A Multidecadal Study of the Number of Antarctic Icebergs Using Scatterometer Data

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Abstract

Studying the size, frequency, and position of Antarctic icebergs helps us understand climatic changes of the Earth's frozen continent. Antarctic icebergs are regularly formed by the separation of massive sections of ice from ice shelves and glaciers. The National Ice Center (NIC) plays a major role in iceberg analysis and forecasting. The NIC uses a variety of satellite sensors to track large Antarctic icebergs and reports iceberg positions approximately every 15-20 days.

There are limitations to the NIC's iceberg tracking technique. The area covered by the images used by the NIC is limited to specific Antarctic regions due to resources required to produce and process these high resolution images. According to the NIC, the number of large Antarctic icebergs has been increasing in recent years. This increase in iceberg activity may be a result of a climatic trend, or may be an artifact of better detection techniques. A long term analysis of Antarctic iceberg activity based on scatterometer and radiometer data is presented. Our analysis suggests this increase is largely due to improved resources and technological advancements for iceberg tracking. As part of the long-term analysis, we analyze several major iceberg calving events that have taken place in recent years. These calving events most likely represent natural variability in iceberg activity. This study identifies the advantages and limitations of tracking icebergs using scatterometer data.

1 Introduction

Above average temperatures during the Antarctic summer months create water filled crevasses that cause ice fractures in ice shelves and glaciers. Icebergs are then formed when stress from winds and tides cause sections of ice to break from the ice shelves or glaciers. Several Antarctic ice shelves are experiencing major retreats as a result of several major calving events.

The National Ice Center (NIC) provides sea ice analysis and forecasts to meet U.S. national interests. The NIC is using a variety of satellite sensors to track and monitor Antarctic icebergs depending on their size and position. The instruments used by the NIC include an infrared Imager, a radiometer, and a SAR. The NIC also obtains iceberg positions provided by the Microwave Earth Remote Sensing (MERS) lab at the Brigham Young University. The average size of the icebergs is approximately 441 square nautical miles while some have reached as high as 3,155 square nautical miles. These large icebergs tracked at the NIC make up the vast majority of fresh water ice coming from the Antarctic continent.

Significant increases in the number of icebergs are reported by the NIC over the last 25 years. The increase is partly due to large iceberg calving events that have taken place in recent years. However, the long-term increase can be attributed to improved resources for iceberg tracking due to technological advancements. In addition, there are limitations in the NIC iceberg tracking method. Due to the high resolution of the images used by NIC, the coverage area is restricted to specific regions of the Antarctic continent. Also, due to the extensive resources needed to track icebergs, the NIC only reports an iceberg position every 15-20 days.

In order to evaluate the NIC's data and independently monitor iceberg activity, BYU utilizes scatterometer and radiometer data to track Antarctic icebergs for segments of time over the last 25 years. Data sets from five different spaceborne scatterometer and radiometer instruments are used in the study. Icebergs are tracked with each data set for various time periods from 1978 to 1999. The images provide coverage of the entire Antarctic continent and allow iceberg positions to be recorded every 1-5 days. These results are analyzed to determine the validity of the reported trend in the number of icebergs over the last 25 years. This study also identifies the advantages and disadvantages of tracking and monitoring icebergs with methods used at the NIC and methods used at BYU.

2 Ice Shelf Breakups

Scientific studies indicate that above-average surface temperatures over a period of a few months in the Antarctic can splinter an ice shelf and instigate a collapse [1]. Using satellite observations of melted water on the ice surface and computer simulations, scientists have demonstrated that crevasses when filled with water can crack entirely through. These crevasses are initially formed as glacial ice flows seaward. Water-filled crevasses that are 15-50 feet (5-15 meters) deep can fracture a 220 yard (200 meter) thick ice shelf. It has been theorized that the ice shelf is then held together by bridges between crevasses until a combination of winds tides, and another season of melting lead to breakup.

Mean summer temperatures play a crucial role in the creation of melt water on the ice surface. Although some areas of the Antarctic have warmed by 2.5 degrees Celsius over the last 50 years [2], few records have been kept of seasonal temperatures over the ice shelves. Data from the NIC seen in Figure 1 suggests that most icebergs created due to ice shelf breakups occur during the summer (JD300-JD100). This plot assumes that the first reported sightings and the birth of the iceberg occur approximately at the same time.

Many ice shelves have experienced or are expected to experience major retreats. The Larsen Ice Shelf on the Antarctic Peninsula has gone through major retreats in 1995 and 1998. Over 775 square miles (2000 square kilometers) of the northern section of this ice shelf disintegrated in 1995 during a major storm. The melt season during this retreat was over 80 days long, about 20 days longer than average. The Ross Ice Shelf in the past has generally been stable. However, within the last year the Ross ice shelf has experienced some major

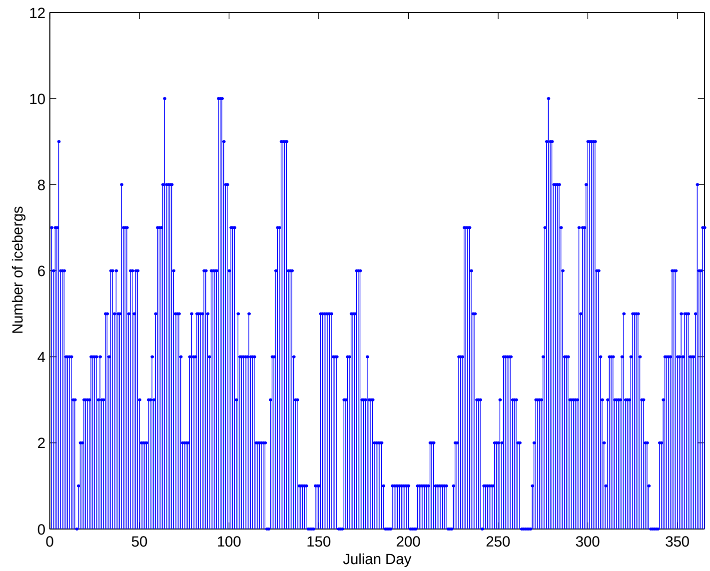


Figure 1: *A distribution of when icebergs were first reported by the NIC during the year.*

calving events. While periodic calving events are expected, some scientists theorize that excessive breaking-up of ice shelves could lead to a rise in sea level. The temporal monitoring of rather large Antarctic icebergs provides scientist with a valuable tool for determining the rate of ice shelf breakups.

3 National Ice Center Tracks Icebergs

The National Ice Center is a multi-agency operational center representing the Department of Defense (Navy), the Department of Commerce's National Oceanic and Atmospheric Administration (NOAA), and the Department of Transportation (Coast Guard). The NIC's mission is to provide high quality sea ice analysis and forecasts designed to meet the requirements of U.S. national interests.

Antarctic icebergs must meet three basic requirements before it is tracked by the NIC. First, the iceberg must measure at least 10 nautical miles along the long axis. Second, the most recent sighting of the iceberg must have occurred within the last 30 calendar days. If it is not sighted within 30 calendar days, it is removed from the NIC's list of current icebergs. The third requirement is that the iceberg must be located below 60 degrees south latitude. There are certain exceptions to these requirements. An iceberg may be kept in the current iceberg tracking database although it has not been sighted for more than 30 days when it is grounded or locked in sea ice. Also the NIC continues to track an iceberg until it breaks up below the resolution of satellite imagery if the iceberg's original size was 10 nm or greater before its breakup.

Iceberg names given by the NIC are determined according to the Antarctic quadrant in which they were originally sighted. Quadrant A is from 0-90 degrees west longitude.

Quadrant B is located between 90 degrees and 180 degrees west longitude. Quadrant C ranges from 180-90 degrees east longitude. Quadrant D is if from 90 degrees East to zero degrees east longitude. The letter of the quadrant along with a number is assigned to each iceberg tracked. For example, iceberg B4 is the fourth iceberg identified in quadrant B. If this iceberg breaks up into separate icebergs they are named B4A, B4B, and B4C etc.

A distribution of the sizes of the Antarctic icebergs reported by the NIC since 1976 is shown in Figure 2. Most of the icebergs tracked by the NIC range in size from 50 to 600 square nautical miles. The average size of the icebergs tracked by the NIC is just over 441 square nautical miles. The largest iceberg ever reported was iceberg B15 which was 3,155 square nautical miles and was first reported in March of 2000. It is assumed that due to their tremendous size, icebergs make up the vast majority of the glacial ice coming from the Antarctic continent.

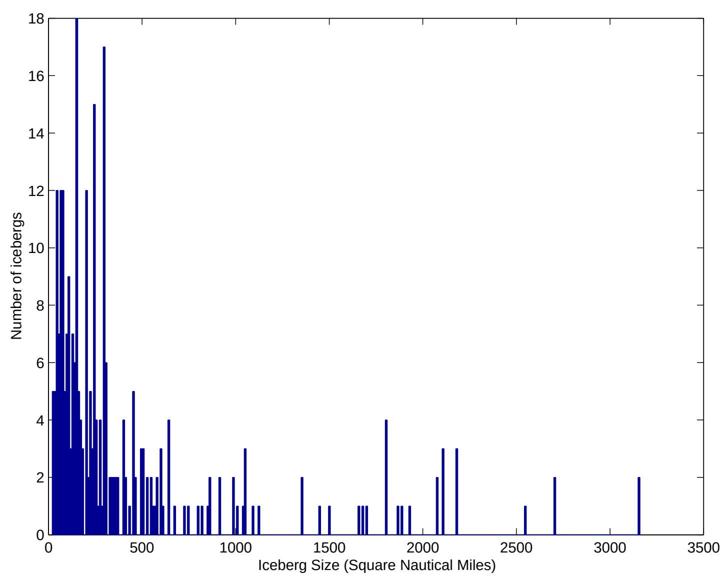


Figure 2: *Distribution of the sizes of the Antarctic icebergs as reported by the NIC.*

The NIC uses a variety of methods for tracking and monitoring Antarctic icebergs. The most commonly used instrument is the Defense Meteorological Satellite Program (DMSP) F13 satellite. The DMSP F13 satellite is in a near circular, sun synchronous, polar orbit. This satellite provides global visible and infrared images of the earth with its Operational Linescan System (OLS). Figure 3a shows an image of the iceberg B10A through clouds using DMSP OLS infrared imagery from F13 on Julian day 238, 1999. The satellite measures data at a 0.56 km resolution, which is averaged on board the satellite to produce global coverage at 2.7 km resolution. A key limitation to using the DMSP instrument is the obstruction in visibility due to the local cloud cover. Due to this limitation, iceberg B10A was lost to the NIC and later located using scatterometer images produced by BYU. The OLS images offer relatively high resolution but low coverage area due to a small swath and image processing.

The Advanced Very High Resolution Radiometer (AVHRR), mounted on board NOAA meteorological satellites is also used by the NIC to track Antarctic icebergs. The AVHRR operates in the visible, infrared, and thermal spectrum with a resolution of 1.1 km. Figure 3c shows an AVHRR image of icebergs B10A and A22B. The advantages and limitations of using AVHRR images to track Antarctic icebergs are similar to the advantages and limitations of the DMSP OLS. These images have a relatively high resolution but local cloud cover obscures the visibility of the icebergs.

The NIC also currently obtains iceberg positions provided by the MERS lab at BYU. The BYU MERS lab uses enhanced resolution images obtained from the SeaWinds scatterometer on board the satellite QSCAT. The MERS lab's method for tracking Antarctic icebergs is discussed in Section 3.2.

The NIC also infrequently tracks icebergs with SAR images from the RADARSAT instrument on board the Earth Observation (EO) satellite and ship-reported iceberg positions. A RADARSAT wide scan SAR B image of icebergs in the Weddell Sea is shown in Fig 3b. RADARSAT images are not restricted by the presence of clouds, fog, smoke, or darkness. These images have a very high resolution (from 8 to 100 meters) but limited coverage.

The time between reported iceberg positions for the NIC typically varies from 15 to 20 days. One reason for the long interval is due to the tremendous effort it takes to obtain images and locate icebergs. Another reason is because the relatively slow movement of many of the icebergs does not necessitate rapid daily iceberg tracking by the NIC.

Figure 4 shows the number of icebergs tracked by the NIC from 1976 to 2001. This figure also shows the number of icebergs tracked by the BYU MERS lab for different time periods. The icebergs tracked by the NIC in the late 1970's are sporadic and few, most likely due to the NIC's limited resources during this time period. During the early 1980's the number of icebergs tracked remains relatively constant (from 4 to 6).

During 1986-1987, the number of icebergs tracked by the NIC significantly increases to between 10-15. There may be several reasons for this sudden increase. The increase could be due to large sections of Antarctic ice shelves breaking off of the main ice shelf. Another reason may be the technological advancement involving more advanced computers and improved satellite instruments which provides better resources for tracking the icebergs. There also may have been an increase in the NIC's effort to track a larger number of icebergs during this time.

Between 1987-1996 the number of icebergs fluctuate and then there are significant jumps during late 1996, early 1999, and early 2000. The fluctuations are normal variations. The jumps in the number of icebergs are associated with large iceberg calving events from Antarctic ice shelves.

The majority of the Antarctic icebergs calve from the Ronne Ice Shelf, the Filchner Ice Shelf, the Larsen Ice Shelf, and the Ross Ice Shelf. As shown in Figure 5, the largest cluster of icebergs reported by the NIC have come from the Weddell Sea. These icebergs calved from either the Ronne Ice Shelf, Filchner Ice Shelf, or the Larsen Ice Shelf and then travel north between 20 degrees to 50 degrees west longitude along what has been named 'Iceberg Alley'. The second largest group of icebergs is located in the Ross Sea. These icebergs calve from the Ross Ice Shelf and travel west along the Antarctic coast being carried by an Antarctic coastal current. Many of these icebergs eventually reach the Weddell Sea and then travel north through the 'Iceberg Alley'. A few icebergs traveling west with the Antarctic coastal current turn north near 90 degrees east longitude, getting caught in the Antarctic

Circumpolar Current (ACC) and travel northeast. Other icebergs in the Ross Sea travel north until they are caught in the ACC and then they move east through the Drake Passage, ending up in 'Iceberg Alley'.

Most of the recent icebergs in the Ross Sea were first reported in 2000 due to several large calving events. Before this time, very few icebergs had been reported breaking from the Ross Ice Shelf.

4 Tracking Icebergs at BYU

As shown in Figure 4, the number of icebergs reported by the NIC has gradually been increasing for the last 25 years. However, this rise in the number of icebergs may primarily be an artifact of increasingly better iceberg-identification and tracking techniques. In order to evaluate the NIC's data and independently monitor iceberg activity, BYU utilizes scatterometer and radiometer data to track Antarctic icebergs for various segments of time over the last 25 years.

Data sets from five different spaceborne scatterometer and radiometer instruments are used in the study. For each data set resolution enhancement is performed by BYU's Scatterometer Image Reconstruction (SIR) and SIR Filtering (SIRF) algorithms. The SIRF algorithm provides enhanced-resolution scatterometer and radiometer images by combining data from multiple overlapping passes of the satellite.

The scatterometer instruments used in this study are the Seasat-A Satellite Scatterometer (SASS), the European Space Agency's Remote Sensing Satellite 1(2) (ERS1(2)), the NASA Scatterometer (NSCAT), and the QuikSCAT/SeaWinds scatterometer (QSCAT). In addition to the use of scatterometers, the Special Sensor Microwave/Imager (SSM/I), a microwave radiometer, is utilized. Table 1 provides information on the number of days of data used per image, the polarization used, the resolution in kilometers per pixel, and the frequency band used for each instrument. Although these images are "enhanced resolution", varying from 8-25 km, they still have a much lower resolution than many of the other instruments used by the NIC.

Table 1: *Information for sensors used to track Antarctic icebergs.*

Sensor	Days/image	polarization	km/pix	Freq
SASS	23	h-pol	4.45	Ku-Band
ERS2	5	v-pol	8.9	C-Band
NSCAT	5	h-pol	4.45	Ku-Band
SSM/I	1	h-pol	8.9	19.35 GHz
QSCAT(egg)	1	h-pol	4.45	Ku-Band

With resolution-enhanced images, distinct features of the Antarctic continent can be seen. Figure 6 and 7 show enhanced-resolution images of the Antarctic continent and the Weddell Sea from the five different sensors mentioned. Sea ice, ice shelves, and land features can be clearly distinguished as measurement values vary across the Earth's surface. Large Antarctic icebergs are identified as objects of contrasting measurement values against the surrounding ocean or sea ice. Although each instrument provides a slightly different resolution, icebergs are clearly visible in all images. Figure 8 shows images of different icebergs from QSCAT and ERS1.

Icebergs are tracked with each data set for various time periods from 1976 to 1999. Animated movies are created for each time period monitored. These movies are used to manually identify and track icebergs found in the Antarctic region. An iceberg is first identified if it is clearly distinguishable from land or ice shelves and if it passes either of two criteria. First, icebergs are identified if they are located in the same positions as indicated by the NIC. Second, icebergs are identified when they were not indicated by the NIC but the iceberg is clearly distinguishable and motion is detected. A few icebergs are additionally identified where they were not reported by the NIC and motion was not detected. In these cases the icebergs were clearly not a part of any land feature or ice shelf. The icebergs tracked at BYU versus icebergs reported by the NIC are shown in Table 2 and Table 3.

Table 2: *Icebergs Tracked at BYU vs. Icebergs Reported by the NIC.*

1978 JD188-281		1992 JD001-365		1994 JD022-365		1996 JD001-126		1996 JD259-365	
NIC	SASS	NIC	ERS1	NIC	ERS1	NIC	ERS1	NIC	ERS2
A1	SA1=A1	A22	E1=A22	A27		A27		A27	
A2	SA2=A2	A28	E2=A28	A33		A22A	E1=A22A	A34	
	SA3	A29	E3=A29	A22A	E1=A22A	A22B	E2=A22B	A35	E1=A35
	SA4	A31	E4=A31	A22B	E2=A22B	A23A	E3=A23A	A22A	E2=A22A
	SA5	A23A	E5=A23A	A23A	E3=A23A	A23B	E4=A23B	A22B	E3=A22B
	SA6	A23B	E6=A23B	A23B	E4=A23B	B9A	E5=B9A	A23A	E4=A23A
	SA7	A24A		B10	E5=B10	B9B	E6=B9B	A23B	E5=A23B
	SA8=B1	A24B		B9A	E6=B9A	B10A	E7=B10A	B9A	E6=B9A
	SA9=C2	A24C		B9B	E7=B9B	B10B	E8=B10B	B9B	E7=B9B
	SA10	A24D		C5	E8=C5	C8	E9=C8	B10A	E8=B10A
	SA11=D2	B10	E7=B10		E9=C10	C9		B10B	E9=B10B
	SA12=D3	B7B	E8=B7B		E10	D10		C8	E10=C8
	SA13	B9A	E9=B9A		E11		E10=C10	C9	
		B9B	E10=B9B				E11=D11	C10	E11=C10
		C5					E12	D11	E12=D11
		C6	E11=C6						E13=D10
		C7	E12=C7						E14
			E13=C10						E15
			E14						
			E15						
			E16						
			E17						
			E18						
			E19						
Total: 2	13	17	19	10	11	12	12	15	15

Although motion plays a critical role in identifying icebergs, some icebergs are identified when there is no detectable motion during some or all of the tracking period. Table 4 lists icebergs tracked at BYU from 1978-1999 which had no discernable movement at some point during the observation period. None of the icebergs displayed any motion during their initial tracking period, suggesting that they were grounded before being tracked by BYU. About two-thirds of the icebergs shown in the Table 4 never displayed any discernable movement during the entire tracking period. A third of the icebergs showed no movement during the first few tracking periods and then eventually showed some movement during the last tracking periods. From Table 4, we see that icebergs showing no movement (grounded) make up a large percentage of the total number of icebergs.

Table 3: *Icebergs Tracked at BYU vs. Icebergs Reported by the NIC.*

1996 JD259-365		1998 JD001-365		1999 JD200-365		1999 JD190-352		1999 JD202-365	
NIC	NSCAT	NIC	ERS2	NIC	ERS2	NIC	SSM/I	NIC	QSCAT
A27	N1=A27	A027		A27		A27		A27	Q1=A27
A34		A36	E1=A36	A39		A39		A39	Q2=A39
A35	N2=A35	A37		A41		A41		A41	
A22A	N3=A22A	A39	E2=A39	A22A	E1=A22A	A22A	S1=A22A	A22A	Q3=A22A
A22B	N4=A22B	A22A	E3=A22A	A22B	E2=A22B	A22B	S2=A22B	A22B	Q4=A22B
A23A	N5=A23A	A22B	E4=A22B	A22C	E3=A22C	A22C	S3=A22C	A22C	Q5=A22C
A23B	N6=A23B	A22C	E5=A22C	A23A	E4=A23A	A23A	S4=A23A	A23A	Q6=A23A
B9A	N7=B9A	A23A	E6=A23A	A35A	E5=A35A	A35A	S5=A35A	A35A	Q7=A35A
B9B	N8=B9B	A23B	E7=A23B	A35B	E6=A35B	A35B		A35B	Q8=A35B
B10A	N9=B10A	A35A	E8=A35A	A35C		A35C		A35C	Q9=A35C
B10B	N10=B10B	A35B		A38A	E7=A38A	A38A	S6=A38A	A38A	Q10=A38A
C8	N11=C8	A35C		A38B	E8=A38B	A38B	S7=A38B	A38B	Q11=A38B
C9	N12=C9	A38A	E9=A38A	A38D		A38D		A38D	
C10	N13=C10	A38B	E10=A38B	A40A		A40A		A40A	Q12=A40A
D11	N14=D11	A38C		B9A	E9=B9A	B9A	S8=B9A	B9A	Q13=B9A
	N15=D10	B9A	E11=B9A	B9B	E10=B9B	B9B	S9=B9B	B9B	Q14=B9B
	N16=D14	B9B	E12=B9B	B10A	E11=B10A	B10A	S10=B10A	B10A	Q15=B10A
	N17	B10A	E13=B10A	C8	E12=C8	C8	S11=C8	C8	Q16=C8
	N18	C8	E14=C8	C9		C9		C9	Q17=C9
	N19	C9		C10	E13=C10	C10	S12=C10	C10	Q18=C10
		C10	E15=C10	C11		C11		C11	Q19=C11
		C11	E16=C11	C12	E14=C12	C12		C12	Q20=C12
		C12		D11	E15=D11	D11	S13=D11	D11	Q21=D11
		D11	E17=D11		E16=A23B		S14		Q22=A23B
		D12	E18=D12		E17=D15		S15		Q23=D14
		D14			E18				Q24=D15
		D15	E19=D15		E19				Q25=B14
			E20		E20				
			E21		E21				
			E22		E22				
			E23		E23				
Total:15	19	27	23	23	23	23	15	23	25

4.1 The BYU Iceberg Database

Using five different satellite instruments, we have produced one of the longest Antarctic iceberg databases available. The BYU database includes icebergs identified during 1978 and icebergs from 1992 to the present. Many icebergs that were not tracked by the NIC are included in this database. For example, the NIC recorded only two icebergs in the Antarctic region in 1978 while BYU tracked 13 icebergs during this time.

There are several advantages to BYU's iceberg database. First, icebergs are reported every 1 to 5 days in BYU's iceberg database versus every 15 to 20 days in the NIC's database. Figure 10 shows the detailed path for two icebergs tracked by BYU. This figure displays the complicated motion through the oceans around Antarctica not evidenced in the NIC data. A comparison of reported iceberg position by the NIC and BYU can be seen in Figures 5 and 9 respectively. The higher temporal resolution provides information about the ocean currents that are primarily responsible for the iceberg's motion. It also gives more accurate and timely position measurements for mariners operating in the Antarctic regions. The second major advantage to BYU's iceberg database is the ability to extend the tracking of several icebergs beyond the NIC's range. For example, iceberg A35 was first reported by the NIC on Julian Day (JD) 347 in 1996 at latitude 75.4 South and longitude 29.6 West. However, A35's original position was reported by BYU on JD136 in 1994 at latitude 65.73 south and longitude 87.06 east. Iceberg A35 originated from the same iceberg as D11 and D12. Given

Table 4: *Icebergs tracked from 1978-1999 that had no discernable movement at some point during the observation period.*

NIC ID	1978 JD188-281	1992 (Ea) JD001-365	1994 (Eb) JD022-365	1996 (Ec) JD001-126	1996 JD259-365	1998 JD001-365	1999 JD190-352	1999 JD202-365
	SASS	ERS	ERS	ERS	NSCAT	ERS2	SSM/I	QSCAT
A23A	-	X	X	X	X	X	X	X
A22	-	X						
A22A	-	-	X	M	M	M	M	M
B9A	-	X	X	X	X	M	M	M
B9B	-	X	X	X	X	X	X	X
C2	X							
C5	-	X	M					
C8	-	-	-	X	X	X	X	X
C9	-	-	-	X	X	X	X	M
C10	-	X	X	X	X	X	X	X
C11	-	-	-	-	-	X	X	X
C12	-	-	-	-	-	X	X	X
D3	X							
D11	-	-	-	X	M	M	M	M
D14	-	-	-	-	X	X	X	X
D15	-	-	-	-	-	X	X	X
SA10	X							
Ea18	-	X						

X = No Movement Detected, M = Some Movement Detected

this evidence icebergs A35, D11, and D12 should have been named D11A, D11B, and D11C. As another example, iceberg B14 was first tracked by the NIC on JD005 in 2000 at latitude 67.1 south and longitude 178 west. With the help of ERS images, this same iceberg was tracked at BYU on JD265 in 1997 at latitude 74.11 south and longitude 130.21 west.

4.2 Number of Icebergs Tracked At BYU versus the NIC

There are distinct differences in the number of icebergs tracked at BYU versus the NIC. Figures 11 and 12 and Tables 2 and 3 show the icebergs tracked by BYU versus those tracked by the NIC. During 1992 the NIC tracked 17 icebergs while BYU tracked 19 icebergs. Many of the 1992 icebergs tracked by BYU are the same icebergs tracked by the NIC. Yet, seven icebergs are identified at BYU which are not identified by the NIC. Also, five icebergs identified by the NIC were not identified by BYU probably due to their small size. Each tracking period exhibits the same trend. The differences in the number of icebergs tracked are related to the advantages and limitations of the methods used. As addressed earlier, the NIC uses images with very high resolution. This allows them to track smaller icebergs than can't be tracked using the limited resolution scatterometer and radiometer images. Most of the icebergs detected by the NIC and not by BYU are of relatively small size. The disadvantage to using the NIC's high resolution images is the relatively low coverage area. Because of the low coverage the NIC generally only tracks icebergs in specific Antarctic regions. The scatterometer and radiometer images produced at BYU have a lower resolution but have a broad coverage area. Images by SSM/I and QSCAT provide daily coverage of the entire Antarctic continent and surrounding oceans. Broad coverage allows new icebergs to be located and monitored over a wider coverage area and with frequent (daily) coverage.

Another reason for the difference in the number of icebergs tracked between the NIC and BYU is related to the different types of images used. Figure 12 shows a comparison of the number of icebergs tracked by the NIC versus icebergs tracked by BYU using various radar instruments during 1996 and 1999. The number of icebergs monitored by the NIC and those tracked using the ERS images are very similar for both years as well as for most tracking periods. There are more icebergs observed using NSCAT and QSCAT images than any other method for both years. More icebergs are tracked because of the improved resolution of NSCAT and QSCAT over the ERS and SSM/I images and the broad coverage area for both NSCAT and QSCAT images. SSM/I images were not as useful and fewer icebergs were visible than other sensors used. Figure 11 shows a comparison for the number of icebergs tracked with different methods and for different tracking time periods.

Are the numbers of Antarctic icebergs increasing? Figure 4 shows the number of icebergs tracked over time by the NIC and at BYU. This plot shows the number of icebergs increasing for both the NIC and for BYU. It is interesting to note the difference in tracking numbers for BYU and the NIC. In 1978 the NIC tracked two icebergs while 13 icebergs were tracked by BYU. This difference may be due to the limited amount of resources available to the NIC at the time. During 1992, there is also a significant difference in the number of icebergs tracked. This may be due to the improved coverage capabilities of the sensors used at BYU versus the NIC. Since 1995 the number of icebergs tracked for both the NIC and BYU are very similar. This is due largely to BYU occasionally supplying iceberg tracking information to the NIC. The main increase in the number of icebergs from 1999 to 2001 is largely due to several large calving events from the Ronne and Ross Ice Shelves. Also, a greater number of icebergs are identified due to the improved resolution of images used and due to improved tracking techniques. Based on BYU's tracking the number of icebergs did not change significantly from 1978-1999. The number of icebergs being tracked has been increasing since 1999. However, the data is insufficient to determine whether this is a cyclic event or a long term increase. As technology improves, smaller icebergs will be included in the list of icebergs tracked.

5 Conclusion

The NIC plays a major role in sea ice analysis and forecasts. As a part of its mission the NIC is using a variety of satellite sensors to track many large Antarctic icebergs. The NIC uses images from an infrared Imager, a radiometer, and a SAR called RADARSAT. The NIC now obtains many of its iceberg positions from BYU due to BYU's efforts in recent years to track icebergs.

The number of icebergs tracked by the NIC has risen over the last 25 years. This increase is largely due to major iceberg calving events that have taken place in recent years. It is also due to improved resources for iceberg tracking and to technological advancements. However, there are limitations in the NIC's iceberg tracking techniques. The area covered by the image used by the NIC are limited to specific areas of the Antarctic continent. This limitation of low coverage is due to the large amount of resources required to produce these high resolution images. Because of the extensive amount of resources required to track icebergs the NIC reports iceberg positions every 15-20 days.

To evaluate the NIC's results and monitor iceberg activity, BYU is utilizing scatterometer and radiometer data to track Antarctic icebergs for different segments of time over the last 25 years. Five data sets from various instruments were chosen to be used in the study. Icebergs were tracked independently with each data set for time periods between 1976 to 2001. Each image used provided coverage of the entire Antarctic continent allowing frequent positions to be reported for each iceberg. We report an increasing trend in the number of visible icebergs over the last 20-25 years. However, this trend is only significant from 1999 to 2001 due to several major calving events during these years. From 1978-1998 the number of icebergs remains fairly constant although there is a significant data gap from 198 to 1992. Whether this recent increasing trend represents a natural variability in the number of icebergs or a long term increase is unknown. More data is needed to determine the exact cause.

This study has shown the advantages and limitations of tracking icebergs with methods used by the NIC versus methods used at BYU. Our increased ability to observe and track the formation of large Antarctic icebergs using remote satellite sensors has contributed significantly to our awareness in icebergs formed in Antarctica.

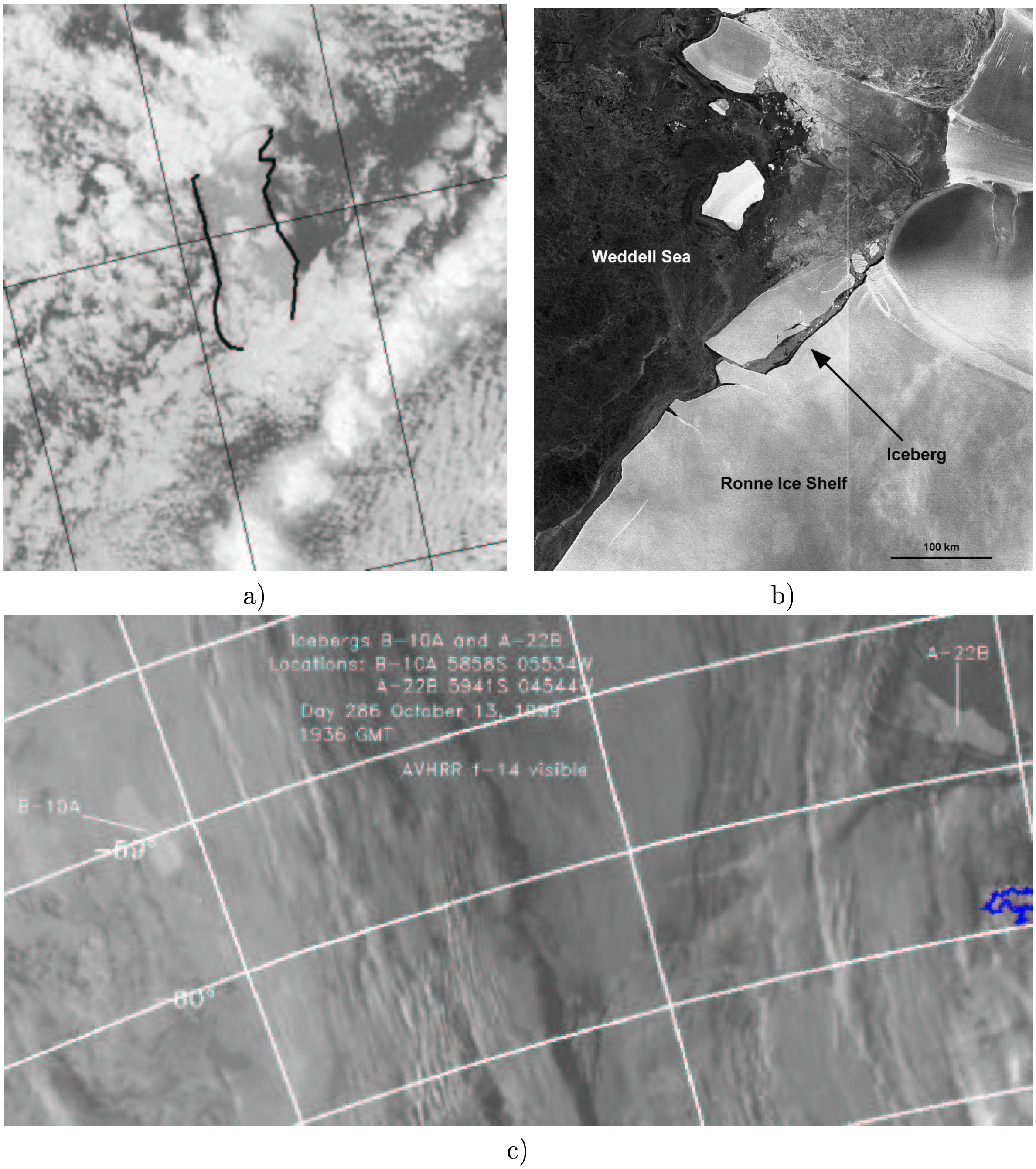


Figure 3: *Iceberg images: a) Outline of B10A through clouds using DMSP OLS infrared imagery from F13 (Julian Day 238, 1999). b) RADARSAT Wide ScanSAR B image of icebergs in the Weddell Sea, acquired on October 20, 1998. c) AVHRR image of B10A and A22B (Julian Day 286, 1999).*

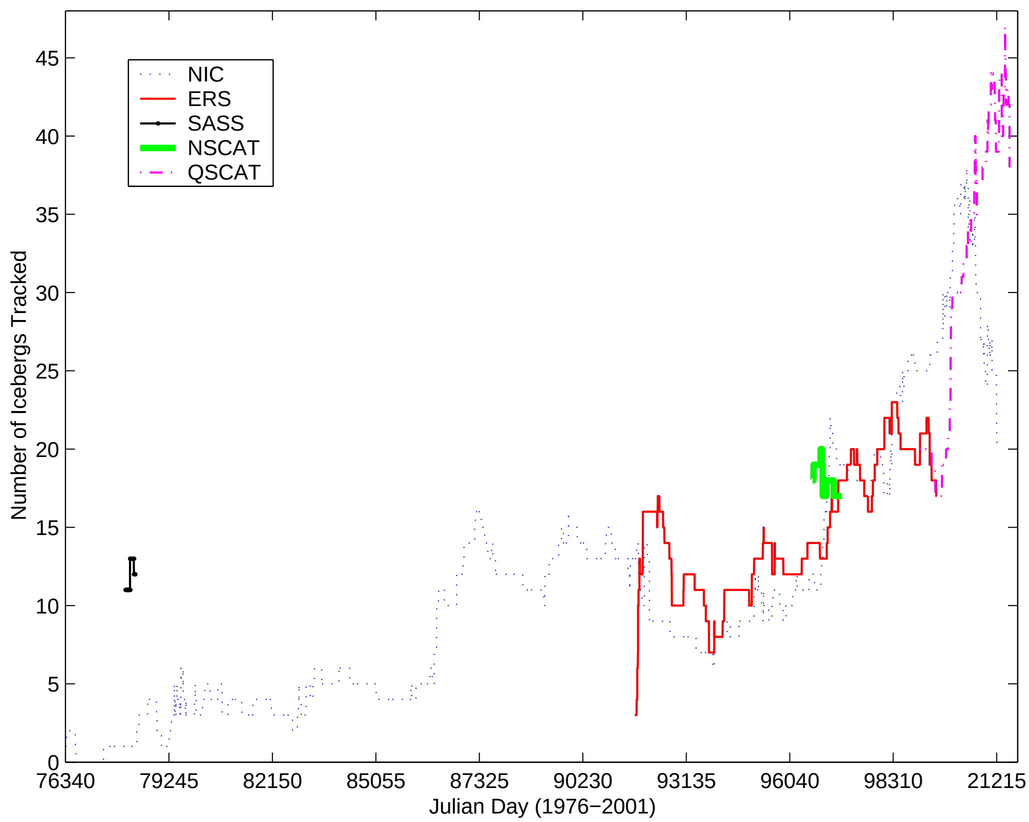


Figure 4: *Number of icebergs tracked over time.*

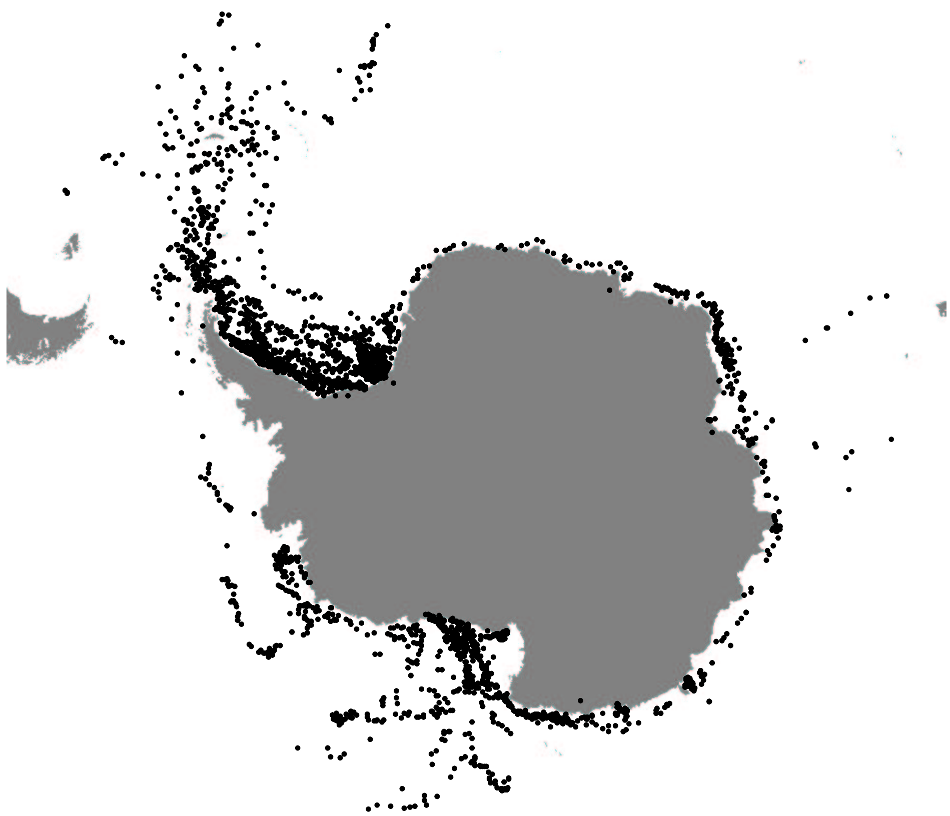


Figure 5: *All positions reported for all icebergs tracked by the NIC (1978-2001), shown as black dots.*

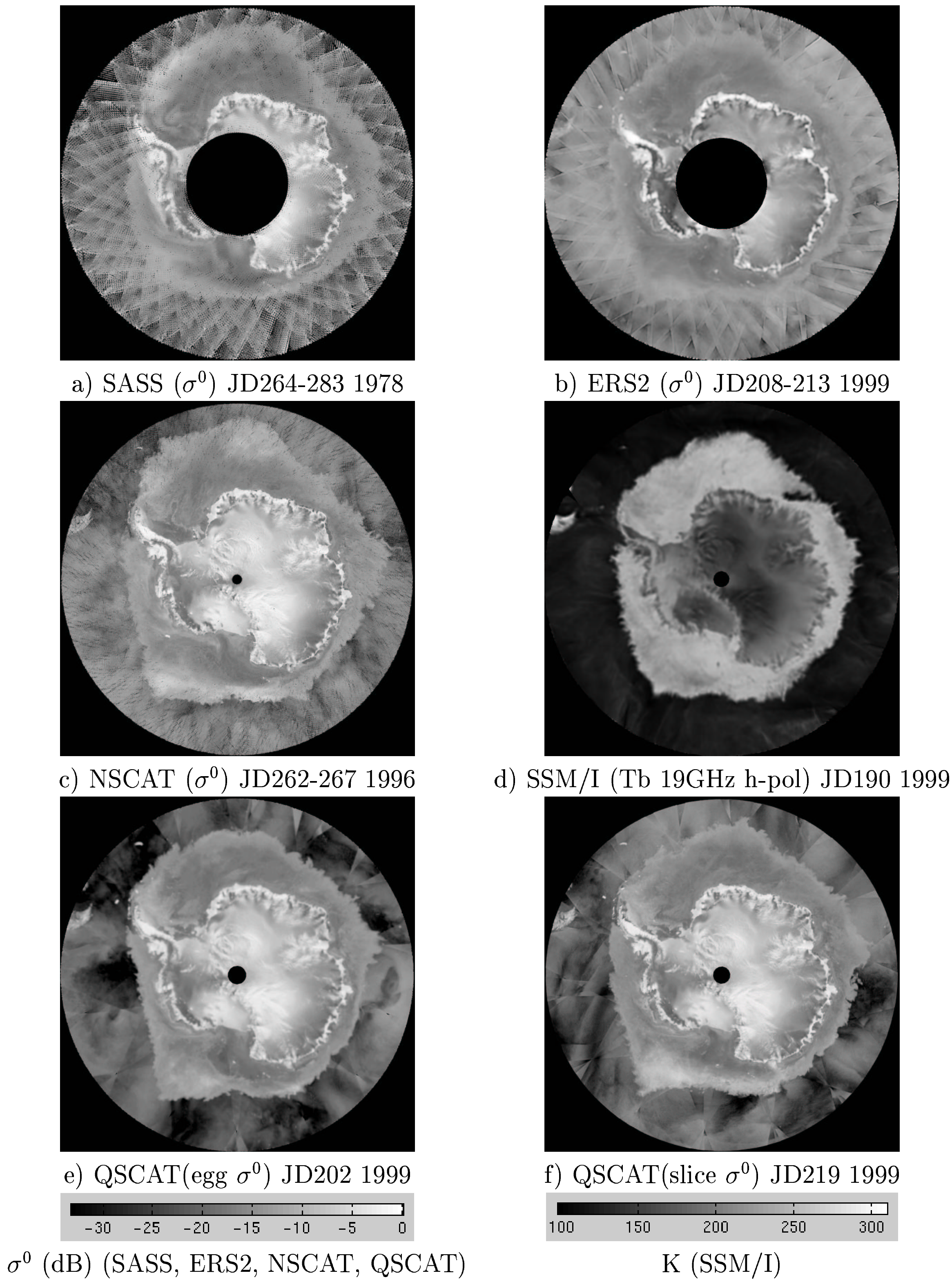
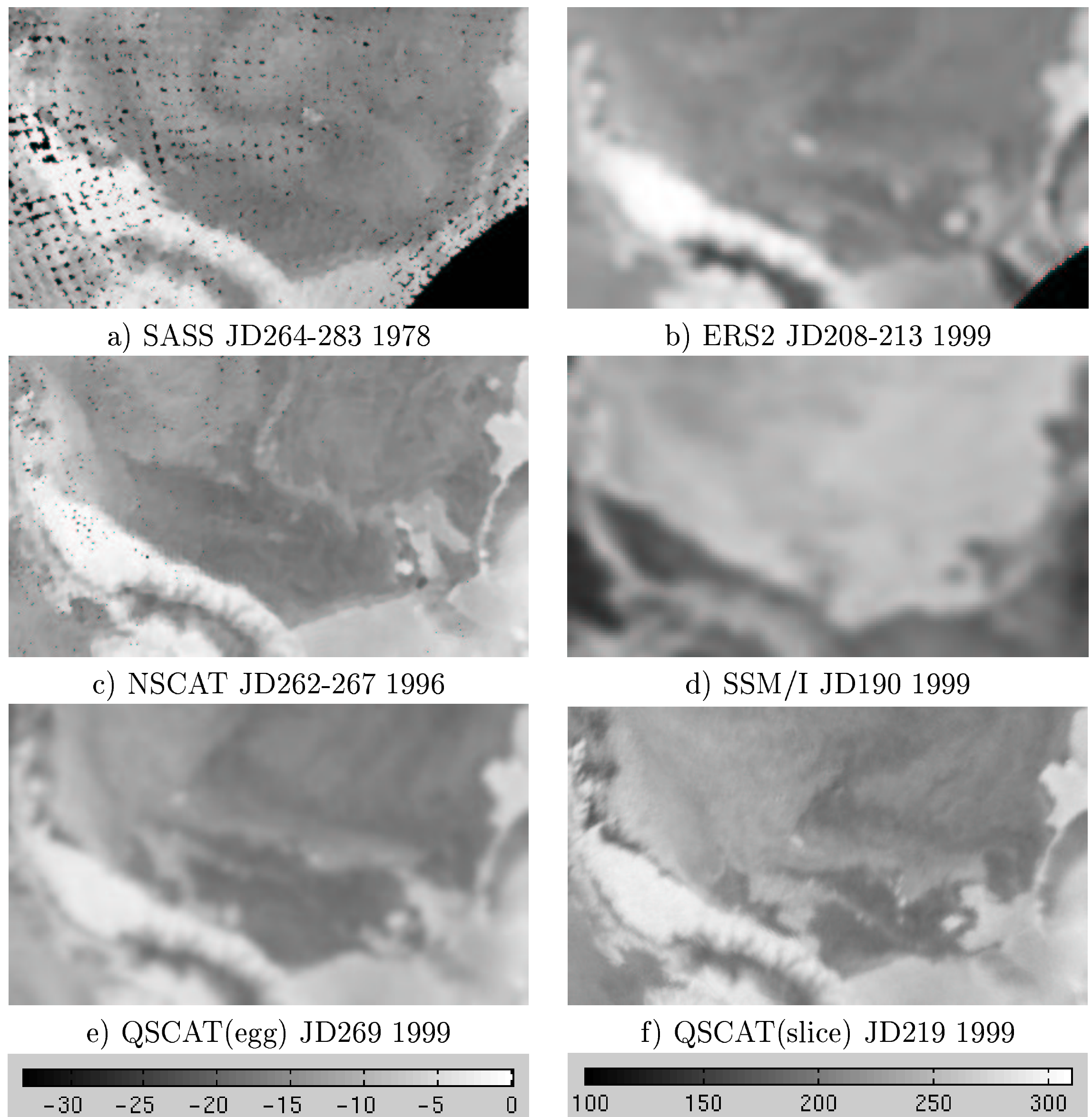


Figure 6: *Enhanced resolution images of Antarctica for various sensors (See Table 1 for details).*



a) SASS JD264-283 1978

b) ERS2 JD208-213 1999

c) NSCAT JD262-267 1996

d) SSM/I JD190 1999

e) QSCAT(egg) JD269 1999

f) QSCAT(slice) JD219 1999

σ^0 (dB) (SASS, ERS2, NSCAT, QSCAT)

K (SSM/I)

Figure 7: *Enhanced resolution images of the Weddell Sea for various sensors (See Table 1 for details).*

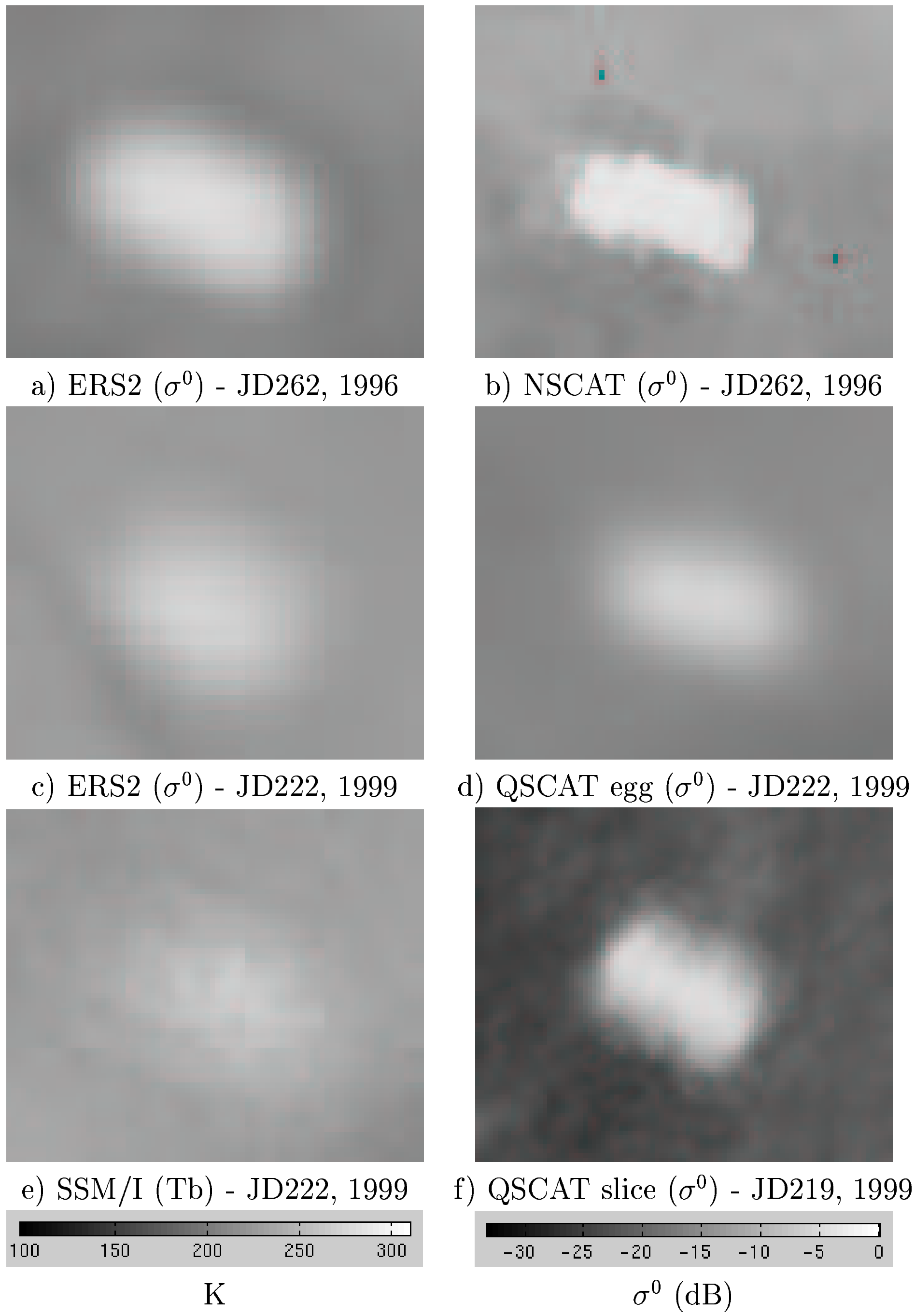


Figure 8: *Images of Iceberg B10A for Different Sensors.*

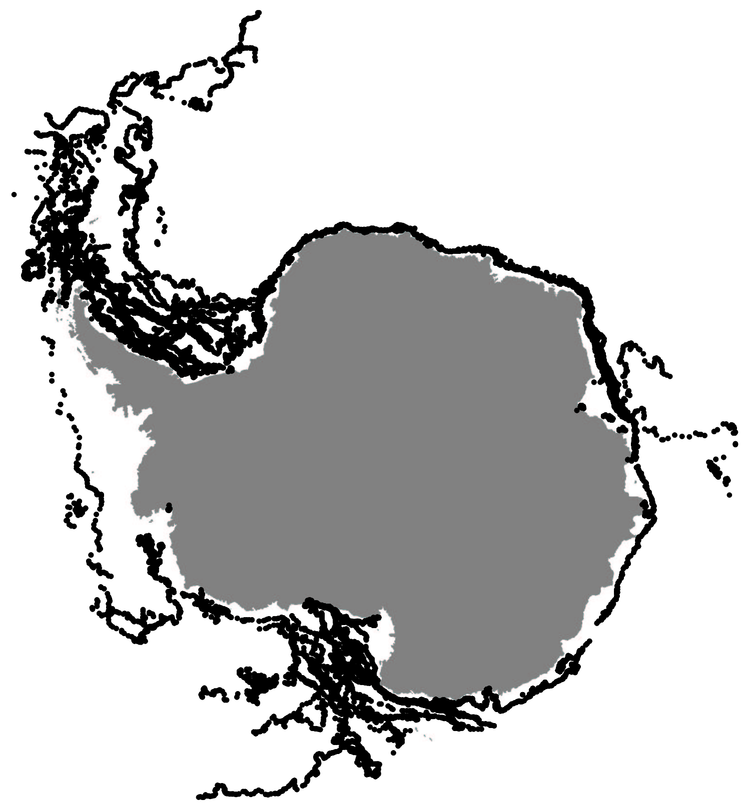
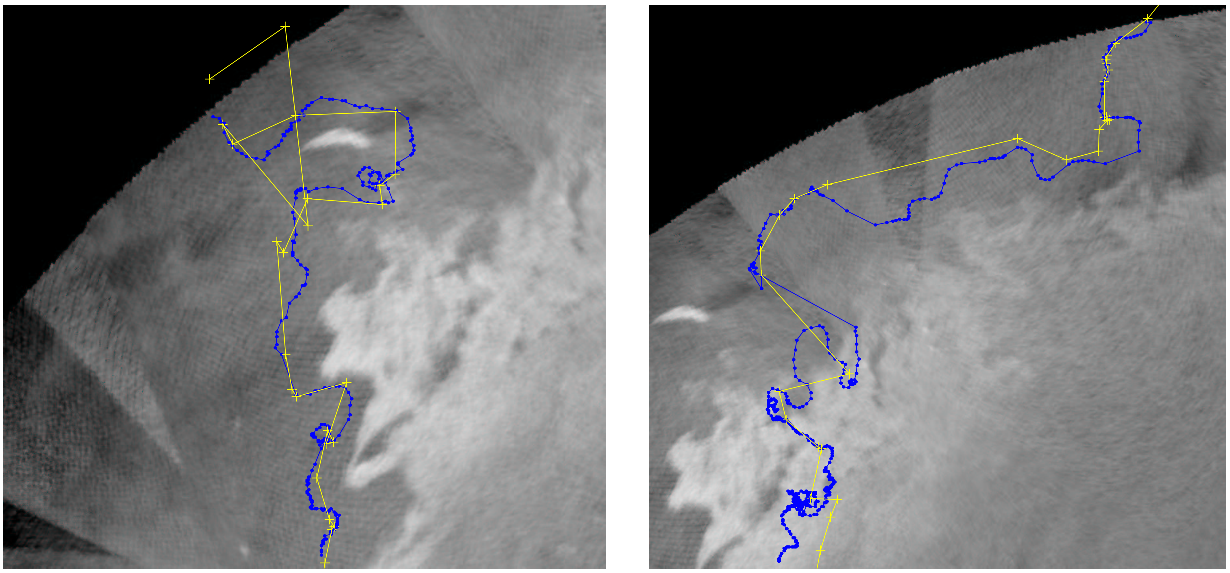


Figure 9: *All positions reported for all icebergs tracked by BYU (1978,1992-2001), shown as black dots.*



a) A22B b) A22C

Figure 10: *Tracks of two icebergs overlaying QSCAT images (BYU vs. the NIC).*

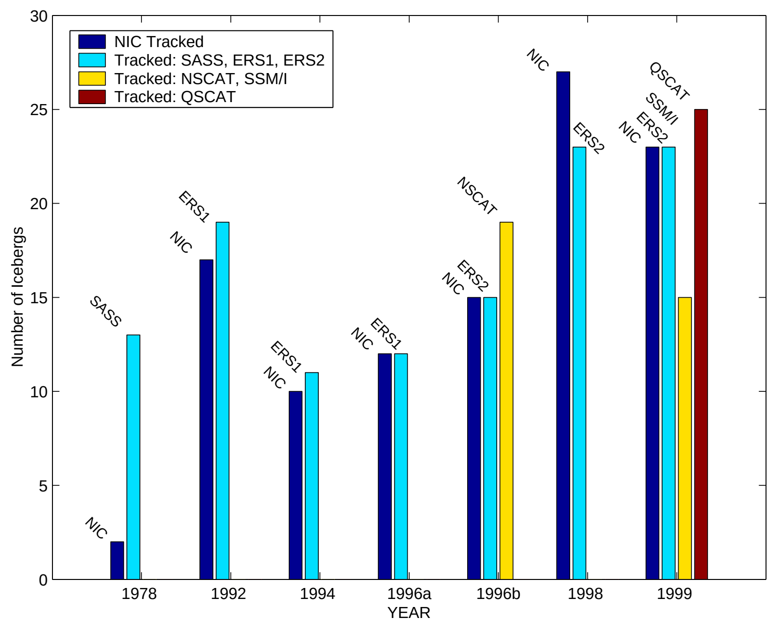


Figure 11: *Number of icebergs tracked at BYU vs. NIC.*

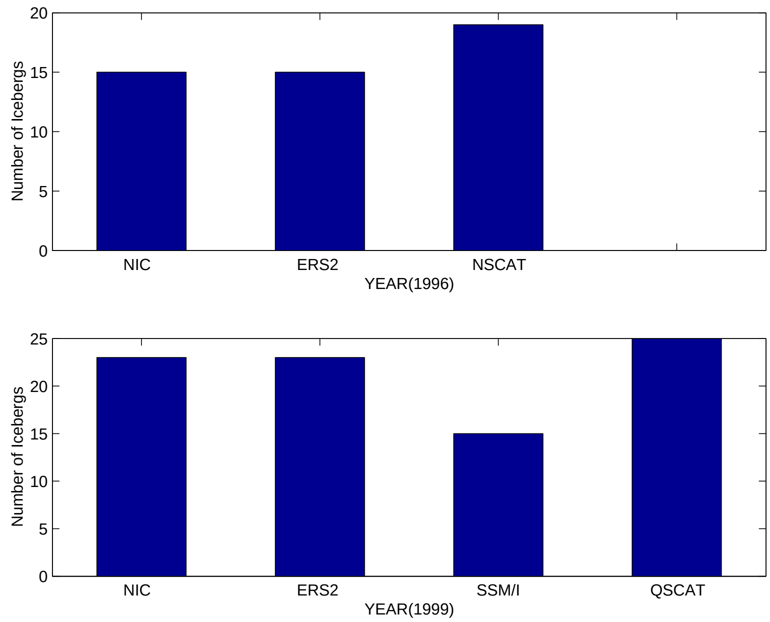


Figure 12: *A comparison of the number of icebergs tracked at NIC vs. icebergs tracked at BYU using various radar instruments during two different years.*

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