Reduction and Loss of an Ice Shelf in Elizabeth City State University Bay, Antarctica: 1972 - 2003

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Abstract—**Gradual reduction of a small ice shelf in the Pine Island Bay area is measured using eleven Landsat images spanning 1972 to 2003. Measurements of Ice shelf area indicate that it expanded slightly during the first two decades of observations from approximately 6.19 km^2 measured on December 7, 1972 to a maximum of about 6.82 km^2 observed in 1986. This maximum was followed by a nearly continuous decrease in area and ultimate disappearance of the ice shelf by January 17, 2003. No ice shelf has reappeared since 2003 as observed in subsequent Landsat images. Ten of the eleven Landsat images were co-registered and warped to one of a pair of 2003 geographic reference images before area measurement. Individual study team members made independent measurements of the ice shelf area apparent in each image. The average of these measurements had a standard deviation of 0.14 km^2.**

The specific cause of this ice shelf disappearance is unknown, but is probably related to increased basal melting by warmer ocean waters reaching Pine Island Bay. Intrusions of warm 'Circumpolar Deep Water' are related to ice shelf and outlet glacier thinning and retreat as reported throughout the Amundsen Sea region. This is the first report of complete ice shelf loss so far south or in the Amundsen Bay region. This small, previously unnamed ice shelf formerly occupied what is now known as the *Elizabeth City State University Bay*.

Keywords-ENVI;ice shelf; Antarctica; grounding line; Landsat

I. Introduction

Observed changes in the Antarctic ice sheet cause concern that accelerated ice loss will increase stress on Earth's coastal regions through more rapid sea level rise. Observed ice losses are strongly concentrated in coastal regions of the ice sheet, in general, and in the Antarctic Peninsula and the Amundsen Sea regions, in particular [1]. Ice shelves are the floating extensions of grounded Antarctic outlet glaciers and are directly involved in retaining the ice sheet and moderating the rate of grounded ice discharge [2, 3]. Whereas ice shelves are non-seasonal extensions of grounded ice sheets, sea ice is an essentially unrelated seasonal phenomenon. In the Antarctic Peninsula (Figure 1), the sudden disintegration of entire ice shelves has initiated large ice mass losses and sustained accelerations of the glaciers feeding those former ice shelves [4, 5, 6]. In the Amundsen Sea region (Figure 1), ice shelf thinning has been reported along with changes in the marginal character of the ice shelves, but not complete ice shelf loss [7]. This paper reports the first loss of an entire ice shelf well south of the Antarctic Peninsula.

The approximately 40-year compilation of Landsat Antarctic coastline observations provide a detailed record of long-term and potentially climate related changes along the ice sheet's margin. The recent development of two Landsat related products of the International Polar Year (IPY) set the stage for this study. The first is the Landsat Image Mosaic of Antarctica (LIMA) [8]. LIMA produced a benchmark data set of Landsat images and a mosaic providing a single high-resolution view of the Antarctic continent. The mosaic consists of 1,073 virtually cloud-free Landsat images collected during 1999-2003. Websites managed by the US Geological Survey and NASA (http://lima.usgs.gov and http://lima.nasa.gov, respectively) make these data available to any user at no cost. The USGS archives Landsat images in either GeoTIFF or National Landsat Archive Production System (NLAPS) format. The second IPY project produced a complete mapping of the Antarctic ice sheet "*grounding line*" using the LIMA images, as well as elevation data from a variety of sources [9]. "Grounding line" mapping can be difficult because different methodologies with different input data can identify slightly different, yet equally valid "grounding line" locations, each a part of what is more appropriately described as a "*grounding zone*" or "*basal stress boundary*". This inclusive terminology encompasses the ice-ocean interface whose characteristics depend on the specific properties of the ice and substratum as well as the phase of the ocean tide [10]. During IPY, study of this interface was an objective of the Antarctic Surface Accumulation and Ice Discharge (ASAID) project. Undulated surfaces revealed in Landsat imagery of the Antarctic coastline were interpreted to be an artifact of the boundary between grounded and floating ice. Ice experiencing sufficient basal stress at the ice sheet base would create an undulated surface boundary quite distinct from ice (like floating ice shelves) that is sufficiently uncoupled from the seabed that such surface features are absent. As such, this boundary is more properly described as the "basal stress boundary" or BSB of the ice sheet and it serves as an excellent proxy to define the end of the grounded ice sheet and the beginning of the floating ice shelf.

The ASAID project accumulated the image-interpretation efforts of an international team of participants using customized software (now available from the National Snow and Ice Data Center) to map the BSB and to supply the analysis results in a standardized manner. One participating institution was Elizabeth City State University (ECSU) Center of Excellence in Remote Sensing Education and Research (CERSER). CERSER's participation in the Center for remote sensing of Ice Sheets (CRESIS) provided a basis for a project with both educational and research objectives. The study reported here represents the efforts of undergraduate students at ECSU to: 1. use LIMA images and the ASAID BSB as a temporal and spatial glaciological benchmark, 2. validate the ASAID-derived BSB, and 3. explore both earlier and later imagery for observable changes in the ice sheet. The study is similar in purpose to other studies that map the changing coastline of Antarctica [6, 7, 11]. It is important to note that the floating edge of Antarctica changes with each iceberg calving event. This limits the climatic significance of infrequent observations of occasional calving events. Observations of changes at the grounded boundary of the ice sheet are arguably more meaningful [12] but ice edge retreat over many years of observation is also indicative of glaciologically-significant change [6, 7]. This study focused on the Pine Island Bay (PIB) coastline (Figure 1a and 1b) because ice in this region exhibits occasionally large iceberg releases, diminishing ice shelves and accelerating ice streams that suggest it may be reacting to climate change phenomena [13].

To perform the study, the ECSU student team, compared three decades of archived pre-2003 Landsat imagery with that used to create the circa-2003 BSB and discovered that a small ice shelf—herein referred to as the *Elizabeth City State University Bay ice shelf*—had apparently disappeared by the time the circa 2003 imagery was acquired. The circa-2003 Landsat imagery was also used to confirm the ASAID BSB in the area. Here we report both the temporal progress of the of the ice shelf's disappearance and analysis of its areal changes over three decades of Landsat observations.

II. LANDSAT IMAGE DATA

Starting in the Spring of 2011, students from ECSU and other historically black universities began surveying the USGS Landsat archive for all images acquired in the PIB vicinity, an area known to be undergoing considerable changes [1, 14, 15]. Relatively cloud free images were acquired for this study and included images recorded by the Landsat 1 and 3 Multispectral Scanner (MSS); the Landsat 4 and 5 Thematic Mapper (TM); and the Landsat 7 Enhanced Thematic Mapper (ETM+). These images were obtained from the United States Geological Survey (USGS) online archives of Landsat imagery through the Global Visualization Viewer (GloVis) (http://glovis.usgs.gov/) and Earth Explorer (http://earthexplorer.usgs.gov/) browsers. These two sites provide access to many Landsat images in the multidecadal database using search options such as path and row address, latitude, longitude, cloud coverage and date. All images were downloaded at no charge. Table 1 provides a summary of the Landsat images used to quantify the ECSU Bay ice shelf history.

Geographic pixel registration accuracy, image distortion and spatial resolution of Landsat imagery steadily improved through the lifetime of the Landsat series. Consequently the earliest Landsat images required additional processing to allow their comparison with higher-resolution and more accurately geo-registered circa-2003 Landsat 7 ETM+ imagery. ECSU students from the *IEEE Geoscience and Remote Sensing Society Eastern North Carolina Chapter CH#03191*, co-registered circa-2003 Landsat ETM+ images with older, archived MSS and TM imagery to achieve a consistent *pixel-by-pixel* geographic correspondence. The images contemporary to 2003 were then *linked* to those older images enabling the viewing of superimposed geographically common areas. *Image linking* allowed a pixel-by-pixel *flickering* or momentary superposition of a small area of one image over another to make any changes between two images more obvious. Further, superimposing the ASAID BSB line on both images enabled the direct comparison of small areas of the Antarctic coast. This allowed a progressive temporal comparison around the periphery of Pine Island Bay. Students sought to identify any area that appeared to be either a possible BSB placement error or a significant change in the amount and location of ice that was not clearly identifiable as seasonal sea ice. The measurement team was trained to distinguish sea ice (if any) from glacial ice (grounded or floating) by distinct differences in texture such as due to sea ice leads (linear cracks in divergent or shearing ice floes), the presence of apparent shadowing, and changes in reflectivity/albedo etc. Sea ice may also appear somewhat darker, depending on thickness and illumination. The presence of occasionally obscuring clouds was typically discernable due to shadowing and the blurring or absence of familiar geographic features.

Early in their survey, the students compared a Landsat 5 TM image acquired in 1986 (Figure 2a) to an ETM+ image from 2003 (Figure 2b) along a portion of the coastline and noticed a potentially significant change. This area was located at approximately 73°56’ S, 102°22’ W on the southern side of Canisteo Peninsula (Figure 1b) in a small embayment somewhat north and east of the Pine Island Glacier’s outlet. Using the two images, the students identified a distinct temporal change in the bay’s ice shelf extent. The earlier (1986) image (Figure 2a) showed the embayment essentially filled with ice whose thickness was apparent by the distinct shadow cast on adjacent seasonal sea ice indicating an ice edge elevation well above sea level while the 2003 ETM+ images (Figure 2b) showed no similar feature in the same region.

Landsat images recorded before and after 1986 were then examined to determine the multi-decadal history of ice shelf extent in the small bay. In TM and MSS images acquired prior to 2003, the presence of an apparently smooth, homogeneously-colored and uniformly illuminated surface that cast a visible shadow onto adjacent sea ice indicated the existence of an ice shelf whose extent appeared to be decreasing slowly with time. Once identified, this changing ice shelf area became the student’s study focus. A complete examination of the full Landsat archive resulted in ten images recorded prior to 2003 containing cloud-free views of the study area (Table 1 and Figure 3). Images acquired during and after 2003 have shown no indication of reformation of the ice shelf. An example of one such image, recorded January 3, 2013, is shown in Figure 2c.

III. METHODS AND RESULTS

The first step in our analysis involved warping each archived pre-2003 Band 4 (0.75 – 0.90 μm) Landsat near-infrared image to one of two 2003 Landsat 7 ETM+ reference images to provide the necessary common, geographically-consistent, pixel registration. Band 4 TM images (spectrally similar to MSS Band 6 images) provided the best scene contrast for ice shelf and sea ice discrimination. For the earliest MSS images recorded at 68 x 83 m pixel resolution, warping was necessary to resample them to the common 30-meter spatial resolution of the TM and ETM+ images. A list of all Landsat images used in this study is provided in Table 1. The complete set of twelve images including the one acquired January 3, 2013 is provided in Figure 3.

The software used for image warping required a minimum of four tie-points fixed to geographic features. However, at least five widely distributed tie points were sought in each image pair (consisting of a sample and reference images) to improve the fidelity of the warp. Once these common points were identified in each image pair, a least squares bi-linear warping was performed to optimize the image-to-image correspondence relative to the selected geographic points. ENVI, a software application distributed by *Exelis Visual Information Solutions*, was used for the image warping procedure as well as the other analysis steps described below. The reason two reference images were used is that in two cases, the earlier Landsat images did not cover sufficient common area with the 2003 ETM+ image and so required use of a different 2003 Landsat ETM+ image as a reference. The image warping statistics indicate that coregistration accuracy achieved was between 1 and 2 pixels (30-60 m). Based on comparison with the ASAID. BSB, pixel registration of the two circa-2003 reference images appeared virtually identical (i.e. pixels in each 2003 image corresponded to common geographic locations).

The ASAID BSB line was then superimposed onto each image. The first ten of the twelve images in Figure 3 show each after warping and with the ASAID BSB superimposed. The agreement of this boundary along the coastline on either side of the ice shelf gives a measure of the accuracy of the registration. Any mismatch along this coast is not exclusively the result of poor mapping as the grounded ice appears to be a calving ice cliff. Therefore, small changes in this edge location will occur over time as blocks of ice reform and fall away either into the ocean or onto sea ice. We have presumed that the BSB location has been stable over the approximately 30-year study period. Factors that might alter the location of the BSB include: sea level rise, isostacy and changes in the bay's basal surface bathymetry, however these are all slow processes and are unlikely to change the BSB position at the Landsat-pixel scale over the thirty years of observation suggesting this is a reasonable assumption.

Supporting the assumption of BSB stability is our observation that all images show essentially the same geographic features along coastline near the bay.

The next step involved each student-analyst manually drawing the seaward boundary of the ice shelf in each image. This boundary, connecting to the ASAID BSB, defined the extent of the ice shelf and allowed the calculation of the ice shelf area as an ENVI Region Of Interest (ROI). The general shape of the ice shelf in the earlier images consists of an unrestricted ice-covered embayment and an adjacent protruding triangular area of ice confined by either islands or shallow portions of the seabed (Figure 2a). Both regions shrink gradually after 1986 with the triangular area disappearing between the 1989 and 1991 images. The embayed area retreats gradually (with a minor resurgence apparent in early 2001) until complete loss by 2003 (Figure 2b and 2c and Figure 3).

Four independent estimates (trials) of the seaward boundary and shelf area were made by each of four members of the research team for each image. The four trials were then averaged resulting in four separate average-area values of the shelf visible in each image. The four shelf-area averages were themselves averaged to minimize measurement subjectivity. Each shelf-area estimate for each image shown in Table 2 and plotted in Figure 4 (along with measurements' error bars) is the result or 16 separate area measurements. The shelf's observed maximum area occurred sometime in the mid-1980's. The maximum observed extent occurred between two points on the bay's coastline: (73°57'25' S, 102°14'45'' W and 73°55'55'' S, 102°30'00' W). The red arrows in Figure 2b and in the eleventh image in Figure 3 indicate these points.

Ice shelf thickness was estimated using the Landsat imagery and simple Pythagorean geometry. The January 4, 2001 image was used because the Landsat ETM+ image offered both superior spatial resolution (15 m) and the obvious presence of sea ice. The high seaward rim of the ice shelf cast a shadow upon the sea ice whose length could be measured. The sun's azimuth, at the local time the image was acquired, provided a baseline allowing identification of six points where a shadow was cast normal to the ice shelf front. A consistent length of 2.5 ± 0.5 pixels (37.5 ± 7.5 meters) was obtained at these locations. Applying the sun's elevation for this image of 30.4^{o} converted the average shadow length of 37.5 meters to an ice shelf height of 22 ± 4 meters. Using an expected average ice shelf density of 917 kg/m^3 and a firn air-column correction of 14.6 meters [16], this ice-front height suggests an ice shelf thickness of 84 ± 36 m at the calving front. A maximum shelf thickness of 120 meters seems consistent with other, larger ice shelves in the region, e.g. the Pine Island ice shelf varies between 300 and 500 meters thick at the shelf front [16].

IV. DISCUSSION AND IMPLICATIONS

Although the temporal record of ice shelf area is not densely sampled (a mean of ~2.5) years between the eleven observations made over 30 years through 2003, the imagery sequence we analyzed suggests an initial period of relative stability, with growth to a maximum ice shelf area of about 6.82 km^2 in about 1986. This was followed by a period of sustained retreat, with the exception of a brief, minor shelf reconstitution in early 2001, until the ice shelf completely disappeared by 2003. Additional changes in area especially during the under-sampled 1970s are certainly possible (Figure 4). Temporally-irregular calving of ice shelves can cause sudden areal losses, but only one brief areal gain was observed in early 2001, amounting to about 0.67 km^2 and apparently due to a brief surge. There also appears to be loss of a very thin section of the ungrounded ice shelf between 2001 and 2002 and its reconstitution in 2003 although this is a very minor area change. This may indicate a small error in the location of the BSB or loss and subsequent reconstitution of a narrow ice cliff section. Small icebergs, possibly moving away from the shelf edge are evident in a number of the frames in Figure 3 (e.g. 1997 Julian day 033). While these icebergs may be calved from the ECSU bay ice shelf, source confirmation is not possible with Landsat's infrequent monitoring. In any event, total iceberg area is never more than a few percent of the total shelf area. Consequently, we believe individual calving events probably do not alter the measured temporal record of area significantly and the sustained ice shelf loss from 1986 to 2003 is a robust trend.

A significant number of icebergs were observed in the 1986 and 1989 images, at the initiation and early stage of ice shelf loss. Similar iceberg frequencies are well documented for ice shelf collapse events elsewhere in the Antarctic Peninsula (6). Thus, it is possible that the maximum area around 1986 was slightly larger than our measurement of about 6.82 km^2. We also note in Figure 3 that open ocean (i.e., little to no sea ice) conditions at the ice shelf front occur only during the Antarctic summer revealed in images from early 1989, 1991, 1997, 2000 and late 2001 images. The first three of these consecutive observations spanned the middle portion of the sustained retreat period while the last two provided a view of the late retreat phase characterized by a slightly reduced but sustained rate of areal loss. Further analysis might be able to correlate *Circumpolar Deep Water* (CDW) arrival to our measured area loss data. If there is any connection between these two observations, then it suggests either sea ice persistence enhances ice shelf loss or open-ocean inhibits it, but not that sea ice presence inhibits ice shelf loss. Thus, based simply on our limited set of observation, a mechanical interaction where sea ice cover retards ice shelf loss appears unlikely. The winter growth and summer melt of sea ice drives the production of high salinity shelf water, which has been attributed to enhance sub-ice-shelf circulation and, thus, basal melt and ice shelf thinning [17]. Minimal sea ice conditions, noted above, may simply be indicative of periods of steady basal melting of the shelf due to warm CDW inflows or just relatively rare 'clear' days due to offshore winds driving both clouds and sea ice seaward providing an ice and cloud free Landsat scene. However, without a more complete record of sea ice cover variations and oceanic current conditions in the vicinity of this ice shelf, the relationship between ocean conditions and ice shelf changes can only be speculated.

An unequivocal conclusion of our study is that no ice shelf has reappeared since 2003. We determined this by examining many image sources (e.g., MODIS and ASTER) in addition to later Landsat imagery. Our Landsat imagery analysis indicates the loss of area was sustained at approximately 0.5 km^2 per year (or 7% of the maximum area per year) for 15 years until the entire ice shelf was gone. The gradual nature of this loss is far less dramatic than the sudden ice shelf disintegrations observed for some ice shelves of the Antarctic Peninsula [4, 5, 6] that have been attributed to intense surface melting and hydraulic fracturing by surface melt water [18]. Although rapid ice shelf collapses have occurred, over the past 50 years or so most Antarctic Peninsula ice shelves are undergoing a more gradual retreat that is similar to our observations [19].

What sets our observations apart is not the volume nor the area of ice shelf lost; rather it is the ice shelf's location in Pine Island Bay, a coastal location much farther south than the well-documented shelf losses on the Antarctic Peninsula. Despite the velocity and elevation changes of grounded ice in this region of Antarctica [20, 21], the major ice shelves in the Amundsen Sea Embayment, including Pine Island Bay, seem to be receiving sufficient volumes of ice to sustain them, albeit with episodic calving events [7]. The complete loss of this ice shelf since about 1986 stands out as a unique event for the immediate area and may be a general consequence of an increase in the amount of warm water circulating in Pine Island Bay. Recent observations in Pine Island Bay have indicated both an increase of CDW entering the sub-ice-shelf cavity beneath Pine Island Glacier's ice shelf as well as a shallower pycnocline effectively leading to warming waters at shallower depths [13]. The pycnocline is that layer of water exhibiting the greatest density gradient. For the present, the 4000 m/a speed of Pine Island Glacier can diminish the erosive effects of rapid sub-shelf melting on its ice shelf that is between 300 and 500 meters thick at its front [16, 20]. Such appears not to have been the case for the much smaller ice shelf studied here. The ECSU Bay ice shelf appears to be somewhat thinner than other nearby ice shelves and is fed by small glaciers with ice moving at between 50-100 m/a based on recent InSAR data (I. Joughin, pers. comm.). It is unlikely that the bed along the BSB adjacent to this ice shelf is as deep as the strongly eroded bed underlying the large Pine Island Glacier, so the demise of this ice shelf is probably due to shoaling of the pycnocline as documented in the overall area [13].

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Date Image Recorded	Landsat Instrument	Landsat Band Number	Band Wavelength (µm)	Spatial Resolution (m)	Path	Row	Archived Image Format
12/07/72	LS-01-MMS	6	0.70 - 0.80	79	001	112	GeoTIFF
12/13/81	LS-02-MMS	"	0.70 - 0.80	79	251	113	"
12/21/86	LS-05-TM	4	0.76 - 0.90	30	001	113	"
01/03/89	LS-04-TM	"	"	"	001	113	"
12/21/89	LS-04-TM	"	"	"	001	113	"
02/23/91	LS-05-TM	4	0.76 - 0.90	30	004	112	"
02/02/97	LS-7-ETM+	"	0.76 - 0.90	"	001	113	"
03/05/00	LS-7-ETM+	"	"	"	001	113	"
01/04/01	LS-7-ETM+	"	"	"	001	113	"
12/12/01	LS-7-ETM+	"	"	"	002	113	"
01/17/03	LS-7-ETM+	"	"	"	002	113	NLAPS-Reference Image
01/24/03	LS-7-ETM+	"	"	"	003	112	NLAPS-Reference Image

Table 1. USGS Archived images used in this study including the two USGS National Landsat Archive Production System (NLAPS) data format images used both as basis for establishing the Basal Stress Boundary and as geographic references for image pixel registration. Instrument column indicates Landsat number and instrument type: M = MSS, T = TM and E = ETM+.

Year Image Recorded	Julian Day	Decimal Year Date	Decimal Base-1972 Date	Temporal Interval	Average Area (km^2)	Ice Shelf Total Mass Estimate* (MT)	Annual Ice Mass Change (MT)
1972	342	1972.94	0.94	0	6.519	1,173	0
1981	251	1981.69	9.69	8.75	6.526	1,175	1
1986	355	1986.97	14.97	5.28	6.820	1,228	53
1989	003	1989.01	17.01	2.04	5.219	939	-288
1989	355	1989.97	17.97	0.96	5.019	903	-36
1991	054	1991.15	19.15	1.18	3.729	671	-232
1997	033	1997.09	25.09	5.94	3.107	559	-112
2000	066	2000.18	28.18	3.09	1.792	323	-237
2001	004	2001.01	29.01	0.83	2.463	443	121
2001	347	2001.95	29.95	0.94	0.527	95	-348
2003	017	2003.05	31.05	1.10	0.000	0	-95

* Constant Thickness of 200 m assumed

Table 2. Summary of the temporal change in ECSU Bay ice shelf measured area and estimated mass. Average areas is based on a total of 16 individual area measurements, made by four students, each of whom derived an average of their four separate area measurement trials.

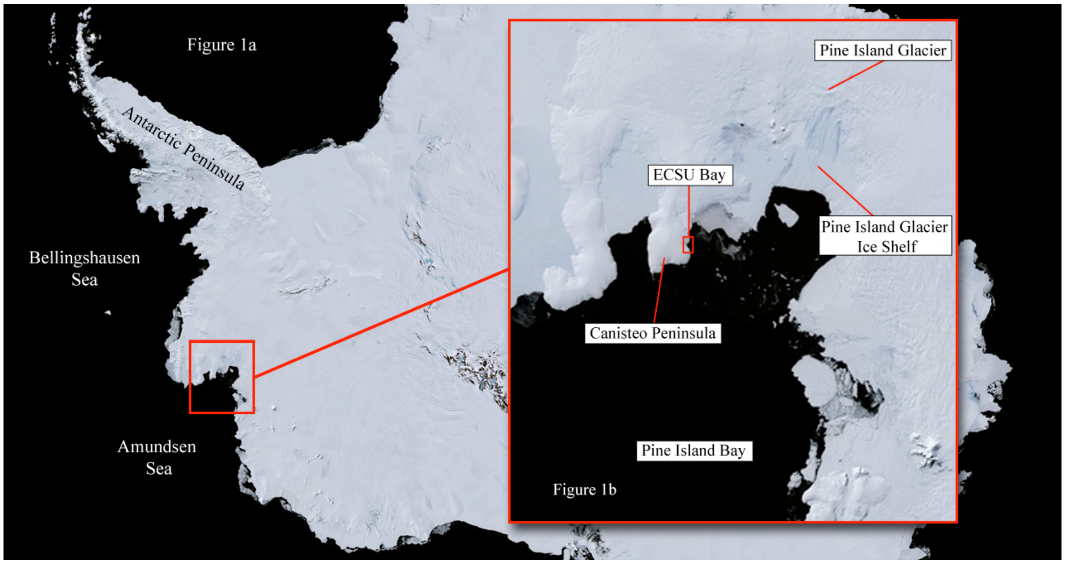

Figure 1a. A portion of the Antarctic Ice Sheet as depicted in the Landsat Image Mosaic of the Antarctic. Figure 1b. Pine Island Bay coastline with location of the Pine Island Glacier and its ice shelf and ECSU Bay small box shows area depicted in Figures 2 and 3. North is, of course, any direction pointing radially away from the Figure's center.

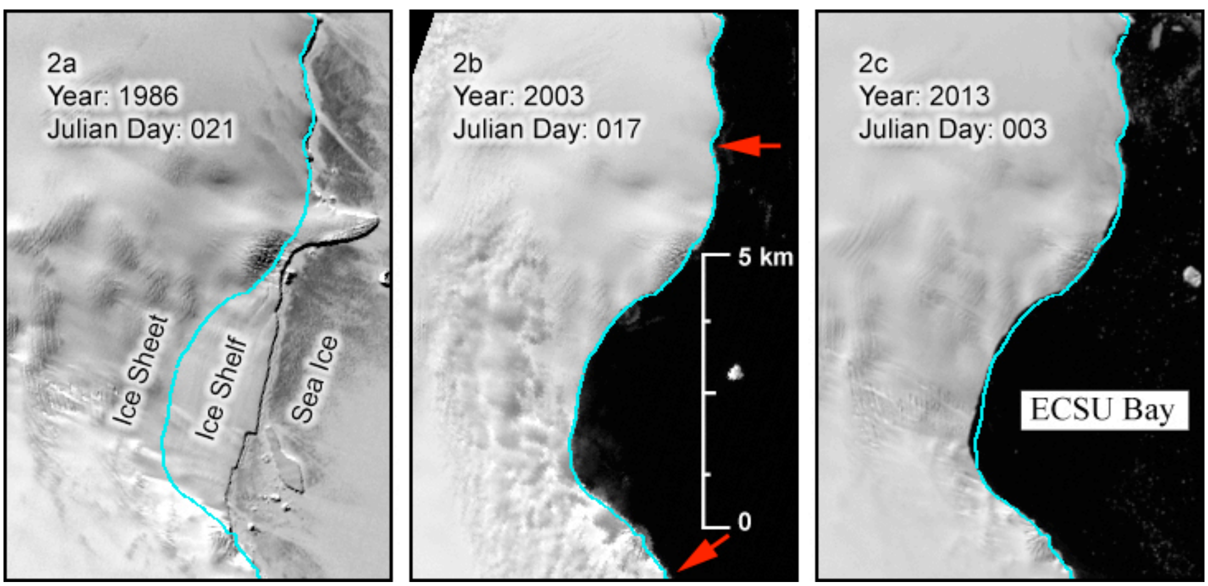

Figure 2. Each Cropped Landsat band 4 image shows the same area of interest at the same spatial resolution but at different times. The light blue BSB is superimposed on each image. Figure 2a. shows the ice shelf occupying ECSU bay as recorded by Landsat 5 TM on December 21, 1986. Figure 2b. was recorded by the Landsat 7 ETM+ on January 17, 2003. Geographic limits defining the ice shelf's observed maximum extent in 1986 are shown by red arrows. Figure 2c. Landsat 7 Band 4 ETM+ image recorded January 3, 2013 showing continued ice shelf absence and location of ECSU Bay. North is approximately to the left. Ocean water is black.

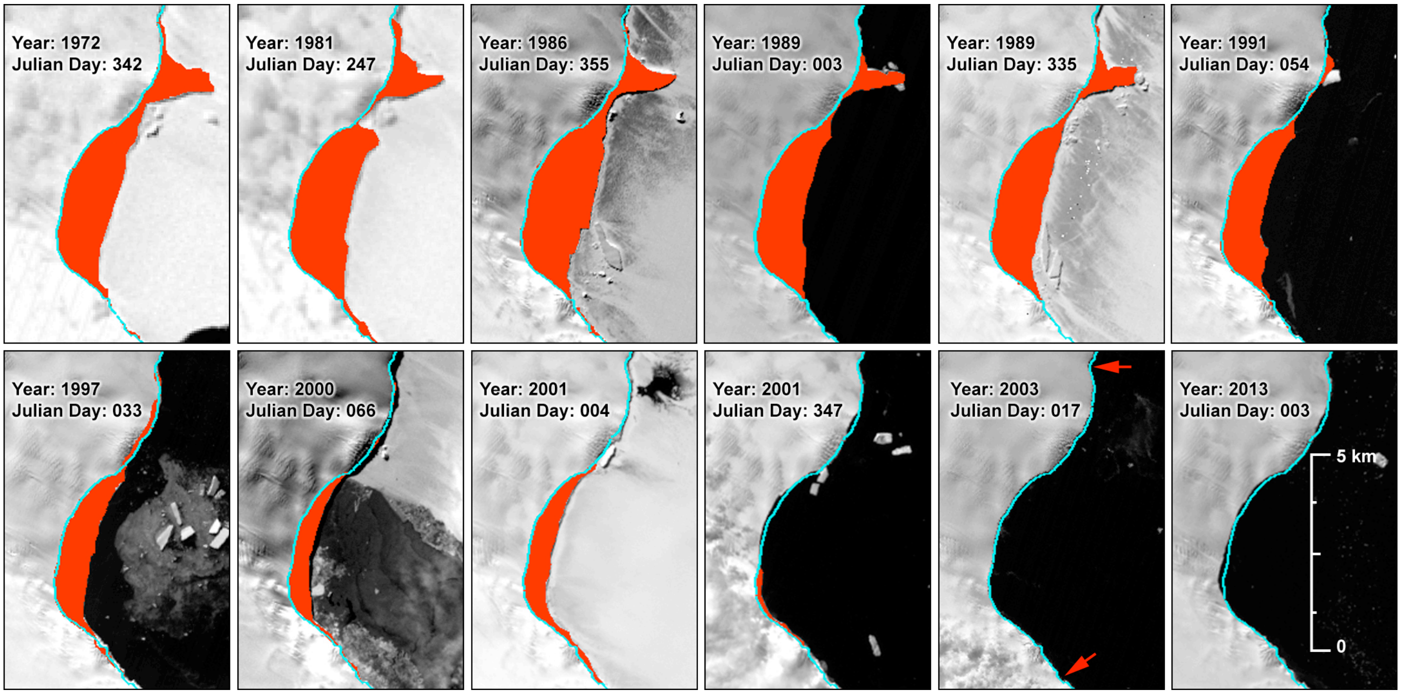

Figure 3. Cropped, Landsat near infrared images showing the area of interest in this study. Light blue colored line is the ASAID grounded ice boundary and red area is the mapped ice shelf extent quantified in Table 2. North is approximately to the left. The year and Julian day that each Landsat image was recorded is indicated.

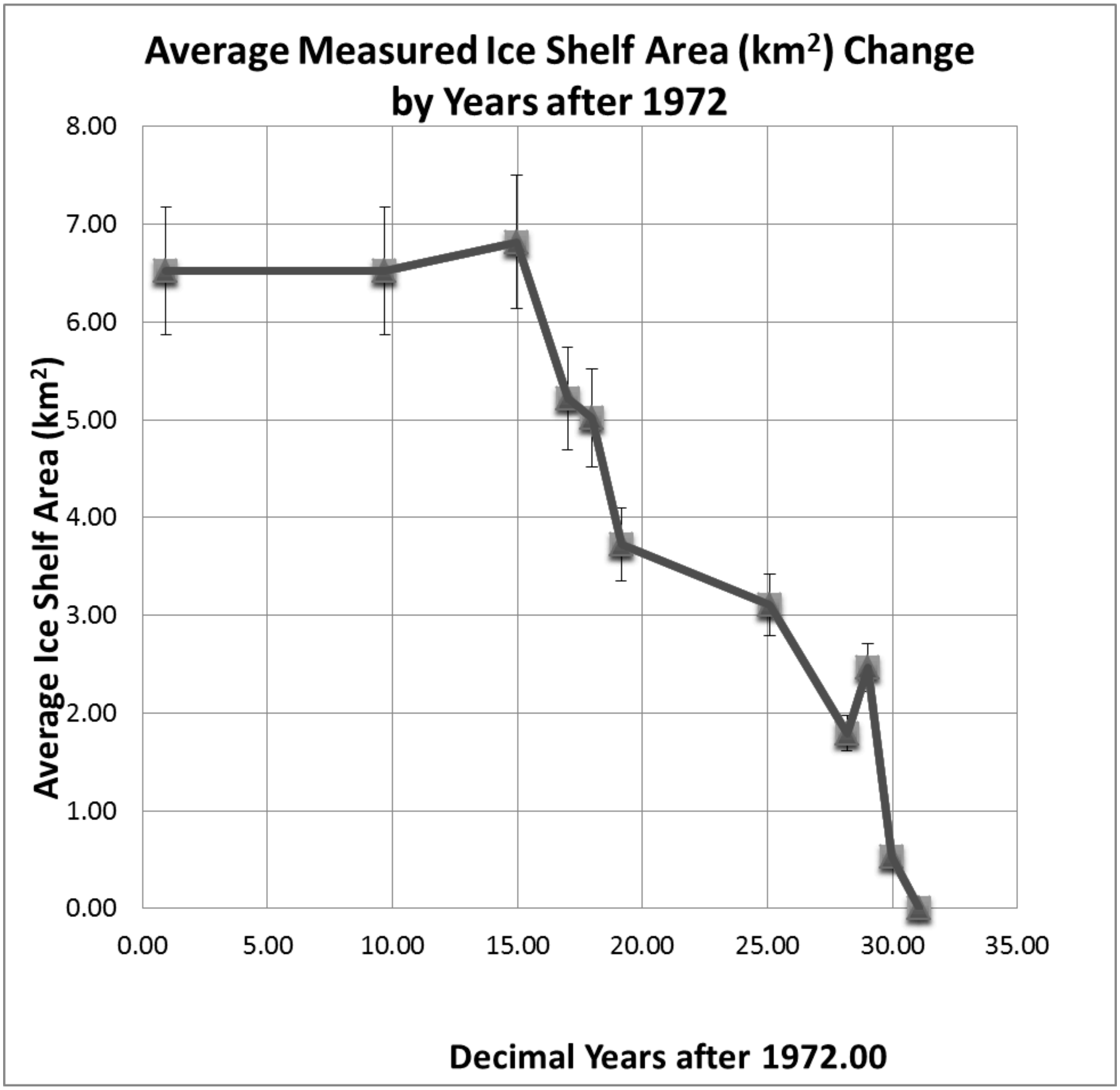

Figure 4. Plot of ice shelf area versus decimal years after 1972, when Landsat imagery becomes available. Data correspond to average of four independent area estimates with standard deviation indicated by error bars. In last two samples, error bars are too small to be visible. Horizontal scale zero point corresponds to 1972.00