÖZET

Deniz buzu, donmuş deniz suyudur. Deniz buzları okyanus atmosfer ilişkileri ve okyanus canlıları için büyük önem arz etmektedir. Küresel iklim değişikliği ile ilgili çeşitli çalışmalarda buz özellikleri ve dağılımları oldukça önemlidir. Deniz buzu gözlemleri dünyada farklı standartlarda yapılmakta olsa da özellikle Antarktika için kullanılan "Antarktika Deniz Buz Süreçleri ve İklim" (Antarctica Sea Ice Processes & Climate - ASPeCT) protokolü en popüleridir. ASPeCT protokolü, tez kapsamında Türkçe'ye tercüme edilmiş olup, İstanbul Teknik Üniversitesi Kutup Araştırmaları Uyg-Ar Merkezi tarafından internet sayfalarında yayına alınmıştır. Bu protokol çerçevesinde çeşitli deniz buzu tipleri tanımlanmıştır. Gözlem yapılırken bulunulan bölgedeki 3 buz tipi belirlenerek, en kalın olan birincil, orta kalınlıkta olan ikincil ve en ince olan üçüncül buz olarak belirlenir. Gözlemler yaklaşık bir kilometre çapındaki alan için yapılır ve gemi hızına göre gözlem sıklığı belirlenir.

Deniz buzu gözleminde buz tipi, buzla kaplı alanın oranı, buz kalınlığı, buz üerindeki kar kalınlığı, buzun parça büyüklüğü, topografyası, kar örtüsü tipi ve açık deniz alanının oranı ölçülerek kayıt altına alınır. Deniz buzları ASPeCT protokolüne göre 13 farklı tipte bulunurlar. Buzun ilk formu olan "öncül buz" (frazil) buz oluşumunun ilk aşamasıdır. Genellikle deniz yüzeyinin birkaç santimetresinde oluşan öncül buz kristalleri, suya yağlı bir izlenim verir. Açık denizlerde dalga türbülansları ile bir kaç metre derinliğe kadar indikleri gözlemlenebilir. "Leblebi" (shuga) öncül veya yağsı buzların topaklanması ile oluşan birkaç santimlik buzlardır. Yüzey rüzgarları ve dalgaların etkileşimi ile leblebi buzları rüzgar yönünde sıralanır ve karakteristik buz bantları oluşturabilir. Öncül buzlardan sonra donmanın bir ileri aşaması olan "yağsı buz" (grease), kristallerin pıhtılaşması ile çorbamsı bir görünüm kazanır. Işığı daha az yansıtarak yüzeye mat bir görünüm kazandırır. Yağsı buz, az akışkan bir sıvı gibi davranır ve farklı buz kütleleri oluşturmaz. İnce elastik bir kabuk gibi olan "parmak buz" (nilas), dalgalar üzerinde kolayca bükülür, basınç altında kabarık bir form alır ve birbirine kenetlenmiş parmaklar gibi görünür. Koyu parmaklar 5 cm'den incedir ve koyu renklidir, ince parmaklar ise 5-10 cm kalınlığındadır ve koyu parmaklara göre ışığı çok daha iyi yansıtır. "Pişiler" (pancake) ağırlıklı olarak çapı 30 cm ile 3 m arasında olan yuvarlak buz formudur ve birbirleri ile çarpışarak daha kalın bir forma geçmeden önce kalınlığı 10 cm'den azdır. Yağsı, leblebi ve çamur buzların birleşmesi ile oluşabileceği gibi, buz kabuklarının veya parmak buzların kırılması, gri buzların ağır hava ve deniz şartları ile şekil değiştirmesi ile de oluşabilir. Antarktik deniz buzlarının gelişiminde "Pişi Döngüsü" yaygın bir süreçtir. On santimetrelerle başlayan pişiler, öncül buzlarla rüzgâr ve dalgaların etkisi ile kümelenerek çaplarını ve diğer pişi buzlarla yığınlar oluşturarak kalınlıklarını arttırır. Bu şekilde pişilerin çapları bir kaç metreye, kalınlıkları ise en fazla bir metreye ulaşır. Sonunda pişiler bir arada donarak daha büyük buz kütleleri veya birleşik buz örtüsünü oluşturur.

Pişilerden sonraki aşamalarda buzlar kalınlıklarına göre sınıflandırılmaya devam ederler. “Genç Gri Buz 0.1-0.15m” (young gray ice 0.1-0.15m), kalınlıkları 10-15 cm arasında olan, erken dönem buzları ile yıllık buzlar arasında bir geçiş formudur. “Genç Gri Buz 0.15-0.30m” (young gray ice 0.15.-0.30m) kalınlıkları 15-30 cm arasında olan, erken dönem buzları ile yıllık buzlar arasında bir geçiş formudur. Genç buzlardan gelişen, kalınlıkları 30 – 70 cm arasında olan, en fazla bir kış buz olarak kalan buz tiplerine “yıllık buz 0.3-0.7m” (first year ice 0.3-0.7m) denmektedir. Genç buzlardan gelişen, kalınlıkları 70 – 120 cm arasında olan, en fazla bir kış buz olarak kalan buz tipleri “yıllık buz 0.7-1.2m” (first year ice 0.7-1.2m), kalınlıkları 120 cm’den fazla olanlara ise “yıllık buz > 1.2m” (first year ice > 1.2m) denmektedir. Yıllık buzların 2 metre kalınlığa ulaştıkları görülebilir.

3 metre veya daha kalın olan ve neredeyse tuz içermeyen, en az iki yaz dönemini erimeden geçirmiş yaşlı buzlara “çok yıllık buz” (multi-year ice) denmektedir. Basınç sebebi ile yaşadıkları kırılmaların üzerlerinde oluşturduğu tepecikler, ikinci yıllarında daha yumuşaktır. Kar kaplı olmayan yerlerinden mavi renkli olduğu görülür. Yüzeylerindeki erimelerle büyük düzensiz ve bağlantılı su kütleleri ve iyi gelişmiş bir su tahliye sistemine sahiplerdir. Çok yıllık buz Arktik bölgeye nazaran Antarktika’da daha az yaygındır ve Weddell Denizi’nin batısı ile izole olmuş kimi diğer koylarla sınırlıdır. Okyanus akıntıları ve atmosferik sirkülasyonun oluşturduğu buzların kıta etrafında sürüklenme hareketi sonucu, buzlar sıcak denizlere sürüklenerek ya da açık denizlerin güneş ışınlarını emerek ısınması kaynaklı erimeler olur. Antarktika’daki çok yıllık buzların %80’i Weddell Denizi’nde bulunmaktadır. Weddell Gyre olarak bilinen saat yönünde dolaşan akıntı, Antarktika Yarımadası’nın doğu tarafı boyunca deniz buzlarını sıkıştırarak, bir yıldan daha fazla buz halinde kalmalarından sorumludur. Sonuç olarak akıntılar buzları daha kuzeye, okyanuslara ve erimeye taşır. Çok yıllık buzların erimesi, özellikle Arktik bölgede sıklıkla görülen bir durum olmaya başlamıştır. Antarktik deniz buzlarının erime sezonu nadiren erimiş buzların sularının üzerlerinde birikmesi ile ilgilidir.

“Çakıl” (brash) buzlar, 2 metreden daha küçük parçalar halinde olan parçalanmış buz formudur; diğer buzların enkazıdır. Çakıl buzlar özellikle çarpışan buzların ve basınç sırtlarının çöktüğü noktalarda yaygındır. Kıyı boyunca; sahile, buz duvarına, buz cephesine bağlı ya da sığlıkta veya oturmuş buzdağları arasında bulunan buz formuna “bağlı buz” (fast ice) denmektedir. Deniz seviyesinde yaşanan değişimler sırasında dikey dalgalanmalar görülebilir. Bağlı buzlar deniz suyundan donabildiği gibi kıyıda buzların istif olmasından oluşarak kıyıdan birkaç metre ile bir kaç yüz kilometre uzağa kadar uzanabilir.

Deniz buzlarının diğer özellikleri de gözlemlenmektedir. Buz parçalarının büyüklükleri, tiplerine göre değişiklik göstermektedir. Gözlem yapılırken parçanın büyüklüğü belirlenir uygun değer kayıt altına alınır. Açıklıklar buzları farklı parçalara ayırırken üzerinde sırt olan buzlar tek parça olarak kaydedilir. Buz yüzeyleri dümdüz olabileceği gibi sırtlarla veya tepeciklerle şekillenmiş olabilir. Gözlem yapılırken bu durum uygun değerler ile kayıt altına alınır. Buzlar gibi kar da birbirinden farklı tiplere sahiptir. Gözlem yapılırken farklı kar tipleri uygun değerler ile kayıt altına alınır. Deniz açıklıkları, buz parçaları arasındaki açıklıkları yani görünen denizleri tanımlar. Gözlem yapılırken farklı boyutlu ve özellikli açıklıklar, uygun değerler ile kayıt altına alınır. Buz kapsamı, herhangi bir deniz buz çeşidinin okyanus yüzeyinde kapladığı alanı gösterir. Gözlem yaparken 10’luk dilimde en yakın rakam kaydedilir. Bir çok buz çeşidi farklı kalınlık aralıklarında belirlenmiştir. Gözlem yapılırken buz ve kar kalınlıkları santimetre olarak ölçülür ve kayıt altına alınır.

En basit ifadeyle uzaktan algılama, doğrudan temas yerine uzaktan algılama anlamına gelir. Elde taşınabilir bir kamera, uzaktan algılama aracının bir örneğidir. Yer bilimleri açısından uzaktan algılama, uyduların yeryüzü veya atmosferdeki özelliklerden elektromanyetik radyasyonu algılama yeteneğine işaret eder. Dünyaya ulaşan güneş enerjisi, insanlar tarafından görülebilen ışık, termal kızılötesi, mikrodalga, radar ve röntgen gibi çeşitli radyasyonlardan oluşur. Mutlak sıfırdan daha yüksek bir sıcaklığa sahip her madde (-273°C veya -459°F) bazı elektromanyetik radyasyon yayar. Bazı uydu sensörleri, dünyanın yüzeyinden veya atmosferinden yansıyan görünür ışığı algılar ve diğerleri, yeryüzünden yayılan radyasyonu tespit eder. Kutup bölgelerinin uzaklığı ve zorlu doğası nedeniyle, uydu gözlemleri Arktik ve Antarktika ile deniz buzu örtüsünü izlemek için çok yararlıdır. Deniz buzu uzaktan algılaması, hem iklim araştırmalarına hem de denizcilik gibi kıyı dışı uygulamalara katkıda bulunabilir. Uydular, elektromanyetik spektrumun görünür, kızılötesi ve mikrodalga bölgelerinde deniz buzunu kolayca ölçebilir. Bununla birlikte, her radyasyon türünün avantaj ve dezavantajları vardır. Spektral bölgelerin hiçbiri, bilim insanlarının her koşulda deniz buzunu en iyi şekilde görüntülemesine izin vermez.

Deniz buzu özelliklerinin uzaktan algılaması her zaman zorlu bir iş olmuştur. 50 cm'den daha az bir kalınlığa sahip ince deniz buzu, hem kutup bölgelerindeki atmosfer ve okyanus arasındaki enerji alışverişinde temel bir rol oynar, hem de deniz buzunun dinamikleri anlamamız için önemlidir. Kar, Arktik ve Antarktik iklim sisteminin önemli bir bileşenidir. Yüksek albedo ve düşük termal iletkenliği nedeniyle, deniz buzu üzerindeki kar, kutup bölgelerinin yüzey enerji dengesini büyük ölçüde belirler. Kar ayrıca uydulardan gözlemlenen sinyali de değiştirir ve buz kalınlığının altimetre ölçümlerinden (diğer bir deyişle, uydu yüksekliğinin Dünya yüzeyinden uzaklığı ölçümleri) hesaplanması için kar örtüsü hakkında bilgi gereklidir. Bu tez, Ufuklar 2020 "Deniz buz örtüsü aşırılıklarının uzaktan algılama ile tespiti ve tahmini" (Space-borne observations for detecting and forecasting sea ice cover extremes - SPICES) projesinin Güney Okyanusu'nda bulunan deniz buzu için eş-konumlandırılmış uydu ve yersel gözlem veri setini oluşturan bir parçasıdır. SPICES, Yapay Açıklıklı Radar'dan (Synthetic Aperture Radar-SAR) çok sırtlaşmış buz bölgelerinin tespiti, çoğunluka yıllık buzla kaplı alanlarda çok yıllık buzların tespiti, Radar altimetre ile kalınlığı profillenen alanalrda en kalın buz formunu bulma, Toprak Nemi ve Okyanus Tuzluluğu (Soil Moisture and Ocean salinity-SMOS) verileri aracılığıyla bölgesel olarak anormal kalın veya ince buz tespiti, erken / geç erime mevsiminin saptanması ve mevsimlik deniz buzullarının aşırılıklarını tahmin etmek için yeni kapasiteler geliştirmeyi amaçlamaktadır. Uzaktan algılama ürünleri, geleneksel olarak, buz seviyesi ve alan dağılımı gibi deniz buzu koşulları hakkında genel bilgiler sağlar. Bununla birlikte, deniz buzu kaynaklı tehlikelerin çoğu kalınlık ile ilgili olmasına rağmen, bu bilgi buz haritası oluşturma, taktik seyrüsefer ve açık deniz etkinliklerinin yönetimi için sınırlı kalmaktadır. Bu nedenle, tez veri kümeleri oluşturarak, deniz buz kalınlığı bilgisi elde etmek için temel sağlamaktadır.

Bu tezin hedefi doğrultusunda, birinci bölümde deniz buzuyla ilgili uydu teknolojisinin tanıtımına ve tezin ana amacına değinilmiştir. İkinci bölüm "Çalışma Alanı: Antarktik Deniz Buzu" ve "Veri Açıklamaları: Deniz Buzu Uydu Uzaktan Algılaması" konularında bilgiler içermektedir. Metodolojiye üçüncü bölümde yer verilmiştir. Dördüncü bölüm, tezin genel amacı için sonuçları ve tartışmayı içermekte ve tüm ilgili uydu verileri ile birlikte yersel referanslı kar-buz verileri içeren bir veri seti oluşturulmaktadır. Beşinci ve son bölümde ise “Deniz buz örtüsü aşırılıklarının uzaktan algılama ile tespiti ve tahmini” fikrinin nasıl geliştirilmesi gerektiği ile ilgili adımlar sonuç olarak sunulmaktadır.

Bu çalışma İstanbul Teknik Üniversitesi BAP Koordinasyon Birimi tarafından desteklenmiştir.

1. INTRODUCTION

Sea ice is simply frozen seawater. However, monitoring sea ice is important for maritime transportation especially in the Barents Sea/Svalbard area, in the Russian Arctic (NSR), in Greenland/Iceland waters, and in the Baltic region during winter. Beyond Europe sea ice monitoring is conducted regionally in North America (Canada and USA), East Asia (Japan, China, Russia), and the Antarctic (Chile and Argentina). Global sea ice monitoring, which includes the whole Arctic and its surrounding seas and the Antarctic, is carried out for climate observations and to support shipping and research expeditions in Polar Regions (USA, Russia, and Norway).

Currently available sea ice products can be categorized as following:

1) Traditional ice charts showing ice information with World Meteorological Organization (WMO) sea ice nomenclature. The charts are produced by national ice services and have typically regional coverage, e.g. the Baltic Sea, Greenland.

2) Global products showing Sea Ice Concentration (SIC), ice edge, ice types first year ice (FYI) versus multiyear ice (MYI), or ice drift. The resolution of the products is typically 10 to 30 km. They are based on microwave radiometer and/or scatterometer data. In the global ice drift products, also SAR data are used.

3) Regional or limited coverage products based mainly on the SAR data (e.g. RADARSAT-2 ScanSAR in MyOcean-2). These include the Baltic Sea ice thickness chart, ice drift, and ice type charts.

4) Sea ice forecast products for ice drift, thickness, and concentration. Some of the sea ice models also assimilate satellite data.

Current and near future satellite sensor data available to generate sea ice parameters. In addition, geocoded satellite images (optical, thermal and SAR) can be delivered to the ships and other users, but these images are not sea ice products themselves, as an expert ice analyst is required to interpret the images for sea ice information. Many high latitude users such as the offshore industry and Arctic shipping require other sea ice products in addition to those currently available, e.g. ice thickness and deformation in spatial scales below 1 km. For seasonal sea ice forecasting, synoptic ice thickness distribution and snow thickness data are needed for the whole Arctic and Antarctic at 10-20 km resolution. These are currently not operationally available yet.

Some of the currently provided sea ice products can be used in the climate modelling and studies, for example, the time series of ice extent and sea ice concentration (SIC). The SIC parameter is critical in the initialization phase of sea ice forecast and impacts strongly on the predicted sea ice thickness. When the snow/ice melting period begins the accuracy of the SIC products gradually degrades. Therefore, in summer the current SIC estimates may contain large errors. In addition, sea ice thickness information may provide a much-needed constraint during the initialization of forecasts. Altimeter data (e.g. CryoSat-2) in theory directly measures the ice freeboard but its results are currently reasonable only for thick ice (> 1 m) areas, because of large relative errors for thin ice, and in winter due to problems with the radar signal penetrating a wet snow cover. Due to the noise present in radar altimeter (RA) freeboard measurements, current RA ice thickness charts typically have a one-month temporal resolution and 25 to 100 km spatial resolution. Main sources of ice thickness uncertainty are the inaccuracy of current snow thickness data, from either climatology, a sea ice/snow model, or radiometer data, and whether radar wave always penetrates to snow/ice interface as it is assumed in the freeboard retrieval. The SMOS satellite offers complementary sea ice thickness information for the CryoSat-2 RA data. It has been demonstrated that lower frequency L-band radiometer data measured by SMOS satellite can be used to retrieve ice thickness up to half a meter with a 35 km spatial resolution (Kaleschke et al., 2012). The L-band brightness temperatures (Tb) are much less sensitive to snow and ice surface characteristics than the higher frequency Tb’s and much more sensitive to ice thickness. The results are, however, sensitive to ice temperature and ice salinity. With the statistical analysis of CryoSat-2 waveforms, it may be possible to also utilize the RA data for other purposes than monthly sea ice thickness charts.

However, the surface roughness of sea ice and snow properties affects the waveform shape and their impact cannot be separated from each other. The analysis of the RA data emphasizes the importance of an accurate knowledge of snow depth over the sea ice in the ice thickness estimation. Studies over seasonal ice zones have shown that the snow depth in coarse (10 km) resolution can be estimated with a reasonable accuracy using passive microwave radiometer data (e.g. AMSR2). Satellite based snow depth estimation method over MYI is still missing.

In operational sea ice charting SAR images are typically analyzed both visually by expert ice analysts and classified automatically into different ice types and open water. In automatic classification both unsupervised and supervised methods, e.g. neural networks, are used. For retrieving sea ice concentration or open water – sea ice discrimination and sea ice edge, segmentation, texture analysis (especially local autocorrelation, edge density), and dual-polarized backscattering (HH/HV) methods are used (Karvonen et al., 2005; Berg and Eriksson, 2012; Bovith et al., 2005; Karvonen et al., 2010a; Karvonen, 2012a; Karvonen, 2012b, Moen et al, 2013). Backscattering and texture analysis are also used in estimation of degree of deformation and ice type classification (Karvonen et al., 2003b; 2004; 2009; Karvonen 2010b). Another approach to sea ice type classification from SAR images is the use of neural network methods (Zakhvatkina et al., 2013; Berg and Eriksson, 2012). A new algorithm based on Support Vector Machines (SVM) method (supervised learning methods with associated learning algorithms that provide data classification) is presently under development at NERSC and will be applied in this project in order to establish operational ice type products (3-4 ice types, degree of ice deformation) from Sentinel-1 SAR imagery. The method is presently developed using RADARSAT- 2 ScanSAR imagery with a noise correction applied for the HV-polarization images. Texture characteristics and expert analysis of the imagery are used as inputs for the ice type classification. The sea ice thickness classes (e.g. 0-10 cm, 10-30 cm, 30-50 cm) up to around 1 m can be obtained based on backscattering and texture analysis combined to background ice thickness information (Karvonen et al., 2003a; Karvonen et al., 2007; Karvonen et al., 2008; Karvonen 2012c). Also, ice thickness retrieval algorithms combining SAR and other EO data (e.g. MODIS and microwave radiometers) have been proposed recently (Similä et al., 2013). This preliminary work has continued.

Space borne remote sensing of thickness is based on the Archimedes law and satellite RA (e.g. ERS-1/2, ENVISAT, CryoSat-2) or laser altimeter (e.g. IceSAT-1) measurements of freeboard (Laxon et al., 2003; Kwok and Rothrock, 2009). The ice thickness retrieval is based input parameters of snow depth, snow, ice and water densities. The altimeter based ice thickness retrieval has a large relative error for thin ice (Laxon et al., 2003). Main physical sources of ice thickness uncertainty are the inaccuracy of snow depth data, currently only taken from climatology estimations with a first-order correction in the seasonal ice zone. Overall role of snow on sea ice is important. Almost all sea ice in the Arctic and Antarctic is covered with snow. Even new ice is rapidly covered with snow due to precipitation or accumulation of blowing snow. Through its substantial thermal, optical, and dielectric properties, the snow cover dominates the surface properties of ice-covered oceans, and thus the snow cover plays a major role in development of the underlying sea ice. It strongly influences the sea ice energy and mass balance and determines most interactions between sea ice and the atmosphere. In the Arctic, sea ice is mostly covered with snow from September to June, while it completely melts during summer, leaving behind the characteristic mixture of melt ponds and bare sea ice. In contrast, snow on the Antarctic sea ice mostly survives summer melt, at least as long as the sea ice underneath survives the melt season. Temperature, grain size, and wetness (liquid water content) of snow on sea ice are initially prescribed by the boundary conditions of air and ice surface temperatures. In addition, wind speed at the time of snowfall, and thereafter, as well as the sequence of accumulation events controls the layering and density structure of the snow cover. Afterwards, changes in atmospheric conditions and additional accumulation dominate the evolution of recent snow layers. Snow conditions own also large spatial variability- drifting snow accumulates on the ridged sea ice areas and have a large impact on freeboard and consequently for the CryoSat-2 derived sea ice thickness (Haapala et.al. 2013).

With time, snow grains and layering change as a result of metamorphism, mostly driven by temperature, temperature gradients, liquid water content, and mechanical forces due to overburden and density distributions. It has to be noted that most metamorphisms are irreversible, impacting the stratigraphy (layer sequence and properties) of the snow cover. The accumulation history and metamorphism cause strong vertical and horizontal variations in the physical properties of snow. Differences in snow layering (stratigraphy) and surface properties on Antarctic sea ice in spring 2006 shown in Nicolaus et. al. (2009). In the paper distinguished are snow covers that have recently accumulated (first year ice, FYI) and those that have already survived one summer melt period (second year ice, SYI), Conclusively, it is of great importance to explicitly consider snow properties and processes when studying sea ice on different scales and with different methods. In that respect, the four most important aspects about snow on sea ice are:

(1) Its substantial thermal properties, impacting sea ice mass balance and temperatures by acting as a strong insulator between sea ice and atmosphere.

(2) Its high scattering, underlying strong seasonal cycles and reflecting most of solar irradiance back to the atmosphere while only little energy is transmitted into the sea ice and finally the upper ocean. This also has strong implications for high latitude ecosystems, as well as biological and bio-geo-chemical processes.

(3) Its role in the fresh-water budget, by transport, accumulation, and melt.

(4) Its dielectric properties and mass distribution, strongly affecting remote sensing (airborne

and satellite) applications.

Finally, deriving the parameters from all data sources is still a big challenge. Therefore, the main purpose of the thesis was to

- Establish a data set of snow and ice measurements from in-situ platforms co-located with all available and relevant satellite.

- Co-location of ice/snow in-situ data to capture temporal variability of ice/snow signatures for the same ice during winter-spring-summer transitions. A large number of data were co-located in a unique dataset for forward model development and validation purposes.

The procedure in the thesis was first constructing a dataset of in-situ reference snow/ice data co-located with all relevant satellite data, followed with establishing an overview of existing in-situ snow/ice data and designing supplementary experiments for compiling representative snow/ice time series. Existing data then compiled, processed and reformatted to match the needs in data analysis. Finally, the in-situ data were collocated with available satellite data and weather data.

2. STUDY AREA AND DATA DESCRIPTION

2.1 Study Area: Antarctic Sea Ice

The Antarctica is the fifth largest continent and Antarctic sea ice zone remains as the least known region of the earth's surface. The continent is circulated by Southern Ocean. Ice extent and concentration, also other ice conditions can be conducted from satellite-derived data but validation of such data is still underway. Sea ice is different once between Arctic and Antarctic is compared because of the geographical differences. Arctic is almost a closed ocean and completely surrounded by land. Therefore, Arctic formed sea ice is not dynamic as sea ice in Antarctic. During the summer period on both poles, ice remains through the summer and continues to grow following fall. Antarctica is geographic opposite of the Arctic and surrounded by the ocean. Therefore, region is allowed to form sea ice freely. As a result the sea ice formed during winter with total extend of 18 million square kilometers tend to melt during summer up to 3 million square kilometers (Cavalieri et al., 2003) This means that Antarctic sea ice mainly thin ice up to 1 to 2 meters comparing to 4 to 5 meters of thick ice in Arctic. Snow thickness in both poles is different too. Arctic is mostly covered with ice and surrounded by land cause less precipitation. On the other hand, Antarctica is entirely surrounded by Southern Ocean where evaporation is high. As a result, Antarctic sea ice covered with thick snow which even accumulate to the point that the weight pushes ice below sea level causing flooded layer (/cryosphere/seaice/index.html)

The role of sea ice in the global climate system has been long recognized and included as a study component of major international weather and climate programs such as Intergovernmental Panel on Climate Change (IPCC), the Polar Sub-Programme of the Global Atmospheric Research Programme, and the World Climate Research Programme. However, several factors have restricted implementation of a coordinated Antarctic sea ice zone program before the present. Many of the countries are already carrying out, and plan to continue, sea ice zone research in both physical and biological sciences within National programs: substantial new information is now available, particularly from the Weddell Sea, Amundsen and Bellingshausen Seas, and the Indian Ocean sector. A number of sophisticated, ice-capable research vessels are now working in the Antarctic, and at the same time, the increased number of nations working in the Antarctic has seen a growth in all types of shipping activity. And new remote sensing capabilities, particularly active radar systems, have greatly enhanced sea ice observation from space (http://aspect.antarctica.gov.au/home).

2.2 Data description: Satellite Remote Sensing Detecting Sea Ice

It is difficult to examine Antarctic sea ice time-varying characteristics due to the vastness and remoteness of the region. Satellite remote sensing data, in principle, allow detection of changes in ice concentration (indicates the fraction of a given ocean grid point covered by ice. It is given as a decimal number, with range from 0-100%) and ice extent (the northern-most position of the ice edge at a given time) over large areas. Passive microwave sensors, unhampered by cloud cover and darkness are particularly well suited to obtain a large spatial and long temporal record of sea ice concentration and extent (Comiso and Nishio, 2008). However, ice characteristics from space have shown weaker correlation with ship-based observations in summer than in winter, both for ice concentration (Knuth and Ackley, 2006) and ice extent (Worby and Comiso, 2004).

As mentioned above and both in chapter 1 and chapter 2.1 that detecting sea ice by satellite remote sensing technique is playing essential role in both poles. Current and near future satellite sensor data available for these sea ice product generation are listed in Table 2.1 Most of the sea ice products are issued daily. From such satellites, there are sea ice parameters can be driven by algorithms. Parameters and importance of these can be listed below:

Sea ice extent: Widely used product for research, operational models and one essential climate variable; Sea ice concentration: Widely used product for research and operational models. Uncertainties exist during melting period; Sea ice motion: Important parameter to monitor pack ice motion in climate scale; Sea ice types from SAR: Fully automatic production of sea ice types, in particular detection of MYI floes, would be widely used product; Sea ice types from scatterometer: Excellent in terms of large-scale mapping of FYI and MYI regions, products mainly used in climate research community; Sea ice types from Radar Altimetry: Novel approach, potentially to become very important application of CryoSat-2 /Sentinel-3 in near-real time sea ice monitoring; Mean sea ice thickness: CryoSat-2 and SMOS derived sea ice thickness estimates are biased. More accurate data, including error estimates, would be highly desirable; Sea ice thickness distribution: an accuracy of present RA sensors do not allow to measure ice thickness distribution. This could be possible by combining information from several satellites; Sea ice albedo: Further development to estimate thermal state of pack ice based on its albedo would be important climate indicator and product to guidance polar operations.

Table 1.1 : Satellite Sensors for sea ice products.

Satellite	Operator	Instrument	Spatial resolution	Wavelength(s) or frequencies	Active/ Passive	Period
AQUA	NASA	AMSR-E	3-60 km	6.9, 10.7, 8.7, 23.8, 36.5 and 89 GHz	P	2002-11
JCOM-W	JAXA	AMSR2	4-75 km	6.9, 10.7, 8.7, 23.8, 36.5 and 89 GHz	P	2012-
SMOS	ESA	MIRAS	35 km	1.4 GHz	P	2010-
SMAP	NASA	Radar	3 km	1.26 GHz	A	2015-
SMAP	NASA	Radiometer	30 km	1.4 GHz	P	2015-
METOP	EUMETSAT	AVHRR/3	1 km	0.58-12.5 um (6 channels)	P	2006-
METOP	EUMETSAT	ASCAT	25-50 km	5.3 GHz<	A	2006-
Oceansat	ISRO	OSCAT	50 km	13.5 GHz	A	2009-14
DMSP	US DoD	SSMIS	12.5-75 km	19.4, 22.4, 37, 50, 92, 150 and 183 GHz	P	2003-
Sentinel-1	ESA/EU	SAR	50 m	5.4 GHz	A	2014-
Sentinel-3	ESA/EU	SLSTR	1 km	0.55 - 12 um (9 channels)	P	2015-
Sentinel-3	ESA/EU	SRAL	0.3-5 km	5.4 and 13.6 GHz	Altimeter	2015-
Cryosat	ESA	SIRAL	0.3-5 km	13.6 GHz	Altimeter	2009-
ENVISAT	ESA	ASAR	0.15-1 km	5.3 GHz	A	2002-2012
ENVISAT	ESA	AATSR	1 km	10.8 um, 12 um	P	2002-2012
QuikSCAT	NASA	SeaWinds	25 km	13.6 GHz	A	1999-2009

In this thesis, ASPeCt ship based observations, AMSR-E, AMSR2, ASCAT, ICESAT, QUIKSCAT and meteorological information have been used.

2.2.1 Antarctic Sea Ice Processes & Climate (ASPeCt) Ship Based Observations

One of the major accomplishments of ASPeCt, since its inception in 1997, is the specification of a standard ice observation protocol for sea ice thickness observations made aboard ships in the Antarctic pack ice. This observation protocol provides a standardized and quantifiable method for observing sea ice that is now accepted as the international standard. Hence, ships entering the Antarctic pack ice zone at any time of year are encouraged to record sea ice observations. Importantly, the results from these observations can be analyzed using computer software that produces distributions of sea ice properties and thickness comparable to the output of numerical models, and therefore provides a highly detailed data set for comparison with model predictions of these parameters than is currently available from satellite products (Worby and Allison, 1999; www.aspect.aq)

Observational data, which conducted on sea ice morphology and distribution systematically mainly, collected on many icebreakers. The data collected include ice concentration, ice type, ice thickness, floe size, topography, snow cover (snow type and thickness), and meteorological data, including sea temperature, air temperature, wind speed, direction, cloud cover and visibility. Ice observations were made according to the ASPeCt protocols (Worby and Allison, 1999; www.aspect.aq)

2.2.2 Advanced Microwave Scanning Radiometer (AMSR-E and AMSR2)

The Advanced Microwave Scanning Radiometer has operated on three satellites: (http://www.remss.com/missions/amsr)

- AMSR-2 on JAXA's GCOM-W1 spacecraft, launched May 18, 2012. This instrument is currently operating.
- AMSR-E on NASA's EOS Aqua spacecraft, launched May 4, 2002. The instrument stopped rotating Oct 4, 2011.
- AMSR on JAXA's ADEOS-II spacecraft, launched Dec 14, 2002. The satellite solar panels failed Oct 25, 2003.

The AMSR-E instrument provides passive microwave data expressed as horizontally and vertically polarized brightness temperature (Tb) from 6.9, 10.7, 18.7, 23.8, 36.5, and 89 (GHz) frequencies. The spatial resolution of the data (pixel size) is 12.5 km by 12.5 km. AMSR-E microwave remote sensing uses various algorithms to estimate the snow depth, sea ice concentration (NASA Team 2), and snow/ice interface temperature (Cavalieri et al., 1997; Comiso et al., 2003; Markus and Cavalieri, 2000). The AMSRE’s geophysical products of ice concentration (Cavalieri and Comiso, 2004) are updated daily (AMSR-E/Aqua Daily L3 12.5 km Tb, Sea Ice

Conc. and Snow Depth Polar Grids) and can be obtained from the National Snow and Ice Data Center (www.NSIDC.org).

After the failure of AMSR-E in 2011, AMSR2 launched by JAXA to the orbit to provide Products: sea surface temperature, surface wind speed, integrated water vapor, cloud liquid water, and rain rate. The AMSR2 instrument provides passive microwave data expressed as horizontally and vertically polarized brightness temperature (Tb) from 6.9, 7.3, 10.7, 18.7, 23.8, 36.5, and 89 (GHz) frequencies. The spatial resolution of the data (pixel size) is 12.5 km by 12.5 km.

2.2.3 Advanced Scatterometer (ASCAT)

This is the satellite uses scatterometer technology. Scatterometers are essentially radars that transmit microwave pulses down to the Earth's surface and then measure the power that is returned back to the instrument. This "backscattered" power is related to surface roughness. For water surfaces, the surface roughness is highly correlated with the near-surface wind speed and direction. Hence, wind speed and direction are retrieved from measurements of the scatterometer's backscattered power.

The first Advanced Scatterometer (ASCAT) was launched on the EUMETSAT MetOp-A satellite in October 2006. It took one year to get fully be in operational. ASCAT continues to operate since 2007 to today. Another ASCAT instrument became operational on MetOp-B when launched in September 2012. Both satellites, MetOp-A and MetOp-B carry identical ASCAT instruments. The main objective of ASCAT is the measurement of wind speed and direction over the oceans, though ASCAT is also used for studying polar ice, soil moisture and vegetation. ASCAT is a C-band, V-Pol scatterometer with 3 vertically polarized antennas transmitting pulses at 5.255 GHz. The fan-beam antennae are oriented at 45, 90, and 135 degrees with respect to the satellite track. The antennae extend on either side of the instrument, resulting in a double swath of observations, each about 500 Km wide separated by a gap of about 360 Km (Figa-Saldana et al, 2002).

2.2.4 Ice, Cloud and land Elevation Satellite (ICESat)

ICESat was the benchmark Earth Observing System mission to measure ice sheet mass balance, cloud and aerosol heights, land topography and c-vegetation characteristics. Between 2003 and 2009, this mission provided elevation data needed to determine ice sheet mass balance, information on cloud property, cloud informations especially common ones over polar areas (https://icesat.gsfc.nasa.gov/icesat/).

The sole instrument on ICESat was the Geoscience Laser Altimeter System (GLAS), a space-based LIDAR. GLAS combined a precision surface LIDAR with a sensitive dual-wavelength cloud and aerosol LIDAR. The GLAS lasers emit infrared and visible laser pulses at 1064 and 532 nm wavelengths. As ICESat orbited, GLAS produces a series of approximately 70 m diameter laser spots that are separated by nearly 170 m along the spacecraft's ground track. During the commissioning phase of the mission, the ICESat was placed into an orbit, which allowed the ground track to repeat every 8 days. During August and September 2004, the satellite was maneuvered into a 91-day repeating ground track for the main portion of the mission (Schutz et al, 2005). Therefore, ICESat Laser Campaigns period 2A, 2B, 2C, 2D, 2E conducted during 2003 and 2004, also campaigns period 3A, 3B, 3C, 3D, 3E, 3F, 3G, 3H, 3I, 3J, 3K conducted during 2004 and 2009.

2.2.5 Meteorological information from European Centre for Medium-Range Weather Forecasts (ECMWF 2m air temperature)

ECMWF periodically uses its forecast models and data assimilation systems to 'reanalyze' archived observations, creating global data sets describing the recent history of the atmosphere, land surface, and oceans. Reanalysis data are used for monitoring climate change, for research and education, and for commercial applications. Current research in reanalysis at ECMWF focuses on the development of consistent reanalyzes of the coupled climate system, including atmosphere, land surface, ocean, sea ice, and the carbon cycle, extending back as far as a century or more. The work involves collection, preparation and assessment of climate observations, ranging from early in-situ surface observations made by meteorological observers to modern high-resolution satellite data sets. Special developments in data assimilation are needed to ensure the best possible temporal consistency of the reanalyzes, which can be adversely affected by biases in models and observations, and by the ever-changing observing system (https://www.ecmwf.int/en/research/climate-reanalysis).

3. METHODOLOGY

In this study ASPeCt ship based observations, ASCAT data, AMSR-E data, AMSR2 data and ICESat data were used to derive sea ice and snow depth comparisons in-between the datasets. There has been two types of methodology set followed and as described below:

Methodology 1 was focusing on Fall / Winter / Spring (periods between March and November) and 2002 - 2015 (AMSR-E / AMSR2 period) consistent to

- Obtain relevant in-situ and ship-based ASPeCt observations
- Decode ASPeCt observations where necessary
- Harmonize data which is slightly different coding of the observations between different cruises and the partly different order of observations as well as the different amount of observations translated from coded into physical values was harmonized such that one can work with the full data set. Approximately 7000 ASPeCt observations were harmonized.
- Append relevant satellite information. Relevant satellite (AMSR-E, AMSR2, and ASCAT) and meteorological information appended.

Methodology 2 used the comparison of data from National Snow and Ice Data Center (NSIDC), SICCI-UB, and a first Markus et al. (2011) algorithm snow depth with ICESat residual elevation and surface roughness with pure data, with ECMWF 2m air temperature, with radar backscatter, with various Gradient Ratios . Therefore, the method focused on

- ICESat residual elevation & standard deviation over 50 km along-track segments as a measure of surface roughness
- 16 measurement periods within 2003-2009

- Relevant satellite (AMSR-E, ASCAT) and meteorological information appended

4. RESULTS AND DISCUSSIONS

This section of the thesis explains the data distribution and selected results of analyses for methodology 1 and methodology 2.

First starting with methodology 1 is that the idea was to obtain relevant in-situ and ship-based ASPeCt observations and decoding those where applied. Accordingly, about 7000 ASPeCt observations were harmonized from different cruises and the partly different order and amount of data to create full data set. The data shown in Figure 4.1 is the spatial distribution of ASPeCt ship-based observation locations around Antarctica split into seasons (up) and years (down). As it is seen from the figure that there are ASPeCt data distribution only few for fall (March-April-May (MAM)) and for winter (June-July-August (JJA)). Distribution shows larger dataset for September-October-November (SON) and December-January-February (DJF).

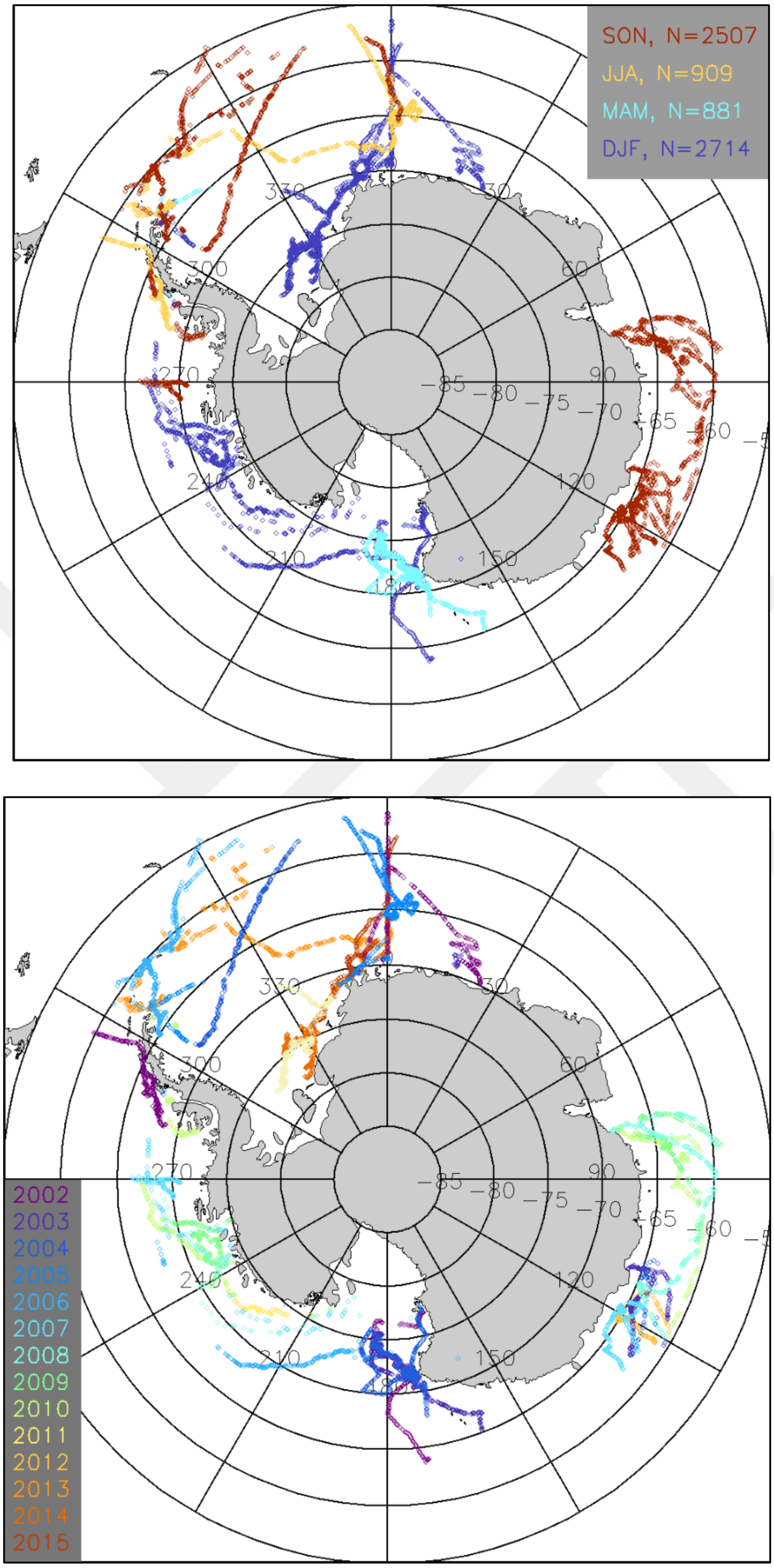


Figure 4.1 : Spatial distribution of ASPeCt ship-based observation locations around Antarctica split into seasons (up) and years (down).

Figure 4.2 shows the ASPeCt data consistency check where scatterplots of ASPeCt parameters using all (black) and „cold“ (ECMWF 2m air temperature < -10°C, blue). The top figure indicates the snow depth increases with sea ice thickness where there is a filter of SIC above 80% and SIT is more than 30 cm. The same filtration was applied to the middle figure to see the comparison between the ice thickness and ridged ice fraction. The middle of the picture shows that the sea ice thickness increases with ridged ice fraction as expected. The last part of the figure at the bottom indicated the snow depth tends to increase with ridged ice fraction where filter of SIC above 80% and SIT is more than 30 cm again applied to limit the bias.

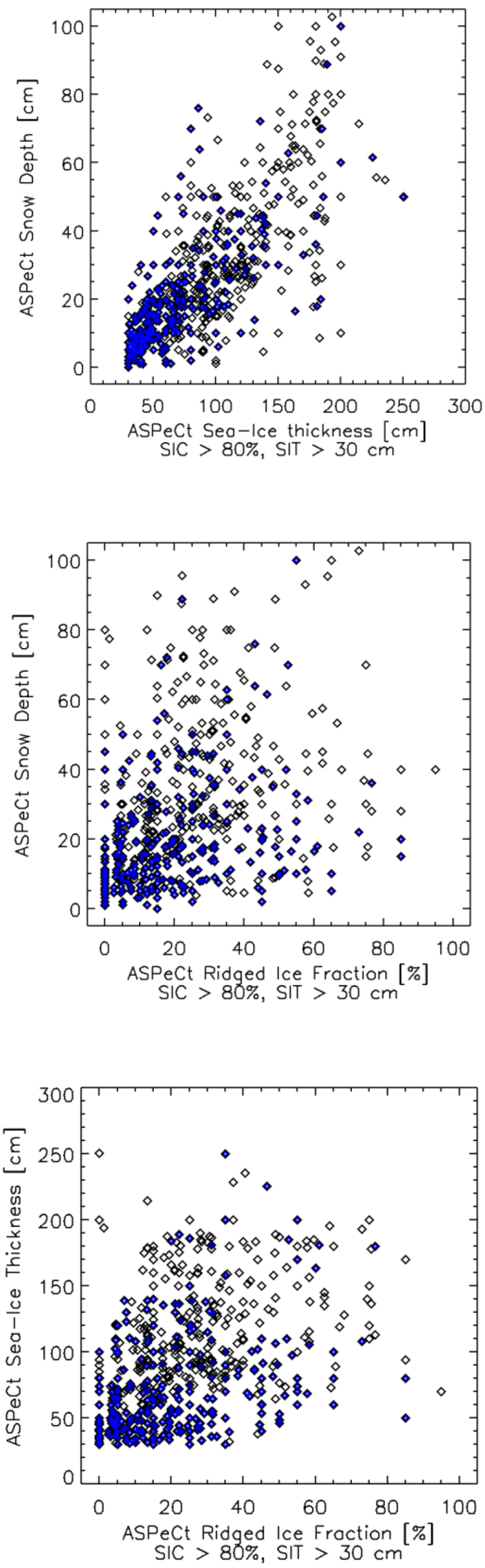


Figure 4.2 Scatterplots of ASPeCt parameters using all (black) and „cold“ (ECMWF 2m air temperature < -10°C, blue): snow depth increases with thickness (top), ice thickness increases with ridged ice fraction (middle), snow depth tends to increase with ridged ice fraction (bottom).

The next result is shown in Figure 4.3, which conducted for the ASPeCt data snow depth versus Satellite (AMSR-E) data Snow Depth. In the figure AMSR-E versus ASPeCt snow depth for sea-ice concentrations are limited with above 80%; black line indicates the 1-to-1 line for easier comparison. Sea ice concentration less than 80 percent were not included into the analyses. The results show that the ASPeCt snow depth is larger than AMSR-E snow depth for thicker snow depths. This is in line with findings in Ozsoy-Cicek et al, 2009. AMSR-E is underestimating the snow depth rough ice. On the other hand, snow depth within the limit of 30 cm, shows good correlation between the two different datasets.

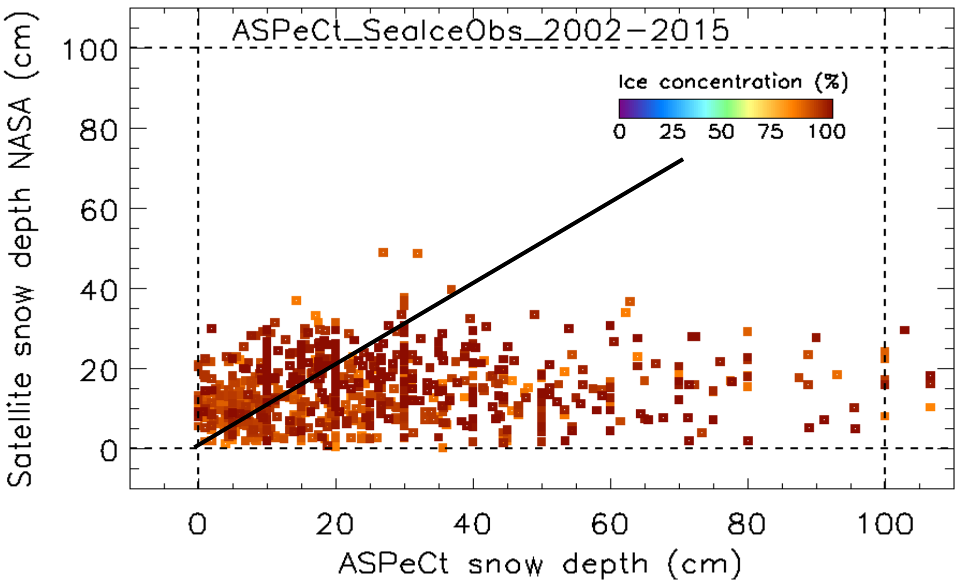
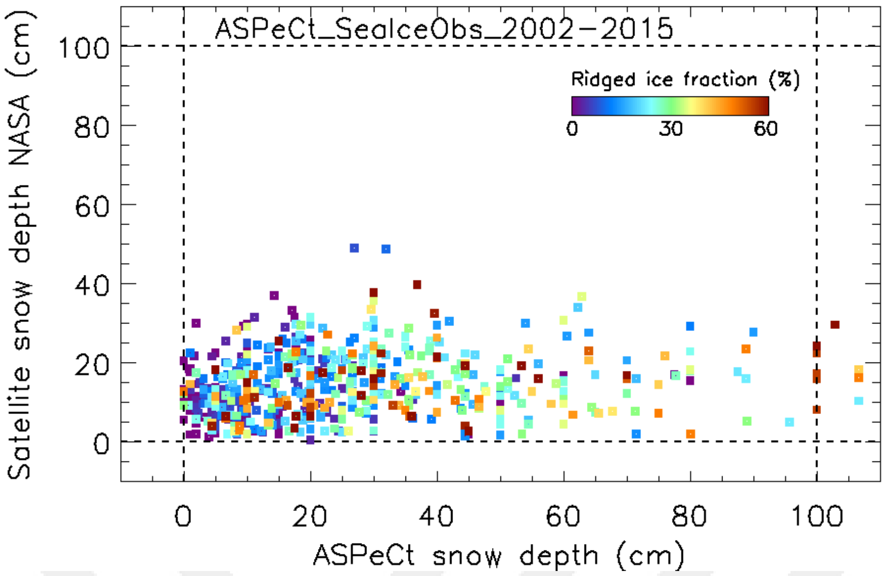


Figure 4.3 : AMSR-E vs. ASPeCt snow depth for sea-ice concentrations > 80% ; black line is 1-to-1 line.



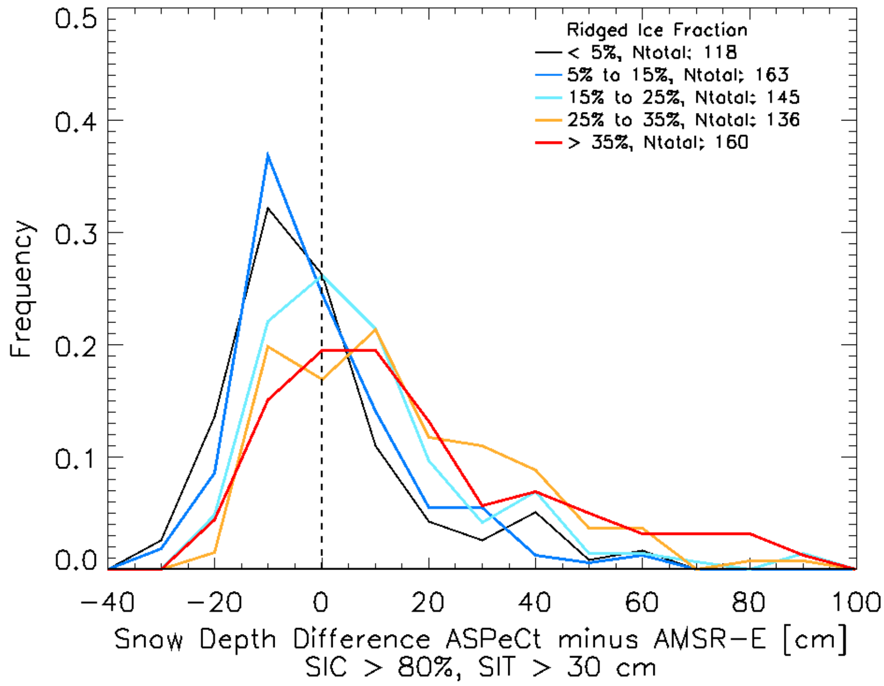
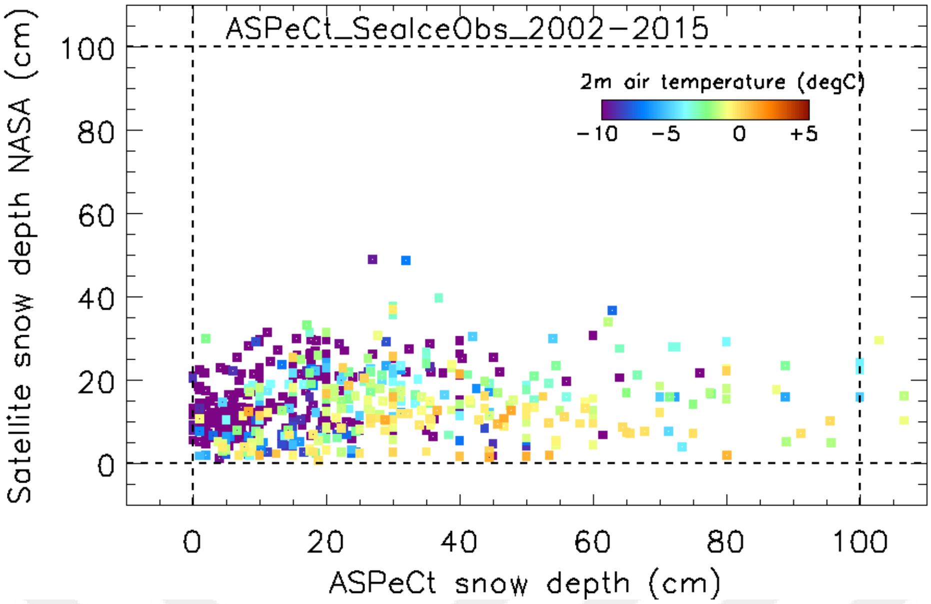


Figure 4.4 : AMSR-E vs. ASPeCt snow depth for sea-ice concentrations > 80% and sea-ice thickness > 0.3 m, color-coded with ASPeCt ridge ice fraction (top); histogram of snow depth difference ASPeCt minus satellite (bottom).

Figure 4.4 indicates the comparison of ASPeCt snow depth deformation to Satellite (AMSR-E) Snow Depth deformation. Sea ice concentration again filtered out and only the ice concentrated above 80% were included into the analyses. The ice thickness less than 30 cm was also discarded. The color-coded with ASPeCt ridge ice fraction results shown at top figure and histogram of snow depth difference mainly ASPeCt minus satellite shown at the bottom figure. Overall results indicate that the ASPeCt snow depth is less than the AMSR-E snow depth for level ice. Also ASPeCt snow depth is larger than AMSR-E snow depth for deformed ice. Both results again is in line with literature already.

The following figure, Figure 4.5 is ASPeCt snow depth comparison to AMSR-E satellite snow depth for sea-ice concentrations above 80% and sea-ice thickness above 0.3 m. Figure is color-coded with ECMWF 2m air temperature (top); histogram of snow depth difference ASPeCt minus satellite (bottom) starting from 0^{o}C degree and provided 5^{o}C degree intervals. The top part of the figure indicates that the correlation between ASPeCt snow depth comparison to AMSR-E satellite snow depth is high when the air temperature is between -8^{o}C and -10^{o}C. This means that the aggrement between the datasets are quite high during the cold conditions. Pretty much the majority of the disagreement starts around the temperatures between -2^{o}C and $+2^{o}$C. Overall, the ASPeCt data underestimates the AMSR-E snow depth for cold cases. In return, ASPeCt data provides larger snow depth comparing to AMSR-E snow depth for warm cases, especially with increasing temperature. The bottom of the figure shows that the lower the temperature, higher the correlation with the increase frequency. The amount of the frequency is also stays good with temperatures between -10^{o}C and -5^{o}C, -5^{o}C and 0^{o}C. The frequency drops after the temperatures 0^{o}C and above.



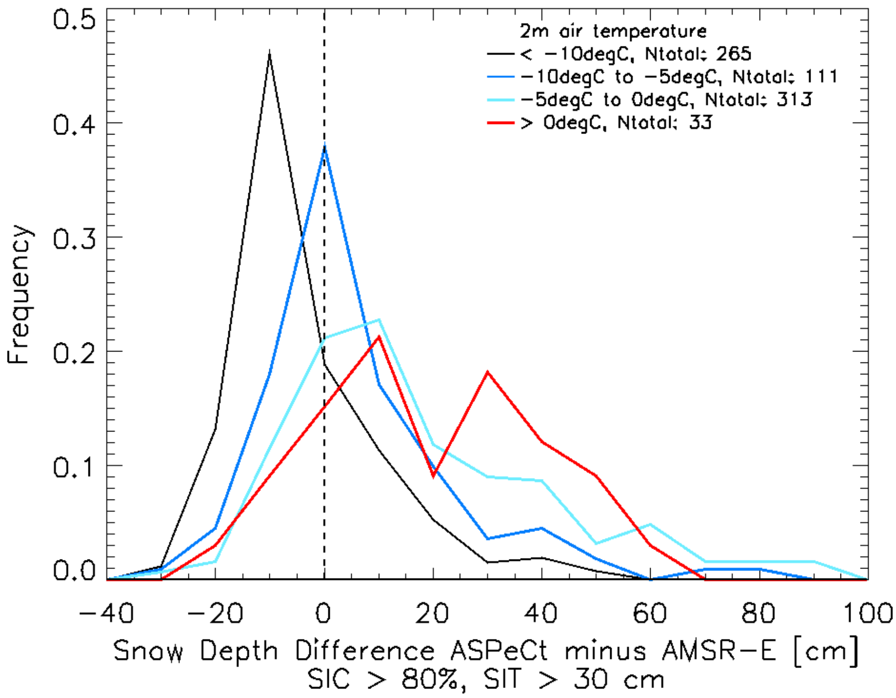


Figure 4.5 : AMSR-E vs. ASPeCt snow depth for sea-ice concentrations > 80% and sea-ice thickness > 0.3 m, color-coded with ECMWF 2m air temperature (top); histogram of snow depth difference ASPeCt minus satellite (bottom).

The last figure is providing the information between the ASPeCt snow depth versus AMSR-E satellite snow depth – ASCAT radar backscatter. AMSR-E snow depth comparison to ASPeCt snow depth conducted for sea-ice concentrations for more than 80% and sea-ice thickness for higher than 0.3 m. The top figure of figure 4.6 is color-coded with ASCAT radar backscatter. The bottom figure is the comparison of ASPeCt snow depth to ASCAT radar backscatter. The overall results indicate simply no relationship between the products. In addition, no relationship found during the comparison between ASPeCt ridged ice fraction and ASCAT radar backscatter.

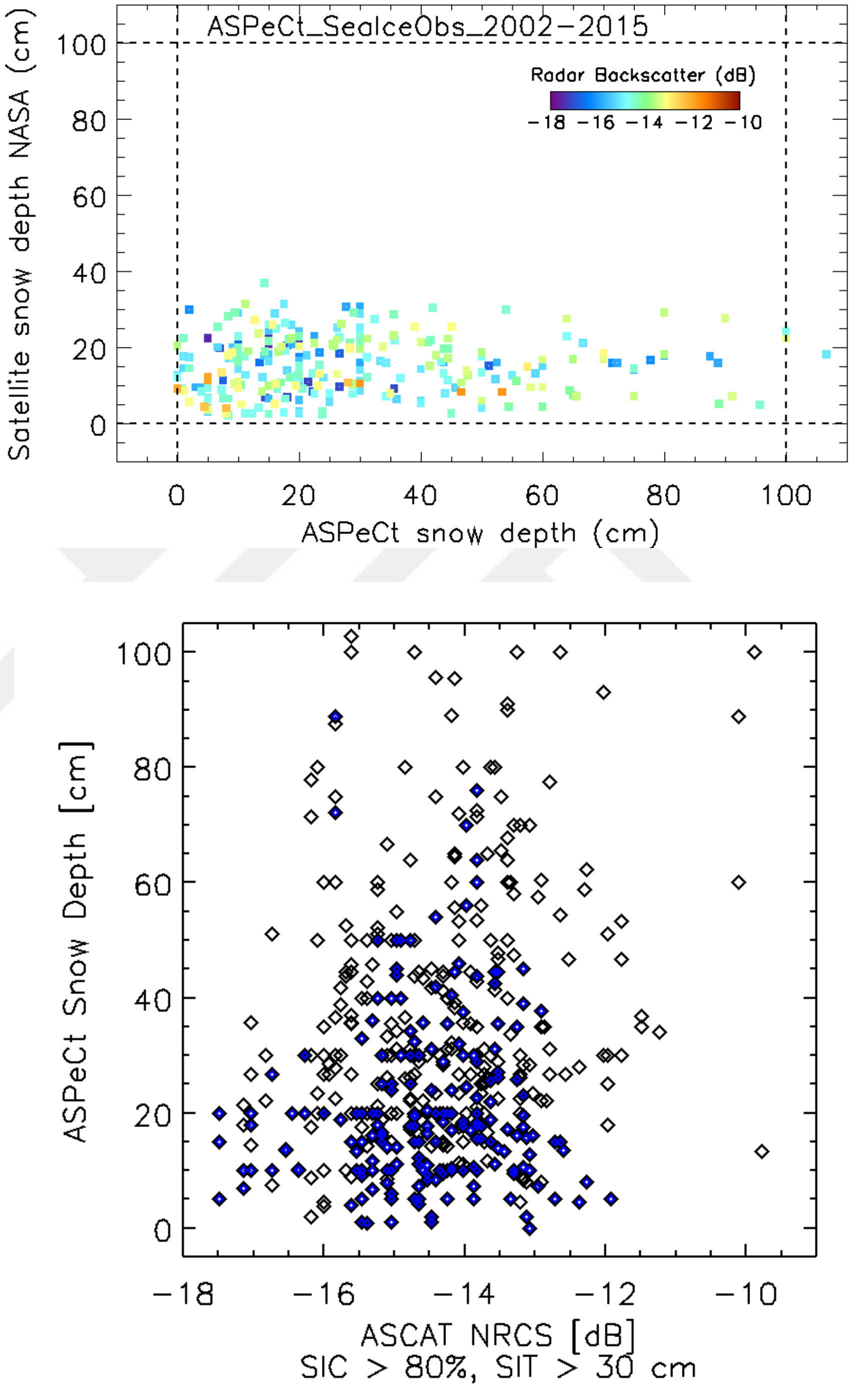


Figure 4.6 : AMSR-E vs. ASPeCt snow depth for sea-ice concentrations > 80% and sea-ice thickness > 0.3 m, color-coded with ASCAT radar backscatter (top); ASPeCt snow depth vs. ASCAT radar backscatter (bottom).

The general summary of methodology 1 with ASPeCt observations so far is that the inter-comparison of ASPeCt ship based snow depth and ridged ice fraction co-located with ECMWF air-temperature and satellite snow depth and C-Band radar backscatter confirms:

- AMSR-E over-estimates snow depth for rough ice,
- AMSR-E under-estimates snow depth for warm conditions,
- ASPeCt might under-estimate large-scale snow depth for level ice due to preferential sampling over thin ice.
- ASPeCt ridged ice fraction seems not to be correlated with ASCAT C-Band radar backscatter.

Methodology 2 used the comparison of data from National Snow and Ice Data Center (NSIDC), SICCI-UB, and a first Markus et al. (2011) algorithm snow depth with ICESat residual elevation and surface roughness with pure data, with ECMWF 2m air temperature, with radar backscatter, with various Gradient Ratios. Therefore, the method focused on

- ICESat residual elevation & standard deviation over 50 km along-track segments as a measure of surface roughness
- 16 measurement periods within 2003-2009
- Relevant satellite (AMSR-E, ASCAT) & meteorological information appended

In the second part of the methodology, residual elevation was analyzed but not the freeboard. Because the step between residual elevation and freeboard contains finding leads to approximate the sea surface height (SSH) which is known to be the most error-prone step. Therefore, in order to avoid artificially large standard deviations of the freeboard or elevation due to wrong SSH approximations, it has been decided to use the residual elevation and compute the standard deviation also with respect to that surface.

Figure 4.7 indicates the ICESat data set explained in chapter 2 with all campaigns. Colors denote low (dark blue) to high (red) surface roughness. Therefore the data distribution is shown in the figure for all campaign periods of 2A, 2B, 2C, 2D, 2E,

3A, 3B, 3C, 3D, 3E, 3F, 3G, 3H, 3I, 3J, 3K. As it is seen from the induvial figure that the data coverage is not the same if comparison is made one to another one. As a result, more data coverage provides more information such as in 2A, 2C, 3A, 3C, 3F, 3I periods.

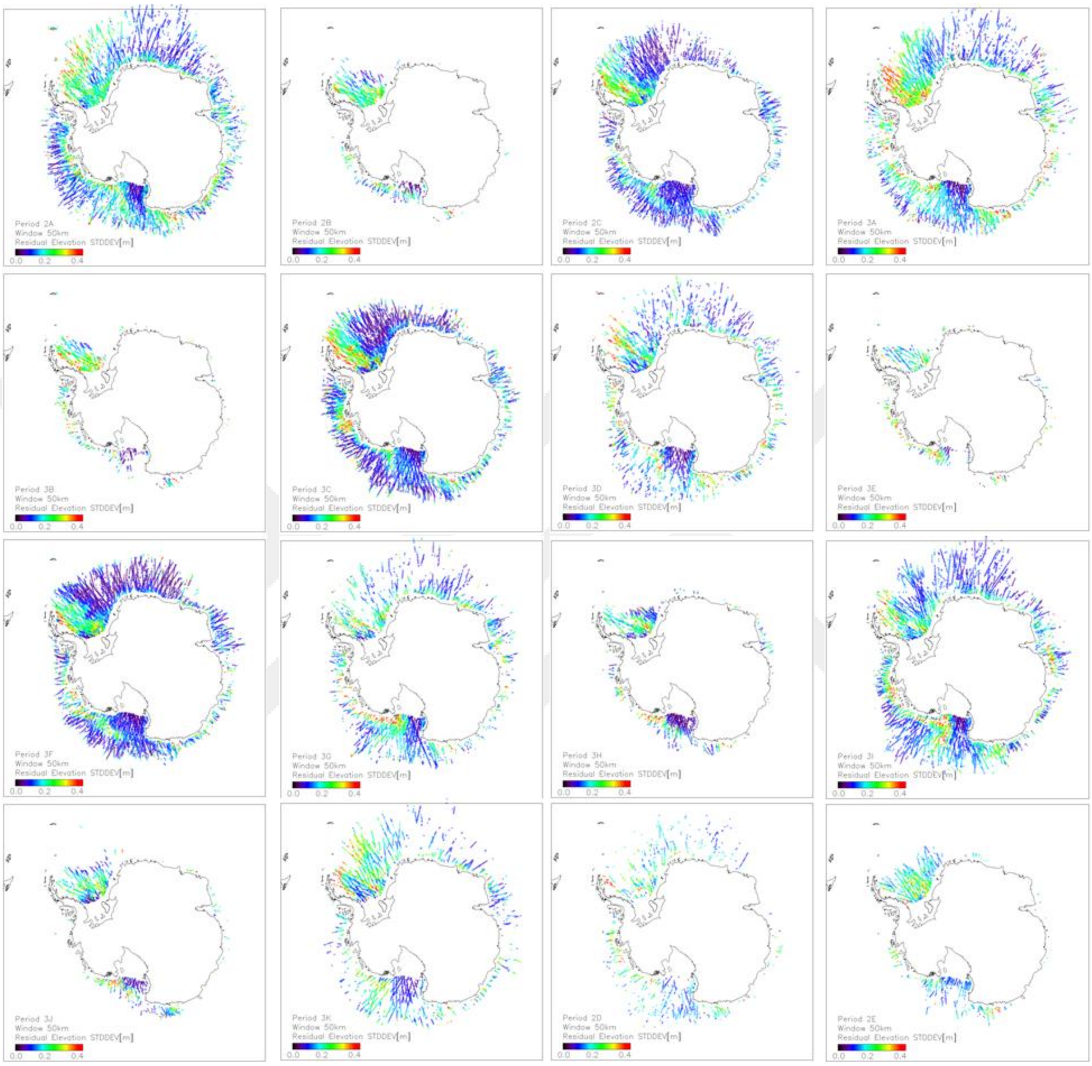


Figure 4.7 : ICESat data coverage from September / November 2003 through March/April 2009.

Figure 4.8a shows the data distribution for summer December, January, February (DJF) and fall March, April, May (MAM), therefore the spatial distribution of co-locations of ICESat and AMSR-E observation for summer (mostly February, a bit December) and fall (all months). Also Figure 4.8b shows the Data distribution for winter June, July, August (JJA) and spring September, October, November (SON), therefore the spatial distribution of co-locations of ICESat and AMSR-E observations for winter (all from June) and spring (mostly from October/November). Colors denotes as black = all co-locations, red = co-locations with > 0 m snow depth and > 80% sea-ice concentration.

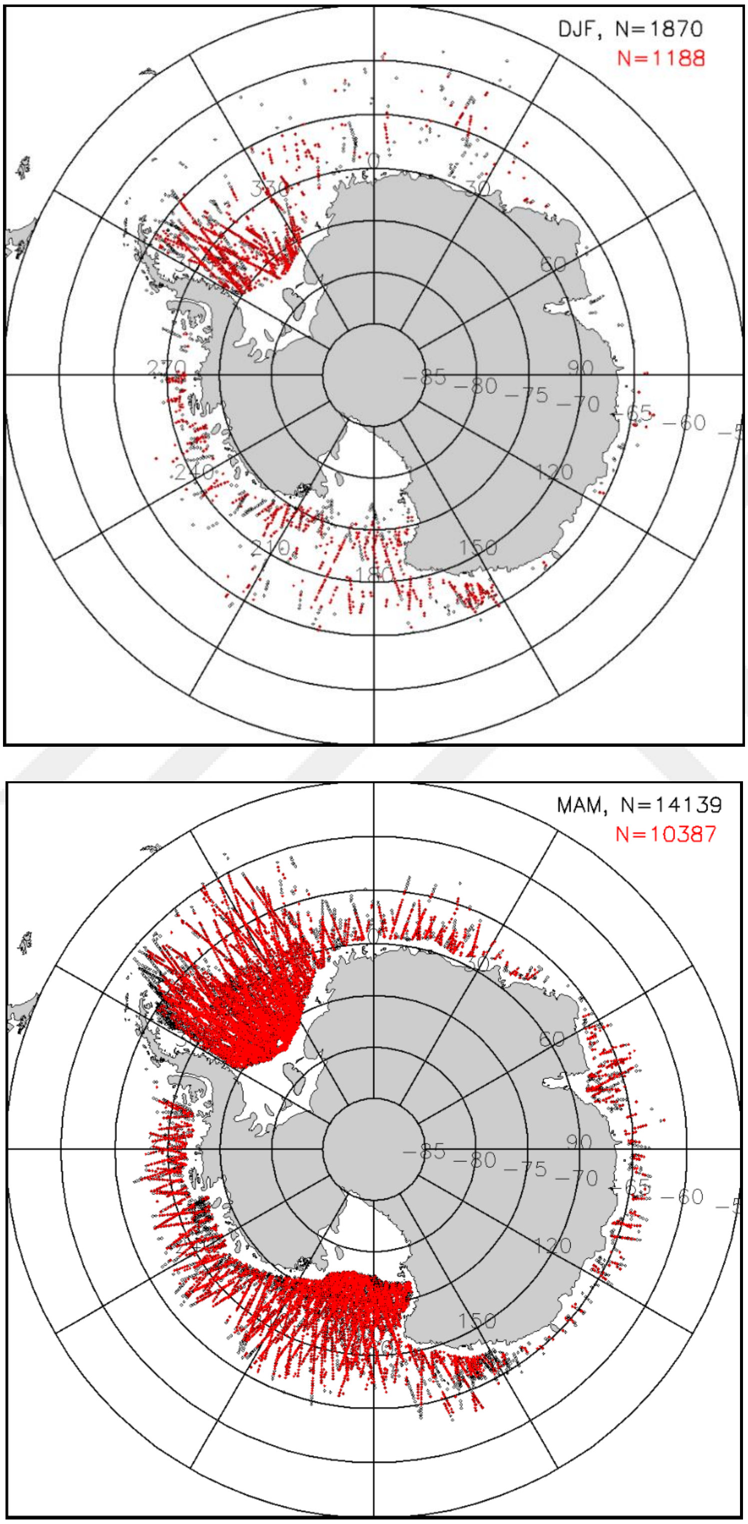


Figure 4.8a : Spatial distribution of co-locations of ICESat and AMSR-E observation for summer (mostly February, a bit December) and fall (all months).

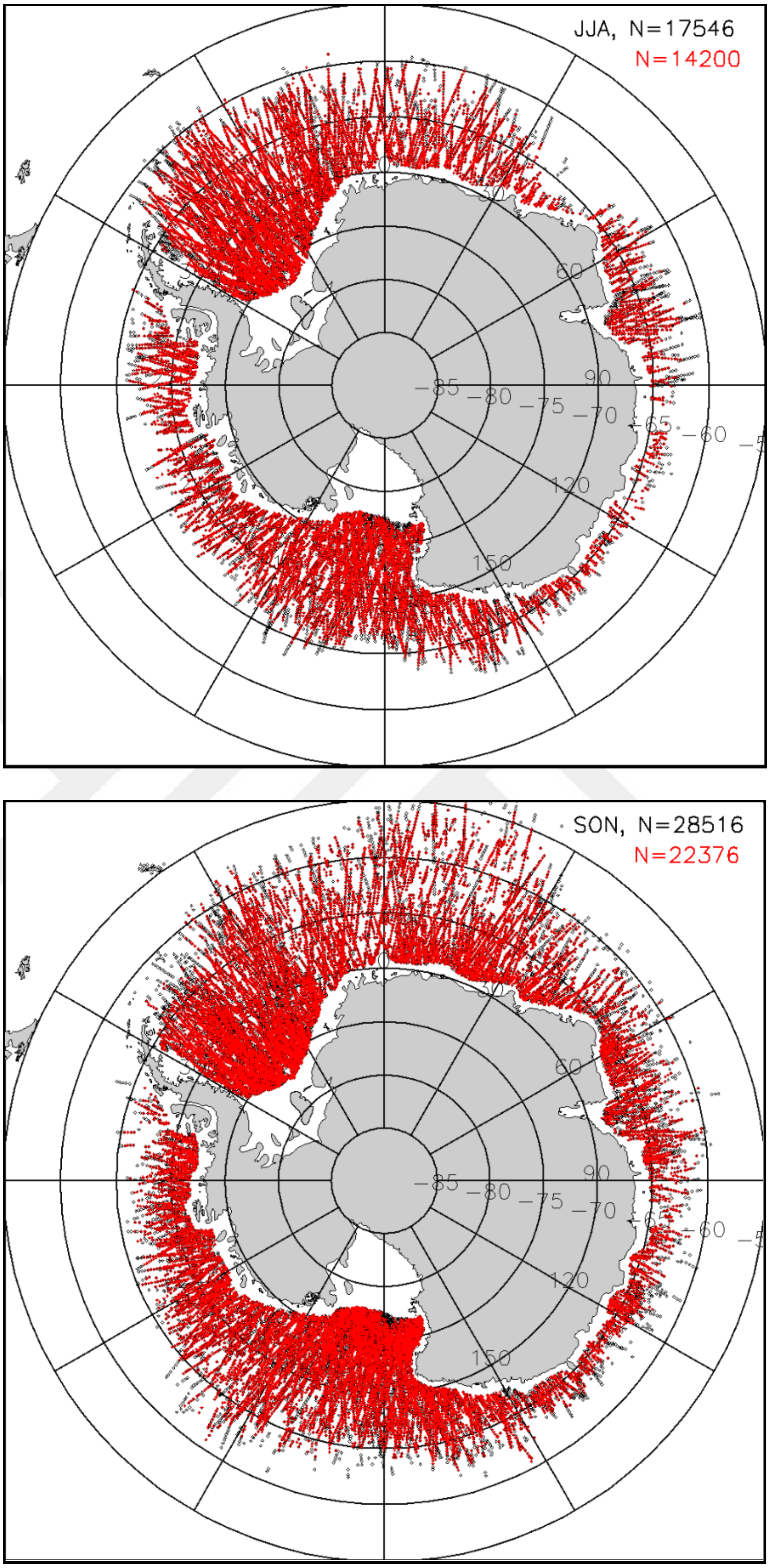


Figure 4.8b : Spatial distribution of co-locations of ICESat and AMSR-E observations for winter (all from June) and spring (mostly from October/November).

The next challenge was to confirm the consistency and to check the data if ICESat roughness and freeboard correlated or not. Figure 4.9 is created to check consistency and ICESat residual elevation standard deviation (i.e. surface roughness) versus residual elevation (i.e. freeboard) for all spring ICESat periods used. Black colors denotes to all data with snow depth higher than 0.0 m. Sea-ice concentration derived from data less than 80% discarded. Blue color denotes same as black with limiting snow depth to 0.0 m and sea ice concentration higher than 80 only kept but only where air T2m less than -5°C data used. The overall answer is straightforward and simply positive that ICESat roughness and freeboard are correlated.

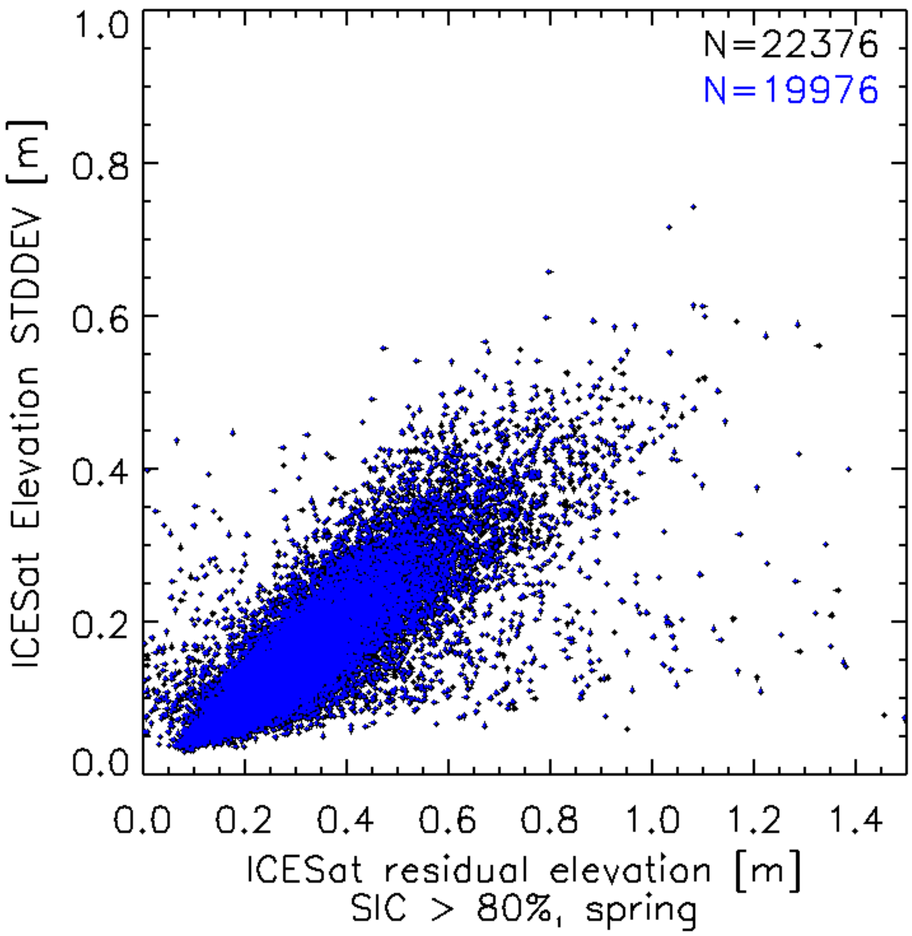


Figure 4.9 : ICESat residual elevation standard deviation (i.e. surface roughness) versus residual elevation (i.e. freeboard) for all spring ICESat periods used.

The next is posed in the study that How is AMSR-E snow depth related to ICESat freeboard and roughness? This question is important to understand the correlation between the snow depths driven from passive microwave data and laser satellite data. Therefore, in figure 4.10 AMSR-E snow depth versus ICESat freeboard and the associated surface roughness for all spring ICESat periods were used. As a result, there are two major conclusion can be derived as

- AMSR-E snow depth does not increase with freeboard
- AMSR-E snow depth tends to decrease with roughness

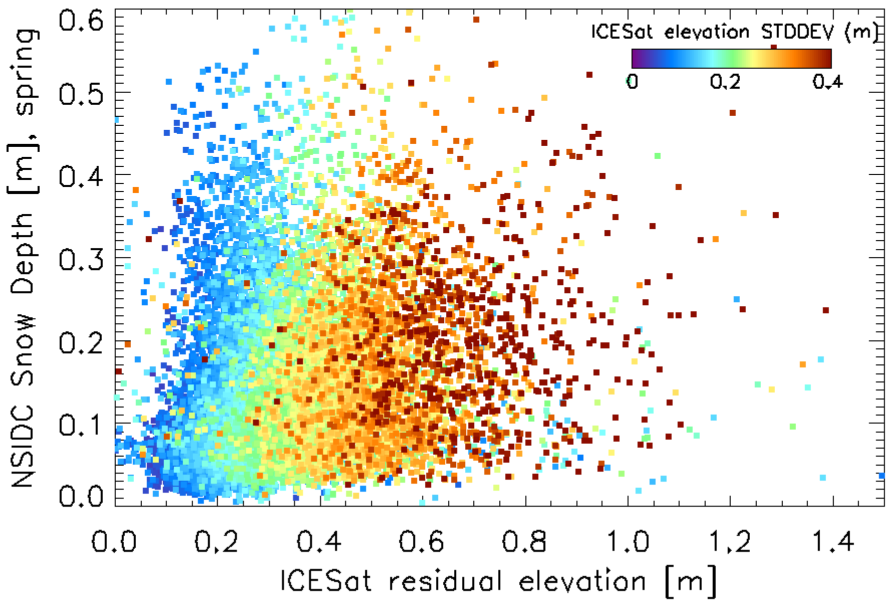


Figure 4.10 : AMSR-E snow depth versus ICESat freeboard and the associated surface roughness for all spring ICESat periods used.

The following figure has conducted to see the answer of another important question which was -How is AMSR-E snow depth related to ICESat freeboard and 2m air temperature? Figure 4.10 indicates the AMSR-E snow depth compared to ICESat freeboard and the associated ECMWF 2m air temperature for all spring ICESat periods used. The figure is color-coded with ECMWF 2m air temperature with in the -10 °C to +5 °C. As result, higher 2m air temperature seems coinciding with lower AMSR-E snow depth as expected, in return lower air temperatures are highly correlated with thick snow. Also ICESat elevation is positively correlated with air temperatures that colder the temperature get the higher residual elevation.

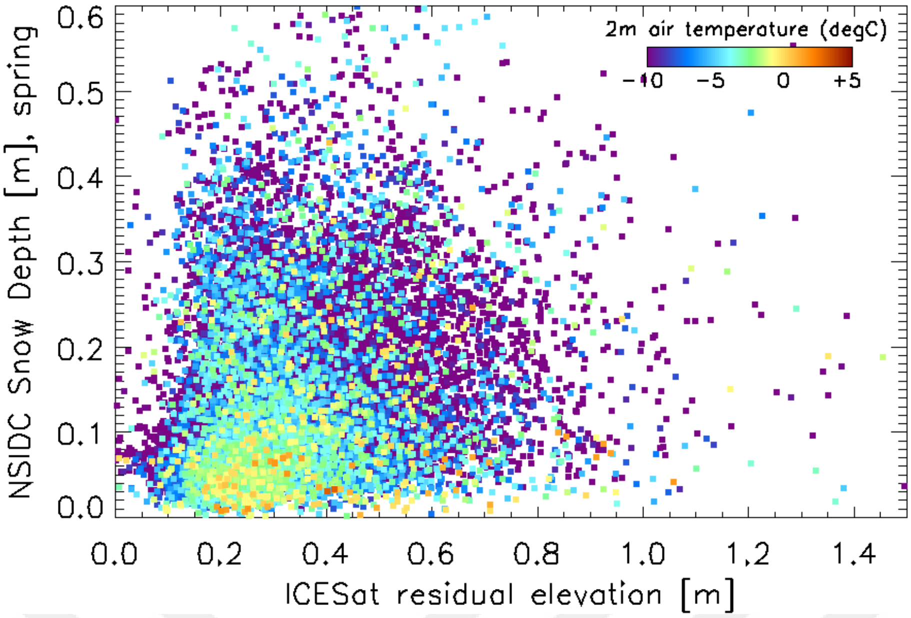


Figure 4.11 : AMSR-E snow depth versus ICESat freeboard and the associated ECMWF 2m air temperature for all spring ICESat periods used.

Figure 4.11 shows the AMSR-E snow depth and ICESat surface roughness with distribution of AMSR-E snow depth over ICESat surface roughness bins of 0.05 m width for (Top, middle and bottom) fall, winter and spring. SIC is less than 80% has discarded from the analyses. Modal AMSR-E snow depth values of the two bins with the highest ICESat surface roughness migrate from ~ 20 cm in fall/winter months (here: March through June) to < 10 cm in spring months (September through November). During fall and winter, high stddev found mainly all over the different heights of snow depth. However, high stddev occurs in spring with total frequency of 5374, which is doubled comparing to other seasons.

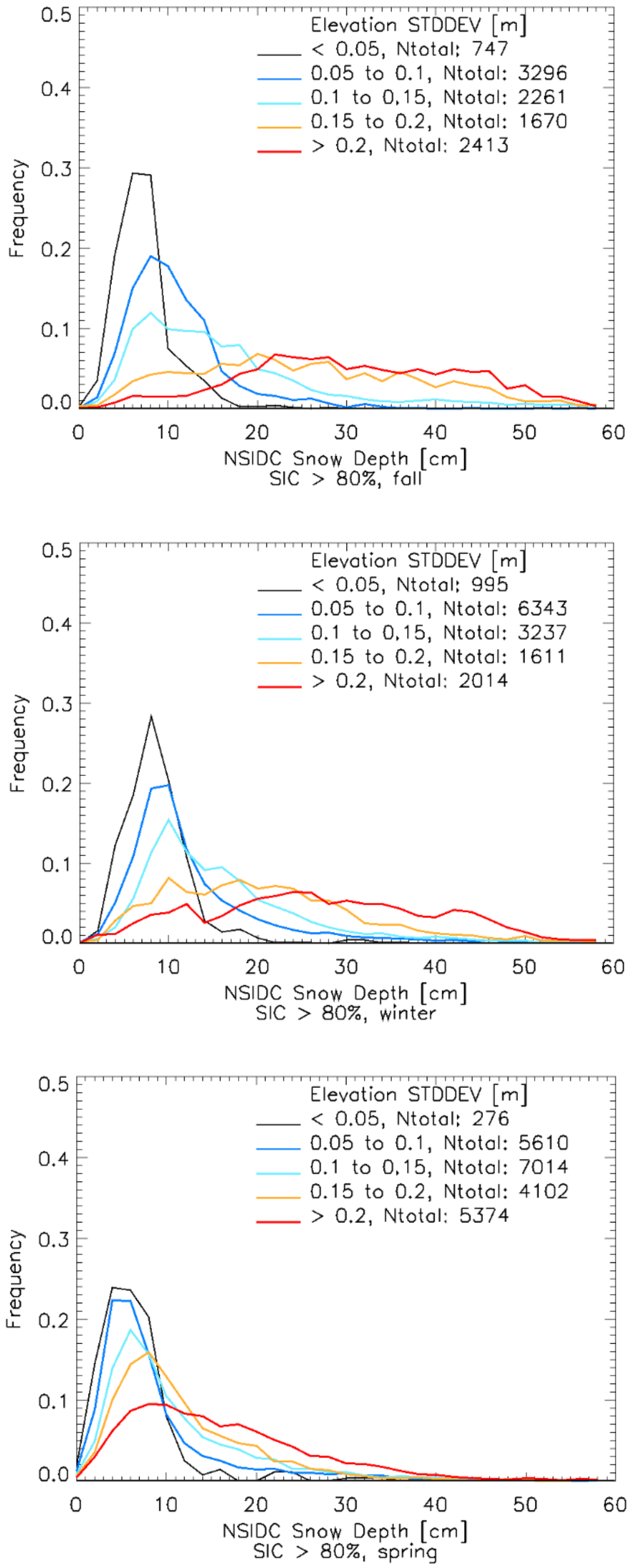
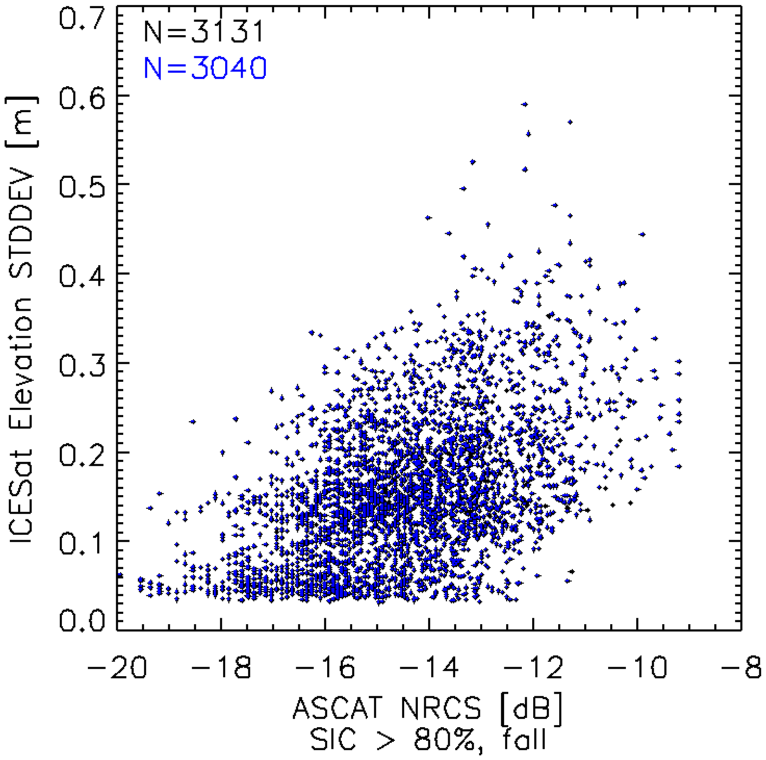


Figure 4.12 : Distribution of AMSR-E snow depth over ICESat surface roughness bins of 0.05 m width for (Top-bottom) fall to spring.



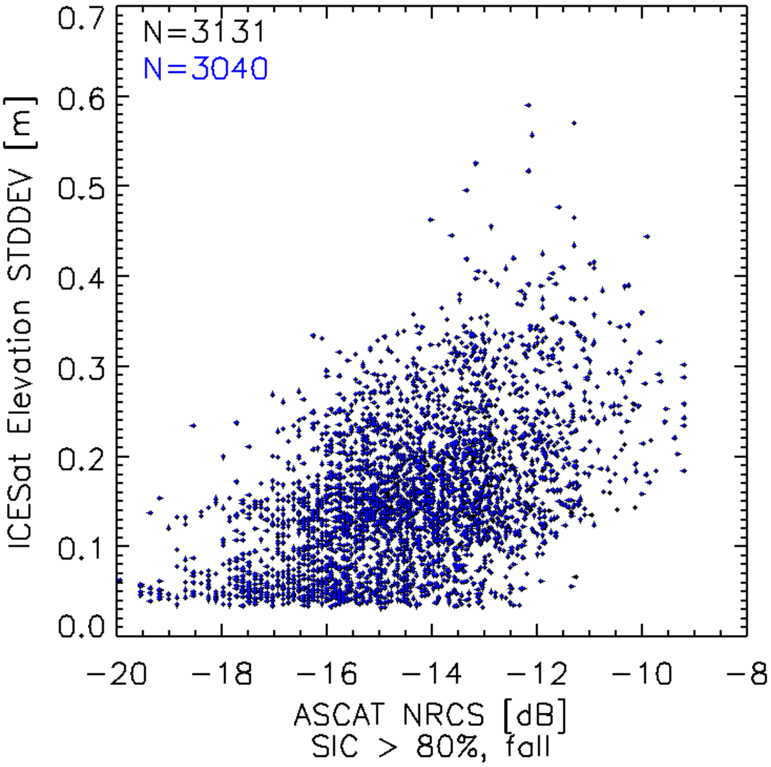


Figure 4.13 : ICESat surface roughness versus ASCAT C-Band radar backscatter (NRCS) for fall (top) & spring (bottom).

The figure above is deriven to look at the question posed to understand how ICESat roughness relates to ASCAT C-Band radar backscatter. Figure 12 shows the ICESat surface roughness compared to ASCAT C-Band radar backscatter (NRCS) for fall (top) and spring (bottom). Black is denoted to all data with snow depth > 0.0 m and sea-ice concentration > 80%, blue is same as black but only where T2m < -5°C.

- The relationship is more promising than the one obtained from ASPeCt ridged-ice fraction observations but is it exploitable.
- No co-locations for winter because of ASCAT started in Oct. 2006 but last ICESat winter period was in May/June 2006.

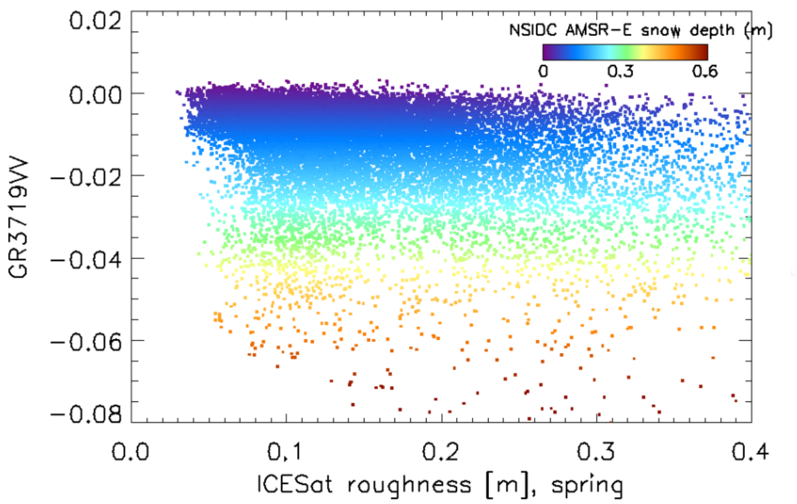


Figure 4.14: AMSR-E GR3719VV vs. ICESat roughness and associated AMSR-E snow depth for all spring ICESat periods used.

One of the last question to be asked to the datasets was to see how do AMSR-E snow depth, GR37V19V and ICESat roughness relate with each other? Therefore the figure 13 is generated by AMSR-E GR3719VV compared to ICESat roughness and associated AMSR-E snow depth for all spring ICESat periods used. The results indicate that the

- AMSR-E snow depth increases with decreasing GR3719VV

- No relation between ICESat roughness & GR3719VV

Illustration of relationship between GR3719VV, ICESat roughness & snow depth computed after Markus et al. (2011) shown in Figure 14. In the figure AMSR-E GR3719VV versus ICESat roughness and associated AMSR-E Markus et al. (2011) method snow depth for all spring ICESat periods used. Markus et al. (2011) empirical method:

SD = -5.45 – 638.67 * GR3719VV_ice + 1.21 * ICESat_roughness

The figure reveal that there are clusters of snow depth layered in terms of different thicknesses. It is in a way good findings that the rough thickness has thick snow cover on top. But on the other hand the gradient ratio, especially in between 3719VV does not distinguish the snow layers.

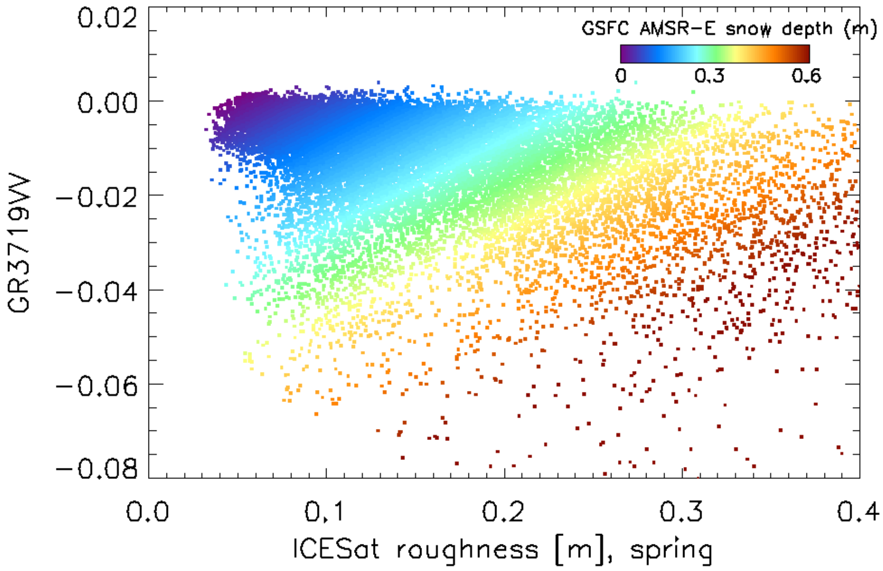


Figure 4.15 : AMSR-E GR3719VV vs. ICESat roughness and associated AMSR-E Markus et al. (2011) method snow depth for all spring ICESat periods used.

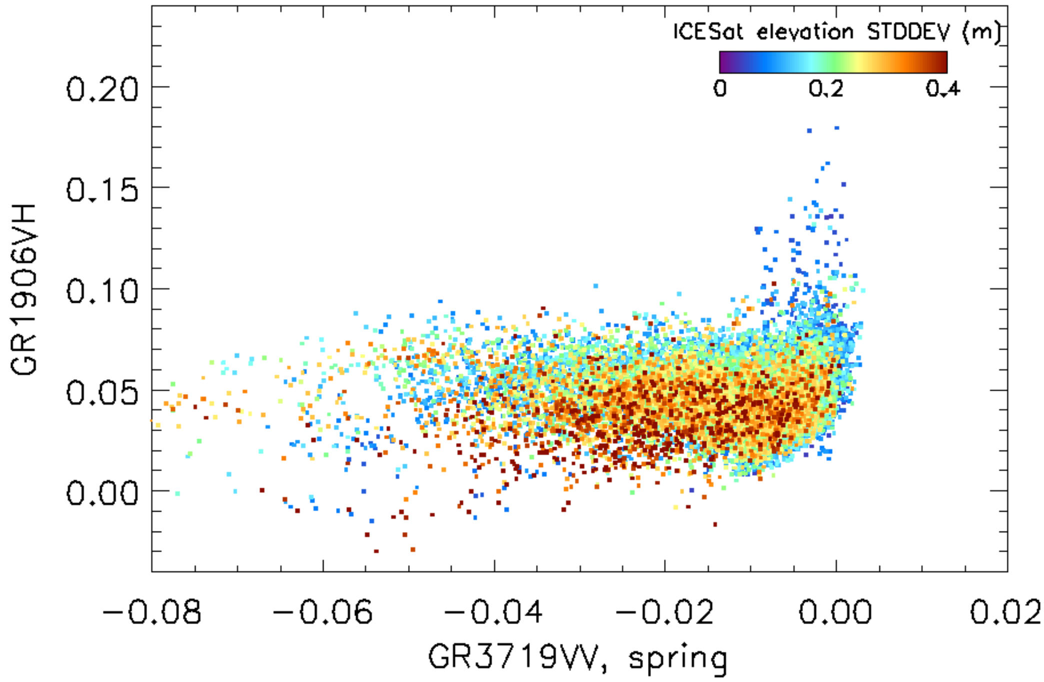
5. CONCLUSION

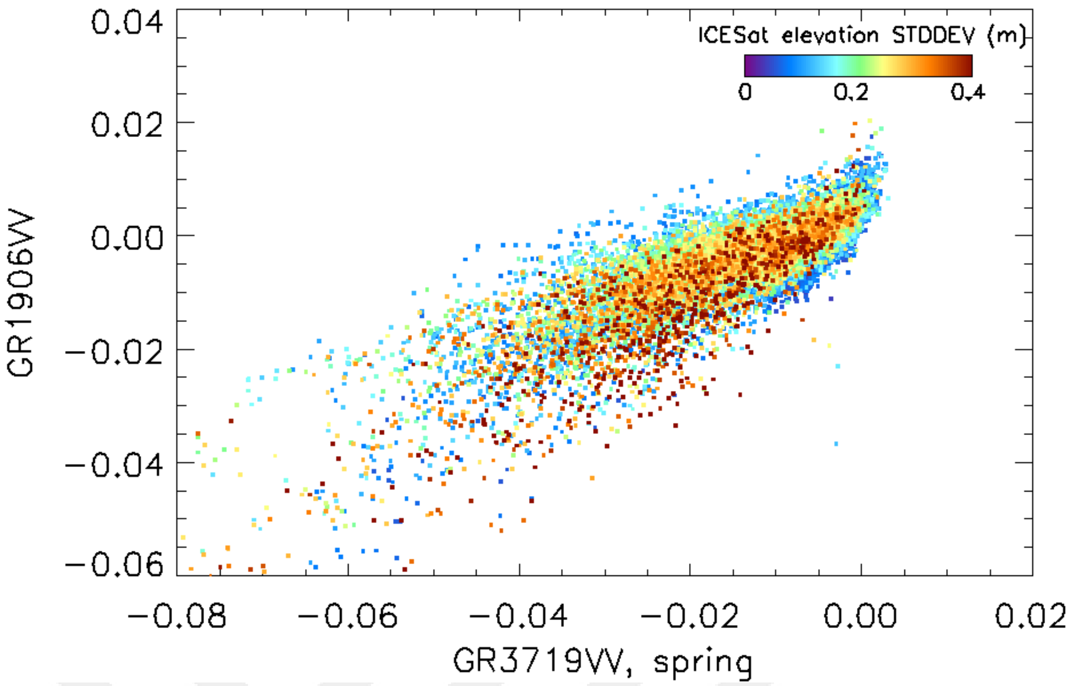
The overall purpose of this thesis was to construct a dataset of in-situ reference snow/ice data collocated with all relevant satellite data. Procedure followed was first establishing an overview of existing in-situ snow/ice data and designing supplementary experiments for compiling representative snow/ice time series. Existing data then compiled, processed and reformatted to match the needs in data analysis. Finally the in-situ data were collocated with available satellite data and weather data. The final dataset will be used in the future for development and validation of algorithms to derive snow/ice parameters from a suite of satellite data. General conclusion for method 1 is that the inter-comparison of ASPeCt ship based snow depth and ridged ice fraction co-located with ECMWF air-temperature and satellite snow depth and C-Band radar backscatter confirms: 1- AMSR-E over-estimates snow depth for rough ice, 2- AMSR-E under-estimates snow depth for warm conditions, 3- ASPeCt might under-estimate large-scale snow depth for level ice due to preferential sampling over thin ice, 4- ASPeCt ridged ice fraction seems not to be correlated with ASCAT C-Band radar backscatter. General conclusion of method 2 is that the comparison of data from National Snow and Ice Data Center (NSIDC), SICCI-UB, and a first Markus et al. (2011) algorithm snow depth with ICESat residual elevation and surface roughness have significant correlations with pure data, with ECMWF 2m air temperature, with radar backscatter, with various Gradient Ratios.

More needs to be performed to have more elaborating the idea of the Space-borne Observations for Detecting and Forecasting sea Ice Cover Extremes. Therefore, this thesis suggests;

- Performing the analysis with the full co-located ICESat – AMSR-E – ASCAT – ECMWF data set being now available.

- Identifying and discarding potential outliers to reduce potentially wrong cases with large surface roughness paired with small residual elevation
- Comparing AMSR-E snow depth and ICESat roughness with other ECMWF parameters, e.g. snow accumulation
- Understanding potential & limitations of the Markus et al. (2011) approach.
- Investigating potential relationships between ICESat roughness and AMSR-E TBs & derived parameters, such as GR3719 or GR1906 (see figure 5.1)




ICESat elevation STDDEV (m)
0
0.2
0.4
0.04
0.02
0.00
−0.02
−0.04
−0.06
GR1906VV
−0.08
−0.06
−0.04
−0.02
0.00
0.02
GR3719VV, spring

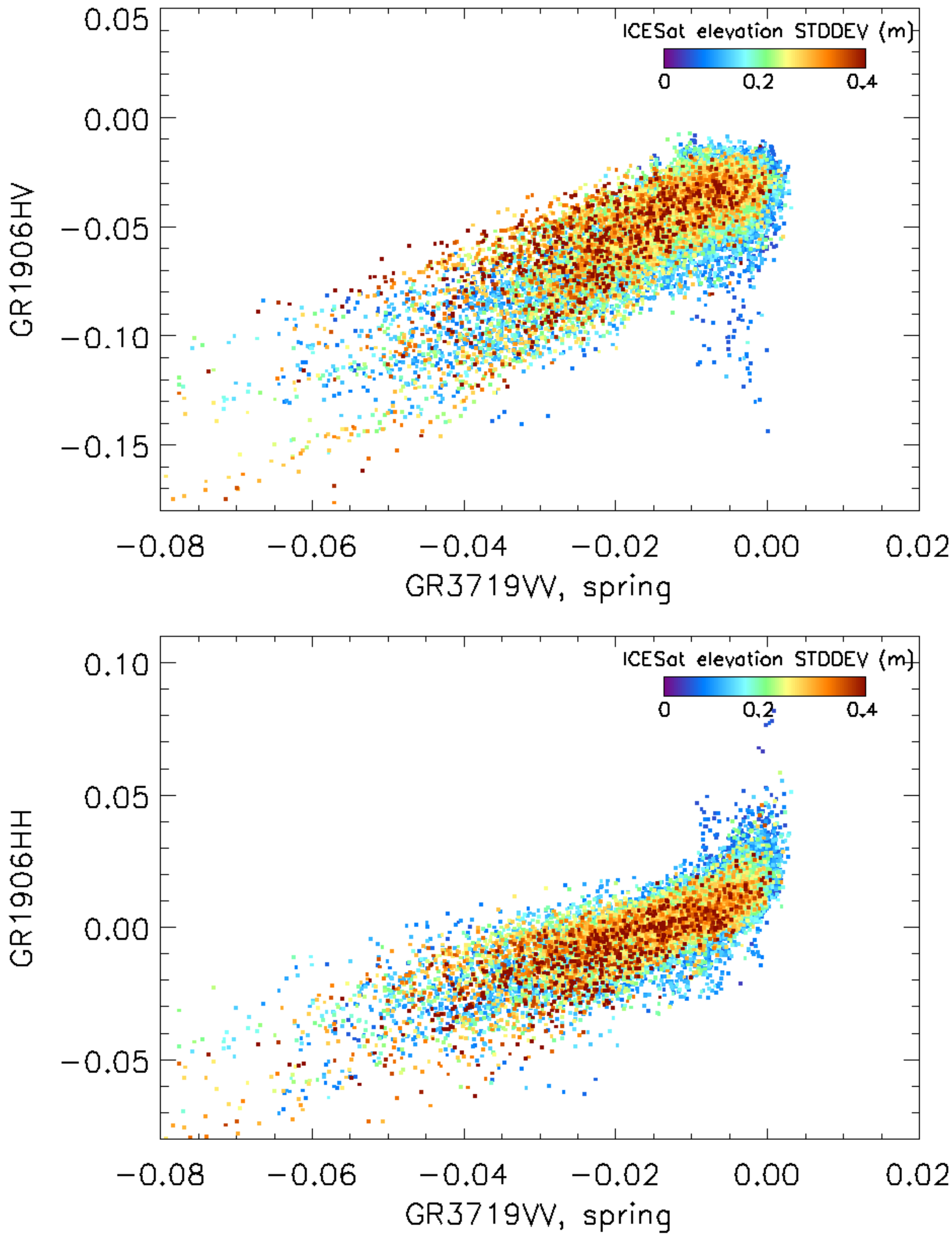


Figure 5.1 : Relating different GRs associated with ICESat roughness (top to bottom).

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