Extreme Arctic Weather and Community Impacts in Nunavut: A Case Study of One Winter's Storms and Lessons for Local Climate Change Preparedness

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ABSTRACT: Arctic communities are experienced with severe weather, but impacts can still be serious, particularly when the intensity or persistence of hazardous conditions is extreme. Such was the case for the community of Clyde River (Kangiqtugaapik), Nunavut, Canada, which experienced 33 blizzard days during winter 2021/22—likely the most at Clyde River since at least 1978/79. Blizzard conditions resulted from unusually frequent high winds rather than excessive snowfall. The most severe stretch included eight blizzard days over an 11-day period, with top wind gusts of 98 km h^{-1}. Winds caused severe drifting, covering homes and blocking streets. Broken heavy equipment, including snow-clearing machines, compounded the impacts, leaving homes without essential services like water delivery and sewage pump-out for days. Residents reported the storms and resulting impacts as some of the worst in memory. The drifting and volume of snow, combined with the lack of available resources to manage it, obliged the community to declare a state of emergency. Projections of increased Arctic precipitation and extreme weather events points to the need for communities to have proper resources and supports, including preparedness and adaptation and mitigation strategies, so they can be better equipped to handle storm and blizzard impacts such as those experienced at Clyde River in the winter of 2021/22. Additional steps that can be implemented to better support and prepare communities include investing in preparedness planning, expanded and enhanced weather information and services, community land-based programming to transfer Inuit knowledge and skills, assessing the usefulness of current forecasts, and new approaches to community planning.

SIGNIFICANCE STATEMENT: In this study, we consider the winter of 2021/22, during which the community of Clyde River (Kangiqtugaapik), Nunavut experienced 33 days with blizzard conditions—more than any other year since at least 1978/79. Blizzards are characterized by strong winds and blowing snow. Low visibility impedes travel, and drifting snow blocks roads and can bury equipment and buildings. In this case, broken snow-clearing equipment and other infrastructure challenges also hampered the community's ability to respond, and residents went days without essential services. Several studies suggest that extreme winds will become more common in the Baffin Bay region in the future. This study demonstrates the need for proper resourcing of communities for preparedness, response, and adaptation strategies, especially with the possibility of extreme winter weather becoming more common.

1. Introduction

Arctic communities, like the primarily Inuit community of Clyde River (Kangiqtugaapik), Nunavut (Fig. 1), are long inured to extreme weather. For many generations, Inuit have lived in close relationship with the land, and severe weather conditions are a part of deep knowledge and lived experience. Through activities such as hunting, fishing, and traveling the land, waters, and sea ice, Inuit have developed a complex knowledge system related to the environment, including weather patterns, winds, and long-term changes (e.g., Nickels et al. 2005; Gearheard et al. 2009; Simonee et al. 2021). Recent decades have seen extensive study and reporting of Inuit observations, knowledge, and experiences of climate and environmental change (e.g., Krupnik and Jolly 2002; Arctic Climate Impact Assessment 2005; Laidler et al. 2009; Watt-Cloutier 2015). Changes in weather and wind patterns and overall less-predictable weather have been highlighted in particular, because they introduce increased risk for land travel and harvesting (e.g., Arctic Climate Impact Assessment 2005; Gearheard et al. 2009; Weatherhead et al. 2010; Clark et al. 2016; Simonee et al. 2021; Carter and Ljubicic 2022). Extreme weather also has impacts on built infrastructure (e.g., Ford et al. 2015; Berner et al. 2016; Swanson et al. 2021).

Eastern Baffin Island is prone to frequent cyclone activity. Historically, cyclones often mature and become occluded over southern Baffin Bay and the area experiences large interannual variability in precipitation depending on storm activity
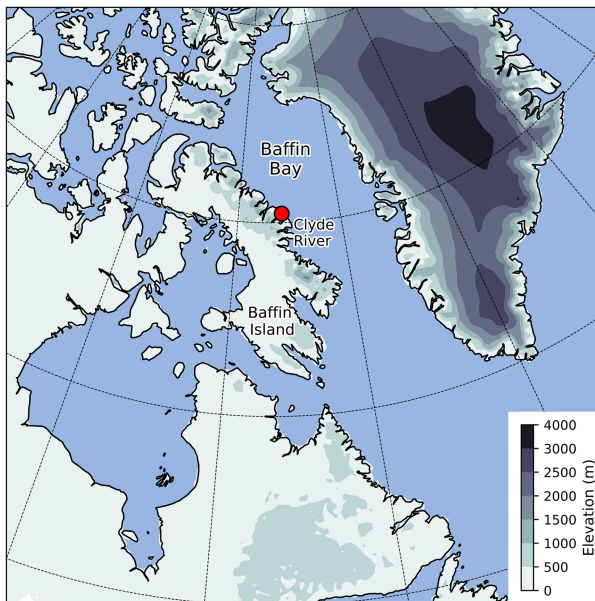
FIG. 1. Location of Clyde River (Kangiqtugaapik), Nunavut, on Baffin Island in the eastern Canadian Arctic.

(Bintanja et al. 2020). Relative to other parts of the Canadian Arctic Archipelago, storms affecting the eastern shores of Baffin Island move more slowly, which commonly brings extended periods of precipitation (Intihar and Stewart 2005). The most extreme single-day precipitation event observed at Clyde River (as identified in weather station records) of 41 mm, on 7 April 1977, combined an abnormally strong occluded cyclone with enhanced moisture transport bearing the hallmarks of an atmospheric river (Serreze et al. 2022).

Blizzard conditions usually involve snowfall, but high winds alone can result in blizzard conditions by reactivating a preexisting snowpack. In the winters of 2014–18, approximately 15% of blizzard conditions in the Clyde River region were purely due to blowing snow (Burrows and Mooney 2021). Clyde River typically experiences the strongest winds when a cyclone brings northwesterly winds that are channeled into the area by topography (Zeng et al. 2011). Both Inuit and visiting scientists note that local topographic effects strongly influence winds, leading to high wind variability (Gearheard et al. 2009; Wan et al. 2010).

Research results regarding trends in storminess for Clyde River and the broader Baffin Bay region have been mixed. Using station data over the period 1979–2007, Gearheard et al. (2009) found no significant changes in average wind speed at Clyde River in any month. While no significant trends were found in the frequency of strong winds ($\geq$30 km h^{-1}), weak winds ($\leq$20 km h^{-1}), and calm conditions ($\leq$2 km h^{-1}) had in general become less common. Wan et al. (2010) reported a slight decrease in average autumn wind speeds and an increase in winter wind speeds at Clyde River over the 1953–2006 timeframe. Wang et al. (2021) by contrast, found that wind speeds were higher throughout Baffin Bay (on average) in September–December by around 1.5 m s^{-1} during the period 2007–16

relative to 1979–88 (but with no change to wind direction). It is hypothesized that the increases in wind speed are tied to decreasing sea ice cover in the region (Mioduszewski et al. 2018).

There is some evidence that precipitation is increasing in the Baffin Bay region. Liston and Hiemstra (2011) found that snowfall in the area increased by approximately 30 mm liquid water equivalent per decade from 1979 to 2009. However, patterns and changes in extreme events are less clear due to the short observational period. In a review of extreme events, Walsh et al. (2020) documented an increase in daily precipitation intensity in northern Canada, also noting an anticipated increase in precipitation over the next several decades based on climate model simulations. McCrystall et al. (2021) report larger increases in precipitation across the Arctic and an earlier transition during the cold season to a rainfall dominated regime in the latest round of simulations (phase 6) for the Coupled Model Intercomparison Project (CMIP6) as compared with earlier models (CMIP5). This is especially apparent in October and November, pointing to the potential for more icing events at this time.

A recent report by the Canadian Climate Institute highlights the social, cultural, environmental, and economic impacts of climate and weather extremes on northern communities, ranging from damaged roads and infrastructure, to cascading impacts on human health and well-being (Clark et al. 2022). The report provides a series of recommendations to address climate-induced risks for communities such as Clyde River, including dedicated and coordinated funding over all three levels of Canadian government (federal, territorial/provincial, municipal/hamlet) for climate resilient infrastructure, federal and territorial/provincial support for the development and maintenance of information about climate risks to infrastructure, innovation and capacity building, and improved regulation to ensure standardization in addressing climate-risk related infrastructure issues (Clark et al. 2022).

In this paper, extreme weather conditions experienced during the winter of 2021/22 at Clyde River are explored from a meteorological and community perspective, drawing on weather data and residents' experiences of the events and impacts on infrastructure and quality of life. From this analysis, recommendations are made for supporting preparedness, mitigation, and adaptation strategies to better serve communities such as Clyde River in the future.

2. Data and methods

a. Community observations of the weather events and resulting impacts

Community observations of the 2021/22 winter weather events and impacts, along with local responses, were gathered primarily from news media and reporting (newspapers, radio), stories, information and observations posted on social media, and conversations with Clyde River residents (by coauthors Natanine and Fox). Fox conducted an informal interview about the storms and impacts in Clyde River with Natanine, the community's Chief Administrative Officer (CAO), who contributed additional observations and experiences of the

events from the perspective of his leadership role and office. Photographs illustrating the snow drifting and other impacts on the community were gathered from social media posts (and included with permission) and also taken specifically to support this study by R. Kautuk, a photographer and drone pilot who is based in Clyde River.

b. Station data for the weather/storms analysis

For this analysis, we define the extended winter, or cold season, as 1 November–30 April. Station data to assess meteorological conditions at Clyde River during the winter of 2021/22 were obtained from Environment and Climate Change Canada (ECCC). Two stations reporting hourly data were used: Clyde A [Climate Identifier (ID): 2400800] from 1978 to 2008 and Clyde River A (Climate ID: 2400804) from 2014 to 2022. Four variables were examined: hourly average wind speed (km h^{-1}), daily peak 3–5-s wind gusts (km h^{-1}), daily precipitation, and hourly manual weather tags (e.g., "light snow" and "blowing snow"). All precipitation totals are in mm of liquid water or water equivalent, which is the depth of liquid water of melted snowfall. The weather tags are essential for identifying precipitation because the measured precipitation fields at Clyde River A record "0" for both no precipitation and missing data. Precipitation gauge data is missing in early November 2021 and all of April 2022.

The Clyde A station record extends back with sporadic observations to 1933, but hourly wind observations begin 16 January 1978 during the day (0700–1600 local time), with observations every three hours (or more frequently) overnight. From 1 April 1984 to 29 July 2008, wind observations were truly hourly. Although the station continued operation until 10 January 2013, wind observations stopped being recorded at night in 2008, and measured precipitation stopped being reported in 2006, although the weather tags and manual visibility observations continued to be recorded. As of a 2006 inspection report, the precipitation gauges were a Type-B rain gauge and Nipher snow gauge (ECCC 2022, personal communication). Whether a U2A anemometer, which was installed in 1977 (Gearheard et al. 2009), was still in use at that time is unclear.

The Clyde River A station began operation when Clyde A stopped, but weather tags do not appear until 29 May 2014. Unlike Clyde A, Clyde River A only includes weather tags for hazardous conditions (precipitation or other causes of low visibility). It does not include other weather tags such as "clear skies" or "partly cloudy," and there is no way to differentiate such weather from "no data" cases. We assume that no weather tag indicates a lack of precipitation or blowing snow. The Clyde River A station is currently operated by Nav Canada with a Vaisala SW425G ultrasonic wind sensor and a combination of manual and automated precipitation measurements. When observers are present, a Type B rain gauge and Nipher snow gauge are used. The automated system uses a Met One precipitation gauge for temperatures above 5°C and a Vaisala PWD22 sensor for temperatures at or below 5°C (P. Despagnés, Nav Canada, 2022, personal communication).

Note that there is another weather station at Clyde River (Clyde River Climate; Climate ID: 2400802) operated by ECCC, but it stopped reporting precipitation at 1400 local time 16 December 2021 and includes no manual weather observations to substitute. There is also a network of five nearby weather stations operated by the community (the Kangiqtugaapik Weather Station Network; https://www.clyderiverweather.org/); however, these stations do not have precipitation data or weather tags and have only been operational since 2009, which is insufficient time for a climatology.

The definition of a "blizzard" used by ECCC for issuing blizzard warnings north of the tree line is when winds of at least 40 km h^{-1} are expected for at least 6 h, causing reduced visibility below 400 m (based on sighting distance) because of blowing and or falling snow (ECCC 2020). Following this definition exactly is hindered by data gaps and apparent inhomogeneities in the manual observations. Therefore, we define a "blizzard day" using several combinations of the following criteria:

A: average wind speed is at least 40 km h^{-1} for at least six consecutive hours,
B1: daily weather tags include at least one of falling snow or blowing snow,
B2: daily weather tags include falling snow, and
C: minimum visibility recorded during the day is 400 m or less.

We constructed time series using four definitions of "blizzard day," all of which include criterion A. Two of the definitions use criterion B1, meaning that snow does not necessarily need to be falling for a blizzard to occur. If there is a "blowing snow" weather tag without a precipitation tag, the blizzard results exclusively from wind transport of a preexisting snowpack. However, the frequency of "blowing snow" observations without contemporaneous "snowfall" is significantly different before and after the winter of 1997/98 ($p < 0.05$ in a Welch's t test). This winter also included a multiweek data gap. Given that these weather tags require human judgment, this shift may represent human bias rather than a physical change. Recognizing that possibility, we also employed criterion B2 for two of our definitions of "blizzard day," requiring snow to be actively falling. Finally, there is a statistically significant shift ($p < 0.01$) after that same winter of 1997/98 toward lower visibility measurements during high wind events through the winter of 2006/07. A multiyear data gap follows. When the data record resumes in 2014/15, visibility measurements jump back to values comparable to 1979–97. Visibility measurements are manual, so once again, we cannot be sure if these shifts represent a physical change or a reporting change. Therefore, we construct one set of definitions including criterion C and one excluding criterion C. Altogether, this makes four observational time series (Table 1). Time series 1 (excluding low visibility) is our primary time series because 1) there are inhomogeneities following both large data gaps and 2) several adverse impacts to the Clyde River community were directly related to the falling and drifting of snow, regardless of visibility (see section 4).

Linear interpolation was used to fill gaps in the wind record that are no more than three hours. This accounts for the variable

TABLE 1. Description of four observational time series of blizzard days used in this study.

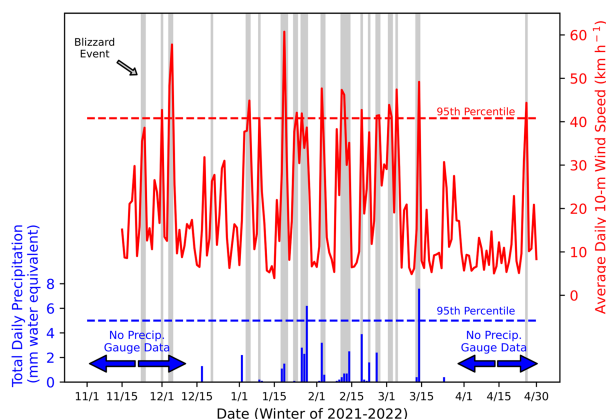| Time series	Criteria	Description
1 (Obs and ERA5)	A and B1	High winds and falling or blowing snow
2 (Obs only)	A, B1, and C	High winds, falling or blowing snow, and low visibility
3 (Obs and ERA5)	A, B2	High winds and falling snow
4 (Obs only)	A, B2, and C	High winds, falling snow, and low visibility

FIG. 2. Time series of average daily wind speed and total daily precipitation from 1 Nov 2021 to 30 Apr 2022 from the Clyde River A weather station. Gray shading indicates the 33 blizzard days recorded using manual qualitative weather observations and wind speed (time series 1 in Table 2). Horizontal dashed lines mark the 95th percentiles for nonzero precipitation (daily sum; blue) and wind speed (daily average; red) for November–April of 1978–2022. Wind speed data are missing before 15 Nov. Quantitative precipitation gauge data are missing or unreliable before 15 Dec 2021 and after 23 Mar 2022.

temporal resolution from 1978 to 1984. If, after interpolation, there were still fewer than 12 h of valid wind observations, that day is considered to have insufficient wind data. Seasonal counts of blizzard days were standardized to 181 days. For example, the cold season of 2021/22 had 14 days for which wind or precipitation data were missing. Of the 167 days with valid data, 33 satisfied the criteria of blizzard (using time series 1), which equates to (181 days per cold season/167 days) × 33 blizzard days = 35.8 standardized blizzard days per cold season. If more than 10% of the cold season days have missing data, the entire cold season was ignored (1997/98 and 2008/09 through 2013/14).

c. ERA5 data for blizzard analysis

To provide a complementary dataset less impacted by data gaps and inhomogeneities, we repeated the blizzard day analysis using output from the fifth major global reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (ERA5). ERA5 is based on the Integrated Forecasting System (IFS) Cy41r2 and includes several improvements on its predecessor (ERA-Interim), such as revisions to the moist physics in the atmosphere and snowpack parameterization (Hersbach et al. 2020). In comparison with other recent atmospheric reanalyses (MERRA-2 and CFSR), ERA5 best matches the frequency and average intensity of observed precipitation events (including extreme precipitation events) on Baffin Island (Loeb et al. 2022). Average hourly wind speed at 10 m, snow depth (depth on the ground), and snowfall (falling from the sky) fields were acquired for the period 1979–2022 for the grid cell containing Clyde River (Hersbach et al. 2018).

ERA5 does not include visibility as a variable, so we could only replicate the criteria for observational time series 1 and 3 (Table 1). Using a wind threshold of 40 km h^{-1} led to severe underestimation of the overall number of blizzard days 1979–2022 (relative to the station record). This is not surprising since each ERA5 grid cell covers an area of 0.25° latitude and 0.25° longitude, whereas the measurements at the weather stations are point observations. To calibrate ERA5 results to observations, the wind speed threshold was lowered to 23.25 km h^{-1}, which provides the same average number of blizzard days per 181-day cold season in the full 1979–2022 observed record. Note, the calibration is relative to the climatological average of the number of blizzard days, not individual years. This means that the same wind threshold is used for all years, and the year-to-year

variability in blizzard days computed from the ERA5 data is not part of the calibration. Therefore, we use the correlation of year-to-year variability from ERA5 results and station data results to validate the use of ERA5 to fill in data gaps and calculate trends. The time series of blizzard days are all normally distributed, so correlations between the ERA5 and observational time series were conducted using Pearson's correlation tests. Ordinary least squares regression was used to assess whether trends are present in the four observational and two ERA5 time series. The 95% confidence interval is used to judge significance.

3. The weather events

a. The winter of 2021/22

Using time series 1 (high winds + falling or blowing snow), the winter of 2021/22 included 33 blizzard days (Fig. 2). Twenty-five of these 33 days included a visibility observation below 400 m. The first event was during 23/24 November, and there were nine days with high winds and falling or blowing snow by 9 January. After a calm period of over a week, eight blizzard days over an 11-day period occurred from 18 through 28 January. Snowfall totaled 14-mm water equivalent during this period. The 10-m sustained wind speed averaged 60 km h^{-1} on 19 January and over 30 km h^{-1} for every day from 23 through 28 January. The maximum wind gust was 98 km h^{-1} on 28 January.

Although this 11-day stretch was the worst, blizzard conditions were also frequent throughout February. Overall, from 18 January to 5 March, 45% of all days were blizzard days. Although snowfall was reported for every blizzard event, the accumulated snowfall was rarely high—sometimes no more than a trace. A weeklong calm stretch starting 5 March was
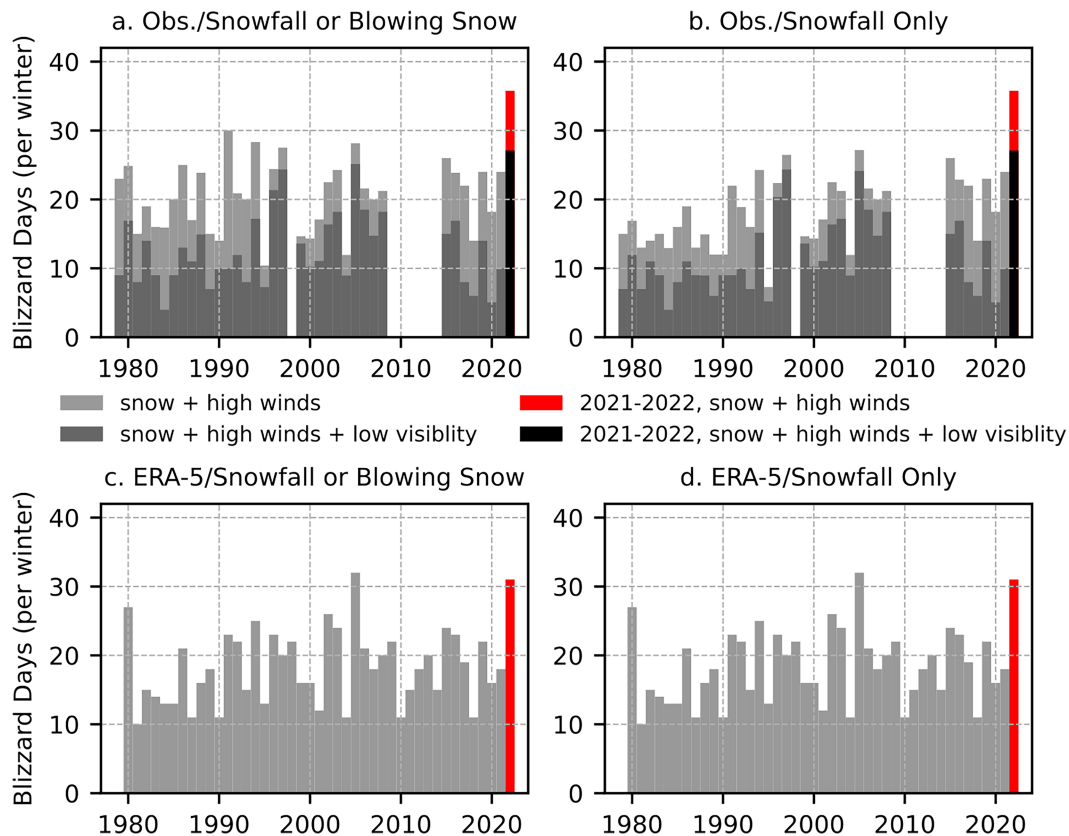
FIG. 3. Number of days per 181-day cold season (November–April) that Clyde River experienced blizzard conditions based on (a),(b) observations and (c),(d) ERA5. Multiple definitions of "blizzard" are used. Shown are (left) high winds with snow either falling or blowing, and (right) high winds with snow actively falling. Shading indicates whether low visibility is used as a criterion (see the legend). Cold seasons ending in 1998 and 2009–14 have insufficient observational records. For years in which fewer than 10% of days have missing observational data, the observational blizzard count is scaled to a 181-day period.

the longest experienced since mid-January. This lasted until the heaviest recorded snowfall of the year on 14 March of 7.6 mm water equivalent. In an apparent fitting climax to a tumultuous winter, winds gusted over 80 km h^{-1}. However, one last blizzard occurred late in the cold season. On 26 April, wind gusts again peaked at over 80 km h^{-1}. Falling and blowing snow were observed, but no precipitation gauge was reporting on this date, so the accumulation is unknown. Based on ERA5 measurements (not shown), 25 mm water equivalent of snow fell on 26 April, which is the third highest daily snowfall for the Clyde River grid cell for 1979–2022—truly extreme.

b. Comparison with past winters

How uncommon was the winter of 2021/22? Because of numerous gaps in the record from precipitation gauges, it is challenging to make snowfall comparisons. Limiting analysis to the cold season (November–April), the 95th percentile for precipitation events (total precipitation > 0 mm) is 5.0 mm water equivalent, which was exceeded only twice by the Clyde River A weather station during the cold season of 2021/22. Based on ERA5 data, the 26 April event was nearly a record at 25 mm, but no precipitation gauge was operational to

verify. Whereas the measured snowfall for these blizzard events was mostly unexceptional (at least from December to March), several of the blizzard events had extreme winds. The 95th percentile of average daily wind speed at Clyde River from November to April 1978–2022 is 40.8 km h^{-1}. This threshold was exceeded for 10.8% of the days during the 2021/22 cold season. The 95th percentile for the average cold season maximum wind gust from 1978 to 2022 is 74.0 km h^{-1}. This threshold was exceeded on 12.1% of the days during the 2021/22 cold season. In other words, extreme winds occurred more than twice as often as during the average cold season.

The 33 days with blizzard conditions during the cold season of 2021/22 is the most recorded since at least 1978/79 (Figs. 3a,b). Note that this ignores 14 days in 2021/22 with no data. A total of 33 blizzard days out of 167 equates to 35.8 days per standard 181-day cold season. If days with snowfall or blowing snow are included, the next stormiest cold season was 1990/91, with 30 days per standard cold season, including 4 January 1991. High winds from this event were previously highlighted by Nadeau (2007) based on output from the North American Regional Reanalysis. If only days with falling snow days are included, 2004/05 is the next stormiest cold season, with 27.2 days per standard

TABLE 2. Linear trends in the number of standardized blizzard days (November–April; from 1978/79 through 2021/22) and their 95% confidence interval. Statistically significant trends are in boldface type.

Time series (criteria): description	Data source	Trend (blizzard days per decade)
1 (A; B1): High winds; snowfall or blowing snow	Station observations	2.47 ± 1.26
	ERA5	1.22 ± 1.41
2 (A; B1; C): High winds; snowfall or blowing snow; low visibility	Station observations	1.51 ± 1.44
3 (A; B2): High winds; snowfall only	Station observations	1.15 ± 1.45
	ERA5	1.22 ± 1.41
4 (A; B2; C): High winds; snowfall only; low visibility	Station observations	0.89 ± 1.48

cold season. If low visibility is added as a criterion, 25 blizzard days are recorded for 2021/22 (using either snow criterion), equating to 27.1 blizzard days per 181-day cold season. This is also the highest value recorded. The second stormiest cold season is 2004/05 at 24.1 or 25.1 blizzard days per standard cold season using snowfall only or snowfall/blowing snow, respectively. Therefore, by any definition of "blizzard day," the winter of 2021/22 was the likely the worst year in Clyde River since at least 1978/79 based on station data.

After calibrating based on the climatological mean of blizzard days, the ERA5 blizzard record closely matches the station record, with Pearson's correlations exceeding 0.80 using either the snowfall-only or snowfall/blowing snow time series. Therefore, we can use ERA5 to fill in the data gaps from the observational record and assess trends. ERA5 time series including blowing snow are nearly identical to those using snowfall only. Using ERA5, the winter of 2021/22 had the second-most blizzard days at 31, with 2004/05 recording 32 (using either definition of "blizzard day"). These are also the top two years using the snowfall-only time series from the station data.

ERA5 records more blizzard days than the weather station during the cold season of 2004/05 mostly because of three February storms. ERA5 records two blizzard days for each storm, whereas in the station data the high winds on the second day of the storm last only 2–5 h—too few to count as a blizzard day. For the cold season of 2021/22, ERA5 has fewer blizzard days than the weather station because ERA5 has no recorded blizzard days in March or April. There is snowfall in ERA5 for all March–April blizzard days recorded by the station, but the ERA5 winds are too weak. This difference is partly counterbalanced by ERA5 recording four blizzard days during the data outage at the weather station at the beginning of November 2021. Overall, ERA5 agrees well with the station data on the timing of storms, but it had more hours with high winds in 2004/05 and fewer hours with high winds in 2021/22. This is the difference between 2021 and 2022 having the stormiest or second stormiest cold season of the past 40+ years.

c. Are there historical trends?

Last, we assessed historical trends in the number of blizzard days (Table 2). All four observational time series have positive trends over the period of study; however, only the two trends using both snowfall and blowing snow (time series 1 and 2) are statistically significant. Additionally, these trends are somewhat dubious for two reasons. First, 2021/22 represents a strong positive outlier, and if removed, the trend for time series 2 is no longer significant.

Second, before the cold season of 1997/98, the difference between "snowfall or blowing snow" and "snowfall only" time series averaged 4.15 days (ranging from 1 to 8), whereas after the winter of 1997/98, the difference averaged 0.33 days (ranging from 0 to 3). In other words, the reporting of "blowing snow" without "snowfall" was notably more common before the winter of 1997/98 than after. We have no record of instrumentation changes at this time, but there is a multimonth data gap at that time. Additionally, the weather tags of "snow" (and its variations) or "blowing snow" are qualitative, manual observations. Therefore, changes in observing guidelines or in personnel between winter 1996/97 and winter 1998/99 could lead to a step change in the frequency of reporting "blowing snow" without "snowfall." In conclusion, we cannot rule out the possibility that significant positive trends in station observations arise from reporting differences rather than a change in climate.

Two benefits of ERA5 are that it 1) has less sensitivity to inhomogeneities in the observational record and 2) contains no data gaps, both of which are better for trend analysis. The ERA5 trends are also positive, although not significant. Therefore, although we can say that blizzard days are more common at the end of the record, whether these positive trends represent the beginning of a climate shift toward more blizzards is uncertain.

4. The impacts

a. Severe winter storms intersect with community infrastructure challenges

Impacts started immediately with the three consecutive storms between the 18 and 28 January 2022. Snowfall and very strong winds created dramatic drifting, blocking almost all community streets and many homes had their doors and windows drifted over. As described earlier, during February and the first half of March, eight more distinct storms (accounting for 15 blizzard days) added to the problems (Fig. 4).

Soon after the initial storm events, the municipality started clearing snow as they normally would. However, two of the community's loaders were broken, and the diesel fuel supply was low. In the two years prior, the municipality had been experiencing problems with its heavy equipment, specifically, clogged exhaust systems that resulted in vehicle breakdowns. The municipality brought in mechanics to work on the

Fig. 4. Drifted snow in the community of Clyde River, 13 Feb 2022 (photographer: A. Paniloo).

machines, but problems continued as initially they could not figure out the issue. It was not until November of 2021 that the mechanic sent out samples of the fuel to be tested and it was discovered that the community's equipment had been running on Jet A fuel and not diesel, for years, something the municipality did not realize. The incorrect fuel damaged newer municipal vehicles that use more modern exhaust systems that are not designed to run on Jet A fuel (Neary 2022).

The limited ability to clear snow during the winter of 2021/22 meant that water and sewage trucks could not reach many of the homes (all buildings depend on trucked water and emptying sewage tanks by trucks). By early February, some homes had gone almost a week without running water and up to two weeks without sewage pump-out, causing approximately 60 home sewage tanks to freeze (Lochead 2022a). To deal with the broken equipment, the community flew in a heavy equipment mechanic and ordered parts for repairs. Obtaining parts was difficult because of disruptions in the global supply chain, including shipping delays (both related to the global pandemic).

On 10 February 2022, Clyde River declared a state of emergency [Canadian Broadcasting Corporation (CBC) News 2022]. By this time there had been 19 blizzard days in 10 separate storm events (Fig. 2). At the time, there was only one operational snowplow, and it was dedicated to clearing the airport runway, a priority in a community that depends on resupply primarily by air, including food (Fig. 5).[1] Meanwhile

residents struggled with no running water. Also, there were worries about access to emergency services (fire, ambulance), since a number of roads were impassable. The municipality reached out to the government and other agencies for assistance. Eventually, they secured 11 barrels of diesel fuel from a nearby Nunavut Parks site for use in the equipment used to clear the airport. More diesel was obtained soon after from a donation from Baffinland Iron Mines (a company that operates a mine approximately 400 km away).

With little operational snow-clearing equipment, community members banded together to help each other dig out by hand. Clyde River Mayor A. Cormack was quoted as saying, "if it happened in Ottawa, the whole army would be there by now" (Lochead 2022b). In the remote Baffin Island location, the community had to depend on its own resources including human power and close community relationships. Residents using shovels and a few small snow blowers spent days clearing stairs and streets.

On 17 February, the community lifted the state of emergency after most snow-clearing vehicles were repaired (Lochead 2022c). Nevertheless, the series of blizzards, combined with broken heavy equipment, left the community with a massive clean-up effort. As the community began to make progress, there were more storms, continuing into mid-March (Fig. 6), creating more challenges and slowdowns to essential services and air resupply. As described earlier, a final blizzard event was recorded on 26 April.

b. Comparing 2021/22 impacts with past winters

Major impacts might also have been expected in the winters of 1990/91 and 2004/05, years that also experienced a high

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[1] The community is also supplied by sealift (ship) once a year with nonperishables, fuel, and other goods and supplies. There are no roads to the community.
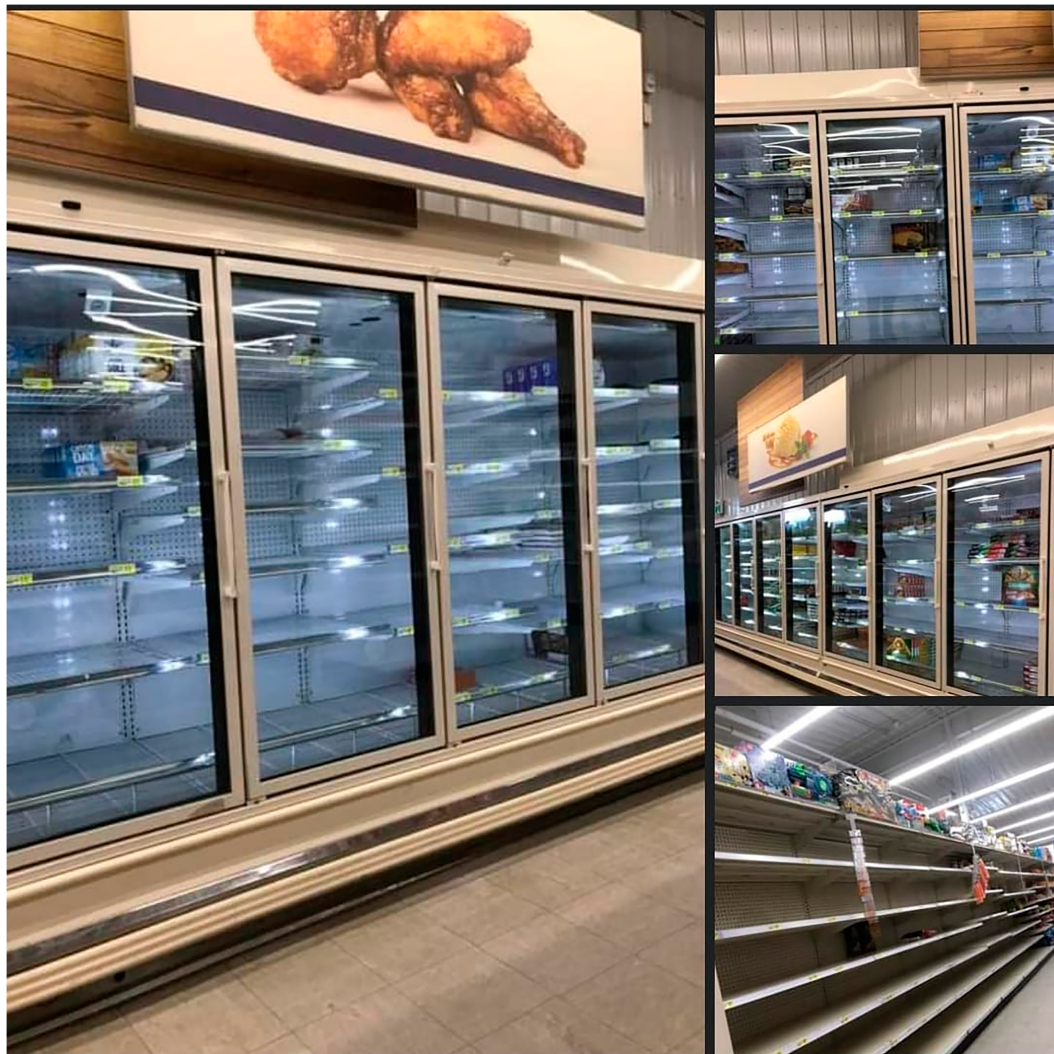
FIG. 5. Empty shelves in Clyde River's only store by the first week of March 2022 (see Venn 2022). Extreme weather, combined with a community's resources and infrastructure used to manage the effects, can impact access to critical services such as water delivery and air transport of food (photographer: V. Enuaraq).

number of blizzards. However, media reports of winter weather impacts in these years are limited to descriptions of severe cold spells (Lethbridge Herald Archives 1990; Medicine Hat News 1990; Weatherspark 2005).

By contrast, there are several media reports of major weather impacts of the 2013/14 winter, attributed to a persistent upper-level low pressure system (Varga 2014). Blizzard conditions on Baffin Island were reported in early January 2014, with sustained wind gusts on the order of 110 km h^{-1}, near hurricane force (CBC News 2014a,b), resulting in power outages in Iqaluit, which lies to the south and west of Clyde River on Baffin Island (Qulliq Energy Association, mentioned in the CBC article) and closure of schools and government offices in Baffin Bay communities, including Clyde River. Social media accounts of harsh weather conditions and their impacts on communities document large accumulations of snow during March 2014 (https://www.facebook.com/photo/?fbid=463831923718705&set=pcb.677423038984870) and the unusual snow accumulation resulting from the 2021/22 sequence of blizzards (https://www.facebook.com/photo/?fbid=4485330111568846&set=gm.5239776026082859&idorvanity=223508541042991).

Unfortunately, although extreme high winds were recorded by two Clyde River weather stations on 7/8 January and 1/2 March 2013/14, the Clyde River A station lacked the necessary snow data at that time to properly compare the total number of blizzard days with winter 2021/22. Based on ERA5 data (Fig. 3), the 2013/14 winter had a below-average number of blizzard days despite these two exceptionally strong wind events. This demonstrates how disruptive impacts may result from a single exceptional storm event, or from the accumulated (or compounded) effects of repeated blizzard conditions.

Fig. 6. Clyde River residents worked together to clear snow by hand from roads and homes after a series of severe winter storms in winter 2021/22 (photographer: R. Kautuk).

Although some storms were indeed extreme on the basis of the strong winds they brought, and the 26 April storm may have brought extreme snowfall, the greatest challenge of 2021/22 was the cumulative effects of 33 blizzard days compounded by broken equipment.

5. Discussion and conclusions

a. Projections of future winter weather

We did not find robust evidence of trends in blizzard frequency for Clyde River in the observational record, but what about the future? Hourly wind data, which would be needed to replicate our analysis in climate models, is not available for major climate model archives like the global CMIP5 and CMIP6 or the regional Coordinated Regional Downscaling Experiment (CORDEX). However, according to multiple modeling studies of seasonal averages, extreme wind events across the Arctic, including Baffin Bay, are expected to increase in frequency (e.g., Reader and Steiner 2022; Vavrus and Alkama 2021). Based on CMIP5 models, projected increases are mostly for winter; in the RCP8.5 scenario, an 8% increase in wind speed is projected for the Baffin Bay area, with over 90% of models agreeing on the sign of this change (Vavrus and Alkama 2021). Similarly, Reader and Steiner (2022) project a general positive trend in wind speeds.

Arctic precipitation is expected to increase through the twenty-first century (Bintanja and Andry 2017). While a greater fraction of this precipitation is expected to fall as rain as the climate warms, winter precipitation is still expected to fall as snow across Baffin Island, including the Clyde River region (see Fig. 3a and supplemental Fig. 3 in McCrystall et al. 2021). Future winter snowfall, combined with stronger winds, argues for an increased frequency of blizzard conditions. However, decreases of 15%–25% (or 40–60 days) in snow covered days across Baffin Bay are also expected by the end of the century (Langen et al. 2018), most pronounced along the coastlines such as Baffin Island. While this points to a potential decrease in blizzard days, these changes in snow cover days are largely driven by a delay in snow onset.

b. Lessons for future planning, resourcing, and preparedness

While it might be expected that northern communities like Clyde River are well-equipped to handle severe winter weather events, the blizzards of 2021/22 revealed that there are limits. The challenges faced by the community can be attributed, at least in part, to the extended duration of severe weather— 33 blizzard days for the winter as a whole, with eight blizzard days over an 11-day period with top wind gusts nearing 100 km h^{-1}. While communities can manage a single blizzard, or a series of events spread out over a reasonably long time period, the cumulative effects of the multiple blizzards of 2021/22 were overwhelming. It also seems clear that the community's response was hampered by insufficient machinery to clear snow. Two of the community's loaders were broken, traced to the use of improper fuel. Obtaining parts was also made difficult by disruptions in the global supply chain and limited incoming flights due to bad weather. These problems also challenged the ability to provide food transport, water delivery, and sewage pumping services to the community.

Indirect evidence of seasonal winds and precipitation from climate model projection of the future suggests that blizzard conditions may become more frequent in the future, although historical trends are not robust. Regardless of any trends, though, the community response to and impacts of the 2021/22

blizzards demonstrate a need to better support communities like Clyde River. In part, recommendations echo the Canadian Climate Institute efforts to address climate-induced risks in northern communities (Clark et al. 2022) and add other community input including the following:

1) Increasing snow removal capabilities, which includes having sufficient heavy machinery and the availability of spare parts.
2) Training opportunities for current and new operators in the community, in heavy machinery maintenance and operation so local expertise and assistance is readily available when needed.
3) Having sufficient fuel and water storage to sustain the community in case of transportation cutoffs.
4) Assessing the potential for snow fencing. Clyde River currently has one snow fence (for one territorial government building located just outside of the community) and it is effective. Additional snow fencing for other parts of the community could be very useful.
5) Reconsidering approaches to community planning to include current and projected weather conditions and climate change, especially winds and snow accumulation. Current planning does not take into account prevailing winds or blowing snow patterns.
6) Assessing the effectiveness of severe winter weather forecasts for the community, both in terms of accuracy and usefulness of information provided (e.g., according to local knowledge and preferences for information).
7) Working with community experts (e.g., Elders, hunters) and other residents to define, develop and deliver more locally relevant weather information and services.
8) Supporting community land-based activities and programming to strengthen land-based knowledge and skills. Inuit have tremendous knowledge about the environment, including weather. This knowledge is critical for observing, monitoring, understanding, and responding to environmental changes. Supporting the transfer of Inuit knowledge, language, skills, and values in the community, especially to youth, is key.
9) Taking steps necessary to maintain reliable station records of precipitation, temperature, humidity, and winds. Such records are critical for understanding the combination of weather conditions that lead to the greatest community impacts.
10) Developing a community preparedness plan for similar extreme events to support local future responses.
11) Ensuring that all of the above have adequate support and funding with direct meaningful input and leadership of the community.

As an encouraging step in demonstrating community resiliency that bears on some of these recommendations, Clyde River codeveloped and operates a community-based weather station network (https://www.clyderiverweather.org/). The network was established by the community with partners in 2009, in response to local observations that weather patterns were changing, coupled with strong interest in more community-relevant weather information and services (Fox et al. 2020). A lack of weather products and tools useful in the community context has long been identified in Clyde River and by other Nunavut and northern communities. Residents are calling for more and better sources of environmental information, in particular to support safe travel decisions (Simonee et al. 2021; Carter and Ljubicic 2022), successful harvesting, and other community planning and activities. Wider efforts to develop such local networks should be supported. For such networks to inform questions of long-term climate and climate change, they must also be maintained for multiple decades. In turn, this information would be valuable in supporting future research related to changing weather, climate, extremes, impacts and responses, and especially studies that coproduce knowledge between Inuit and visiting scientists.

Data availability statement. Surface station data was acquired from Environment and Climate Change Canada (https://climate.weather.gc.ca/historical_data/search_historic_data_e.html). ERA5 data were acquired from the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (https://doi.org/10.24381/cds.adbb2d47).

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