An Examination of the Non-Formation of the North Water Polynya Ice Arch

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Abstract: The North Water (NOW), situated between Ellesmere Island and Greenland in northern Baffin Bay, is the largest recurring polynya in the Canadian Arctic. Historically, the northern border of the NOW is defined by an ice arch that forms annually in Kane Basin, which is part of the Nares Strait system. In 2007 the NOW ice arch failed to consolidate for the first time since observations began in the 1950s. The non-formation of the NOW ice arch occurred again in 2009, 2010, 2017 and 2019. Satellite Advanced Very High Resolution Radiometry data shows that large floes broke off from the normally stable landfast ice in Kane Basin for each of these years, impeding ice arch formation. A closer analysis of a 2019 event, in which 2500 km$^2$ of ice sheared away from Kane Basin, indicates that significant tidal forces played a role. The evidence suggests that thinning ice from a warming climate combined with large amplitude tides is a key factor in the changing ice dynamics of the NOW region. The non-formation of the NOW ice arch results in an increased loss of multiyear ice through Nares Strait.

Keywords: remote sensing; arctic waters; sea ice; marginal ice zones; tides

1. Introduction

A polynya is an area of the polar ocean that remains relatively ice-free in climatic conditions that would normally result in thick ice cover. These anomalous areas, which significantly impact the biology, climate, and oceanography of a region, are broadly categorized as sensible or latent heat polynyas. For sensible heat polynyas, vertical mixing of warmer water from depth due to ocean current advection or wind-induced upwelling prevents the formation of sea ice. In the case of a latent heat polynya, ice is continually swept away from the region by winds and ocean currents. The subsequent formation of new ice releases energy into the environment through latent heat of fusion. During winter, polynyas have an ocean-to-atmosphere heat flux approximately two orders of magnitude greater than the surrounding ice pack and dominate the regional heat budget [1]. These high latitude oases are centers of considerable biodiversity and provide important habitats for marine mammals and birds [2].

Situated between Greenland and Ellesmere Island in northern Baffin Bay, the North Water (NOW) is the largest recurring polynya in the Canadian Arctic with a maximum area of approximately 80,000 km$^2$ (Figure 1a). Typically, the NOW forms when pack ice transported southward through Nares Strait becomes congested during winter and forms an ice arch just north of Smith Sound in Kane Basin. The configuration of the polynya is established as newly formed ice is continually swept southward from the ice arch by prevailing winds and ocean currents (Figure 1b). Physical processes for NOW maintenance include latent heat of fusion, oceanic sensible heat, tidal influences and orographically channeled winds [3–12]. The ice arch generally breaks down in spring, allowing floes to enter Baffin Bay from the Arctic basin via Nares Strait.
Figure 1. (a) A map of the Nares Strait system showing Kane Basin, Smith Sound and the North Water (NOW) polynya. (b) Historically the northern border of the NOW is defined by an ice arch (red arrow) that forms during winter in Kane Basin. (c) Since 2007 the NOW ice arch has failed to consolidate in five years, but relatively short-term ice arches at the northern terminus of Nares Strait have formed (blue arrow). As shown in (b,c), Nares Strait freezes completely when the NOW ice arch forms but remains comparatively ice free along with the NOW when only the northern ice arch consolidates. (Satellite images in (b,c) are METOP-A Advanced Very High Resolution Radiometer Channel 4 thermal infrared with coastlines outlined.)
Nares Strait is approximately 500 km in length with depths varying from 200 m to 500 m. The northern section, which consists of Kennedy and Robeson Channels, varies from 30 to 50 km in width, while Kane Basin to the south widens to a maximum of 130 km. Prevailing winds funnel from the north through Nares Strait as a result of the orientation of the channel and mountainous topography of the region [13]. Arctic Ocean water flows southward through Nares Strait with a mean surface current speed ranging from 10 to 15 cm/s [14]. The highest tides in the Canadian Arctic occur in Kane Basin [15], which can reverse the Nares Strait current exiting Smith Sound and significantly change the ice dynamics on a diurnal basis [10]. The mean annual outflow of Arctic sea ice through Nares Strait is approximately 40,000 km² [16] and is dominated by thick multiyear ice originating north of Ellesmere Island in the Last Ice Area [17].

The NOW was established approximately 4500 years ago as evidenced by prehistoric bird colonies. The rich biological diversity of the region has allowed human settlement since 1250 AD [18]. The annual consistency of the NOW ice arch was noted on air reconnaissance surveys beginning in the 1950s and continued to show remarkable stability with the advent of global multispectral satellite observation in the late 1970s [19]. Geophysical changes began to occur in the NOW during the 1990s. The amount of open water in the polynya during winter increased during the decade, which may be attributable to a predominantly more negative phase of the North Atlantic Oscillation resulting in warmer temperatures [20]. In 1993 the NOW ice arch consolidated for only 10 days, while the first known spatial deviation of the structure occurred in 1995 when it formed 100 km north of Kane Basin [21]. In 2007 the NOW ice arch failed to consolidate for the first time since observations began in the 1950s [19,21], allowing a record area (87,000 km²) and volume (254 km³) of Arctic Ocean ice to pass through Nares Strait in a season [16]. The NOW ice arch failed to form again in 2009, 2010, 2017 and 2019, but during these years an ice arch consolidated at the northern terminus of Nares Strait (Figure 1c). During the five years in which the NOW ice arch failed to consolidate, Nares Strait was blocked for an average of 71 days each year by northern ice arches, which is significantly less than the 173-day average from 1979 to 2019 when the NOW ice arch formed [21]. Consequently, the non-formation of the NOW ice arch is a contributing factor to the dramatic loss of multiyear ice in the Arctic basin [22].

This paper examines the non-formation of the NOW ice arch using satellite data in the optical and thermal infrared (TIR) regime. Following an overview of the methods, the ice dynamics of Kane Basin are described using satellite data for the five years of ice arch non-formation. An in-depth analysis is then carried out for 2019 using satellite TIR imagery and ground based environmental information, including tidal data, sea ice classification, surface air temperature, and wind velocity. The final sections are a discussion of the results and conclusions.

2. Methods

2.1. Satellite Data

This study uses Advanced Very High Resolution Radiometry (AVHRR) imagery obtained from National Oceanic and Atmospheric Administration (NOAA)-18 and European Space Agency METOP-A satellites. The AVHRR sensor images the Earth in visible and TIR wavelengths with a spatial resolution of 1.1 km at nadir. The large swath of the sensor in conjunction with the polar orbit of the host satellites allows Nares Strait and the NOW to be imaged seven times a day with a temporal resolution of approximately 100 min between successive passes. The study area is relatively close to satellite nadir for passes between 1500Z and 1800Z daily offering good spatial resolution. Table 1 contains pertinent information for the AVHRR sensor. All AVHRR data were retrieved online from NOAA’s Comprehensive Large Array-Data Stewardship System [23].
Surface temperatures were determined for METOP-A AVHRR images using the single channel Composite Arctic Sea Surface Temperature Algorithm (CASSTA) [24]. In clear sky conditions CASSTA uses Channel 4 to determine the temperature of three regimes: sea surface, ice surface, and marginal ice zones containing a combination of seawater and ice. The single channel architecture mitigates inaccuracies of split window algorithms that generally overestimate surface temperatures in the Arctic environment by using the difference between Channel 4 and Channel 5 brightness temperatures as a proxy for atmospheric absorption of TIR energy [25].

AVHRR requires cloud-free conditions for surface analysis using visible and TIR wavelengths. The Arctic maritime environment typically experiences extensive cloud cover, particularly during the warmer months [26], which is a challenge for the analysis of AVHRR imagery. For this study the high number of daily satellite passes allowed sufficient assessment for 2007, 2009, 2010 and 2017, while unusually clear conditions from 19 to 26 February 2019 permitted a detailed analysis for that year. Clouds prevented a similar analysis for the other years. Data from a weather-independent high-resolution sensor such as synthetic aperture radar (SAR) was not available for this study.

### 2.2. Tidal Data

Simulations indicate that ocean-ice stress caused by tides reduce the extent of landfast ice [27]. Additionally, it is estimated that over the past decade, tides have been responsible for an approximately 15% reduction in the volume of Arctic sea ice [28]. Another study found that tidal forcing decreased ice volume by 17.8% in the Canadian Arctic Archipelago due to the suppression of ice formation in winter [29]. Tides generally have small amplitudes in the Arctic, but Kane Basin is an exception. It has been observed that a standing wave forms in Nares Strait from barotropic semidiurnal tides, resulting in significant tidal amplitudes that may be important in the formation and breakup of ice arches to the north and south [15]. Tides near the NOW ice arch reach an amplitude greater than 4 m and may reverse the direction of the Nares Strait outflow at Smith Sound [10]. Figure 2a shows Acoustic Data Current Profiler (ADCP) data of the near surface current in Smith Sound over a tidal cycle. As the tide builds the current reaches a maximum of 40 cm/s northward, reducing to zero at high tide before reaching a maximum of 80 cm/s southward as the tide ebb. Tidal charts for the Pim Island tide station were used for the analysis of Kane Basin ice dynamics for 2019 [30]. Figure 2b shows the average location of the NOW ice arch from 1979 to 2006 and 2007 to 2020 in relation to the ADCP and tidal data. Since 2007 there is a northern migration of the average position of the ice arch when compared to earlier years, which may be linked to climate change. The migration is approximately 30 km farther north, placing the eastern border of the ice arch an additional 30 km from the Greenland coast, which may affect the structural integrity of the formation.

| Parameter | Comment |
|-----------|---------|
| Channel 1 | 0.58–0.68 µm (Visible) |
| Channel 2 | 0.725–1.00 µm (Visible/Near Infrared) |
| Channel 3a | 1.58–1.64 µm (Near Infrared) |
| Channel 3b | 3.55–3.93 µm (Medium Infrared) |
| Channel 4 | 10.30–11.30 µm (Thermal Infrared) |
| Channel 5 | 11.50–12.50 µm (Thermal Infrared) |
| Altitude  | 827 km (METOP-A), 858 km (NOAA-18) |
| Orbit Type | Sun Synchronous |
| Orbital Period | Approximately 100 min |
| Spatial Resolution | 1.1 km at nadir degrading to approximately 8 km at swath edge |
| Swath Width | Approximately 2900 km |
The formation and dissolution of the NOW ice arch has demonstrated considerable temporal variability over the past 40 years. Satellite data since 1979 shows that the NOW ice arch may form as early
as November or as late as April, while the breakdown of the structure varies from April to September. On average, the ice arch forms mid-January and persists until the end of June. Overall, ice arches in the Nares Strait system, including both the NOW and northern ice arches, prevent the flow of multiyear ice from the Arctic basin for 161 days per season with a standard deviation of 76.7 days [21]. In this context a season is considered the beginning of freezing in the fall and extending to the summer melt the following year.

In the Nares Strait system, ice is normally first established in the sheltered waters of eastern Kane Basin. First year ice begins to build in September and by January the eastern portion of Kane Basin is generally classified as landfast ice with a thickness more than 120 cm [32] that can persist well into the melt season. The thick ice in Kane Basin serves as a solid anchor for the eastern side of the NOW ice arch (Figure 3), while the western edge is stabilized by thick landfast ice close to land. If the ice in eastern Kane Basin becomes unstable then the ice arch is unable to consolidate.

![Figure 3.](image.png)

Figure 3. (a) A METOP-A AVHRR Channel 4 thermal infrared image of the NOW for 05 Jan 2020 1713Z and (b) the surface temperature of the same scene with a land mask. Thick first year ice in Kane Basin (red arrows) provides a stable platform for the eastern edge of the ice arch. Sea and ice surface temperatures were determined with the Single Channel Composite Arctic Sea Surface Temperature Algorithm (CASSTA).

### 3.2. 2007 Season

It is reported that no ice arches consolidated in the Nares Strait system during the 2007 season [16], although a short-term northern ice arch appeared from 30 March to 07 April. This was the first recorded time that the NOW ice arch did not form in a season. In late April it appeared that the ice arch may
consolidate, but a large section of ice broke from eastern Kane Basin and prevented formation of the structure (Figure 4).

![Figure 4](image)

**Figure 4.** (a) A NOAA-18 AVHRR Channel 1 visible image with a land mask of the NOW for 07 April 2007 and (b) 20 April 2007. On 07 April the short-term northern ice arch is intact, and ice is becoming congested in Kane Basin where the ice appears solid to the east (red arrow). Thirteen days later the northern ice arch has collapsed and ice in Kane Basin has fractured into several floes, the largest more than 2000 km² (blue arrow).

### 3.3. 2009 Season

The 2009 season was remarkable, with the first observed instance of an ice arch at the northern terminus of Nares Strait in conjunction with the non-formation of the NOW ice arch in Kane Basin. The northern ice arch consolidated on 08 January and broke 184 days later on 12 July. The phenomenon resulted in record low ice cover in the NOW and led to anomalously high sea surface temperatures during the summer [33]. Northern ice arches have occurred 17 times since 1979, however, until 2009, they preceded the formation of the NOW ice arch by an average of 30 days [21]. In 2009 the NOW ice arch appeared to be consolidating within a week of the northern ice arch formation, but a significant area of landfast ice in Kane Basin became unstable and broke away in the ensuing month (Figure 5). Extensive cloud cover prevented observation of the ice breakup in Kane Basin with AVHRR imagery. Nares Strait remained uncharacteristically free of floes until the collapse of the northern ice arch in July.
Figure 5. A METOP-A AVHRR Channel 4 thermal infrared image with a land mask of the NOW for (a) 11 January 2009 and (b) 19 February 2009. On 11 January, three days after the northern ice arch consolidated, Kane Basin is congested with ice and appears to be in the early development of an ice arch. By 19 February, the Kane Basin landfast ice has retreated eastward and there are few floes in the Nares Strait system because of the northern ice arch.

3.4. 2010 Season

The 2010 season represented the third lowest number of days in the satellite record in which Nares Strait was blocked by ice arches [21]. A northern ice arch consolidated in mid-March and collapsed by mid-April, while an ice arch failed to form in Kane Basin for a second season in a row. The NOW ice arch was in the process of solidifying in mid-January when ice in Kane Basin shattered into several large floes that destabilized the landfast ice (Figure 6). The Kane Basin ice regenerated over the next two months, but broke once again in April.
3.5. 2017 Season

Following six seasons in which the NOW ice arch averaged 194.5 days of consolidation, 2017 featured a sole northern ice arch that persisted for 108 days between 23 January and 11 May [21].
Notably, a large floe 90 km by 25 km broke from the Kane Basin ice on 26 January (Figure 7). The ice in the region did not fully regenerate for the rest of the season.

![Figure 7. A METOP-A AVHRR Channel 4 thermal infrared image with a land mask of the NOW for (a) 25 January 2017 and (b) 26 January 2017. In a 24-h period a large floe breaks from the Kane Basin ice in the critical region of NOW ice arch formation (see red and blue arrows).](image)

3.6. 2019 Season Detailed Case Study

In 2019 the northern ice arch solidified on 16 February and broke down 32 days later on 20 March. Four days after the northern ice arch formed, a crack was observed in the landfast ice in eastern Kane Basin. Relatively cloud-free weather allowed a close examination of the event. On 19 February, the Kane Basin ice appears solid on satellite imagery. A small crack in the ice is observed on 20 February 1536Z and appears to grow by the next satellite pass at 1716Z. Over the next six days approximately 2500 km² of ice is cleaved from the Kane Basin landfast ice and flushed through Smith Sound. Figure 8 shows the satellite imagery of the initial crack in the ice compared to tidal information at Pim Island. Between the 1536Z and 1716Z satellite images on 20 February a high tide of 4.61 m occurred at 1555Z [30]. Weather at the time of the breakup was partly cloudy with a temperature of –39°C and winds from the east at 8 km/h [31]. Winds were light during the two days prior to breakup and temperatures ranged from –38 °C to –40 °C. Additionally, there were no obvious impacts from southward moving floes that could have weakened the ice in Kane Basin. Given the conditions, the evidence suggests that tidal forces were a key contributor to the ice breakup in Kane Basin. Figure 9 shows the thermal evolution of the ice breakup and illustrates southward movement of cold first year ice from Kane Basin and cold multiyear ice originating from the northern ice arch.
Figure 8. (a) On 19 February 2019 1737Z the ice in Kane Basin appears solid (yellow arrow). (b) Twenty-two hours later a small crack appears at the southwest edge of the Kane Basin ice (red arrow), coinciding with a tidal height of 4.5 m as seen on the tide height chart. (c) One hundred minutes later the high tide of 4.61 m has passed and the crack in the ice has expanded in Kane Basin (blue arrow). (d) Less than 24 h later a large floe has broken free of Kane Basin (green arrow). All panels are METOP-A AVHRR Channel 4 thermal infrared image with coastlines outlined. Tidal height in (b) and (c) is for Pim Island 20 Feb 1100 to 2200Z [30].
Figure 9. METOP-A AVHRR Composite Arctic Sea Surface Temperature Algorithm (CASSTA) images of the NOW for February 2019. (a) On 19 February eastern Kane Basin is covered with thick first year ice, which has a very cold signature. (b) The first crack in the Kane Basin ice is observed on 20 February during high tide, which is followed by (c) the removal of a large flow on 21 February. (d–f) Between 24 and 26 February several large floes break from the landfast ice in Kane Basin and are flushed southward through Smith Sound. The four large floes in (d) are approximately 2500 km$^2$ in total (red arrow).

4. Discussion

Over the past four decades, there has been a significant reduction of sea ice in the Arctic because of surface air temperatures that are increasing quicker than the global average, a phenomenon known as Arctic Amplification [34]. More than 50% of multiyear ice has been lost in the past two decades, leaving more than two thirds of the Arctic Ocean covered by seasonal ice [35]. In the Arctic Basin there is a trend toward younger, thinner ice that is more easily melted and broken up [36]. With respect to the NOW, there has been an expansion of open water during winter since the mid-1990s and an increased...
prominence of thinner ice [20]. After many years of noted stability and recurrence, the NOW ice arch has failed to consolidate in five seasons since 2007. Although there is significant variability between years making it difficult to predict ice arch formation in any one season, there is a downward trend of 2.1 days of ice arch consolidation per season in the Nares Strait system since 1979 [21]. The recent variability in the NOW ice arch is likely a response to Arctic Amplification.

Satellite imagery indicates that the non-formation of the NOW ice arch is associated with a destabilization of ice in Kane Basin that serves as the eastern anchor of the structure. The surface flow in Kane Basin is reduced as the channel widens from approximately 40 km to 130 km [37], allowing the formation of thick first year ice in the calmer waters on the eastern side. Since 2007, the average latitude of the NOW ice arch has moved further north compared to previous years [21]. This northward migration of the ice arch requires greater stability of the Kane Basin landfast ice since the eastern part of the arch is farther from land (Figure 2b).

It is notable that the northern ice arch has formed in 40% of the seasons since 1979 but occurred in each of the five years in which the NOW ice arch failed to consolidate. For three of these years the northern ice arch was intact when ice in Kane Basin became unstable. In 2009 and 2017 it may be argued that the NOW ice arch did not consolidate, since the long-term northern arches in those years prevented the multiyear ice contribution to the structure. While this is likely a factor, similar configurations prior to 2009 allowed the NOW ice arch to form as late as 93 days after the northern arch formation. As such, there is no clear correlation between the non-formation of the NOW ice arch and the existence of the northern ice arch.

The observed breakage of ice in Kane Basin prior to ice arch formation could be the combination of several physical factors, including warm temperatures, winds, thinning ice, impact from southerly moving floes and tidal fluctuations. In 2019 there is compelling evidence that tidal forces played an important role in breaking up ice in Kane Basin, thereby destabilizing the eastern boundary of the ice arch. During the 2019 event the winds were calm, surface air temperatures very cold and satellite imagery shows no obvious impacts from floes moving through Nares Strait. Conversely, the first observable crack in the ice coincided with a high tide of 4.61 m at nearby Pim Island. This represented the highest tide of the month at nearby Pim Island [30]. The evidence suggests that the combination of a maximum tide that occurred on the same day that a crack was observed in the Kane Basin ice on 20 February (red arrow). The 4.61 m tide represented the second highest tide of the year for Pim Island [30].

Figure 10. Maximum tide heights for February 2019. The highest tide of the month at nearby Pim Island occurred on the same day that a crack was observed in the Kane Basin ice on 20 February (red arrow). The section of ice that broke away from Kane Basin was reported as 3/10 vast floe, thin first year ice (30 to 70 cm thick) and 7/10 landfast, thick first year ice (>120 cm thick) [32]. The section of thinner ice may have been a contributing factor in the Kane Basin breakup. The overall thinning ice in the Arctic because of rising temperatures and longer melting seasons makes the ice more prone to ocean-ice tidal stresses.
5. Conclusions

The NOW ice arch in Kane Basin has failed to consolidate in five seasons (2007, 2009, 2010, 2017, 2019), a phenomenon that had not been observed prior to 2007 dating back to ice reconnaissance flights in the 1950s. In each of these years an ice arch formed at the northern terminus of Nares Strait for periods ranging from 7 to 184 days. The formation of ice arches in the Nares Strait system serve an important function in preventing the southward movement of multiyear ice from the Arctic Basin into Baffin Bay. The non-formation of the NOW ice arch reduces the seasonal blockage of Nares Strait by 102 days when compared to years that it consolidated. This leads to an increased loss of multiyear ice from the Arctic Basin southward through Nares Strait. Based on Nares Strait ice flux rates [16], the non-formation of the NOW ice arch corresponds to an average additional seasonal ice loss from the Arctic basin in the order of 20,000 to 30,000 km², most of which is multiyear ice [17]. However, the inherent unpredictability of the NOW ice arch formation makes it difficult to incorporate this information in Arctic climate models.

Structurally, the NOW ice arch requires stable ice on the eastern edge in Kane Basin. During the years in which the NOW ice arch failed to form there were events when large floes broke off from the normally strong first year ice in Kane Basin. There are several factors that could cause the weakening and breaking of ice in Kane Basin. Arctic Amplification has led to an overall thinning of polar ice in recent years and has affected the ice dynamics of the Nares Strait system [21]. The average position of the NOW ice arch has migrated northward since 2007, which means that the eastern edge is further from land and more susceptible to breakage. Clear skies allowed for a detailed analysis of the February 2019 breakup of ice in Kane Basin with AVHRR visible and TIR data. The satellite imagery indicates that tidal forces in the region, which are the strongest in the Arctic, caused large floes to break off from the Kane Basin ice. Newly formed cracks in the ice were concurrent with the highest tide of the month and second highest of the year. The evidence suggests that the combination of a warming climate and strong local tides are significant factors in the changing ice dynamics of the NOW region.

For future work, archival SAR data could potentially be used for 2007, 2009, 2010 and 2017 to find similar correlations between ice breakup in Kane Basin and tidal forcing.

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