

The Influence of Extratropical Cyclones in the Seasonal
Growth and Decay of Sea Ice in Hudson Bay

by

Ana Cláudia Cardoso de Jesus

A Thesis submitted to the Faculty of Graduate Studies of
The University of Manitoba
in partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE

Department of Environment and Geography
University of Manitoba
Winnipeg

Copyright © 2025 by Ana Cláudia Cardoso de Jesus

Abstract

Hudson Bay, a large continental marginal sea of the Arctic Ocean, experiences seasonal sea ice, with sea ice advancing around November and retreating by July. Hudson Bay also experiences extratropical cyclones throughout the year, which modulate sea ice in Hudson Bay through both dynamic and thermodynamic mechanisms. Despite their known influence in other parts of the Arctic, the role of extratropical cyclones in shaping sea ice conditions in Hudson Bay remains poorly understood. This study addresses this gap by examining how extratropical cyclones affect sea ice concentration (SIC) and sea ice effective thickness (SIT) in Hudson Bay from 1979 to 2023. Using sea ice data from NSIDC and PIOMAS (Pan-Arctic Ice-Ocean Modeling and Assimilation System), as well as ERA5 sea ice and atmospheric data, we analyzed cyclone-driven anomalies in atmospheric and sea ice variables across three seasons: freeze-up (November-December), ice-covered (January-April), and break-up (May-July). By categorizing cyclones according to their positions (north, south, east, west) relative to Hudson Bay grid cells, we investigated the influence of extratropical cyclones on the SIC and SIT across the Bay. Results reveal that sea ice responses to cyclones are both seasonally dependent and spatially variable. SIC changes are most closely tied to a combination of dynamic and thermodynamic anomalies, particularly air temperature, sensible heat flux, and ice motion, which is driven by the wind pattern. Meanwhile, SIT variability is primarily driven by dynamic processes, including ice advection and convergence. Cyclone positioning plays a critical role in modulating these effects, with cyclones located to the west or east of the grid cells exhibiting more consistent influences on ice, resulting in either faster or slower growth or decay across the seasons. Lastly, the cumulative impact of cyclones in the seasonal SIT was observed along the western, southern, and eastern boundaries of Hudson Bay, with cyclones contributing an average of 50 cm in total growth during the ice-covered season.

Acknowledgments

I am grateful to my supervisors, Dr. Alex Crawford and Dr. Julianne Stroeve, for the fantastic guidance they provided throughout my master's program, always orienting me to the best way to conduct this research project through their splendid knowledge.

I would also like to thank my committee members, Dr. John Hanesiak and Dr. Jens Ehn, for taking the time to read and evaluate my work.

I am thankful to Dr. Juliana Marson for her time acting as the chair for my thesis defense.

I am very thankful for my friends, who have provided emotional support directly or indirectly during tough times. My special thanks to my friend Aura, who has been very supportive of me.

Finally, I would like to thank Jason Northage for his consistently dedicated technical support throughout my program, as technology was my primary tool for conducting this research project.

Dedication

This work is dedicated in loving memory of my grandparents, who became my parents and raised me with love, teaching me resilience. Though they are no longer with me, their influence remains a guiding force in my life.

TABLE OF CONTENTS

ABSTRACT

ACKNOWLEDGMENTS

DEDICATION

TABLE OF CONTENTS

LIST OF FIGURES

1. Introduction.....	1
2. Literature Background.....	2
2.1 Impacts of Global Warming on Arctic Sea Ice.....	2
2.2 Sea Ice Variability in Hudson Bay and Environmental Impacts.....	3
2.3 Synoptic-Scale Weather Systems.....	5
2.4 Climatology of Cyclones in the Northern Hemisphere.....	6
2.5 Dynamic and Thermodynamic Implications for Sea Ice.....	8
3. Research Rationale.....	12
4. Objective.....	13
5. Data and Methodology.....	14
5.1 Study Area.....	14
5.2 Atmospheric and Sea Ice Data from ERA5.....	16
5.3 Sea Ice Concentration Data from NOAA/NSIDC Climate Data Record.....	17
5.4 PIOMAS Data.....	18
5.5 Cyclone Tracking Method.....	20
5.6 Daily Average of the Atmospheric and Sea Ice Data.....	21
5.7 Statistical Method.....	22
6. Results.....	24

6.1 Analysis of the Sea Ice Tendency to Grow and Decay.....	24
6.1.1 Sea Ice Concentration from NSIDC.....	24
6.1.2 Sea Ice Concentration from ERA5.....	27
6.1.3 Sea Ice Concentration from PIOMAS.....	29
6.1.4 Sea Ice Effective Thickness.....	31
6.2 Dynamic Analysis.....	34
6.2.1 Sea Ice Advection and Convergence.....	34
6.2.3 Zonal and Meridional Ice Motion (U-V).....	38
6.3 Thermodynamic Analysis.....	42
6.3.1 Air Temperature and Sensible Heat Flux.....	42
6.3.2 Thermodynamic Growth of Sea Ice.....	47
7. Discussion.....	50
7.1 Dynamic and Thermodynamic Effects on Sea Ice by Season.....	51
7.1.1 Freeze-up Season.....	51
7.1.2 Ice-Covered Season.....	53
7.1.3 Break-up Season.....	55
7.1.4 Cumulative impact.....	58
7.2. Limitations.....	59
7.2.1 Snow Cover.....	60
7.2.2 ERA5 Bias.....	60
7.2.3 Thermodynamic Growth Estimates.....	61
7.3. Implications and Future Work.....	61
8. Conclusion.....	62
REFERENCES.....	65

LIST OF FIGURES

Figure 1: Sea ice concentration in fall (November to December) and spring/summer (May to July) in Hudson Bay from 1980 to 2005 illustrates the pattern of freeze-up and break-up. Adapted from Hochheim et al. (2010).....	3
Figure 2: Seasonal frequency (left) and intensity (right) of extratropical cyclones in the northern hemisphere (1979-2009). The frequency is given by the number of monthly tracks and intensity by cyclonic vorticity unit, or $1.0 \times 10^{-5} \text{ s}^{-1}$. From Plante et al. (2015).....	7
Figure 3: Sea ice concentration decreased between August 2 and 10 due to the “Great Arctic Cyclone 2012”. From Parkinson and Comiso (2013).....	9
Figure 4: Study area map of Hudson Bay showing a representative grid cell and its surrounding 1200 km radius search area. This circular area is divided into four directional sectors used in the analysis: West (yellow), East (green), North (pink), and South (purple), relative to the central grid cell.....	15
Figure 5: Sea ice concentration (SIC) tendency from the NSIDC dataset under cyclone and no-cyclone conditions over Hudson Bay grid cells. The first column (a, f, k) shows SIC tendency during days with no cyclones. The second column (b, g, l) shows the difference in SIC tendency when cyclones are located to the west, calculated as cyclone minus no-cyclone cases. The third column (c, h, m) shows SIC tendency differences for cyclones to the east, the fourth column (d, i, n) for cyclones to the north, and the fifth column (e, j, o) for cyclones to the south, each compared to no-cyclone conditions. The first row represents the freeze-up season (November-December), the second row corresponds to the ice-covered season (January-April), and the third row depicts the break-up season (May-July). Red shades indicate a faster increase in sea ice concentration, while blue shades indicate slower growth or greater decay. Grey dots mark grid cells where the differences between cyclone and no-cyclone cases are statistically significant ($p < 0.05$).....	26

Figure 6: As in Figure 5, but with SIC data from ERA5.....	28
Figure 7: As in Figure 5, but with SIC data from PIOMAS.....	30
Figure 8: As in Figure 5, for the Sea ice effective thickness (SIT) data from PIOMAS.....	32
Figure 9: Mean sea ice advection and wind patterns (vectors) under cyclone and no-cyclone conditions over Hudson Bay grid cells. The first column (a, f, k) shows ice advection and wind vectors during periods with no cyclones. The second column (b, g, l) presents the difference when cyclones are located to the west, calculated as cyclone minus no-cyclone cases. The third column (c, h, m) shows differences for cyclones to the east, the fourth column (d, i, n) for cyclones to the north, and the fifth column (e, j, o) for cyclones to the south, each compared to no-cyclone conditions. The first row represents the freeze-up season (November-December), the second row corresponds to the ice-covered season (January-April), and the third row shows the break-up season (May-July). Positive values indicate enhanced sea ice advection (associated with increased ice transport or growth), while negative values indicate reduced advection or slower sea ice growth. Wind vectors show the corresponding mean atmospheric circulation patterns. Grey dots mark grid cells where the differences between cyclone and no-cyclone conditions are statistically significant ($p \leq 0.05$).....	35
Figure 10: As in Figure 9, for the ice convergence.....	37
Figure 11: Mean U-component of sea ice motion (U-ice motion) and wind patterns (vectors) under cyclone and no-cyclone conditions over Hudson Bay grid cells. The first column (a, f, k) shows U-ice motion and wind vectors during periods with no cyclones. The second column (b, g, l) presents the difference when cyclones are located to the west, calculated as cyclone minus no-cyclone cases. The third column (c, h, m) shows differences for cyclones to the east, the fourth column (d, i, n) for cyclones to the north, and the fifth column (e, j, o) for cyclones to the south, each compared to no-cyclone conditions. The first row represents the	

freeze-up season (November-December), the second row corresponds to the ice-covered season (January-April), and the third row shows the break-up season (May-July). Positive U-ice values indicate eastward sea ice motion, while negative values indicate westward motion. Wind vectors illustrate the corresponding atmospheric circulation patterns. Grey dots mark grid cells where the differences between cyclone and no-cyclone conditions are statistically significant ($p \leq 0.05$).....40

Figure 12: As in Figure 11, but for the mean V-component of sea ice motion (V-ice motion).....41

Figure 13: Mean air temperature and wind patterns (vectors) under cyclone and no-cyclone conditions over Hudson Bay grid cells. The first column (a, f, k) shows mean air temperature and wind vectors during periods with no cyclones. The second column (b, g, l) presents the difference when cyclones are located to the west, calculated as cyclone minus no-cyclone cases. The third column (c, h, m) shows differences for cyclones to the east, the fourth column (d, i, n) for cyclones to the north, and the fifth column (e, j, o) for cyclones to the south, each compared to no-cyclone conditions. The first row represents the freeze-up season (November-December), the second row corresponds to the ice-covered season (January-April), and the third row shows the break-up season (May-July). Positive values indicate warmer air temperatures, while negative values indicate colder air temperatures. Grey dots indicate grid cells where differences between cyclone and no-cyclone conditions are statistically significant ($p \leq 0.05$).....43

Figure 14: As in Figure 13, but for the mean surface sensible heat flux (SSHF).....45

Figure 15: As in Figure 13, but for the mean thermodynamic growth.....48

Figure 16. Total Sea Ice Thickness (SIT) growth by season. The first column illustrates the mean SIT (cm/day) during days without cyclones. The second column shows the difference in SIT (cm/day), calculated as SIT during cyclone days minus SIT during non-cyclone days.

The third column displays the total SIT growth (cm) for all days combined (mean SIT multiplied by the total number of cyclone and non-cyclone days). The fourth column presents the total SIT growth difference (cm), specifically for cyclone days (SIT difference multiplied by the number of cyclone days). Rows represent different seasons: freeze-up (November-December, first row), ice-covered (January-April, second row), and break-up (May-July, third row).....58

1. Introduction

Hudson Bay is a large inland sea surrounded by the provinces of Manitoba, Ontario, Quebec, and Nunavut. It experiences seasonal sea ice, with sea ice formation beginning in November and melting and breaking up by July. However, global warming has extended the ice-free season, primarily due to later freeze-up and, to a lesser extent, earlier break-up in the area.

In addition to global warming, the growth and decay of sea ice in Hudson Bay may be sensitive to large-scale weather systems, such as extratropical cyclones, which frequently pass through the region and are often associated with frontal systems. The winds generated by these cyclones have a dynamic impact on sea ice, while the cold and warm sectors of the frontal system contribute to thermodynamic effects. These thermodynamic influences involve both sensible heat flux and radiative processes, including longwave and shortwave radiation.

Since the impacts of mid-latitude weather systems on sea ice in Hudson Bay have not been extensively studied, this study analyzes the dynamic and thermodynamic implications of extratropical cyclones on seasonal sea ice in Hudson Bay using a combination of satellite and reanalysis datasets. Understanding these processes can improve short-term forecasts of sea ice advance and retreat on synoptic timescales, such as daily to weekly predictions, which benefits communities in the region that rely on sea ice predictions to plan their activities. These forecasts are also crucial for shipping operations, as longer ice-free periods may open new navigational routes or increase risks associated with unpredictable ice conditions. Additionally, sea ice is a critical habitat for polar bears and other Arctic and sub-Arctic wildlife; changes in its timing and extent can impact their movement, hunting, and survival.

2. Literature Background

2.1 Impacts of Global Warming on Arctic Sea Ice

Over the past decades, a substantial decline in the extent and concentration of Arctic sea ice has been observed. This is linked to global warming, mainly attributed to the increasing concentrations of greenhouse gases in the atmosphere (Parmentier et al., 2013; Stroeve and Notz, 2018). This decline in sea ice underscores growing concerns about climate change, as the significant rise in global surface temperatures since the pre-industrial era (1850-1900) has profound global and local implications. According to the World Meteorological Organization (WMO), 2024 was the warmest year since the beginning of the 20th century, with a temperature about 1.55 °C above the pre-industrial average.

However, the effects of this global temperature increase are not evenly distributed across the planet. Among all regions, the Arctic has exhibited the most pronounced warming trend in recent decades, emerging as a region of particular concern in climate research. This apparent divergence from global averages has led to an increased focus on the processes driving accelerated warming at high latitudes (England et al., 2021; Previdi et al., 2021), a phenomenon known as Arctic amplification (Serreze and Barry, 2011). According to Rantanen et al. (2022), vast regions of the Arctic Ocean warmed four times faster than the global mean between 1979 and 2021, with Arctic temperatures rising by 0.73°C per decade compared to 0.19°C per decade globally, primarily driven by the reduction in sea ice cover.

Loss of ice and snow means that darker ocean surfaces are exposed, which have lower albedo (i.e., they absorb more heat, which can then be transferred to the atmosphere via upwelling longwave radiation and turbulent heat fluxes (Perovich and Richter-Menge, 2009).

This feedback mechanism, in which ice loss leads to greater heat absorption, further contributes to rising temperatures in the Arctic (Nicolaus et al., 2012).

2.2 Sea Ice Variability in Hudson Bay and Environmental Impacts

Typically, sea ice freeze-up in Hudson Bay starts in the northern region between November and December, extending southward and southeastward. The southeastern region is the last to freeze up. Meanwhile, sea ice break-up is observed between June and July, starting in the northern and eastern regions, but the southwestern region is the last to become ice-free (Figure 1) (Hochheim et al., 2010).

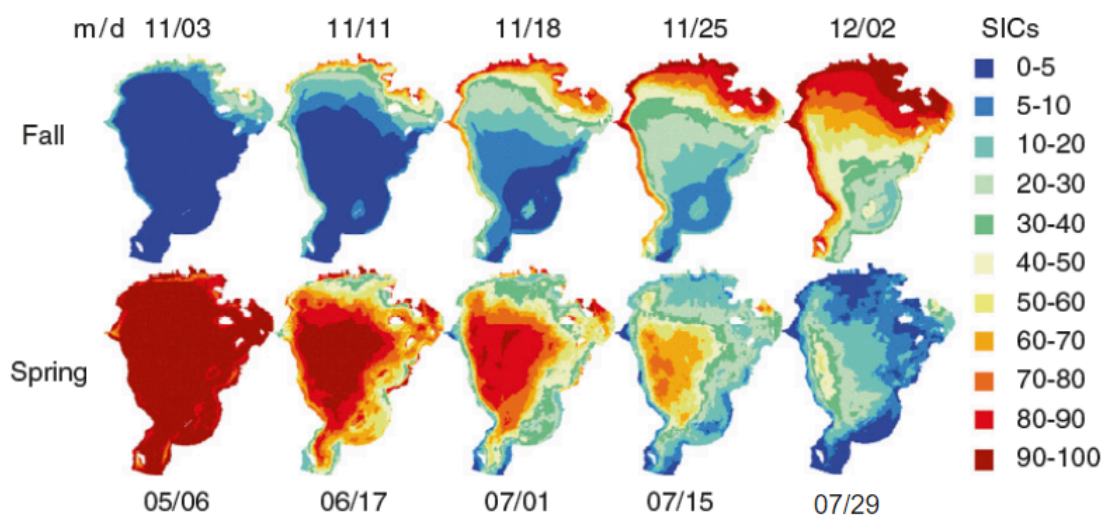


Figure 1. Sea ice concentration in fall (November to December) and spring/summer (May to July) in Hudson Bay from 1980 to 2005 illustrates the pattern of freeze-up and break-up. Adapted from Hochheim et al. (2010).

However, the sea ice freeze-up and break-up patterns have changed over the past decades due to rising global temperatures (Serreze and Stroeve, 2015). For instance, the study by Hochheim and Barber (2014) showed that average surface temperature increased from 1.53°C to 2.89°C in the fall and 0.83°C to 1.61°C in the spring over the Hudson Bay area from

1980 to 2010. Their investigations also revealed a delay in freeze-up of about 1.6 to 2.4 weeks (in the fall season) and an earlier break-up of about 1.5 weeks (in the spring) before the prior sea ice retreat dates in Hudson Bay.

In addition to anthropogenic warming, sea ice variability in Hudson Bay is shaped by natural atmospheric and oceanic processes acting on interannual timescales. Variability in fall SSTs in the subpolar North Atlantic, linked to the Atlantic Multidecadal Oscillation (AMO), influences winter atmospheric patterns by strengthening northwesterly winds, which affect ice thickness and spring breakup, and these atmospheric patterns occur due to the deepening of winter troughs, which reinforce this wind pattern, further shaping ice distribution across the region (Tivy et al., 2011).

Also, Atmospheric teleconnections, especially the North Atlantic Oscillation (NAO) during the cold season, further affect sea ice variability through both thermodynamic (temperature-related) and dynamic (wind-related) mechanisms (Kinnard et al., 2006). More recent studies have also highlighted the influence of cyclonic wind patterns, showing that shifts in winter wind regimes can drive pronounced regional differences in sea ice thickness and break-up timing across Hudson Bay (Kirillov et al., 2020). Recognizing these natural drivers is essential for interpreting historical patterns of sea ice change in the region.

Locally, sea ice loss brings adverse consequences, especially to wildlife that rely on sea ice. According to Johnson et al. (2020), the open water period between 1985 and 2018 increased from 105 days to 145 days due to the later freeze-up and earlier break-up, which has caused an imbalance in the wildlife that rely on sea ice. For instance, animals such as polar bears are experiencing shorter hunting periods than usual, as they typically use sea ice to hunt seals, their typical prey. When polar bears are forced to spend more time onshore due to a shortened sea ice season, they experience nutritional stress and may struggle to regain

body condition, particularly if their level of starvation is severe (Castro de la Guardia et al., 2017; Obbard et al., 2016).

Moreover, it is observed that the population of these animals is diminishing in western Hudson Bay, which is directly related to the increasing period of open water and polar bears onshore (Lunn et al. 2016).

2.3 Synoptic-Scale Weather Systems

Large-scale atmospheric systems play a critical role in shaping midlatitude weather patterns. For instance, large-scale weather systems such as extratropical cyclones have been monitored due to their potential to produce extreme weather along their tracks (Simmonds et al., 2008). These systems can generate heavy precipitation and powerful winds driven by pressure gradients (Catto, 2016). Extratropical cyclones typically develop in baroclinic zones, which are associated with vertical wind shear generated by the horizontal temperature gradient (Holton and Hakim, 2013). The development and maintenance of extratropical cyclones involves dynamics in the lower, middle, and upper troposphere. At the surface, the configuration of a cyclone starts from an initial disturbance related to low pressure and cyclonic relative vorticity (positive in the Northern Hemisphere). Within a low-pressure system, air converges at the surface, while divergence occurs in the upper troposphere, around 200 hPa. This enhances rising air, which reaches its highest speed at a non-divergent level (around 500 hPa) and east of the trough axis.

For the atmospheric pressure to drop, the divergence aloft must be greater than the convergence at the surface. Another typical feature for extratropical cyclones is the temperature advection at the lower levels of the troposphere, in which warm air is advected (poleward) on the east side of the cyclones while cold air is advected (equatorward) on the

west side of the system. Besides temperature advection, extratropical cyclones also play a role in moisture transport, especially from lower to higher latitudes (Carlson, 1991; Lackmann, 2011).

Extratropical cyclones over Hudson Bay are typically associated with frontal systems, which are the boundaries between air masses with different temperatures and, consequently, distinct densities. When cold air advances and pushes warm air, the boundary between the cold and warm air is referred to as a cold front. Here, warm air abruptly rises, generating clouds and precipitation. Meanwhile, the warm front, which also produces clouds and precipitation, is a boundary between warm and cold air, where the warmer mass moves toward the colder. That said, ahead of the cold front is the warm sector of the cyclone, and behind the cold front is the cold sector (Bluestein, 1993; Stull, 2015).

2.4 Climatology of Cyclones in the Northern Hemisphere

Cyclones exhibit varying frequency and intensity depending on the region and season. In the Arctic, for instance, cyclogenesis in winter tends to occur in the North Atlantic, the east coast of Greenland, Scandinavia, and the lee of the northern Rockies. During summer, however, storms form more frequently over the Eurasian coastline and in the Barents and Kara Seas (Vessey et al., 2020). The analysis by Valkonen et al. (2021) and Zahn et al. (2018) reveals that while intense cyclones are more frequent in winter, the total number of cyclones is often higher in the summer, especially in areas like the Chukchi Sea and Central Arctic. Additionally, Crawford and Serreze (2016) presented that in the Arctic (Atlantic side of the Arctic Ocean) and the Gulf of Alaska, cyclogenesis from 1979 to 2014 was more frequent in winter. In contrast, cyclone activity happened more in summer over the Central Arctic Ocean and eastern Siberia. The study by Crawford et al. (2022) suggests that cyclone intensification during the winter in the Arctic Ocean is linked to lower sea ice concentration, enhancing

upward turbulent heat fluxes and weakening static stability. Weakened static stability means less resistance to vertical motion, which, combined with strong vertical wind shear, favors the development of intense cyclones.

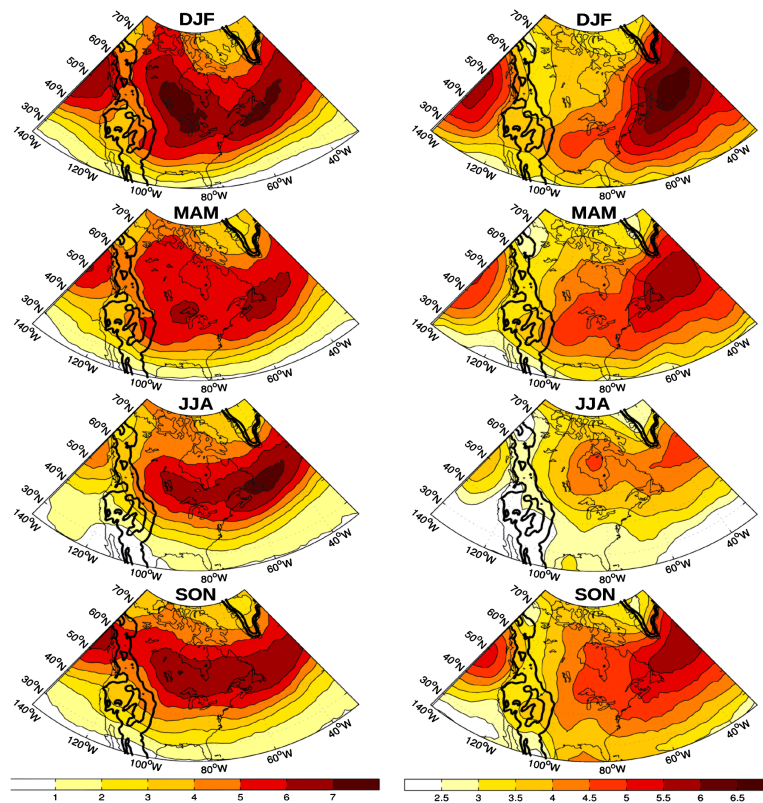


Figure 2. Seasonal frequency (left) and intensity (right) of extratropical cyclones in the northern hemisphere (1979-2009). The frequency is given by the number of monthly tracks and intensity by cyclonic vorticity unit, or $1.0 \times 10^{-5} \text{ s}^{-1}$. From Plante et al. (2015).

In Canada, continental extratropical cyclones frequently form in the lee of the Rockies, moving eastward and dissipating near Greenland (Plante et al., 2015). According to Plante et al. (2015), in winter, cyclone frequency is highest over the lee side of the Canadian Rockies, the Great Lakes, Newfoundland, and the North Atlantic, with peak intensity over Newfoundland, the North Atlantic, and along the U.S East coast due to the strong sea surface temperature gradient. In summer, cyclone frequency decreases, especially in the Rockies, Northern Canada, and the southern United States. This study also reveals that Hudson Bay

experiences stronger cyclones (intense cyclonic vorticity) in September, October, and November (Figure 2), likely due to the ice-free area during this season, which supplies more moisture. Also, Chen et al. (2022) found that, consistent with Plante et al. (2015), cyclones tend to be more intense in Hudson Bay during autumn, with storms from 1979 to 2020 showing stronger wind speeds, particularly in September, October, and November.

2.5 Dynamic and Thermodynamic Implications for Sea Ice

Cyclones significantly influence sea ice growth and decay through thermodynamic and dynamic processes. Thermodynamically, cyclones can affect sea ice cover through temperature advection, cloud cover, and precipitation. Temperature advection can either decrease or increase sea ice growth rates, depending on whether a region is situated to the east of a cyclone, where warm air is advected, or to the west, where colder air predominates (Clancy et al., 2022). Cloud cover associated with cyclone frontal systems has opposing effects on sea ice: it reduces incoming shortwave solar radiation, promoting ice growth, but also retains outgoing longwave radiation, which contributes to ice melt. The longwave radiation effect in the Arctic typically dominates, leading to net sea ice melt (Sorteberg and Walsh, 2008; Sledd et al., 2025). Ice melt rates are also influenced by the sea ice albedo, with snow-covered ice reflecting more solar radiation and thus melting more slowly (Light et al., 2008).

Additionally, cyclone-driven precipitation, primarily in the form of snow, influences sea ice thickness by insulating the ice surface and slowing ice growth (Maaß et al., 2013; Boisvert et al., 2018). A case study by Boisvert et al. (2016) supports these mechanisms, showing that warm and humid air advection during a winter cyclone across the Barents and Kara Seas disrupted the surface energy balance and reduced local sea ice concentration.

Valkonen et al. (2021) further emphasized this thermodynamic influence, identifying the Barents Sea to northern Greenland is highly sensitive to cold-season cyclone activity and associated sea ice decline.

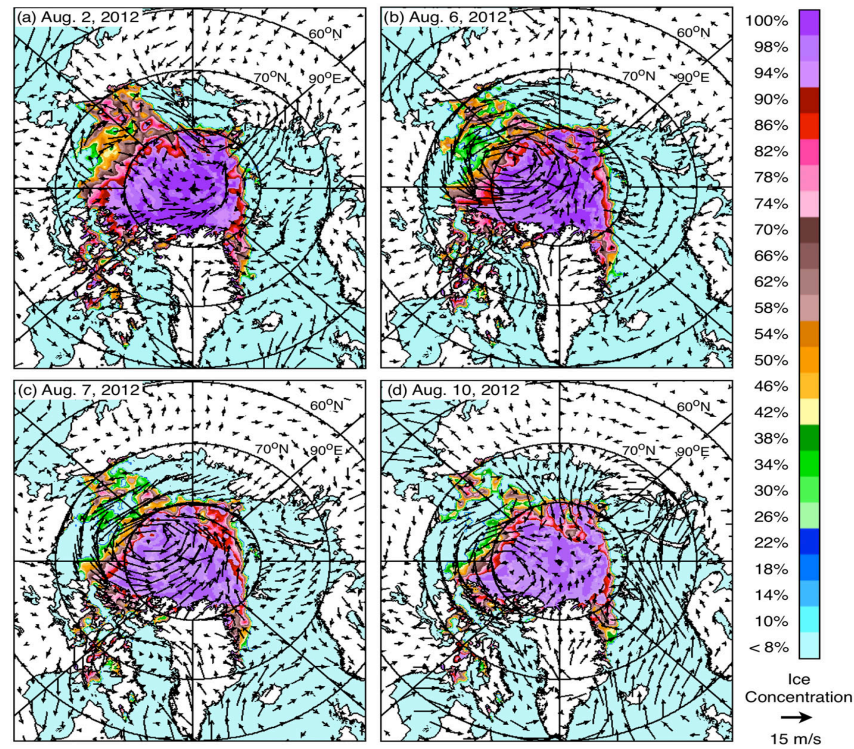


Figure 3. Sea ice concentration decreased between August 2 and 10 due to the “Great Arctic Cyclone 2012”. From Parkinson and Comiso (2013).

Dynamically, cyclones impact sea ice primarily through wind-driven transport, causing convergence or divergence that results in ice thickening or thinning (Spren et al., 2011; Schreiber and Serreze, 2020). A notable case highlighting dynamic processes is "The Great Arctic Cyclone of August 2012," documented by Simmonds and Rudeva (2012). This intense cyclone formed over northern Siberia on August 2, reached a central pressure of 966 hPa by August 6, and dissipated near the Canadian Archipelago after approximately 13 days. Sea ice extent in August 2012 reached the lowest level recorded over the previous 33 years of satellite data. Parkinson and Comiso (2013) indicated that the cyclone significantly contributed to sea ice reduction (Figure 3) by dynamically fragmenting and transporting ice

toward warmer waters, facilitating melt. The reduction in sea ice also exposed ocean areas, reducing albedo and increasing solar radiation absorption, further enhancing melt (Zhang et al., 2013). Lukovich et al. (2021) noted that subsequent ice recovery occurred in the Central Arctic after this cyclone, due to refreezing, despite continued ice loss in the Pacific sector.

Another intense cyclone event in August 2016 further illustrated significant dynamic influences on sea ice. Lukovich et al. (2021) observed a decrease in sea ice volume north of the Canadian Arctic Archipelago, Greenland, and north of the Beaufort Sea, attributed to the dynamic transport of thicker ice away from these regions. In contrast, increased ice volume was observed north of Norway due to ice advection into the area. Overall, these 2012 and 2016 cyclones underscore the importance of cyclone intensity and track in determining whether dynamic or thermodynamic processes dominate regional sea ice variability. Finocchio et al. (2022) also highlighted the critical importance of sea ice thickness in dynamic processes, as thinner ice is more susceptible to wind-driven divergence, fracturing, and melting, particularly when cyclones intensify the mixing of warmer ocean water into the ice layer.

Several studies have investigated the combined dynamic and thermodynamic impacts of cyclones on sea ice concentration (SIC). Clancy et al. (2022) analyzed Arctic cyclones from 1985 to 2016, revealing ice convergence west of cyclones and divergence east, primarily driven by ice dynamics, although thermodynamic factors also contributed to changes in sea ice. Similarly, Aue et al. (2022) examined winter cyclones (1979-2020) in the Greenland, Barents, and Kara Seas, reporting regional differences: SIC decreased in the Greenland Sea due to warm, moist air advection and ice divergence, increased in the Barents Sea from cold, dry advection, and showed insignificant change in the Kara Sea. Aue and Rinke (2023) further confirmed significant cyclone-induced SIC changes throughout the year, especially during the cold season. These studies demonstrate that cyclone location relative to

sea ice, along with local air temperature, humidity, and wind direction, critically determines regional SIC responses.

Overall, dynamic and thermodynamic processes driven by cyclones intricately control the growth, decay, and distribution of Arctic sea ice. Regions frequently traversed by cyclones, especially the Barents and Kara Seas, are particularly vulnerable due to their repeated exposure to these interacting mechanisms.

Research Rationale

Hudson Bay is the largest inland sea in the world, covering an area of about 1.2 million square kilometers (470 square miles). The area is a crucial habitat for polar bears, seals, and migratory birds. The region is also relevant from an economic perspective and serves as a shipping route for the tourism industry, among other practices. For example, Churchill, located west of Hudson Bay, is often a destination for tourists and researchers interested in knowing the local wildlife. Due to global warming, the sea ice has advanced later and retreated earlier, impacting wildlife such as polar bears and decreasing their population (Johnson et al. 2020). Among many consequences, it causes an imbalance in the local wildlife and also tends to make the region less attractive for visitors due to the reduced number of local animals.

This research will provide key insights into how mid-latitude weather systems influence sea ice dynamics in Hudson Bay. While the Central Arctic Ocean and Barents/Kara Seas have been extensively studied, the impact of extratropical cyclones on sea ice growth and melt in Hudson Bay remains unexplored. Understanding the effects of cyclones on Hudson Bay sea ice is crucial for refining climate models and improving seasonal and short-term sea ice predictions specific to the region. Accurate forecasts are crucial for navigation, shipping route planning, and ensuring safer and more efficient operations as sea ice conditions become increasingly variable. Additionally, these forecasts can help coastal communities and industries adapt their activities to changing sea ice patterns.

Objective

This study aims to assess the influence of extratropical cyclones on the seasonal growth and decay of sea ice in Hudson Bay, with a focus on determining whether dynamic or thermodynamic processes, or a combination of both, primarily drive these impacts. To achieve this, we address the following research questions:

1. Do extratropical cyclones affect seasonal sea ice in Hudson Bay dynamically, thermodynamically, or through both mechanisms?
2. How does the directional position of cyclones (north, south, east, or west) relative to the grid cells affect local sea ice conditions?
3. To what extent does the effect of cyclonic activity vary across the three key seasonal phases of sea ice development in Hudson Bay: freeze-up (Nov–Dec), stable ice cover (Jan–Apr), and break-up (May–Jul)?
4. Are certain cyclone positions or seasons more strongly associated with enhanced sea ice growth or accelerated decay?

Data and Methodology

5.1 Study Area

Our study focuses on Hudson Bay, which covers the region between 50°N and 66°N latitude and 96°W and 74°W longitude. The analysis was conducted using grid cells across Hudson Bay. We defined a circular search area with a 1200 km radius for each grid cell to identify nearby cyclones. The surrounding area was then divided into four directional sectors (north, south, east, and west) relative to the central grid cell, as illustrated in Figure 4. Only cyclones located within 1200 km of a given grid cell were considered when assessing the influence of storm activity on sea ice at that location.

A representative grid cell is shown, with each directional category visually distinguished by a different color. This directional classification allows us to examine how sea ice responds to cyclones located to the west, east, north, or south of each cell. The analysis spans the period from 1979, marking the beginning of satellite-based sea ice records, through 2023, the most recent year with complete data available at the time of processing. This time frame provides a comprehensive basis for assessing the influence of cyclonic activity on sea ice conditions in Hudson Bay.

The study is structured around three key seasonal periods, each corresponding to a distinct phase in the life cycle of sea ice. The first period, from November to December, represents the freeze-up phase, when sea ice begins to form across Hudson Bay. During this phase, we focused on the rate at which sea ice expands in coverage and increases in thickness, capturing both horizontal and vertical growth. The second period, from January to April, captures the phase when the Bay is typically covered by ice. In this stage, we analyzed ice conditions to determine whether sea ice tends to grow, decay, or remain stable within each

directional quadrant of the grid cells, while also considering that thicker ice becomes increasingly resistant to both dynamic and thermodynamic processes. The third period, from May to July, represents the break-up phase, when sea ice begins to melt and retreat. During this time, we examined the rate and extent of sea ice decay. This seasonal segmentation provides a detailed understanding of how extratropical cyclone activity influences sea ice tendencies throughout the year in Hudson Bay.

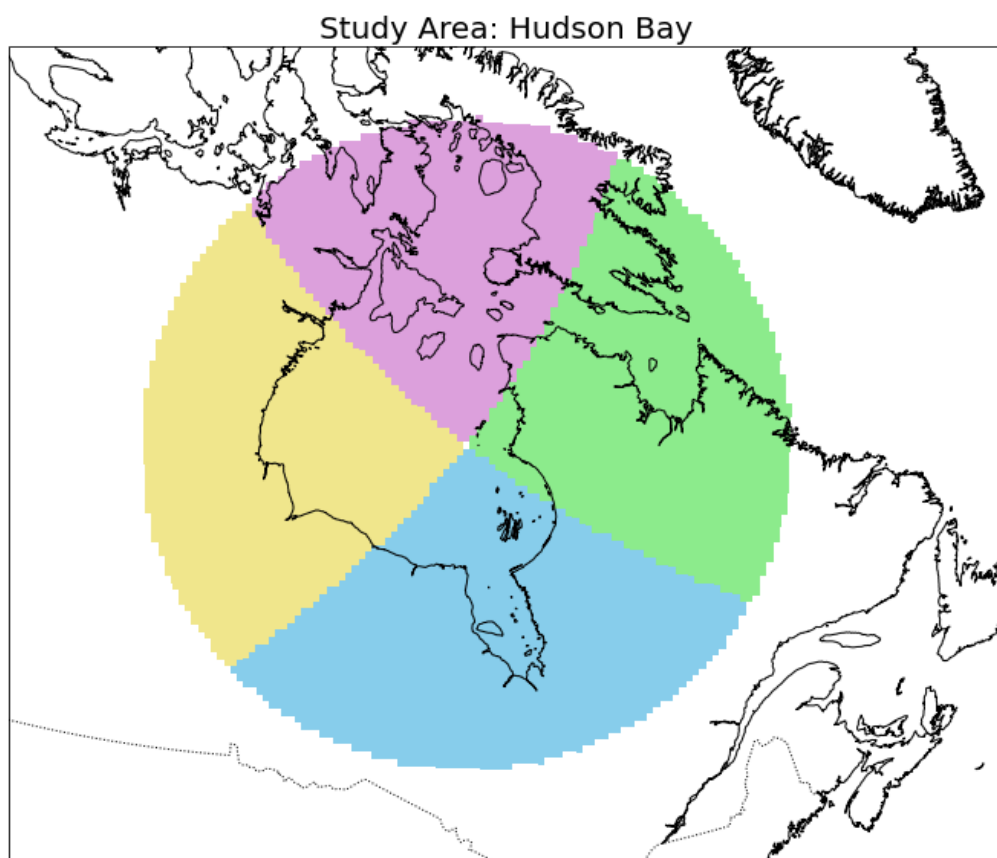


Figure 4. Study area map of Hudson Bay showing a representative grid cell and its surrounding 1200 km radius search area. This circular area is divided into four directional sectors used in the analysis: West (yellow), East (green), North (pink), and South (blue), relative to the central grid cell.

5.2 Atmospheric and Sea Ice Data from ERA5

Firstly, we use ERA5 reanalysis data from the ECMWF (*European Centre for Medium-Range Forecasts*) (Hersbach et al., 2020), the most recent ECMWF reanalysis, which offers the highest global atmospheric reanalysis resolution, where the atmospheric data are available in the regular horizontal grid of resolution $0.25^\circ \times 0.25^\circ$ latitude and longitude. The data coverage is global, with a vertical resolution of 37 pressure levels, from 1000 hPa to 1 hPa. ERA5 data are available hourly from 1940 to the present. For the dynamic analysis, horizontal wind components at the 925 hPa pressure level were used, including zonal (u) and meridional (v) wind velocity (m/s). For the thermodynamic analysis, air temperature ($^\circ\text{C}$) at 925 hPa and sensible heat flux (SSHF) (W/m^2) were included. SSHF values follow the ECMWF ERA5 sign convention, where positive fluxes represent energy transfer from the atmosphere to the surface (downward), resulting in surface warming. Negative values indicate an upward flux, with the surface losing heat to the atmosphere.

In addition to the atmospheric data, we included sea ice concentration (SIC) from ERA5, expressed in units ranging from 0 to 1 (0% to 100%). From 1949 through 1978, ERA5 Sea surface temperature (SST) and SIC data were sourced from the HadISST2 (Hadley Centre Sea Ice and Sea Surface Temperature) dataset and provided daily data with a resolution of $0.25^\circ \times 0.25^\circ$ latitude/longitude grid. From 1979 to 2006, the SIC data transitioned to the OSI SAF (Ocean and Sea Ice Satellite Application Facility) product, providing more detailed, satellite-derived daily data that was regridded from its original 10 km polar stereographic grid to match the $0.25^\circ \times 0.25^\circ$ grid used in ERA5. Finally, from September 2007 onwards, both SST and SIC data were sourced from high-resolution products, OSTIA (Operational Sea Surface Temperature and Sea Ice Analysis) for SST and

the operational OSI SAF for SIC, on a $0.05^\circ \times 0.05^\circ$ grid, reflecting significant advancements in data resolution and accuracy (Hersbach et al., 2020).

Due to the high performance of ERA5 reanalysis, this study uses atmospheric and sea ice data from this source. Many studies have demonstrated that ERA5 provides better results overall than other reanalyses. For instance, the study by Graham et al. (2019) examined the performance of several reanalyses compared to observed data during winter, spring, and early summer in the Arctic in 2015. They evaluated ERA-I, ERA5, JRA-55, CFSv2, MERRA-2, and ASRv2 in their ability to simulate surface radiative fluxes. They found that ERA5 performed better than all other reanalyses during spring and summer, while ASRv2 showed the lowest skill for surface radiative fluxes in summer.

Graham et al. (2019) also assessed other atmospheric variables, such as air temperature, wind speed, and sensible heat flux. They found that the performance of ERA5 was generally consistent with that of the other reanalyses. However, they pointed out that spring (April–June) was the season when the reanalyses showed the lowest overall accuracy. Similarly, the study by Barrett et al. (2020) also analyzed the performance of several reanalyses for precipitation in the Arctic Ocean. They found that the best reanalysis for estimating precipitation, primarily snowfall, over sea ice was ERA5.

These studies demonstrate the accuracy of ERA5, and we are confident that the ERA5 data source has provided us with consistent results.

5.3. Sea Ice Concentration Data from NOAA/NSIDC Climate Data Record

This work also utilizes sea ice concentration data from the National Snow and Ice Data Center (NSIDC), specifically the NOAA/NSIDC Climate Data Record (CDR) of passive microwave sea ice concentration, version 4. The passive microwave sea ice data was

used to compare with the results of ERA5 SIC for more consistent analyses. The CDR of sea ice concentration provides a detailed and reliable time series of sea ice measurements derived from passive microwave data by combining estimates from two algorithms: the NASA Team (NT) (Cavalieri et al., 1984) and the NASA Bootstrap (BT) (Comiso, 1986). Covering the period from October 25, 1978, to September 30, 2023, the CDR provides data on a 25 km x 25 km polar stereographic grid with sea ice concentration as the primary parameter. Before August 1987, the data were recorded every two days, and after this point, they were collected daily. It is sourced from various platforms, including the Defense Meteorological Satellite Program (DMSP) satellites 5D-2/F11, F13, F8, 5D-3/F17, and Nimbus-7, utilizing sensors such as the Scanning Multichannel Microwave Radiometer (SMMR), the Special Sensor Microwave/Imager (SSM/I), and the Special Sensor Microwave Imager/Sounder (SSMIS). The spatial coverage includes the northern polar region (89.84°N to 31.1°N), with global longitude coverage from 180°E to -180°W. The passive microwave data were interpolated to fill gaps and ensure uniformity throughout the dataset.

5.4 PIOMAS Data

We also used sea ice concentration and effective thickness, as well as sea ice velocity, zonal motion (u), and meridional motion (v) data from the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS). The data are available from 1978 to the present, during which time satellite sea ice concentration data were also available. The grid system used in PIOMAS is a generalized curvilinear system, covering the Northern Hemisphere from 45° N to 90° N with a resolution of 360 x 120 grid cells. PIOMAS utilizes the Parallel Ocean Program (POP) ocean model in conjunction with the thickness and enthalpy distribution (TED) sea ice model. The system uses atmospheric inputs from NCEP-NCAR reanalyses

data, including surface winds, air temperature, humidity, radiative fluxes, precipitation, and evaporation. The sea ice model provides surface heat, salt (or freshwater), and momentum fluxes to the ocean as boundary conditions, while the ocean model supplies the ice model with information about currents and heat exchange. PIOMAS employs three distinct integration approaches. The first approach assimilates sea ice concentration (IC), utilizing data from the Hadley Centre from 1958 to 1995 and NSIDC from 1996 onwards. The second approach (IC-SST) assimilates ice concentration and sea surface temperature (SST) with the SST data derived from NCEP/NCAR reanalyses, representing the version of PIOMAS used in our study. A third integration, referred to as model-only, operates without data assimilation (Zhang and Rothrock, 2003; Schweiger et al., 2011).

Following Lukovich et al. (2021) and Crawford et al. (2023), we calculated the rate of sea ice effective thickness change with time ($\frac{\partial h_{eff}}{\partial t}$), advection (Adv), convergence ($Conv$), and thermodynamic growth ($Thrm$) for each grid cell in Hudson Bay. The calculations to analyze these variables were managed as follows:

$$\frac{\partial h_{eff}}{\partial t} = Thrm + Adv + Conv \quad (1)$$

$$Conv = -h_{eff} (\nabla \cdot u) \quad (2)$$

$$Adv = -\mathbf{u} \cdot (\nabla h_{eff}) \quad (3)$$

$$Thrm = \frac{\partial h_{eff}}{\partial t} - (Adv + Conv) \quad (4)$$

where h_{eff} the sea ice effective thickness, and t is time (daily). As sea ice is advected, it can converge or diverge; then the term $\nabla \cdot u$ in equation 2 represents the divergence of sea ice (the negative sign is to convert it to convergence); for $\nabla \cdot u > 0$, it indicates that the sea ice

is diverging; meanwhile, for $\nabla \cdot u < 0$, it means the convergence of sea ice. Nevertheless, when $\nabla \cdot u = 0$, that indicates a steady-state flow. Represented by equation 3, advection of sea ice is driven by how the ice moves (u) relative to the gradient of its thickness (∇h_{eff}), which represents the rate and direction of thickness change. The negative sign indicates the movement of sea ice from thicker to thinner areas. Lastly, in Equation 4, the thermodynamic growth was taken as the total sea ice change residual minus the sea ice advective and convergent change.

5.5 Cyclone Tracking Method

Our methodology uses the CEOS/NSIDC Extratropical Cyclone Tracking algorithm (CNECT), developed by Crawford et al. (2021), to identify and track cyclones within the study period and region. The CNECT dataset covers the Northern Hemisphere and provides cyclone track information in CSV format at 3-hour intervals, with a spatial resolution of 25 km. Each file contains the location, propagation, intensity, and size of cyclones. We selected all storms that intersect the domain, spanning from 42.5°N to 74.5°N latitude and 110°W to 60°W longitude.

To relate cyclone positions to sea ice variability in Hudson Bay, we used the CNECT dataset to determine whether a cyclone was located to the north, east, south, or west of each grid cell within the Bay (Figure 4). A spatial mask was applied to restrict the analysis to approximately 2,000 ocean-only grid cells across Hudson Bay. For each of these grid cells, we defined a circular search area with a 1200 km radius to identify nearby cyclones. This surrounding area was then divided into four directional sectors, north, east, south, and west, relative to the central grid cell, as illustrated in Figure 4. Only cyclones located within this 1200 km radius were considered when assessing the influence of storm activity on local sea

ice conditions. Using this directional classification, we then tracked cyclone presence over time. Cyclone positions were available at 3-hourly intervals, but because sea ice and the atmospheric variables were averaged daily, cyclone influence was assessed on a daily basis. For each day, we determined whether at least one cyclone was present within a 1200 km radius of a given grid cell, and in which directional sector(s) it occurred. Days with no cyclones detected in any quadrant were classified as “no cyclone.” The 3-hourly resolution of the cyclone data allowed us to capture changes in cyclone position throughout the day, meaning a single storm could appear in different directional sectors as it moved. In some cases, more than one cyclone could be present within the search radius on the same day.

5.6 Daily Averages of the Atmospheric and Sea Ice Data

After identifying whether a cyclone was present in one of the four directional quadrants (west, east, north, or south) relative to each Hudson Bay grid cell (Figure 4), daily averages of atmospheric variables were calculated for both cyclone and non-cyclone conditions. This analysis was performed for each grid cell from 1979 to 2023. This allowed for a detailed investigation of how cyclone position influences atmospheric conditions, specifically wind speed, direction, temperature, and sensible heat flux.

Sea ice data were processed in the same way as the atmospheric variables and over the same period. To assess the daily tendency of sea ice to grow or decay, we calculated the day-to-day difference in sea ice concentration and effective thickness by subtracting the previous day's value from the current day's value. In addition, daily means over time were calculated for ice motion, convergence, advection, and thermodynamic growth. All calculations were based on datasets with daily resolution. Since passive microwave sea ice data had a two-day temporal resolution from 1979 to 1987, these data were interpolated to

produce a consistent daily time series across the entire study period. To ensure the analysis focused only on periods when sea ice was present, all days with zero sea ice concentration were masked from the dataset.

5.7 Statistical Method

The analysis was conducted seasonally, from November to December, January to April, and May to July, corresponding to periods when sea ice is present in Hudson Bay. This seasonal breakdown allowed us to more effectively assess the dynamic and thermodynamic impacts of extratropical cyclone activity on sea ice. The analysis included all daily results of atmospheric and sea ice variables for each grid cell across the study domain. To evaluate the effect of cyclones, we compared the mean values of each variable under cyclone and no-cyclone conditions.

This grid cell-by-grid cell approach enabled a spatially explicit understanding of how cyclone position influences sea ice and atmospheric conditions. For each comparison, we applied an independent samples t-test (Kim, 2015; Kim and Park, 2019), a parametric statistical test used to determine whether the difference in means between two independent groups is statistically significant. This test assumes normally distributed data, meaning most values cluster around the mean, forming a bell-shaped curve where extreme values are less common.

The two comparison groups were defined as follows:

- Group 1: Cyclones present in one of the four directional quadrants (west, east, north, or south) of each grid cell.
- Group 2: No cyclone present in any quadrant of the grid cell.

These t-tests were applied separately for each season and for each variable (e.g., sea ice concentration, temperature, wind, advection, convergence). The results were interpreted based on the p-value:

- If $p < 0.05$, the difference between the means was considered statistically significant, and the null hypothesis (that the means are equal) was rejected.
- If $p \geq 0.05$, the result was considered not statistically significant, and the null hypothesis was not rejected.

To visualize the impact of cyclone presence, we calculated the difference between the mean values for cyclone cases and no-cyclone cases (i.e., cyclone minus no cyclone) for each variable and directional category. For example, if the mean air temperature when a cyclone was to the west of a given grid cell was -12°C and the mean under no-cyclone conditions was -15°C , the resulting difference was $+3^{\circ}\text{C}$, indicating a warming effect when cyclones were present to the west.

This same approach was applied to each of the four directions and to all variables, including both sea ice and atmospheric datasets. The results were presented as spatial maps for each directional cyclone case (west, east, north, south), showing the magnitude of the difference relative to the no-cyclone condition.

6. Results

In this section, we analyze the results to determine whether dynamic processes, thermodynamic processes, or a combination of both primarily influence changes in sea ice conditions in Hudson Bay. The analysis is presented seasonally, divided into three key phases: the freeze-up season (November-December), the ice-covered season (January-April), and the break-up season (May-July). For each season, we compare cases with no cyclones present in any grid cell to those where cyclones are present in one of the four directional quadrants (west, east, north, or south) relative to each grid cell.

The results are based on daily data from 1979 to 2023 and are expressed as the difference in mean values between cyclone and no-cyclone conditions. Statistical significance was evaluated using an independent samples t-test at the 5% significance level (see Section 5.8), with significant differences indicated by grey dots on the result maps. The analysis begins with sea ice tendency, which indicates whether sea ice is growing or decaying more rapidly under the influence of a cyclone. This is followed by an assessment of dynamic variables and, finally, thermodynamic variables, to evaluate how each process contributes to the observed changes in sea ice.

6.1 Analysis of the Sea Ice Tendency to Grow and Decay

6.1.1 Sea Ice Concentration from NSIDC

The results of sea ice concentration (SIC) from the NSIDC data indicate that, during the freeze-up season (Figure 5a), SIC tends to grow by over 2.0% per day across Hudson Bay on days without cyclones, being more substantial in the southern and eastern regions of the Bay ($> 3.0\%$ per day). To assess the impact of cyclone presence, we calculated the anomaly

in SIC growth between days with cyclones and days without cyclones. A positive anomaly indicates enhanced ice growth when cyclones are present, while a negative anomaly indicates reduced growth.

When cyclones are located west of grid cells (Figure 5b), in the freeze-up season, they tend to slow SIC growth, with a negative anomaly of about -1.0% per day across the northwest, north, and parts of central Hudson Bay. In contrast, cyclones east of the grid cells (Figure 5c) accelerate SIC growth, showing positive anomalies greater than +1.0% per day extending from northern to southern Hudson Bay. Cyclones to the north (Figure 5d) also enhance SIC growth, particularly along the eastern side of the Bay, with positive anomalies exceeding +1.0% per day. Cyclones located south of the grid cells (Figure 5e) result in more spatially variable responses, with no statistically significant anomaly compared to no-cyclone conditions.

During the ice-covered season (January-April) (Figure 5 g-j), the differences in SIC growth or decay between cyclone and no-cyclone conditions are minimal, with values remaining close to zero across most of Hudson Bay in all cyclone scenarios (compared to Figure 5f). Nevertheless, negative anomalies indicating slightly stronger ice decay are observed along the northwest edge of the Bay when cyclones are located to the west or north of the grid cells (Figure 5h-i), and along the eastern side when cyclones are south of the grid cells (Figure 5j).

In the break-up season (May-July) (Figure 5k-o), sea ice concentration decays more rapidly when cyclones are present. Negative anomalies of -2.0% per day or less appear in central Hudson Bay when cyclones are located west of the grid cells (Figure 5l). Faster ice decay is also observed in northern Hudson Bay when cyclones are situated to the east (Figure 5m), and in the northwest when they are to the north (Figure 5n). In contrast, cyclones south

of the grid cells (Figure 5o) have only a minor effect, with small and localized negative anomalies along the eastern side of the Bay.

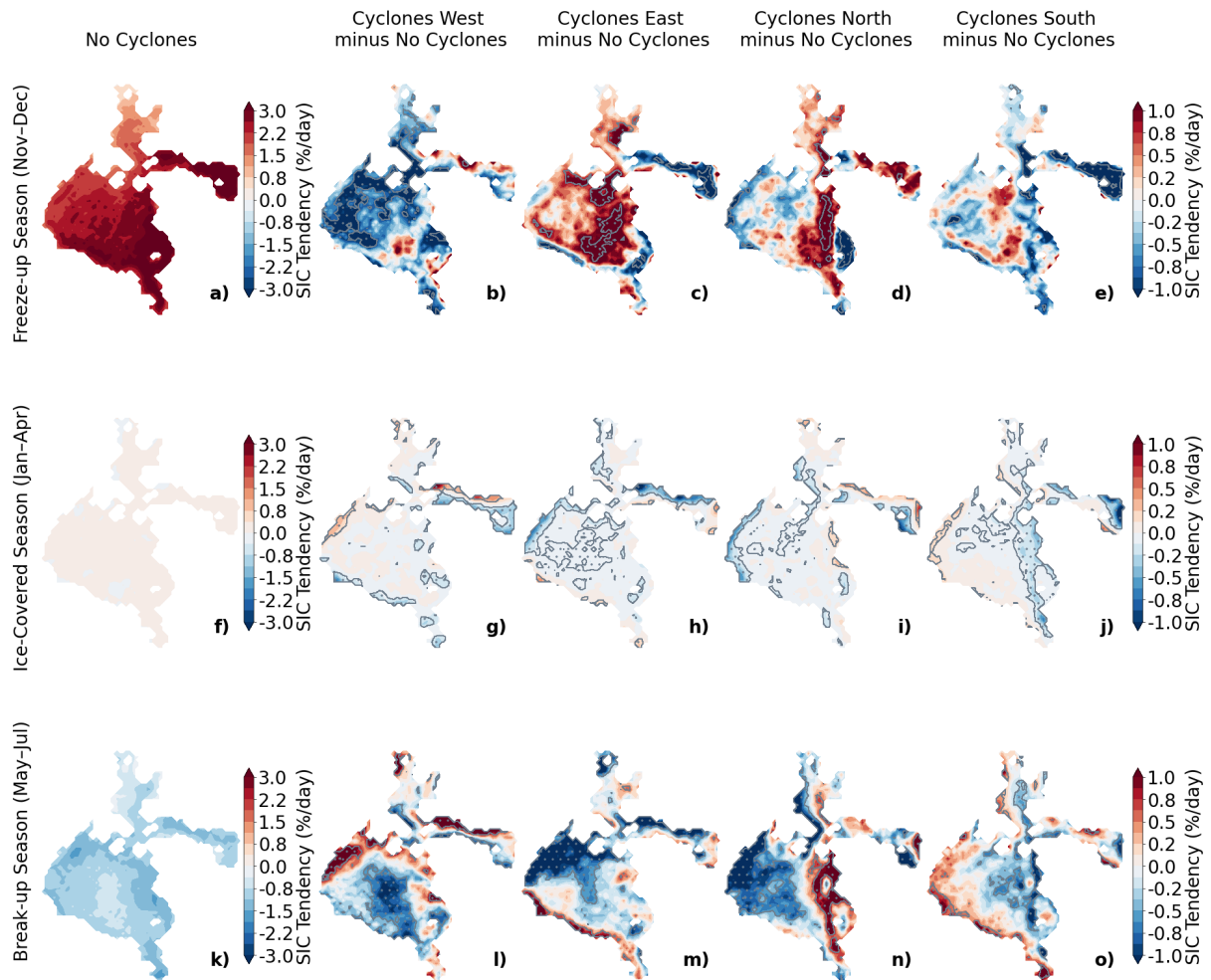


Figure 5. Sea ice concentration (SIC) tendency from the NSIDC dataset under cyclone and no-cyclone conditions over Hudson Bay grid cells. The first column (a, f, k) shows SIC tendency during days with no cyclones. The second column (b, g, l) shows the difference in SIC tendency when cyclones are located to the west, calculated as cyclone minus no-cyclone cases. The third column (c, h, m) shows SIC tendency differences for cyclones to the east, the fourth column (d, i, n) for cyclones to the north, and the fifth column (e, j, o) for cyclones to the south, each compared to no-cyclone conditions. The first row represents the freeze-up season (November-December), the second row corresponds to the ice-covered season (January-April), and the third row depicts the break-up season (May-July). Red shades indicate a faster increase in sea ice concentration, while blue shades indicate slower growth or greater decay. Grey dots mark grid cells where the differences between cyclone and no-cyclone cases are statistically significant ($p < 0.05$).

6.1.2 Sea ice Concentration from ERA5

Figure 6 presents differences in sea ice concentration (SIC) between cyclone and no-cyclone conditions, derived from ERA5 data. During the freeze-up season (Figure 6a-e), ERA5 results closely align with NSIDC data in terms of spatial patterns, although the magnitude of the anomalies is generally larger in ERA5. Both datasets show significantly positive anomalies in SIC growth (greater than +1.0% per day) in central and southern Hudson Bay when cyclones are located east of the grid cells (Figure 6c), and enhanced ice growth (also $> +1.0\%$ per day) along the eastern side of the Bay when cyclones are north of the cells (Figure 6d). Similarly, both datasets indicate negative anomalies in SIC growth (less than -1.0% per day) in the northern and northwestern Bay when cyclones are west of the grid cells (Figure 6b). Additionally, ERA5 shows a positive anomaly in SIC growth (about +1.0% per day) in southern Hudson Bay when cyclones are located to the south (Figure 6e), which is less evident in the NSIDC results.

During the ice-covered season (Figure 6f-j), anomalies emerge between the datasets. ERA5 indicates more negative anomalies, reflecting enhanced SIC decay compared to NSIDC, particularly from central to northern Hudson Bay when cyclones are east of the grid cells (Figure 6h), and from central to western regions when cyclones are north (Figure 6i). ERA5 also shows a notable negative anomaly in SIC in eastern Hudson Bay when cyclones are south of the grid cells (Figure 6j). While NSIDC data reflect similar spatial patterns of slower ice growth, the changes are more limited in extent and magnitude. Overall, the negative anomalies in SIC compared to no-cyclone conditions are approximately -0.25% per day, with more pronounced negative anomalies along the Bay's boundaries (about -0.5% per day), indicating slower growth.

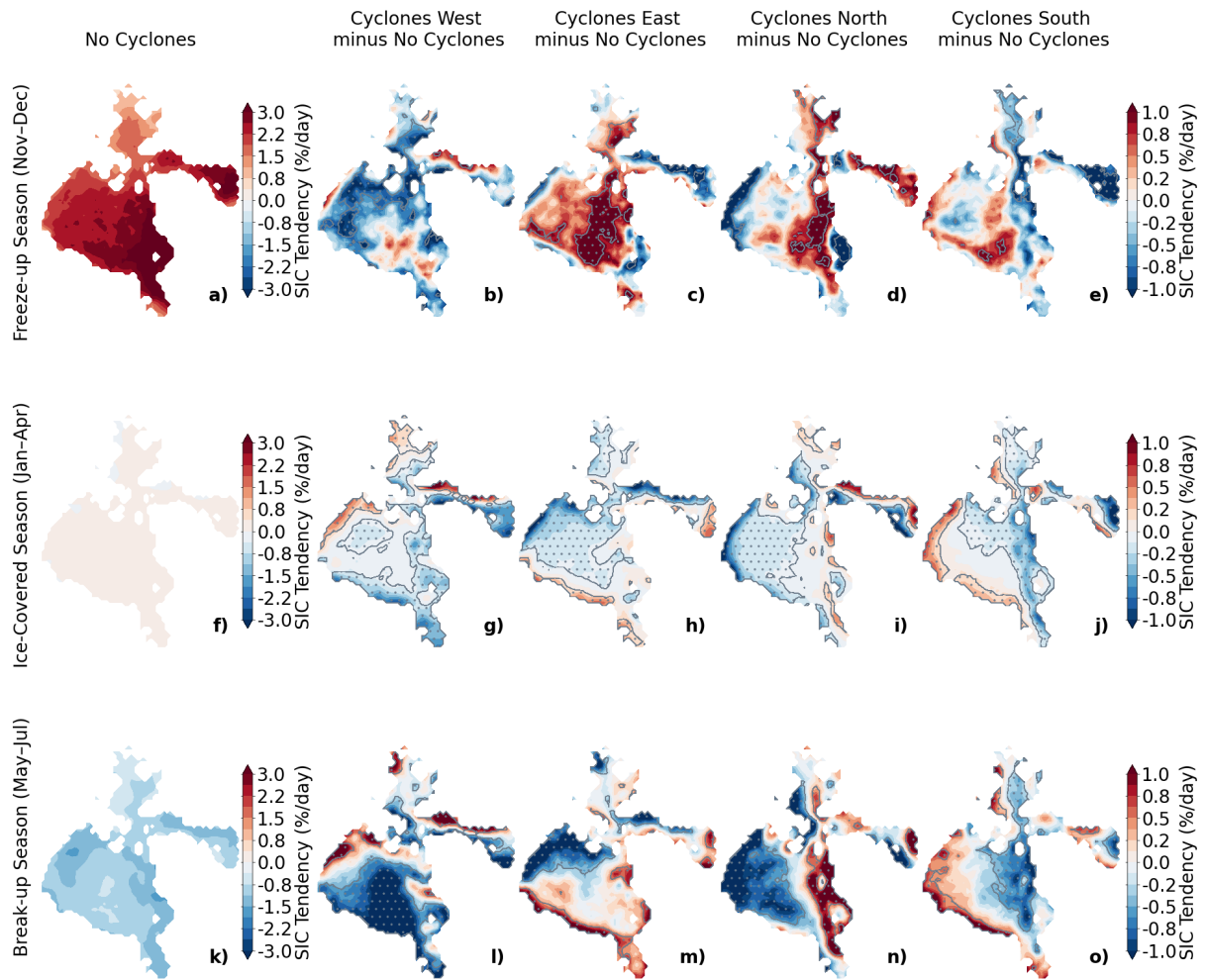


Figure 6. As in Figure 5, but with SIC data from ERA5.

During the break-up season (Figure 6k-o), both datasets consistently show negative anomalies in SIC (faster decay) in northern Hudson Bay when cyclones are east of the grid cells (Figure 6m), and from central to western Hudson Bay when cyclones are north (Figure 6n), with negative anomalies below -1.0% per day. However, anomalies arise for cyclones west of the grid cells: ERA5 data show widespread SIC decay across nearly the entire Bay, with anomalies below -1.0% per day (Figure 6l), whereas NSIDC data indicate more limited decay in the central region (Figure 5l). In the case of cyclones south of the grid cells, ERA5 shows a stronger and more widespread negative anomaly in SIC (below -0.5% per day) in eastern Hudson Bay (Figure 6o), compared to the more modest and localized differences observed in the NSIDC results (Figure 5o).

6.1.3 Sea Ice Concentration from PIOMAS

The PIOMAS dataset shows spatial agreement with NSIDC and ERA5 in terms of where sea ice concentration (SIC) growth and decay occur in response to cyclones, but in no-cyclone cases, the magnitude and spatial extent of the anomalies are generally smaller. During the freeze-up season, cyclones located west of grid cells (Figure 7b) are associated with negative anomalies (around -0.5% per day) in the northwest and eastern Hudson Bay. However, this response is more limited in both area and magnitude compared to NSIDC (Figure 5b) and ERA5 (Figure 6b). Similarly, cyclones east of grid cells (Figure 7c) are linked to positive anomalies in SIC growth in southern Hudson Bay (around +0.5% per day), but these values are smaller than the magnitudes shown in NSIDC (Figure 5c) and ERA5 (Figure 6c), which are greater than +1.0% per day. This pattern of weaker positive anomalies continues for cyclones to the north (Figure 7d) and south (Figure 7e), where PIOMAS also shows smaller changes in SIC growth compared to the other datasets.

Throughout the ice-covered season (Figure 7f-j), PIOMAS results align well with NSIDC and ERA5, showing weaker anomalies in SIC between cyclone and no-cyclone conditions. Changes are mostly confined to the edges of Hudson Bay, with positive anomalies of about +0.5% per day and negative anomalies of around -0.5% per day, while central regions remain close to zero.

During the break-up season (Figure 7k-o), PIOMAS identifies smaller areas of enhanced SIC decay compared to NSIDC (Figure 5k-o) and ERA5 (Figure 6k-o). For cyclones west of the grid cells (Figure 7l), PIOMAS shows negative anomalies near -0.5% per day in the southern Bay, whereas both NSIDC and ERA5 show broader and stronger negative anomalies (below -1.0% per day) enhancing SIC decay across central, western, and southern Hudson Bay. When cyclones are located east of the grid cells (Figure 7m), all three

datasets consistently indicate rapid SIC decay in northern Hudson Bay, with negative anomalies below -1.0% per day for NSIDC and ERA5, and about -0.5% for PIOMAS.

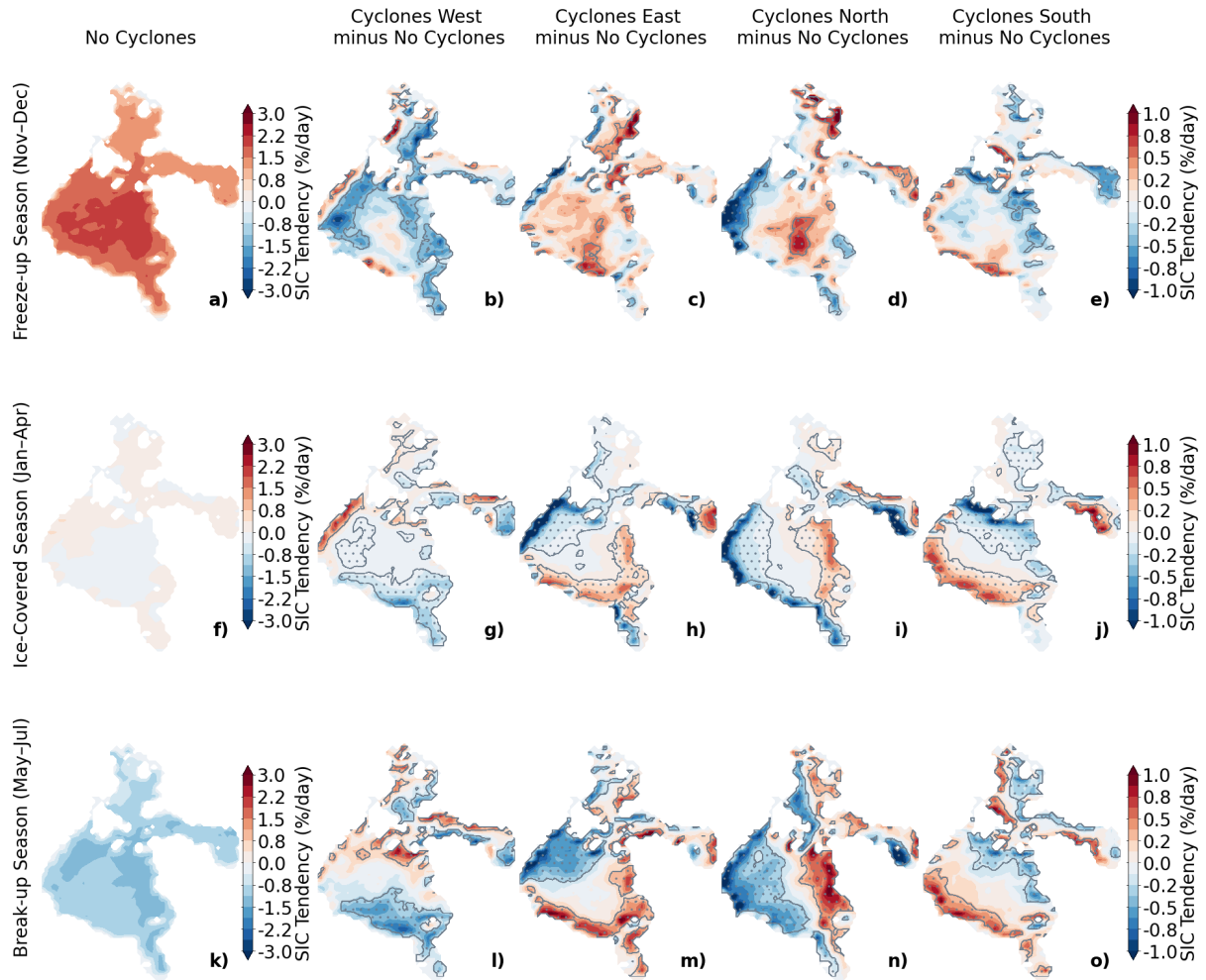


Figure 7. As in Figure 5, but with SIC data from PIOMAS.

For cyclones north of the grid cells (Figure 7n), all datasets identify enhanced ice decay across the north, northwest, south, and parts of central Hudson Bay. However, PIOMAS shows a slightly smaller negative anomaly (around -0.2% to -0.5% per day), while NSIDC and ERA5 show stronger anomalies below -1.0% per day.

Overall, NSIDC, ERA5, and PIOMAS datasets agree on the general locations within Hudson Bay where cyclone presence affects SIC growth and decay. The spatial patterns are

consistent across datasets, highlighting key regions influenced by cyclone position relative to grid cells. However, the datasets differ in the magnitude and spatial extent of the SIC tendency anomalies. PIOMAS consistently shows less pronounced and more localized daily anomalies in SIC than NSIDC and ERA5. ERA5 typically displays the largest magnitude of the differences and the widest coverage, while NSIDC results generally fall between ERA5 and PIOMAS. These anomalies show that PIOMAS smooths the sea ice response to cyclone activity relative to the other datasets.

6.1.4 Sea Ice Effective Thickness

The results of sea ice effective thickness (SIT), representing sea ice volume, show spatial response patterns that differ from those observed for sea ice concentration (SIC). In most cases, positive or negative anomalies in SIT between cyclone and no-cyclone conditions are concentrated near the boundaries of Hudson Bay rather than in the central region.

During the freeze-up season, cyclones located west of the grid cells (Figure 8b) are associated with negative anomalies in SIT growth (approximately -0.5 cm/day) across much of Hudson Bay, indicating reduced thickening relative to no-cyclone conditions. Only the northwest edge exhibits a positive anomaly (greater than +0.8 cm/day), indicating localized growth enhancement. Cyclones positioned east of the grid cells (Figure 8c) produce positive anomalies in the south (around +0.4 cm/day) and negative anomalies in the northwest (below -0.5 cm/day). When cyclones are located north of the grid cells (Figure 8d), SIT growth slows significantly in the northwest and along the southern border, with negative anomalies below -0.5 cm/day. In contrast, the northeast and eastern Bay experience enhanced growth, characterized by positive anomalies near +0.5 cm/day. Cyclones south of the grid cells

(Figure 8e) primarily reduce SIT growth along the eastern side of Hudson Bay, with positive anomalies mostly limited to the western boundary.

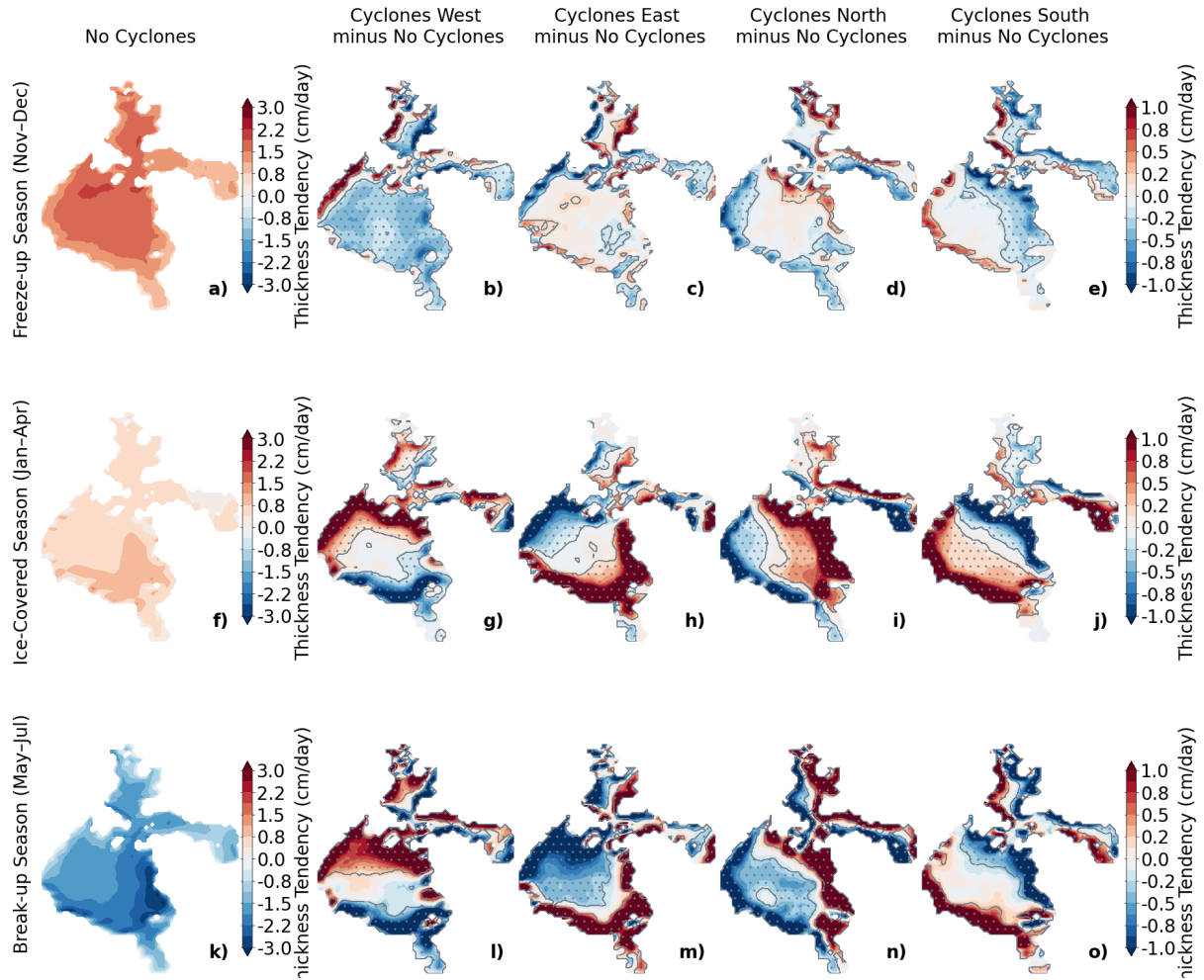


Figure 8. As in Figure 5, for the Sea ice effective thickness (SIT) data from PIOMAS.

During the ice-covered season (Figure 8f-j), cyclone presence results in more substantial SIT tendency anomalies compared to no-cyclone conditions, with positive anomalies typically above +1.0 cm/day and negative anomalies below -1.0 cm/day. Cyclones west of the grid cells (Figure 8g) reduce SIT growth in the southern region with negative anomalies < -1.0 cm/day, while promoting faster growth in the northwest and north with positive anomalies $> +1.0$ cm/day. Cyclones east of the grid cells (Figure 8h) enhance SIT

growth across much of the Bay, especially in the eastern, southern, and parts of the western regions ($> +1.0$ cm/day). Cyclones north of the grid cells (Figure 8i) produce widespread positive anomalies ($> +1.0$ cm/day) from the central Bay to the northeast, with localized negative anomalies (< -1.0 cm/day) in the northwest and southern areas. In contrast, cyclones south of the grid cells (Figure 8j) show the opposite pattern: enhanced SIT growth with positive anomalies $> +1.0$ cm/day in the northwest, west, south, and central Bay, and negative anomalies < -1.0 cm/day indicating slower growth in the southern and eastern regions.

During the break-up season (Figure 8k-o), the spatial patterns of SIT decay (negative anomalies) or reduced decay (positive anomalies) largely mirror those observed in the ice-covered season, though the magnitude of SIT loss is greater. The strongest negative anomalies (< -1.0 cm/day) demonstrating faster SIT decay occur when cyclones are east (Figure 8m) or north (Figure 8n) of the grid cells, affecting most of Hudson Bay. These regions align with areas with slower SIT growth during the earlier season.

In summary, these results highlight distinct spatial responses of SIT to cyclone position, which differ from those observed for SIC. While both variables, SIC and SIT, are influenced by cyclone presence and direction, SIT tendency anomalies tend to be concentrated along the boundaries of Hudson Bay, whereas SIC tendency anomalies are more spatially extensive and often include central regions. This contrast is most apparent during the freeze-up season, when SIC shows widespread changes across the Bay while SIT responses remain more localized. In contrast, during the break-up season, SIC and SIT responses show greater spatial agreement, indicating widespread ice loss under certain cyclone positions.

Additionally, the magnitude of SIT, positive and negative anomalies, is most significant during the ice-covered and break-up seasons, suggesting that cyclone activity exerts a more substantial influence on sea ice volume during these periods than during freeze-up. One likely explanation is that sea ice is generally thicker in January-April than in

November-December, which allows dynamic processes (e.g., convergence, divergence, ridging) to exert a greater effect on the ice. Thicker ice during the mid and late winter periods provides more material to be redistributed by cyclone-induced winds and stress, thereby amplifying the SIT response compared to the early stages of ice formation.

6.2 Dynamic Analysis

6.2.1 Sea Ice Advection and Convergence

Previously, we described the daily sea ice tendency to grow or decay at varying rates, explaining that sea ice variability in Hudson Bay is considerable by season, particularly in the presence of cyclones, across the four directional regions of the grid cells. This section presents the ice dynamic analysis, which refers to the daily mean of ice advection (Figure 9), convergence (Figure 10), zonal ice motion (U) (Figure 11), representing west-east movement, and meridional ice motion (V) (Figure 12), representing north-south movement. A positive value for ice advection and convergence indicates net ice growth, while a negative value indicates ice decay. In contrast, a positive signal for sea ice motion implies eastward or northward ice transport, whereas a negative signal indicates westward or southward movement. Ice advection, convergence, and motion are overlaid with the vector of the mean horizontal wind at 925 hPa (for the same days) to visualize the influence of wind patterns on ice dynamics under cyclone and no-cyclone conditions. The reference vector for wind speed is 10 m/s.

The mean horizontal wind direction in the absence of cyclones over Hudson Bay is generally northwesterly. When cyclones are located west of the grid cells, the prevailing winds shift to southwesterly; when cyclones are east of the grid cells, winds remain northwesterly; when cyclones are situated north, the winds become westerly; and when

cyclones are south, winds are weakly northeasterly, affecting sea ice advection and convergence. This is true across all seasons.

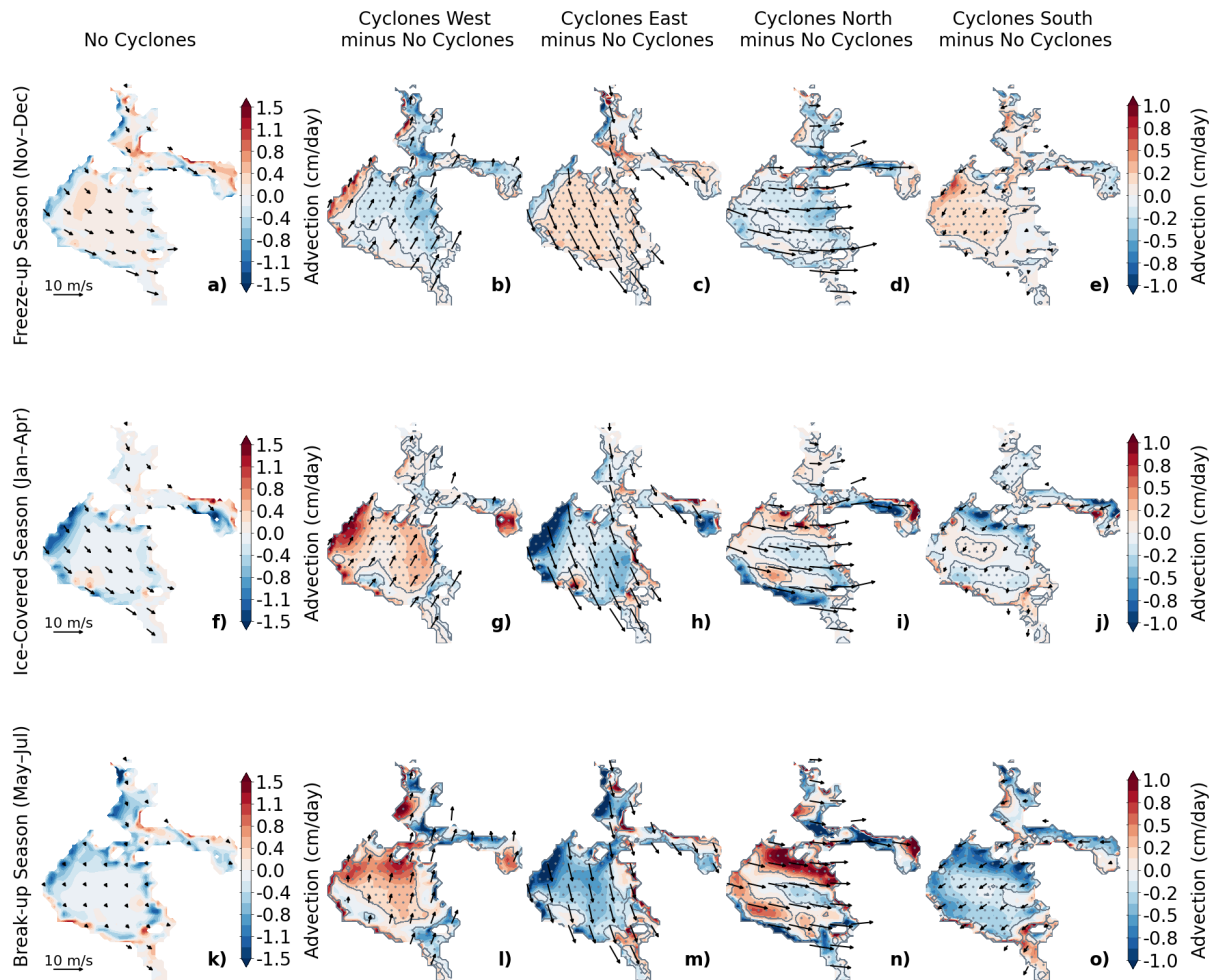


Figure 9. Mean sea ice advection and wind patterns (vectors) under cyclone and no-cyclone conditions over Hudson Bay grid cells. The first column (a, f, k) shows ice advection and wind vectors during periods with no cyclones. The second column (b, g, l) presents the difference when cyclones are located to the west, calculated as cyclone minus no-cyclone cases. The third column (c, h, m) shows differences for cyclones to the east, the fourth column (d, i, n) for cyclones to the north, and the fifth column (e, j, o) for cyclones to the south, each compared to no-cyclone conditions. The first row represents the freeze-up season (November-December), the second row corresponds to the ice-covered season (January-April), and the third row shows the break-up season (May-July). Positive values indicate enhanced sea ice advection (associated with increased ice transport or growth), while negative values indicate reduced advection or slower sea ice growth. Wind vectors show the corresponding mean atmospheric circulation patterns. Grey dots mark grid cells where the differences between cyclone and no-cyclone conditions are statistically significant ($p \leq 0.05$).

During the freeze-up season, the differences in ice advection and convergence between cyclone and no-cyclone conditions reveal distinct spatial patterns (Figures 9 and 10). In the absence of cyclones (Figures 9a and 10a), baseline conditions show positive mean advection of approximately +0.4 cm/day, indicating net sea ice growth. Advection anomalies, defined as differences from this baseline, are generally negative near the Bay's boundaries. When cyclones are west of the grid cells (Figures 9b and 10b), negative advection anomalies of approximately -0.4 cm/day appear in the central and northeast regions, indicating reduced growth compared to no-cyclone conditions. Positive anomalies persist along the northwest border. Convergence anomalies remain positive in the northeast, near +1.0 cm/day, though slightly negative anomalies emerge in the southwest. Cyclones to the east (Figures 9c and 10c) lead to positive advection anomalies of about +0.2 cm/day across most of Hudson Bay and strong positive convergence anomalies in the south, reaching approximately +1.5 cm/day. Cyclones to the north (Figures 9d and 10d) are associated with negative advection anomalies of around -0.4 cm/day in the eastern Bay and the strongest positive convergence anomalies, exceeding +1.5 cm/day, particularly in the northeast, driven by westerly winds. When cyclones are located to the south (Figures 9e and 10e), positive advection anomalies occur in the far northwest (around +0.4 cm/day), and convergence anomalies are broadly positive (around +0.5 cm/day) across the western, central, and southern Bay associated with northeasterly wind patterns.

In the absence of cyclones during the ice-covered season (Figures 9f and 10f), the mean advection is slightly negative across Hudson Bay, especially in the northwest, where it reaches about -1.0 cm/day, likely due to persistent northwesterly winds transporting ice southward. Convergence values are weakly positive with no cyclones present. When cyclones are west of the grid cells (Figures 9g and 10g), positive advection anomalies greater than +0.5 cm/day emerge in the northwest, while positive convergence anomalies above +2.0 cm/day

dominate the northwest and extend southward. Cyclones east of the grid cells (Figures 9h and 10h) result in negative advection anomalies below -0.5 cm/day in most of the Bay and convergence anomalies less than -1.5 cm/day across the western borders of the Bay. When cyclones are north (Figures 9i and 10i), a mixed pattern emerges with localized positive advection anomalies around $+0.4$ cm/day and widespread strong positive convergence anomalies ($> +1.5$ cm/day). However, minor negative anomalies appear along the western edge. Cyclones south of the grid cells (Figures 9j and 10j) are associated with negative advection anomalies in the north and northeast, and predominantly positive convergence anomalies.

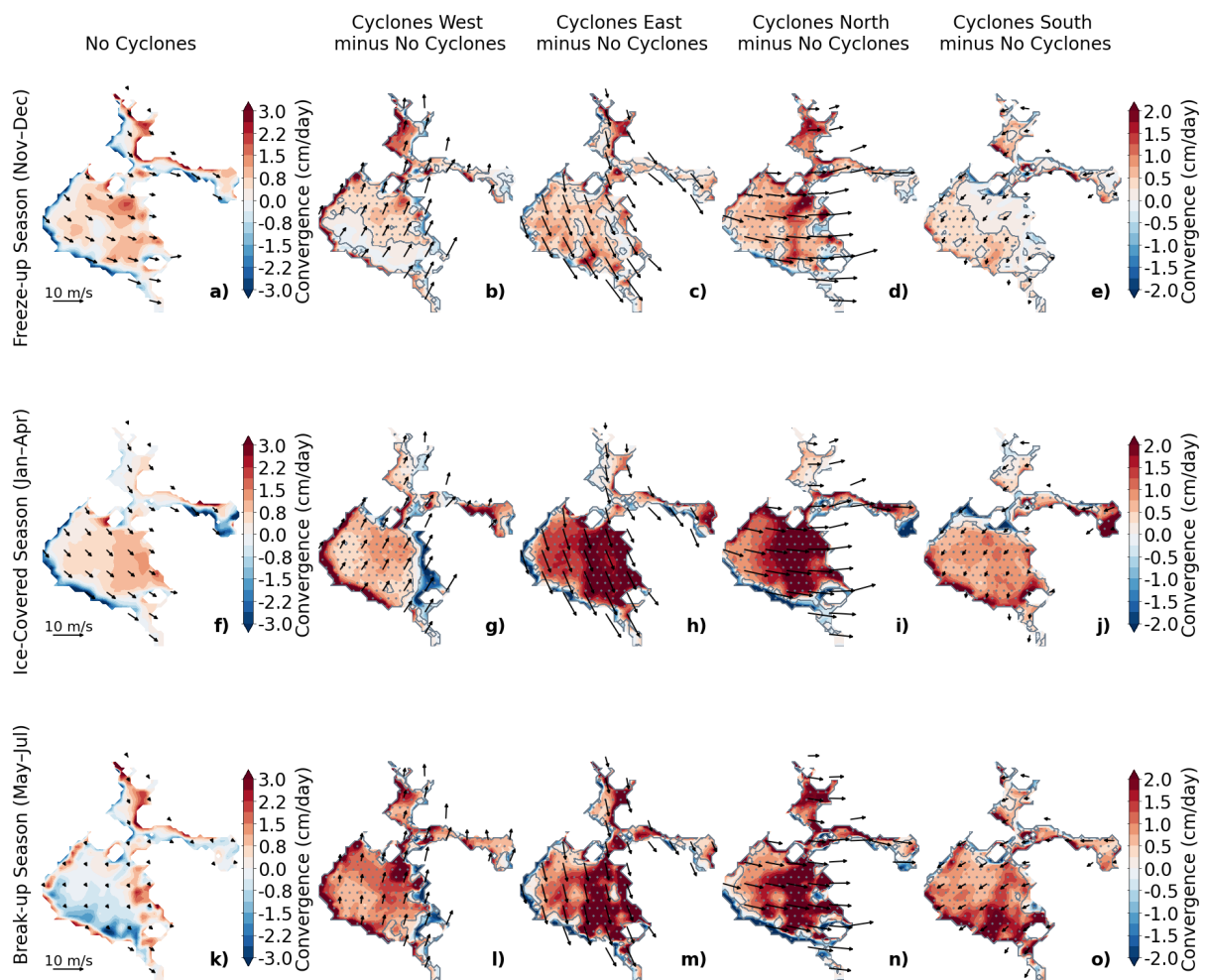


Figure 10. As in Figure 9, for the ice convergence.

During the break-up season (Figures 9k-o and 10k-o), similar patterns persist. Under no-cyclone conditions, mean advection is predominantly negative, and convergence is also negative, especially in the south. Cyclones west of the grid cells (Figures 9l and 10l) generate southerly winds that induce positive advection anomalies greater than +0.5 cm/day in the north and positive convergence anomalies ($> +1.0$ cm/day) in central and western regions. Cyclones to the east (Figures 9m and 10m) cause negative advection anomalies and enhanced ice loss along the western border. When cyclones are north (Figures 9n and 10n), strong positive advection anomalies appear in the north and south, while convergence anomalies are mixed, with losses along the western and southern margins. Cyclones south of the grid cells (Figures 9o and 10o) result in widespread negative advection anomalies and ice decay, particularly in the northern and eastern regions.

6.2.3 Zonal and Meridional Ice Motion (U-V)

Under no-cyclone conditions (Figures 11a, 11f, 11k and 12a, 12f, 12k), sea ice motion in Hudson Bay shows generally weak zonal and meridional components. Zonal motion is a mix of eastward and westward flow, with velocities near zero, except during the freeze-up season, when eastward motion reaches approximately +0.10 m/s in the southern Bay (Figure 11a). Meridional motion is predominantly southward, particularly during freeze-up, with more pronounced negative velocities below -0.10 m/s in the western and southern regions (Figure 12a).

When cyclones are present during the freeze-up season, anomalies in both components emerge depending on the cyclone's location. For example, cyclones located west (Figures 11b and 12b) or north (Figures 11d and 12d) of the grid cells result in eastward anomalies in zonal motion across much of the Bay, indicating either an enhancement of eastward motion or a reduction in westward flow. In the meridional component, both cases

(cyclones located to the west and north) produce northward anomalies, which reflect a reversal of the dominant southward flow (no-cyclone cases) toward the northward motion. Cyclones to the north produce more pronounced eastward anomalies exceeding $+0.05$ m/s, while cyclones to the west generate stronger northward anomalies of about $+0.05$ m/s.

In contrast, cyclones situated east of the grid cells (Figures 11c and 12c) produce westward zonal anomalies of approximately -0.025 m/s, indicating a weaker enhancement of westward motion. In the meridional direction, a mixed pattern emerges: northward anomalies (about $+0.025$ m/s) dominate the eastern Bay, signifying reduced southward flow or localized reversals, while southward anomalies (about -0.025 m/s) persist in the northwest, west, and southern regions, reflecting a weaker northward motion. Cyclones located south of the grid cells (Figures 11e and 12e) induce westward anomalies in zonal motion and northward anomalies in meridional motion across Hudson Bay, meaning a weakening of the typical southward and eastward motion, and in southern and eastern Hudson Bay and a reversal of zonal motion in the northwest.

During the ice-covered season, baseline sea ice motion patterns under no-cyclone conditions show minimal variation (Figures 11f-j and 12f-j), though overall ice motion speeds decrease. Zonal anomalies become more complex, with eastward anomalies occurring when cyclones are located to the north (exceeding $+0.05$ m/s, Figure 11i) or west (approximately $+0.025$ m/s, Figure 11g), suggesting either enhanced eastward motion (cyclones north) or weakened westward flow (cyclones west). Westward anomalies occur when cyclones are situated to the south (Figure 11j), indicating a weakening of eastward motion in the southeast and an amplification of westward motion in the northwest. Meridional ice motion during this season remains predominantly southward under no-cyclone conditions (about -0.05 m/s, Figure 12f), and southward anomalies intensify slightly when cyclones are located to the east (about -0.025 m/s, Figure 12h). In contrast, cyclones positioned to the west (Figure 12g),

north (Figure 12i), and south (Figure 12j) generate northward anomalies, indicating a weakening of southward motion when cyclones are located west and south. The most pronounced northward anomalies, around +0.03 m/s, are associated with cyclones to the west.

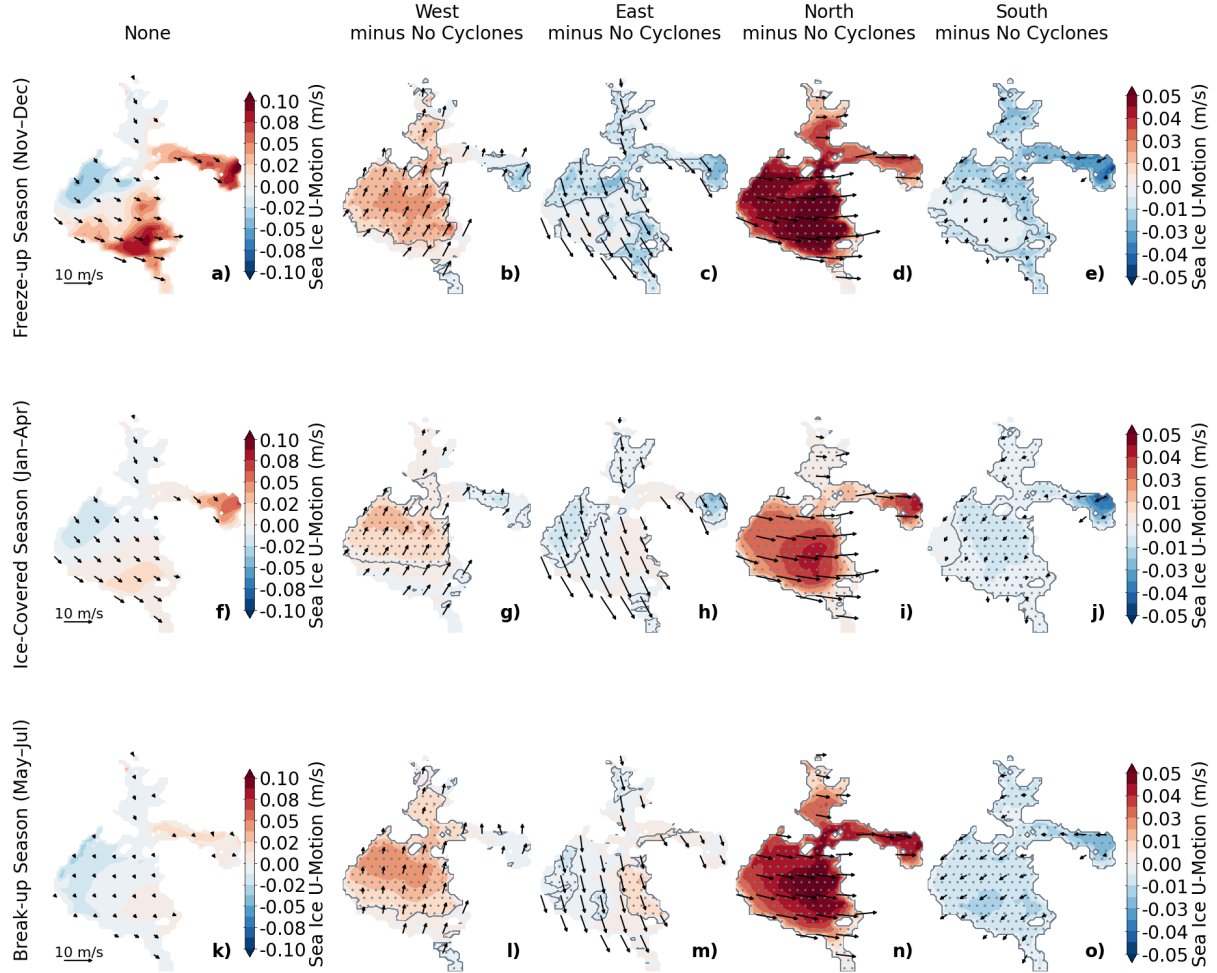


Figure 11. Mean U-component of sea ice motion (U-ice motion) and wind patterns (vectors) under cyclone and no-cyclone conditions over Hudson Bay grid cells. The first column (a, f, k) shows U-ice motion and wind vectors during periods with no cyclones. The second column (b, g, l) presents the difference when cyclones are located to the west, calculated as cyclone minus no-cyclone cases. The third column (c, h, m) shows differences for cyclones to the east, the fourth column (d, i, n) for cyclones to the north, and the fifth column (e, j, o) for cyclones to the south, each compared to no-cyclone conditions. The first row represents the freeze-up season (November-December), the second row corresponds to the ice-covered season (January-April), and the third row shows the break-up season (May-July). Positive U-ice values indicate eastward sea ice motion, while negative values indicate westward motion. Wind vectors illustrate the corresponding atmospheric circulation patterns. Grey dots mark grid cells where the differences between cyclone and no-cyclone conditions are statistically significant ($p \leq 0.05$).

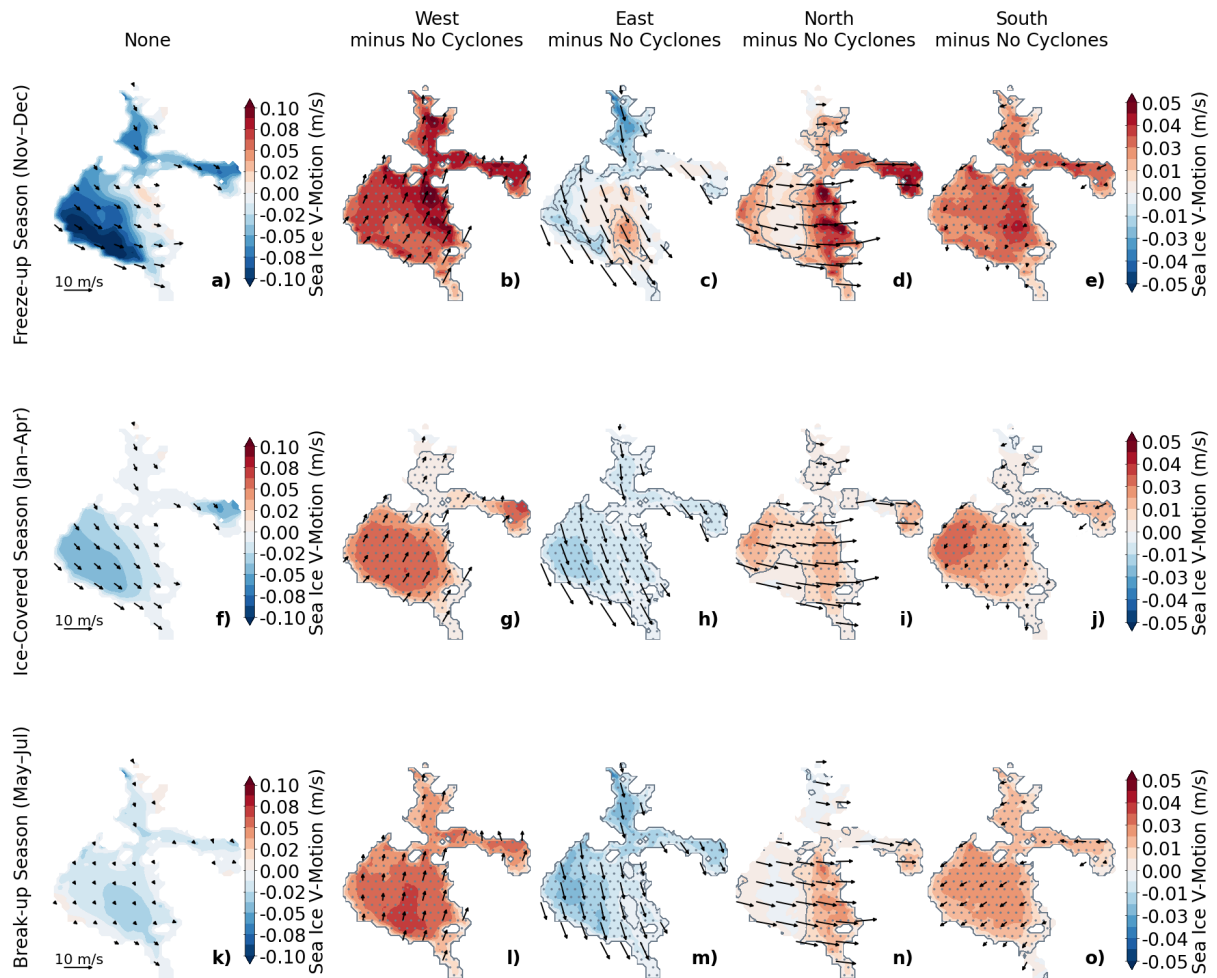


Figure 12. As in Figure 11, but for the mean V-component of sea ice motion (V-ice motion).

During the break-up season (Figures 11k-o and 12k-o), similar trends are observed. When cyclones are located to the east (Figure 11m), zonal motion anomalies are westward in the western region and eastward in the eastern region. This pattern reinforces the prevailing eastward sea ice motion and suggests a slight acceleration in speed. For cyclones to the north (Figure 11n), the anomalies are strongly eastward, exceeding +0.05 m/s, indicating enhanced eastward flow. Meridional ice motion during this season is again predominantly southward under no-cyclone conditions (Figure 12k), but becomes less southward when cyclones are situated to the west (Figure 12l), north (Figure 12n), or south (Figure 12o), reflecting a weakening of the dominant southward motion. Only when cyclones are located to the east

(Figure 12m) enhances southward anomalies appear (about -0.025 m/s), representing an enhancement of the baseline southward flow.

Given the dynamic analysis, it is noticeable that cyclone-driven wind patterns influence ice dynamics in Hudson Bay, changing the patterns and magnitude of the positive and negative anomalies of ice advection, convergence, and ice motion in U and V directions, which means faster/slower ice growth or decay depending on the position of cyclones relative to the grid cells.

6.3 Thermodynamic Analysis

6.3.1 Air Temperature and Sensible Heat Flux

Previously, we described the dynamic patterns of sea ice in Hudson Bay. This section analyzes the variables relevant for thermodynamic investigations: air temperature (Figure 13) and surface sensible heat flux (SSHF) (Figure 14). Furthermore, we examine the thermodynamic growth, which refers to the total sea ice change residual after subtracting sea ice advection and convergence, as outlined by equation (4) in Section 5.5 of the methodology.

Figures 13 and 14 illustrate how cyclone positioning influences both air temperature and surface sensible heat flux (SSHF) across Hudson Bay. In this analysis, only the “no cyclone” case represents a temporal mean, while the cyclone cases represent anomalies, differences from that mean. Positive SSHF values indicate a downward transfer of energy from the atmosphere to the surface, while negative values indicate an upward transfer from the surface to the atmosphere. The relationship between temperature and SSHF reflects the thermal structure of extratropical cyclones and their associated wind patterns.

During the freeze-up season, cyclones exert a strong influence on both surface air temperature and energy exchange. Under no-cyclone conditions, mean air temperatures fall

below -10.0°C , and SSHF values are strongly negative, with values below -12.0 W/m^2 , indicating substantial upward energy transfer from the surface, a key feature of strong surface cooling during early ice formation.

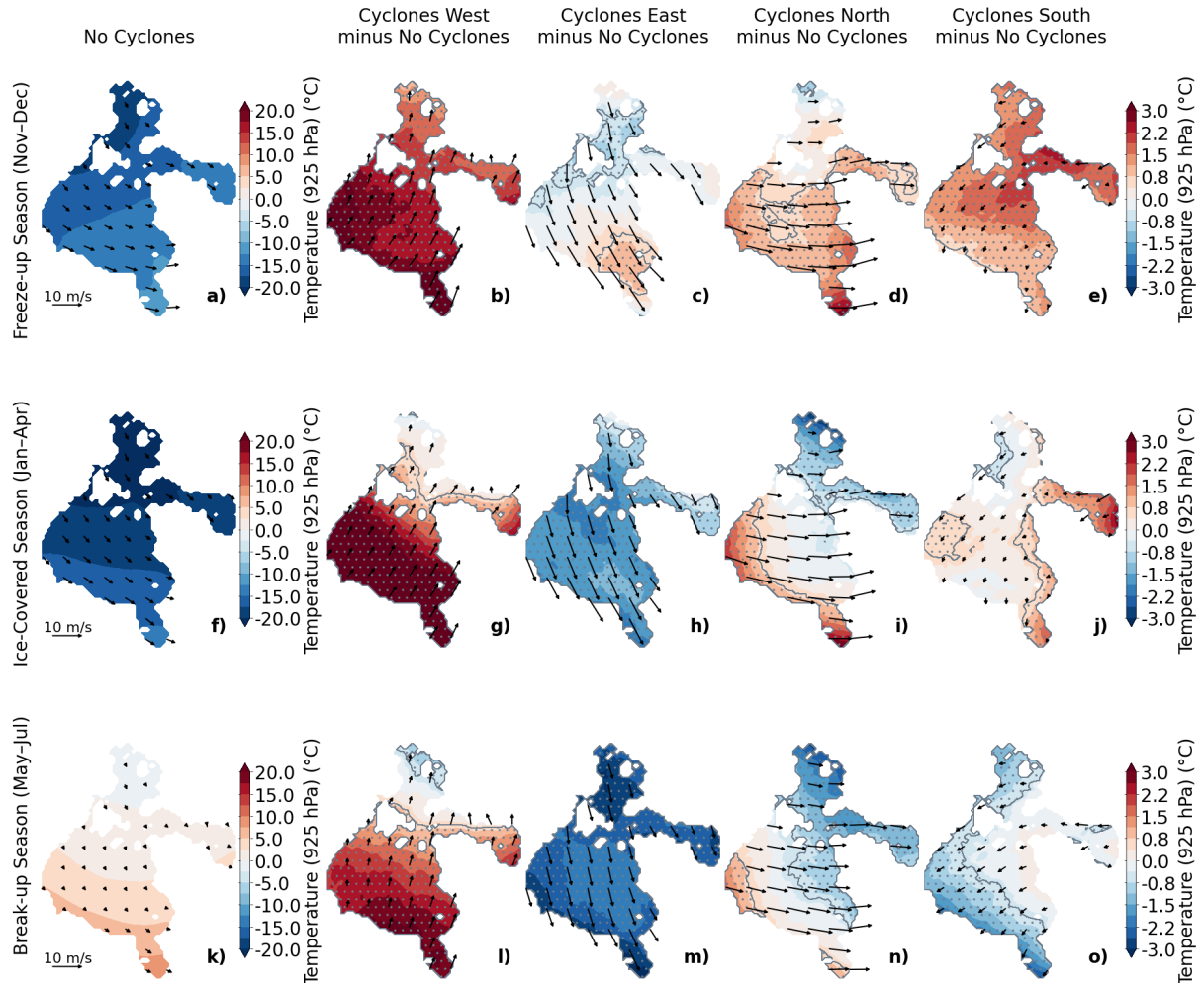


Figure 13. Mean air temperature and wind patterns (vectors) under cyclone and no-cyclone conditions over Hudson Bay grid cells. The first column (a, f, k) shows mean air temperature and wind vectors during periods with no cyclones. The second column (b, g, l) presents the difference when cyclones are located to the west, calculated as cyclone minus no-cyclone cases. The third column (c, h, m) shows differences for cyclones to the east, the fourth column (d, i, n) for cyclones to the north, and the fifth column (e, j, o) for cyclones to the south, each compared to no-cyclone conditions. The first row represents the freeze-up season (November-December), the second row corresponds to the ice-covered season (January-April), and the third row shows the break-up season (May-July). Positive values indicate warmer air temperatures, while negative values indicate colder air temperatures. Grey dots indicate grid cells where differences between cyclone and no-cyclone conditions are statistically significant ($p \leq 0.05$).

When cyclones are located west of the grid cells, air temperature anomalies increase by approximately $+3.0^{\circ}\text{C}$ relative to the no-cyclone baseline, due to warm southwesterly air advection. SSHF also shows a positive anomaly of about $+4.0\text{ W/m}^2$, indicating a reduced upward flux or a shift toward net downward energy transfer. This combination of warmer air and reduced surface cooling suggests a net heat gain at the ice surface, potentially slowing freeze-up. Cyclones situated east of the grid cells produce a smaller temperature anomaly of about $+1.0^{\circ}\text{C}$ in the southern Bay, while in the rest of Hudson Bay, the anomalies are weakly negative (less than -0.8°C). In contrast, SSHF anomalies are more strongly negative, with values decreasing by over $+4.5\text{ W/m}^2$, reinforcing upward energy transfer and surface cooling. This pattern reflects the influence of cold northerly winds dominating much of the Bay, despite the slight warming observed in the south.

For cyclones positioned to the north and south of the grid cells, temperature anomalies reach about $+1.5^{\circ}\text{C}$ above the no-cyclone mean. These effects are likely due to weaker cold air advection caused by westerly or northeasterly wind patterns. SSHF anomalies in these cases are more spatially variable: north-positioned cyclones result in a modest increase in upward energy transfer, with anomalies around -1.5 W/m^2 , while cyclones located to the south produce a mix of anomalies, positive values reaching up to $+4.0\text{ W/m}^2$ in the far northwest, west, and south (indicating enhanced surface heating), and negative values of approximately -1.5 W/m^2 in the east, where surface cooling remains dominant.

During the ice-covered season, spatial patterns in temperature and SSHF anomalies continue to reflect the position of cyclones. Under no-cyclone conditions, SSHF remains slightly negative, indicating continued, though weaker, upward heat transfer. Cyclones west of the grid cells result in a positive anomaly of more than $+3.0^{\circ}\text{C}$ compared to no-cyclones and generate a positive SSHF anomaly of about $+1.5\text{ W/m}^2$. This indicates a reduction in surface cooling, although the effect is weaker than during the freeze-up season. Cyclones

located east of the grid cells produce a cooling anomaly of about -2.0°C , and SSHF anomalies also decrease by about $+2.0\text{ W/m}^2$, enhancing surface energy loss. Cyclones positioned to the north yield a temperature anomaly of approximately $+1.5^{\circ}\text{C}$ in the western Bay, along with a slight positive SSHF anomaly of about $+1.0\text{ W/m}^2$, reflecting a slight reduction in upward flux. Meanwhile, cyclones to the south also lead to positive temperature anomalies of around $+0.8^{\circ}\text{C}$. Still, they are associated with mostly negative SSHF anomalies near -1.0 W/m^2 , except for slight localized warming in the northwest where positive values appear.

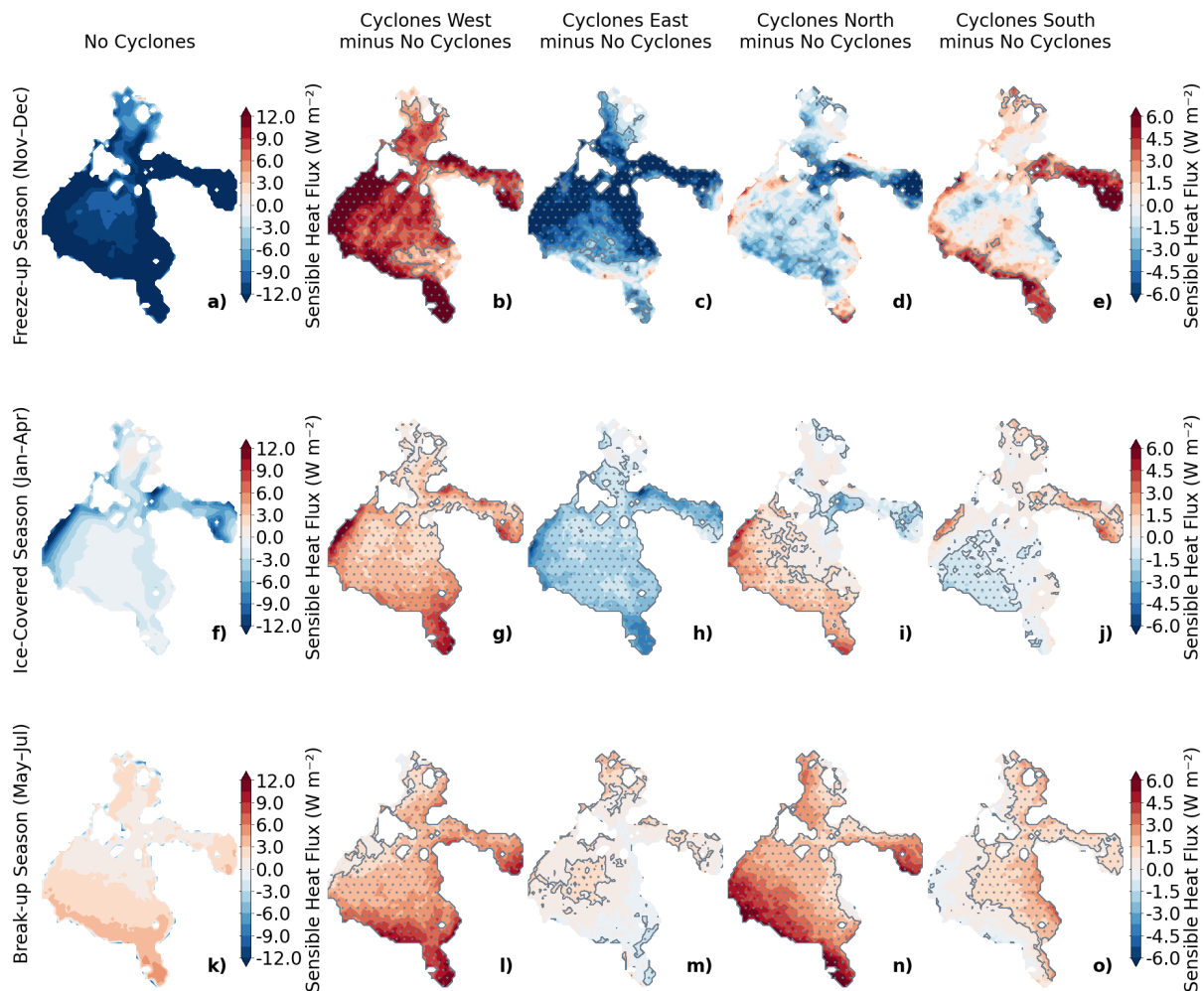


Figure 14. As in Figure 13, but for the mean surface sensible heat flux (SSHF).

By the break-up season, no-cyclone conditions feature generally positive SSHF values, as surface temperatures rise above 0°C and atmospheric heating of the surface becomes dominant. Cyclones located west of the grid cells cause the most significant warming, with temperature anomalies reaching over $+3.0^{\circ}\text{C}$, and also produce the strongest downward energy transfer, with SSHF anomalies exceeding $+4.0\text{ W/m}^2$, particularly in the southern Bay. When cyclones are located east of the grid cells, it results in negative temperature anomalies of about -2.0°C , and SSHF anomalies weaken, with only slight positive values in the central Bay, suggesting minimal additional surface heating. North-positioned cyclones reduce temperatures by about -0.8°C in the eastern Bay but contribute to substantial downward energy transfer in the western Bay, where SSHF anomalies again reach about $+4.0\text{ W/m}^2$. Cyclones to the south result in about $+0.8^{\circ}\text{C}$ anomaly and a limited increase in SSHF, around $+1.5\text{ W/m}^2$, concentrated along the eastern Bay.

In summary, cyclone position strongly modulates both surface air temperature and SSHF in Hudson Bay. Cyclones located west of the grid cells consistently lead to higher temperatures and increased downward energy flux, reflecting the advection of warmer air and enhanced surface heating. In contrast, east-positioned cyclones are associated with cooler air and stronger upward heat flux, reinforcing surface cooling. Cyclones to the north and south produce more mixed outcomes, but generally result in modest warming and a shift toward downward energy transfer depending on the seasonal background state. These observed patterns are consistent with the classical structure of extratropical cyclones, which feature distinct warm and cold sectors. When cyclones are positioned west of the grid cells, the region lies within the warmer, eastern sector of the system, where southerly or southwesterly winds transport warmer air into Hudson Bay. In contrast, when cyclones are situated east of the grid cells, the area falls within the colder, western sector, where northerly winds advect

cooler air. This asymmetry results from the dynamics of low-pressure systems, in which colder air is typically advected from the west or northwest on the left side of cyclones, while warmer air is advected on the east side of cyclones (Carlson, 1991; Lackmann, 2011).

6.3.2 Thermodynamic Growth of Sea Ice

The final analysis focuses on the thermodynamic growth of sea ice (Figure 15), describing the growth of sea ice under conditions with and without cyclones present over Hudson Bay. Observing the no-cyclone cases (Figure 15a) during the freeze-up season, the thermodynamic growth of sea ice is approximately +2.0 cm/day across Hudson Bay, with stronger growth concentrated in the central area and along the Bay's borders ($> +2.0$ cm/day). However, when cyclones are present, thermodynamic growth slows by at least -0.5 cm/day across much of the region.

During the freeze-up season, when cyclones are located west of the grid cells (Figure 15b), thermodynamic growth is about -0.5 cm/day slower over nearly the entire Bay, except in the southwest region, where the difference approaches zero. When cyclones are situated east of the grid cells (Figure 15c), thermodynamic growth slows even further, particularly in the southern and western parts of Hudson Bay, where the difference reaches -1.0 cm/day. Cyclones positioned north of the grid cells (Figure 15d) also result in considerably slower thermodynamic growth, especially across a broad area extending from the northeast to the southern regions of the Bay, again with a difference of approximately -1.0 cm/day compared to no-cyclone conditions. In cases where cyclones are situated south of the grid cells (Figure 15e), the most substantial slowing of thermodynamic growth is observed in the southern region of Hudson Bay, also approaching a difference of -1.0 cm/day.

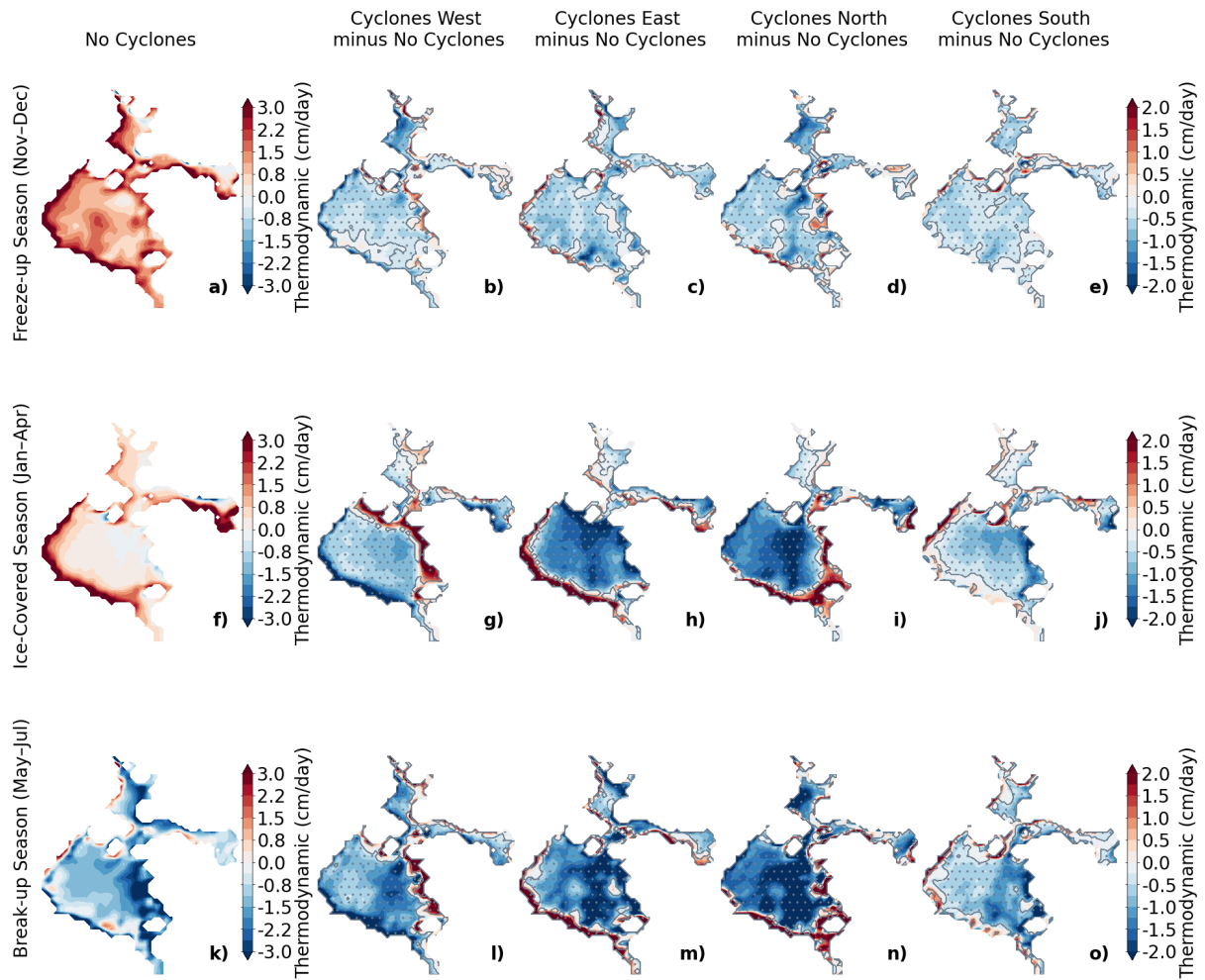


Figure 15. As in Figure 13, but for the mean thermodynamic growth of sea ice.

During the ice-covered season, thermodynamic growth remains predominantly positive when no cyclones are present (Figure 15f), with the strongest growth observed along the northwest, west, and southern borders of Hudson Bay, exceeding +2.0 cm/day. However, when cyclones are positioned east (Figure 15h) and north (Figure 15i) of the grid cells, thermodynamic growth significantly slows across almost the entire Bay, with differences lower than -1.0 cm/day compared to no-cyclone cases. Notably, for cyclones east of the grid cells (Figure 15h), positive thermodynamic growth is enhanced only along the western border of the Bay. Similarly, for cyclones north of the grid cells (Figure 15i), positive growth anomalies exist only along the southern and eastern borders. In both cases, the positive differences along the borders exceed +1.0 cm/day. For cyclones located west of the grid cells

(Figure 15g), substantial negative thermodynamic growth anomalies are observed in the central, southern, and western regions of the Bay, while positive thermodynamic growth anomalies occur along the eastern borders. Conversely, when cyclones are situated south of the grid cells (Figure 15j), thermodynamic growth slows notably in the northern and eastern parts of Hudson Bay.

During the break-up season, thermodynamic growth is predominantly negative (representing ice melt) in Hudson Bay when no cyclones are present (Figure 15k), particularly in the eastern region. When cyclones are present, the thermodynamic growth of sea ice becomes more strongly negative, especially for cyclones positioned west (Figure 15l), east (Figure 15m), and north (Figure 15n) of the grid cells, with values falling below -1.0 cm/day. For cyclones located south of the grid cells (Figure 15o), the most substantial negative anomalies are observed in the southern and eastern regions. As for positive anomalies (slower melt), they remain confined to the coastal borders of Hudson Bay, consistent with patterns seen during the ice-covered season.

Overall, the most notable negative differences in thermodynamic sea ice growth occur when cyclones are situated east and north of the Hudson Bay grid cells across all seasons. For cyclones located west and south of the grid cells, negative differences are more pronounced during the ice-covered and break-up seasons, particularly along the eastern and southern sides of the Bay. Positive differences in thermodynamic growth consistently remain along the borders of Hudson Bay in all cyclone-present cases and throughout all seasons.

Thermodynamic growth of sea ice is observed primarily in areas experiencing divergence during cyclone passage, which are generally limited to coastal regions. This spatial alignment corresponds with the observation that positive thermodynamic anomalies are mostly found along the Bay's margins, while interior regions, where convergence is more common, tend to show reduced growth or increased loss.

7. Discussion

The results from all sea ice data sources, NSIDC (Figure 5), ERA5 (Figure 6), and PIOMAS (Figure 7), demonstrate that the response of the sea ice concentration (SIC) tendency to cyclone activity exhibits similar spatial patterns. The primary difference among the datasets lies in the magnitude of the sea ice tendencies. ERA5 consistently shows higher magnitudes of difference between cyclone and no-cyclone cases compared to NSIDC, while PIOMAS presents less pronounced differences.

The position of cyclones relative to each grid cell yields different patterns in SIC tendency and in the dynamic and thermodynamic variables. For cyclones located west and east of the grid cells, notable effects are observed in similar locations in Hudson Bay in all sea ice datasets. For instance, cyclones situated west of the grid cells tend to reduce ice growth (freeze-up season) and accelerate ice decay (break-up season), whereas cyclones located to the east tend to promote faster ice growth (freeze-up season) and slower ice decay (break-up season). This typical pattern is attributed to the structure of extratropical cyclones, which have a colder sector on the west side, characterized by northerly winds, and a warmer sector on the east side, with southerly winds (Figure 13).

When it comes to SIT, the positive and negative anomalies of SIT tendencies are localized near the Bay's boundaries across all seasons, occurring closer to the far northern, southern, western, and eastern borders of Hudson Bay, depending on the location of cyclones relative to each sector.

7.1 Dynamic and Thermodynamic Effects on Sea Ice by Season

7.1.1 Freeze-up Season

The response of SIC in Hudson Bay grid cells to extratropical cyclones reflects a combination of dynamic and thermodynamic influences. When cyclones are located west of the grid cells (Figure 5b), which corresponds to more negative anomalies in SIC tendency, southerly winds prevail, advecting warmer air into the Bay, resulting in positive temperature anomalies. These warmer conditions coincide with positive anomalies in SSHF. This configuration supports findings by Rigor et al. (2002) and Cao et al. (2019), which link southerly wind events and enhanced atmospheric energy input to delayed sea ice formation in other Arctic regions.

In contrast, cyclones positioned east of the grid cells (Figure 5c) are associated with more positive anomalies in SIC tendency, generating northerly winds that advect colder air into Hudson Bay, resulting in mostly negative temperature and SSHF anomalies. This aligns with the faster SIC growth. The northerly winds also align with the fact that the stronger positive SIC tendency anomalies occur in the southeast of the Bay and are less pronounced in the northwest, suggesting that ice motion, influenced by the northerly winds, is relevant to shaping the SIC patterns when the storms are located to the east of the grid cells.

The SIC response based on the cyclone's position relative to an area is consistent with the findings of Aue et al. (2022) and Clancy et al. (2022) in the Arctic. Similar to their findings, these contrasting effects on sea ice, depending on whether cyclones are situated to the west or east, are linked to Hudson Bay grid cells falling on the eastern or western side of the cyclones. However, the Arctic is expansive, while Hudson Bay is a relatively enclosed inland sea. This positioning influences whether a grid cell experiences southerly or northerly winds and warm or cold air advection, resulting in a more negative or positive anomaly in the

sea ice tendency, which in turn makes the sea ice grow slower or faster. Hudson Bay's roughly circular shape makes local wind patterns especially important for shaping its sea ice. Depending on cyclone location, onshore and offshore winds strongly influence ice conditions, in addition to thermodynamic processes.

Cyclones located north of the grid cells are associated with more spatially variable responses. Westerly winds prevail in this configuration, producing eastward ice motion, resulting in faster SIC growth (Figure 5d) along the eastern side of Hudson Bay, where the winds are onshore, but for the western border, where the winds are offshore, the SIC tends to grow more slowly. Cyclones situated south of the grid cells (Figure 5e) result in smaller SIC tendency anomaly magnitudes and a more spread distribution, with positive SIC tendency anomalies occurring in the southern region and a small portion of the northern Bay. This suggests that the winds entering the northeast of Hudson Bay cause sea ice redistribution in many areas.

While the anomalies in SIC tendency showed an alignment with air temperature, SSHF, and ice motion driven by wind patterns, the anomalies in SIT tendency were more influenced by ice advection and convergence influenced by the winds. Additionally, the thermodynamic growth of sea ice anomalies also showed relevance. Interestingly, across all seasons, when cyclones are present, positive ice convergence anomalies dominate, while negative thermodynamic growth anomalies prevail. The signs of both ice convergence and thermodynamic growth also oppose each other along the borders of the Bay, regardless of whether cyclones are present or not. This suggests that whether the thermodynamic growth of sea ice occurs faster or slower across the borders depends on whether the ice diverges or converges along the borders. In other words, sea ice divergence allows for more thermodynamic growth where sea ice has thinned or leads have opened, whereas sea ice convergence limits thermodynamic growth by consolidating and thickening the sea ice.

For cases in which cyclones are located west of the grid cells (Figure 8b), negative SIT tendency anomalies dominate over the Bay, with a notable positive anomaly occurring only in the northwest region. This pattern closely coincides with negative ice advection anomalies in most areas, being positive only in the northwest of the Bay. Furthermore, the most pronounced positive ice convergence anomalies occur along the northwest and west borders. The positive air temperature anomalies also correspond to predominant negative SIT tendency anomalies across Hudson Bay. However, thermodynamic growth anomalies are negative, suggesting that dynamics is a dominant factor for this case. In contrast, opposite patterns manifest for cyclones positioned to the east.

For cyclones positioned to the north (Figure 8d), the negative SIT tendency anomalies in the southern and northwestern sectors align with negative ice convergence anomalies along the western side of the Bay, and the negative SIT tendency anomalies in the northeast border correspond to the positive meridional ice motion anomalies pronounced in this area. Conversely, when cyclones are positioned to the south (Figure 8e), positive SIT tendency anomalies occur in the western and southern areas, which are linked to more positive anomalies of ice advection and convergence occurring on the west side of Hudson Bay. These patterns in those regions, relative to the position of the cyclones, again indicate a dominant influence of dynamic processes, which relates to the study by Saucier et al. (2004), in which the changes in SIT in both the northwestern and southern areas were found to be primarily influenced by ice advection and ridging.

7.1.2 Ice-Covered Season

During the ice-covered season, the SIC tendencies across Hudson Bay remain minimal overall, with changes restricted to localized areas near the margins. In the absence of cyclone activity, SIC remains stable; however, cyclones introduce spatially variable changes

along the Bay's boundaries, which are mainly influenced by dynamic processes. A modestly negative anomaly in SIC tendency is noted in the southwest boundaries when cyclones are located west of the grid cells (Figure 5g), in the northwest boundaries for cyclones situated east (Figure 5h) and north (Figure 5i), and along the eastern side of the Bay when storms are located south of the grid cells (Figure 5j). These negative anomalies in SIC tendency in the Bay's boundaries are associated with the ice motion influenced by the wind pattern.

In contrast to the SIC tendency anomalies, the magnitudes of SIT tendency anomalies are pronounced, exhibiting strong positive and negative anomalies near the Hudson Bay boundaries. Across all cyclone cases, SIT variability during the ice-covered season is primarily governed by dynamic processes, resulting in advection and convergence/divergence along the Bay's boundaries. Meanwhile, SSHF and air temperature do not show strong spatial alignment with SIT changes. Instead, the dynamic processes, with opposing wind patterns, produce clear directional SIT responses. For instance, cyclones located to the west of the grid cells (Figure 8g) result in positive SIT tendency anomalies in the northern regions and negative anomalies in the southern regions of the Bay, which are linked with positive ice advection anomalies in the northern regions and negative anomalies in the southern regions. Meanwhile, cyclones located to the east exhibit an opposing pattern, with negative ice advection and convergence in the northwest, indicating that these two dynamic influences are relevant in shaping the SIT tendency anomalies in that region. Still, for cyclones positioned to the east, it is notable that the ice divergence is negative along the west boundary, while the thermodynamic growth of sea ice is positive. At the same time, the SIT tendency anomalies are also positive in most of the western boundaries of the Bay, suggesting a thermodynamic influence on the positive SIT tendency anomalies on this side of Hudson Bay.

While the considerable SIT tendency anomalies for cases of cyclones located to the west and east were mainly in the northern and southern regions, for cyclones situated to the

north or south, the anomalies are substantial in the western and eastern regions. For cyclones located to the north (Figure 8i), the negative SIT tendency anomalies are pronounced in the western regions, where the ice advection and convergence anomalies are negative. In contrast, positive SIT tendency anomalies occur on the eastern side of the Bay, aligning with more substantial positive zonal ice motion anomalies in this area. The thermodynamic growth of sea ice shows a positive anomaly on the west side; however, the dynamic processes dominate. The SIT tendency anomaly pattern for cyclones located to the south (Figure 8j) indicates an opposite situation compared to those positioned to the west. Again, it suggests that the dynamic processes prevail in modulating the positive and negative SIT tendency anomalies for the south-positioned cyclone cases.

The dynamic influence on sea ice during the winter was also observed by Kimura and Wakatsuchi (2004), who analysed the dynamic and thermodynamic influences on sea ice in the Sea of Okhotsk and found that convergence and divergence played a critical role in shaping the coastline. While offshore winds cause ice divergence, onshore winds result in ice convergence. Likewise, Kirillov et al. (2020) also found that dynamic processes, such as convergence and divergence, were more relevant in modulating the SIT in Hudson Bay during winter, rather than the thermodynamic growth of sea ice, which demonstrated a minimal influence on sea ice changes.

7.1.3 Break-up Season

During the break-up season, accelerated SIC decay prevails in the presence of cyclones, as indicated by substantial negative SIC tendency anomalies. Under no-cyclone conditions, widespread ice decay occurs due to consistently positive (downward) SSHF and air temperatures rising above 0°C, indicating net atmospheric energy input to the surface. SSHF anomalies are predominantly positive in all cyclone cases, aligning with accelerated

SIC loss, as earlier reductions in albedo enhance radiation absorption and further intensify ice melt. Air temperature anomalies are mainly negative when cyclones are present, except when cyclones are located west of the grid cells, in which the temperature anomalies are positive. In this case, sea ice tends to decay faster in most of Hudson Bay, especially in the central area where the negative SIC tendency anomalies are pronounced (Figure 5l). At the same time, the air temperature and SSHF anomalies are more positive than in the no-cyclone cases, supporting accelerated melt through increased surface energy input. Cyclones positioned east of the grid cells (Figure 5m) resulted in more pronounced negative SIC tendency anomalies in the northern Bay, due to ice motion influenced by the northerly winds generated under this cyclone position. When cyclones are located north of the grid cells, westerly winds dominate, driving eastward ice motion across the central Bay. This leads to negative SIC tendency anomalies across the west side of the Bay and the central area (Figure 5n), indicating faster ice decay. In contrast, the eastern side experiences positive SIC tendency anomalies, meaning slower ice decay. At the same time, positive air temperature anomalies and more substantial positive SSHF anomalies occur in the western regions of the Bay. Lastly, cyclones south of the grid cells (Figure 5o) are associated with negative SIC tendency anomalies across eastern Bay, a region where the SSHF air temperature anomalies are more positive. Additionally, the westward ice motion is influenced by offshore winds entering the east side of the Bay, promoting ice divergence and loss. The SIC tendency anomalies observed for both cases, cyclones to the north or south, are related to a combination of thermodynamic and dynamic processes, which corresponds to the faster or slower ice decay on the west or east side of Hudson Bay relative to the cyclone's location.

In all cases, the presence of positive anomalies in the sensible heat flux (SSHF) indicates stronger downward sensible heat transfer, despite cooler air temperatures at 925

hPa, during cyclone events compared to the no-cyclone scenario, suggesting that the ice surface is cooler than the air temperature.

The SIT tendency anomalies also predominantly reflect accelerated ice decay, especially for cyclones positioned east or north of Hudson Bay grid cells. Extensive negative SIT tendency anomalies (faster decay) occur, especially in central, eastern, and southern sectors, strongly corresponding with negative ice advection anomalies, and offshore winds for cases of cyclones located to the east (Figure 8m). The negative ice advection anomalies for cases with cyclones situated to the north (Figure 8n) occur in the western borders and the central area of the Bay, with offshore winds promoting ice motion away from the western side towards the eastern regions.

Conversely, cyclones positioned west (Figure 8l) result in positive SIT tendency anomalies (slower decay) along the northern sectors, extending to the central region, which aligns closely with positive ice convergence and advection anomalies. Finally, for cases with storms located to the south (Figure 8o), positive SIT tendency anomalies (slower decay) occur on the western side, where the winds are onshore, and negative (faster decay) anomalies occur on the eastern side, where the winds are offshore. In this case, both ice advection and convergence anomalies are positive across the western boundaries of the Bay, favoring the slower SIT decay in this area. The patterns of the thermodynamic ice growth during the break-up season follow the same pattern as the previous seasons, in which their anomalies oppose the ice convergence anomalies, becoming positive only in areas where the ice diverges. Overall, the dynamic processes demonstrated a greater influence on the positive or negative SIT tendency anomalies across all seasons, which is related to ice transport, divergence, or convergence, depending on the cyclones' locations. Similarly, as highlighted by Lukovich et al. (2021), while an intense cyclone caused a decrease in sea ice in some regions of the Arctic, other areas observed an increase in sea ice, and this contrast occurred

due to the transport of thicker ice from one area to another. This study demonstrates that the dynamic influence on sea ice is dependent on the location of cyclones relative to a specific area.

7.1.4 Cumulative impact

Throughout Section 7.1, we discussed the dynamic and thermodynamic impacts on sea ice when a cyclone is located to the west, east, north, or south of the Hudson Bay grid cells. Those impacts reflect the immediate influence at the cyclone's location but do not account for the total cumulative effect. Given this, Figure 16 highlights the total seasonal impact on sea ice in Hudson Bay when cyclones are present.

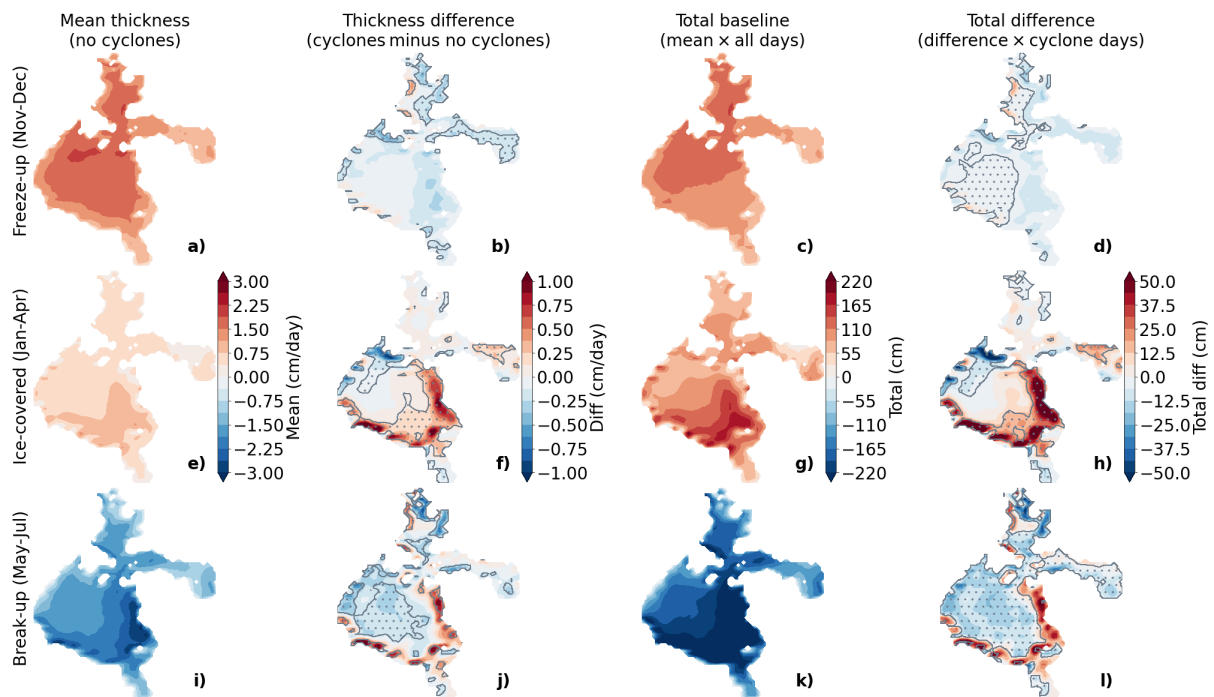


Figure 16. Total Sea Ice Thickness (SIT) change by season. The first column illustrates the mean SIT (cm/day) during days without cyclones. The second column shows the difference in SIT (cm/day), calculated as SIT during cyclone days minus SIT during non-cyclone days. The third column displays the total SIT change (cm) for all days combined (mean SIT multiplied by the total number of cyclone and non-cyclone days). The fourth column presents the total SIT change difference (cm), specifically for cyclone days (SIT difference multiplied by the number of cyclone days). Rows represent different seasons: freeze-up (November-December, first row), ice-covered (January-April, second row), and break-up (May-July, third row). Grey dots indicate grid cells where differences between cyclone and no-cyclone conditions are statistically significant ($p \leq 0.05$).

During the freeze-up season, both the SIT daily tendencies (Figure 16b) and the total SIT differences (Figure 16d) are minimal. In contrast, during the ice-covered season, the daily SIT tendency (Figure 16f) and the total difference (Figure 16h) exhibit a substantial positive anomaly along the western, southern, and eastern boundaries of the Bay. The total baseline SIT growth (Figure 16c), representing the cumulative SIT increase for all days with and without cyclones, is most pronounced in southern Hudson Bay, reaching values from about 110 to 165 cm in total. Specifically, the total SIT difference associated with cyclone days (Figure 16h) indicates a significant cumulative change of over 50 cm for the ice-covered season, corresponding to a daily anomaly rate around 1.0 cm/day (Figure 16f), indicating that storms accelerate ice growth along these boundary regions, observed by the increased ice thickness (Figure 16h). A negative anomaly is observed exclusively in the northwest region.

During the break-up season, the total SIT decay for all days with and without cyclones (Figure 16k) is substantial in the southern area (around -220 cm in total). However, the SIT decay slows along the western, southern, and eastern boundaries under the influence of cyclones, as indicated by the daily rate difference (Figure 16j) and the total difference (Figure 16l). Faster SIT decay occurs primarily in the central and northern areas, highlighted by negative anomalies of approximately -12 cm (Figure 16l).

7.2. Limitations

While this study offers a comprehensive analysis of sea ice concentration (SIC) and sea ice thickness (SIT) variability in Hudson Bay under the influence of extratropical cyclones, several limitations should be acknowledged. These limitations pertain to data constraints, unaccounted physical processes, and assumptions within the analytical framework.

7.2.1 Snow Cover

One of the key limitations is the absence of direct consideration of snow cover. Snow plays a significant role in modulating sea ice thermodynamics by acting as an insulating layer that reduces heat exchange between the ice surface and the atmosphere (Maaß et al., 2013). Additionally, cyclones are important to the amount of snow that falls when they pass over an area. Also, snow accumulation introduces uncertainty in SIT measurements due to the difficulty in accurately accounting for snow depth in altimetry data. In contrast, snow typically aids SIC measurements by enhancing the detectable contrast between ice-covered and open water surfaces; it is a lack of snow cover that complicates accurate SIC assessments. Since snow depth and density were not included in this analysis, their effects on sea ice variability remain unquantified and may influence thermodynamic interpretations.

7.2.2 ERA5 Bias

While ERA5 reanalysis data provide high-resolution atmospheric fields and surface fluxes critical to this study, they also present known limitations. Notably, within the dataset, ERA5 does not indicate any sea ice growth in November, despite observational evidence that freeze-up typically begins during this period. This discrepancy may result from limitations in how sea ice is represented in ERA5, where sea ice concentration is treated as a boundary condition based on OSI-SAF (for SIC) and OSTIA (for sea surface temperature) datasets. Consequently, the early-season sea ice tendency, particularly under west-positioned cyclones in November, may be underrepresented in ERA5, potentially impacting the interpretation of cyclone-related thermodynamic effects, especially the SSHF (Hirahara et al., 2016; Wang et al., 2019).

7.2.3 Thermodynamic Growth Estimates

In this study, thermodynamic growth is derived as the residual of the total sea ice tendency minus the contributions from advection and convergence. This diagnostic approach enables estimation of non-dynamic ice changes; however, it relies on the accuracy of the dynamic terms. Errors or uncertainties in estimating advection or convergence, such as inaccuracies in ice motion vectors or wind fields, can lead to incorrect attribution of sea ice changes to thermodynamics, distorting the estimated thermodynamic growth. Furthermore, in our method, we did not calculate external thermodynamic drivers such as snow insulation, ocean heat flux, or shortwave and longwave radiation. As a result, the thermodynamic growth values reflect the residual in the decomposition of the sea ice change rate, which should be viewed as an approximation. While they help identify spatial patterns, they may be influenced by other unaccounted factors such as longwave and shortwave radiation, snow insulation, and oceanic heat fluxes. Our interpretation primarily focuses on sensible heat flux and air temperature, and does not capture the full complexity of the surface energy budget.

7.3. Implications and Future Work

This study highlights the importance of both dynamic and thermodynamic processes in shaping synoptic-scale sea ice variability in Hudson Bay, particularly in relation to cyclone positioning. The findings suggest that incorporating cyclone-relative patterns into future sea ice analyses can enhance the understanding of regional ice behavior, particularly during freeze-up and break-up periods for SIC, as well as during ice-covered and break-up seasons for SIT. However, the limitations mentioned could be addressed for a more comprehensive analysis. Including these factors, along with regionally adapted sea ice models (with direct

measurements of thermodynamic growth) and high-resolution observations, would support a more complete understanding of cyclone-sea ice interactions.

8. Conclusion

This thesis investigated how extratropical cyclones influenced seasonal sea ice variability in Hudson Bay from 1979 to 2023, focusing on the dynamic and thermodynamic processes and their combined effects during the freeze-up (November-December), ice-covered (January-April), and break-up (May-July) seasons. The analysis demonstrates that a single mechanism rarely drives sea ice responses; instead, a combination of dynamic and thermodynamic processes, influenced by cyclone positioning relative to Hudson Bay grid cells and the geometry of the Bay, governs the observed variability. The relative importance of these mechanisms depends on whether SIC or SIT is examined.

For SIC, the impacts were aligned with both dynamic and thermodynamic processes. During the freeze-up season, cyclones located west of Hudson Bay grid cells consistently introduced warmer air temperatures and increased SSHF through southerly winds, leading to slower ice growth. Conversely, cyclones positioned east generated northerly winds that advected colder air, thereby reducing SSHF and promoting faster ice growth. Cyclones located north or south led to more spatially variable responses, which were primarily dictated by wind-driven ice redistribution. During the break-up season, cyclones generally amplified negative SIC tendencies (accelerated ice decay) compared to no-cyclone conditions, again influenced by dynamic and thermodynamic processes. In contrast, the ice-covered season exhibited minimal SIC variability, primarily confined to boundary areas driven by dynamic ice motion.

In terms of SIT, anomalies were primarily driven by dynamic processes, especially ice advection and convergence, with the thermodynamic processes showing minor or minimal effects. During the freeze-up season, SIT anomalies exhibited clear spatial patterns strongly influenced by ice convergence and advection, highlighting dynamic processes as the dominant drivers. Thermodynamic growth anomalies counteracted anomalies in ice convergence. Similarly, during the ice-covered season, SIT variability remained substantial near the Bay boundaries. SIT variability was almost exclusively governed by dynamic processes (advection and convergence), with thermodynamic effects having a minimal influence. The break-up season also emphasized the predominance of dynamics, with ice advection and convergence dictating patterns of faster or slower SIT decay across the Bay. At the same time, thermodynamic growth anomalies were generally inverse to ice divergence patterns, reinforcing the significance of ice redistribution. Furthermore, the cumulative seasonal SIT growth highlights these dynamic influences, with the total thickness tendency anomaly surpassing 50 cm during the ice-covered season along the western, southern, and eastern boundaries. During the breakup season, these same areas exhibit overall slower SIT decay relative to the locations of cyclones.

Overall, the directional position of cyclones (north, south, east, or west) had a significant impact on local sea ice conditions, resulting in distinct spatial patterns for both SIC and SIT growth and decay. Cyclones west and east showed particularly consistent and pronounced effects, with west-positioned cyclones generally associated with slower ice growth or enhanced sea ice decay and east-positioned cyclones promoting faster growth during the freeze-up season. Cyclones located north or south exhibited more complex regional variability, highlighting the sensitivity of sea ice to specific cyclone trajectories.

In conclusion, this study demonstrates that a combination of dynamic and thermodynamic processes drives sea ice changes in Hudson Bay. Cyclone position

significantly modulates this relationship, determining whether sea ice grows more rapidly or decays faster in different regions and seasons. These findings offer insight into the spatial variability in cyclone-sea ice interactions, underscoring the importance of considering both dynamic and thermodynamic mechanisms when evaluating sea ice responses to atmospheric forcing by season. A better understanding of these processes not only advances scientific knowledge regarding the impacts of extratropical cyclones on sea ice in Hudson Bay but also supports more accurate short-term sea ice forecasts, which are essential for local communities and activities such as maritime navigation.

References

- Aue, Lars, et al. "New insights into cyclone impacts on sea ice in the Atlantic sector of the Arctic Ocean in winter." *Geophysical Research Letters* 49.22 (2022): e2022GL100051.
- Aue, Lars, and Annette Rinke. "Cyclone impacts on sea ice concentration in the Atlantic Arctic ocean: Annual cycle and recent changes." *Geophysical Research Letters* 50.17 (2023): e2023GL104657.
- Barrett, Andrew P., Julianne C. Stroeve, and Mark C. Serreze. "Arctic Ocean precipitation from atmospheric reanalyses and comparisons with North Pole drifting station records." *Journal of Geophysical Research: Oceans* 125.1 (2020): e2019JC015415.
- Bluestein, H. B. "Observations and Theory of Weather Systems. Vol. II. Synoptic–Dynamic Meteorology in Midlatitudes." (1993).
- Boisvert, Linette N., Alek A. Petty, and Julianne C. Stroeve. "The impact of the extreme winter 2015/16 Arctic cyclone on the Barents–Kara Seas." *Monthly Weather Review* 144.11 (2016): 4279-4287.
- Boisvert, Linette N., et al. "Intercomparison of precipitation estimates over the Arctic Ocean and its peripheral seas from reanalyses." *Journal of Climate* 31.20 (2018): 8441-8462.
- Cao, Yong, Lingen Bian, and Jinping Zhao. "Impacts of changes in sea ice and heat flux on Arctic warming." *Atmospheric and Climate Sciences* 9.1 (2018): 84-99.
- Carlson, Toby N. "Mid-latitude weather systems." (1991).
- Castro de la Guardia, L., et al. "Sea ice cycle in western Hudson Bay, Canada, from a polar bear perspective." *Marine Ecology Progress Series* 564 (2017): 225-233.
- Catto, J. L. "Extratropical cyclone classification and its use in climate studies." *Reviews of*

- Geophysics* 54.2 (2016): 486-520.
- Cavalieri, Donald J., Per Gloersen, and William J. Campbell. "Determination of sea ice parameters with the Nimbus 7 SMMR." *Journal of Geophysical Research: Atmospheres* 89.D4 (1984): 5355-5369.
- Chen, Ting-Chen, et al. "Seasonality of Continental Extratropical-Cyclone Wind Speeds Over Northeastern North America." *Geophysical Research Letters* 49.15 (2022): e2022GL098776.
- Clancy, Robin, et al. "A cyclone-centered perspective on the drivers of asymmetric patterns in the atmosphere and sea ice during Arctic cyclones." *Journal of Climate* 35.1 (2022): 73-89.
- Comiso, Josefino C. "Characteristics of Arctic winter sea ice from satellite multispectral microwave observations." *Journal of Geophysical Research: Oceans* 91.C1 (1986): 975-994.
- Crawford, Alex D., and Mark C. Serreze. "Does the summer Arctic frontal zone influence Arctic Ocean cyclone activity?." *Journal of Climate* 29.13 (2016): 4977-4993.
- Crawford, Alex D., et al. "CEOS/NSIDC Extratropical Cyclone Tracking (CNECT)", DOI, CanWIN, Version 13.2. (2021). Retrieved from <https://canwin-datahub.ad.umanitoba.ca/data/project/cnect>
- Crawford, Alex D., et al. "Reduced sea ice enhances intensification of winter storms over the Arctic Ocean." *Journal of Climate* 35.11 (2022): 3353-3370.
- Crawford, Alex D., et al. "Sources of seasonal sea-ice bias for CMIP6 models in the Hudson Bay Complex." *Annals of Glaciology* (2023): 1-18.
- England, Mark R., et al. "The recent emergence of Arctic amplification." *Geophysical Research Letters* 48.15 (2021): e2021GL094086.
- Finocchio, Peter M., James D. Doyle, and Daniel P. Stern. "Accelerated sea ice loss from late

- summer cyclones in the new Arctic." *Journal of Climate* 35.23 (2022): 7751-7769.
- Graham, Robert M., et al. "Evaluation of six atmospheric reanalyses over Arctic sea ice from winter to early summer." *Journal of Climate* 32.14 (2019): 4121-4143.
- Hersbach, Hans, et al. "The ERA5 global reanalysis." *Quarterly Journal of the Royal Meteorological Society* 146.730 (2020): 1999-2049.
- Hirahara, Shoji, et al. "26 sea surface temperature and sea ice concentration for ERA5." *Eur. Centre Medium Range Weather Forecasts, Berkshire, UK, ERA Rep. Ser 26* (2016).
- Hochheim, Klaus P., and David G. Barber. "An update on the ice climatology of the Hudson Bay system." *Arctic, antarctic, and alpine research* 46.1 (2014): 66-83.
- Hochheim, K., D. G. Barber, and J. V. Lukovich. "Changing sea ice conditions in Hudson Bay, 1980–2005." *A little less arctic: Top predators in the world's largest northern inland sea, Hudson Bay* (2010): 39-52.
- Holton, James R., and Gregory J. Hakim. *An introduction to dynamic meteorology*. Vol. 88. Academic press, 2013.
- Johnson, Amy C., et al. "Influence of sea ice dynamics on population energetics of Western Hudson Bay polar bears." *Conservation Physiology* 8.1 (2020): coaa132.
- Kim, Tae Kyun. "T test as a parametric statistic." *Korean journal of anesthesiology* 68.6 (2015): 540-546.
- Kim, Tae Kyun, and Jae Hong Park. "More about the basic assumptions of t-test: normality and sample size." *Korean journal of anesthesiology* 72.4 (2019): 331-335.
- Kimura, Noriaki, and Masaaki Wakatsuchi. "Increase and decrease of sea ice area in the Sea of Okhotsk: Ice production in coastal polynyas and dynamic thickening in convergence zones." *Journal of Geophysical Research: Oceans* 109.C9 (2004).

- Kinnard, Christophe, et al. "Climatic analysis of sea-ice variability in the Canadian Arctic from operational charts, 1980–2004." *Annals of Glaciology* 44 (2006): 391-402.
- Kirillov, Sergey, et al. "Atmospheric forcing drives the winter sea ice thickness asymmetry of Hudson Bay." *Journal of Geophysical Research: Oceans* 125.2 (2020): e2019JC015756.
- Lackmann, Gary. "Midlatitude synoptic meteorology." (*No Title*) (2011).
- Light, Bonnie, Thomas C. Grenfell, and Donald K. Perovich. "Transmission and absorption of solar radiation by Arctic sea ice during the melt season." *Journal of Geophysical Research: Oceans* 113.C3 (2008).
- Lukovich, Jennifer V., et al. "Summer extreme cyclone impacts on Arctic sea ice." *Journal of Climate* 34.12 (2021): 4817-4834.
- Lunn, Nicholas J., et al. "Demography of an apex predator at the edge of its range: impacts of changing sea ice on polar bears in Hudson Bay." *Ecological Applications* 26.5 (2016): 1302-1320.
- Maaß, Nina, et al. "Snow thickness retrieval over thick Arctic sea ice using SMOS satellite data." *The Cryosphere* 7.6 (2013): 1971-1989.
- Nicolaus, Marcel, et al. "Changes in Arctic sea ice result in increasing light transmittance and absorption." *Geophysical Research Letters* 39.24 (2012).
- Obbard, Martyn Ernest, et al. "Trends in body condition in polar bears (*Ursus maritimus*) from the Southern Hudson Bay subpopulation in relation to changes in sea ice." *Arctic Science* 2.1 (2016): 15-32.
- Parkinson, Claire L., and Josefino C. Comiso. "On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm." *Geophysical Research*

- Letters* 40.7 (2013): 1356-1361.
- Parmentier, Frans-Jan W., et al. "The impact of lower sea-ice extent on Arctic greenhouse-gas exchange." *Nature climate change* 3.3 (2013): 195-202.
- Perovich, Donald K., and Jacqueline A. Richter-Menge. "Loss of sea ice in the Arctic." *Annual review of marine science* 1.1 (2009): 417-441.
- Plante, Mathieu, et al. "Extratropical cyclone climatology across eastern Canada." (2014).
- Previdi, Michael, Karen L. Smith, and Lorenzo M. Polvani. "Arctic amplification of climate change: a review of underlying mechanisms." *Environmental Research Letters* 16.9 (2021): 093003.
- Rantanen, Mika, et al. "The Arctic has warmed nearly four times faster than the globe since 1979." *Communications earth & environment* 3.1 (2022): 168.
- Rigor, Ignatius G., John M. Wallace, and Roger L. Colony. "Response of sea ice to the Arctic Oscillation." *Journal of Climate* 15.18 (2002): 2648-2663.
- Saucier, F. J., et al. "Modelling the sea ice-ocean seasonal cycle in Hudson Bay, Foxe Basin and Hudson Strait, Canada." *Climate Dynamics* 23 (2004): 303-326.
- Schreiber, Erika AP, and Mark C. Serreze. "Impacts of synoptic-scale cyclones on Arctic sea-ice concentration: A systematic analysis." *Annals of Glaciology* 61.82 (2020): 139-153.
- Schweiger, Axel, et al. "Uncertainty in modeled Arctic sea ice volume." *Journal of Geophysical Research: Oceans* 116.C8 (2011).
- research letters* 39.23 (2012).
- Serreze, Mark C., and Roger G. Barry. "Processes and impacts of Arctic amplification: A research synthesis." *Global and planetary change* 77.1-2 (2011): 85-96.
- Serreze, Mark C., and Julianne Stroeve. "Arctic sea ice trends, variability and implications

- for seasonal ice forecasting." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 373.2045 (2015): 20140159.
- Simmonds, Ian, Craig Burke, and Kevin Keay. "Arctic climate change as manifest in cyclone behavior." *Journal of Climate* 21.22 (2008): 5777-5796.
- Simmonds, Ian, and Irina Rudeva. "The great Arctic cyclone of August 2012." *Geophysical research letters* 39.23 (2012).
- Sledd, Anne, et al. "Surface energy balance responses to radiative forcing in the Central Arctic from MOSAiC and models." *Journal of Geophysical Research: Atmospheres* 130.6 (2025): e2024JD042578.
- Sorteberg^{1*}, Asgeir, and John E. Walsh². "Seasonal cyclone variability at 70 N and its impact on moisture transport into the Arctic." *Tellus A: Dynamic Meteorology and Oceanography* 60.3 (2008): 570-586.
- Spreen, Gunnar, Ron Kwok, and Dimitris Menemenlis. "Trends in Arctic sea ice drift and role of wind forcing: 1992–2009." *Geophysical Research Letters* 38.19 (2011).
- Stroeve, Julianne, and Dirk Notz. "Changing state of Arctic sea ice across all seasons." *Environmental Research Letters* 13.10 (2018): 103001.
- Stull, Ronald B. *Practical meteorology: an algebra-based survey of atmospheric science*. University of British Columbia, 2015.
- Tivy, Adrienne, et al. "Origins and levels of seasonal forecast skill for sea ice in Hudson Bay using canonical correlation analysis." *Journal of Climate* 24.5 (2011): 1378-1395.
- Valkonen, E., J. Cassano, and E. Cassano. "Arctic cyclones and their interactions with the declining sea ice: A recent climatology." *Journal of Geophysical Research: Atmospheres* 126.12 (2021): e2020JD034366.
- Vessey, Alexander F., et al. "An inter-comparison of Arctic synoptic scale storms between

four global reanalysis datasets." *Climate Dynamics* 54 (2020): 2777-2795.

(2018): 2737-2751.

Wang, Caixin, et al. "Comparison of ERA5 and ERA-Interim near-surface air temperature, snowfall and precipitation over Arctic sea ice: effects on sea ice thermodynamics and evolution." *The Cryosphere* 13.6 (2019): 1661-1679.

World Meteorological Organization. *State of the Global Climate 2024*, WMO-No. 1368, World Meteorological Organization, Geneva, 2025.
Available at

<https://library.wmo.int/records/item/69455-state-of-the-global-climate-2024>

Zahn, Matthias, et al. "Trends of cyclone characteristics in the Arctic and their patterns from different reanalysis data." *Journal of Geophysical Research: Atmospheres* 123.5 (2018): 2737-2751.

Zhang, Jinlun, et al. "The impact of an intense summer cyclone on 2012 Arctic sea ice retreat." *Geophysical Research Letters* 40.4 (2013): 720-726.

Zhang, Jinlun, and D. Andrew Rothrock. "Modeling global sea ice with a thickness and enthalpy distribution model in generalized curvilinear coordinates." *Monthly Weather Review* 131.5 (2003): 845-861.