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THESIS

**EVALUATION OF MODELED SEA ICE
DEFORMATION TRENDS IN THE WESTERN
ARCTIC DUE TO CLIMATE CHANGE**

by

Edward K. Jacobs

December 2023

Thesis Advisor:
Co-Advisor:

Wieslaw Maslowski
Younjoo Lee

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**EVALUATION OF MODELED SEA ICE DEFORMATION TRENDS
IN THE WESTERN ARCTIC DUE TO CLIMATE CHANGE**

Edward K. Jacobs
Lieutenant Commander, United States Navy
BS, University of Maryland, College Park, 2011

Submitted in partial fulfillment of the
requirements for the degree of

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December 2023**

Approved by: Wieslaw Maslowski
Advisor

Younjoo Lee
Co-Advisor

Peter C. Chu
Chair, Department of Oceanography

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ABSTRACT

The main thesis of this research is that sea ice thinning due to Arctic amplified climate warming will increase the operational risk of pressure ridge interaction. To address this, 9-km sea ice output from the Regional Arctic System Model (RASM) is analyzed over the period of 1980–2017. We diagnose changes in sea ice deformations, with an enhanced focus on decadal trends in the Western Arctic. Changes in sea ice area, mean and ridged ice thickness, drift velocity, and deformations are analyzed to: (1) diagnose spatial patterns, trends, and linkages among them, (2) verify model results against observations, and (3) identify areas of varying risks due to a changing sea ice state. Ridging is shown to be commonly occurring across areas where relatively thick sea ice interacts with thinner ice. We show that trends, including their sign, in sea ice deformations and ridged ice thickness are not the same throughout the Central nor Western Arctic. We find that ridged ice is increasingly forming along the Transpolar Drift route, which is projected to be one of the most utilized pan-Arctic commercial transit routes. Future research is recommended to (i) advance understanding of Arctic cyclone impacts on sea ice divergence, (ii) model the impact of landfast ice on sea ice drift and deformation, and (iii) evaluate the role of increasing model resolution in representing spatiotemporal trends of sea ice in the Arctic.

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LIST OF ACRONYMS AND ABBREVIATIONS

AA	Arctic Amplification
AC	Anadyr Current
ACC	Alaskan Coastal Current
ADCP	Acoustic Doppler Current Profiler
AIDJEX	Arctic Ice Dynamics Joint Experiment
AO	Arctic Oscillation
AOR	Area of Responsibility
ASC	Alaskan Stream Current
ASL	Arctic Submarine Laboratory
BC	Baffin Current
BG	Beaufort Gyre
BIC	Bear Island Current
BSC	Bering Slope Current
CAA	Canadian Arctic Archipelago
CH ₄	Methane
CICE	Community Ice Code
CMIP	Coupled Model Intercomparison Project
CO ₂	Carbon Dioxide
CS	CryoSat
DA	Arctic Dipole Anomaly
DOD	Department of Defense
EEZ	Exclusive Economic Zones
EGC	East Greenland Current

EIC	East Iceland Current
EOF	Empirical Orthogonal Function
ESC	East Spitsbergen Current
ESRL	Earth System Research Laboratory
EVP	Elastic-Viscous Plastic
FWC	(liquid) Freshwater Content
FY	First-Year
GCM	Global Climate Model
GESM	Global Earth System Model
GHG	Greenhouse Gas
GIN	Greenland, Iceland and Norway
IBCAO	International Bathymetric Chart of the Arctic Ocean
IC	Irminger Current
ICEX	Ice Exercises
IPCC	Intergovernmental Panel on Climate Change
IS	ICESat: Sat Ice, Cloud, and land Elevation Satellite
ITP	Ice Tethered Profilers
JMC	Jan Mayan Current
LIDAR	Light Detection and Ranging
LKF	Linear Kinematic Feature
MC	Murman Current
METOC	Meteorology and Oceanography
MIZ	Marginal Ice Zone
MY	Multi-Year
NAC	Norwegian Atlantic Current

NAD	North Atlantic Drift
NADW	North Atlantic Deep Water
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCC	Norwegian Coastal Current
NCEP	National Centers for Environmental Prediction
NIC	Naval Ice Center
NOAA	National Oceanic and Atmospheric Administration
NPO	North Pacific Oscillation
NPS	Naval Postgraduate School
NRA	NCAR Reanalysis
NSAR	National Strategy for the Arctic Region
NSIDC	National Snow and Ice Data Center
NSR	Northern Sea Route
NWP	Northwest Passage
OBL	Ocean Boundary Layer
PDO	Pacific Decadal Oscillation
PLAN	People's Liberation Army Navy
PSW	Pacific Summer Water
PWW	Pacific Winter Water
RASM	Regional Arctic System Model
RGPS	RADARSAT Geophysical Processor System
SAR	Synthetic Aperture Radar
SAT	Surface Air Temperature

SB	Siberian Branch (of Transpolar Drift)
SCC	Siberian Coastal Current
SCICEX	Science Ice Exercise
SIT	Sea Ice Thickness
SLP	Sea Level Pressure
SSM/I	Special Sensor Microwave/Imager
TPD	Transpolar Drift
U.S.	United States
ULS	Upward Looking Sonar
USA	United States Army
USAF	United States Air Force
USCG	United States Coast Guard
USGS	United States Geological Survey
USMC	United States Marine Corps
USN	United States Navy
USNORTHCOM	U.S. Northern Command
USSF	United States Space Force
VP	Viscous-Plastic
WGC	West Greenland Current
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting model
WSC	West Spitsbergen Current

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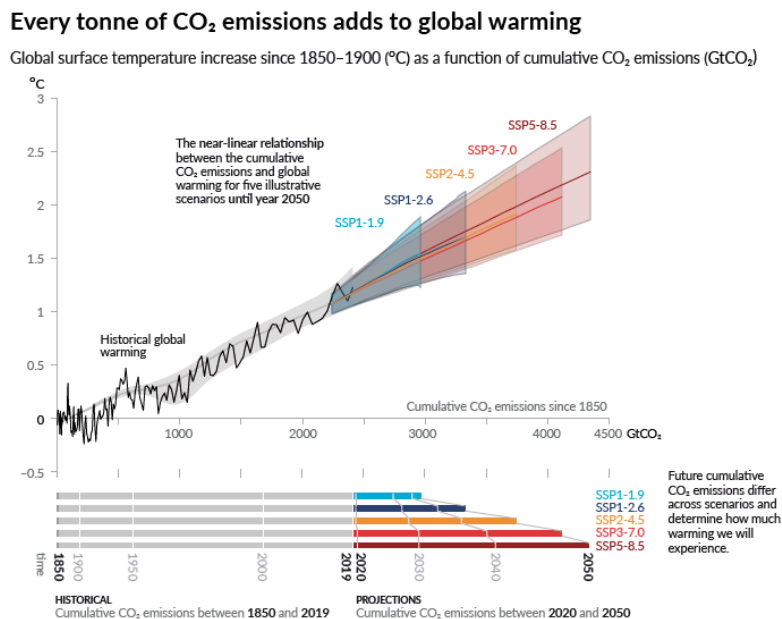
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I. INTRODUCTION

A. BACKGROUND

The Earth's near surface atmosphere has been warming and, even under the most aggressive carbon reduction scenarios modeled in the Intergovernmental Panel On Climate Change (IPCC) Sixth Assessment Report (AR6), called Shared Socio-economic Pathways (SSPs), is predicted to continue to warm throughout the 2050s (IPCC AR6 2023, 775). The National Security Strategy (NSS) published in October of 2022 states that “of all of the shared problems we face, climate change is the greatest and potentially existential for all nations” (Biden Jr. 2022b, 9). The Intergovernmental Panel On Climate Change (2023) report “reaffirms with high confidence the AR5 (Fifth Assessment Report) finding that there is a near-linear relationship between cumulative anthropogenic CO₂ emissions and the global warming they cause” as seen in Figure 1 (IPCC AR6 2023, 28).

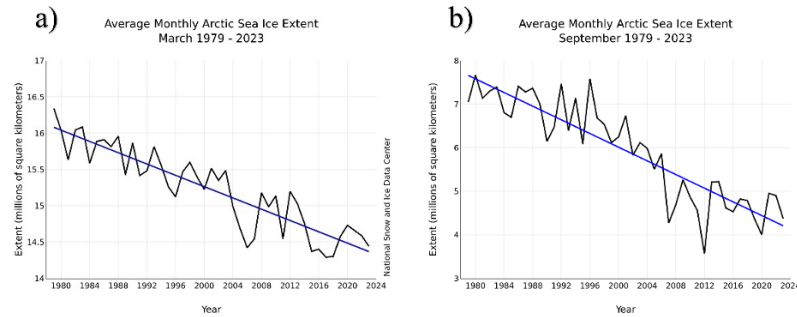


Relationship between CO₂ emissions and the increase in global surface temperature with the black line indicating historical data from 1850–2019, the grey shading indicates the estimate of historical anthropogenic warming, and the color shading indicates the individual SSP scenario projections.

Figure 1 Impact of CO₂ on global warming Adapted from: IPCC AR6 (2023).

Over the past 43 years the Arctic has been warming faster than anywhere else on the planet (IPCC AR6 2023, 773), with the most recent data and analysis showing Arctic warming 3.8 times that of the global average (Rantanen et al. 2022, 6). There are several factors contributing to enhanced Arctic warming, referred to as Arctic Amplification (AA), when compared to the rest of the world. Those include: ice-albedo feedback, lapse-rate feedback, cloud feedback, Planck feedback, enhanced oceanic heat absorption and transport, meridional atmospheric heat and moisture transport, as well as potential contributions from decreased sulfate aerosol pollution in Europe (Acosta Navarro et al. 2016) and reductions of aerosols originating in Asia consisting of natural organics, sulfate, sea salt, and dust (Merikanto et al. 2021, 5866). More discussion of their role in AA is included in the next chapter.

As the Arctic system warms, the monthly averaged sea ice extents (SIEs) for all months have decreased, with the largest decline in September and the lowest in March (Figure 2). The annually averaged sea ice edge and age, which is commonly used as a proxy for limited sea ice thickness (SIT) measurements, have decreased as well (Figure 3), with the 17 lowest SIEs recorded by satellites occurring in the past 17 years, 2007–2023 (Table 1). While sea ice age and SIT are typically positively correlated, their relationship is not necessarily linear, as it also depends on atmospheric forcing, ice-floe interactions, and specific growth/melt conditions.



Data input from Goddard: Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data and NRTSI-G: Near-Real-Time DMSP SSMIS Daily Polar Gridded Sea Ice Concentrations.

Figure 2 Average monthly arctic sea ice extent in (a) March and (b) September. Adapted from National Snow and Ice Data Center (NSIDC) (2023).

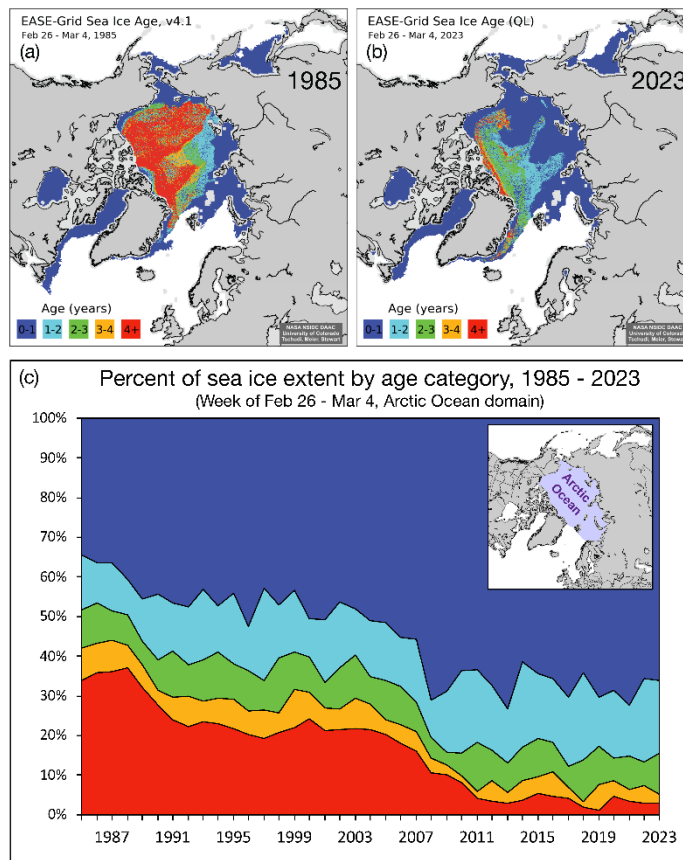


Figure 3 Sea ice extent by ice age category for (a) the mean of February 26–04 March of 1985, (b) the mean of February 26–04 March of 2023, and (c) the mean of February 26–04 March of 1985–2023 from NSIDC sourced satellite imagery. Source: Meier (2019).

Table 1. Seventeen lowest minimum SIE years from 1979–2023 (the satellite record)

RANK	YEAR	MINIMUM ICE EXTENT		DATE
		IN MILLIONS OF SQUARE KILOMETERS	IN MILLIONS OF SQUARE MILES	
1	2012	3.39	1.31	Sept. 17
2	2020	3.82	1.47	Sept. 16
3	2007	4.16	1.61	Sept. 18
	2016	4.17	1.61	Sept. 10
	2019	4.19	1.62	Sept. 18
6	2023	4.23	1.63	Sept. 19
7	2011	4.34	1.68	Sept. 11
8	2015	4.43	1.71	Sept. 9
9	2008	4.59	1.77	Sept. 19
	2010	4.62	1.78	Sept. 21
11	2018	4.66	1.80	Sept. 23
	2017	4.67	1.80	Sept. 13
	2022	4.70	1.81	Sept. 19
14	2021	4.77	1.84	Sept. 16
15	2014	5.03	1.94	Sept. 17
	2013	5.05	1.95	Sept. 13
17	2009	5.12	1.98	Sept. 13

Values within 0.04 millions of square kilometers or 0.015 millions of square miles are considered tied. Source: National Snow and Ice Data Center (2023, Table 1)

Due to overall higher atmospheric surface temperatures associated with AA during winter/freezing months, the porosity of first-year ice has increased, lowering its mechanical, compressive and flexural strength (Wang et al. 2023), which will be revisited in section II.C.4. Decreasing sea ice thickness, area, and mechanical strength, are aided by the above-mentioned positive feedback mechanisms and lead to an increased overall ice floe drift speed (Figure 4).

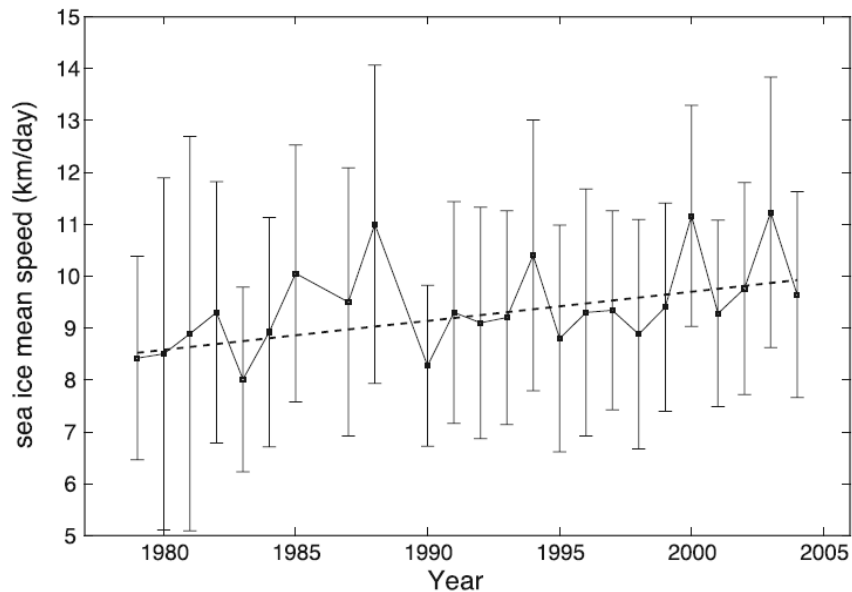


Figure 4 Arctic mean sea ice drift speed along Greenland coast in winter: 1979–2004 Source: Rampal et al. (2009, figure 11).

As thick, multi-year ice (MYI) decreases, it is replaced with thinner, first-year ice (FYI) with increased porosity (Wang et al. 2023), which coupled with ice drift, increases the probability of sea ice deformation without significant changes / trends in atmospheric forcing (Rampal et al. 2009). Over the vast expanse of the Arctic ice pack, Linear Kinematic Features (LKFs) often form in response to synoptic scale weather systems but also in part to mesoscale oceanic forcing (Kwok et al. 2008; Itkin et al. 2023). LKFs are narrow (10-100s m) and long (order of 100s km) bands of deformations, or failure zones resulting in either cracks/leads or ridges, depending on whether ice floes are being pulled apart (i.e., divergent) or colliding against each other (i.e., convergent). These cracks are often long enough to be observed in satellite images and can form in high resolution sea ice simulations (Hutter et al. 2022). However, due to their relatively narrow size, they are difficult to get explicitly resolved with sea ice models with resolutions greater than 9-km (Hutter et al. 2022).

B. RATIONALE

Pressure ridges pose a navigational hazard to military surface and subsurface operations, as well as to commercial shipping. The primary objective of this research is to assess the spatio-temporal trends of sea ice deformations with emphasis on divergence/convergence using multi-decadal (1980–2017) output from the fully-coupled Regional Arctic System Model (RASM). As of December 2023, there are no operational or scientific products or guides on the spatial or temporal distribution of pressure ridges or probability of their formation. This thesis intends to provide new information available from state-of-the-art climate models like RASM, to help mitigate the navigational risks in the Arctic posed by rapidly changing ice conditions. Given that RASM has been demonstrated to realistically represent the mean state, variability, and trends in Arctic sea ice and climate, this thesis examines sea ice deformations in RASM in order to facilitate future outlook on Naval Arctic operations, with emphasis on the likelihood of winter-time formation of future ridges and leads as the Arctic climate continues to warm, sea ice retreats in summers and thins year-around.

The National Strategy for the Arctic Region (NSAR) was updated in October 2022, for the first time since 2013, with emphasis on improving the U.S.'s understanding of the Arctic operating environment Strategic Objective 1.1, Biden Jr., *National Strategy for the Arctic Region*, (2022). As the Arctic warms and overall ice thickness decreases, human presence there is expected to increase. There has already been an increase in commercial traffic (Lindsey 2022; Figure 5) and foreign military exercises and operations (Biden Jr., *National Strategy for the Arctic Region*, 2022b) throughout the Arctic region. In order to keep the United States safe, the Department of Defense has moved towards increasing the U.S. Arctic footprint, which brings with it an increased exposure of United States personnel to Arctic navigational hazards.

Annual increase in ship traffic by region (summer 2009–2018)

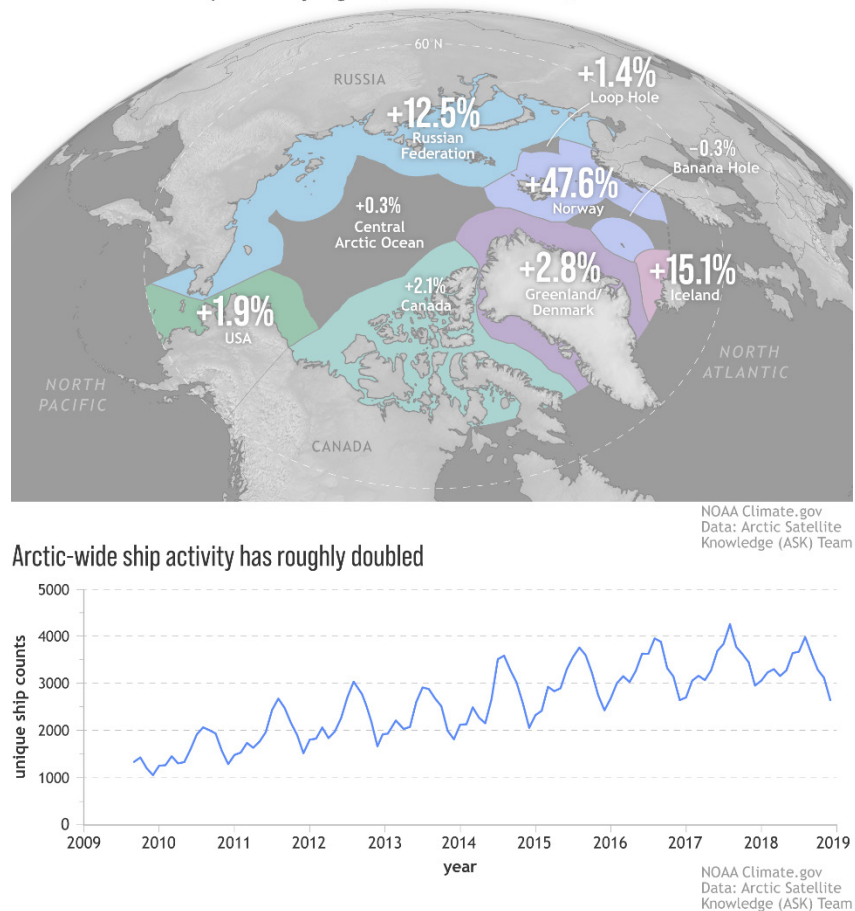


Figure 5 Arctic ship traffic trend from 2009–2018. Source: Lindsey (2022).

The Arctic is predicted to become more accessible than ever before, with the latest Intergovernmental Panel on Climate Change (IPCC) AR6 (Sixth Assessment Report) scenarios pointing to the Arctic being practically sea-ice free by 2050 (IPCC AR6 2023, 16). Hence, the countries surrounding the Arctic Ocean will see greater initiatives as more of it becomes available for use. The People’s Republic of China (PRC) has declared itself a “near Arctic nation” and is seeking to increase their presence and influence in the Arctic through scientific studies, resource gathering and investments (Biden Jr. *National Security Strategy*, 2022). Moreover, Russia has been increasing its Arctic military footprint and infrastructure in the Arctic for over a decade (Biden Jr. *National Security Strategy*, 2022). The United States seeks a “peaceful, stable, prosperous, and cooperative” Arctic; to meet these goals, the U.S. intends to invest in Arctic infrastructure, continue to promote freedom

of navigation, attempt to mitigate climate change in the area, and encourage private sector investment and use of the natural resources within the Arctic (Biden Jr. *National Security Strategy*, 2022, 44).

As first-year ice is more readily deformed than multi-year ice, the Arctic will see more instances of pressure ridges capable of damaging or marooning vessels at sea. Hence, U.S. Navy led exercises and studies in the Arctic, like Ice Exercise (ICEX), are critical to understanding and predicting the Arctic environment and how to operate in it. Section III.E elaborates more on the purpose and history of ICEX. As many of these exercises take place on the ice floes, and the ice becomes thinner and more unpredictable, it is necessary to analyze trends and patterns of the sea ice so that convergence events can be better predicted. Understanding the temporal and spatial location and orientation these convergence events are more likely to occur can help to reduce risk posed by navigational hazards. Predicting divergent events, where leads open in the ice, can assist personnel involved in research and training events on the ice by improving area understanding and finding operating locations that have a lower risk.

As a result of Arctic Amplification (AA) sea ice area, thickness, and volume have declined while uncertainty about its seasonal to decadal evolution has increased. The need for operationally focused research into navigating the new Arctic has become clear. In particular, the formation of ice pressure ridges and keels pose a tremendous risk to increasing civilian and military marine surface and subsurface operations, yet their distribution and characteristics over the recent past are not well established and the capability to forecast their future trends is currently missing. This study shows that as the Arctic warms, causing MY sea ice volume (SIV) and mechanical strength decrease and the FYI fraction to increase, the probability of occurrence of deformations caused by convergence increases along the Western Arctic Transpolar Drift route. By combining convergence with ice thickness, we aimed to see if the increased number and severity of convergence linked with increased navigational danger. Due to increased probability of stronger convergence events there is concurrently a higher probability of ridge-keel systems being formed with the overall thinning of sea ice.

II. LITERATURE REVIEW

Given the main focus of this research is on the Arctic sea ice, this literature review in the following two sections concentrates on key atmospheric and oceanic processes that can impact the sea ice state, variability, and trends. It then proceeds to give an overview of relevant Arctic sea ice and modeling research.

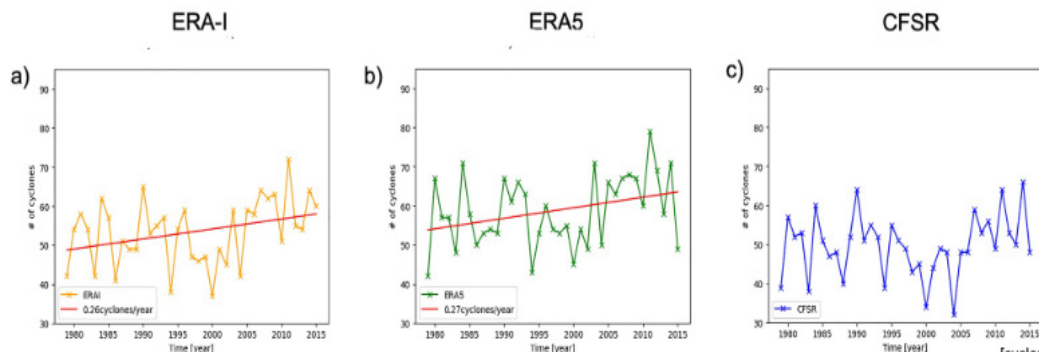
A. ATMOSPHERIC PROCESSES

1. Arctic Amplification (AA)

Arctic Amplification (AA) describes an amplified warming of the Arctic region compared to the long-term global average near surface air temperature (Dai et al. 2019; Jenkins and Dai 2022; Acosta Navarro et al. 2016; Screen and Simmonds 2010; Previdi et al. 2021; Taylor et al. 2022). The exact cause of AA is still debated, but it is widely accepted that the overall AA trend is due to anthropogenic warming (IPCC AR6 2023). As will be discussed in section C.1 of this chapter, Plank feedback, lapse rate feedback, ice-albedo feedback, water-vapor feedback, cloud feedback, and ocean and atmospheric heat and moisture transport are considered as significant factors that contribute to the unequal heating of the Arctic (Beer and Eisenman 2022).

Francis and Vavrus (2012) present that AA causes weakened zonal winds, due to weaker 500–1000 hPa thickness gradients, with greater 500 hPa ridge peak amplitude (northward elongation), correlated with increased atmospheric greenhouse gas concentrations, Arctic positive feedback mechanisms, and atmospheric pressure oscillations in the North Atlantic and North America (140°W–0°). Their work shows that enhanced Arctic warming is one of the causes of the increasing occurrence and variety of extreme weather events due to weather system blocking and slowing from decreased poleward thickness gradient and subsequently elongated atmospheric ridges extending from the midlatitudes to the Arctic (Francis and Vavrus 2012). The effects from AA are likely the result of sea-ice loss, allowing solar energy to be absorbed instead of reflected and, earlier land snow melt, causing soil to dry and warm faster in the year (Francis and Vavrus 2012).

Although mean wind speeds in the Arctic have not shown a significant pan-Arctic trend since the 1980s (Rampal et al. 2009; Spreen et al. 2011), there is evidence of increased occurrence and strength of atmospheric cyclones (Valkonen et al. 2021; Figure 6). The presence of low pressure, cyclonic systems in the Beaufort Sea force ice drift opposite to its common flow along the clockwise, anticyclonic, Beaufort Gyre, increasing the potential of ice breakup, redistribution, and deformation throughout the Western Arctic.



(a) European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA)-interim, (b) ERA version 5 (ERA5), and (c) Climate Forecast System Reanalysis (CFSR)

Figure 6 Reanalysis data depicting winter cyclone occurrences in the Arctic over time from 1979–2015 North Atlantic Oscillation (NAO). Source: Valkonen et al. (2021, figure 3).

In 1924, Gilbert Walker explained correlations between pressure level fluctuations between the Azores and Iceland as well as between the Pacific and Indian Oceans, classifying Northern and Southern Oscillations (Stephenson et al. 2003; Walker 1924). He further broke the Northern Oscillations into the North Atlantic Oscillation (NAO) and North Pacific Oscillation (NPO) and explained that the NAO was based on the Icelandic Low and Azores High pressure fluctuations, which were observed to be directly proportional to each other and would oscillate in strength over a several-year period. In 1932, Walker and Bliss published a quantitative equation for the NAO index (eq. 1) consisting of pressure and temperature measurements from around the North Atlantic, averaged from December through February (Stephenson et al. 2003; Walker and Bliss 1932).

$$NAO_{index} = P_{Vienna} + T_{Bodo} + T_{Stornoway} + 0.7P_{Bermuda} - P_{Stykkisholm} - P_{Ivigtut} - 0.7T_{Godthaab} + 0.7 \frac{T_{Hatteras} + T_{Washington}}{2}$$

(1)

Hurrell (1995) introduced a new NAO index defined as the pressure difference between Lisbon, Portugal and Stykkisholmur, Iceland. Hurrell explained that the significant decade long shifting of pressure observations and warming temperatures fit with some model simulations that accounted for increases in anthropogenic greenhouse gas emissions, and that the NAO could be facilitating an enhancement of the tropical hydrologic cycle (Hurrell 1995). As of 2023 the NAO index is based on the pressure difference between the Subtropical High near the Azores and the Subpolar Low near Iceland (Figure 7), with two distinct phases (National Centers for Environmental Information 2023). The positive NAO phase is associated with above average heights and pressure for the eastern U.S., northern Atlantic, and western Europe, as well as above-normal temperatures in the eastern United States and across northern Europe and below-normal temperatures in Greenland and often across southern Europe. This typically brings higher than average precipitation to northern Europe and below average precipitation to south and central Europe (National Centers for Environmental Information 2023). The negative phase is associated with below-average temperatures in the eastern U.S., northern Atlantic, and western Europe, and higher than average temperatures across Greenland and southern Europe, with above average precipitation in southern Europe but below average precipitation in northern Europe (National Centers for Environmental Information 2023). Figure 7 show the NAO index over time in the winter months of January, February, March (JFM) and depicts an oscillating but positive trend, it also shows the AO index which will be discussed below. The months JFM are used to describe the AO pattern since the winter months / cold season has shown to have the largest variability and therefore captures the overall AO trend better than if all months are used (Climate Prediction Center 2023b).

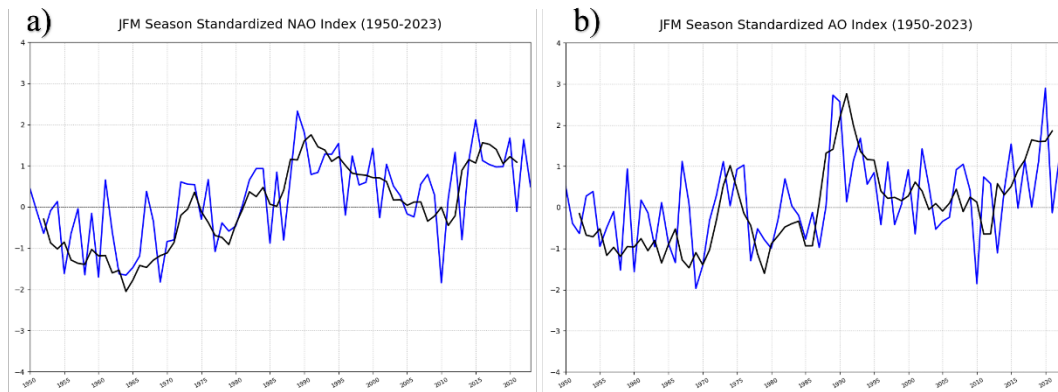


Figure 7 JFM mean NAO and AO index from 1950–2023 Source: Climate Prediction Center (2023a,b).

2. Arctic Oscillation (AO)

The Arctic Oscillation (AO), or Northern Annular Mode (NAM), is a large-scale mode of climate variability, characterized by a pattern of winds circulating counterclockwise (or cyclonically) around the Arctic, centered around 55°N (Thompson and Wallace 2000). It is the first eigenmode of the empirical orthogonal function (EOF) of wintertime sea level pressure (SLP) (Climate Prediction Center 2023b) and although it resembles the NAO, it has a stronger surface air temperature fluctuation coupling over the Eurasian continent and is centered primarily over the Arctic (Thompson and Wallace 1998). When the AO is in a positive phase the airflow is more zonal, due to an enhanced temperature/pressure gradient between the Arctic and mid-latitudes, making it less likely for cold Arctic air to penetrate down to the mid-latitudes or for warmer mid-latitude air to impact the Arctic. During the AO negative phase, the airflow is more meridional, due to the weakened temperature/pressure gradient, allowing more northward warm air advection from the mid-latitudes and southward cold air advection from the Arctic.

Figure 8 shows that the positive AO phase has lower 500–1000mb thickness in the Arctic, leading to relatively high pressure and anti-cyclonic surface wind circulation in the western Arctic and over north-central Canada. This high-pressure system, often called the Beaufort High, persists from the surface through the mid-troposphere where it interacts with the upper-level jet stream and causes upper-level convergence and filling of upper-level troughs (Climate Prediction Center ATLAS No. 8 2023). Upper tropospheric troughs

are associated with downstream vorticity advection, which in turn causes downstream ridge building due to surface low intensification. During the positive AO phase, where the upper-level airflow has been observed to be primarily zonal, we have upper tropospheric troughs that are not as deep as in the negative phase and therefore cause weaker positive vorticity advection and allow for decreased low-level intensification. The semi-persistent low-pressure system located east of the Beaufort High is often referred to as the Icelandic Low. As high-pressure steers low pressure, during the positive AO phase the Icelandic Low is pushed east by the Beaufort High, bringing cold, dry air over northern Europe, and keeping the eastern U.S. and southern Europe warm and with higher moisture from southern maritime tropical air.

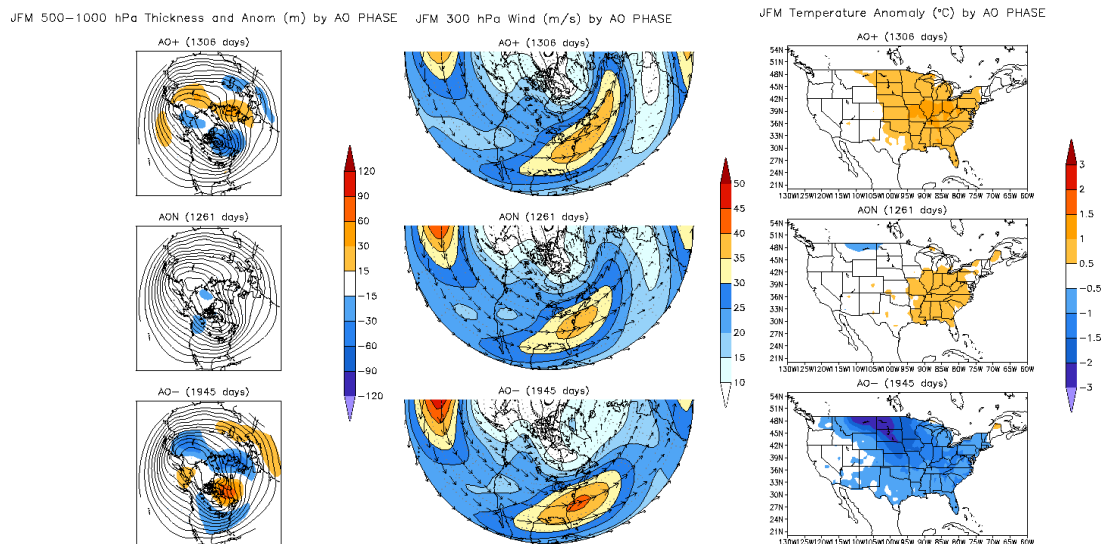


Figure 8 AO JFM 500–1000mb thickness (left), upper level winds (center) and U.S. temperature anomalies (right) averaged over a composite of days for positive, neutral, and negative phases. Source: Climate Prediction Center ATLAS No. 8 (2023).

However, the average temperature gradient between the Arctic and mid-latitudes relaxes under AA, and even in the positive AO phase strong high-pressure systems of cold polar air, created by uneven surface cooling, can advect south, which in turn can steer warm midlatitude air poleward (Francis and Vavrus 2012; Cardinale and Rose 2022). Areas of persistent high pressure are typically associated with clear skies. During Northern

Hemisphere (NH) winters, the Arctic gets little to no sunlight and therefore little to no shortwave radiation to be absorbed. As will be discussed in section C.1.c. of this chapter, without cloud cover the longwave radiation (heat) coming from the Arctic can escape to space more easily than if there were clouds, further causing cooling. The positive trend in AO index since the late 1980s, seen in Figure 7, may very well be an attempt at homeostatic balancing of the earth's temperature during a time of anthropogenic global warming (Climate Prediction Center 2023b).

3. Arctic Dipole Anomaly (DA)

The Arctic Dipole is a large-scale atmospheric circulation pattern that helps drive southward sea ice transport through Fram Strait due to its meridional orientation (Chen et al. 2023), and it is the second leading EOF eigenmode of sea level pressure (SLP) and of 500mb geopotential height, when north of 70° latitude (Watanabe et al. 2006). Despite only contributing 19% to the variance of SLP, changes in sea ice export through the Fram Strait between the DA positive and negative phases are comparable to changes due to the AO phase sign (Watanabe et al. 2006). The positive phase of the DA is associated with the anticyclonic, high pressure system that is semi-permanent in the Western Arctic and the primary forcing mechanism driving the Beaufort Gyre and Transpolar Drift (Chen et al. 2023). In this phase, anomalous winds from the Western Arctic flowing along the Transpolar Drift (TPD) out through Fram Strait, can export even more sea ice out of the Arctic than during the positive AO phase (Watanabe et al. 2006). The phases of AO and DA sometimes overlap, and other times oppose.

B. ARCTIC OCEAN PROCESSES

The Central Arctic has two main deep basins: the Eurasian (consisting of the Amundsen and Nansen Basins) and the Canadian (consisting of the Canada and Makarov Basins), and several marginal seas, including Beaufort, Chukchi, East Siberian, Laptev, and Lincoln sea (Figure 9, Figure 10, Figure 11). The Lomonosov Ridge separates the Eurasian Basin from the Canadian Basin and runs across the North Pole. This bathymetric feature has significant impacts on the intermediate and subsurface ocean currents (Figure 12 and Figure 13). The circulation of surface waters in the Canada Basin is schematically

represented by the anticyclonic Beaufort Gyre, which is in response to the Beaufort High discussed in section A.3. of this chapter.

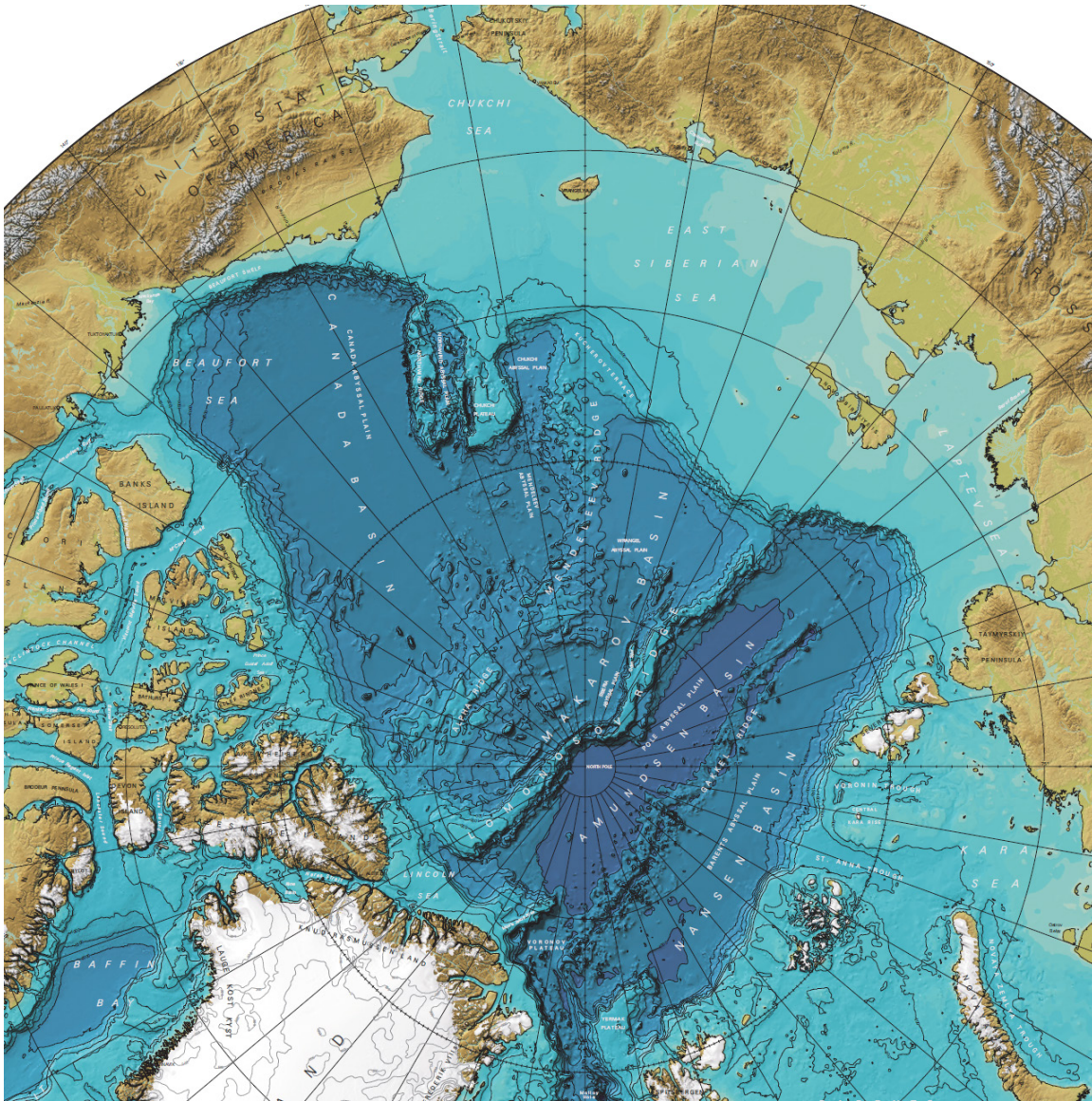


Figure 9 Bathymetry of the Central Arctic. Adapted from: (Jakobsson et al. 2004).

In the Western Arctic the water column has a distinct layer of Pacific waters, relatively warm and fresh Pacific Summer water (PSW) right below the surface mixed layer and cold and relatively fresh Pacific Winter water (PWW) forming the cold halocline

separating warm and salty Atlantic water below (DiMaggio 2014; Figure 14). This creates a unique thermal gradient where relatively cold water is less dense than warmer water, due to salinity differences which dominate water density in the Arctic Ocean. It also creates a sort of time-bomb effect for the melting of sea-ice in the Arctic, where the weakening of the cold halocline due to warming ocean and changes in atmospheric forcing can increase the entrainment of warm Atlantic water into the surface mixed layer where it can accelerate sea ice melt (DiMaggio 2014), as discussed further in section C.1.d of this chapter.

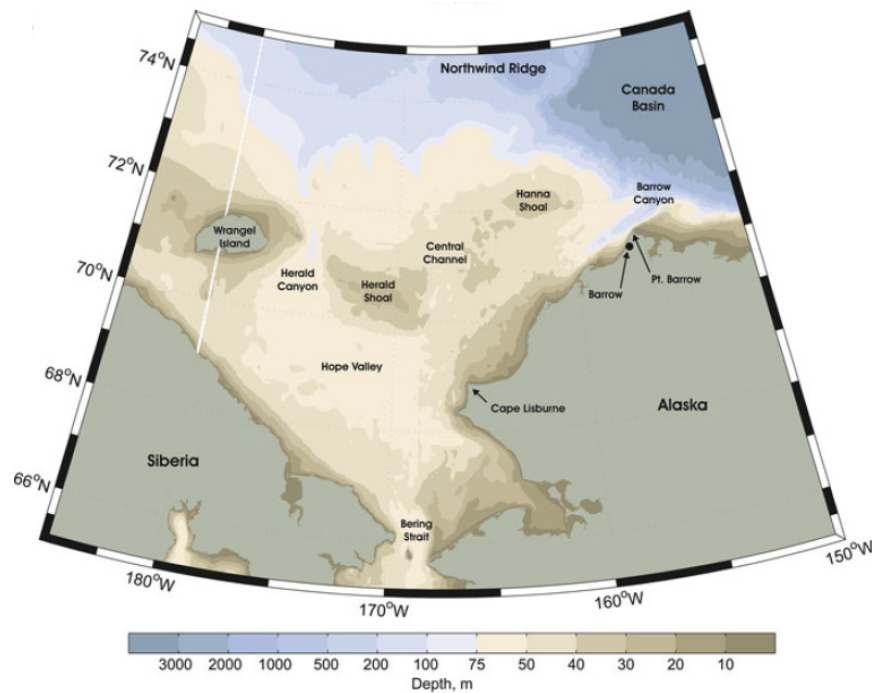


Figure 10 Bathymetric map of the Chukchi Sea. Source: Grebmeier and Maslowski (2014).

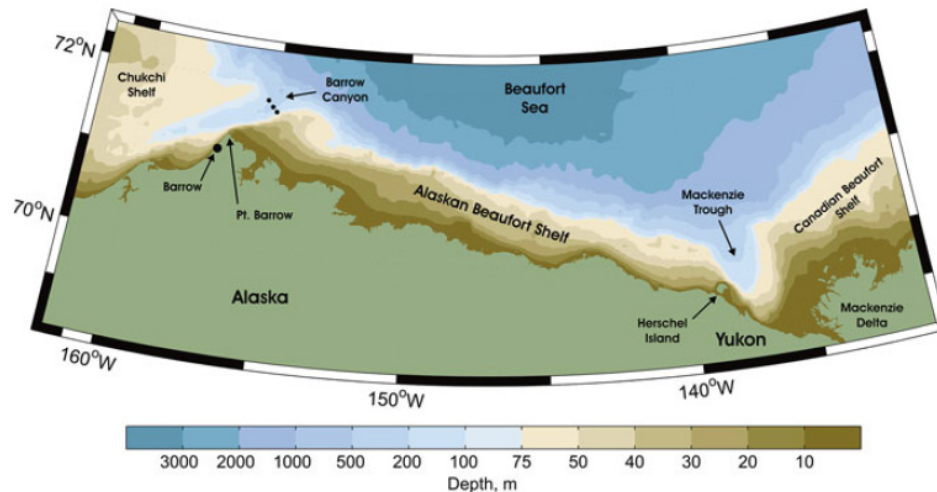


Figure 11 Bathymetric map of the Alaskan Beaufort Shelf. Source: Grebmeier and Maslowski (2014).

Oceanic import into the Central Arctic is from the North Atlantic via the Barents Sea and Fram Strait, and from the North Pacific via Bering Strait (Figure 13). Oceanic export is only into the North Atlantic via Fram / Denmark straits and the Canadian Arctic Archipelago / Davis Strait, with sporadic outflows via Bering Strait (Figure 12). The bathymetry of the Western Arctic impacts the behavior of intermediate and deep currents and water masses there, where the shallow southern Chukchi Shelf allows less dense Pacific water into the Arctic, the warmer Atlantic waters trapped beneath it as well as the colder deep water beneath that cannot flow through the Bering Strait since they are trapped bathymetrically (Figure 10 and Figure 11).

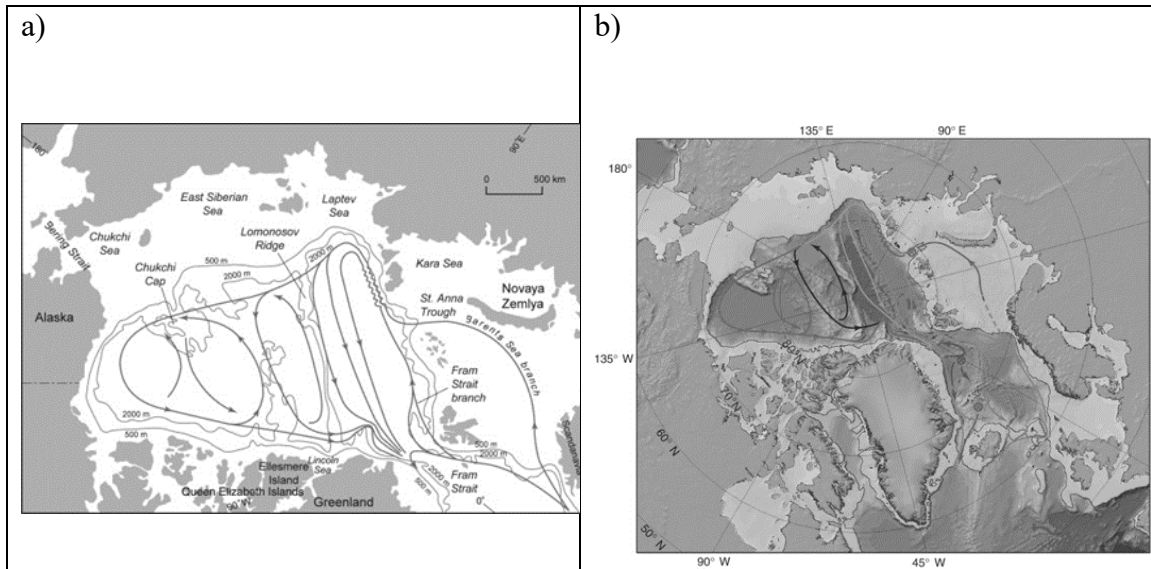
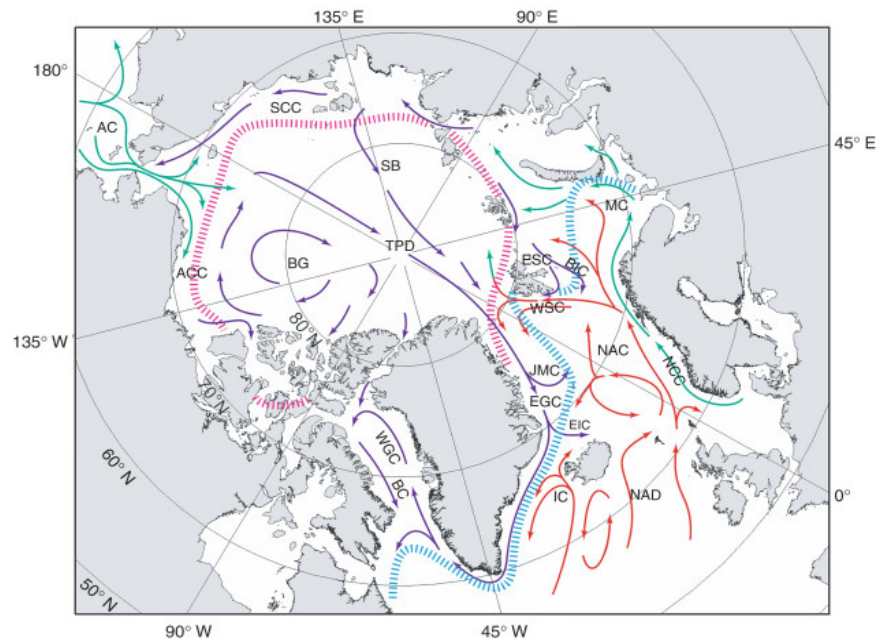


Figure 12 (a) Flow and mixing of Atlantic and Arctic intermediate waters. Source: Rudels (2001); Cochran et al. (2019, figure 3) and (b) Arctic Ocean Subsurface and Intermediate circulation. Adapted from Rudels (2009); Cochran et al. (2019, figure 7).



Red arrows indicate warm Atlantic-driven currents, blue arrows indicate cold, less-saline Arctic-driven currents, green arrows indicate lower-salinity transformed currents, the red stripped line is minimum ice extent in 2009, and the blue stripped line is maximum ice extent in 2009. See Acronym section for current abbreviations.

Figure 13 Arctic Ocean surface circulation. Source: Rudels (2009); Cochran et al. (2019, figure 4).

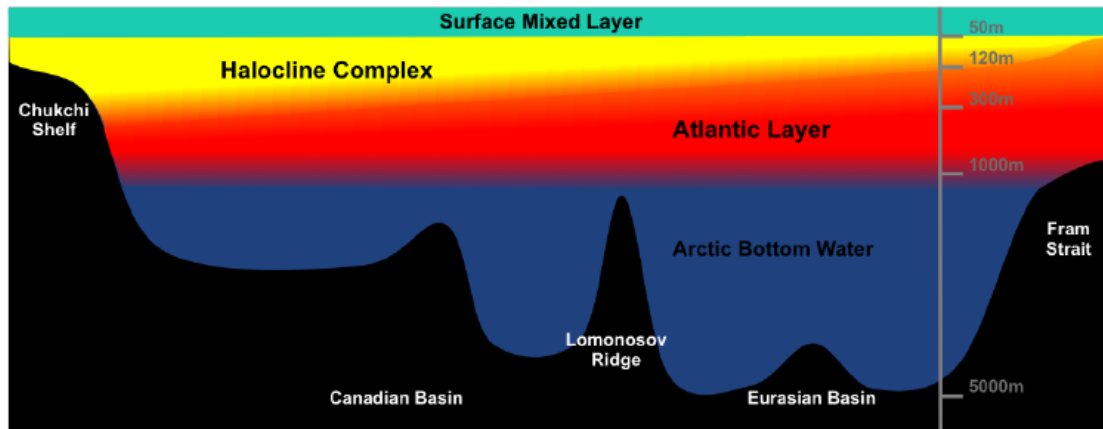


Figure 14 General layers of the Arctic Ocean. Source: DiMaggio (2014, figure 4).

C. ARCTIC SEA ICE

Sea ice is frozen seawater that floats on the ocean surface. It is often broken into four categories based on behavior, appearance, and thickness, but the exact definition of each ice category varies between authors. According to Weeks (2010), which provides a fully comprehensive account of sea ice, its history, properties and studies up-to-date, and is generally considered the standard within the scientific sea ice community, the four categories are: new, young, first-year ice (FYI) and multi-year ice (MYI). Each category contains a mixture of solid hydrogen dioxide, solid salts, liquid brine consisting of liquid water and dissolved salts, and various gases (typically air). New ice is newly formed ice until it reaches approximately 10 cm in thickness. Young ice typically has a thickness between 10 and 30 cm. FYI typically has a thickness between 0.3 and about 2 meters and has not previously survived a melting season. MYI is typically defined as ice thicker than 2 meters, and it can have different physical properties outside of thickness, (i.e., decreased porosity, decreased density, and deeper blue coloration), and it is sea ice that has survived at least one melt season (Weeks 2010). The rate at which sea ice is formed depends on the surrounding environment, with colder temperatures leading to faster freeze times. How much conductive heat flux occurs, and therefore how fast ice forms, depends on the difference in temperatures at the ice-ocean interface and ice-air interface, as well as surface conditions and ice-ocean properties such as ocean temperature, salinity, mixed layer depth,

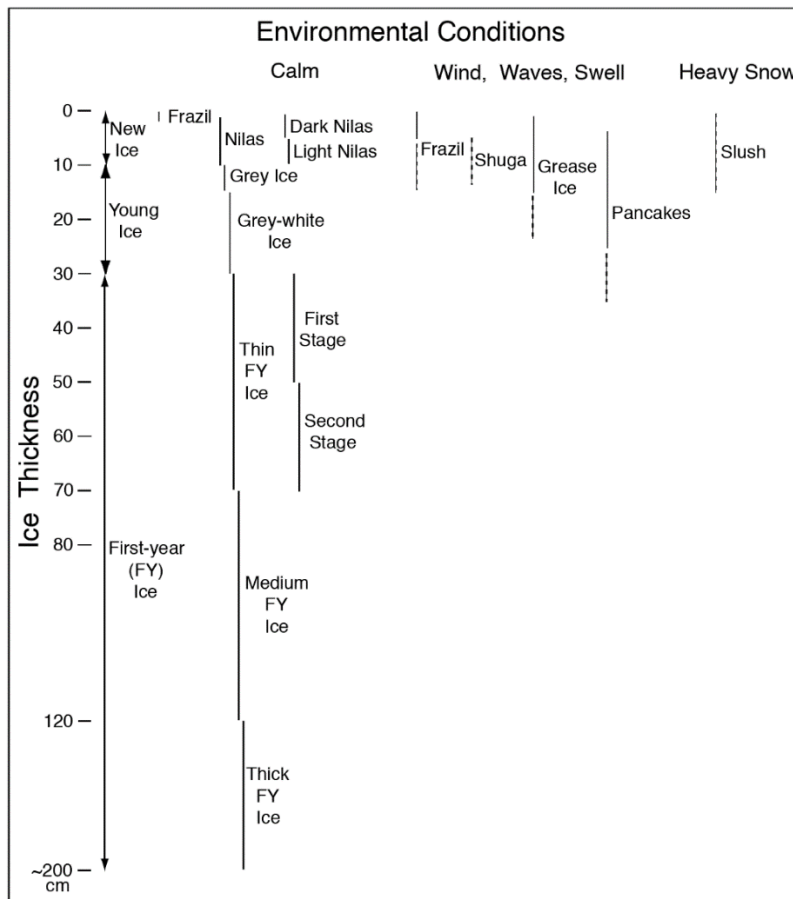
and ice age, color, and thickness/absence of snow freeboard. When determining the properties of newly formed ice the surroundings must be taken into account such as the state of any freezing nuclei already present in the ocean, thickness of the ice already present, sea surface temperature (SST), ocean salinity, surface air temperature, ice density, ocean heat flux, latent heat of brine and therefore amount of salt present in the sea water, thermal conductivity of ice and, if present, the thickness of and thermal conductivity of snow freeboard, which is dependent on the density of snow and snow type (Weeks 2010). The presence of snow on ice complicates ice growth, as it prevents ice melt, by blocking interaction with shortwave solar radiation and prevents direct interaction of ice freeboard with the atmospheric surface layer. Depending on atmospheric surface temperatures, the snow freeboard could foster either a positive or negative heat flux into the ice.

The magnitude and variability of wind, waves, swell and snow as well as temperature and salinity affect ice freeze up, with different types of ice produced, which have very different mechanical properties and behaviors. Small ice crystals, also called platelets or nuclei, that form first in turbulent waters are called frazil ice. If there is little to no upper ocean turbulence during the freezing of ice, the sea surface will supercool until a disturbance or adequate temperature decrease creates a nuclei for the rest of the supercooled water molecules to nucleate around, skipping the frazil ice phase and transitioning from open ocean to what is called sheet ice, which has a smooth and unbroken surface (Untersteiner 1986). Under mildly to severely turbulent conditions, frazil will eventually start freezing together to form a flexible layer (<5 cm thick) that is viscous enough to flow with some wave motion. Depending on the environmental roughness where frazil ice is located it will turn into either grease ice or nilas. Grease ice is formed when conditions are rougher and cause the ice platelets to aggregate and flow together, forming a suspension up to several meters deep, with low reflectivity and matte-like appearance at its surface. Grease ice also exhibits mechanical behavior similar to a viscous fluid as opposed to a ridged body (Weeks 2010; Untersteiner 1986). Under calmer conditions frazil ice can form an elastic layer called dark nilas, or black ice. The dark nilas is thin and mostly transparent, with a flexibility that comes from higher levels of salt brine (12–20%) within the ice that, in conjunction with relatively warmer freezing ocean temperatures, allow the

platelets of ice making up the nilas' structure to slide around each other without fully splitting apart (Weeks 2010). When nilas thickens to greater than 5 cm, it is often classified as light nilas due to its change in color (Weeks 2010). Nilas formed in calm coastal areas with low salinities can often be classified as ice rind, which is a brittle, shiny crust of floating ice that can easily break into small individual pieces. Shuga is a rarer type of ice that forms from the further freezing of grease ice or from ice that is anchored to the sea floor, possibly created from ice fingers that are formed during the brine rejection process.

Ice is considered “young ice” when its thickness is between 10 and 30 cm, and is further categorized as gray ice when it is between 10 and 15 cm, and gray-white ice when its thickness is between 15 and 30 cm (Weeks 2010; Figure 15). Gray ice is more brittle than nilas and will break apart and raft together as individual pieces. Gray-white ice is less flexible but has more mass/inertia than gray ice, lending to a tendency to ridge instead of raft when converging with other pieces of gray-white ice. Often, disk-shaped, pancake ice can be formed from any of the new ice states, due to further freezing, breaking, and frictional effects of ice interactions (Weeks 2010). This pancake ice, when aggregated, is often the first step in the formation of an initial ice cover or layer.

Once ice has reached 30 cm it is classified as FYI until it reaches minimum MYI age and thickness, approximately 200 cm. The thickness of 30 cm represents a threshold when brine rejection slows.



A schematic diagram showing the thickness–environmental space in which different types of sea ice form. Note that the thickness ranges of the ice types that form under poor weather conditions are not exactly specified and can vary over a wide range. ~200 cm Thick FYI.

Figure 15 First year ice formation Source: Weeks (2010).

MYI grows at a slower rate than FYI simply because it is thicker. MYI is typically less dense than FYI, due to brine rejection over time and gas filling the empty brine channels.

1. Arctic Relevant Feedbacks

There are several feedbacks impacting the state, variability, and trend of Arctic sea ice. Some of the most important in the Arctic are: (1) Ice-Albedo feedback, (2) Lapse Rate feedback, (3) Water Vapor, or Cloud Radiation feedback, and (4) Ice-Ocean feedback (Weeks 2010; Rampal et al. 2009; Roberts et al. 2019; Perovich and others 1996; Perovich et al. 1998; Vavrus 2004; Wang et al. 2023a; Figure 16).

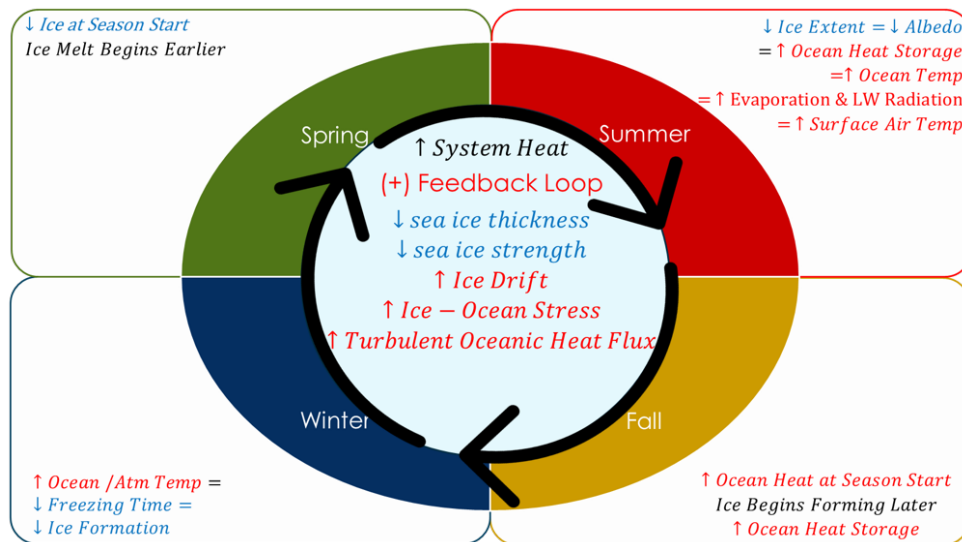


Figure 16 Arctic feedback loops

a. *Ice Albedo Feedback Loop*

The surface albedo, or reflectivity feedback, is a positive feedback cycle where increased surface temperatures have caused an increase in ice melt and a retreat of ice area (Weeks 2010). As the white to light blue ice melts, it either creates melt ponds on the ice surface or exposes the dark blue open ocean. Albedo is measured from 0, denoting total absorption or no reflectivity, to 1, denoting total reflectivity and no absorption.

Figure 17 shows that ice with new snow on top has an albedo of 0.87, or is 87% reflective, where open water has an albedo of 0.06, or is only 6% reflective. Sea ice albedo ranges from 0.45 for sediment-laden ice to 0.7 for bare ice but with the addition of early autumn snow can increase overall surface albedo up to 0.9. Melting ice decreases the surface albedo and can cause absorption of up to 84% more solar shortwave radiation compared to snow covered ice. According to Perovich et al. (1998), albedo of snow and ice for infrared wavelengths (> 780 nm) is lower than it is for visible wavelengths, meaning that longwave radiation is absorbed by snow and ice more readily than shortwave radiation (Figure 18, Figure 19). With the declining trend of ice cover due to AA, the surface albedo is decreasing in the Arctic Ocean, therefore allowing for more oceanic absorption of solar shortwave radiation and atmospheric longwave radiation from clouds, which in turn adds more heat to the mixed layer and causes ice ablation (Weeks 2010).

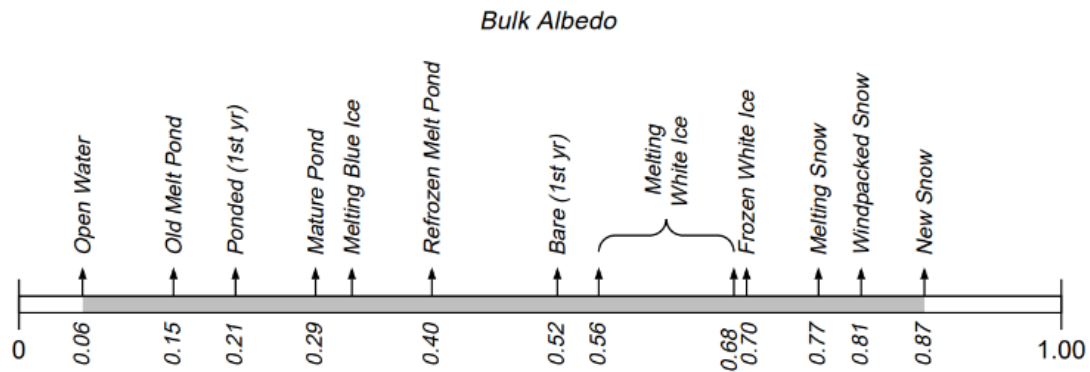


Figure 17 Total albedo of sea ice. Source: (Perovich and others 1996).

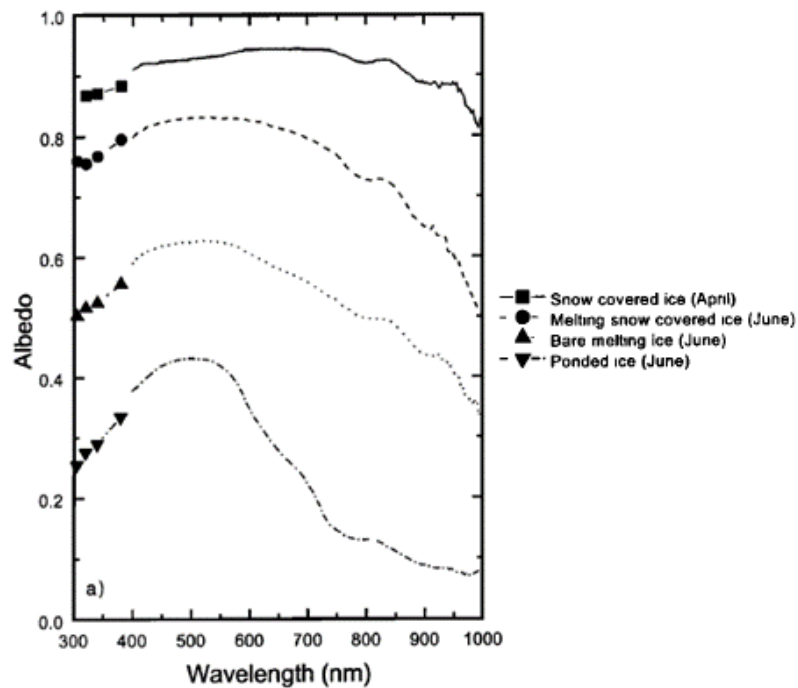


Figure 18 Snow/ice albedo as functions of wavelength. Source: Perovich et al. (1998).

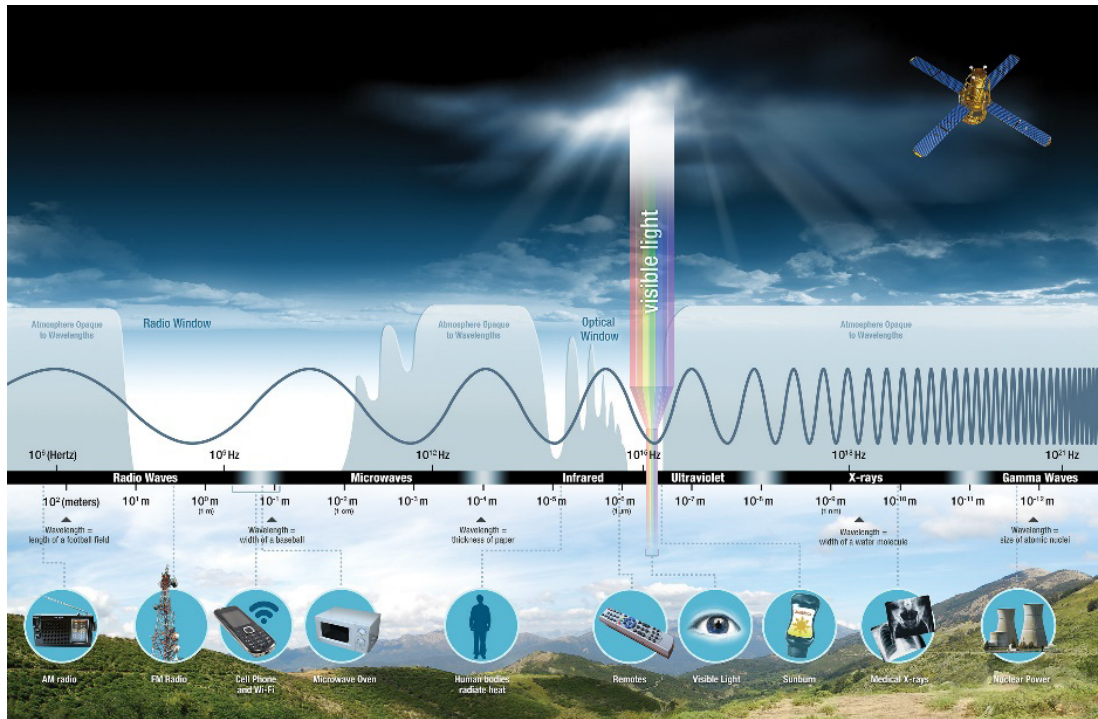


Figure 19 The electromagnetic spectrum. Source: Butcher (2016).

b. *Lapse Rate Feedback*

The conduction, radiative, or lapse rate feedback, which explains how thinning ice accelerates the air-sea heat transfer and facilitates atmospheric surface warming due to uneven heating. Sea ice acts as a barrier between the ocean and the atmosphere. When ice thins, its thermal conductivity increases and allows for increased conduction, or transfer of heat energy, between surface air and ocean water, which can lead to surface warming and further ice melt (Weeks 2010). As the temperature in the Arctic is so low, compared to the mid-latitudes or tropics, the air is comparatively dry, even at the surface over the ocean. The cold air is unable to hold a large amount of water vapor, so when evaporation occurs, the water vapor released from the ocean at the surface quickly condenses, releasing latent heat of condensation into the surface environment, as opposed to experiencing unstable lifting and warming of the air column that we often see in convective systems closer to the equator. When condensation occurs and heat is released near the surface, the cycle of warming and ice melt continues and increases. Lapse rate feedback is the positive portion of the Earth's temperature feedback loop, consisting of lapse rate and Planck feedbacks

(Goosse et al. 2018). Planck feedback is the mechanism at work in increasing longwave radiation when temperature increases, but as temperatures in the Arctic are still low compared to the tropics or mid-latitudes, the Planck radiative offset of lapse rate warming is not as impactful (Goosse et al. 2018).

c. Water Vapor / Cloud Radiation Feedback

As anthropogenic greenhouse gases increase in the atmosphere, they cause an increase in atmospheric temperature, and therefore an increase in the evaporation and subsequent concentration potential of water in the atmosphere. Water vapor is the most impactful greenhouse gas, but unlike carbon dioxide (CO₂), is highly dependent on temperature when determining the amount that can be held by the surrounding fluid (Held and Soden 2000). The more water vapor that is present in the atmosphere, the more likely cloud formation is, and with clouds comes surface layer thermal trapping.

Clouds influence the temperature budget by both absorbing incoming solar shortwave radiation and reflecting/transmitting longwave radiation both towards the Earth and back into space (Figure 20), and by absorbing and reflecting/transmitting outgoing surface longwave radiation back towards the surface and, depending on the cloud thickness and water concentration, back into space. In the Arctic, clouds reduce wintertime surface cooling by 40–50 $W\ m^{-2}$ and reduce summertime surface heating by 20–30 $W\ m^{-2}$, which locally can cause an annual net heat increase of about 20 $W\ m^{-2}$ (Vavrus 2004).

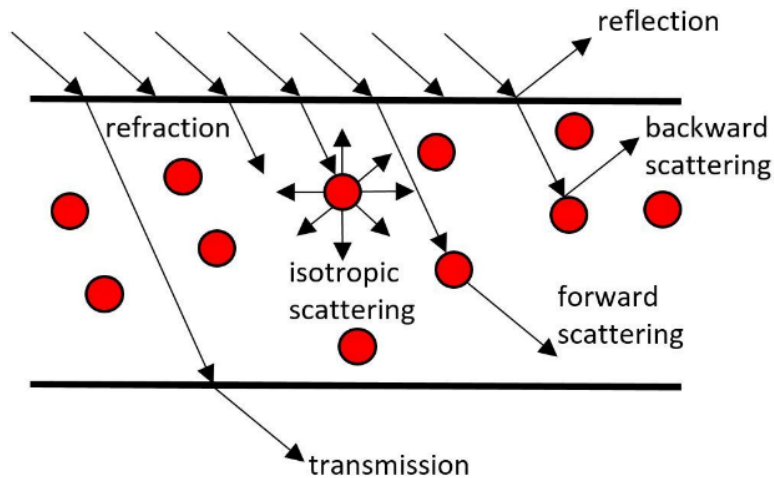


Figure 20 Boundary layer depiction of interaction with incoming radiation.
Source: Chowdhury et al. (2017).

d. Ice-Ocean Feedback

The positive feedback mechanism most relevant to and motivating this study is the ice-ocean, feedback (IOF). It is commonly and implicitly considered a part of ice-albedo feedback, particularly related to increased absorption of solar radiation and its accelerating impact on sea ice decline. However, the dynamical processes involved in such ocean-ice interactions are commonly simplified and they can be summarized as follows.

It starts with sea ice thickness decreasing in response to the warming climate. The AO/NAO have shown an overall positive trend for the past several decades, which has been associated with increased export of sea ice south (Figure 8) through the Fram Strait (Kwok 2009). The positive Pacific Decadal Oscillation (Mantua 1999) can contribute to Arctic warming through warm Pacific water advection through the Bering Strait into the Western Arctic (Woodgate et al. 2006). Some studies suggest (DiMaggio 2014) that warm Pacific water advected and trapped just below the surface mixed layer in the Western Arctic (Figure 14), under certain circumstances could be entrained upward to enhance sea ice melt from below.

As ice thins, it moves faster (Gascard et al. 2008; Rampal et al. 2009) and its mechanical strength decreases (Roberts et al. 2019). In addition, ice formed under relatively warm conditions is commonly more porous, as it increases both brine and gas

volume fractions (Figure 23; Table 2) which reduce its mechanical strength (Wang et al. 2023). Thinner, faster moving, and weaker ice is prompt to more deformations, including divergence, to occur. The positive divergence events create leads or cracks in the ice that can expose open ocean to surface air cooling to produce new ice. The Arctic Ocean, allows for large atmospheric surface warming in areas with sea ice loss during autumn and winter months (Jenkins and Dai 2022). The increase in divergence, or lead formation, helps to increase future lead formation as once ice cracks and then refreezes back together, it remains mechanically weaker at the point of previous failure than it was before the damage occurred.

Increased deformation rates increase the sea ice surface and bottom roughness. Combined with an increased ice drift this results in an increase of the surface friction velocity and ice-ocean stress (Maykut and McPhee 1995; Rampal et al. 2009), which in turn increases the vertical ocean heat flux into the surface mixed layer and to the ice (Maykut and McPhee 1995). Solar heat input into the upper ocean through thin ice and leads as well as the presence of relatively warm PSW below the surface mixed layer in the Western Arctic provide an increasing heat source to further decline sea ice thickness and area under this positive dynamic IOF loop.

The IOF mechanism ties directly to the albedo feedback, as it provides the physical description of and expands the last step in the albedo feedback loop, i.e., ocean heat melting more sea ice. According to Rampal et al. (2009) more deformations, which are an important factor in the IOF, will increase variability of ice thickness, which will also decrease ice albedo. This can be thought of similarly to how a flat pond has a strong reflection of sunlight away from the surface, but when ripples or waves are formed on the surface the sunlight is reflected not just away from the surface but also back towards the water's surface as shown in Figure 21, hence further increasing absorption of solar energy.

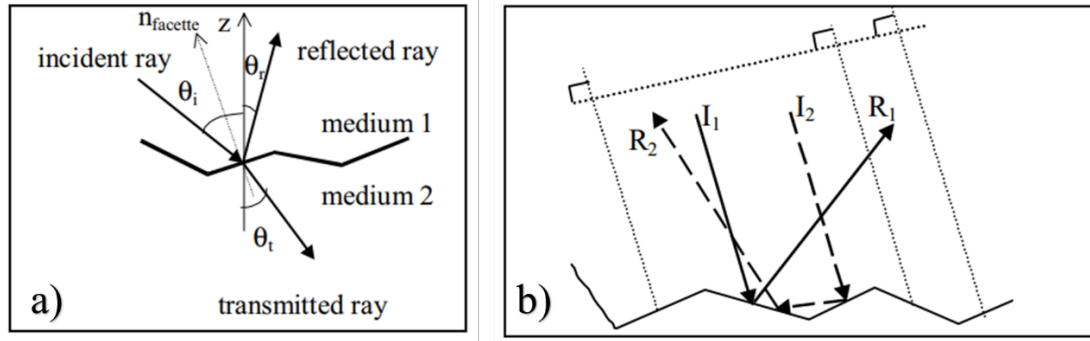


Figure 21 (a) Typical ray diagram for a non-flat surface, (b) Two incident beams showing I_1 reflecting once, and I_2 reflecting twice. Adapted from: Schott et al. (2003).

2. Sea Ice Thickness

The total sea ice thickness (SIT) cannot be directly measured by satellites, as the satellite altimeters measure ice freeboard, which is the height of ice relative to the ocean height in lead openings between ice floes (Zygmuntowska et al. 2013), and it accounts for 10–15% of the total SIT. While not ideal, a single polar orbiting satellite can complete a full scan of the Arctic in about 3 days (Korosov et al. 2022). Submarine measurements account for sea ice freeboard, which represents 85–90% of the total SIT, but their coverage is limited both in space and time. Yet, such data are critical for calibration of satellite measurements, model evaluation, and processing techniques, as section III.E will elaborate on.

The overlapping remote sensing of sea ice from two satellites provides another way to improve the accuracy of derived sea ice products, including the total SIT. By taking 3 winters of overlapping measurements from 2018–2021 using the lidar of IceSat-2 (IS-2) and the Synthetic Aperture Radar (SAR) altimeter of CryoSat-2 (CS-2) and comparing the air-snow measurement and snow-ice freeboard (snow + ice) measurement, (Kacimi and Kwok 2022) calculate the snow depth on top of the ice, total SIT, and sea ice volume (SIV). They compare the snow thickness data derived this way with the commonly used Warren climatology data (Kacimi and Kwok 2022) to show that climatology overestimates snow depth and therefore ice thickness and volume, in part due to not accounting for the increasing melt seasons. Overall, they show that MYI is declining more severely.

Having more realistic measurements of snow thickness improves the accuracy of the total SIT estimates from the IS-2, where freeboard measurements represent the height of the surface, which can be snow or sea ice, relative to the sea surface (Kacimi and Kwok 2022). With more accurate ice thickness data, it is possible to better train and validate models, to understand which are performing better and to potentially articulate why. Model output is only as good as the observations that the model is trained on, especially in the case of data assimilation (DA) where observations have continuous impact throughout the model runs. Accurate and timely observations also can help better explain the impacts of anthropogenic and natural climate forcing, so they can be more realistically represented in predictive models for the Arctic sea ice and climate condition forecasts as well as to convey the urgency for updated climate policy and action.

3. Ice Drift Speed

Following the IOF loop, as ice thickness and area decrease the Arctic has experienced an overall increasing trend in sea ice drift (Figure 4), while the Arctic mean wind speed has remained relatively constant (Figure 22; Rampal et al. (2009)).

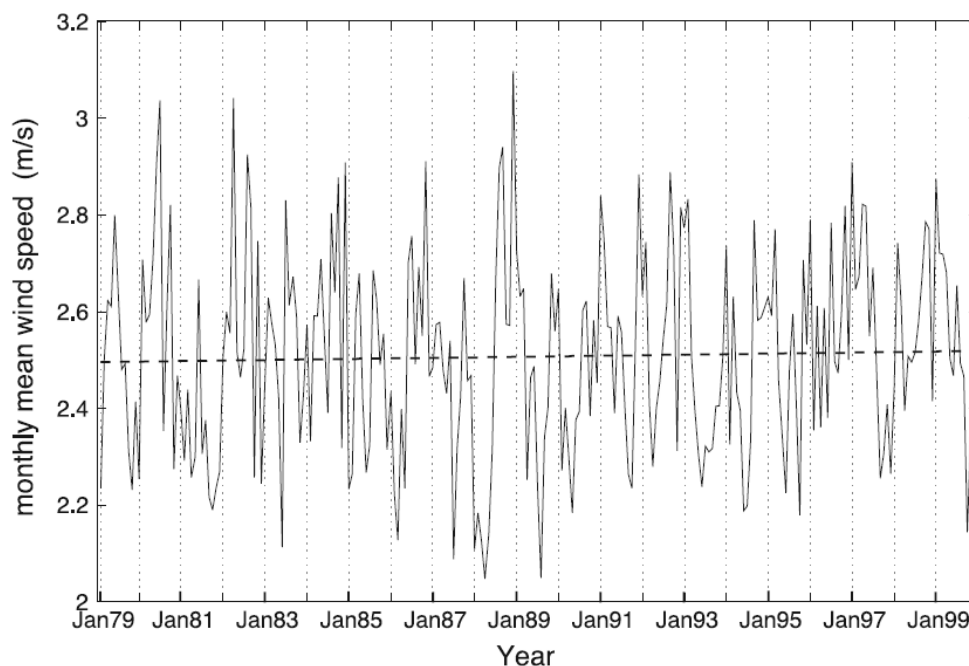


Figure 22 Arctic monthly mean wind speed for 1979–1999. Source: Rampal et al. (2009, figure 10).

4. Deformations and Pressure Ridges

Pressure Ridges in sea ice are formed from ice floe convergence and, to a lesser extent, the shearing motion between ice floes. Vertical sea ice deformations most commonly occur along leads in thicker ice, that have closed, due to the efficiency of bending, buckling, subducting and overthrusting at the ice edges compared to the energy required for internal compressive fracturing (Roberts et al. 2019). As the Arctic warms, sea ice porosity has increased, with FYI shown to be more porous than MYI (Table 2).

Table 2. Reported Arctic summer sea ice porosity. Source: Wang et al. (2023, Table 4).

First-year ice			Multiyear ice		
Date	porosity	Reference	Date	porosity	Reference
Aug. 2008	25.3 %	Wang et al. (2020)	Jul.–Aug. 1979	16.2 %	Overgaard et al. (1983)
Aug. 2010	20.5 %		Aug.–Sep. 1991	16.0 %	Eicken et al. (1995)
Aug.–Sep. 2012	27.5 %		Aug. 2008	20.6 %	Wang et al. (2020)
Aug. 2014	32.5 %		Aug.–Sep. 2012	19.3 %	
Aug. 2016	28.5 %		Aug. 2014	27.5 %	
			Aug. 2016	23.5 %	

As strain magnitudes, of convergence events, increase, ice mass will be added to a pressure ridge causing its volume and therefore the depth of its keel to increase (Roberts et al. 2019). Ice porosity transforms converging ice similarly to strain, with increased porosity enabling ice to ridge to greater volumes than with lower porosity ice, even though the density of more porous ridges will be lower (Roberts et al. 2019).

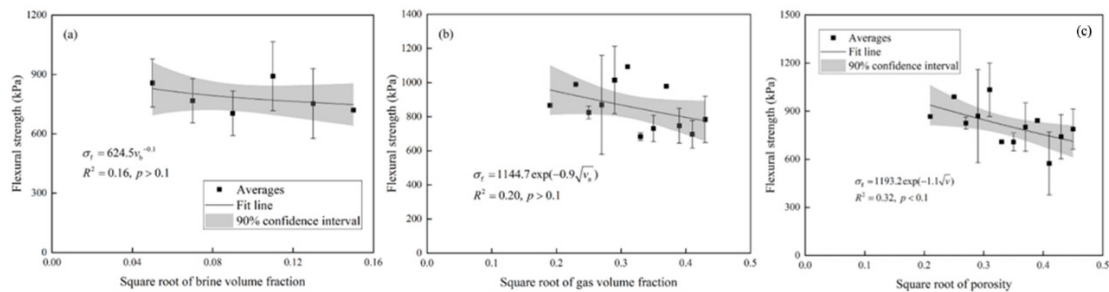


Figure 23 Flexural strength in relation to (a) brine volume fraction, (b) gas volume fraction, and (c) total porosity. Source: Wang et al. (2023).

Wang et al. (2023a) explain the porosity effect on the mechanical properties of summer sea ice in the Arctic by taking ice columnar samples and applying controlled force to ice sampled oriented horizontally, vertically, and samples that were granular. They find that (i) sea ice mechanical properties are largely controlled by its physical properties, (ii) changes of sea ice strength may have already occurred in the summer Arctic, and (iii) flexural strength and uniaxial compressive strength in the summer Arctic decreased, with

a rate of 2 kPa per year and 0.01 MPa at least, respectively, for FYI and MYI (Wang et al. 2023). Figure 23 and Table 2 from their paper show that as the Arctic summers warm, that the ice being formed is increasing in porosity and with increased porosity comes a decrease in mechanical/flexural strength. The year-round strain rate of sea ice is shown in Figure 24, noting that mean summer and winter strain rates had more than doubled in under 30 years (Rampal et al. 2009).

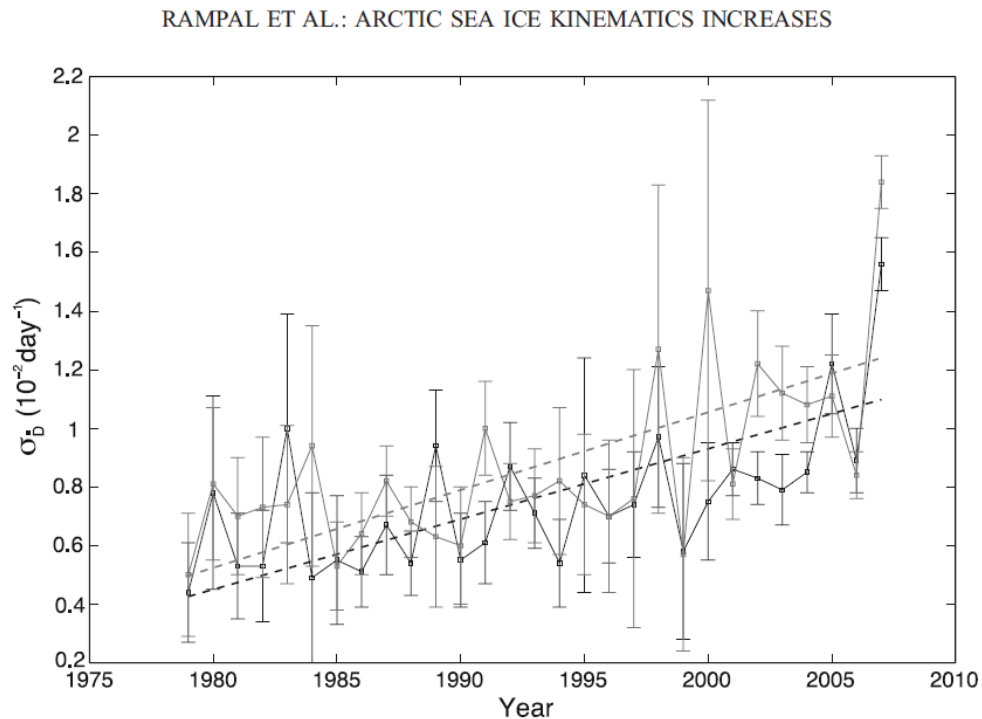


Figure 24 Mean sea ice strain for all months from 1979–2007. Source: Rampal et al. (2009).

Roberts et al. (2019) provide physically based analytical solutions to describe ridging (Figure 25). They state that when sea ice deforms, most of the kinetic energy consumed in the process is not converted to potential energy but instead is permanently lost through friction and inelastic deformation, and that ridge porosity transforms the sea ice thickness distribution in a similar way to strain and by increasing strain, ice mass is added to a ridge so that all its extremities expand. Increasing porosity has the same morphological impact but adds no extra mass to ridges, only volume. Roberts et al. (2019)

describe coarse-grained morphology as constraining the shape, extent, and porosity of ridges, while assuming each ridge half is isostatic (i.e., floats at an elevation that depends on its thickness and density), which allows complex ridged regions to be simplified within an area. In order to approach the coarse graining of ridges they (1) determine a morphological description of a ridge that appropriately describes its floating state in terms of mass and volume conservation, (2) choose appropriate mechanics model to account for the nonconservative vector in the Euler-Lagrange equation to permit application of a stationary principle that constrains the porosity and shape of a ridge, and (3) derive ridge frequency statistics for the broader pack that result from quantization of ridging into coarse-grained units. Coarse graining is a method of reducing complex interactions between particles to a system of simplified interactions between clusters of particles by allowing complex ridged regions to be simplified within individual areas that share similar characteristics (Roberts et al. 2019).

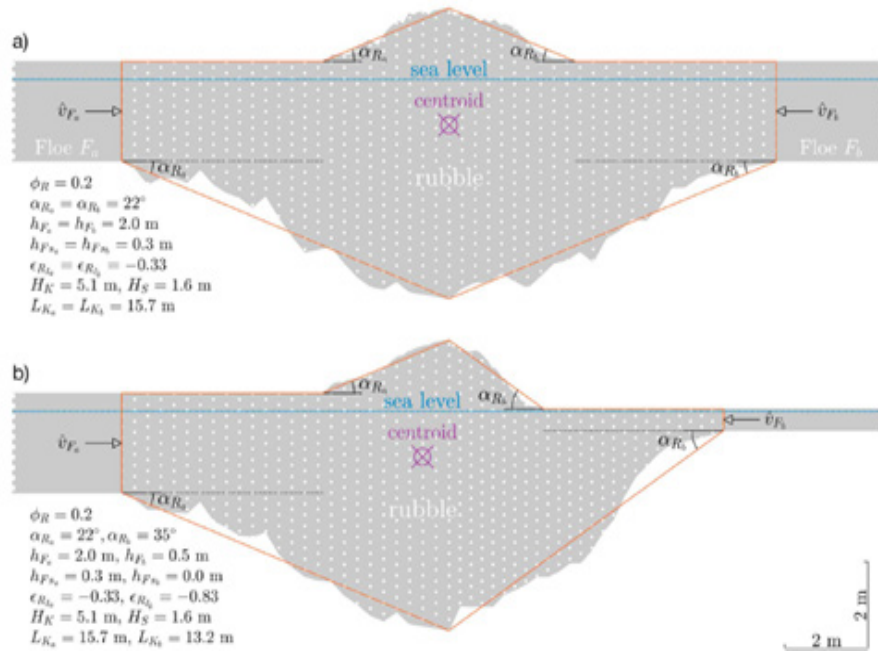


Figure 25 Depiction of orthographic cross section (a) symmetric, (b) asymmetric pressure ridges. Adapted from Roberts et al. (2019, figure 5).

D. ARCTIC SEA ICE MODELING

In the last few decades there have been back and forth shifts of scientific opinions on how the Arctic environment impacts global climate. These uncertainties and divergent opinions stem from insufficient Arctic observations, and model limitations in representing critical, often small-scale processes, like leads and ridges, and their interactions across the ocean-ice-atmosphere interface (Maslowski et al. 2012). Rampal et al. (2011) explain that when ice area is misrepresented, the ice kinematics and deformations as well as positive feedbacks discussed in C.1 are also misrepresented.

As of November 2023, the IPCC AR6 has been released with guidance based on the Phase 6 of the Coupled Model Intercomparison Project (CMIP6), which coordinates model activities from 21 separate Model Intercomparison Projects (MIPs) (Mcsweeney and Hausfather 2018; Eyring et al. 2016). Figure 26 shows the breakdown of MIPs that are included in CMIP6 along with the topics that they are being used to address (Eyring et al. 2016). Numerical models have improved dramatically between 2011 and 2023 through technological advances, capabilities for higher resolutions and processing power as well as through increased and better observations to train from. However, due to the nature of global models, that they are meant to depict large scale events over the entire Earth, they still run into issues when depicting the Arctic while attempting to use the same set of physics and coefficients for global processes everywhere (Watts et al. 2021).

The majority of models in the CMIP6 ensemble outputs which were analyzed in the IPCC AR6 report, used a horizontal resolution between 50 and 500 km (Watts et al. 2021). Models with these resolutions may show global events and trends but are not able to accurately resolve many mesoscale features in the Arctic. For example: the Bering Strait is approximately 82 km wide at its narrowest point, so a model with 110 km spatial resolution will average the entire Strait and not be able to depict the heterogeneity of oceanic fluxes across the strait. Studies have confirmed that models configured at 9-km grid or less allow for much more accurate representation of sea ice (Hutter et al. 2022).

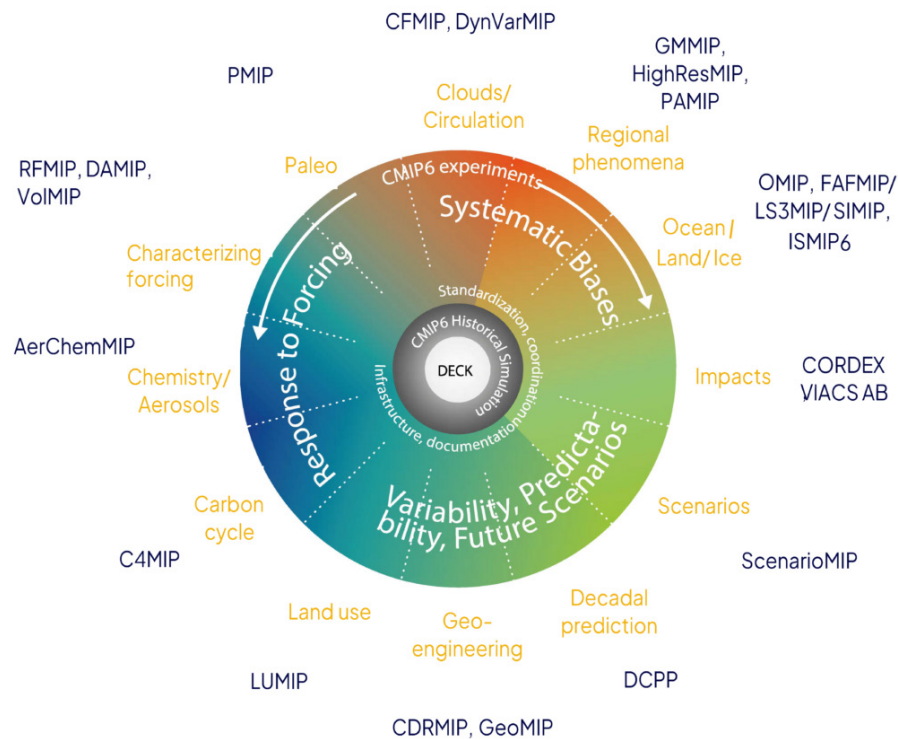


Figure 26 CMIP6 Endorsed Model Intercomparison Projects. Source: Eyring et al. (2016).

Figure 27 from Watts et al. (2021) shows the Spatial Probability Score (SPS) and the Integrated Ice Edge Error (IIEE) of the CMIP6 ensemble compared to RASM. When considering ice edge location SPS gives a total deviation from observed values while IIEE explains positive and negative deviations as being separate deviations. Effectively, if in the west a model overestimates ice edge but underestimates it in the east, then its SPS score will still indicate good performance but it's IIEE score will indicate very poor performance. RASM performed well in both SPS and IIEE but stood out as the best performing model based on IIEE.

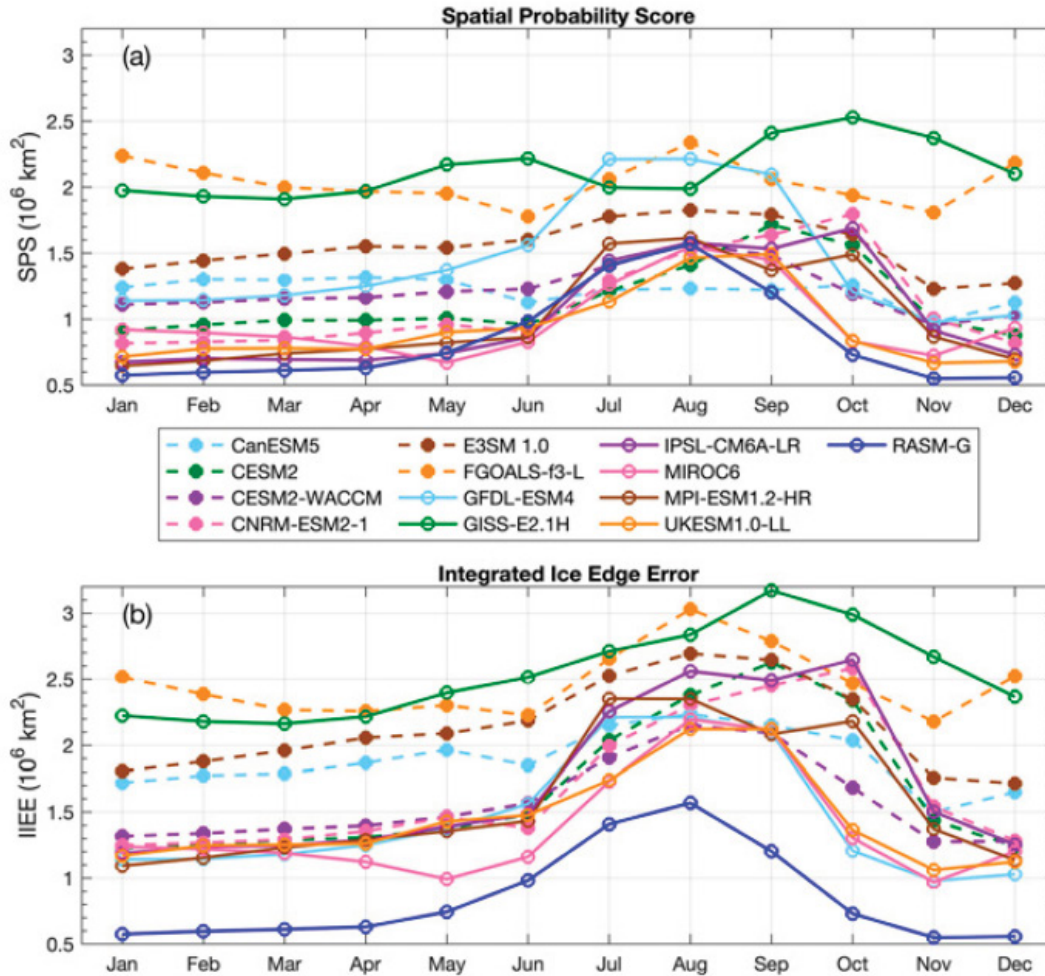


Figure 27 Pan-Arctic monthly mean of Spatial Probability Score and Integrated Ice Edge Error between 1980 and 2014 for CMIP6 and RASM reanalysis models. Adapted from: Watts et al. (2021, figure 7).

One of the key limitations of all models are insufficient observations to improve model parameterizations of sub-grid/unresolved processes or evaluate/tune modeled fluxes at the surface or across various gates and pathways, or to feed into the models or reanalysis.

1. Regional Arctic System Model (RASM)

The Regional Arctic System Model (RASM), has been developed and used to model processes within and coupling across the atmosphere, ice, ocean, and land hydrology components (Watts et al. 2021; Maslowski et al. 2012; Roberts et al. 2015). RASM uses a rotated spherical co-ordinate grid configured for the ocean and sea ice components at

horizontal resolution of $1/12^\circ$ ($\sim 9\text{km}$) or $1/48^\circ$ ($\sim 2.3\text{km}$) (Figure 28). For this study the 9-km configuration was utilized. It has 45 vertical levels for the ocean, consisting of 8 levels in the upper 50m, 15 levels in the 50–200m section of the water column, and the remaining 22 levels spread evenly below 200m (Roberts et al. 2015). RASM is fully coupled with the coupler exchanging fluxes every 20 minutes among the atmosphere (WRF3.7.1), land-hydrology (VIC4), ocean (POP2), and sea ice model components (CICE6) (Lee et al. 2023). WRF3.7.1 has a 50km horizontal resolution with 40 vertical levels, and a temporal resolution of 2.5 minutes; VIC4 also has a 50km horizontal resolution and has 3 vertical soil layers with a temporal resolution of 20 minutes. However, for this study, an ice-ocean RASM configuration was forced with the Japanese 55-year Reanalysis to make sure that analyzed sea ice trends are in response to realistic, observationally constrained atmospheric forcing.

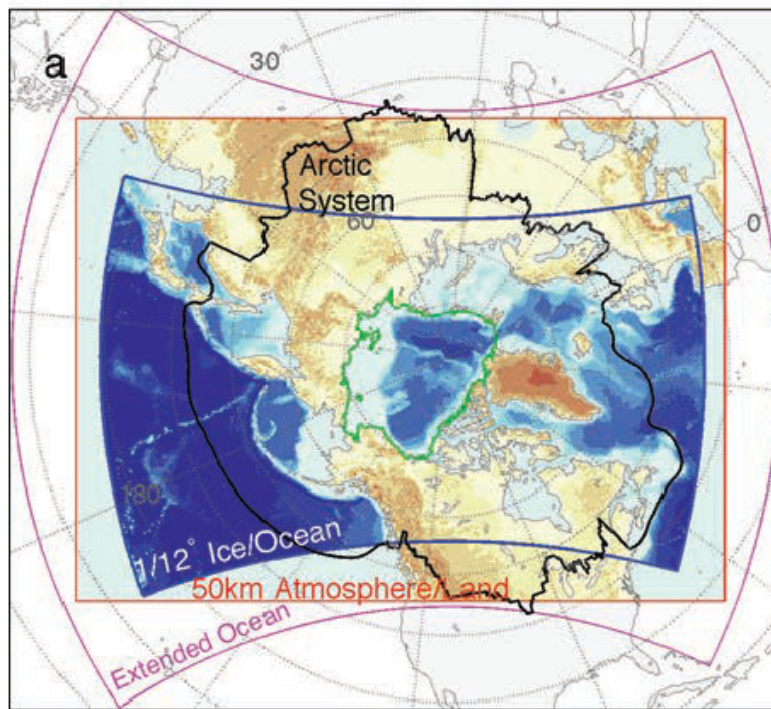


Figure 28 RASM domains. Adapted from Roberts et al. (2015, figure 1).

2. Convergence and Divergence

Ice rheology, or the study of the flow of matter, is also a constantly evolving field. Its representation in a model could be vastly different if it uses a different rheology as it depends on type of rheology implemented, spatial and temporal resolution, atmospheric and oceanic forcing or coupling, bottom bathymetry, etc. As discussed in Wang et al. (2023a) and Roberts et al. (2019), ice morphology changes dramatically under different conditions, e.g., ice formed in a warmer climate will deform more readily and have a higher porosity than ice formed in a colder climate. MYI, which has a much lower area now than it did two decades ago, deforms much less readily than FYI.

As part of the Sea Ice Rheology Experiment (SIREx), Bouchat et al. (2022) examined the scaling and statistical properties of sea-ice deformation fields by comparing methods used to represent movement and deformation of Arctic sea-ice cover, and evaluating the ability of sea-ice models to reproduce satellite observed deformations. They found that coupling ice with atmospheric models, instead of forcing with reanalysis, improves temporal and spatial parameters and scaling (Figure 29). They also explain the different ways that models have handled sea ice rheology, by treating it as: Viscous-Plastic (VP) where sea ice assumed to deform as plastic material when mech stresses reach critical loads in compression, shear, tension and as a creeping, highly viscous fluid for smaller stresses, Elastic-Viscous-Plastic (EVP) with the same physical concepts as VP but with damped artificial elastic waves allow explicit numerical implementation of dynamical equations, Elastic-Anisotropic-Plastic (EAP) which uses EVP elastic waves but with anisotropy of ice stress, parameterizing the interactions of diamond-shaped floes, or Elasto-Brittle (EB) and Maxwell-Elasto-Brittle (MEB) which use a classical plastic response of ice traded for brittle parameterization accounting for fracturing and sliding of ice along fault planes (Bouchat et al. 2022).

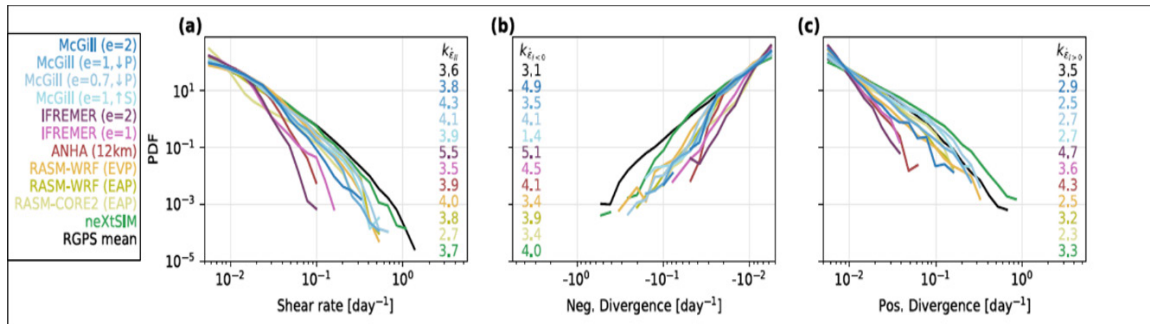


Figure 29 Probability density functions of (a): maximum shear rate, (b): convergence and (c) divergence as produced by different models. Adapted from Bouchat et al. (2022, figure 1).

Also, as a part of the SIREx, Hutter et al. (2022) evaluate model ability to resolve linear kinematic features (LKFs), including their lifetime and growth rate compared to those derived from the RADARSAT Geophysical Processor System (RGPS) observations (Figure 30). LKFs are elongated deformation bands (Hutter et al. 2022) formed by positive or negative divergence of ice floes. They find that LKFs emerge in simulations with increasing resolution and/or improved ice physics. That temporal and spatial resolution of a simulation and spatial resolution of atmospheric boundary conditions affect simulated LKFs as much as model rheology and numerics. Models analyzed by Hutter et al. 2022 used: high spatial resolution, short time steps, different physics or rheologies, different numerical techniques, like a Lagrangian moving grid, high-resolution atmospheric boundary conditions in space and time, or a combination of these techniques. They find that only simulations with a resolution smaller than 2 km produced sea ice concentration down to 50% in grid cells tagged as leads (Hutter et al. 2022).

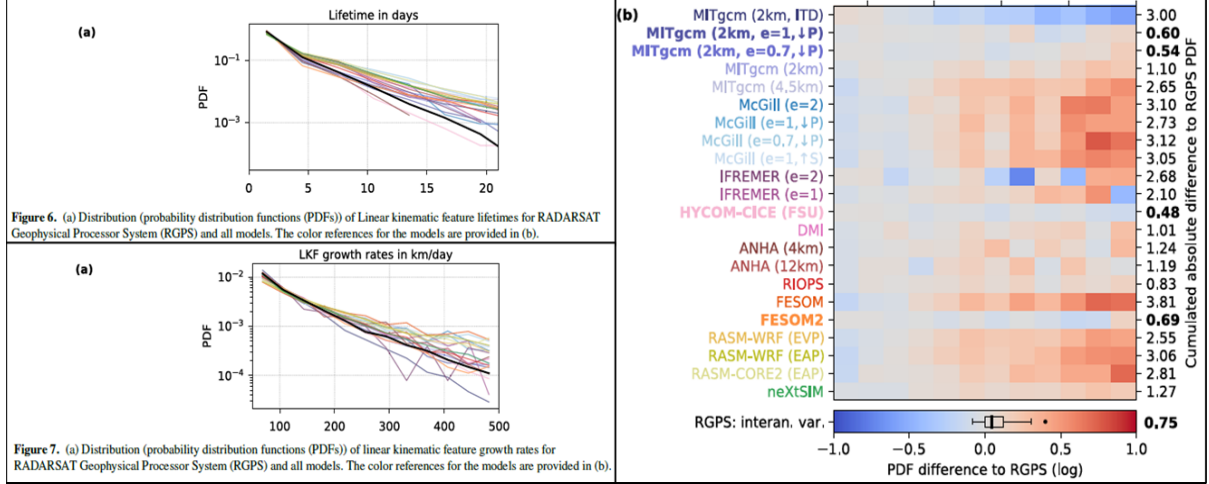


Figure 30 LKF lifetime and growth rate observations from RGPS. Adapted from: Hutter et al. (2022, figures 6, 7).

Divergence (divu) is described by the CICE manual as $\nabla \cdot \mathbf{u}$, for a 2-dimensional velocity field at each point side of a grid cell compared to the grid cells around it. $\mathbf{u}$ is the horizontal ice velocity, L is the grid cell edge length, with N, S, E, W indicating cardinal directions. This is a measure of the sum of the change in speed of the ice along the edges of a CICE/RASM grid cell towards or away from the surrounding grid cells, then divided by the grid cell area to give units of 1/s or, as used in RASM, when multiplied by a constant, %/day.

$$\nabla \cdot \mathbf{u} = \frac{1}{A} \left[\left(\frac{u_{NE} + u_{SE}}{2} \right) L_E + \left(\frac{u_{NW} + u_{SW}}{2} \right) L_W + \left(\frac{u_{NE} + u_{NW}}{2} \right) L_N + \left(\frac{u_{SE} + u_{SW}}{2} \right) L_S \right] \quad (2)$$

(CICE Consortium 2023a)

R_{net} is described as the net rate of ice pack area loss, with C_S , as the fraction of shear dissipation energy that contributes to ridge building, set by default to 0.25, D_D is divergence, and Δ is a function of divergence and shear.

$$R_{net} = \frac{C_S}{2} (\Delta - |D_D|) - \min(D_D, 0) \quad (3)$$

(CICE (10), 2.6 web)

$$|D_D| = \text{divu}$$

$$\min(D_D, 0) = \text{divu} < 0 = \text{convergence} = (-)\text{divu}$$

$$R_{net} = 0.125(\Delta - \text{divu}) - ((-)\text{divu})$$

Ratio of mean ridge ice thickness, vrdg , to thickness of ridging ice,

$$h_n = \text{vrdg} / \text{ardg} = T\text{vrdg} \quad (4)$$

is:

$$k_n = \frac{(H_{min} + H_{max})}{(2h_n)}, \quad (5)$$

where $H_{min} = 2h_n$ and $H_{max} = 2\sqrt{H^*h_n}$, with H^* set to 25m, which is a good approximation for MYI, but H^* set to 50 may line up better for FYI approximations.

$$k_{nMY} = \frac{(2h_n + 2\sqrt{25h_n})}{(2h_n)} = 1 + \frac{5}{\sqrt{h_n}} \quad (6)$$

$$k_{nFY} = \frac{(2h_n + 2\sqrt{50h_n})}{(2h_n)} = 1 + \frac{5\sqrt{2}}{\sqrt{h_n}} \quad (7)$$

Figure 31 shows that ridged FYI has a keel-to-sail thickness ratio (H_k/H_s) of 4.46, a keel-to-sail area ratio (A_k/A_s) of 8.0, and an angle of keel repose, α_k , of 26.6° , while MYI has a keel-to-sail ratio of 3.34, a keel-to-sail area ratio of 8.8, and an angle of keel repose of up to 50° (Timco and Burden 1997). These metrics explain that ridged FYI, on average, has a narrower keel that spans less area and is less abrupt when compared to MYI.

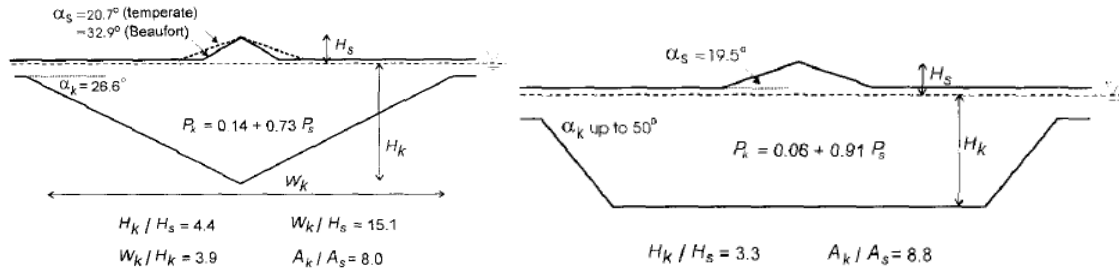


Figure 31 (left) Sketch of “average” FY ridge, and (right) Sketch of “average” MY ridge. Adapted from: Timco and Burden (1997, figures 16, 17).

Table 3. First year and multi-year ice keel thickness compared with ice output variables

First-Year Ice	Multi-Year Ice
$H_{\text{SFY}} + 4.46H_{\text{SFY}} = \text{Tvrdg}$	$H_{\text{SMY}} + 3.34H_{\text{SMY}} = \text{Tvrdg}$
$5.46H_{\text{SFY}} = \text{Tvrdg}$	$4.34H_{\text{SMY}} = \text{Tvrdg}$
$H_{\text{SFY}} = \frac{\text{Tvrdg}}{5.46}$	$H_{\text{SMY}} = \frac{\text{Tvrdg}}{4.34}$
$H_{\text{kFY}} = \frac{4.46 * \text{Tvrdg}}{5.46}$	$H_{\text{kMY}} = \frac{3.34 * \text{Tvrdg}}{4.34}$
$H_{\text{kFY}} = 0.8168 * \text{Tvrdg}_{\text{FY}}$	$H_{\text{kMY}} = 0.7696 * \text{Tvrdg}_{\text{MY}}$

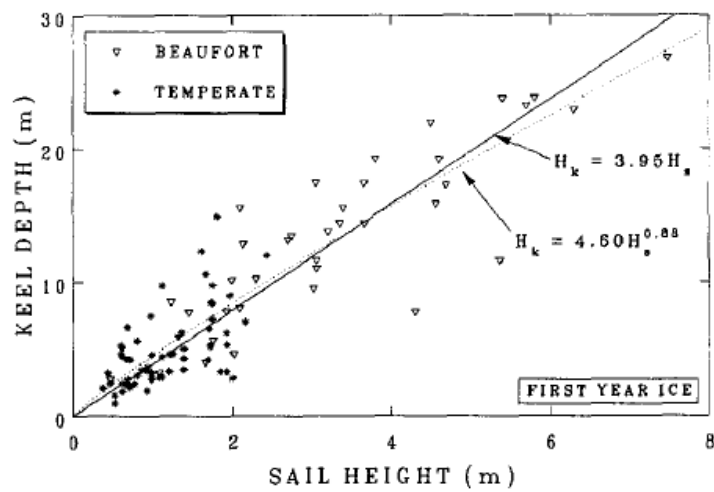


Fig. 3. Keel depth versus sail height for first-year ridges.

Figure 32 Keel depth vs. sail height of FY ridged ice. Source: Timco and Burden (1997, Fig. 3).

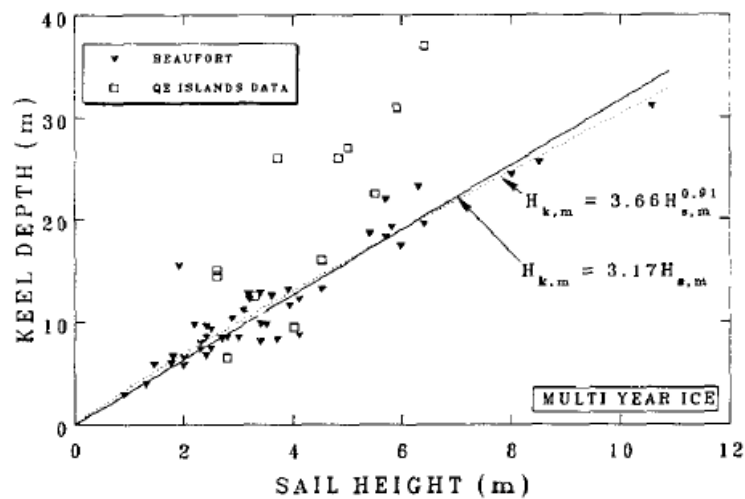


Fig. 12. Keel depth versus sail height for multi-year ridges.

Figure 33 Keel depth vs. sail height of MY ridged ice. Source: Timco and Burden (1997, Fig. 12).

III. U.S. NAVY RELEVANCE

As already stated, the Arctic continues to become more accessible than ever before, which increases international focus on and interest in the region. The People's Republic of China (PRC) has declared itself a "near Arctic nation" and is seeking to increase their influence in the Arctic through scientific studies, resource gathering and investments (Biden Jr. *National Security Strategy*, 2022, 44). Russia has been increasing its Arctic military footprint and infrastructure for over a decade (Biden Jr. *National Security Strategy*, 2022, 44). The United States seeks a "peaceful, stable, prosperous and cooperative Arctic," and to meet these goals intends to invest in Arctic infrastructure, continue to promote freedom of navigation, attempt to mitigate climate change impacts, and encourage private sector investment and use of the natural resources within the Arctic (Biden Jr. *National Security Strategy*, 2022, 44).

Over the last decade the PRC has increased economic, diplomatic, scientific, and military activities within the Arctic circle, often coupling scientific exploration with intelligence and/or resource gathering (Biden Jr. *National Strategy for the Arctic Region*, 2022). It has expanded its icebreaker fleet and has sent People's Liberation Army Navy (PLAN) vessels into the Arctic. The PRC has worked to build ties to Arctic communities and in 2013 sought to gain influence within the region through the award of rights of the Greenland based mineral and metal mine Isua mine project to Chinese based General Nice, a coal and iron ore importing company (BBC 2013), but as of 2021 this license had been revoked due to inactivity at the site (Gronholt-Pedersen 2021). Since 2004, the PRC has operated from a research station on the island of Svalbard, Norway, which they have been allowed access to as signatories of the 1920 Spitsbergen Treaty, to launch scientific exploration missions and to keep an enduring presence in the Arctic (Department of the Army 2021). In 2018 the PRC launched the Polar Silk Road Initiative, building off the Belt and Road Initiative, to increase political ties with northern nations and to subsequently increase the PRC sphere of influence (Figure 34).



Figure 34 Polar Silk Road. Source: Department of the Army (2021).

The Russian Foreign Policy regarding the Arctic mirrors the U.S. rhetoric of seeking peace, stability, and environmental sustainability while reducing threats to national security and traditional livelihood of indigenous Arctic peoples (President of the Russian Federation 2023). They indicate a want to advance the Northern Sea Route, shown in red on Figure 36, as a viable transportation route in order to improve relations and ties between Europe and Asia (President of the Russian Federation 2023). However, Russia also asserts that they will counteract “the unfriendly states’ policy” to militarize the Arctic and limit Russia’s use of sovereign territory (President of the Russian Federation 2023, 21), which they claim far outside of their 200 mile Exclusive Economic Zone (EEZ) as seen in Figure 35 and Figure 37.

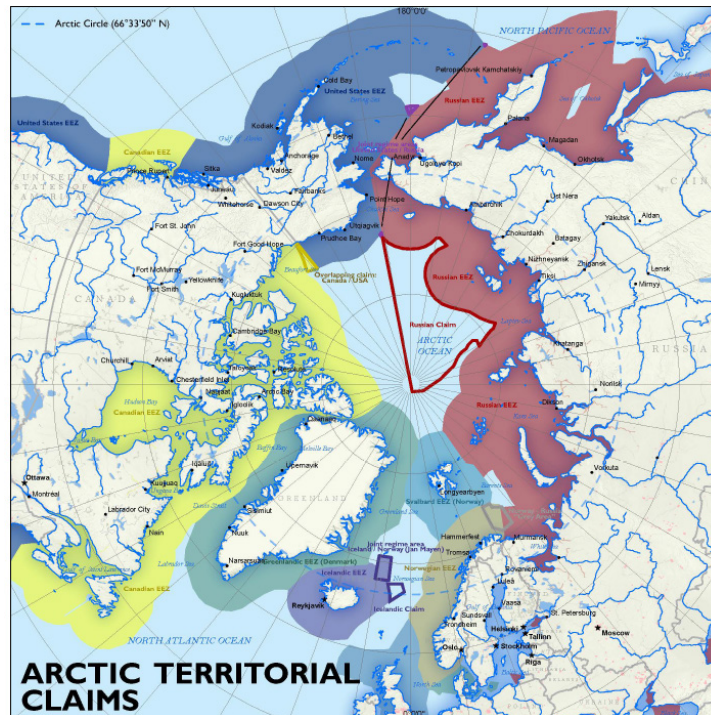


Figure 35 Arctic territorial claims. Source: U.S. Army Training and Doctrine Command G-2 (2020).

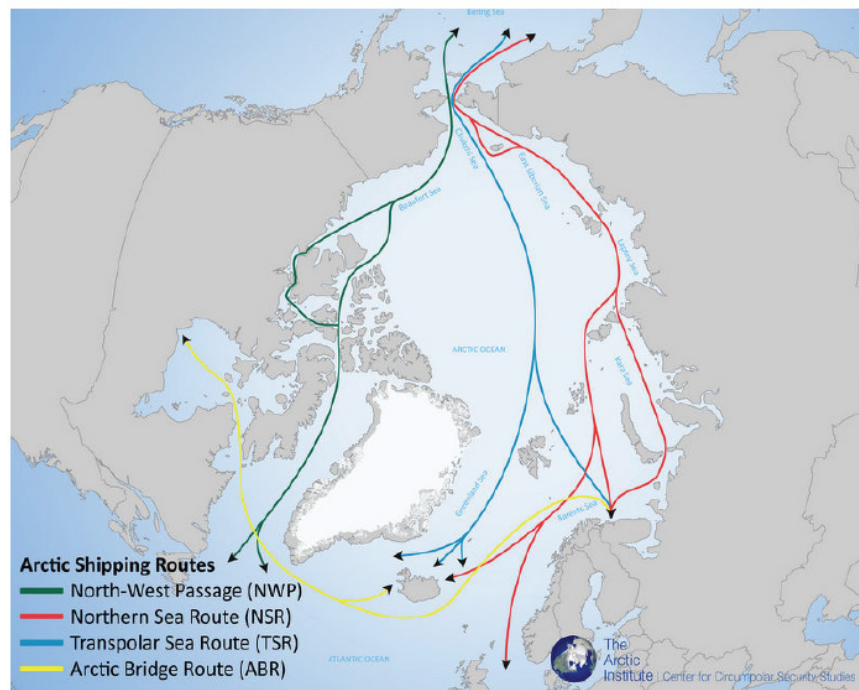


Figure 36 Arctic shipping routes. Source: Rosen and Thuringer (2017, figure 10).



On map: (1) indicates the North Pole, (2) indicates the Lomonosov Ridge, (3) indicates the 200-mile EEZ line, and (4) indicates disputed areas.

Figure 37 Arctic EEZ and Russian additional claimed territory. Source: Rosen and Thuringer (2017, figure 5).

A. U.S. STRATEGIC GUIDANCE

In the past decade Arctic and Near-Arctic Nations have greatly increased their interest and presence in the Arctic Ocean (Figure 35). The National Security Strategy (NSS), National Defense Strategy (NDS), and National Strategy for the Arctic Region (NSAR) published in 2022 emphasize the critical importance of maintaining a stable and peaceful Arctic through increased U.S. Arctic presence and development of policies that will slow and eventually reverse the effects of anthropogenic warming. The NSAR describes its primary objectives as security, climate change and environmental protection, sustainable economic development, and international cooperation and governance. These objectives are intertwined with the principles of working with and alongside Alaska Native Tribes and Communities, deepening relationships with allies and partners, planning for environmental changes to the Arctic and the tyranny of distance, and coordinating with governments, private organizations, academia and others to create and expand an allied

network that is both domestic and international. The purpose of which is to commit to a whole-of-government evidence-based approach that emphasizes communication and collaboration among U.S. government programs, agencies, and departments.

The United States' Navy (USN), Coast Guard (USCG), Airforce (USAF), and Army (USA) have all issued specific guidance on how they intend to increase their Arctic presence in the coming years, with the Marines Corps (USMC) and Space Force (USSF) plans included in the USN and USAF guidance respectively. The Arctic Blueprint 2021, released by the Department of the Navy, expresses how essential it is that the U.S. approach Arctic operation strategy in a unified manor in order to maintain sea control and project naval power alongside partner and allied nations (Department of the Navy 2021). The Joint Forces will leverage current alliances along with new ones, among government agencies and civilian partnerships within the U.S. as well as abroad. The Navy itself must increase Arctic training, knowledge, infrastructure, and operations to be able to show that the U.S. is capable and ready to defend the north (Department of the Navy 2021).

B. CURRENT U.S. CAPABILITIES

Although the United States has greatly increased interest and interaction in the Arctic over the past few years, the June 2018 quote from Secretary of Defense James Mattis, “Certainly America has got to up its game in the Arctic” (Lamothe 2018, 7), still seems to represent the current situation as a similar sentiment is echoed by the Commander of United States Northern Command (NORTHCOM) General Glen D. Vanherck’s statement before the House Armed Services Committee in March of 2023 that “lack of domain awareness, limited timely access to forces that are ready to operate throughout my areas of responsibility, including the Arctic, and a lack of resilient infrastructure enabling the Joint Force to fight in and from the homeland while ensuring forward power projection” (Vanherck 2023) are limiting factors for the NORTHCOM operations. The Joint Services have begun implementing strategic objectives through updates in strategic guidance and direction as well as holding joint exercises in Alaska, Greenland, and Canada. However, there is still a large amount of work to do as the United States Coast Guard is the only U.S. agency with ice breaking capable ships. The USCG has only one heavy and one medium

conventionally powered icebreaker, the USCGC Polar Star and the USCGC Healy, which handle all pathfinding requirements to ensure safe ice transit (Poulin 2023). The U.S. Navy and Coast Guard have recently been enabled to address this shortfall through a joint effort to produce a new generation of Polar Security Cutters, with the first expected to be delivered in 2025 (Padilla and Fleming 2023).

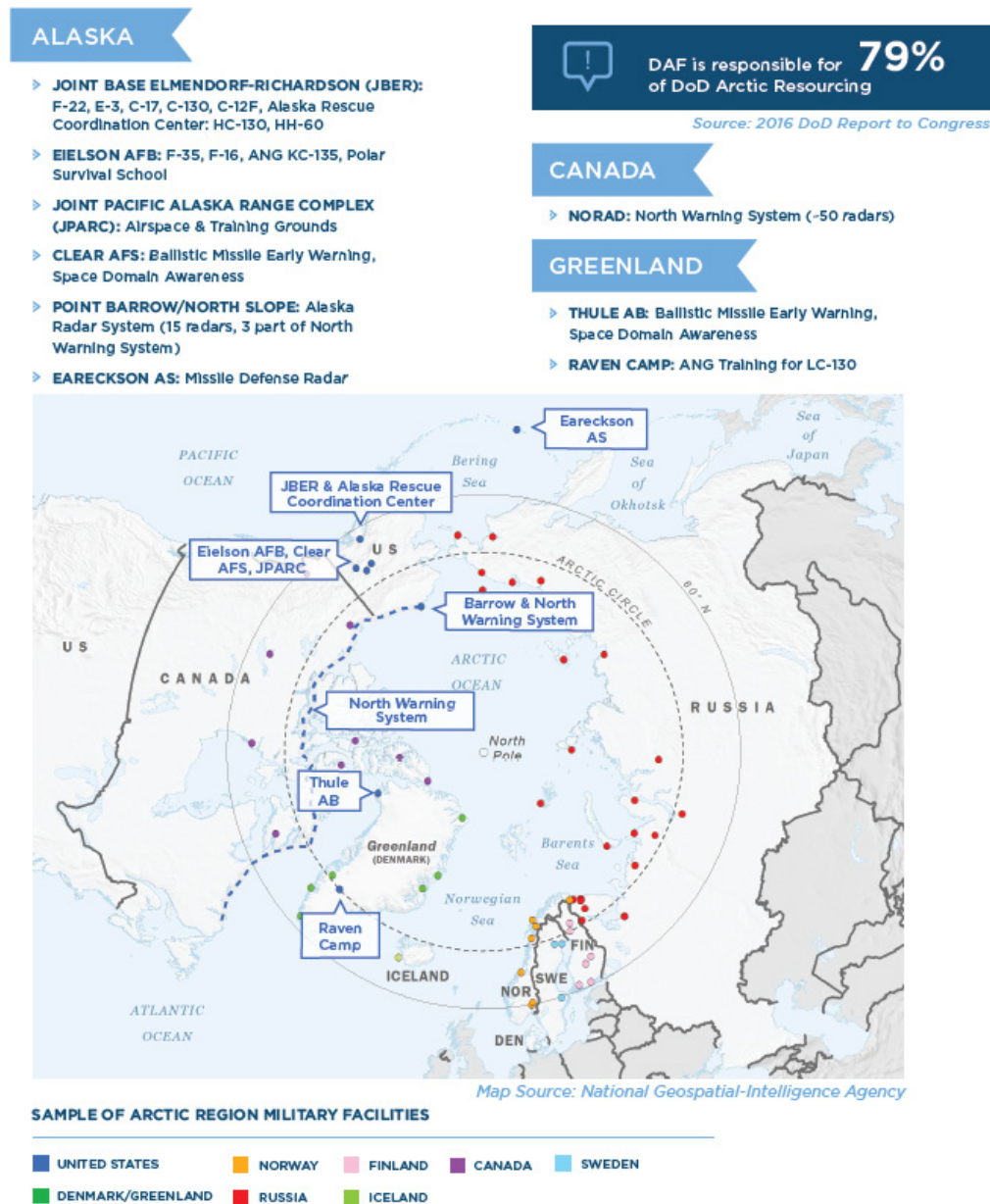


Figure 38 2016 locations of Arctic region military facilities by country ownership. Source: Department of the Air Force (2020).

In 2021 the U.S. Army (USA) released guidance specifically towards Arctic operations, which directs USA to work together with the Joint Force to achieve multi-domain superiority via increased cold weather, mountainous, and high-altitude training, posturing, and equipment capabilities. They intend to achieve this with a fully Army approach consisting of the regular army, national guard, and reserve units (Department of the Army 2021).

The U.S. Space Force (USSF) is directed to work with allies, partners, the Joint Force, and private sector to build and strengthen relationships, develop new technologies, and enhance capabilities and sensors to monitor, and forecast environmental Arctic impacts (Department of the Air Force 2020). The U.S. Air Force (USAF) is also directed to build relationships in the same capacity as USSF, but will focus on platform capability, refueling and air support, as well as exploring mobility options and strategic areas in order to support and protect assets within the Arctic and defend the Arctic airspace (Department of the Air Force 2020).

The U.S. Coast Guard (USCG), as a member of the Department of Homeland Security is tasked with defending the U.S. but also protecting commerce, promoting sovereignty, safety and stewardship in the Arctic. In order to accomplish this, they are tasked to: (1) enhance capability to operate effectively in a dynamic Arctic, (2) strengthen the rules-based order, and (3) innovate and adapt to promote resilience and prosperity (Poulin 2023). They are also tasked with increasing Arctic capability and analysis to include expediting purchase and delivery of Arctic capable and commercially available platforms and assessment of existing and potential future homeports.

C. SUBSURFACE OPERATIONS

Many submersible vessels have upward-looking sonar, lidar, or camera systems that can detect the under-ice topography and measure ice thickness. When those systems fail, an emergency occurs where surfacing quickly is critical, or the submersible must pass through a shallow area knowing where and when large ice keels are likely to form or be present, can help decreasing the risk of operations. If a submarine needs to surface, having a map of ice thickness distribution as well as where convergent events are less likely and

divergent events, i.e., leads, have a high probability of occurrence, a submarine captain could determine if an area nearby would have a lower risk associated surfacing even without fully or properly functioning sensors.

Operating a submarine or deploying an Autonomous Underwater Vehicle/ Unmanned Underwater Vehicle (AUV/UUV) underneath the ice has a considerable risk associated with it. Ice keel depths can be upwards of 15 m (~49 ft) with the deepest being over 25 m (~82 ft) as recorded in the Fram Strait region between 2013 and 2014 (Ekeberg et al. 2015). The depth of the central channel in the eastern Bering Strait, the deepest section on the U.S. side, is 49–55 m (~160 to ~180 ft) with significantly shallower depths toward the Diomed Islands and Alaskan Coast. Downstream in the Chukchi Sea, the area of the eastern shelf between the Herald Bank and Cape Lisburne, Alaska has average depths of about 40–45 m (Hill et al. 1984). With a typical beam on the U.S. attack submarines of approximately 10m (34 ft), passing through this area at the same time as a large ice ridge would have considerable risk, leaving only 5–10 m (16.4–32.8 ft) clearance, amounting to 2.5–5 m (8.2–16.4 ft) above and below the boat if it passed perfectly centered in the water column between the ocean floor and the bottom of the keel (Naval Sea Systems Command 2023).

D. SURFACE OPERATIONS

Ridged ice poses a considerable hazard to shipping traffic in the Arctic, with the U.S. only having one heavy ice breaker, the USCGS Polar Star, which is able to break ice up to 6.4 m (21 ft) thick (Read 2019). As ice ridges / keels are often greater than 7 m deep, they pose a great navigational obstacle even for the most capable ship the U.S. has available at present.

Figure 39 shows the projection of Arctic passage availability times as well as the number of vessels expected to pass through the listed routes, with the Northern Sea Route (NSR) anticipated to increase traffic by a factor of ten and the Bering Strait to double in traffic. As the Arctic warms, the Arctic navigation by civilian and military groups becomes more attainable. However, this study shows that even though the Arctic sea ice is thinning, that does not necessarily make it safer to operate. It makes it more unpredictable. In

addition to ridging hazards, the more ocean surface exposure, the more ocean-air interaction that will occur. As it was shown in Figure 16, with declining sea ice area there will be more air-sea heat exchange, especially in winter months due to the greatest temperature gradient between surface air temperature of the ocean surface near freezing temperature of $\sim 1.8^{\circ}\text{C}$. These increased air-sea heat fluxes can cause navigational hazards like fog, as well as other risks associated with ice accretion on structures.

The orientation of ice ridges in relation to the vessel route also matters. A ship will try to navigate within or parallel to a lead, instead of perpendicular to the lead orientation, as it increases the risk of encountering very thick ice due to LKFs, which could be similar to running aground, if the ridged ice is thick enough.

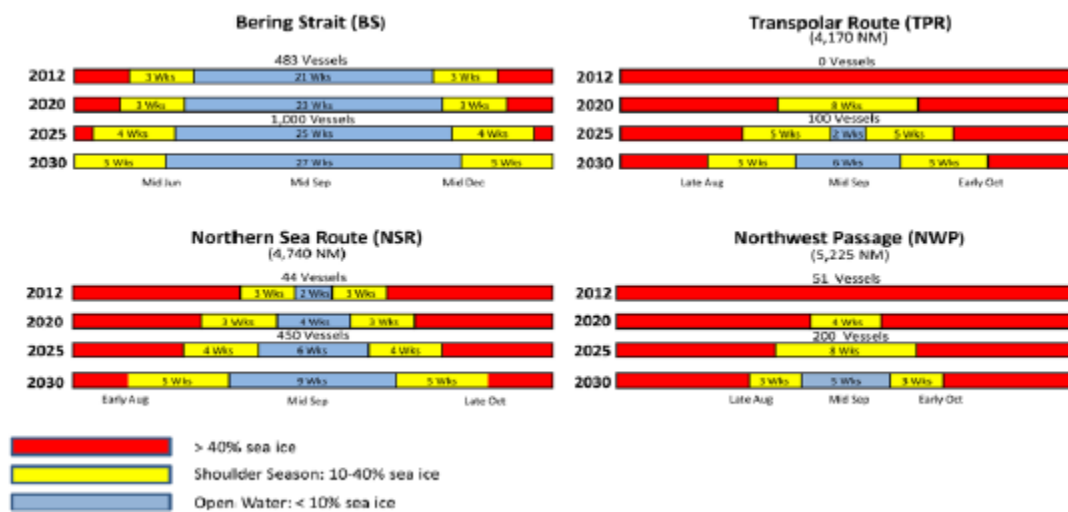


Figure 39 2014 Projection of timelines for Arctic navigation through key routes. Source: Task Force Climate Change (2014).

The thickness of pressure ridges is not the only hazardous attribute associated with them. The orientation of the ridge in relation to the vessel attempting to navigate it also matters. Ridges typically form as a linear kinematic feature (LKF), which is a narrow band of continuous or near-continuous ridging events. Effectively these are formed when the edge of a large mass of ice collides with the edge of another mass. If a ship passes close to but parallel to the LKF axis, they may encounter thicker ice, but will gradually move

through it. If the ship encounters the LKF in a perpendicular orientation, it could be similar to running aground, if the ridged ice is thick enough.

E. ICE EXERCISES

The Ice Exercise (ICEX) is a U.S. Navy Arctic Submarine Lab (ASL) led joint and combined effort that is designed to research, test, and evaluate the capabilities of the U.S. Joint Forces and scientists alongside civilian and military teams from allied nations. As of the latest ICEX in 2022, the United States has held 98 ICEX in the Arctic (Naval News Staff 2022). The planning phase involves finding an ice floe suitable to build an ice camp and runway that will not break apart during the exercise. Analyzing the age, thickness, and previous deformations of a floe is critical in determining its suitability. From the camp, the surface teams conduct detection testing, area analysis, and sensor testing and calibrations, both above the ice and in coordination with participating submarines below. As the global interest in the Arctic increases due to more of it being accessible for longer periods of the year, these exercises become more and more critical in establishing the U.S. native living knowledge of operating in the Arctic environment.

One of the unique ICEX cases was the Scientific Ice Expeditions (SCICEX) program in the 1990s, which demonstrated the benefits of submarine use to study Arctic marine science in terms of “physical, chemical, and biological oceanography, sea ice geophysics, and marine geology and geophysics” (Rothrock et al. 1999, i). SCICEX combined military operations with scientific data collection and analysis by pairing submariners with scientists onboard, and after collection, working together to make data releasable to the scientific community and general. The exercises have gathered hydrographic data through the water column such as subsurface currents, temperatures, and salinities, biological and chemical tracer information such as CO₂, methane (MH₄), different radioactive isotopes, and chlorophyll. SIT was measured and compared to satellite observations of the same location to see satellite measurement discrepancies using the upward-looking submarine sonar. Additional on-board sensors were used to record ice and ocean acoustic and optical properties, as well as bathymetric and gravitational data (Rothrock et al. 1999).

IV. DATA AND METHODS

Data from daily RASM 9-km numerical model output, reanalysis case R2200rGcriv03f, from 1980 through 2017 is analyzed in the following section. Results are broken into an Arctic wide analysis, a Wester Arctic analysis, and 9 case study grid points located throughout the area. Due to the annual variation of Arctic sea ice, the data analysis presented here is broken into two temporal scenarios: (1) year-round, where overall climatic trends are captured and by, (2) isolating the months of January, February, and March (JFM) to capture the behavior of sea ice deformations when the ice edge is largely outside of the central Arctic basin. Decadal trends were analyzed by doing a simple trendline analysis for the data set, of rise over run, in order to find the slope of the timeseries for each variable studied, 13,870 days for the full dataset and 3420 days for the JFM dataset. The primary variables analyzed throughout this discussion are ice convergence ((-)divu) and divergence ((+)divu), in units of percent change per day, aggregated ice area (aice), in units of percent per 100, mean grid cell ice thickness (hi), in units of meters, ridged ice thickness (Tvr dg), in units of meters, and ice drift speed (vtot), in units of meters per second.

A. RASM OUTPUT

The primary data used for this study has been the RASM/CICE output fields from the ice-ocean RASM configuration forced with the Japanese 55-year Reanalyses (JRA55; Onogi et al. 2007). The following fields have been extracted and used for analyses: ice area aggregate (aice_d), ice area categories (aicen_d), level ice area fraction (alvl_d), ridged ice area fraction (ardg), strain rate divergence (divu_d), mean grid cell ice thickness (hi_d), sea surface temperature (sst_d), ice drift x-velocity (uvel_d), ice drift y-velocity (vvel_d), mean level ice volume (vlvl_d), mean ridged ice thickness (vr dg_d), and mean ice thickness categories (vicen_d). The “_d” notation indicates that they are “daily” model output values. Since this study only extracted daily values, the “_d” is dropped from the notation hereafter.

Ice velocity (x) and ice velocity (y) were used to create ice drift speed (ispd):

$$ispd = \sqrt{(uvel)^2 + (vvel)^2} \quad (8)$$

Expanding off of equations for ridged ice thickness (Roberts et al. 2019; Timco and Burden 1997; CICE Consortium 2023a) and relating them to the equations in RASM for handling sea ice, we can say that $H_k + H_s = \text{Maximum ridge thickness}$ which translates to the RASM variable for mean ridged ice thickness divided by fractional area of ridged ice in a grid cell $\left(\frac{vrdg}{ardg}\right)$, which will be labeled “Tvrdg” for “Total Ridged Ice Thickness.” Using the keel-to-sail thickness relationships described by Timco and Burden (1997), shows that FYI keels down farther than it ridges up and that it deforms more readily than MYI, which has a lower keel-to-sail ratio (Table 3). Although there is not a dramatic difference between keel-to-sail ratios in FY and MYI, I hypothesize that the most dangerous ridges, dangerous due to factors of rapid growth, depth, and keel angle or sharpness, will form from ice convergence between different ice thickness categories.

Mean ridged ice volume per unit area (vrdg) and ridged ice area fraction (ardg) were used to create total ridged ice thickness (Tvrdg):

$$Tvrdg = \frac{vrdg}{ardg} \quad (9)$$

Mean level ice thickness (vlvl), level ice area fraction (alvl), mean ridged ice volume (vrdg) and ridged ice area fraction (ardg) were compared to mean grid cell ice thickness (hi) with ice area aggregate (aice), and mean ice thickness categories (vicen) with ice area categories (aicen) to confirm that, with n indicating category number. In models using CICE, ice can be broken down into five or more main categories separated by upper and lower boundary thicknesses (CICE Consortium 2023b).

$$\frac{vrdg + vlvl}{ardg + alvl} = \frac{hi}{aice} = \sum_{n=1}^5 \frac{vicen(n)}{aicen(n)} \quad (10)$$

Strain rate divergence (divu) was separated into negative, (-)divu, and positive, (+)divu, values. Hereafter, (-)divu is referred to as “convergence” and (+)divu is referred

to as “divergence,” which is important to note, as many papers and model output notations refer to both convergence and divergence as just one term, divergence.

Each variable was assessed in terms of daily mean, monthly mean, and annual mean per single grid cell and plotted geographically. Daily mean magnitude for each variable over 38 years is calculated by extracting daily RASM output netCDF files. These variables are initially stored in yearly aggregated arrays with 365 timesteps. Each year array is then broken up by month, creating 456 individual arrays, each with 28 to 31 timesteps, depending on the month. The monthly array timesteps are then added together and divided by month length, creating 456 individual arrays with 1 timestep each, depicting the mean value for each month. Then the monthly averaged arrays are aggregated by year and added together, creating 38 arrays with 12 timesteps each. Those 38 arrays are added together to create 1 array with 456 timesteps. Finally, the array containing 456 months of daily mean is divided by 456 to create 1 array with 1 timestep showing the total mean value of all 13,870 days.

Yearly mean magnitude for each variable over 38 years is calculated by extracting daily RASM output netCDF files. These variables are initially stored in yearly aggregated arrays with 365 timesteps. Each year array is then broken up by month, creating 456 individual arrays, each with 28 to 31 timesteps, depending on the month. The monthly array timesteps are then added together and divided by month length, creating 456 individual arrays with 1 timestep each, depicting the mean value for each month. Then the monthly averaged arrays are aggregated by year and added together, creating 38 arrays with 12 timesteps each. Those 38 arrays’ 12 timesteps are added together and divided by 12 to depict the yearly mean values for each year from 1980 to 2017. The yearly mean for 1980 of each variable is subtracted from the 2017 yearly mean, to show the snapshot difference of 2017–1980, to see if drastic changes had occurred. For the analysis of the winter months of January, February, and March (JFM), the same calculations were used but replacing 456 total months with 114, 12 months annually with 3, and 13,870 total days with 3,420. JFM also had linear regression trendline analysis completed for each grid cell and subsequently visualized on geographic projections in both the Central and Western Arctic areas.

An 11 by 8 grid cell area, called “ICEX,” located approximately 200 nautical miles from the coast of Prudhoe Bay, AK. The variables assessed within this area are averaged over the 88 grid cells it contains to produce time series analysis and extreme (outside of 1 standard deviation) values, where the data is fitted with a least squares approximation as well as plotted alongside a moving mean of 6 months to help visualize trends. An additional 8 individual grid points across the Central and Western Arctic were assessed to see how different locations differed in their trend analysis.

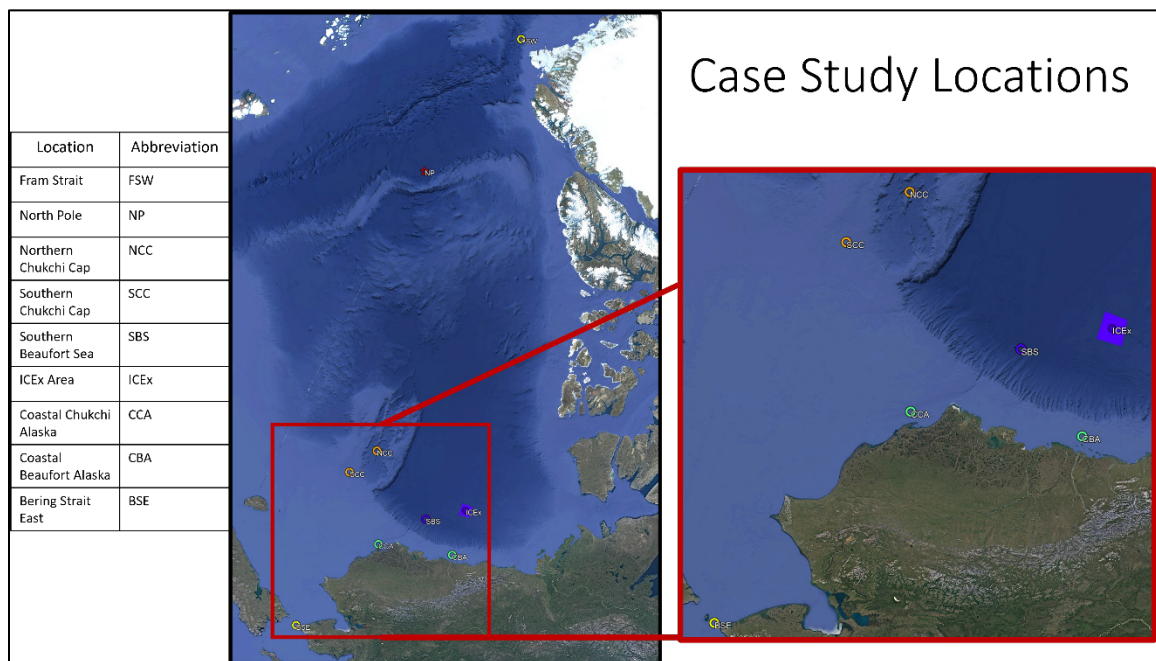


Figure 40 Case study locations with (left) names and abbreviations, (center) locations in the Central Arctic, and (right) zoomed locations in the Western Arctic

V. RESULTS AND DISCUSSION

A. CENTRAL ARCTIC

For the purpose of this research, the Central Arctic is defined here as the region north of Bering Strait and the Canadian Arctic Archipelago, and down to 80°N latitude between Greenland and Severnaya Zemlya.

Figure 42 shows the 38-year climatological mean of RASM monthly ice area with the respective sea ice edge (SIE) of 15% SIA from satellite observations. It is clear that on average both RASM realistically depicts the mean annual cycle of the total ice area expanding from October to March and contracting from April to September, giving an average ice area maximum in March and an ice area minimum in September, as in observations. Figure 42, Figure 43, Figure 55, and Figure 56 show that RASM does an overall good job handling ice area and ice edge, with RASM's error equal to approximately the error in satellite observational biases, ~1.3 million km², caused by translucency of certain types of new ice, like dark nilas, grease ice, and frazil ice or slush under windy conditions within the Marginal Ice Zone (MIZ) (Zygmuntowska et al. 2013). In terms of biases, there is one area along the east Greenland shelf and slope where RASM consistently overestimates SIA in winter and underestimates it in summer. The cause of this is likely an insufficient recirculation of warm Atlantic water within the East Greenland Current (EGC) in winter and an underestimation of sea ice export via Fram Strait along the Greenland shelf in summer. Another area that RASM underestimates SIA is in the Western Arctic/Beaufort Sea, which could be caused by a misrepresentation of the flow and mixing of warm Pacific Summer Water (PSW) in the Western Arctic.

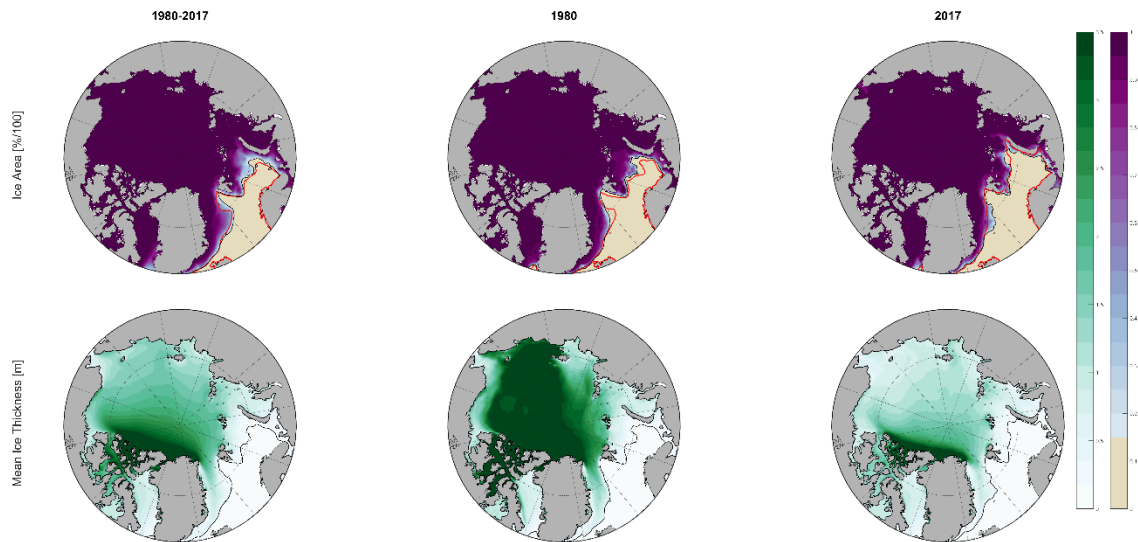
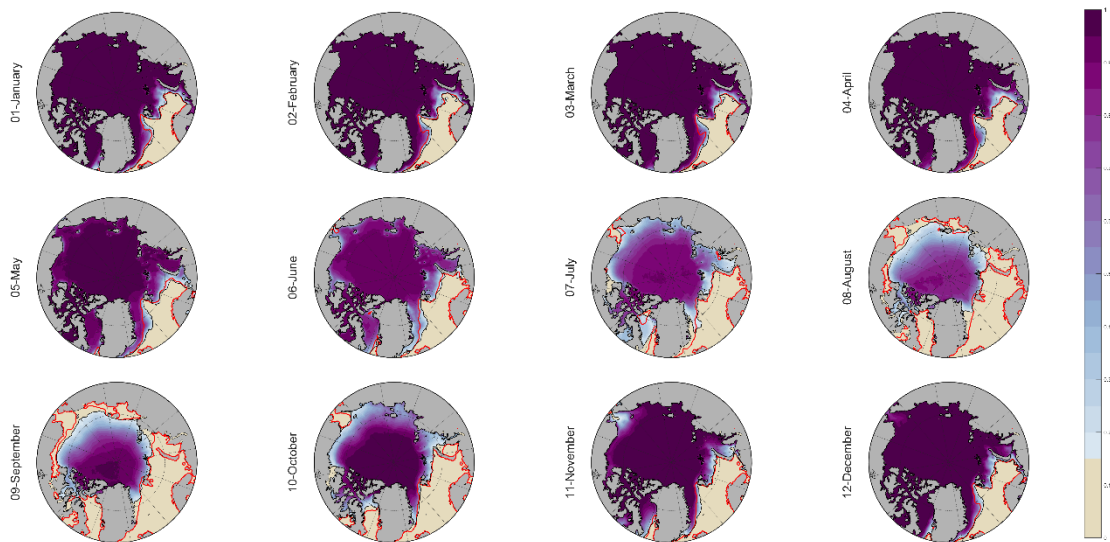


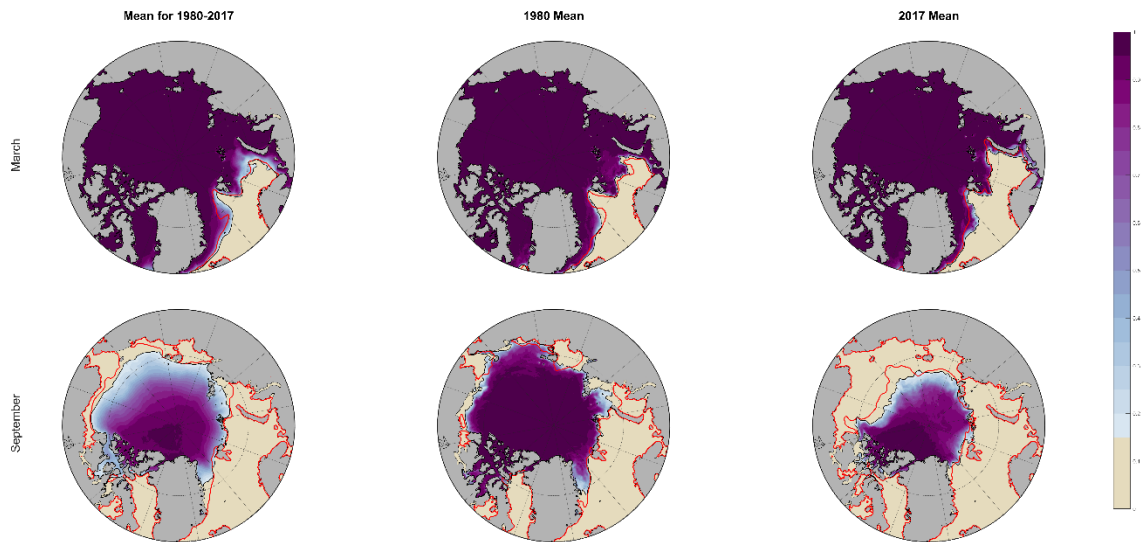
Figure 41 RASM (top row) annually averaged ice area and (bottom row) annually averaged mean ice thickness showing (left) 38-year mean, (center) 1980 daily average, and (right) 2017 daily average

1. Ice Area



Units in $\%100^{-1}$. Black line indicates RASM Model Ice Area Edge, defined by grid cell with 15% ice area coverage. Red line indicates the observed Near-Real-Time NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration (<https://nsidc.org/data/g10016>)

Figure 42 Ice area fraction: Monthly climatology, for the full dataset (38 years) in the Central Arctic



Units in $\%100^{-1}$. Black line indicates RASM Model Ice Area Edge, defined by grid cell with 15% ice area coverage. Red line indicates the observed Near-Real-Time NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration (<https://nsidc.org/data/g10016>).

Figure 43 Ice area fraction: Comparison of March and September (left) long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Central Arctic

The differences in maximum and minimum seasonal ice area are shown in Figure 43. The months of March and September were chosen as common representants of maximum and minimum SIA. While September is consistent with minimum SIA across the RASM simulation, the selection March for maximum SIA is also justified based on the RASM temporal melt/freeze periods described in the analysis of Figure 42, and based on trendline analysis showing that although in the 1980s the ocean would continue freezing through April, in recent years it is more likely to have reached its ice maximum in March (Figure 44 and Figure 45). The RASM SIA in March seems to be similar between 2017 and 1980, with the exception of the Nordic and Barents Seas. This 2-dimensional information by itself however is misleading, as we will see in Figure 47 that mean winter SIT has dramatically declined over 38 years. The RASM SIA in September shows a drastic decline between 1980 and 2017, in agreement with observations.

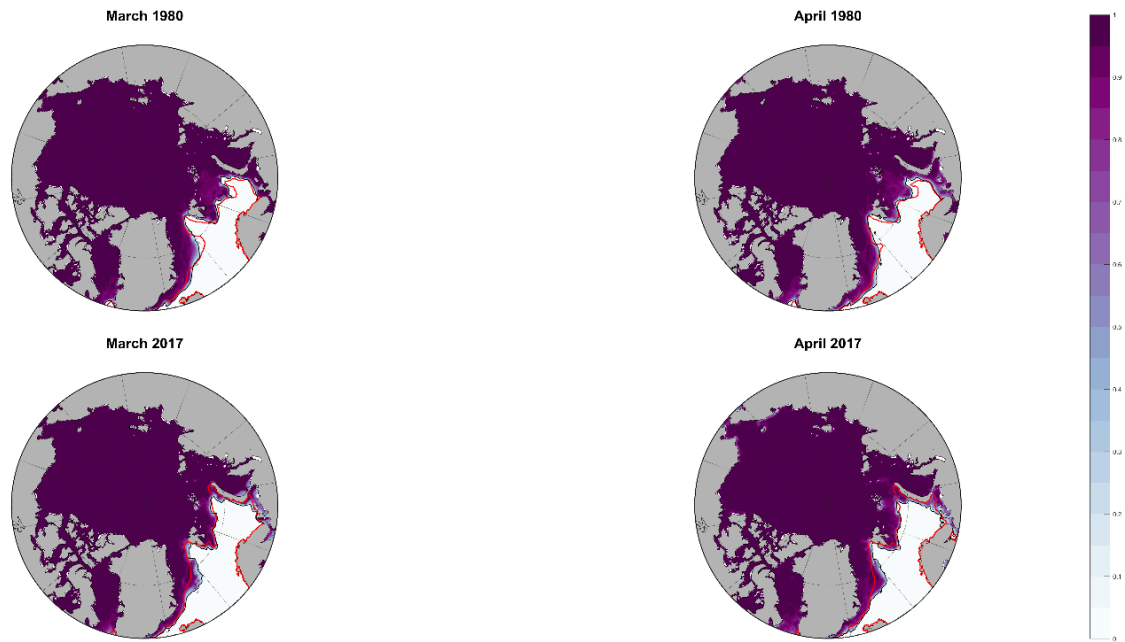


Figure 44 Comparison of ice area between March and April of 1980 and 2017 – Central Arctic

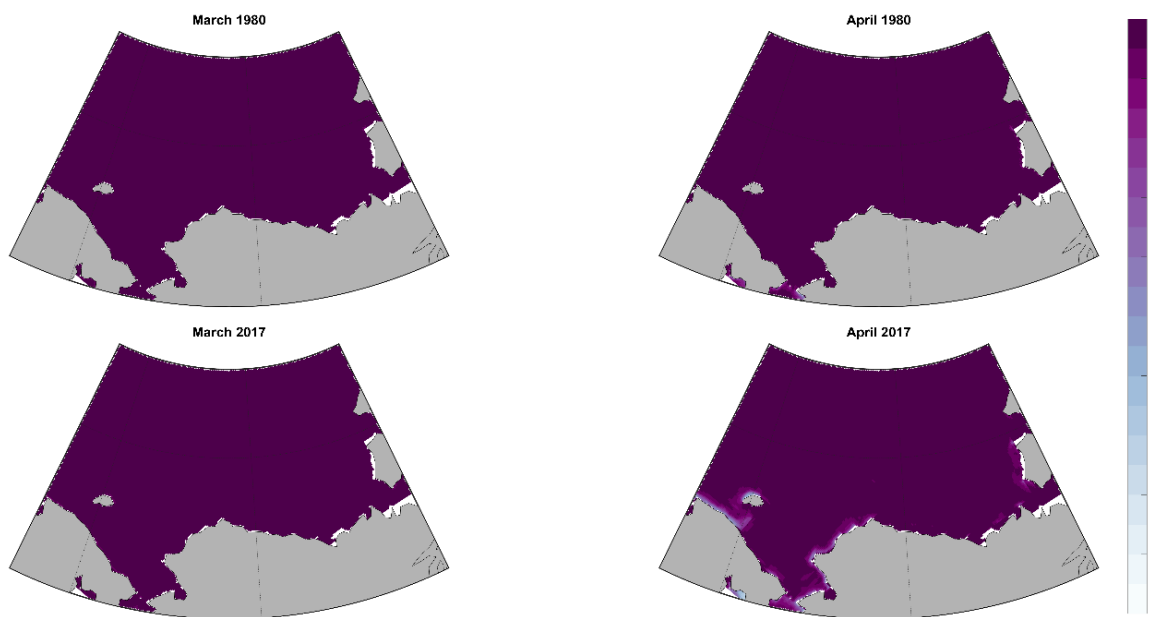


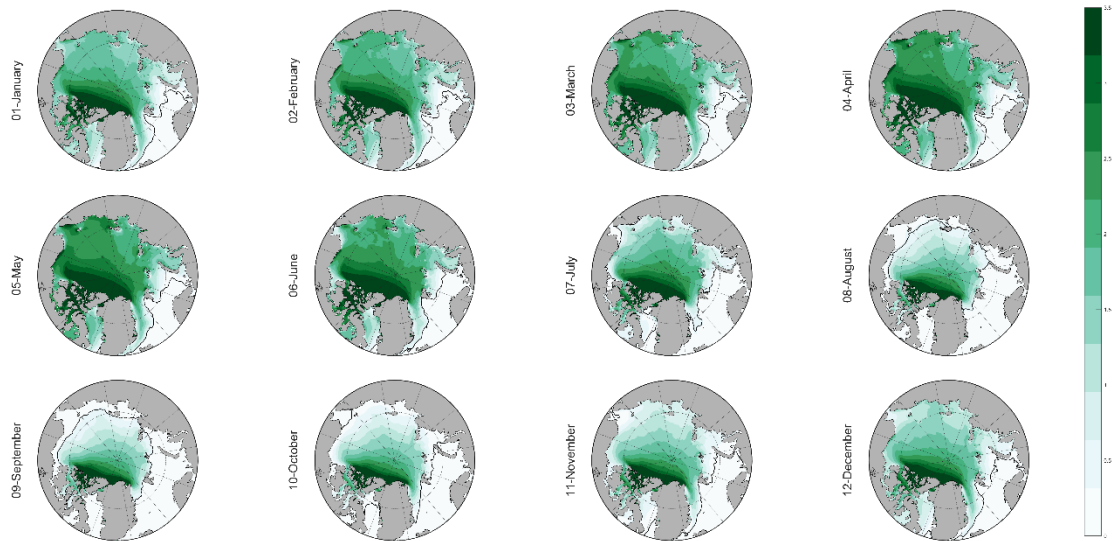
Figure 45 Comparison of ice area between March and April of 1980 and 2017 – Western Arctic

September is consistent with minimum ice levels across the RASM simulation. The winter freeze up of ice area during March seems to be similar in 2017 as it was in 1980, with the exception of the Nordic and Barents Seas in the Eastern Arctic. This information by itself however is misleading as Figure 43 also shows the drastic decrease in ice area in September between 1980 and 2017, and as we will see in Figure 47, which shows how dramatically mean sea ice thickness has declined over 38 years.

2. Ice Thickness

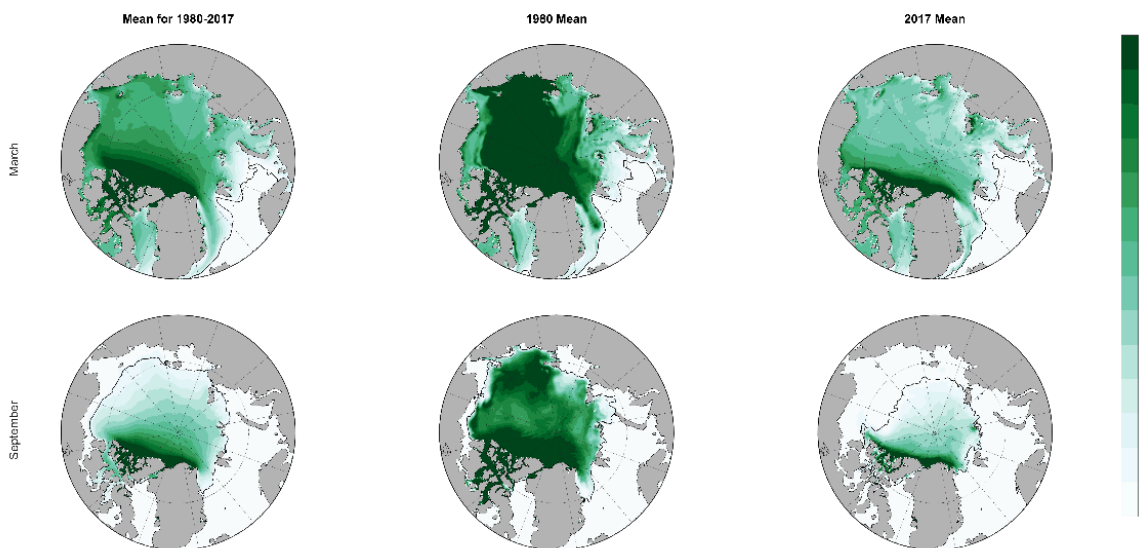
Mean grid cell SIT is analyzed to examine the RASM sea ice thickness distribution for comparison with observationally derived SIT distribution. According to Figure 46, the thickest sea ice is north of the Canadian Archipelago and Greenland, with a tongue of thicker ice extending clockwise from the Canadian Archipelago into the Beaufort Sea between January to June. This extension of thicker sea ice is primarily caused by the advection of ice along the Beaufort Gyre, that historically sets up over the Beaufort Sea in the Canada Basin in response to the persistent cold season high-pressure system, the Beaufort High. Figure 46 shows the monthly climatology of mean ice thickness for 38 years with a similar variability in ice growth and melt over the annual cycle as shown for SIA in Figure 42. However, the latter also indicates the average location of thick MYI.

Figure 47 shows the drastic decline in overall ice thickness in the Arctic from 1980 to 2017. It also shows that September 1980 mean ice thickness is thicker and more widespread across the Arctic than in March of 2017. As of 2017, the only place in the Arctic that consistently has MYI is in and around the CAA.



Units in *m*. Limits from 0 to >3.5m). The black line depicts the RASM ice area at 15% grid cell coverage for the same period.

Figure 46 Mean ice thickness: Monthly climatology, for the full dataset (38 years) in the Central Arctic



Units in *m*. Limits from 0 to >3.5m). The black line depicts the RASM ice area at 15% grid cell coverage for the same period.

Figure 47 Mean ice thickness: Comparison of March and September (left) long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Central Arctic

Ridged ice thickness, when compared to mean ice thickness, shows a more contrasting depiction of the advection of thick, ridged ice from the Northern Canadian Archipelago through the Beaufort Sea, especially between February and April. Understanding how the ridged ice is advected around is critical for the interpretation of measurements and model results and for prediction of navigational hazards associated with pressure ridges. Figure 48 shows the monthly mean distribution and thickness of ridged ice, averaged over 38 years, which depicts the average magnitude and distribution of ridged ice. Figure 49 shows comparable declining trend in ridged ice thickness as we saw in mean ice thickness. However, we can notice a northward shift in the position of advected ridged ice, from primarily along the Southern Beaufort Sea in 1980 to further north, right through the trans-polar navigation route in 2017 (Figure 49). Figure 50 is shown for the direct comparison of average mean ice thickness and ridged ice thickness between 1980 and 2017. This is a side-by-side comparison is used to show that thicker ridged ice does not necessarily correspond to areas with large mean ice thickness, although they do oftentimes overlap.

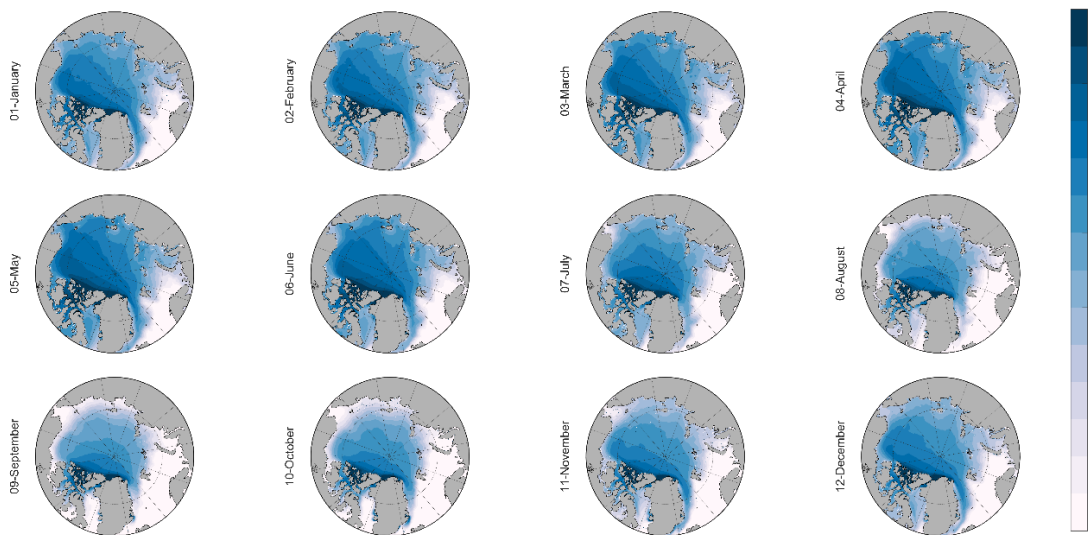


Figure 48 Ridged ice thickness: Monthly climatology, for the full dataset (38 years) in the Central Arctic. Units in *m*.

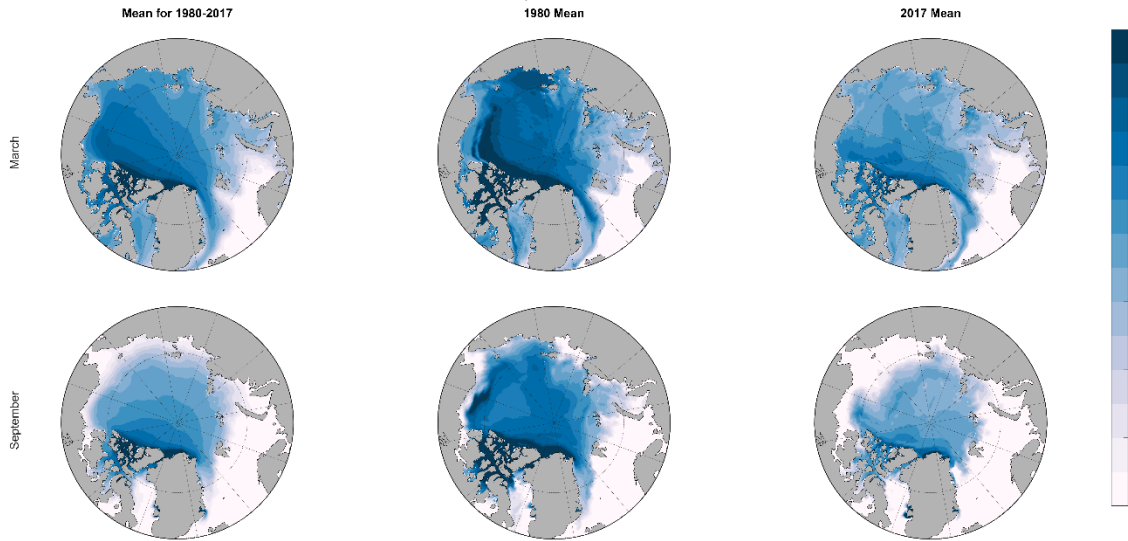


Figure 49 Ridged ice thickness: Comparison of March and September (left) long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Central Arctic. Units in *m*.

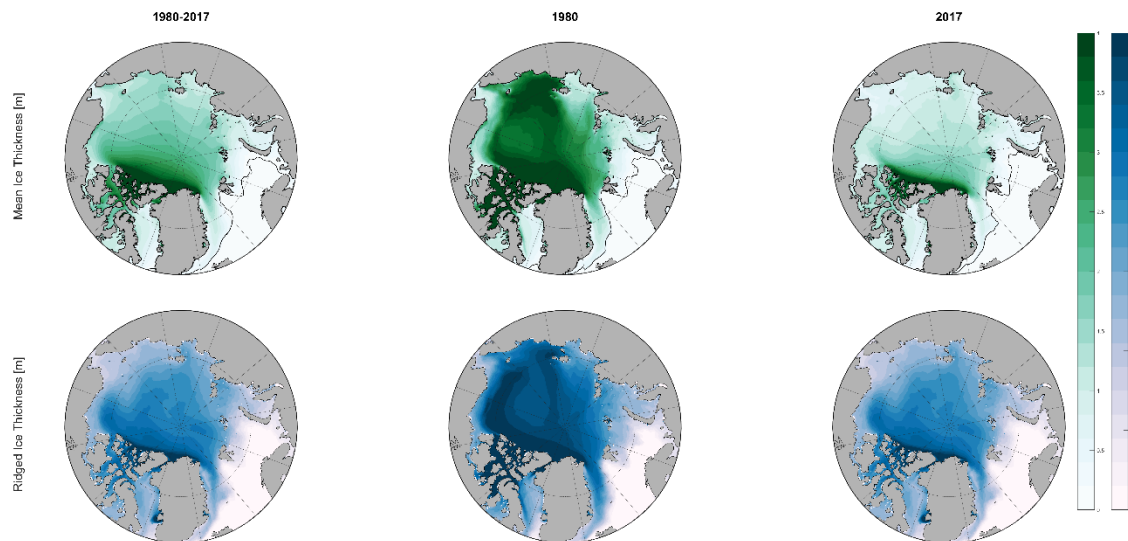


Figure 50 Comparison of mean ice thickness and ridged ice thickness long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Central Arctic. Units in *m*.

3. Ice Drift Speed

Ice Drift Speed corresponds with ice thickness, with Figure 51 corresponds to that of SIT (Figure 46), depicting increasing speeds as the melt season begins between April and June and continue to increase throughout the Central Arctic through November. As the ice floes weaken and begin to break up they are more easily impacted by atmospheric forcing and with decreased ice cover there is an increase in ocean-atmospheric boundary interaction which can continue to break up the ice as sea state becomes a factor.

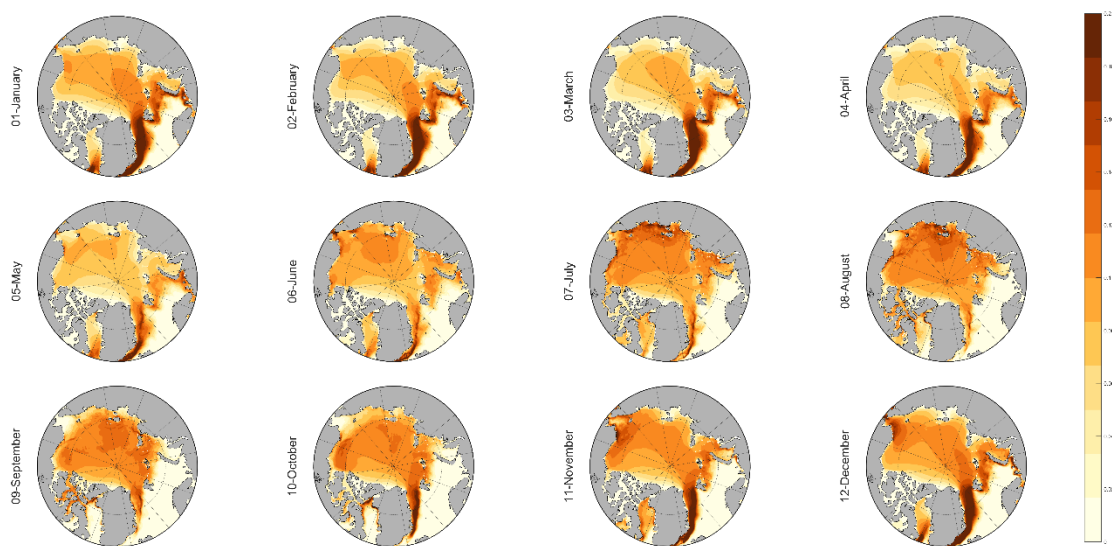


Figure 51 Ice drift speed: Monthly climatology, for the full dataset (38 years) in the Central Arctic. Units in ms^{-1} .

4. Convergence and Divergence

Convergence is primarily seen within and near the marginal ice zone and near shore and increases probability of occurrence and magnitude as the ice melts throughout the year (Figure 52). The convergence shown directly along the shore may be an artifact of the RASM case utilized in this study, as it does not fully account for the physics for “fast-ice,” ice that extends from surface to sea floor, and treats it as non-anchored ice, thereby causing differences in flow near the coast and over shallow shelves. More research is underway to understand the differences in and impact of RASM cases with the fast-ice parameterization

enabled compared to the fast-ice disabled. As the Arctic has warmed and the marginal ice edge (MIE) retreat northward, especially in the Western Arctic, we see that convergence follows (Figure 53). However, as convergence retreats northward the area of occurrence greatly increases in width expanding with the MIZ from the continental shelf in 1980 to practically the entire northern Arctic in September of 2017, except for a small area around the north pole and extending to the Canadian Arctic Archipelago (CAA). This relates to the overall surface circulation around the North Pole (Figure 13) and the advection of warm Atlantic and Pacific waters as well as MYI. There is also similar trends in divergence as there are in convergence across the Central Arctic (Figure 54). Apart from still having year-round thicker ice, as of 2017, the location of the Lomonosov Ridge and its influence on the intermediate water currents also likely dictates part of the surface flow pattern as it either diverts the intermediate waters entirely or causes buoyant lifting, known as ageostrophic advection, along the ridge, which decreases water column thickness and therefore decreases vorticity.

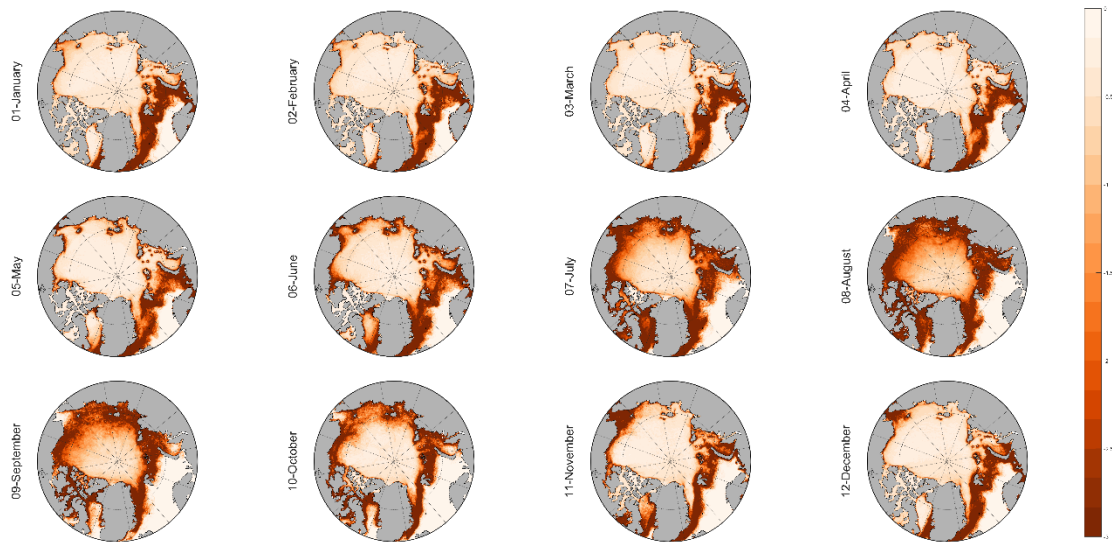


Figure 52 Convergence: Monthly climatology, for the full dataset (38 years) in the Central Arctic. Units in $\% * day^{-1}$.

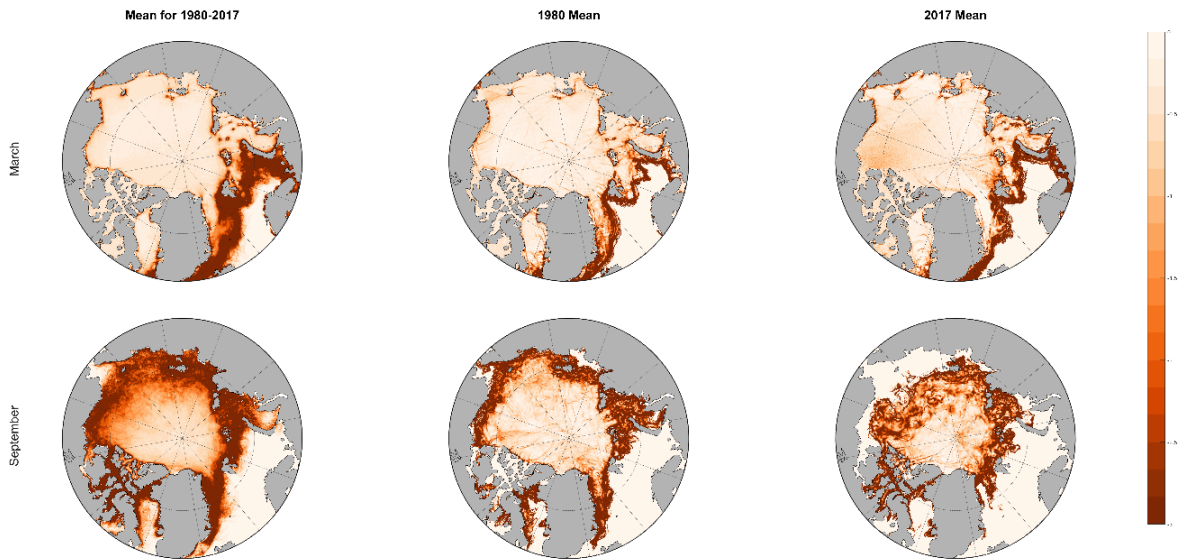


Figure 53 Convergence: Comparison of March and September (left) long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Central Arctic. Units in $\%day^{-1}$.

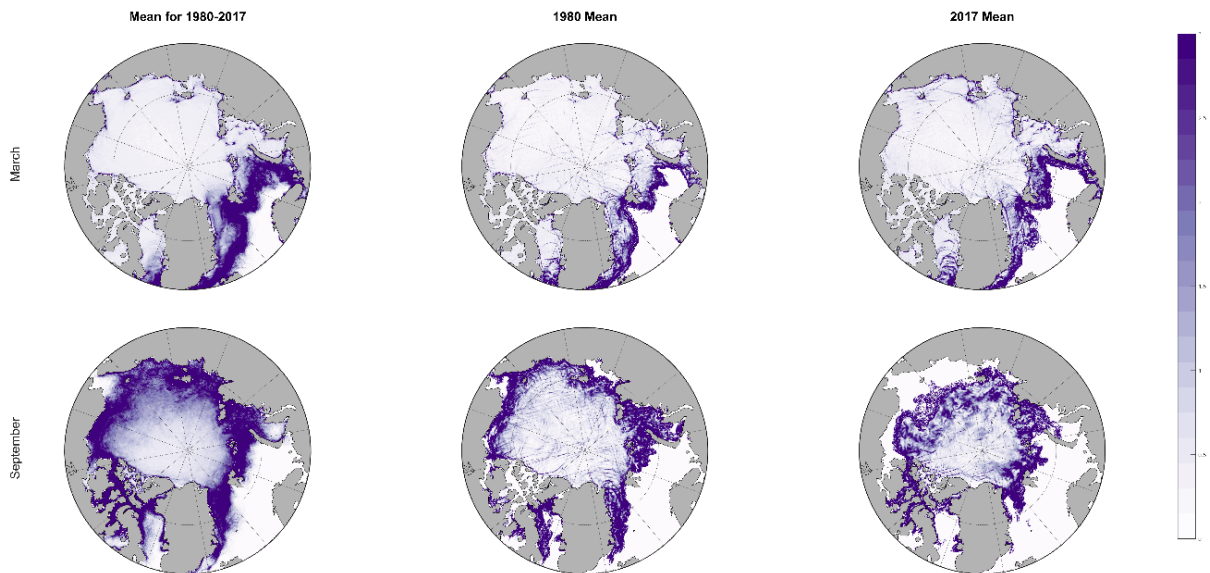


Figure 54 Divergence: Comparison of March and September (left) long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Central Arctic. Units in $\%day^{-1}$.

Focusing on central Arctic trends and analysis from the Bering Strait in the west to the Fram Strait, there are clear decreases in overall ice area and ice thickness (Figure 41),

while total ice drift speed, divergence, and convergence have all increased significantly and greatly expanded or modified the area where extreme value occurrence takes place. Specifically, we see that areas with a decreasing trend of SIT have a positive correlation to divergence, convergence, and ice drift speed. All these variables' trends increase in the marginal ice zone, which has grown substantially in size over the past several decades. The locations of increased convergence/divergence occurrences have moved from primarily occurring over the continental shelves in the 1980s to throughout the Beaufort Sea, North of Svalbard, and with greatly increased presence in the Eurasian and Southern Makarov Basins. Where historically, the chances of pressure ridge formation were low, now have a much higher probability and cover a much greater range of area, increasing the unpredictability. We start with the long-time mean distribution of SIA and SIT in the Central Arctic, with the annual means at the beginning and end of the RASM 1980–2017 simulation comparing changes over the 38-year period (Figure 41). While the annual SIA is nearly the same in all 3 panels, SIT shows a considerable decrease from 1980 to 2017.

B. WESTERN ARCTIC

In the Western Arctic region simple differences between 2017 variables and 1980 variables were done to show the direct changes from the start to end of this dataset. Although similar trends to the pan-Arctic approach were noticed, the resolution of mean data output, which, due to being taken from a smaller area with fewer grid points, becomes less smoothed out and able to show finer, more resolved, features and trends. It can be seen in the yearly data that overall convergence and divergence have an increasing trend in magnitude and probability of occurrence, however, they have a decreasing trend where ice drift speed also has decreased.

1. Ice Area

Similar to the discussion of results for the Central Arctic, Figure 55 shows a SIA maximum in March and minimum in September, while Figure 56 shows extreme loss of area ice extent between September of 1980 and 2017. However, we have an average freeze that covers the entire Western Arctic sea surface area by January with melt not observed until April. Clearly JFM are the best months to model how ice moves within ice-pack as

opposed to free-drift as the Western Arctic does not change ice concentration between these three months. RASM performs well, but has a larger error in the Western Arctic, possibly due to a combination of warm Pacific waters entering the Beaufort Sea via the Bering Strait, and the storing of warm, salty Atlantic waters underneath the surface mixed layer, which can cause ice melt rapidly if cyclonic atmospheric circulations interact with the ice-ocean boundary.

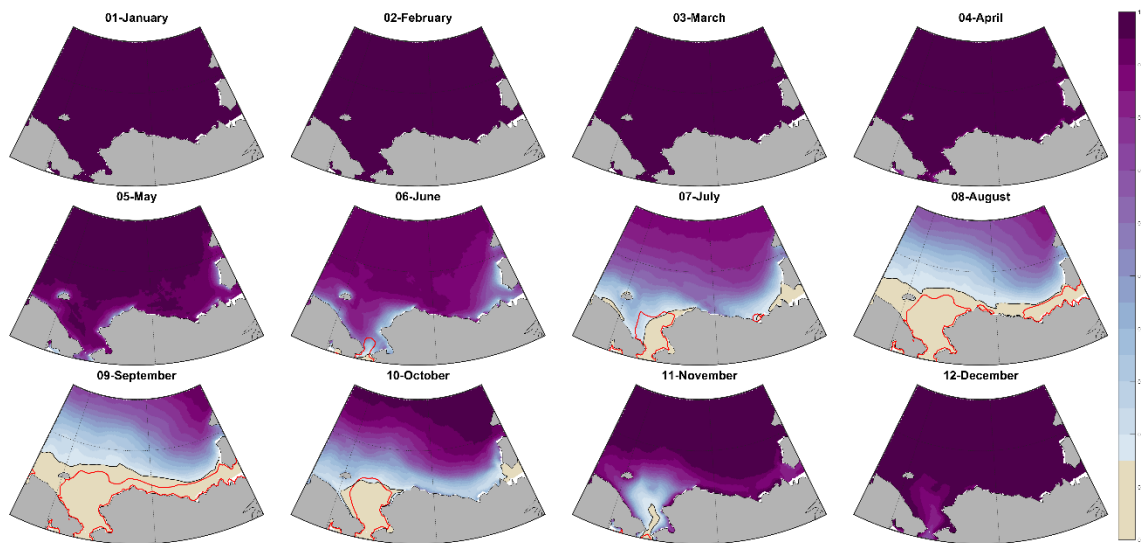
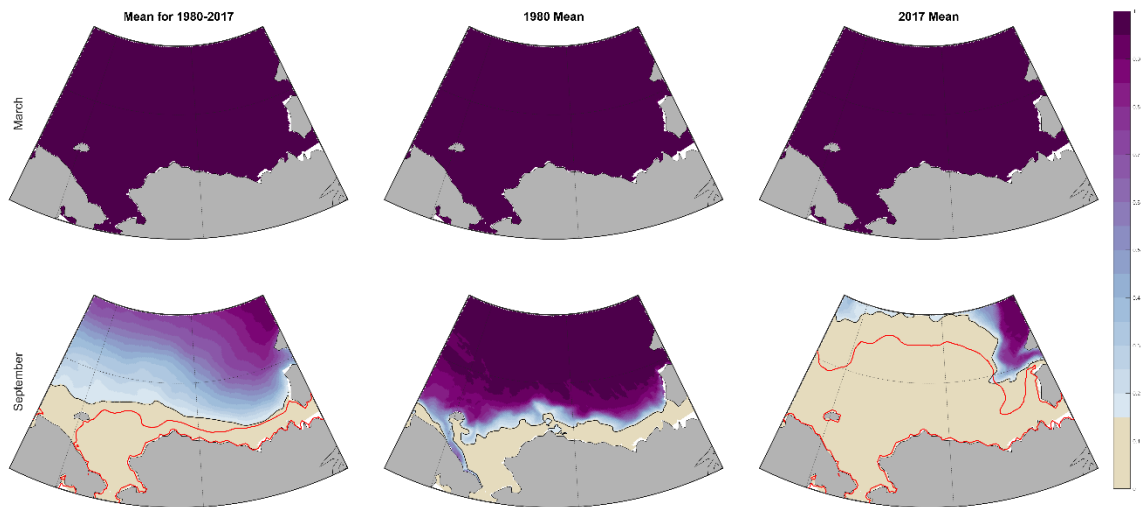


Figure 55 Ice area fraction: Monthly climatology, for the full dataset (38 years) in the Western Arctic

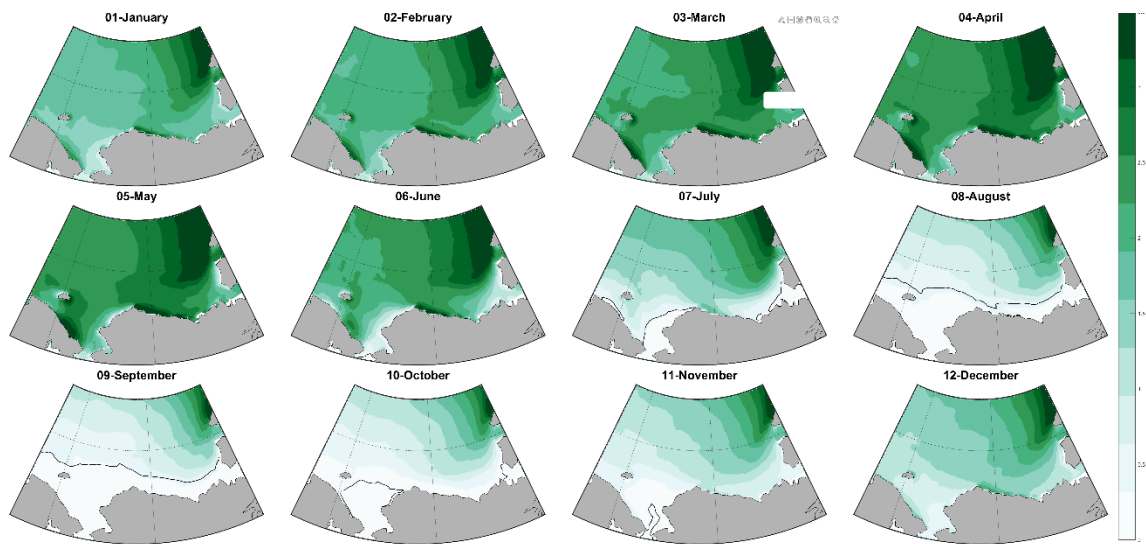


Black line indicates RASM Model Ice Area Edge, defined by grid cell with 15% ice area coverage. Red line indicates the observed Near-Real-Time NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration (<https://nsidc.org/data/g10016>)

Figure 56 Ice area fraction: Comparison of March and September (left) long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Western Arctic

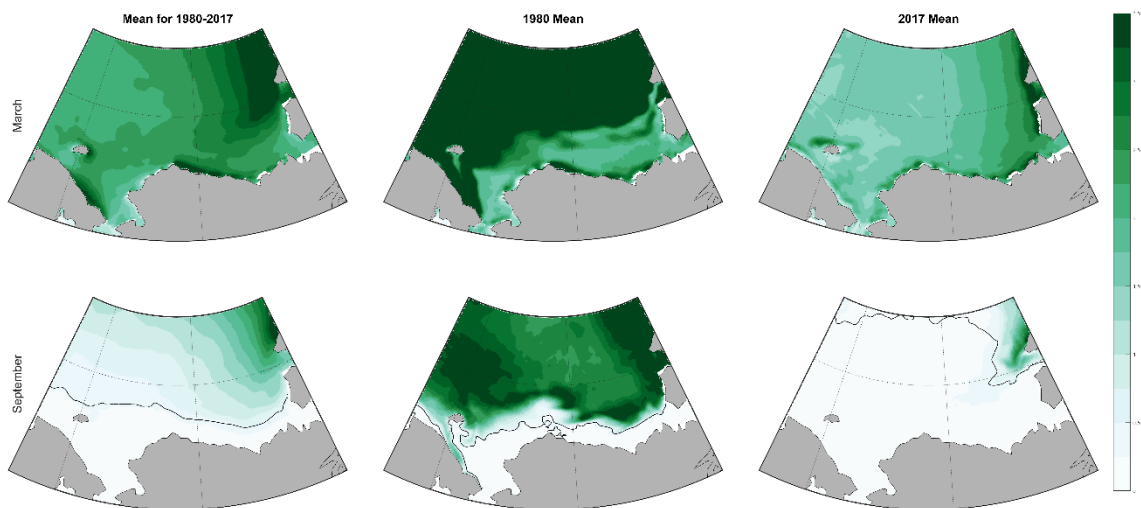
2. Ice Thickness

Even though mean Ice Area begins to decline in April, the Western Arctic continues to gain thick ice through May as ice from the CAA is advected into the area (Figure 57). Even though the CAA ice is being advected into the WA, the Beaufort Sea is almost entirely ice free by September 2017 (Figure 58).



Units in *m*. Limits from 0 to >3.5m). The black line depicts the RASM ice area at 15% grid cell coverage for the same period.

Figure 57 Mean ice thickness: Monthly climatology, for the full dataset (38 years) in the Western Arctic



Units in *m*. Limits from 0 to >3.5m). The black line depicts the RASM ice area at 15% grid cell coverage for the same period.

Figure 58 Mean ice thickness: Comparison of March and September (left) long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Western Arctic

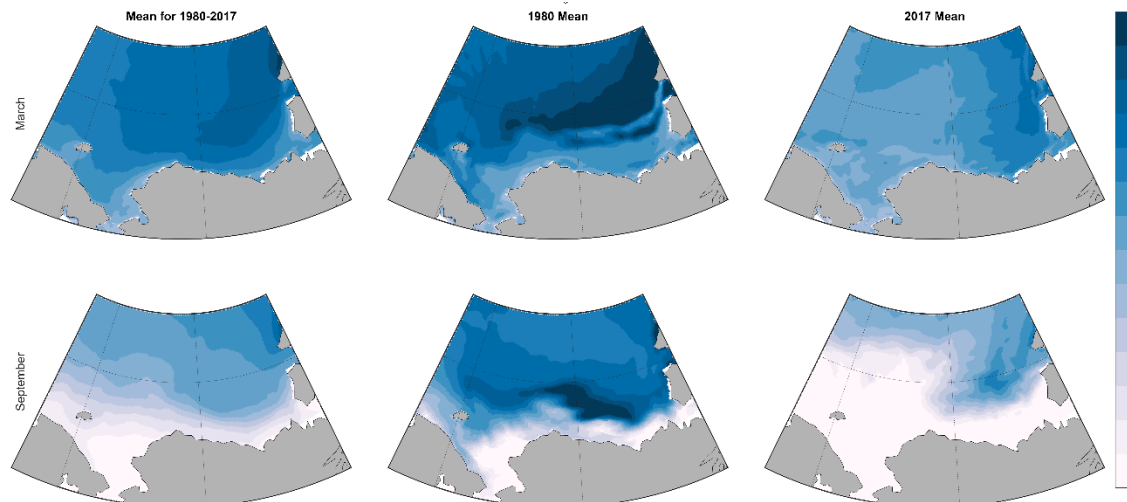


Figure 59 Ridged ice thickness: Comparison of March and September (left) long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Western Arctic. Units in *m*.

It is interesting that in September of 2017, the ridged ice extends further west (towards the Bering Strait) than the mean ice thickness depicts (Figure 58 and Figure 59). This means that for ice to have survived the melt season and moved into the West Beaufort Sea that the ice had to be ridged at one point, in order to maintain enough thickness. It also means that in order for ridged ice to survive where mean ice thickness is close to zero, but ridged ice still exists (Figure 59), that the floe is likely not solid and consists of disparate pieces of ice travelling together, potentially increasing the likelihood of large ridge formation if appropriate atmospheric forcing occurs.

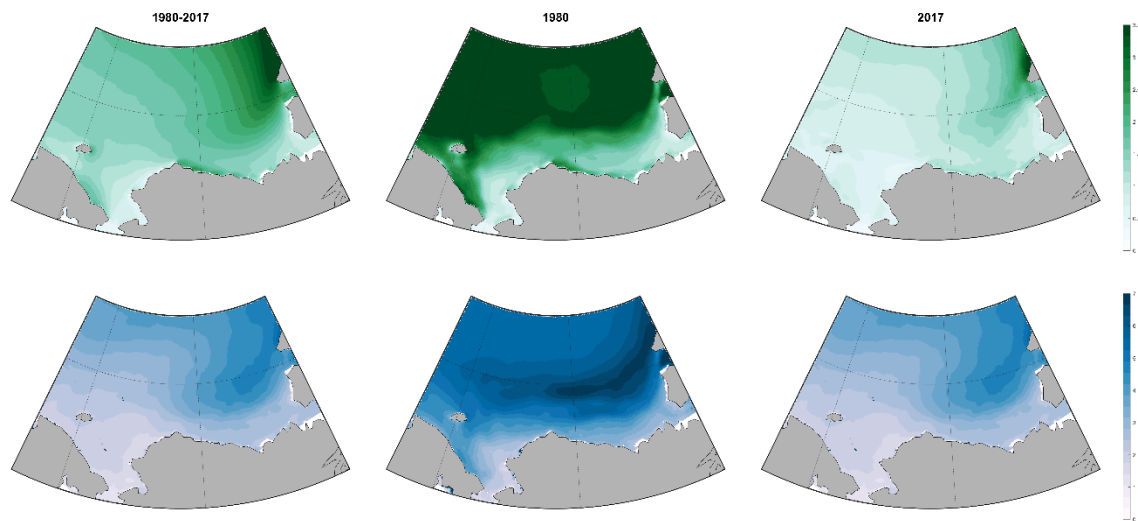


Figure 60 Comparison of mean ice thickness and ridged ice thickness long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Western Arctic. Units in *m*.

3. Ice Drift Speed

Ice drift speed in the Western Arctic shows similar trends to the Central Arctic with maximum speeds typically occurring in November (Figure 61) and it has increased in the winter months from 1980 to 2017 (Figure 62). The speed has definitely increased northward, but speed maximums that were near shore in September of 1980 are not present in 2017 due to there not being ice in those locations. When comparing Figure 58 to Figure 62, the mean ice thickness in 1980 near the Alaskan coast is approaching zero, with the average SIE located to the north, however, as this is a 38-year monthly mean, is likely that the increased speeds noticed are from very thin ice being advected along the Beaufort Gyre.

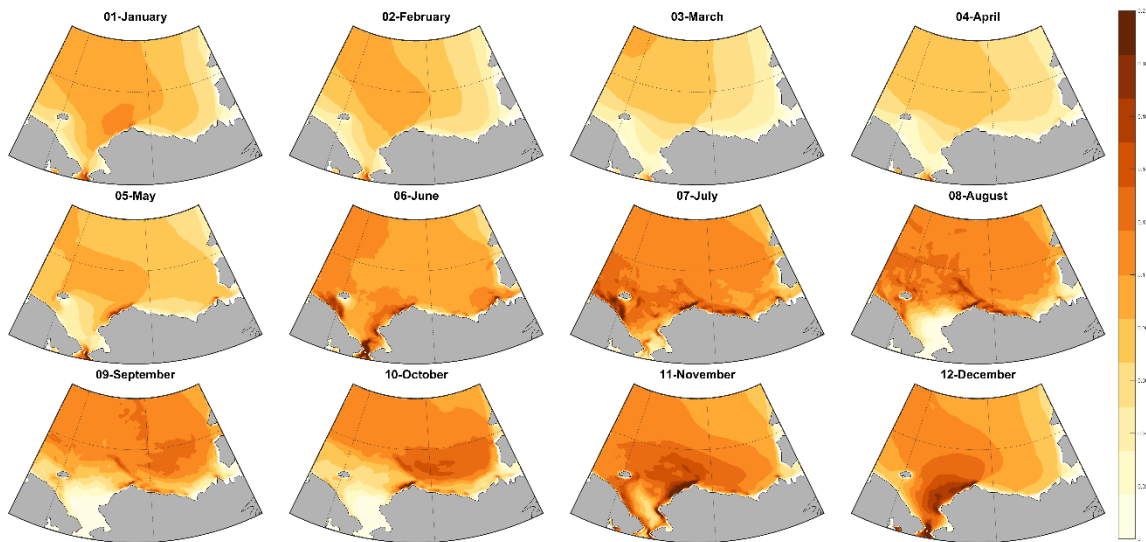


Figure 61 Ice drift speed: Monthly Climatology, for the full dataset (38 years) in the Western Arctic. Units in ms^{-1} . Limits from 0 to $>0.2ms^{-1}$).

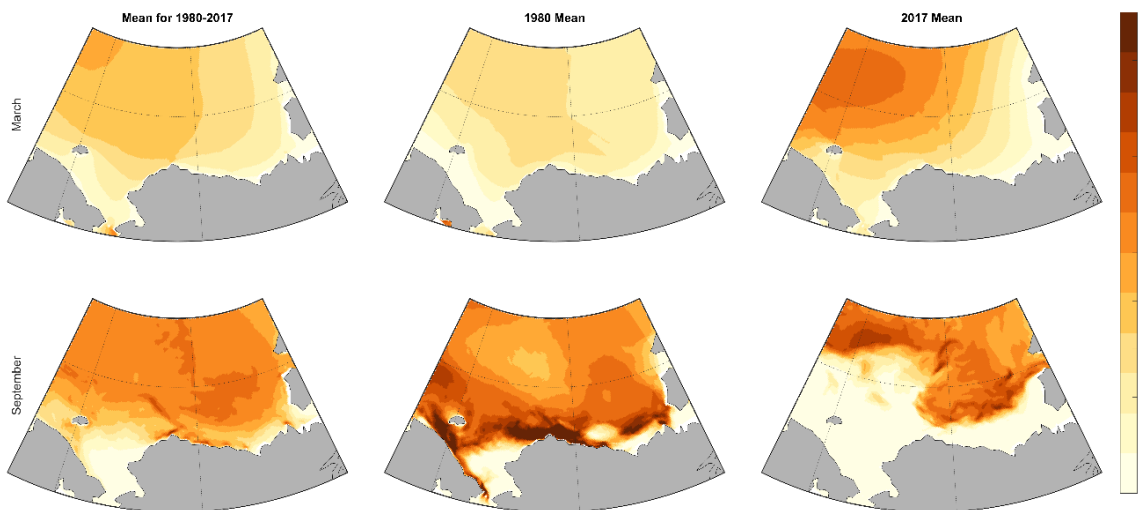


Figure 62 Ice drift speed: Comparison of March and September (left) long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Western Arctic. Units in ms^{-1} .

4. Convergence and Divergence

Winter convergence is localized near the coasts and over the continental shelf regions (Figure 63), with mean maximum convergence occurring in August. Figure 64 and Figure 65 show not only a northward increase in convergence and divergence, but an

increase in area effected by the events. In 1980 the convergence and divergence events in March and September were localized primarily over the shelf in the MIZ, but in 2017 they affect the entire Beaufort Sea with high magnitudes and probabilities of occurrence in September and even an increased magnitude and occurrence in March (Figure 64).

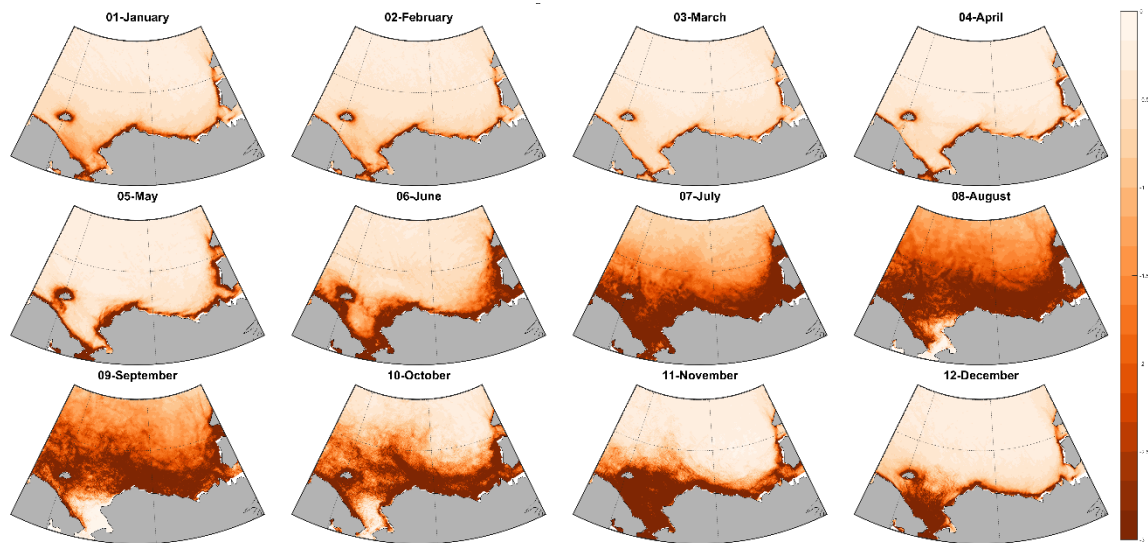


Figure 63 Convergence: Monthly climatology, for the full dataset (38 years) in the Western Arctic. Units in $\% \cdot \text{day}^{-1}$.

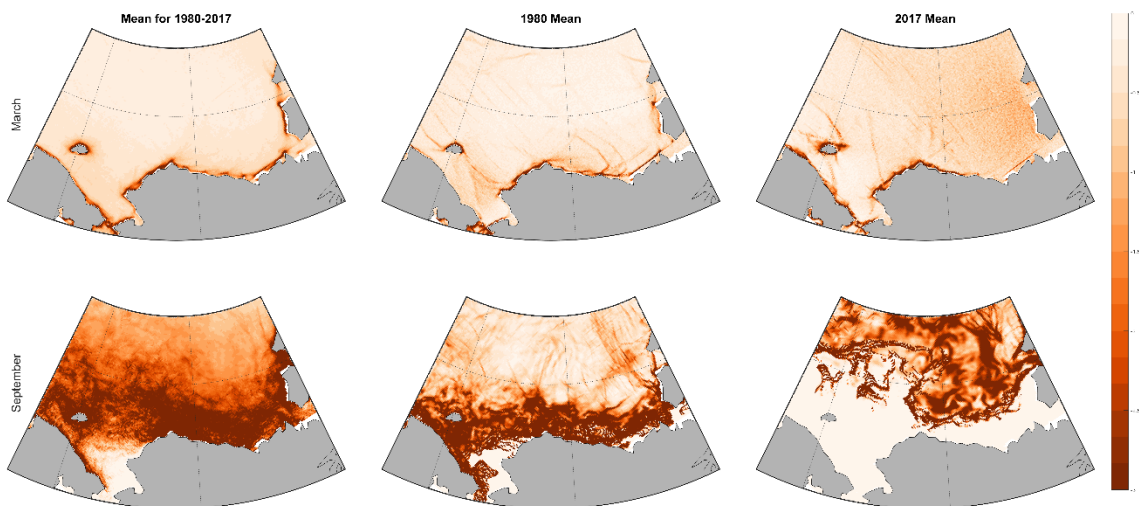


Figure 64 Convergence: Comparison of March and September (left) long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Western Arctic. Units in $\% \cdot \text{day}^{-1}$.

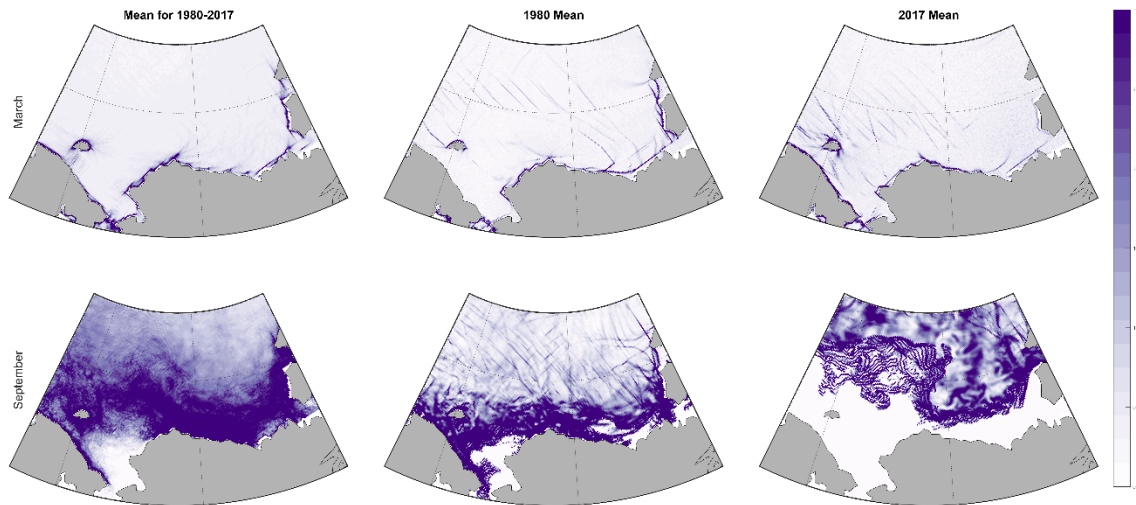


Figure 65 Divergence: Comparison of March and September (left) long-term mean (1980–2017), and monthly mean, by year, for (center) 1980 and (right) 2017 in the Western Arctic. Units in $\%day^{-1}$.

5. January, February, March (JFM)

The Arctic behaves very differently in summer versus winter, especially in recent years where there is considerably less ice. One of our main foci of this study was to aid researchers and military exercise safety on the ice, given that the timing of ICEX and other on-ice training evolutions typically take place between February and March. We also hypothesize that there is a higher probability of deep keeled pressure ridges forming from ice greater than 2 m thick, or from the interaction with older, less elastic ice. If a submarine needs to surface in the summertime, the chances of finding thin ice or open water are much higher than in the winter. Figure 66 shows the mean sea ice thickness (SIT) over 38 years, with the left plots showing the mean of all months, while the middle plots show the mean during JFM, and the right show the mean during April, May, June (AMJ). These plots indicate that AMJ would likely yield interesting decadal trend analysis, since, as stated in section A.1. of this chapter, even though in the 1980s the ocean would continue freezing into April, but now it is more likely to have its ice maximum in March (Figure 44 and Figure 45).

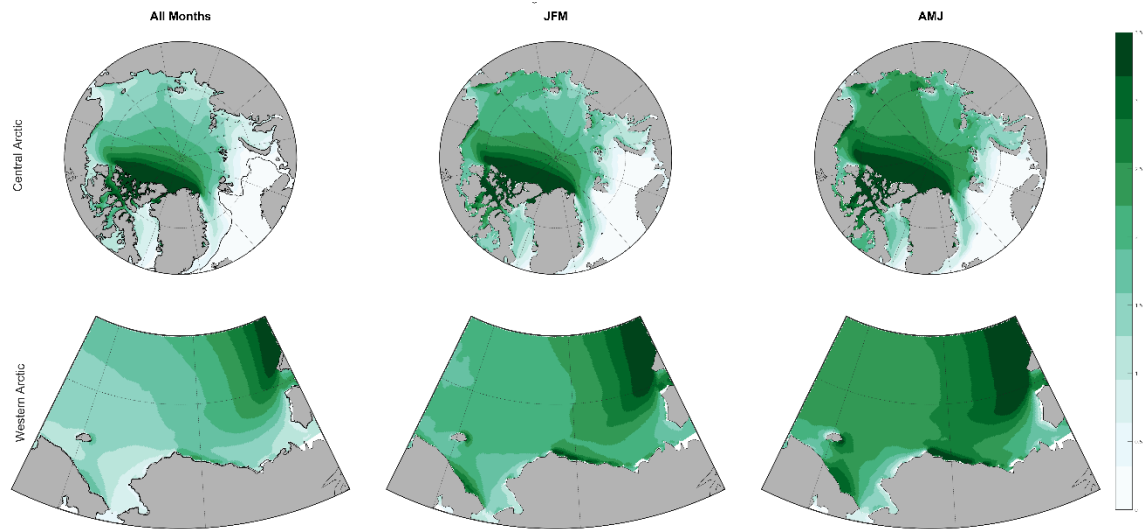


Figure 66 Mean ice thickness: Comparison of all months, JFM and AMJ (left) averaged daily mean magnitude for the entire dataset in the Central and Western Arctic. Units in *m*. Limits from 0 to >3.5m).

By taking the mean magnitude of convergence in 2017 and subtracting the mean magnitude of convergence in 1980, Figure 67 shows a decrease in convergence over the Beaufort and Chukchi Shelves, which is depicted as such due to there no longer being ice at all in 2017 for more of the year than 1980. Choosing a period to analyze that does not require the averaging of opposing annual seasonal cycles is preferable in order to depict seasonal trends, without having data smoothing that occurs when the mean is taken. January, February, March (JFM) was the spatial period chosen to focus on for this study because of these reasons.

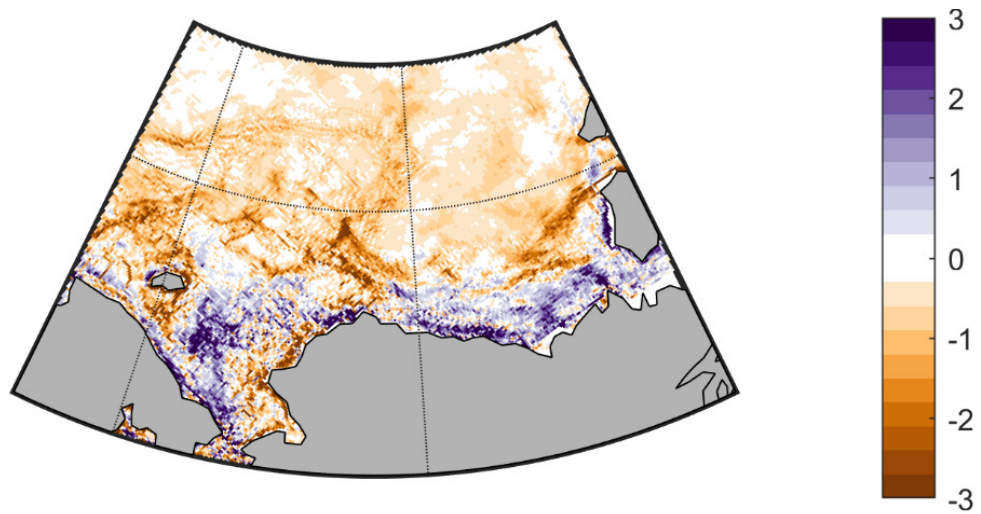


Figure 67 Change in annual mean convergence between 1980 to 2017

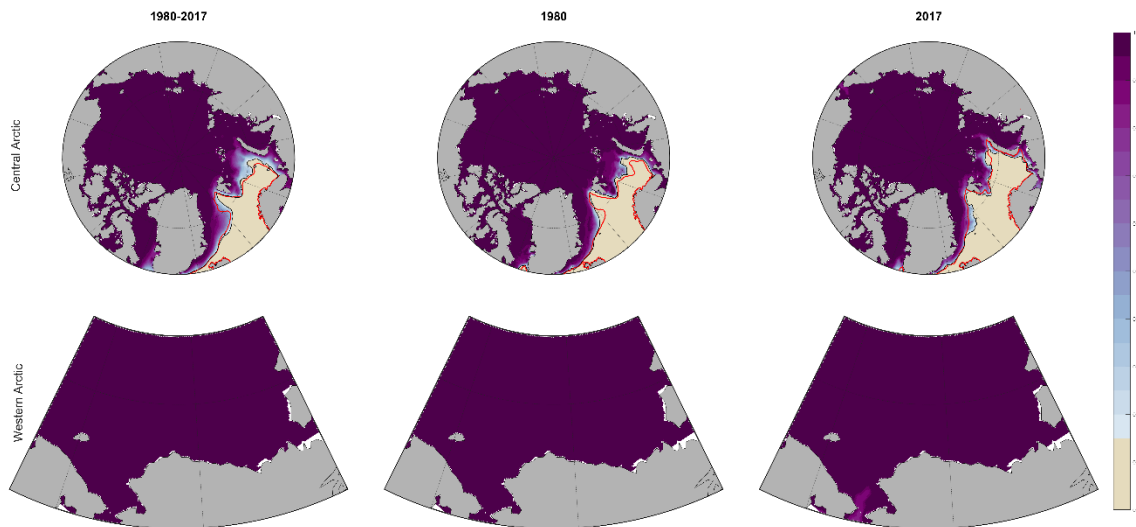
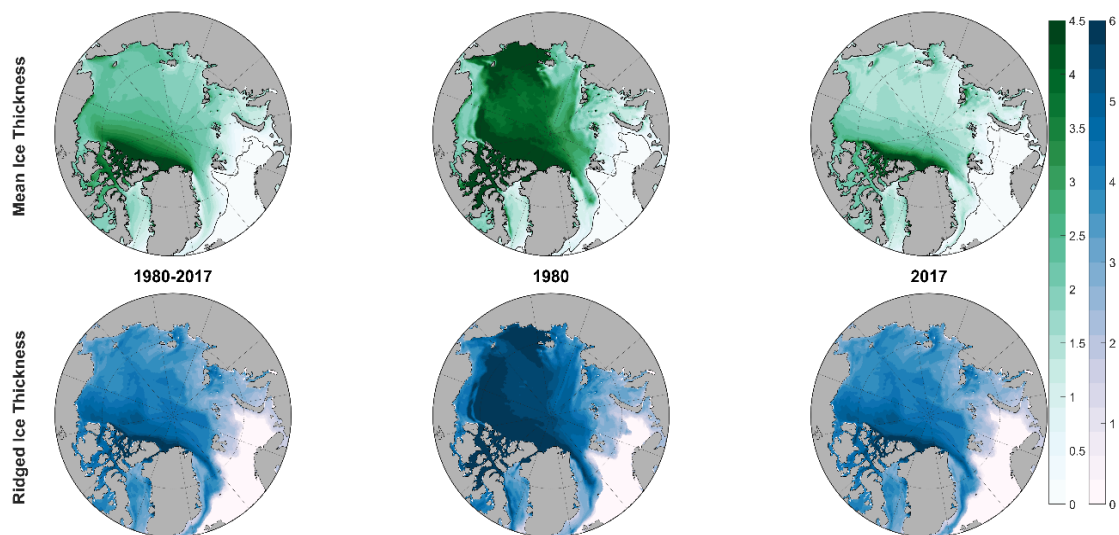


Figure 68 JFM Central vs. Western Arctic ice area (aggregate) fraction with (left) 38-year mean, (center) 1980 mean, and (right) 2017 mean



Mean ice thickness is shown on the top row and ridged ice thickness is shown on the bottom row.

Figure 69 Central vs. Western Arctic ice thickness for March with (left) 38-year mean, (center) March 1980 mean, and (right) March 2017 mean

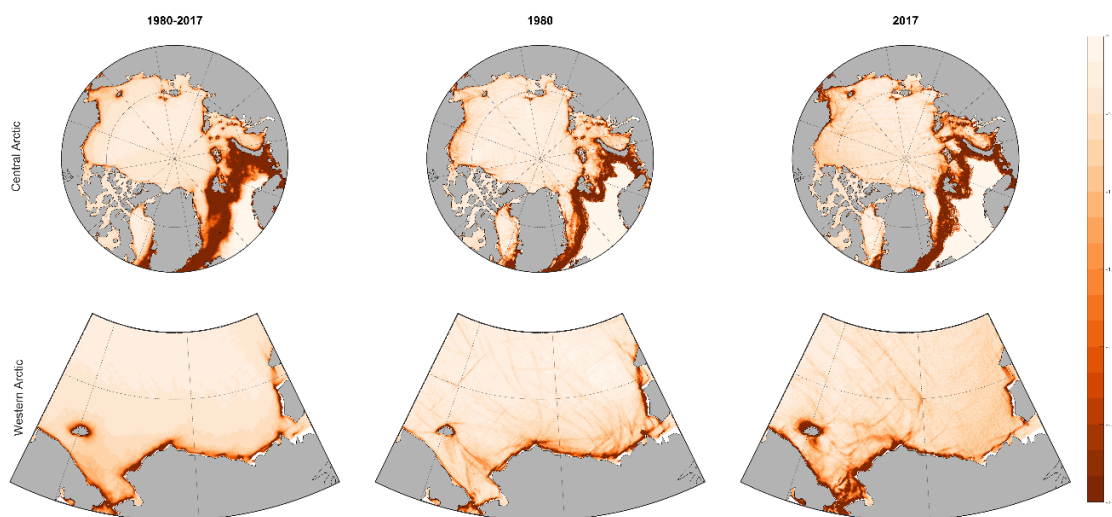


Figure 70 JFM Central vs. Western Arctic convergence with (left) 38-year mean, (center) 1980 mean, and (right) 2017 mean

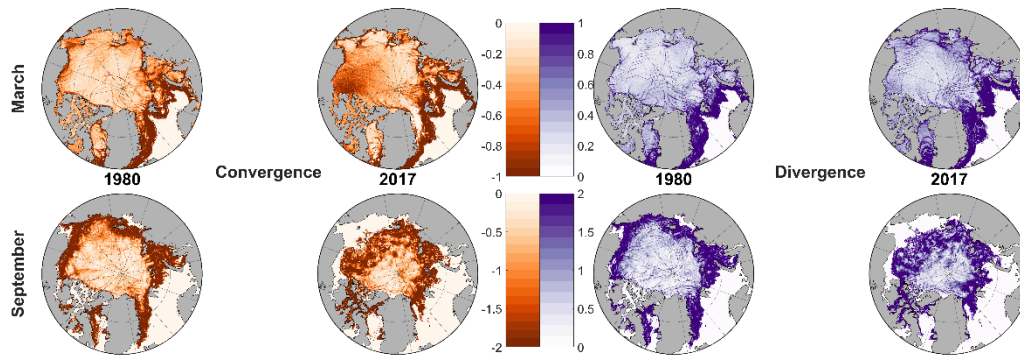


Figure 71 March and September Central Arctic (left) convergence and (right) divergence for 1980 and 2017

Between 1980 and 2017 for both convergence and divergence in Figure 71 we see the northward progression and width expansion of MIZ clearly in September, due to more of the ice being in free drift. Both variables have increased Arctic-wide in the winter and summer months due likely to the combination of increased Arctic cyclone intensity and occurrence (Valkonen et al. 2021), a positive trend in the AO (section II.A.3) and NAO (section II.A.2), and the overall decrease in sea ice thickness and mechanical strength.

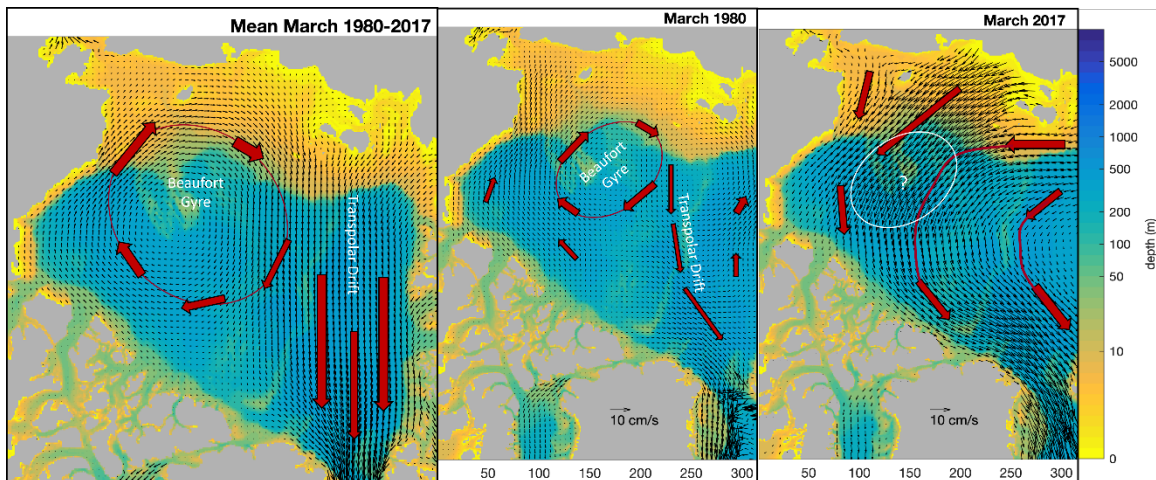
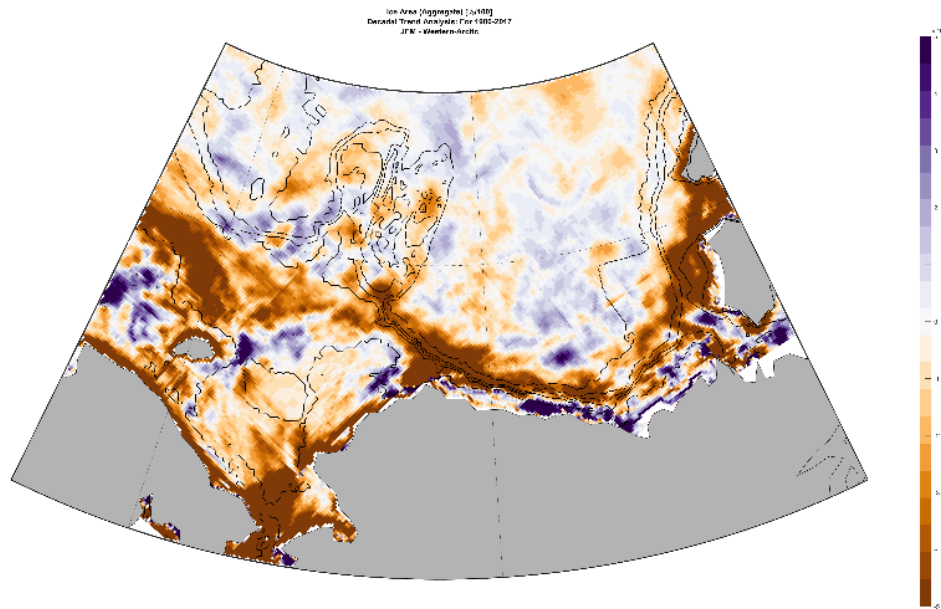


Figure 72 March mean ice drift velocity vectors overlaid on a bathymetric plot, depicting the (left) 38-year mean, (center) 1980 mean, and (right) 2017 mean

In Figure 72 the Beaufort Gyre is shown in the 38-year mean of ice drift velocity even when it is not present in 2017 due to the semi-permanence of the feature over the 38-year period. It shows the positive leaning trend of the DA (section II.A.4), which is shown (Watanabe et al. 2006; Chen et al. 2023) to be associated with a more prominent Beaufort Gyre, stronger transpolar drift, and increased Arctic ice export through the Fram Strait.

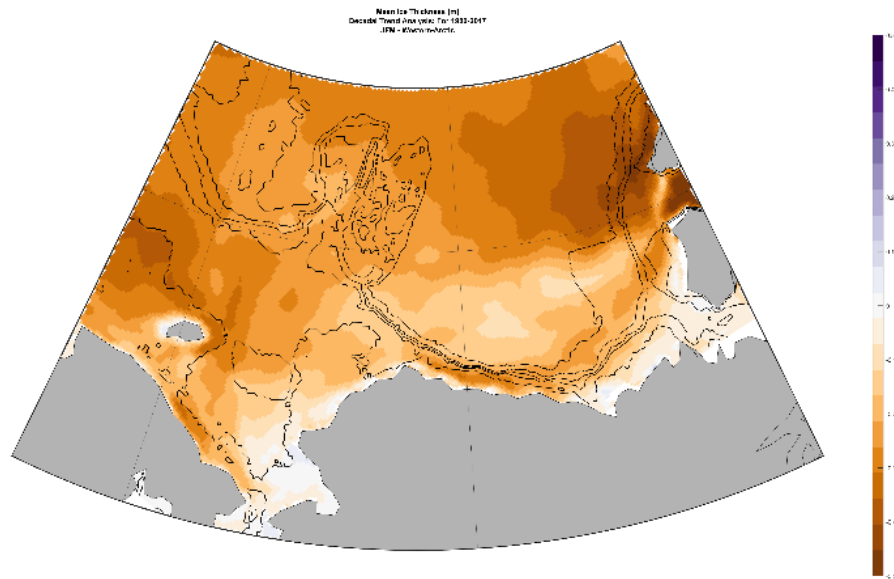
a. Time Series and Trend Analysis

Time series were analyzed for ice area, mean ice thickness, ridged ice thickness, ice drift speed, convergence, divergence, and convergent ridging for each grid cell in the Western Arctic and the decadal trend in linear regression was calculated and plotted in Figure 73, Figure 74, Figure 75, Figure 76, Figure 77, and Figure 78. This yielded an overall decreasing trend in Western Arctic ice area (Figure 73) and thickness (mean (Figure 74) and ridged (Figure 75)), and an increase in Western Arctic ice drift speed (Figure 76), convergence (Figure 77), and divergence (Figure 78).



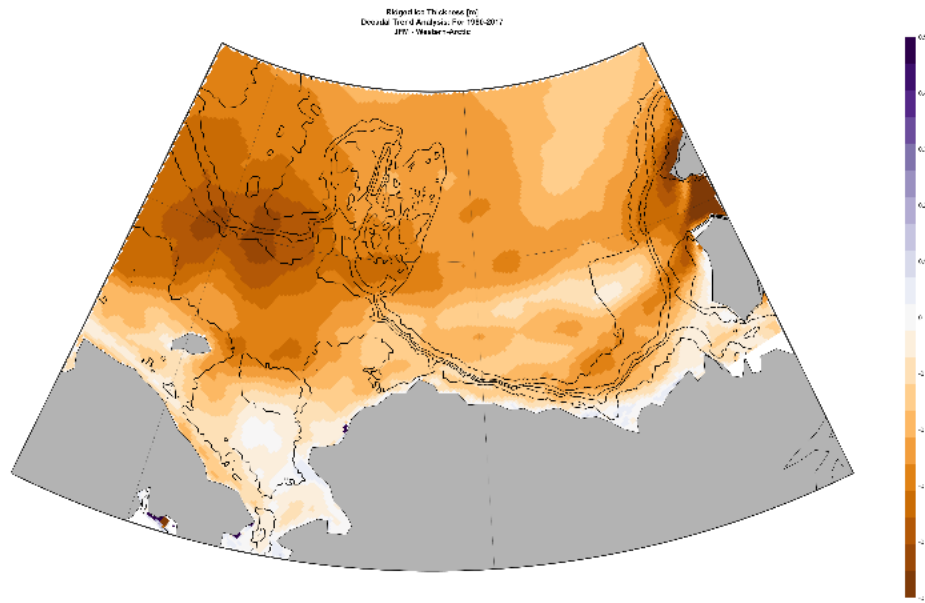
Linear regression is performed on ice area, for each RASM grid cell in the Western Arctic region, over January, February, and March (JFM) from 1980 to 2017. A total of 3420 days. The slope of the linear regression line [with units of %/100 per 3420 days] is multiplied by a grid mask of 342,000 so that positive, purple, values show an increase in ice area and negative, orange, values show a decrease in ice area, in units of percent. Showing the trend of daily change in ice area over 38 years at each grid cell. Bathymetry is overlaid showing contours of 50, 250, 500, 1000, and 2000 meters depth.

Figure 73 Decadal trend of ice area fraction: Western Arctic, JFM, 38-year linear regression decadal trend of daily magnitude vs. time



Linear regression is performed on mean ice thickness, for each RASM grid cell in the Western Arctic region, over January, February, and March (JFM) from 1980 to 2017. A total of 3420 days. The slope of the linear regression line [with units of meters per 3420 days] is multiplied by a grid mask of 3420 so that positive, purple, values show an increase in mean ice thickness and negative, orange, values show a decrease in mean ice thickness, in units of meters per second. Showing the trend of daily change in mean ice thickness over 38 years at each grid cell. Bathymetry is overlaid showing contours of 50, 250, 500, 1000, and 2000 meters depth.

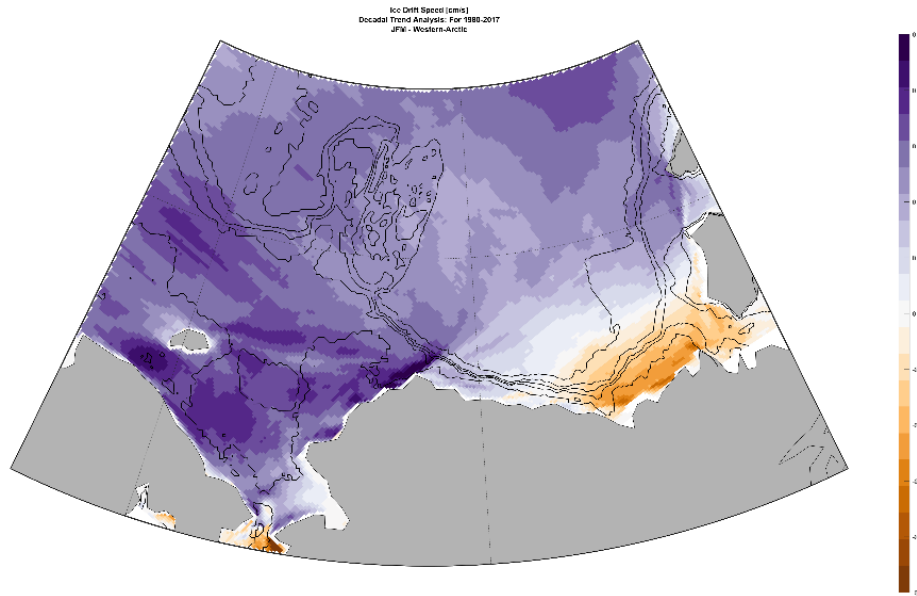
Figure 74 Decadal trend of mean ice thickness: Western Arctic, JFM, 38-year linear regression decadal trend of daily magnitude vs. time.



Linear regression is performed on ridged ice thickness for each RASM grid cell in the Western Arctic region, over January, February, and March (JFM) from 1980 to 2017. A total of 3420 days. The slope of the linear regression line [with units of meters per 3420 days] is multiplied by a grid mask of 3420 so that positive, purple, values show an increase in total ridged ice thickness and negative, orange, values show a decrease in ridged ice thickness, in units of meters. Showing the trend of daily change in total ridged ice thickness over 38 years at each grid cell. Bathymetry is overlaid showing contours of 50, 250, 500, 1000, and 2000 meters depth.

Figure 75 Decadal trend of ridged ice thickness: Western Arctic, JFM, 38-year linear regression decadal trend of daily magnitude vs. time

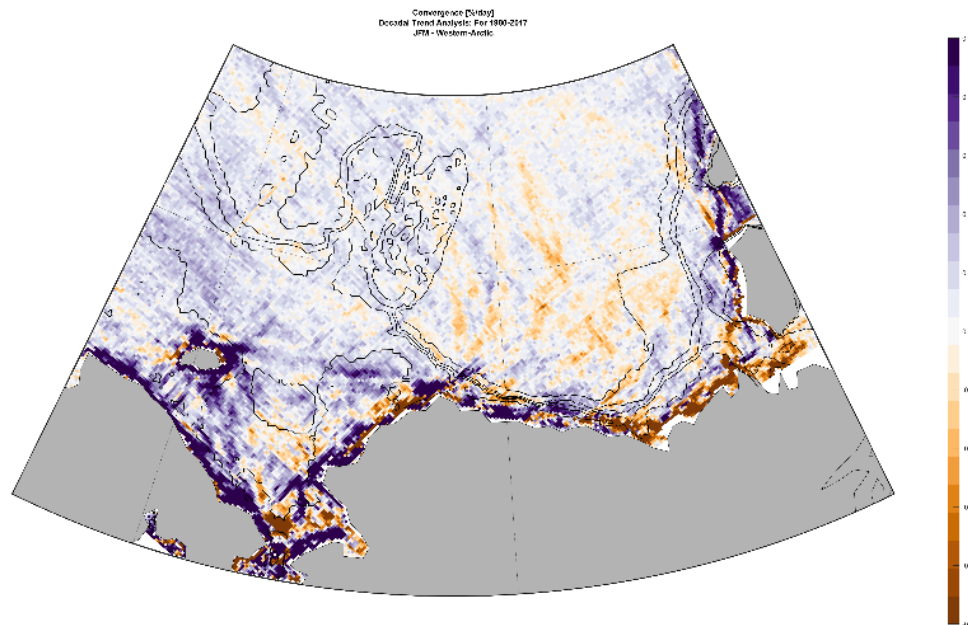
Both mean (Figure 74) and ridged (Figure 75) ice show an overall decreasing trend in thickness but there is an area in the southern Beaufort Sea for both mean and ridged, and along the CAA for ridged that show a slower decrease in ice thickness. This area of more moderate trending of sea ice thickness decrease is likely due to the location of MYI that is advected anticyclonically via the Beaufort Gyre from the southeast to southwest Beaufort Sea.



Linear regression is performed on the ice drift speed, for each RASM grid cell in the Western Arctic region, over January, February, and March (JFM) from 1980 to 2017. A total of 3420 days. The slope of the linear regression line [with units of meters per second per 3420 days] is multiplied by a grid mask of 3420 so that positive, purple, values show an increase in drift speed and negative, orange, values show a decrease in drift speed, in units of meters per second. Showing the trend of daily change in drift speed over 38 years at each grid cell. Bathymetry is overlaid showing contours of 50, 250, 500, 1000, and 2000 meters depth.

Figure 76 Decadal trend of ice drift speed: Western Arctic, JFM, 38-year linear regression decadal trend of daily magnitude vs. time

Ice drift speed is shown (Figure 76) to have an increasing trend throughout the Western Arctic with the exception of the Gulf of Amundson and just outside of it over the Beaufort Shelf. This could potentially be due to decreasing ice coupled with a change in Arctic cyclone activity, as we know that ice declined has been associated with an increase in ice drift speed (Rampal et al. 2009). There is a chance that the decrease in speed near the Gulf of Amundsen is due to the RASM case used not recognizing “fast ice,” also called “landfast ice.” Fast ice is sea ice that freezes from the surface of the ocean down to the sea floor, or ridged ice that is deep enough to interact with the sea floor and become anchored. Only certain models and cases within those models recognize fast ice, with many calculating ice physics based on the assumption that ice is floating on the ocean surface and not interacting with the seafloor.

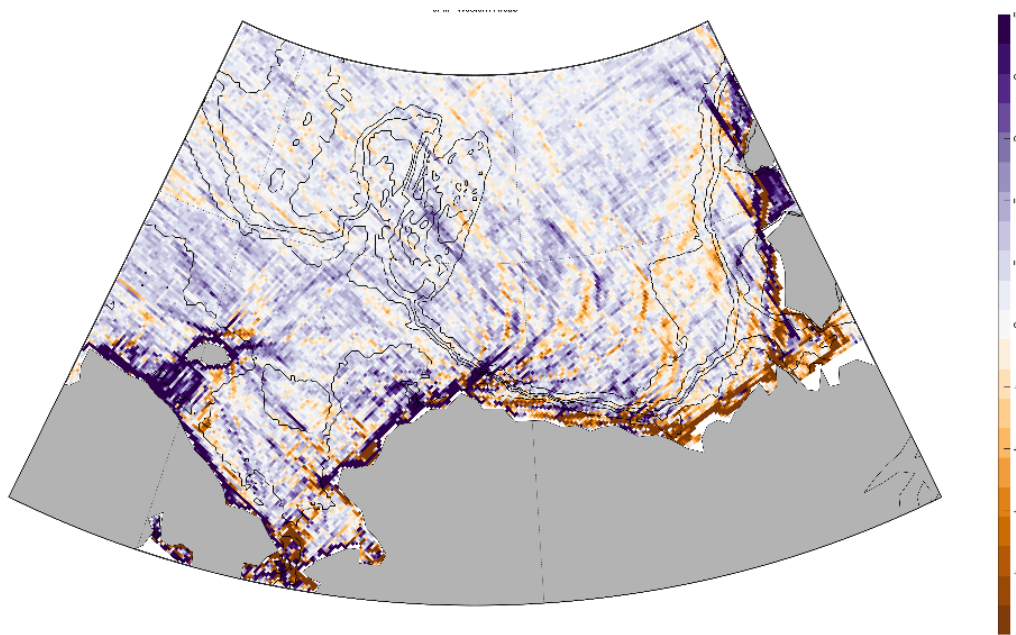


Linear regression is performed on the negative divu variable, depicting convergence, for each RASM grid cell in the Western Arctic region, over January, February, and March (JFM) from 1980 to 2017. A total of 3420 days. The slope of the linear regression line [with units of percent change per day per 3420 days] is multiplied by a grid mask of negative 3420 so that positive, purple, values show an increase in convergence and negative, orange, values show a decrease in Convergence, in units of percent change per day. Showing the trend of convergence over 38 years at each grid cell. Bathymetry is overlaid showing contours of 50, 250, 500, 1000, and 2000 meters depth.

Figure 77 Decadal trend of convergence: Western Arctic, JFM, 38-year linear regression decadal trend of daily magnitude vs. time

Trends in convergence and divergence are complex and not necessarily straightforward to explain. We need better tools, models with higher spatial and temporal resolution, more fully coupled models, better and more observations to help train models. Figure 77 shows convergence is decreasing in central/south Beaufort Sea and near the Gulf of Amundsen but has a consistent increase in the Chukchi and East Siberian Seas. Divergence is mostly increasing throughout the Western Arctic, including most of the Beaufort Sea (Figure 78). From these figures it is shown that convergence and divergence are not one-to-one spatially, as there is a larger increase in divergence than increase in convergence and that the lines of increasing convergence and increasing divergence tend to occur spatially offset from each other. These trends occur during the winter months (JFM) in the places where we have seen the Ice Area in the Western Arctic extend

throughout the domain (Figure 55). Hence, decreased ice concentration is not likely play a large role in these trends, as the ice area decadal trend (Figure 73) has mostly statistically insignificant values. What is likely causing the difference and offset between convergence and divergence is an increase in the number and strength of Arctic cyclones (Valkonen et al. 2021). These low-pressure systems cause convergence at the surface of the atmosphere, but for the ocean at the sea surface the low pressure causes upwelling followed by surface divergence. If cyclones are becoming more common and more intense as Valkonen et al. (2021) state, then it would follow that divergence would be increasing more than convergence, and that if ice is diverging from one location that it would be converging wherever the diverged ice interacts with a different floe, causing the offset seen when Figure 77 and Figure 78 are spatially compared.



Linear regression is performed on divergence, for each RASM grid cell in the Western Arctic region, over January, February, and March (JFM) from 1980 to 2017. A total of 3420 days. The slope of the linear regression line [with units of percent change per day per 3420 days] is multiplied by a grid mask of 3420 so that positive, purple, values show an increase in divergence and negative, orange, values show a decrease in divergence, in units of percent change per day. Showing the trend of daily divergence over 38 years at each grid cell. Bathymetry is overlaid showing contours of 50, 250, 500, 1000, and 2000 meters depth.

Figure 78 Decadal trend of divergence: Western Arctic, JFM, 38-year linear regression decadal trend of daily magnitude vs. time

The most interesting and telling trend analyzed in this study is that of convergent ridging, created by taking the two-day difference in ridged ice thickness and using a mask of zeros and ones indicating the location of a convergence value, thereby removing any advection of ridges from one grid cell into another and only showing true ridge formation due to convergence events. The decadal trend for JFM in the Western Arctic was analyzed and is depicted in Figure 79, where it is shown that for the 38-years between 1980 and 2017 the area in the southern Beaufort Sea has mostly been decreasing in ridging event occurrence and magnitude, while most of the Chukchi Sea, East Siberian Sea, and northern Beaufort Sea have all increased in occurrence and magnitude of convergent ridging.

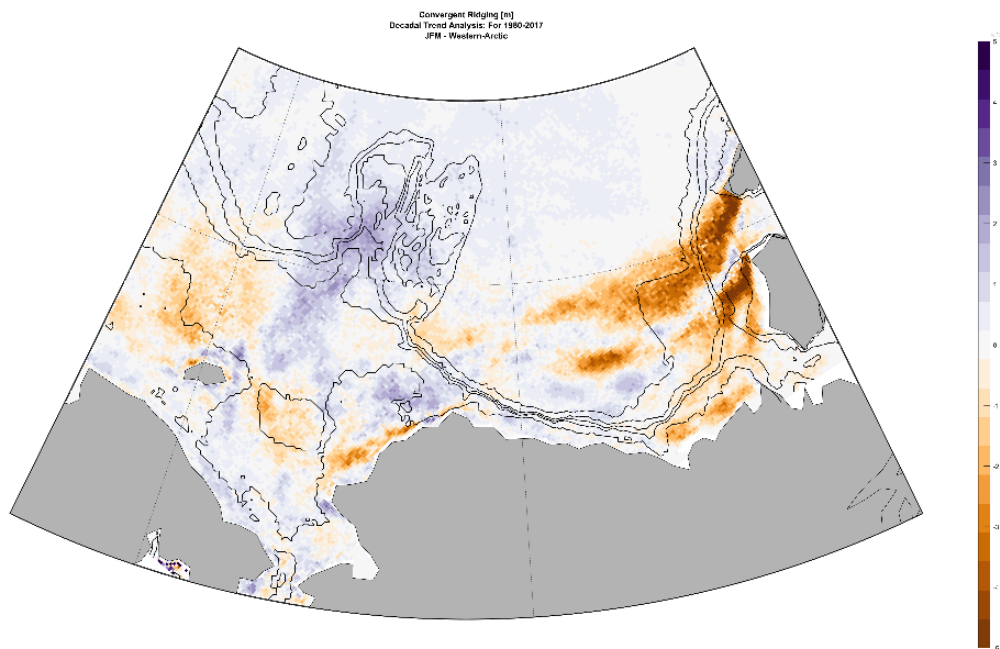
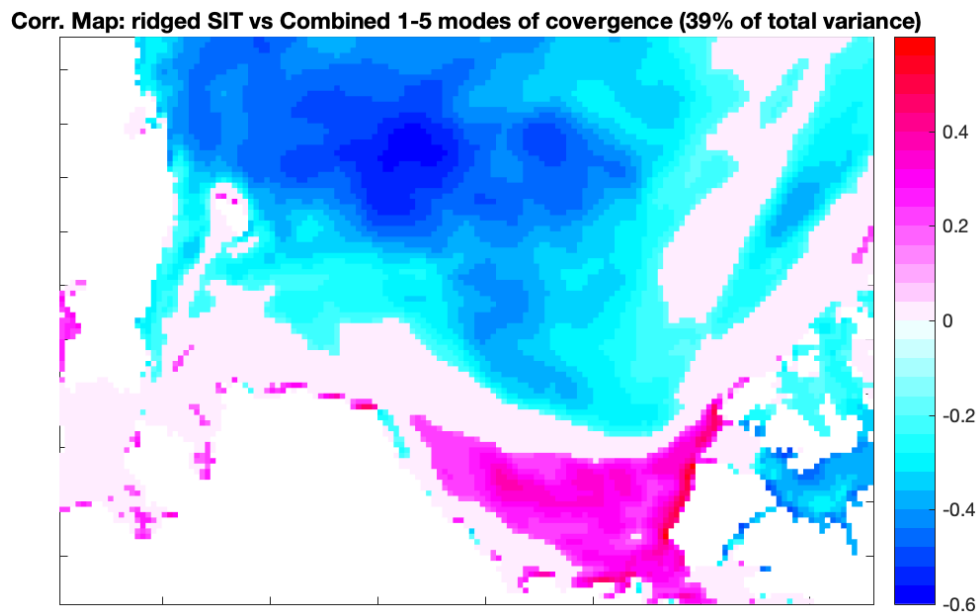


Figure 79 Decadal trend of convergent ridging: Western Arctic, JFM, 38-year linear regression decadal trend of daily magnitude vs. time

These relationships are further evaluated using the Singular Value Decomposition (SVD) method between ridged ice thickness and convergence (Fig. 86) with positive correlation in the southern Beaufort Sea and negative correlation along the TPD and in the Northern Beaufort Sea and East Siberian Sea. The first five modes of the SVD analysis of the ridged ice thickness and convergence explain 39% of the total co-variance. Although

Figure 80 does not remove the advection term in ridging ice the correlation matches well when the trend analyzes for ridged ice thickness (Figure 75), convergence (Figure 77), and convergent ridging (Figure 79) are compare to show a decreasing trend for ridged ice thickness throughout the Western Arctic, and a mostly decreasing trend for convergence in the southern Beaufort Sea but increasing trends over the TPD, East Siberian Sea, and Northern Beaufort Sea. Figure 79 and Figure 80 match these trends well.



Values between -0.2 and 0.2 are statistically insignificant due to the SVD only analyzing the months of January, February, and March.

Figure 80 Singular Value Decomposition (SVD) of ridged ice thickness and convergence, representing modes 1–5 and explaining 39% co-variance

This study has focused primarily on the Western Arctic for two main reasons: (1) the Western Arctic has undergone the most dramatic changes over the satellite record, i.e., since 1980, and (2) the U.S. operates primarily out of the Western Arctic, an area that this study has already shown has trended towards increased variability. By focusing on the Western Arctic, we can discuss in more detail the sea ice conditions there as well as differentiate them relative to the Central Arctic.

C. CASE STUDIES

In order to see the connection between ridge formation and convergence, the daily change in ridged ice thickness and a mask field for removing advection where I set every grid cell with a convergence value in it equal to 1 and then multiplied the mask by the daily difference in ridged ice thickness. Daily change in ridged ice thickness was just a subtraction of n-1 day from n-day. I displayed daily plots for JFM in the Western Arctic showing (1) Daily Change in Ridged Ice Thickness, (2) Ice Drift Velocity, Ice Drift Speed with directional vectors overlayed, (3) Divergence, (4) Daily Change of Ridged Ice Thickness with the convergence mask applied, (5) Total Ridged Ice Thickness with the convergence mask applied, and (6) Convergence. By multiplying the convergence mask by an ice thickness field, I took out the model's ability to mistake advection from one grid cell to another as new ridge growth. In order to overlay the field, I created two separate mask that removed negative change in Ridged Ice Thickness and set them equal to 1.000000001, then located the grid cells where ridged daily change of ridged ice thickness with the convergence mask applied was negative and set that equal to zero. Then by locating the positive change in ridged ice thickness, changed them to negative by multiplying by negative 1, setting the variable containing the daily change in ridged ice thickness grid cells that ridges were still located after the convergence mask was applied equal to 1, I was able to set the values of the new advection removing mask greater than -0.1 equal to 1, and returning to the daily change in ice thickness values that still remained at 1.000000001 I set those equal to zero as I knew no ridges formed there due to convergence. Finally multiplying the daily change in ridged ice thickness by the no advection mask showed me where new ridging was occurring compared to where RASM was reporting an increase in ridge height. I performed a very similar method for overlaying the location of actual ridge growth on top of the unaltered ridged ice thickness.

The result shows a correlation between the location of ice thickness variability, i.e., where thicker ice and thinner ice share a boundary, the change in direction of ice drift velocity, and a convergence event. It may be speculated that, when an atmospheric forcing event, the primary driver for ice drift, occurs, and the ice floe changes direction, the thinner, less massive ice, which has less inertia, changes direction faster than the thicker ice,

causing collisions and ridging to occur. If the floe direction changes from pushing the thicker ice towards the thinner ice, to pushing the thinner ice towards the thicker ice, the inertia, if built up enough, of the thicker ice will continue moving it towards the thinner ice, and the wind will be forcing the thinner ice towards the thicker ice at the same time, increasing the convergence and causing an asymmetric ridge (Figure 25, center image). Alternatively, if the drift shifts to coming from behind the thicker ice, then the thinner ice will quickly slow down faster than the thicker ice and have a higher probability of divergence occurring, than convergence.

1. Time Series and Trend Analysis

In section IV.A, Figure 40 depicted 9 locations for case studies. Time series plots were created for each of the 6 RASM output variables discussed in this paper at each of those case study locations. Those time series plots were fitted with a linear regression line of the first order and multiplied by a constant to produce the decadal trend (slope). Table 4 shows the results of those trend analyses with red indicating a negative or decreasing trend and blue indicating a positive or increasing trend. Interestingly convergence and divergence have similar trends at all locations except the Northern Chukchi Cap (NCC) when considering all months, but have mostly opposite trends during JFM, except for at the North Pole, NCC and Bering Strait East (BSE). Of note, the area chosen for ICEX, which is described in detail in section IV.A, has an increasing trend for divergence in the months of JFM, which indicates an increase in risk with building future ice camps in the location.

Table 4. Case study trend analysis from time series linear regression fit presented at a decadal scale

(Values for Decadal Trend - Linear Regression)	Bering Strait East	Coastal Beaufort Alaska	Coastal Chukchi Alaska	ICEx Area	Southern Beaufort Sea	Southern Chukchi Cap	Northern Chukchi Cap	North Pole	Fram Strait
All Months									
Convergence	-0.3505	0.098316	-0.04558	0.123789	0.077184	0.213184	-0.04797	0.035	-0.03171
Divergence	-0.22939474	0.195921	-0.16355	0.241526	0.266289	0.192158	0.048053	0.005053	-0.15087
Mean Ice Thickness	-0.03423684	-0.27303	-0.18603	-0.2105	-0.23526	-0.28097	-0.28455	-0.44953	-0.27863
Ridged Ice Thickness	-0.09173684	-0.38468	-0.35961	-0.31797	-0.3545	-0.43505	-0.32066	-0.31416	-0.32197
Ice Area	-0.02586842	-0.06263	-0.04824	-0.04053	-0.05316	-0.06989	-0.04811	-0.00195	0.007816
Ice Drift Speed	-0.00418421	0.002395	-0.00868	0.0035	-0.00039	0.000223	-0.00447	0.004263	0.001184
JFM									
Convergence	-0.09792105	-0.00163	0.089158	-0.00053	0.007447	0.014868	-0.07274	0.026474	-0.03468
Divergence	-0.12236842	0.003816	-0.00582	0.005789	-0.05466	-0.013	-0.01987	0.000239	0.017974
Mean Ice Thickness	-0.03052632	-0.22295	-0.147	-0.11284	-0.16076	-0.23158	-0.22155	-0.42837	-0.35176
Ridged Ice Thickness	-0.04228947	-0.28421	-0.14361	-0.16118	-0.17642	-0.30582	-0.09653	-0.32042	-0.34592
Ice Area	-0.00136842	-0.00017	-0.00034	7.16E-06	-0.00055	-8.6E-07	-0.00076	-9.7E-05	-0.00171
Ice Drift Speed	-0.00160526	0.002605	0.003632	0.001395	0.003	0.002474	0.001368	0.003816	0.002105

The most interesting trend comparison I noticed between convergence and divergence at most Western Arctic case study locations in wintertime, is that they often have a difference in the sign of their decadal linear regression slopes. So, declining convergence leads to increasing divergence within the area. This holds true for all points analyzed in this area except for the NCC and Bering Strait East. As stated in section B.5.a when comparing trends between convergence and divergence, this offset may be due to increased number and intensity of cyclones, coupled with decreased ice thickness and strength.

2. Atmospheric Forcing and Ice Drift Speed Impacts on Convergent Ridging

Atmospheric velocity was compared to ice drift velocity, divergence, convergence, two-day change in ridged ice thickness, ridged ice thickness, and convergent ridging to see what kind of atmospheric events had the highest chance of producing convergent ridging. Daily mean data was plotted for each of these fields, with convergent riding overlayed on

the ridged ice thickness plot, for each day in JFM from 1980–2017 (Figure 81 and Figure 82). Although ridging events occurred throughout the simulation period, 28 atmospheric events were chosen to represent multiple types of atmospheric forcing (Table 5).

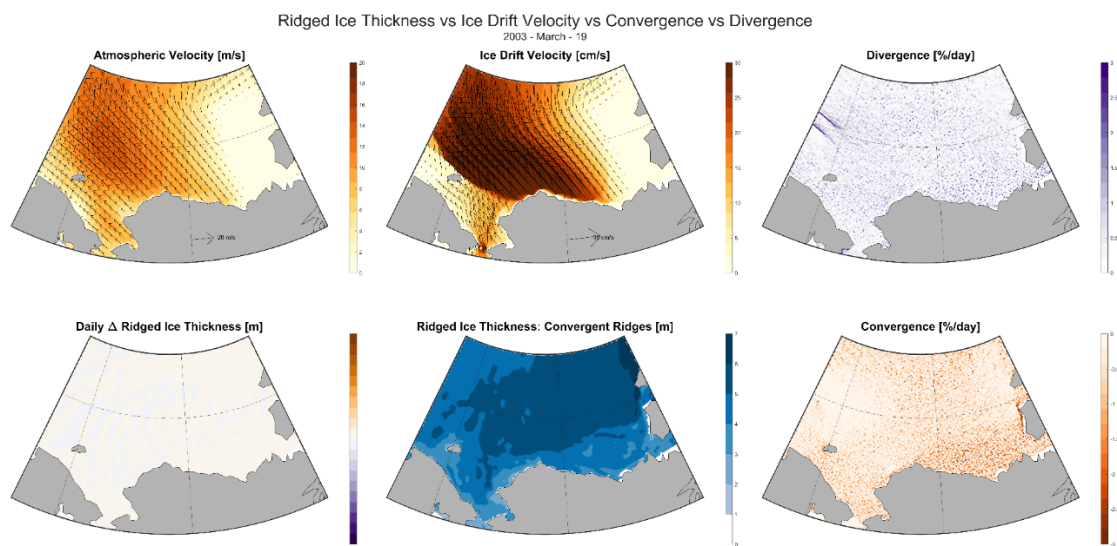
Table 5. Table of case study atmospheric forcing events

Year	Month	Start Date	End Date	Ridging/No Ridging
1981	2	7	9	ridge
1981	3	13	15	no ridge
1982	1	10	15	ridge
1982	1	19	21	ridge
1982	2	19	22	no ridge
1983	2	27	3	ridge
1989	1	4	9	ridge
1991	1	28	31	ridge
1992	1	13	23	ridge
1994	2	10	16	ridge
1999	1	1	4	ridge
1999	1	24	28	ridge
2002	2	1	4	no ridge
2003	2	27	3	ridge
2003	3	17	25	no ridge
2004	1	4	9	ridge
2005	1	1	7	ridge
2005	1	8	12	ridge
2006	2	7	8	ridge
2007	1	29	3	ridge
2008	1	18	22	ridge
2008	2	19	24	ridge
2008	3	19	22	no ridge
2010	1	20	4	ridge
2011	2	15	18	ridge
2013	3	7	11	ridge
2016	1	24	29	ridge
2017	3	8	14	ridge

When the end date shows a number less than the start date that indicates that the event followed continued into the following month.

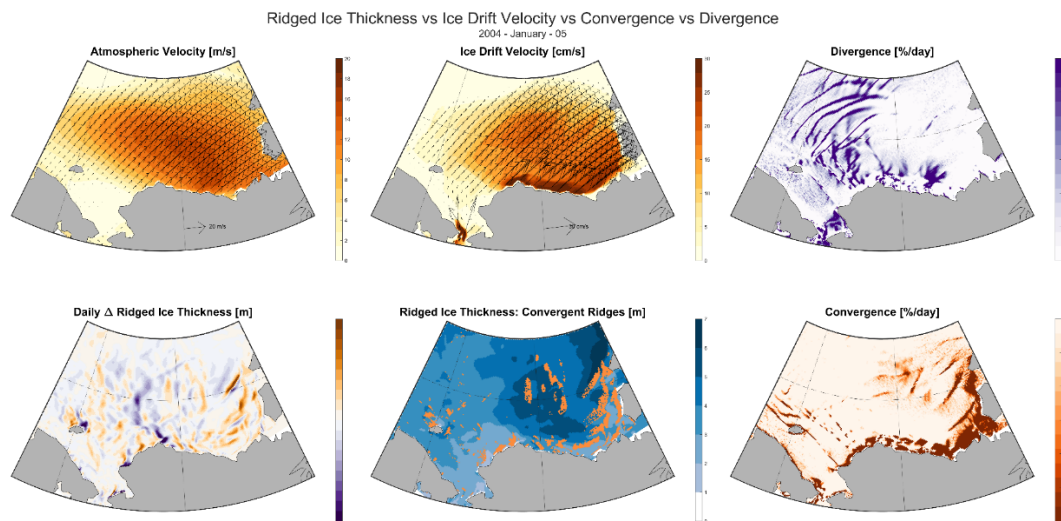
A closer look at the March 2003 (Figure 81) and January 2004 (Figure 82) events are shown below, with Figure 81 showing a case of a strong anticyclonic system moving through the Western Arctic and no ridging occurring even with an acceleration of ice drift due to atmospheric forcing almost at gale wind speeds (~15kts) and a change in direction of wind flow. There is little to no divergence or convergence occurring at this time, which

as March is the maximum ice freeze up, could be somewhat associated with the Western Arctic ice being in ice-pack. Figure 82 shows a cyclonic system pass through the Western Arctic and cause large amounts of convergent ridging. Through the 28 cases that were examined, the majority of them occurred in January, when the ice is relatively thinnest. The January 2004 case shows both convergence and divergence depicted as LKFs, and offset from each other on different sides of the Western Arctic, with increased convergence in the Southern Beaufort Sea and increased divergence in the Northeast Siberian Sea.



The panels of each hex-plot show the wind velocity (top left), ice drift velocity (top center), divergence (top right), daily change in ridged ice thickness due to convergence (bottom left), daily ridged ice thickness with convergent ridging overlaid in orange (bottom center), and convergence (bottom right).

Figure 81 2003 March 19 – No ridging event showing the daily progression of a strong anti-cyclonic system impacting the Western Arctic



The panels of each hex-plot show the wind velocity (top left), ice drift velocity (top center), divergence (top right), daily change in ridged ice thickness due to convergence (bottom left), daily ridged ice thickness with convergent ridging overlaid in orange (bottom center), and convergence (bottom right).

Figure 82 2004 January 05 – Ridging event showing the daily progression of a strong anti-cyclonic system impacting the Western Arctic

VI. SUMMARY AND CONCLUSIONS

Sea ice output from the Regional Arctic System Model (RASM) have been analyzed over the period of 1980–2017 to evaluate sea ice deformation trends in the Arctic Ocean. This research has been motivated by other recent studies documenting that the Arctic has warmed almost four times faster compared to the global average (Rantanen et al. 2022), which has accelerated sea ice decline (Lee et al. 2023) and increased the international interest in the Arctic. As a result of this Arctic Amplification (AA), sea ice area, thickness, and volume have declined while uncertainty about its seasonal to decadal evolution has increased. Such changes have emphasized the need for operationally focused research into navigating the new Arctic. Understanding potential effects of different feedbacks on the Arctic sea ice state, variability, and trends has become a high priority. In particular, the formation of ice pressure ridges and keels pose a tremendous risk to increasing civilian and military marine surface and subsurface operations, yet their distribution and characteristics over the recent past are not well established and the capability to forecast their future trends is currently missing.

To address some of those limitations, modeled changes in sea ice area, mean and ridged ice thickness, drift speed and direction, and deformations have been analyzed to: (1) diagnose spatial patterns, trends, and linkages among them, (2) verify model results against the available observations, and (3) identify areas of varying risks due to a changing sea ice state. Our analysis of the 38-year RASM sea ice output for the Central Arctic shows decreases in SIA, mean SIT and ridged SIT, while the trends in ice drift, divergence and convergence have all shown increases. While convergence and divergence are the same sea ice variable with an opposite sign, we have separated it this way as they represent dramatically different physical processes and risk to marine operations. While convergence is often associated with sea ice ridging, divergence is associated with cracks and leads and new ice formation.

Focusing on the Western Arctic similar trends are diagnosed from RASM as in the Central Arctic, with decreasing sea ice area and ice thickness, while increasing convergence, divergence, and ice drift speed. The linear kinematic features associated with

convergence and divergence move north, increase in frequency and magnitude through the simulation period relative to their 1980 locations and increase quantity and magnitude. When results in the Western Arctic are analyzed over the winter months, i.e., January, February, and March, we show overall increasing divergence and ice drift speed in most areas. Convergence trends in the Western Arctic show increases in the East Siberian Sea, the northern Beaufort Sea, and along the TPD route, but decreasing convergence trends in the southern Beaufort Sea and near the Gulf of Amundsen. The sea ice area trend in the Western Arctic during JFM is shown to vary very little over time, while mean and ridge ice thickness have declined, to varying degrees, everywhere. The variations in SIT trends in the Beaufort Sea have a strong association with CAA MY ice advection into the Western Arctic at varying locations throughout the 38 years, showing a primarily northward shift.

Comparison of the 9 case study locations indicates an overall opposite trend between convergence and divergence in winter. We hypothesize that this is due to increasing occurrence and intensity of cyclones in the Western Arctic which locally increase sea ice divergence.

In order to analyze the actual ridging events and trends, we have derived what we have termed convergent ridging, from daily differences in ridged ice thickness limited only to locations where convergence is occurring to filter out advection of ridged ice between grid cells. We find that winter decadal trends in convergent ridging are increasing over the TPD, East Siberian Sea, and Northern Beaufort Sea, and decreasing in the southern Beaufort Sea. This finding is of particular interest as marine traffic along the TPD has increased since the 1980s and is projected to further increase. With an overall increase in convergence events over the TPD and the advection MYI from the CAA further north in the Beaufort Sea / Canada Basin, the potential for ridge formation or advection into the TPD is more likely than it was in the past, posing a significant increase in navigational hazards and uncertainty for civilian and military ocean transit through the Western Arctic.

Trends in Arctic sea ice reflect the impact of the ice-ocean feedback loop but the story is quite complicated at a regional / local scale. Continued measurements of ice thickness, drift, and deformation as well as the upper ocean hydrography are needed. Fully coupled process-resolving Arctic system models can aid USN address the operational

requirements via synthesis of limited observations and prediction. We have determined that ice ridging often occurs at the boundary of thick and thinner ice when the thicker ice is forced into thinner ice. When the wind forces thin ice towards and into thick ice, we don't see significant convergent ridging, but when wind forcing accelerates thick ice into thinner ice, convergent ridging commonly occurs. This different response is likely due to difference in the inertia between thicker and thinner ice and force of impact between floes, following $F = ma$.

Future research would benefit from detailed analysis of changes in atmospheric forcing in the Western Arctic, especially by assessing the impact of increasing occurrence and magnitude of Arctic cyclones on sea ice divergence/convergence. Further modelling and comparison of the impact of landfast ice on sea ice drift and deformation near- and off-shore would be of considerable help in the coastal Arctic areas, particularly along the Alaskan coast in the Chukchi and Beaufort seas but also within the Gulf of Amundsen and over the eastern Beaufort shelf. Quantifying the impact of higher model resolution, such as RASM with 2km grid spacing, and comparing modeled sea ice behavior and trends between models at increasing resolution will allow understanding the benefits of explicitly resolved model physics for modeling and prediction of the Arctic evolving physical environment, including its sea ice.

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