Editor, *The Cryosphere*:

Responses to the comments and suggestions to the anonymous reviews of manuscript tc-2016-201 *Rapid Wastage of the Hazen Plateau Ice Caps, Northeastern Ellesmere Island, Nunavut, Canada,* follow below. We appreciate the efforts of the reviewers, who clearly spent a great deal of time with this manuscript and as a result have greatly improved it.

Respectfully,

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Reviewer #1

This paper documents the near demise of 4 small ice caps in NE Ellesmere Island - ice caps that have a >50 year history of study. The paper is of some interest because of this long history, but it could be made more interesting if more effort were made to place the results in a broader regional context.

We thank the reviewer for his/her obviously very careful read of this paper. We agree that the paper needed to better place the results into a broader context. We have attempted to appropriately respond to the reviewer's comments and recommendations that follow below.

Specifically, there is no mention at all of the work of Gabriel Wolken, who used trimline mapping to document the pattern of post Little Ice Age glacier retreat across the Queen Elizabeth Islands and interpret observed patterns in terms of past climate dynamics (The Holocene 18 (4), 615-628 and 629-641, 2008). Nor is there mention of the chapter on this region in the GLIMS book (edited by Jeff Kargel and others; Global Land Ice Measurements from Space, pp 205-228 (Springer, 2014)), which provides a sub-regional breakdown of post 1950's ice retreat across the area as a function of initial ice cap/glacier size. Many small ice caps have disappeared from this region in the past 60 years, but this would not be obvious from reading the submitted manuscript).

Equally, there is no reference to the 4 in situ mass balance time series from the area which provide a nice picture of the short term variability in climate-mass balance linkages that would help with the interpretation of the results presented here - or of the regional ice mass change time series from GRACE, which would do the same thing. The relevant data are published annually in the Arctic section of the

BAMS “State of the Climate” report and are readily available (as are the mass balance time series from WGMS). Nor is any comparison with ice core records from the region, which would also help to provide longer term context for the work (e.g. Fisher et al., 2012, Global and Planetary Change 84, 3-7).

As a result, the paper seems somewhat disconnected from what is already known about post LIA and recent glacier change in the region and its drivers. I think this issue has to be addressed if the paper is to pass the “significance” test for publication in The Cryosphere. The paper does nicely document the history of these specific ice caps in more detail than would be possible for most others in the same region (hence good for originality) , and the detail is sufficient to allow reasonably sophisticated comparison of ice cap retreat rates and patterns with other climate and mass balance indicators for the region - but this is not really attempted (hence fair for scientific quality and significance). This leaves the paper with a rather anecdotal feel. I think this needs to be changed before I could recommend publication in this journal.

We have attempted to place the paper into the broader context of existing research. Note that Reviewer 2 pointed out the same shortcoming. First, to help set the stage, the first sentence of the second paragraph of the introduction how highlights out intent to place the results into better context:
“This paper documents the behavior of the Hazen Plateau ice caps over the past 55+ years in the context of other glaciological studies in the Canadian Arctic.”

Next, and importantly, some reorganization was necessary. Specifically, the summarized history of change that was a the end of Section 2 (Previous work) was moved to the end of Section 3.1, and expanded to include a fuller discussion of the history of the ice caps from the LIA to the present (including the area estimates from ASTER through 2016) within the broader context of the studies pointed out above by the reviewer. Section 3 was renamed (Updated History, 1959-2016).

The first bullet of the discussion now includes a comparison with the study of Wolken et al. (2008):

“To place these findings in a broader context, for the Queen Elizabeth Islands as a whole, trim lines based on high-resolution satellite imagery point to a 37% reduction in perennial snow and ice extent between the LIA maximum extent and the year 1960. Over the lower lying central and western islands, a complete removal of perennial snow and ice occurred by 1960 (Wolken et al., 2008)”.

The second bullet highlights that the period of reduced mass loss and occasional mass gains from the1960s through at least part of the 1970s is seen across the Canadian Arctic:

“From the 1960s through part of the 1970s, the ice caps may have experienced a period of reduced loss or occasional growth (1971/1972, 1982/1983) in response to cooling. This basic pattern likely holds for Canadian Arctic glaciers and ice caps as a whole (Bradley and Miller, 1972; Hattersley-Smith and Serson, 1973; Ommanney, 1977; Bradley and England, 1978; Braun et al., 2004; Sharp et al., 2014)”.

The third bullet introduces the persistent subsequent mass losses:

"Since then, apart from occasional years such as 1982/1983, annual mass balances of the four ice caps have been persistently negative (Braun et al., 2004). This is in turn consistent with the broader pattern of reductions in mass and area of Arctic glaciers and ice caps (Dowdeswell et al., 1997; Dyurgerov and Meier, 1997; Arendt et al., 2002; Koerner, 2005; Sharp et al., 2011, 2014; Fisher et al., 2012; Sharp et al., 2014; Mortimer et al., 2016). It is also consistent with a negative mass balance of the Greenland Ice Sheet since at least the 1990s (Shepard et al., 2012)".

This set the stage for the next two (entirely new) paragraphs which discuss specific results from other studies:

"Mass balance summaries for four monitored glaciers and ice caps in the Canadian Arctic (Devon Ice Cap, Meighan Ice Cap, Melville South Ice Cap and the White glacier) are provided as part of the American Meteorological Society State of the Climate reports. As assessed over the period 1980 through 2010, all four have had negative average annual mass balances, ranging from -0.15 m w.e. for the Devon Ice Cap to -0.29 w.e. for the Melville South Ice Cap (AMS, 2016). Cumulative changes in regional total stored water for the period 2003 through 2015 based on gravimetric data from the GRACE mission (Gravity Recovery and Climate Experiment) are qualitatively consistent with these mass balance measurements (AMS, 2016). Based on ice core data, Fisher et al. (2012) document rapid acceleration of ice cap melt rates of over the last few decades across the entire Canadian Arctic; the large reductions in area of the Hazen Plateau ice caps, in particular the lower-elevation St. Patrick Bay ice caps, is consistent with this finding. However, reflecting variable climate conditions, annual balances are also quite variable. For example, for the 2013/2014 balance year (the most recent data available), the White Glacier had a strongly negative balance (-0.42 m w.e.) while the small Meighan Ice Cap actually gained mass (+0.06) (AMS, 2016). Sharp et al. (2014) show that while the larger ice bodies in the Canadian Arctic have seen the larges losses in mass, the smaller masses have lost a larger proportion on their areas. This is also consistent with the behavior of the Hazen Plateau ice caps. Below we examine variability in climate conditions over the Hazen Plateau and links to mass balance and area changes".

Later on, in Section 3.2, Associated Climate Conditions, when speaking of the temperature time series, we note that: "The time series of decadal mean summer temperatures at the 700 hPa level for the major glaciated regions of the Canadian Arctic presented by Sharp et al. (2011) based on the NCEP/NCAR reanalysis (their Figure 9.3) is broadly consistent with the pattern shown in Figure 5".

The State of the Climate published by the American Meteorological Society that the reviewer recommended also provide some useful insight into the 2012/2103 mass balance year, now discussed in the last paragraph of Section 3.2, in which we call a new figure (Figure 6) showing the summer 825 hPa temperature anomaly pattern:

"Regarding the summer of 2013, the obvious exception to the pattern of recent warm years, the ASTER data and daily images from the Moderate Resolution Imaging Spectroradiometer (MODIS) show extensive cloud cover through the summer, making it difficult to determine whether the snow cover ever entirely cleared off the plateau. It is likely, however, that the 2012/2013 balance year was positive for the Hazen Plateau ice caps - the Devon Ice Cap, Meighan Ice Cap and the White Glacier all gained mass. Only the Melville South Ice Cap, lying well to the west, had a negative balance (AMS, 2014). Consistent with this view, **Figure 6** shows that summer (J,J,A) averaged 850 hPa temperature anomalies over the Queen Elizabeth Islands from the NCEP/NCAR reanalysis were about 2°C below the 1981-2010 baseline in the area centered over Axel Heiberg and Ellesmere islands. This reflects the influence of an unusually deep circumpolar vortex at the 500 hPa level centered just south of the Pole along about 90°W longitude. By sharp contrast, the notable area reduction of the St. Patrick Bay ice caps between August 2014 and 2015 aligns with the very warm summer of 2015, essentially tied with 1957 as the highest in the record. From **Figure 7**, July 2015 temperatures at the 850 hPa level from the NCEP/NCAR reanalysis were 3-4°C above the 1981-2010 baseline over most of northeastern Ellesmere Island. Mass balance estimates for monitored glaciers in the Queen Elizabeth Islands for the 2014/2015 season that would provide context were not available us at the time that this paper came to press".

Note that Figure 6 and 7 are presented at a scale that shows conditions over all of the Queen Elizabeth Islands instead of focusing (as the original Figure 6 did) just on Ellesmere Island.

The paper is however quite readable (good for presentation quality) although I do suggest below quite a number of detailed edits that would make it more readable.

We thank the reviewer for these suggested edits and additions.

Specific Points (keyed by line number):

71-74: Specify uncertainties associated with the ice cap area estimates - important to know how large these are relative to the observed changes

Text has been added: "We estimate that these area estimates are accurate to within 5%".

77: what is the range of surface elevations covered by this transect and how does it compare with the total elevation range of the ice cap?

Additional text has been added to the paragraph: "The range in elevation along this transect was about 60 m, which compares to a range for the entire ice cap of about 160 m."

85-86: this statement seems like unnecessary speculation, given that the comparison is with the behaviour of a single studied ice cap.

The sentence has been cut.

91: Why assume the 1982 melt season ended by the end of August ? Evidence for this claim? Climate data?

It is of course possible that more melt occurred, although all visible melt had stopped by the time that the field camp had been evacuated and the daily maximum air temperature drops rapidly in late August. However, given that more melt may have occurred, the estimate mass balance of -0.14 w.e. is likely a minimum estimate. The text has been revised to note this. Reviewer 2 also pointed this out.

92-94: an annual mean MB value for a given time interval might be more useful than a period mean and, if there is a stake line, it would be useful to say something about how the annual balance varies with elevation.

The elevation range of the ice cap is quite small and as such, based on the first author's field notes, no variation in the mass balance with elevation was apparent.

96: decreased in area (rather than shrunk in area)

Corrected.

103: Is -0.49 the annual value or a period mean? Not clear.

It is the total over the period. The text has been amended to: Based on these sparse data*,* Bradley and Serreze (1987) estimated that over the period 1976-1983, the Simmons ice cap experienced a total mass loss of at least -0.49 meters water equivalent.

104: inferred by Hattersley-Smith…..

Corrected.

106-107: Treats temperature and mass balance as interchangeable terms - not justified, so talk about temperature as that is what the data relate to (or present a quantitative relationship that justifies inferring MB from T

This was poor wording on our part. The paragraph now reads: "However, the summer of 1983 was fairly cool and the snow never completely melted off the surrounding tundra. The 1982/1983 annual mass balance for the larger St. Patrick Bay ice cap was estimated at +0.14 m water equivalent, and given their higher elevation, it is reasonable to assume that the 1982/1983 balance of the Simmons and Murray ice caps was also positive".

109: 1982/83 balance of the Simmons…..

Corrected.

116-117: annual balances of both ice caps were negative in all years, ranging from….

Corrected.

120: The larger and smaller ..of their 1959 areas respectively, while the

Corrected.

Murray...had shrunk to 70%......their 1957 areas

Corrected.

123: inserted allowed us to make a minimum estimate (-1.10 m w.e.) of the mass loss…

Corrected.

125-128: given the measurement approach, I think some assessment of the associated errors is warranted.

Text has been added to the paragraph: "This is based on the mean remaining depth of stake insertion into the ice in 1983 and an assumed ice density of 900 kg m (Braun et al., 2004)".

129:……studies, and the results from…..

Corrected.

131: maximum, and likely to have formed

It seems better as "…..but rather likely formed…"

133: in the first couple….

Corrected.

134-135: On the basis of a mapped lichen tramline, Braun et al. (2004) speculate that

Corrected.

135-138: Here the authors should make reference to Wolken's study (The Holocene) of lichen trimlines in the QEI; I'd also like to see a tabulation of all the available surface mass balance measurements and the time periods they represent.

The section has been modified as follows: "Braun et al. (2004) speculate on the basis of a mapped lichen trim line that the Murray ice cap may have attained a maximum LIA extent of about 9.6 km^2, over twice the mapped 1959 area of 4.35 km^2. Similar trim lines were observed around the other three ice caps and although not mapped in detail, strongly point to much more extensive ice cover during the LIA. To place these findings in a broader context, for the Queen Elizabeth Islands as a whole, trim lines based on high-resolution satellite imagery point to a 37% reduction in perennial snow and ice extent between the LIA maximum extent and the year 1960. Over the lower-lying central and western islands, a complete removal of perennial snow and ice occurred by 1960 (Wolken et al., 2008)".

A new table (Table 1) has been added that summarizes all available direct mass balance estimates of the ice cap. Note that the similar table of Braun et al. (2004) includes some additional estimates for other year based on indirect approached.

143: List all the known positive balance years so we can see how many there have been

Done.

147: Note there are GRACE mass balance time series for the QEI (see the Arctic section of successive annual BAMS “State of the Climate” reports) and for the Russian Arctic, Svalbard, and Alaska, so you could make broader scale Arctic comparisons with your data time series.

We now include mention of the GRACE results in the revised Section 3.1.

152: areas (in km2) from all…

Corrected.

157: of the Murray

Corrected.

162: 2016, the Murray…….in 1959. By sharp contrast, ……...only 0.15 km2

Corrected.

168: reductions in…..area are striking

Corrected.

170: is shown in Figure 3, based on outlines from 1959, 2001, and 2016.

Corrected.

177: Note that none of these studies discuss glacier area changes, and you don’t reference the one that does (paper in the GLIMS book)

We now include more references, which include studies of both mass and area changes. The sentence has been amended: “This is in turn consistent with the broader pattern of reductions in mass and area of Arctic glaciers…..”

197: is it meaningful to make comparisons with pan-Arctic means given the scale of this study?

We clearly state that we are making an assumption that the inferred LIA conditions over the Hazen Plateau from the study of Kaufman et al. (2011), are at least broadly similar to those for the Arctic as a whole. It is not clear what more can be done here to obtain an optimal local estimate.

200-203: Sharp et al (2011) provide evidence that would support this assumption (i.e. that 850 hPa and surface air temperatures show similar patterns)

The text has amended to point this out.

Reviewer #2

Overview: This paper documents the important and timely phenomenon of disappearing ice caps in the Canadian high arctic. A time series of area measurements is compiled primarily from previously published observations, with a small contribution of new measurements to document shrinkage and predict the timing of the demise of the plateau ice caps. Some previously published surface mass balance measurements are reported but not discussed. The area changes documented in this study are linked through qualitative comparison to annual temperature 850hPa radiosonde temperatures from Alert. A major shortcoming of this paper is the under-utilization of available long term records from other arctic glaciers to determine if the rate of glacier change over the Hazen plateau is representative or anomalous of the broader scale glacier changes occurring in the Canadian high Arctic. A more rigorous quantitative analysis of the complete time series of changes to the Hazen plateau ice caps should be made in order to contribute to the broader understanding of the rates of climate change in the Canadian high arctic and the current and future rate of contribution of ice caps and glaciers in this region to global sea-level rise.

We thank the reviewer for his/her efforts. Reviewer 1 and Reviewer 2 have highlighted the same shortcoming of our paper – a failure to adequately place the results from our paper on the context of other studies for the Canadian high Arctic. In response to Reviewer 1 we have made concerted efforts to rectify this problem. This includes comparisons with the efforts by Sharp et al. (2014), Fisher et al. (2012), Wolken et al. (2008) and the mass balance summaries provided in the annual American Meteorological Society State of the Climate Summaries. As noted, providing this fuller context required some reorganization of the text. We feel that the paper is now much more relevant.

Comments: L58-60: A major shortcoming of this paper is lack of new geophysical data generated for this study, as such, there is no needs for a methods section. The distinction between which data were produced by the authors for this paper, and data/information from previously published material needs to be more clear.

Correct, we saw no need for a methods section. Apart from the ice cap areas our analysis does not provide new geophysical data, but we do not see this as a weakness. Indeed, by piecing together the old and the new, we have a 55+ year records of the behavior of these ice caps! We have amended the last paragraph to better distinguish what is old and new:

“This paper documents the behavior of the Hazen Plateau ice caps over the past 55+ years in the context of other glaciological studies in the Canadian Arctic. The analysis is based on a combination of past work using aerial photography, direct mass balance measurements from several field investigations, GPS surveys of ice cap areas collected as part of these investigations - along with new information on ice cap areas using data at 15 m resolution from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) instrument. ASTER flies onboard the NASA's Earth Observing System Terra satellite, launched in December 1999. It provides reflectance at a 15 m resolution and is a key asset of the international GLIMS initiative (Global Land Ice Measurements from Space) for mapping glacier outlines (Raup et al., 2007; Kargel et al., 2014)”.

While the authors illustrate the rate of shrinkage of the Hazen plateau ice caps though plots of the time series, there is no attempt made to determine if the rapid changes as determined from this study are occurring at anomalous relative to those documented for other high arctic glaciers.

Through efforts to place the results from our paper into a broader context, the rapid area reductions of the Hazen Platea ice caps are very much in line with what is happening in the rest of the Arctic. See especially the revisions to Section 3.1.

L49: It would be more informative if the actual elevations of the ice cap are rather than just the maximum surrounding area (ie. “: : :ice caps are in an area with maximum elevations s between 750-900 m;: : :”) as stated.

One of the problems here is that the elevation range has changed quite a bit over time. However, we have attempted to add some clarity to the text: “As of 2001, the larger St. Patrick Bay ice cap ranged in elevation between about 880 m and 720 m above sea level, with the smaller one spanning 820 m to 700 m. The Murray and Simmons ice caps lie in higher terrain; in 2001, both fell between about 1100 m and 1000 m above sea level”.

Extent of LIA glacier cover (Wolken et al.) should be included in the analysis to provide a longer term perspective to the changes discussed in this study.

See above, this was also pointed out by Reviewer 1 and has been addressed in the first bullet of Section 3.1: “To place these findings in a broader context, for the Queen Elizabeth Islands as a whole, trim lines based on high-resolution satellite imagery point to a 37% reduction in perennial snow and ice extent between the LIA and the year 1960. Over the lower lying central and western islands, a complete removal of perennial snow and ice occurred by 1960 (Wolken et al., 2008)”.

L53-54: the authors should clarify what form of precipitation this statement (“: : :, with a late summer and early autumn maximum..”) refers to ie. Rain or snow, or a combination of both, as they can have opposite impacts on the mass balance of small ice caps with no firn to absorb liquid precip.

Based on personal experience, it can be either. The text has been amended: “Like much of the Queen Elizabeth Islands, the Hazen Plateau is presently a polar desert; annual precipitation is typically only 150-200 mm, with a late summer and early autumn maximum (Serreze and Barry, 2015). Summer precipitation may be variously rain or snow.”

L83: Presumably these ice caps are stagnant. However, the authors refer to the ice caps “: : :extending its margins,..” which may be misinterpreted as advancing via flow, which is almost certainly not the case. It is most likely that the” extended” margins are actually perennial snow packs which would be of lower density material than the original ice cap. This should be clarified

This comes directly from the Hattersely-Smith and Serson (1973) paper published in *Journal of Glaciology*. We have attempted to clarify as follows: “They concluded that while the ice cap had been in decline (as suggested from the 1947 and 1959 photographs), by the early 1970s it had returned to good health, “thickening slightly and extending its margins” (icy firn was observed atop the dirty melt surface and a perennial snow cover extended beyond the ice cap margins).

L83: “: : :thickening slightly : : :” how was ‘thickening’ determined?

See above, they observed firn atop the former melt surface.

L91: “Assuming that the 1982 melt season had largely ended by early August: : :” unless there is temp data to support this claim, there is no reason to assume that the melt season ended in early august. High arctic glaciers at these elevations commonly experience melting into late august.

Reviewer 1 also pointed this out and the text has been amended accordingly. “Assuming that the 1982 melt season had largely ended by early August (all visible melt had stopped by the time that the field camp had been evacuated), the 1981/1982 mass balance for the larger ice cap was estimated at -0.14 m w.e.. Given that more melt may have occurred, this is likely a minimum estimate.” The new Table 1 (the measured mass balances) also indicates that this is a minimum estimate.

L94 and 103: it is more informative (and more common in glaciology) to report mass balance as an annual (ie a-1) value even when measurements span multiple years.

Conversions for periods spanning multiple years have been provided in both the text and in the new Table 1 requested by Reviewer 1.

192 “ While arguably it might be better to look at the 925 hPa level,” the authors need to explain why this is the case.

Simply put, it is closer to the plateau surface. The text has been amended to point this out.

L178/179: the studies referenced refer to loss of ice mass or surface mass balance, not specifically area change. This is an important distinction (and should be discussed) because area reductions of the larger dynamic ice caps are also a function of dynamic response time whereas the margins of small plateau ice caps respond immediately to surface ablation and would shrink at faster rates relative to the dynamic ice masses.

Reviewer 1 pointed this out as well. We now include more references, which include studies of both mass and area changes. The sentence has been amended: “This is in turn consistent with the broader pattern of reductions in mass and area of Arctic glaciers…..”

Figure 5: it would be helpful to integrate the annual and multi year average surface mass balance measurements and/or area change values from all studies (this one and all referenced herein) into fig 5 in order to show the relationship between temp change and ice cap response.

Reviewer 1 wanted to see all of the directly measured mass balances, and in response, we added a new table new (Table 1). Trying to integrate all of the information into Figure 5 proved awkward and crowded. Hence we have compromised, and have indicated on Figure 5 the annual mass balance estimates for the larger St. Patrick Bay (SBP) ice cap for the 1981/1982 and 1982/1983 balance years, and for the Murray Ice Cap (M) for the 1999/2000, 2000/2001, 2001/2002 and 2002/2003 balance years (in m w.e.). We then added some text to more completely discuss the relationships between temperature anomalies and mass balances. The figure caption has also been edited.

L54: the Serreze and Barry 2015 is listed as 2014 in the refs.

It should be 2014; the text has been amended.

Figure 2. scale and north arrow unreadable – too small.

We should have caught this. The scale and north arrow have been made much bigger. We of course edited Figure 3 as well.

Figure 1. need to indicate location of Environment Canada weather stations from which data is used. Alert is identified, but should be stated in the caption that it is one location of the long term temp data. Eureka (from which precip data is obtained) is not on the map at all.

The caption has been amended and the figure has been amended to show station Eureka.

Rapid Wastage of the Hazen Plateau Ice Caps, Northeastern Ellesmere Island, Nunavut, Canada

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Abstract

Two pairs of small stagnant ice bodies on the Hazen Plateau of northeastern Ellesmere Island, the St. ~~-~~Patrick Bay ice caps and the Murray and Simmons ice caps, are rapidly shrinking, and the remnants of the St. Patrick Bay ice caps are likely to disappear entirely within the next five years. ~~-~~ Vertical aerial photographs of these Little Ice Age relics taken during August of 1959 show that the larger of the St. Patrick Bay ice caps had an area of 7.48 km^2, and the smaller one 2.93 km^2~~.~~; t~~T~~he Murray and Simmons ice caps covered 4.37 km^2 and 7.45 km^2 respectively. Outlines determined from ASTER satellite data for July 2016 show that, compared to 1959, the larger and the smaller of the St. Patrick Bay ice caps had both been reduced to only 5% of their former area, with the Murray and Simmons ice caps faring better at 39% and 25%, likely reflecting their higher elevation. Consistent with findings from other glaciological studies in the Queen Elizabeth Islands, ASTER imagery in conjunction with past GPS surveys documents a strikingly rapid wastage of the St. Patrick Bay ice caps over the last 15 years. These two ice caps shrank noticeably even between 2014 and 2015, apparently in direct response to the especially warm summer of 2015 over northeastern Ellesmere Island. The well-documented recession patterns of the Hazen Plateau ice caps over the last 55+ years offer an opportunity to examine the processes of plant recolonization of polar landscapes.

Keywords: Arctic, ice caps, mass balance, Little Ice Age, Hazen Plateau, Ellesmere Island, ASTER

1. Introduction

The Hazen Plateau of northeastern Ellesmere Island, Nunavut, Canada, is a rolling upland, with elevations rising from about 300 meters above sea level near Lake Hazen to over 1000 m along the northeast coast of the island. The plateau is unglaciated with the exception of two pairs of small stagnant ice caps - the unofficially-named St. Patrick Bay ice caps, and, 110 km to the southwest, the Murray and Simmons ice caps (**Figure 1**). They are collectively referred to here as the Hazen Plateau ice caps. As of 2001, ~~The~~ the larger St. Patrick Bay ice cap~~s~~ ranged in -elevation between about 880 m and 720 m above sea level, with the smaller one spanning ~~-~~820 m to 700 m. ~~are in an area with maximum elevations between 750-900 m; t~~The Murray and Simmons ice caps lie ~~are~~ in higher terrain; in 2001, both fell between about 1100 m and 1000 m above sea level. ~~, ranging from 950 to 1100 m.~~ The Hazen Plateau ice caps are interpreted as forming and attaining their maximum extents during the Little Ice Age (LIA, c. 1600-1850) (Koerner, 1989). Like much of the Queen Elizabeth Islands~~Canadian Arctic Archipelago~~, the Hazen Plateau is presently a polar desert; annual precipitation is typically only 150-200 mm, with a late summer and early autumn maximum (Serreze and Barry, 2014~~5~~). Summer precipitation may be variously rain or snow. Summers are very cool but variable; assessed as part of a multiyear glaciological study (Braun et al., 2004), the average 10 m July air temperature at the Murray ice cap summit (1100 m) measured for the years 1999 through 2001, respectively, was 4.0°C, 0.2°C and 1.6°C.

This paper documents the behavior of the Hazen Plateau ice caps over the past 55+ years in the context of other glaciological studies in the Canadian Arctic. ~~.~~ The analysis is based on a combination of past work using aerial photography, direct mass balance measurements from several field investigations, and GPS surveys of ice cap areas collected as part of these investigations –~~,~~ along with new information on ice cap areas using ~~and~~ data at 15 m resolution from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) instrument. ASTER flies onboard the NASA's Earth Observing System Terra satellite, launched in December 1999. It provides reflectance at a 15 m resolution and is a key asset of the international GLIMS initiative (Global Land Ice Measurements from Space) for mapping glacier outlines (Raup et al., 2007; Kargel et al., 2014).

2. Previous Work

Table 1 lists all available direct mass balance estimates of the ice caps (in meters water equivalent, or w.e.). Table 2 provides all available estimates of ice cap areas (km^2). The first information on the St. Patrick Bay ice caps that we are aware of is oblique aerial photographs taken in late July of 1947 as part of the U.S. Operation Polaris Trimetregon Survey. These photographs show the ice caps standing out prominently against the snow-free tundra surface. Vertical aerial photographs collected by the Canada Department of Energy, Mines and Resources followed in August of 1959. These photographs show prominent, e~~E~~xposed surface dirt layers and stratigraphic layering ~~g are prominent~~ on the St. Patrick Bay ice caps, and the Murray and Simmons ice caps are~~were~~ also bare of snow. From digitizing the 1959 photographs and mapping the ice cap outlines , ~~**(Table 1)**,~~ the larger of the St. Patrick Bay ice caps then had an area of 7.48 km^2, and the smaller one 2.94 km^2. The Murray and Simmons ice caps covered, respectively 4.37 and 7.45 km^2 (Serreze, 1985; Bradley and Serreze, 1987; Braun et al., 2004). We estimate that these areas are accurate to within 5%.

In July of 1972, Canadian scientists H. Serson and J. A. Morrison surveyed the larger of the two St. ~~-~~Patrick Bay ice caps. They landed by helicopter in foul weather to find the ice cap totally covered with snow. They installed eight accumulation stakes along a roughly two kilometer transect partway across the ice cap. The range in elevation along this transect was about 60 m, which compares to a range for the entire ice cap of about 160 m. Later that same summer, on August 20-21, the ice cap was visited by G. Hattersley-Smith and A. Davidson, who noted a "partial cover of winter snow all around the ice margins for at least a kilometer" (Hattersley-Smith and Serson, 1973), in~~a~~ striking contrast with conditions depicted in the August 1947 and 1959 aerial photographs. They concluded that while the ice cap had been in decline (as suggested from the 1947 and 1959 photographs), by the early 1970s it had returned to good health, "thickening slightly and extending its margins" (icy firn was observed atop the dirty melt surface and a perennial snow cover extended beyond the ice cap margins). This is~~,~~ consistent with a known shift towards cooler summers and increased precipitation over the eastern Canadian Arctic (Bradley and Miller, 1972; Bradley and England, 1978). Hattersley Smith and Serson estimated a mass balance for the 1971/1972 season of +0.14 m w.e. ~~The smaller St. Patrick Bay ice cap and the higher-elevation Murray and Simmons ice caps presumably exhibited the same behavior (Braun et al., 2004).~~

In 1982 and 1983, the St. Patrick Bay ice caps were the focus of detailed energy and mass balance investigations (Serreze, 1985; Bradley and Serreze, 1987; Serreze and Bradley, 1987). The stake network was expanded on the larger St. Patrick Bay ice cap ~~was expanded~~ and several stakes were installed on the smaller one. At the end of the 1982 field season in early August, the entire ice cap was bare ice with a well-developed cryoconite surface. Assuming that the 1982 melt season had largely ended by early August (all visible melt had stopped by the time that the field camp had been evacuated), the 1981/1982 mass balance for the larger ice cap was estimated at -0.14 m w.e.~~water equivalent~~. Given that more melt may have occurred, this is likely a minimum estimate. Based on the stake line installed in 1972, Bradley and Serreze (1987) estimated that the overall mass balance for the period 1972-1982 was approximately -1.3 m w.e. (-0.14 a^{-1})~~water equivalent~~. This result finds qualitative support in comparisons between the 1959 aerial photographs and subsequent vertical aerial photographs taken on 1 August 1978 showing that the larger and smaller of the ice caps had decreased ~~shrunk~~ in area by 7% and 11% over that interval. ~~(Table 1).~~ Like the 1959 photographs, the August 1978~~,~~ photographs revealed a snow-free plateau and bare ice with a prominent ablation surface. Aerial photographs taken four years earlier, on 4 August 1974, showed broadly similar conditions. As part of the St. Patrick Bay Project, a network of stakes installed on the Simmons ice cap in 1976 (Bradley and England, 1977) was re-surveyed on 11 July 1983. Of the 18 original stakes, only 6 could be located; the others were presumed to have melted out. Based on these sparse data, Bradley and Serreze (1987) estimated that over the period 1976-1983, the Simmons ice cap experienced a total mass loss of at least ~~came up with a minimum mass balance estimate for the Simmons ice cap of~~ -0.49 meters w.e. (-0.08 a^{-1}). ~~water equivalent~~ ~~over the period 1976-1983.~~ Collectively, these observations provided strong evidence that the period of recovery inferred ~~argued~~ by Hattersley-Smith and Serson (1973) was short-lived.

However, the summer of 1983 was ~~fairly~~ cool, and the ~~apparent exception to the overall pattern of mass loss since at least 1959. The~~ snow never completely melted off the surrounding tundra. The 1982/1983 annual mass balance for the larger St. Patrick Bay ice cap was estimated at +0.14 m w.e. ~~water equivalent~~, and given their higher elevation, it is reasonable to assume that the 1982/1983 balance year for the Simmons and Murray ice caps was also positive.

Table 1. Directly measured mass balances (meter water equivalent) of the Hazen Plateau ice caps. Where a value represents a multiyear record, the average annual value is shown in parentheses. Asterisks denote minimum estimates.

Balance year or period	Large St. Patrick Bay	Small St. Patrick Bay	Murray	Simmons
1971/72	+0.14^{1}	-----	-----	-----
1971/72-1981/82	-1.3^{2} (-0.14)^{2}	-----	-----	-----
1975/76-1982/83	-----	-----	-----	*-0.49 (-0.08)^{2}
1981/82	*-0.14^{2}	-----	-----	-----
1982/83	+0.14^{2}	-----	-----	-----
1983/84-1997/98	-----	-----	-----	*--0.49 (-0.03)^{4}
1983/84-1999/00	*-1.01 (-0.06)^{3}	*-1.26^{3} (-0.07)^{3}	-----	-----
1998/99	-----	-----	-0.49^{3}	-----
1999/00	-----	------	-0.29^{3}	-0.40^{3}
2000/01	-----	-----	-0.47^{3}	-0.52^{3}
2001/02	-----	-----	-0.29^{3}	-----

Sources: [1]Hattersley-Smith and Serson (1973); [2]Bradley and Serreze (1987); [3]Braun et al. (2004)

To our knowledge, there were no further visits ~~were made~~ to the Hazen Plateau ice caps until 1999, when C. Braun, D. Hardy and R. Bradley of the University of Massachusetts Amherst established a network of 11 accumulation stakes on the Murray Ice Cap, which they ~~was~~ further expanded in the year 2000. A new network of 15 stakes was established on the Simmons ice cap in 2000. Winter snow accumulation was measured on both ice caps in late May of 1999 through 2001, and summer ablation was measured in late July and early August from 1999-2002. For the four years analyzed, 1999-2002, annual balances of both ice caps were negative in ~~for~~ all years,~~ for both ice caps,~~ ranging from -0.29 m w.e. (Murray ice cap in 2000) to -0.52 m w.e. (Simmons ice cap in 2001).~~ water equivalent.~~

In the summer of 2001, C. Braun and D. Hardy used portable GPS to survey the perimeter of all four ice caps. ~~Compared to 1959, t~~The larger and smaller of the St. Patrick Bay ice caps had shrunk to 62% and 59% of their 1959 areas, respectively. ~~former areas.~~ The Murray and Simmons ice caps had shrunk to ~~covered~~ 70% and 53% of their 1959 ~~former~~ areas~~ (Table 1)~~. Some of the accumulation stakes inserted into the larger St. Patrick Bay ice cap in 1982 and 1983 were located but all had melted out. Knowing how deep they had been originally inserted enabled ~~helped to pin down~~ a minimum estimate (-1.01 m w.e., -0.06 a^{-1}) of the mass loss between 1984 and 2000. This is based on the mean remaining depth of stake insertion into the ice in 1983 and an assumed ice density of 900 kg m^{3}~~ of -1.01 m water equivalent~~ (Braun et al., 2004). In the late summer of 2003, C. Braun mapped the margins of the Murray and Simmons ice caps via portable GPS by holding the device out the window of a low-flying helicopter. The same approach was used to assess the ice cap margins in 2006, this time by University of Massachusetts graduate student T. Cook.

3. Updated History,~~History of Change~~ 1959 to 2016

3.1 Ice Cap Areas

~~Table 1 lists the ice cap areas from all available observations through July of 2016 in square kilometers and as a percent of areas covered in the 1959 aerial photographs.~~ The use of ASTER in conjunction with the air photographs and GPS surveys enables a fairly detailed assessment of changes in ice cap areas from 1959 through the present. Clear-sky late summer (July or August) scenes of the St. Patrick Bay ice caps showing a strong brightness contrast between the ice and the bare, dark plateau surface,- enabled manual mapping of the ice cap perimeters from ASTER for the years 2005, 2009, 2014, 2015 and 2016. For the Murray and Simmons ice caps, ASTER estimates were obtained for 2001, 2007 and 2016. For 2001, areas of ~~for~~ the Murray and Simmons were available from both ASTER and the surface-based GPS surveys. Considering the GPS surveys for this year as ground truth, the ASTER areas for this year are accurate to within 1% for the Murray ice cap and 3% for the Simmons ice cap. It is assumed that this is representative of the accuracy of area mapping from ASTER for the other years.

As of July 2016, and Murray and Simmons ice caps cover 39% and 25% of the areas ~~covered~~ in 1959 based on the aerial photographs. -By sharp contrast, both of the St. Patrick Bay ice caps in 2016 cover only 5% of their former areas, and ~~. Both~~ have been reduced to ice patches, with the smaller ice body now covering only ~~a scant~~ 0.15 km^2.

Table 2~~1~~. Surface areas (km^2) and % areas compared to 1959 aerial photographs

	Larger St. Patrick Bay Ice Cap Area and % of 1959		Smaller St. Patrick Bay Ice Cap Area and % of 1959		Murray Ice Cap Area and % of 1959		Simmons Ice Cap Area and % of 1959	
1959	7.48^1	100%	2.94^1	100%	4.37^1	100%	7.45^1	100%
1978	6.69^1	89%	2.74^1	93%	------	------	------	------
1999	------	------	------	------	3.28^2	75%	------	------
2000	------	------	------	------	3.15^2	72%	------	------
2001	4.61^2	62%	1.72^2	58%	$3.05^2(3.08^4)$	70%	$3.94^2(3.83^4)$	53%
2003	------	------	------	------	2.91^3	66%	3.31^3	44%
2005	3.68^4	49%	1.03^4	35%	------	------	------	------
2006	------	------	------	------	2.86^3	65%	3.19^3	43%
2007	------	------	------	------	2.76^4	63%	2.92^4	39%
2009	2.54^4	34%	0.63^4	21%	------	------	------	------
2014	1.03^4	14%	0.29^4	10%	------	------	------	------
2015	0.52^4	7%	0.18^4	6%	------	------	------	------
2016	0.35^4	5%	0.15^4	5%	1.72^4	39%	1.84^4	25%

[1]Aerial photographs, [2]Surface GPS surveys, *Braun et al.* (2004), [3]GPS helicopter surveys, [4]ASTER

Outlines of the St. Patrick Bay ice caps for 1959 from aerial photography, for 2001 from GPS surveys, and for 2014 and 2015 from ASTER are shown in **Figure 2**. The reductions in ice cap area~~s~~ are~~is~~ striking. Note the obvious shrinkage even between the years 2014 and 2015. Shrinkage of the Murray and Simmons ice caps is -shown ~~similarly documented~~ in **Figure 3**, based on outlines from ~~but showing~~ 1959, 2001 and 2016. The shrinkage of these two ice caps is clearly evident, albeit less pronounced.

Using the area estimates through 2002 and extrapolating forward, Braun et al. (2004) suggested that the Hazen Plateau ice caps would disappear by the middle of the 21st century or soon thereafter, and that, given their larger size, the Simmons ice cap and the larger of the two St. Patrick Bay ice caps would be the last to go. However, based on data through 2016 and extrapolating forward (**Figure 4**), it now appears that both of the St. Patrick Bay ice caps will disappear around the year 2020. ~~Consistent with findings for other Arctic glaciers (e.g, Gardner et al., 2011; Sharp et al., 2011; Mortimer et al., 2016), there has been a rapid loss in ice-covered area since the beginning of the 21st century. Likely reflecting their higher elevation, the Murray and Simmons ice caps may yet persist until 2030-2040.~~

From the analyses described above, and results from other glaciological investigations for the Canadian Arctic and the Arctic as a whole, the following conclusions are drawn:

- The Hazen Plateau ice caps are unlikely to be relics of the last glacial maximum, but rather likely formed during the Little Ice Age (LIA, c. 1600-1850) (Koerner, 1989). They may have retained their LIA extents through the first couple decades of the 20th century (Hattersley-Smith, 1969; Sharp et al., 2014), but have been in overall decline ever since. Braun et al. (2004) speculate on the basis of a mapped lichen trim line that the Murray ice cap may have attained a maximum LIA extent of about 9.6 km^2, over twice the mapped 1959 area of 4.35 km^2. Similar trim lines were observed around the other three ice caps and although not mapped in detail, strongly point to much more extensive ice cover during the LIA. To place these findings in a broader context, for the Queen Elizabeth Islands as a whole, trim lines based on high-resolution satellite imagery point to a 37% reduction in perennial snow and ice extent between the LIA maximum extent and the year 1960. Over the lower-lying central and western islands, a complete removal of perennial snow and ice occurred by 1960 (Wolken et al., 2008).

- From the 1960s through part of the 1970s, the ice caps may have experienced a period of reduced loss or occasional growth (1971/1972, 1982/1983) in response to cooling. This basic pattern likely holds for monitored Canadian Arctic glaciers and ice caps as a whole (Bradley and Miller, 1972; Hattersley-Smith and Serson, 1973; Ommanney, 1977; Bradley and England, 1978; Braun et al., 2004; Sharp et al., 2014).

- Since then, apart from occasional years such as 1982/1983, annual mass balances of the four ice caps have been persistently negative (Braun et al., 2004). This is in turn consistent with the broader pattern of reductions in mass and area of Arctic glaciers and ice caps (Dowdeswell et al., 1997; Dyurgerov and Meier, 1997; Arendt et al., 2002; Koerner, 2005; Sharp et al., 2011, 2014; Fisher et al., 2012; Sharp et al., 2014; Mortimer et al., 2016). It is also consistent with a negative mass balance of the Greenland Ice Sheet since at least the 1990s (Shepard et al., 2012).

Mass balance summaries for four monitored glaciers and ice caps in the Canadian Arctic (Devon Ice Cap, Meighan Ice Cap, Melville South Ice Cap and the White Glacier) are provided as part of the American Meteorological Society (AMS) State of the Climate reports. As assessed over the period 1980 through 2010, all four have had negative average annual mass balances, ranging from -0.15 m w.e. for the Devon Ice Cap to -0.29 w.e. for the Melville South Ice Cap (AMS, 2016). Cumulative changes in regional total stored water for the period 2003 through 2015 based on gravimetric data from the GRACE mission (Gravity Recovery and Climate Experiment) are qualitatively consistent with these mass balance measurements (AMS, 2016). Based on ice core data, Fisher et al. (2012) document rapid acceleration of ice cap melt rates of over the last few decades across the entire Canadian Arctic; the large reductions in area of the Hazen Plateau ice caps, in particular the lower-elevation St. Patrick Bay ice caps, is consistent with this finding. However, reflecting variable climate conditions, annual balances are also quite variable. For example, for the 2013/2014 balance year (the most recent data available), the White Glacier had a strongly negative balance (-0.42 m w.e.) while the small Meighan Ice Cap actually gained mass (+0.06) (AMS, 2016). Sharp et al. (2014) show that while the larger ice bodies in the Canadian Arctic have seen the largest losses in mass, the smaller masses have lost a larger proportion on their areas. This is also consistent with the behavior of the Hazen Plateau ice caps. Below we examine variability in climate conditions over the Hazen Plateau, and links to mass balance and area changes.

3.2 Associated ~~Links with~~ Climate Conditions

The annual mass balance of low-accumulation ice caps and glaciers in the Canadian High Arctic is known to be primarily governed by summer warmth rather than winter accumulation (e.g., Bradley and England, 1978; Koerner, 2005). To place the behavior of the Hazen Plateau ice caps in a climate context, use is made of summer-averaged (June through August) 850 hectopascal (hPa) temperature anomalies from the radiosonde record at Alert, located on the northeast coast of Ellesmere Island (Figure 1) along with estimated summer temperature anomalies for the LIA. The Alert radiosonde record extends back to 1957. We use monthly mean records contained in the Integrated Global Radiosonde Archive (IGRA, Durre et al., 2006), based on daily 00 and 12 UTC soundings. Summer averages (J,J,A) were eliminated if based on fewer than 70 values. The 850 hPa level is about 1400 m above sea level for a standard atmosphere, hence roughly ~~5~~600-70~~65~~0 m above the surface in the vicinity of the St. Patrick Bay ice caps and 300-400~~350~~ m above the surface in the vicinity of the Murray and Simmons ice caps. While arguably it might be better to look at the 925 hPa level as it is closer to the plateau surface, this level has many missing values in the IGRA record. The time series of anomalies, computed with respect to the standard averaging period 1981-2010, follows ~~is shown~~ in **Figure 5**.

Kaufman et al. (2010) took advantage of a variety of proxy sources (e.g., tree rings, ice cores, lake cores) to assemble a record of Arctic summer surface temperature anomalies that extend back 2000 years. From their analysis, LIA summer Arctic temperatures anomalies averaged around -0.6°C with respect to a 1961-1990 reference period. The 1961-1990 summer mean of -3.2°C from the radiosonde data compares to a mean of -2.6°C for 1981-2000. The latter period is hence about 0.6°C warmer. With the assumption that (a) ~~Assuming that~~ temperature anomalies at ~~the~~ 850 hPa ~~level~~ have been similar to those at the surface (supported by Sharp et al. (2011) in their analysis of Canadian Arctic ice caps but possibly complicated by the temperature inversion structure), and ~~that~~ (b) LIA conditions over the Hazen Plateau were at least broadly similar to those for the Arctic as a whole, these results imply that Arctic LIA temperature anomalies were about -1.2°C relative to a 1981-2000 baseline. This estimated LIA temperature anomaly is shown in Figure 5 as a dashed line.

If it is also accepted that the ice caps were broadly in equilibrium with average LIA summer temperatures, Figure 5 suggests ~~points to~~ generally strong negative annual balances from the beginning of the record through the early 1960s. This was followed by smaller negative and occasionally positive annual balances from the middle of the 1960s through about 2000, and a preponderance of strong negative balances from the beginning of the century through the present. For comparison with the radiosonde record, we also examined 850 hPa summer temperatures over the Hazen Plateau from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al., 1996) which extend back to 1948. Given that the Alert radiosonde data are assimilated into the reanalysis, it follows that the radiosonde and NCEP/NCAR time series look similar for the period of overlap. The NCEP/NCAR records suggest that the period 1948-1956 not covered by the IGRA record was ~~fairly~~ warm overall~~,~~ with mostly positive anomalies relative to the 1981-2000 baseline. The cooling between the late 1940s through the middle 1960s broadly corresponds to the cooling over the eastern Canadian Arctic such as discussed by Bradley and Miller (1972),~~) and~~ Bradley and England (1978) and other studies. ~~.~~The time series of decadal mean summer temperatures at the 700 hPa level ~~Pa level~~ for the major glaciated regions of the Canadian Arctic presented by Sharp et al. (2011) based on the NCEP/NCAR reanalysis (their Figure 9.3) is also consistent with the pattern shown in Figure 5.

An examination ~~Looking at some~~ of selected ~~the~~ individual years is instructive. ~~, b~~Based on summer 1957 temperatures, the 1956/1957 annual balance must have been strongly negative. The same can be said for 1959/1960 and 1962/1963. By sharp contrast, the summer of 1972, when Hattersley-Smith and Serson (1973) visited the ice caps and remarked upon the extensive August snow cover over the plateau and estimated a positive balance of +0.14 m w.e. (for the 1971/1972 season), -was- the coldest in the radiosonde record, and about 2°C below the estimated LIA average. There is also a clear contrast between 1982 (a known negative annual balance year for the St. Patrick Bay ice caps) and 1983 (a known positive balance year, with summer 850 hPa temperatures slightly below the LIA average). Given the low temperatures for the summer of 1992, which followed the 1991 eruption of Mt. Pinatubo, the balance for 1991/1992 was likely~~almost certainly~~ positive. -In the sense that -summer temperatures were above the estimate LIA average,~~Measured~~ negative balances for the Murray ice caps for 1998/1999 through 2001/2002 (Braun et al., 2004) are all consistent with Figure 5. Note however that the largest negative balance of -0.49 m w.e. for 1999/2000 corresponds to the coldest of the four summers,- arguing for influences of local effects on summer temperature or perhaps a low winter accumulation.

Regarding the summer of 2013, the obvious exception to the pattern of recent warm years, the ASTER data and daily images from the Moderate Resolution Imaging Spectroradiometer (MODIS) show extensive cloud cover through the summer, making it difficult to determine whether the snow cover ever entirely cleared off the plateau. It is likely, however, that the 2012/2013 balance year was positive for the Hazen Plateau ice caps - the Devon Ice Cap, Meighan Ice Cap and the White Glacier all gained mass. Only the Melville South Ice Cap, lying well to the west, had a negative balance (AMS, 2014). Consistent with this view, **Figure 6** shows that summer (J,J,A)- averaged 850 hPa temperature anomalies over the Queen Elizabeth Islands from the NCEP/NCAR reanalysis were about -2°C below the 1981-2010 baseline -in the area centered over Axel -Heiberg- and Ellesmere islands. This reflects the influence of an unusually--deep circumpolar vortex at the 500 hPa level, centered just south of the Pole along about 90°W longitude. By sharp contrast, t~~T~~he notable area reduction of the St. Patrick Bay ice caps between August 2014 and 2015 aligns with the very warm summer of 2015, essentially tied with 1957 as the highest in the record. From **Figure 7~~6~~**, July 2015 temperatures at the 850 hPa level from the NCEP/NCAR reanalysis were 3-4°C above the ~~standard~~ 1981-2010 baseline over most of northeastern Ellesmere Island. Mass balance estimates for monitored glaciers in the Queen Elizabeth Islands for the 2014/2015 season that would provide context ~~,~~were not available us at the time that this paper came to press.

4. Conclusions

Regarding accelerating wastage of the St. Patrick Bay ice caps since the dawn of the 21st century, the outsized warming of the Arctic in recent decades compared to the rest of the Northern Hemisphere (termed Arctic Amplification), is overall most strongly expressed during the cold season, and is not nearly as prominent in summer (Serreze and Barry, 2011). Nevertheless, from the NASA Goddard Institute for Space Sciences (GISS) analysis (http://data.giss.nasa.gov/gistemp/), the trend in July surface air temperatures over Northeastern Ellesmere Island over the period 1960-2015 is about 2°C (expressed as a total change) which stands out compared to the rest of the Arctic. On the basis of a satellite-derived record (from MODIS) of summer land surface temperatures, the more recent period of 2000 to 2015 has seen an average warming rate over the Queen Elizabeth Islands of 0.06°C per year, or a total of nearly 1.0°C, most of this occurring between 2005 and 2012 (Mortimer et al., 2016). They associate this warming with increasingly negative mass balances for glaciers and ice caps in the region. However, conditions over the Hazen Plateau are highly variable, and the summers of 1957, 1960 and 1963 were almost as warm as those seen in 2015, and the summer of 2013 was quite cool, very likely resulting in a positive balance for 2012/2013. ~~.~~

Rapid wastage of the St. Patrick Bay ice caps over the past 15 years likely also reflects a reduction in summer albedo, as dirt layers become progressively exposed and accumulate at the surface. ~~-~~During the 1982 and 1983 field campaigns, it was observed that summer precipitation over the ice caps was typically in the form of snow, temporarily increasing the surface albedo and adding some mass. The frequency of summer snowfall has likely declined in the (generally) sharply warming climate over the past 15 years. Also, as suggested from the prominent decline in the area of the larger St. Patrick Bay ice cap between 2014 and 2015, when there is an especially warm summer, the thin collar of ice at the ice cap margins (a feature evident in ~~from~~ field observations) will be prone to completely melting. The less pronounced area reduction of the Murray and Simmons ice caps must partly be due to their higher elevation and relatively cooler summer conditions. However, the elevation difference is only about 200-300 m, which argues that the stronger response of the St. Patrick Bay ice caps to warming may also be related to ice thickness. Regional differences in the temperature lapse rate (notably the temperature inversion structure) could also be involved.

It is possible that the Hazen Plateau caps could see some temporary recovery given the large natural variability in the Arctic. However, as noted by Alt (1978) and Bradley and England (1978), for stagnant ice caps such as these, all it takes is one warm summer to erase any accumulated mass gains of a previous decade. Assessing variability and trends in Arctic precipitation is notoriously difficult, but as evaluated over the period 1950-2007, annual precipitation has generally increased across Canada, and especially across Northern Canada. For example, a~~A~~t station Eureka in central Ellesmere Island (see Figure 1), annual precipitation appears to have increased by at least 40% (Zhang et al., 2008). Trends over the plateau are not known, but this suggests that, if anything, precipitation changes are helping to buffer the ice caps from summer mass loss.

Paradoxically, perhaps, loss of the Hazen Plateau ice caps may open new research opportunities. As they recede, plant remains are exposed that can be dated and used to better understand the past climate history of the region. From radiocarbon dates on rooted tundra plants exposed by receding cold-based ice caps on Baffin Island – given ~~, and knowing~~ that the plants are killed when the snowline drops below the collection sites – ~~,~~ Miller et al. (2013) were able to construct a record of summer temperatures over Arctic Canada for the past 5000 years. La Farge et al. (2013) discovered that ice loss in Sverdrup Pass, Ellesmere Island, has exposed nearly intact plant communities for which radiocarbon dates point to entombment during the LIA. They also found that these recently-~~-~~exposed, subglacial bryophytes can regenerate, which may have important implications for recolonization of polar landscapes. The area surrounding the receding Hazen Plateau ice caps provides a unique opportunity to examine this process of recolonization in the High Arctic, as the rates of ice recession are now well-documented for the last 55+ years (Table 1).

Author Contribution: M. Serreze led the overall effort. C. Braun, D. Hardy, and R.S. Bradley provided GPS data and historical documents. B. Raup analyzed the ASTER data. All authors contributed to the writing.

Data Availability: Radiosonde data for station Alert are available at from the Integrated Global Radiosonde Archive (ftp://ftp.ncdc.noaa.gov/pub/data/igra/). ASTER data can be obtained through the NASA Land Processes DAAC (https://lpdaac.usgs.gov/).

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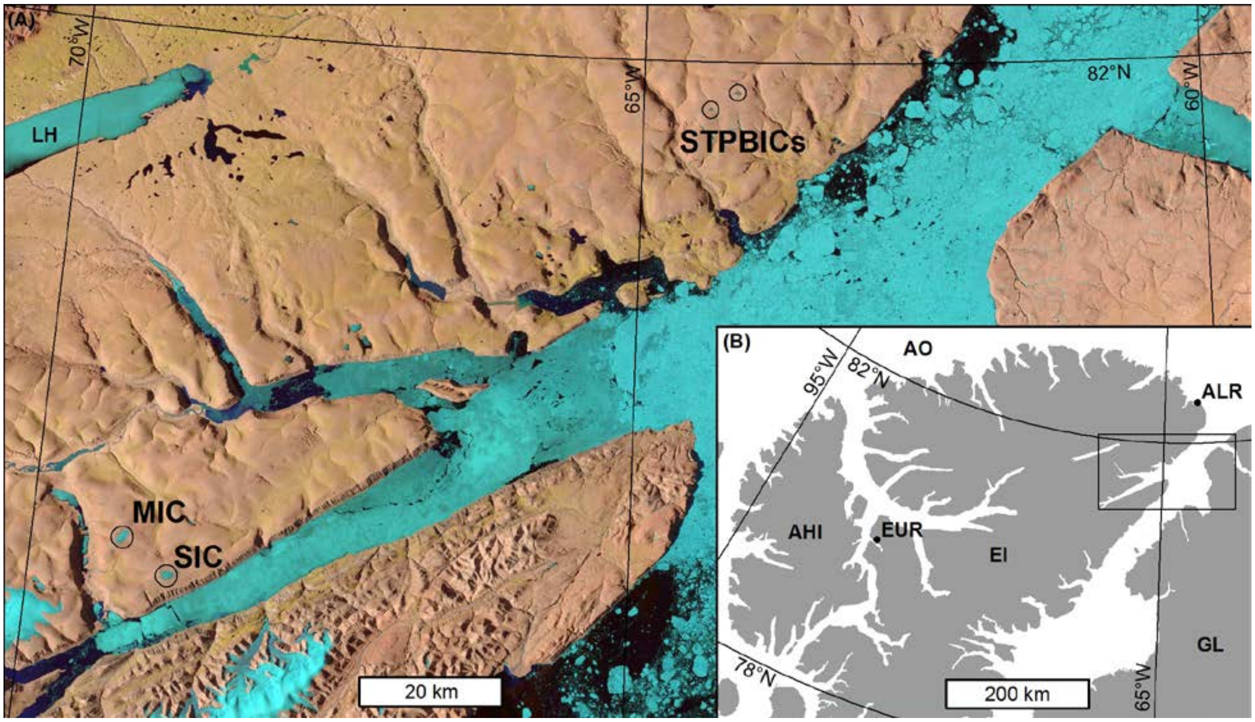

Figure 1. The location of the St. Patrick Bay (STPBIC), Murray (MIC) and Simmons (SIC) ice caps. The inset map shows Ellesmere Island (EL), Axel -Heiberg Island (AHI), Greenland (GL), the Arctic Ocean (AO) and station Alerts (ALR) and Eureka (EUR). -Use is made of 850 hPa temperature data from the Alert radiosonde record and precipitation records -from Eureka.

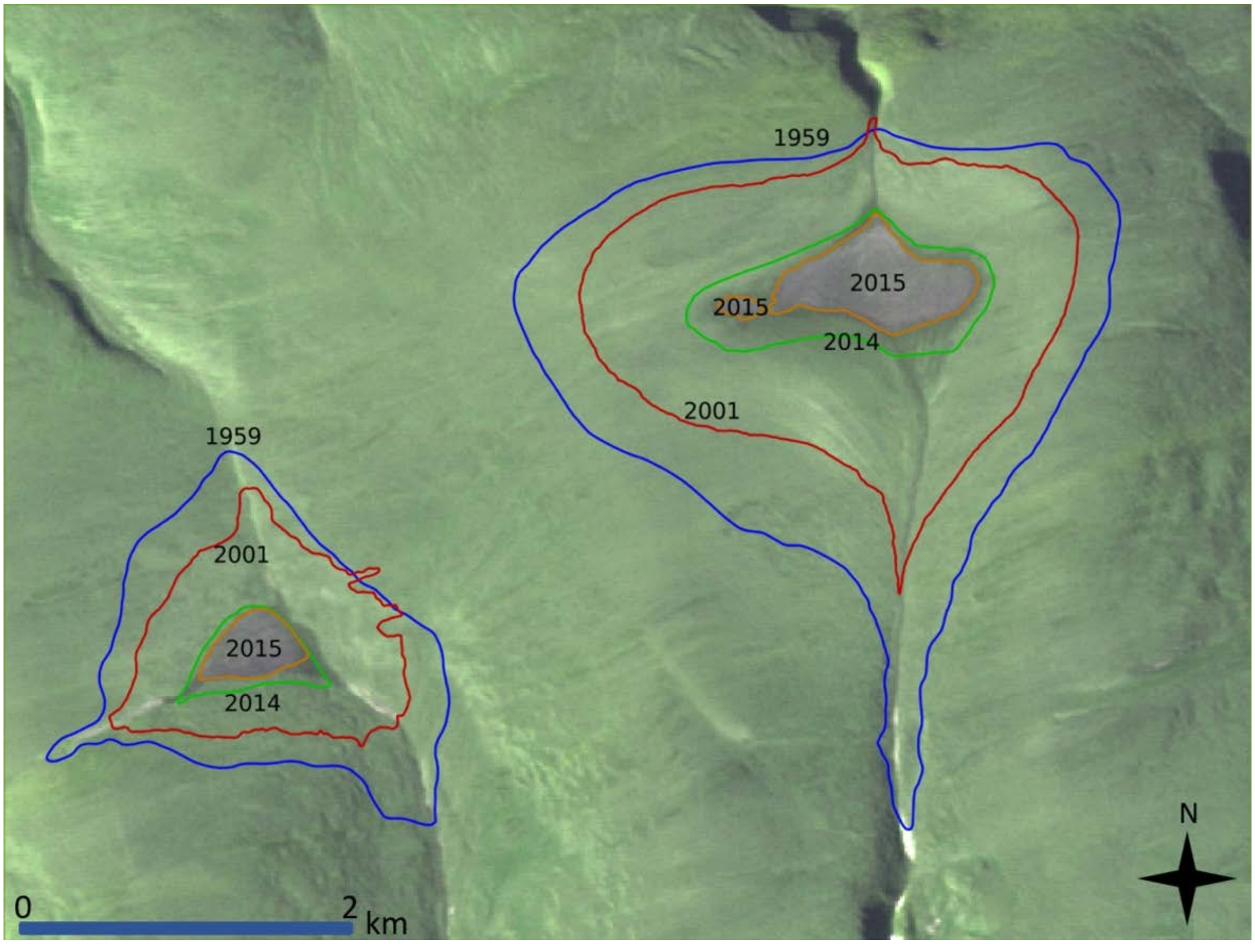

Figure 2: Outlines of the St. Patrick Bay ice caps based on aerial photography from August 1959, GPS surveys conducted during August 2001, and for August of 2014 and 2015 from ASTER. The base image is from August 2015.

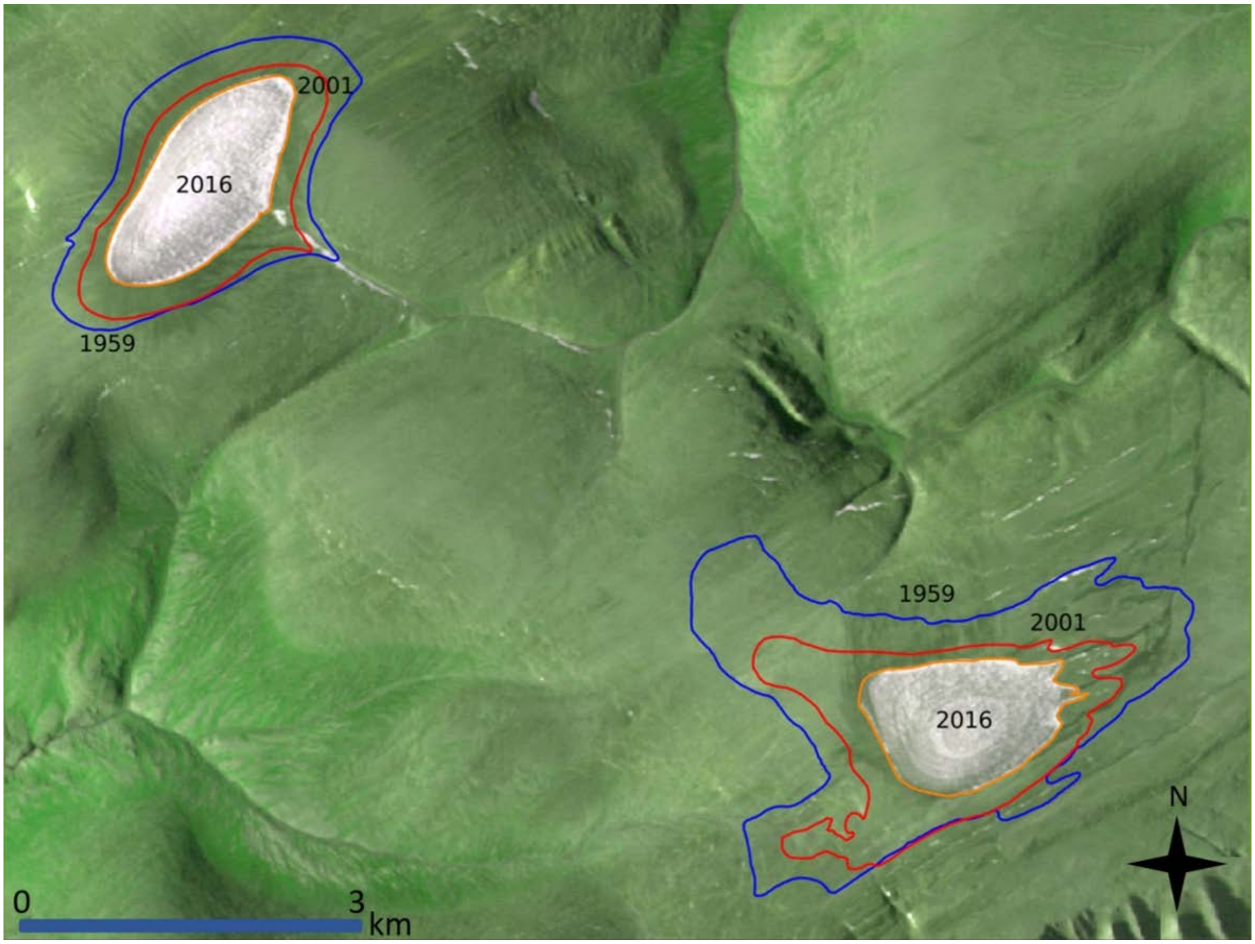

Figure 3: Outlines of the Murray and Simmons ice caps based on aerial photography from August 1959, GPS surveys conducted during August 2001, and for July 2016 from ASTER. The base image is from August 2016.

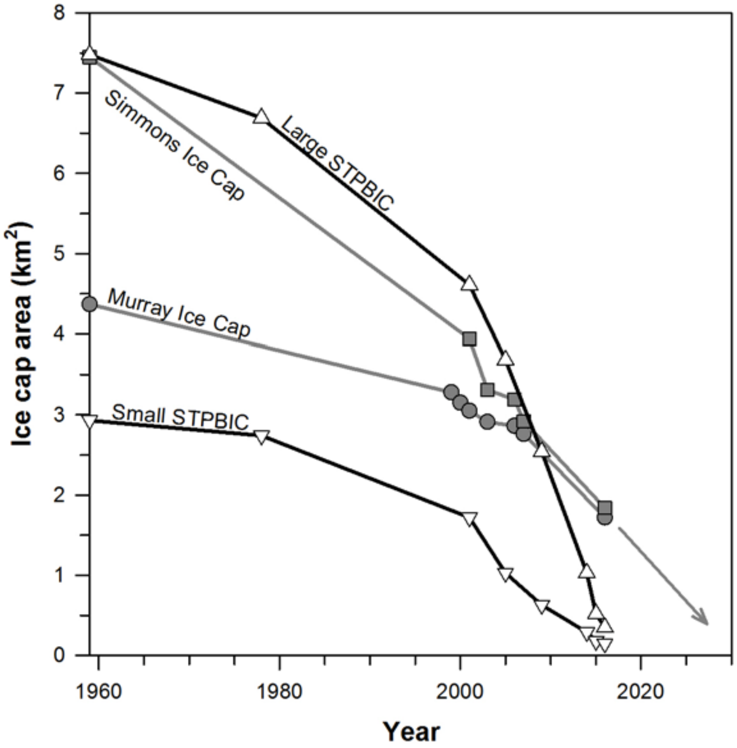

Figure 4. Time history of ice cap areas and projected times of disappearance.

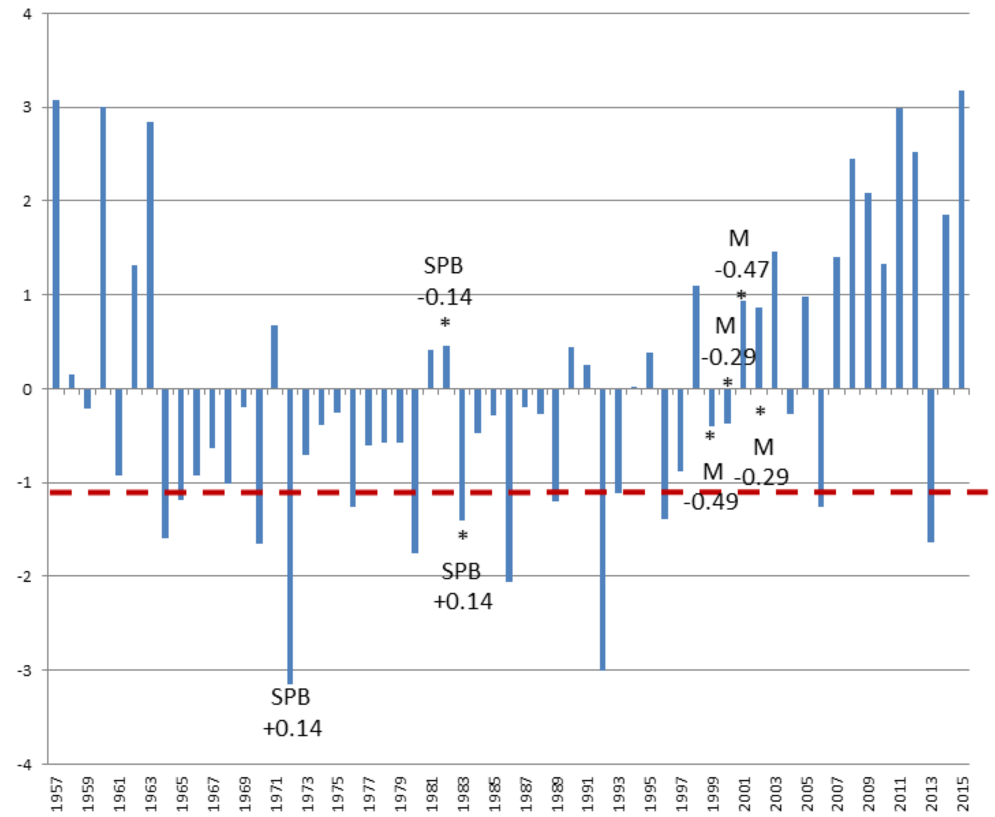

Figure 5. Temperature anomalies at the 850 hPa level (^{o}C) over the period 1957-2016 (referenced to the period 1981-2010) from the Alert radiosonde record. The dashed red line shows the estimated summer average Arctic temperature anomaly for the LIA relative to 1981-2010. Also shown are the annual mass balance estimates for the larger St. Patrick Bay (SBP) ice cap for the 1981/1982 and 1982/1983 balance years, and for the Murray Ice Cap (M) for the 1999/2000, 2000/2001, 2001/2002 and 2002/2003 balance years (in m w.e.).

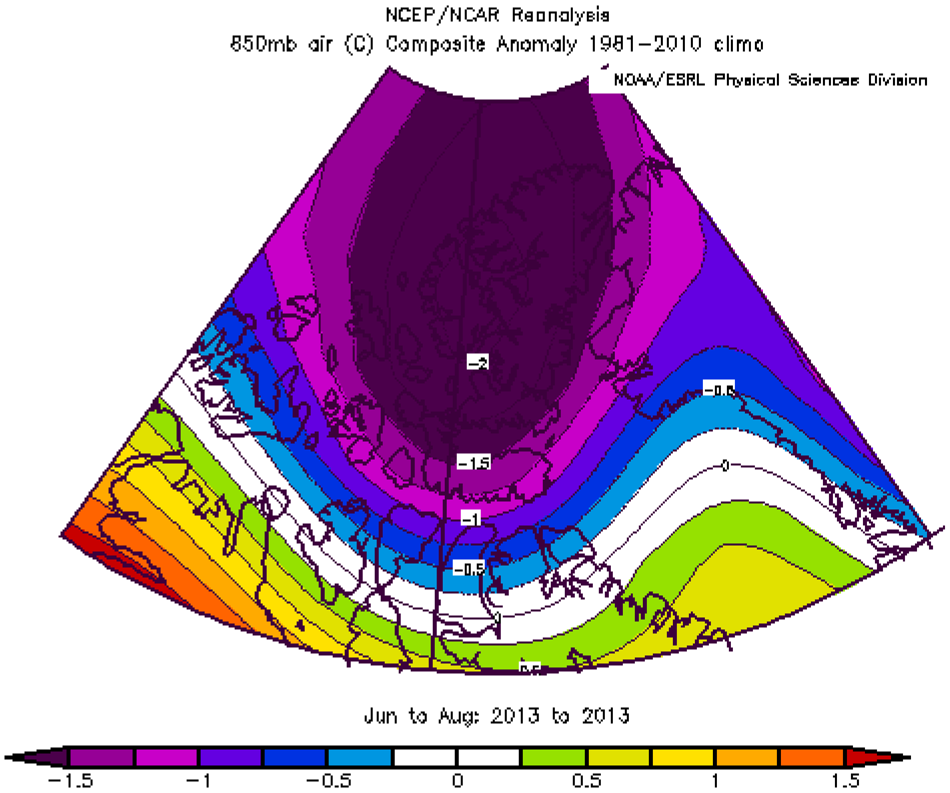

Figure 6. Summer (J,J,A) 2013 air temperature anomalies at the 850 hPa level from the NCEP/NCAR reanalysis relative to a 1981-2010 baseline.

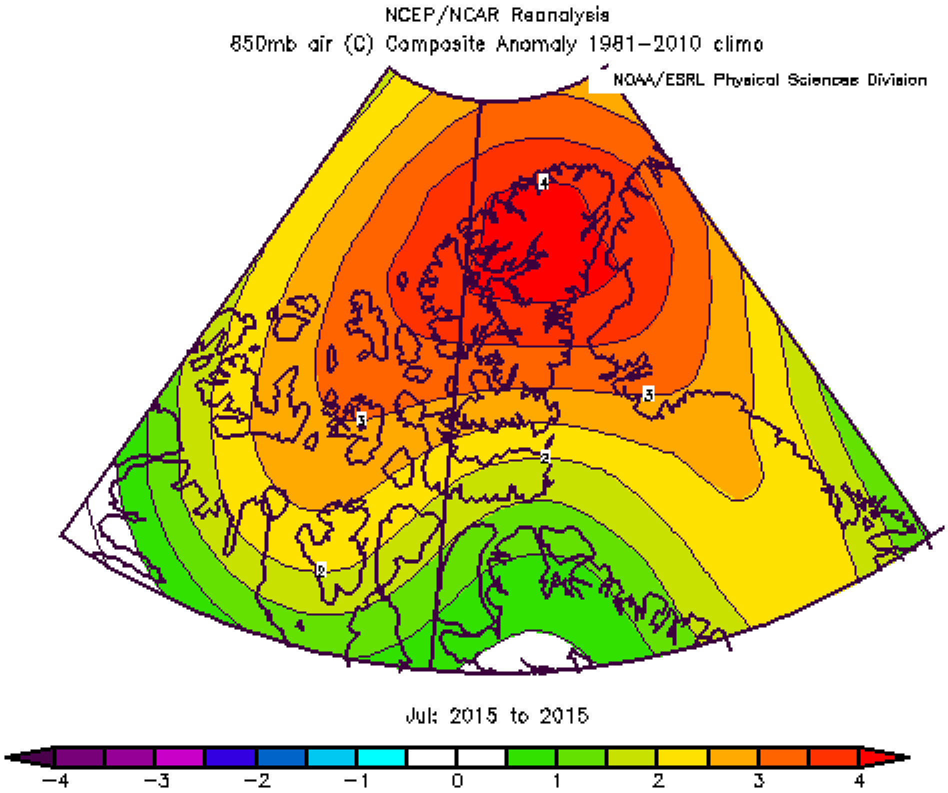

Figure 7~~6~~. July 2015 air temperature anomalies at the 850 hPa level from the NCEP/NCAR reanalysis relative to a 1981-2010 baseline.