Understanding the Factors Contributing to Pressured Ice in the Hudson Strait, Canada: an interdisciplinary analysis of winter ship besetments

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A thesis submitted to the University of Ottawa
in partial fulfillment of the requirements for the degree of
Master of Science in Geography

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Abstract

Ice strengthened vessels travelling through Arctic waters can have extreme difficulty passing through areas of ice pressure. Pressured ice and ice ridges can cause ships to become stuck, or beset, introducing additional environmental and economic costs. Understanding where and when ridges are forming along a shipping route would allow for better planning of safe winter navigation through ice-covered waters, however, there are many dynamics involved in the formation of pressure ridges that makes forecasting them with accuracy, in a specific geographic region, incredibly difficult. Winter shipping operations, in the Hudson Strait, Canada, are often impacted by pressured ice and ridges, sometimes causing ships to be delayed for several days at a time. Meteorological data is used in this thesis study to 1) to determine if land based meteorological data from weather stations can be used as a proxy for weather conditions experienced by ships in the marine areas where pressured ice and ridges are common, and 2) better understand the possible climatic factors that influence the besetment of ships in pressured ice in the Hudson Strait. This study is completed using information from ship logbooks detailing the difficult ice conditions encountered by ships transiting through the Hudson Strait in the winter months, and compares meteorological data from a land based station in Salluit, QC to meteorological data recorded on a ship, nearby, in the Hudson Strait.

There was moderate statistical significance found when comparing the meteorological data recorded at the land based station and the data recorded on the ship when it was nearby. The results of this study show that the land based meteorological data from the Salluit station can be used to understand the variability of the meteorological data in the marine area nearby, in the Hudson Strait. This study did not find a pattern when comparing the meteorological data recorded prior to transits that progressed with ease against the transits that progressed with difficulty through the Hudson Strait in the winter months. As a result, for the chosen study transits, the meteorological data available from the land based station in Salluit could not be used to predict situations of significant pressure ridging in the nearby marine area. Using reanalysis data, this study did find similarities in atmospheric pressure patterns and wind patterns, when investigating the conditions leading up to the chosen difficult transits. This finding indicates that large scale atmospheric patterns can influence, and can be used to better understand, ice drift and convergence of the ice pack in certain regions. Convergence of the ice pack can create pressure ridges and result in more difficult ice conditions for transiting ships. This research fills an important knowledge gap in understanding what meteorological conditions have a strong influence on ice dynamics impacting the difficulty that ships can have when transiting the Hudson Strait in the winter months.

Acknowledgments

I would like to thank my supervisor Dr. Jackie Dawson for all of the support and guidance she has provided throughout the writing of this thesis. I am very appreciative of all the opportunities she presented me with. I would also like to thank my committee members Dr. André Viau and Dr. Stephen Howell for their valuable support and advice throughout my Masters.

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List of Acronyms

AIRSS	Arctic Ice Regime Shipping System
CAA	Canadian Arctic Archipelago
CIS	Canadian Ice Service
FYI	First year ice
HBC	Hudson Bay Complex
HS	Hudson Strait
IPCC	International Panel on Climate Change
LIC	Low Impact Corridors
MARPOL	International Convention for the Prevention of Pollution from Ships
MYI	Multi year ice
NORDREG	Vessel Traffic Services Reporting Zone Arctic Canada
NSR	Northern Sea Route
POLARIS	International Code for Ships Operating in Polar Waters
SOLAS	International Convention for Safety of Life at Sea
TSR	Transpolar Sea Route
ZOI	Zone of Interest

CHAPTER 1: INTRODUCTION

1.1 Introduction

Air temperature in the Arctic is increasing faster than elsewhere in the world (Blunden and Arndt, 2017) and has played a key role in a declining sea ice extent, observable since the beginning of the satellite record in 1979 (Serreze et al., 2016; Serreze et al., 2009; Strove et al., 2011). An increase in both surface air temperatures and sea surface temperatures have been observed (Stroeve et al., 2014; Stroeve et al., 2008) coupled with an accelerated decrease of Arctic sea ice in the past 2 decades (Serreze & Stroeve, 2015; Simmonds, 2015; Stroeve et al., 2014; Stroeve et al., 2008). These increases in temperature, delayed freeze-up dates, and earlier melt seasons are impacting the length of the open water season (Stroeve et al., 2014). The Arctic Ocean can absorb a greater amount of heat during longer open water seasons, leading to an ice cover that is more vulnerable to warmer air temperatures, and decreases in sea ice extent and thickness (Stroeve et al., 2014). These changes in climate and ice have improved the maritime navigation conditions in the Arctic and have influenced higher rates of shipping activity in Arctic waters including an increase in tourism, cargo transport, fishing, and tanker activities related to resource extraction (AMAP, 2012; Pizzolato et al., 2016; 2014).

It is is predicted that there will be continued reductions in sea-ice extent and thickness in the future. Along side these changes, shipping activity along major shipping routes of the Northern Sea Route, Transpolar Route, and the Northwest Passage (NWP) are expected to continue to rise (Gascard et al., 2017; Melia et al., 2016; Smith and Stephenson, 2013). With greater open water areas and longer melt seasons, it is likely that we will also see vessels traveling at faster speeds through the Canadian Arctic waters. As discussed by Kubat et al. (2005), an increase in speed and frequency of Arctic vessels will result in a higher potential of vessel damage and associated pollution to the Arctic environment. Sea ice changes are highly spatially and temporally variable across the Canadian Arctic (Gascard et al., 2017; Tivy et al., 2011), the regional variability in ice conditions will continue to have significant impacts on the navigational safety of vessels traveling through the Canadian Arctic. Shipping through Arctic waters also poses additional risks due to the remoteness as well as the harsh conditions (Vanguard, 2015).

Multi-year ice is the most significant hazard to transiting ships, however, another form of hazardous sea ice that ships can encounter when navigating through Arctic waters is ice "under pressure". This type of sea ice occurs when winds, tides, or currents interact in regions where ice concentration is high and can pose a significant threat even for highly ice-strengthened vessels (Kubat and Sudom, 2008; Mussells et al., 2017). Ice-ship collisions in Arctic waters can significantly damage a vessel (Kubat et al., 2014) and pose serious consequences such as possible pollutant spills (Vanguard, 2015). Between the late 1970s and the early 2000s, there were over 200 reports of vessels damaged by ice and around 1/3 of those incidents had the potential to cause environmental pollution (Transport Canada, 2003) The harsh conditions in the Arctic are likely a cause of the disproportionate amount of accidents that occur there, despite the limited number of ships that transit the area (The Council of Canadian Academics, 2016). A study by Valdez Banda et al. (2015) found that winter shipping accidents most commonly occurred in consolidated ice and ridged ice. In 2008, Kubat and Sudom conducted a survey on captains and ship operators who worked in the Arctic and noted that ice under pressure can be extremely hazardous to ships and that more information is urgently needed about where and when pressure is developing.

Ship captains commonly use the operational ice charts created by the Canadian Ice Service (CIS) when they are navigating ships through ice-infested waters to help them when making important navigational decisions (M. Kean, personal communication, March 5, 2018). However, ice charts show details of ice patterns at a larger spatiotemporal resolution than is needed to understand the intricacies of sea ice that result in the formation of areas of pressure. The majority of research on pressure ridges that has been completed to date has been completed at the scale of a few kilometers (Kubat and Sudom, 2008; Kubat et al., 2012) or used satellite imagery to investigate ridge formation (Mussells et al., 2017, 2016). Shipping companies and captains are calling for more detailed research in order to improve the understanding of the formation of pressure ridges at a ship scale. Additional understanding of the formation of pressure ridges could improve models and forecasts that are used to predict the location and timing of ridges.

1.2 Project Objectives

The overarching goal of this study was to improve understanding of the presence, formation, and impact of pressured ice in the Hudson Strait, Canada where bulk carriers provide year-round service to the Raglan Nickel mine in Deception Bay, Quebec. Pressure events and resulting ice ridges are common in the Hudson Strait region throughout the winter season

(Mussells et al., 2017). These ice conditions create navigation hazards for the ice-strengthened vessels that are regularly traveling through the Strait to service the Raglan mine. To respond to the need identified by ship captains and shipping companies to improve the understanding of pressured ice as a navigational challenge, this research focuses on pressure ridges that were historically encountered by ships along the shipping route to/from the Raglan mine in the Hudson Strait between 2005 and 2017. These shipping events were analyzed in relation to relevant meteorological conditions that were recorded in the same spatial and temporal periods. Understanding weather related risks when navigating through ice-covered waters is important for risk mitigation in the Arctic (Gascard, 2017).

The main objective of this study was to better understand the key weather variables that are important to the development of pressure ridges in the Hudson Strait.

More specifically, this project was focused around 3 main objectives:

1) Investigate the reliability of using meteorological variables from regional land based weather stations be understand the weather conditions being experienced locally by ships transiting the Hudson Strait near Deception Bay;
2) Conduct a sea ice climatology to gain a better understanding of the sea ice patterns in the Hudson Strait and the influence they might have on the dynamics of ice conditions for transiting ships;
3) Discern the relative role of different meteorological variables in influencing the formation of pressure ice situations that caused historic besetments of the *MV* Arctic in the Hudson Strait, Canada.

1.3 Study Region: the Hudson Strait

1.3.1 Background

The study region for this project is the Hudson Strait (HS) in the Hudson Bay Complex (HBC) of Arctic Canada. The HS is a narrow passage between the Hudson Bay basin and Canadian Arctic Archipelago (via Fury and Hecla Strait) to the North Atlantic Ocean. The HS is bordered by Baffin Island to the north and by northern Quebec and Ungava Bay to the south (Figure 1) and is covered annually by ice for more than 8 months of the year (Drinkwater, 1986; Saucier et al., 2004). In recent years, there has been a significant decline in the sea ice coverage at ~20% per decade (Derksen et al., 2012; Galbraith and Larouche, 2011; Hoccheim and Barber, 2010). The average ice breakup date in the HS has occurred 17.5 days earlier, and average freeze up date has occurred 16.8 days later, in 1996-2015 vs. average break up and freeze up dates in 1980-1995 (Andrews, et al., 2017; Hochheim and Barber, 2014). This trend is consistent with the findings of several other studies documenting earlier sea ice retreat in the Canadian Arctic (Collow et al., 2015; Kowal et al., 2015; Markus et al., 2009; Serreze and Stroeve, 2016; Stroeve et al., 2014, 2011).

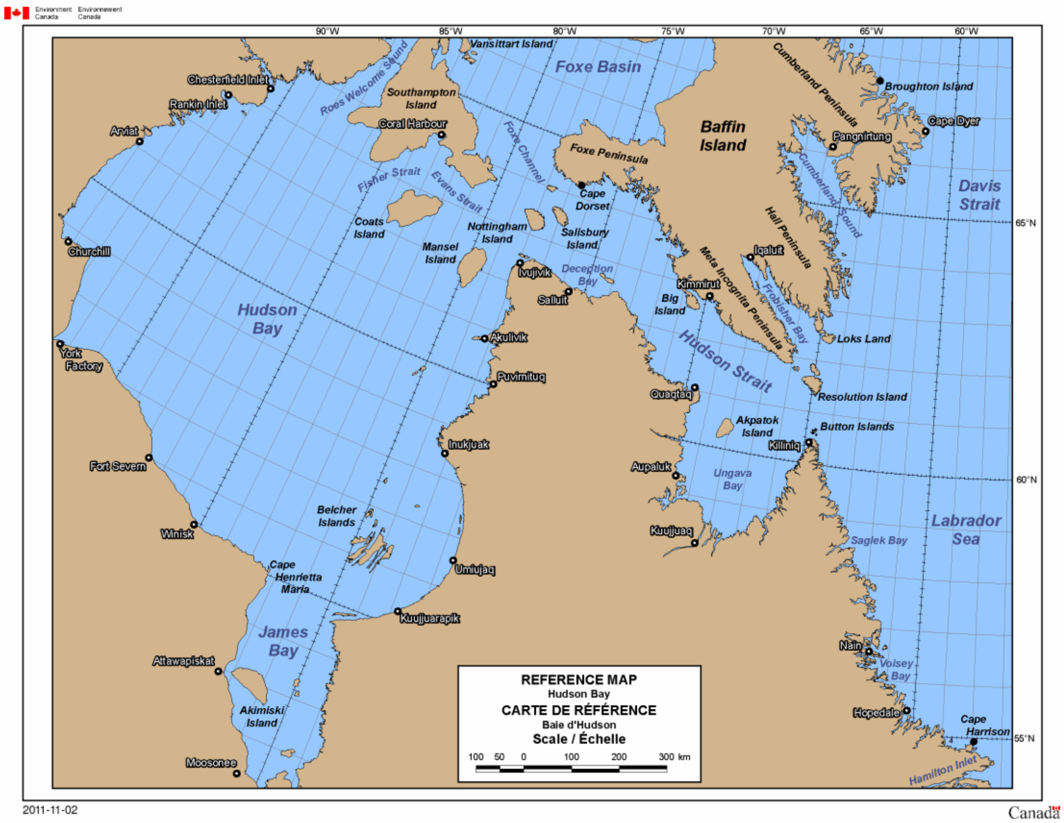

Figure 1. Map of the Hudson Bay Complex (Canadian Ice Service, 2011).

The HS experiences high volumes of shipping activity attributed to diverse shipping purposes throughout the year (e.g. Pizzolato et al., 2016). Between 2007 and 2013 an average of 59 unique vessels made an average of 176 transits through the HS (Vard Marine Inc. 2015). Only vessels that reported to NORDREG were included in the calculation, and therefore smaller vessels, including pleasure craft, recreational boats, and other private vessels may not have been captured (Vard Marine Inc. 2015).   Although most transits through the HS occur in the summer, ice breaking cargo vessels service the Raglan and Nunavik mine sites via Deception Bay, QC, year round (Vard Marine Inc. 2015).

Between December and May, when the HS is fully ice-covered, the sea ice can be very difficult to travel through, even for ice-breaking vessels (Mussells et al., 2017). During periods of high ice concentration, the ice floes in HS are still mobile making transits more challenging. Ice floe movement through the Strait is influenced by a variety of factors such as ocean currents, winds, tides, proximity to land, and ice concentration and thickness (Kubat and Sudom 2008). As ice floes converge, the ice can be put under immense pressure. Ridges of 2-3 m in height have been observed in the HBC (Markham, 1986).

Regions of high ice pressure can be hazardous for ships transiting the passage, and can cause them to become beset (Mussells et al., 2016). In the HS, when a vessel is trapped in ice, or beset, they must attempt to free themselves, and when free, they must try to continue through the ice by repeatedly backing the ship and ramming the ice ahead (M. Kean, personal communication, March 5, 2018). This process of 'backing and ramming' results in the use of more heavy fuel oil (HFO) and the emission of more greenhouse gases. In some situations, the ship must wait until the pressure is released (M. Kean, personal communication, March 5, 2018). A trapped vessel may require assistance from an icebreaker, or may experience damage from the pressured ice resulting in pollution to the environment (Kubat and Sudom 2008). The situations arising from a ship becoming beset can be financially costly, and environmentally damaging. A better understanding of the formation and release of pressure events in the HS would provide insight that could allow for improved navigational safety of shipping operations through the Strait (Mussells, 2016).

1.3.2 Oceanography of the Hudson Bay Complex

The HBS is composed of freshwater as a result of a large riverine input as well as inflows of Arctic water from Fury and Hecla Straits (Drinkwater, 1986). The Strait has an average width of 100 km, depth of 300-900 m, and runs northwest for 400 km from is eastern entrance (Saucier et al., 2004; Staneo and Saucier, 2008). Although the net volume of flow is outwards from the Strait towards the Atlantic Ocean, currents in the Strait run in opposite directions (Staneo and Saucier, 2008). The northwest current flows into the HBS, along Baffin Island, and the southeast current flows out of the HBS along the northern Quebec coast. The eastern entrance to the Strait is characterized by strong turbulent flows as a result of strong tides meeting tides and islands (Staneo and Saucier, 2008).

1.3.3 Seasonal variability of sea ice in the Hudson Strait

Sea ice in the HBS is influenced by strong tidal currents (tidal range can be higher than 12 m in Ungava Bay), local and regional atmospheric forcing, and oceanic conditions in Baffin Bay, the Labrador Sea, and the Arctic Ocean (Saucier et al., 2004). Air masses originating over the Canadian Arctic Archipelago (CAA) are important determinants of the climate in the region as cold, dry, continental type air masses from the CAA flow southward over the Strait (Drinkwater, 1986). The influence of the Arctic air mass over the Strait keeps the temperatures in the region below zero for 8 months of the year (i.e. October to May)(Drinkwater, 1986).

The HS is seasonally ice covered following completely ice-free summers. Based on the CIS 30-year climatological period (1981-2010), by December 4th, most of the HS is ice covered (Figure

2). Ice concentration is described by the fraction of a total area covered by ice. This fraction is measured in tenths, meaning 50% ice coverage in an area would be described as 5 tenths (5/10) ice concentration. Figure 3 shows the average freeze up progress in the HS, based on concentration of ice cover (in tenths) from the middle of November to the beginning of January. The HS begins freeze up on the western side, with ice first beginning to form in Foxe Basin during November (figure 3A). The ice cover then extends to western HS by the end of November, growing from the coastlines (figure 3B). By December 4th, most of the Strait is ice covered, with just the eastern entrance and Ungava Bay remaining predominantly ice free (figure 3C). By January 1st, the entire HS is 9-9+ tenths covered in sea ice. By this time, there is also a significant amout of land fast ice (i.e. ice locked to the shore), between 110-160cm (Drinkwater, 1986), that has formed along the southern coast of Baffin Island and in the inlets along the northern Quebec coast (figure 3D). Throughout the winter, polynyas, large and reoccurring cracks of open water, commonly open up along the southern coast of Baffin Island due to prevailing winds from the northwest (Catchpole and Faurer, 1983).

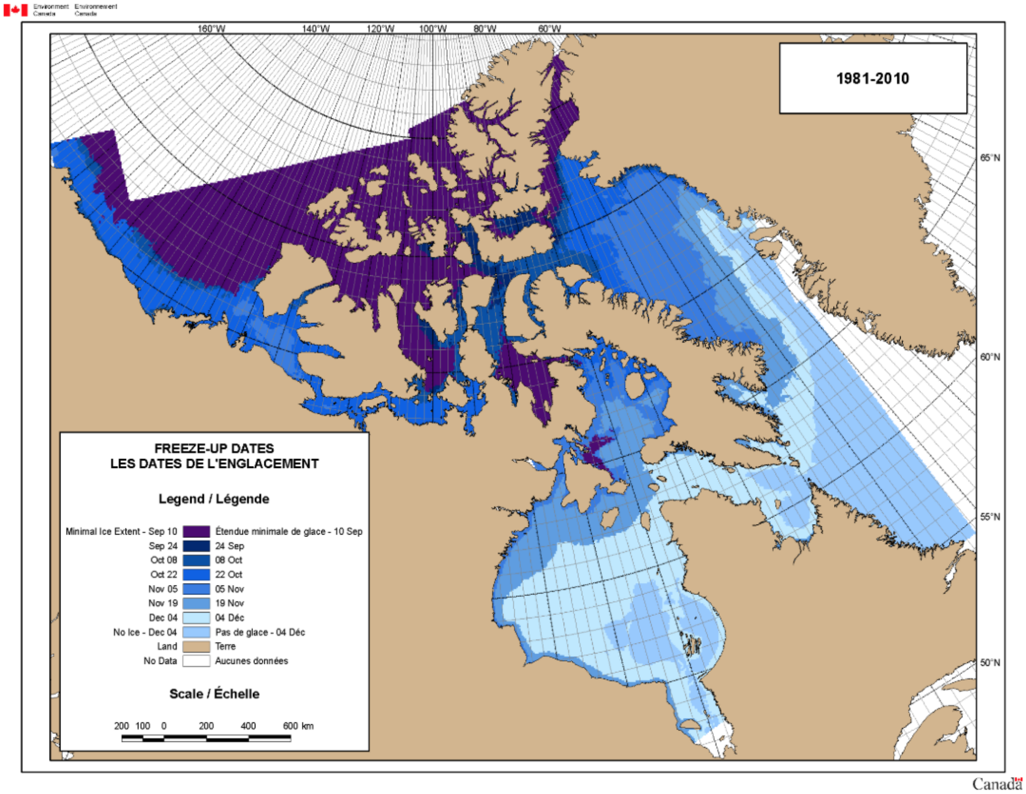

Figure 2. Median freeze-up dates in the Hudson Strait, 1981-2010 (CIS, 2011).

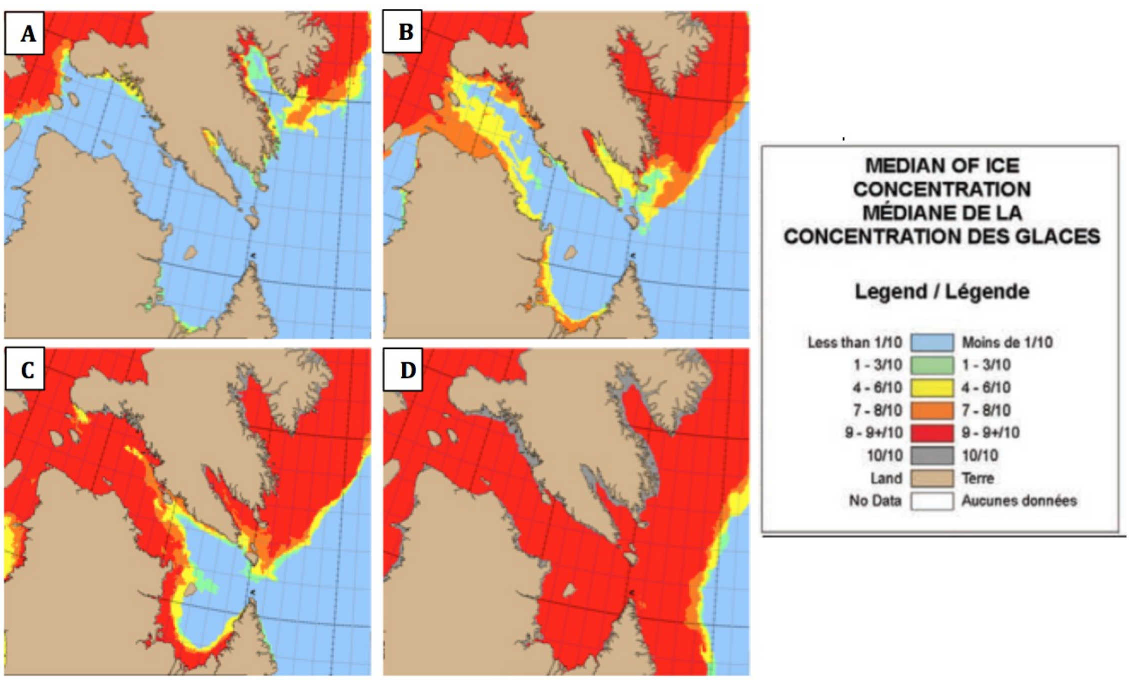

Figure 3. Median sea ice concentrations in the Hudson Strait on November 19 (A), November 26 (B), December 4 (C), and January 1 (D) based on a 30 sea ice climatology from 1981-2010 (CIS, 2011).

A combination of ice melt and transport out of the Strait play a role in the annual summer clearing of the HS. As temperatures warm, and ice begins to melt, leads become more frequent in the southern regions of the Strait, until the remaining ice pack is restricted to Ungava Bay (Catchpole and Faurer, 1983). Galbraith and Larouche (2011) found that the seasonal shift from ice covered to open water area occurs relatively quickly in the HBS, with a recorded average of 90% to 10% coverage in 7.8 weeks in Hudson Bay, and similar findings in the HS.

The earlier ice break up in the HS recorded in recent years (Andrews et al., 2017; Hochheim and Barber, 2014) coincides with increasing air temperatures in the region. Specifically, records for the HS show that, of the 19 warmest summers on record, 11 occurred between 1991 and 2009 (Galbraith and Larouche, 2011). Moreover, Joly et al. (2011) estimated that temperatures could likely rise an average of 3.9°C in the HBS region, with higher rates of warming occurring in the winter than in the summer by the mid-century or end of century. This study indicates a warming scenario that would result in the sea-ice season in the HBS being reduced by 7-9 weeks (Joly et al., 2011).

1.3.4 Pressured ice and ridges in the Hudson Strait

Pressure ridging of ice is common in the HS as the ice concentration in the winter is high, and the ice remains mobile (Mussells et al. 2016). Mussells et al. (2016) found that ice ridges often occurred in the shear zone at the entrance to Deception Bay, at the entrance to the HS near Resolution Island, and in the area between Charles Island and the coastline. Mussels et al. (2016) also found that low ridging seasons often had a more variable freeze up and break up period. Mussels et al. (2017) found similarities when looking at the amount of time the *MV Arctic* spent beset and the density of ridging across the HS. Higher density of ridges was often associated with more besetments. However, great variability still existed when looking at the difficulty the *MV Arctic* had as it transited through zones identified with high ridge density. Transiting some areas identified with high ridging density, the *MV Arctic* did not become beset, while she did become beset while transiting some areas with low ridge density (Mussels et al. 2017). Between the 1997-98 and 2011-12 winter season, no significant change in the number of ridges identified over time was discovered, although the number identified from year to year varied (Mussells et al., 2017).

1.3.5 Atmospheric circulation patterns affecting the Hudson Strait

Winds have been discussed as a driving factor creating pressured ice and ridges (Mussells et al., 2016; Kubat et al. 2012). Geostrophic winds have been shown to be important determinants of ice drift on short time scales (Kwok, Pang and Kacimi, 2017; Thorndike and Colony, 1982). While winds commonly move from areas of high pressure to areas of low pressure, ice drift has been found to occur along isobars of atmospheric surface pressure (Leppäranta, 2011; Thorndike and Colony, 1982).

Atmospheric pressure in the HS is dominated by a low-pressure system over the Davis Strait causing north to north-westerly winds to be prominent, due to the cyclonic nature of the low pressure system (Drinkwater 1986). This system brings cold continental Arctic air over the HS. Anomalies in atmospheric circulation have been found to have an impact on the patterns of advance and retreat in the HS (Drinkwater 1986). Northerly winds often bring an earlier ice advance season, and are associated with an intense low system over the north Atlantic, specifically south-west Greenland and the Davis Strait. Westerly winds over the HS are associated with a low centered over southeastern Baffin Island. Southerly winds are discussed as bringing an earlier ice retreat in the HS and are associated with low-pressure systems centered over Foxe Basin or Northwest Quebec (Drinkwater 1986). Mussels et al. (2016) found that most seasons with low ridge densities, between 1997 and 2012, had anomalous high-pressure anomalies over HS.

1.3.6 Shipping patterns in the Hudson Strait

The HS is used as a shipping route for diverse purposes throughout the year consisting of cargo ships traveling from the Port of Churchill, community re-supply ships, tourism ships such as cruise ships and private yachts, and vessels servicing resource extraction operations (Vard Marine Inc., 2015). Between 2007 and 2013 an average of 59 unique vessels made an average of 176 transits through the HS (Vard Marine Inc. 2015). Pizzolato et al. (2016) show that, between 1990 and 2015, the HS experienced the strongest significant increase in shipping activity compared to other regions in the Canadian Arctic (also see Dawson et al., 2018). One main reason for vessel transits through the Strait is that the Strait serves as a shipping access route to the Port of Churchill, Manitoba however, the port closed in 2016 and its future use was uncertain (Andrews et al., 2017). In 2018, a new company, the Arctic Gateway Group, purchased the Port of Churchill and railroad and proceeded to repair the railway to allow for continued use of the port (Barghout, 2018). The federal government also contributed financially to facilitate the change of ownership and repairs of the port and railroad (Kavanagh, 2018b).

With the railroad fixed, the Port of Churchill will reopen and there will be potential for increased ship traffic in the area.

Resource extraction voyages are also responsible for heavy ship traffic through the HS in the winter season (Vard Marine Inc., 2015). The Raglan nickel mine, one of two operational mines on the shores of the HS, is serviced year round by an ice-breaking vessel, the *MV Arctic* (figure 4), owned by Fednav Ltd. shipping company. Between 2005 and 2014, the *MV Arctic* completed 33 one-way winter transits through the HS (Mussells et al., 2017). With a global demand for natural resources and promising possibilities of resource extraction due to easier access to remote locations and more feasible transportation of products, it is likely we will see continued exploration in the region (AMAP, 2012). Even if no additional offshore oil extraction or coastal mining operations are established, vessel traffic will likely rise even with exploration initiatives (AMAP, 2012).

Figure 4. Photo of the MV Arctic, (Fednav, 1978).

1.4 Outline of thesis

This thesis is article based and is organized by chapters. This first chapter is an introduction to the thesis and as seen above includes some background information on the study topic and region. The second chapter outlines some of the key literature and fundamental areas of information for the thesis topic such as relevant definitions, information on sea ice, shipping trends, risks, and regulations in the Arctic. The third chapter is formatted as a research article, with the intention to develop the work into a peer reviewed journal article. The title of the research article is: "Understanding of Factors Contributing to Pressured Ice in the Hudson Strait, Canada: an interdisciplinary analysis of resource ship besetments". The introduction and study area section of the research article necessarily include some repition from the other thesis chapters, in order to ensure that the arcticle can stand on its own as a single document. The final chapter outlines the study conclusion incluidng some final comments, a desctiption of the limitations of the study, and a comment on future research directions and needs.

CHAPTER 2: BACKGROUND

2.1 Sea Ice Properties, Thermodynamics and Dynamics

2.1.1 Physical Properties of Ice

In order to investigate the causes and impacts of pressured sea ice, it is important to understand the basic physical properties of sea ice. Sea ice is frozen ocean water that consists of ice crystals, solid salts, air, and brine. It is commonly classified by age; first year, second year, and multiyear ice. First year ice (FYI) forms as air temperature cools below the freezing point, which allows surface waters to freeze over. The maximum thickness of FYI that has not been deformed is ~2 m (Maykut and Untersteiner, 1971). FYI that survives through the summer melt season gets reclassified as second year ice (SYI) on October 1st. Ice that survives more than 2-years is called multi-year ice (MYI), although SYI is sometimes grouped into this label as well. As ice ages through the winter season, or over several years, the brine is rejected downwards through the icepack resulting in lower salinity making the ice stronger and more hazardous to transiting ships (Canadian Coast Guard, 2012).

2.1.2 Sea-ice thermodynamics

Sea ice thermodynamics are the processes that cause the freeze up and melt of sea ice and are important in determining ice coverage extent and thickness. The interaction between sea ice thermodynamics and sea ice dynamics (described below) is important in the build-up of sea ice pressure. Sea ice thermodynamics will be described through the categories of freeze up, winter, melt onset and advanced melt.

2.1.2.1 Freeze up

Sea ice forms when surface air temperatures drop below zero and cool the surface layer of the ocean. As the surface water lowers in temperature, the density of the water increases (Canadian Coast Guard, 2012). This change in density causes convective mixing, however in the Arctic Ocean, this mixing is moderated by the salinity and density stratification of the water column. As air temperature drops, the cooler surface water cannot sink below the deeper more salty water, allowing the top layer of the ocean to cool below freezing and begin forming ice even before the rest of the water column has cooled. This allows ice to form very quickly (Serreze and Barry, 2005). Ice crystals then begin to cluster together towards the surface of the water forming a slush called frazil ice. As freezing continues, the crystals increase in size and number and together form a layer of frazil ice, called grease ice. As cooling proceeds, winds and waves interact to converge and pile grease ice, forming semi consolidated ice, or pancake ice, young ice and first year ice (Canadian Coast Guard, 2012; Omstedt, 1985).

2.1.2.2 Winter Ice:

During the winter, sea ice continues to thicken and consolidates into young ice and eventually FYI growing through bottom accretion. Young ice can be sub-divided into grey ice, with a thickness between 10-15cm, and grey-white ice, with a thickness between 15-30cm. When young ice is under pressure, it is more likely to raft than to ridge. FYI can be subdivided into thin FYI, with a thickness between 30-70cm, medium FYI, with a thickness between 70-120, and thick FYI, with a thickness over 120cm (Environment Canada, 2005). When thicker ice is put under pressure, more difficult navigation conditions exist (M. Kean, personal communication, March 5, 2018).

2.1.2.3 Melt Onset and Advanced Melt

Sea ice melt is initiated when air temperatures start to rise above 0° C. As snow cover on the sea ice begins to melt, ponds of water develop on the surface of the ice, first forming in depressions on the ice surface (Barber, 2005). These areas of pooling water on the ice surface contribute to lower surface albedo, advancing the absorption of incoming solar radiation and increasing the sea ice melt (Eicken, 2003). Thaw holes develop as surface puddles melt through the ice pack to the water below reducing the strength of the ice (Environment Canada, 2005).

2.1.3 Sea-ice dynamics

When the ice is not land fast (i.e. locked to the shore), it is in constant motion due to external forces of wind and water stress (Kubat et al., 2014). This dynamic motion causes the convergence and divergence of ice, changing its thickness, concentration, and distribution (Serreze and Barry, 2005). These processes can result in the creation of pressure ridges.

2.1.3.1 Lead and Polynyas

Leads, or polynyas, are large cracks of open water that open up between ice flows, or between the shore and the ice pack. These cracks are important for heat transfer from the ocean to the atmosphere as they allow the water to interact directly with the atmosphere above, without insulation from the ice cover. Leads are linear breaks in the ice that commonly re-freeze quickly in the winter months, while polynyas are larger, non-linear, openings that have not yet re-frozen and that are quasi-stationary, sometime even reoccurring on an annual basis (Khvorostyanov et al., 2003). The presence of leads and polynyas is important for navigation as they indicate that the ice is not under pressure in that area (M. Kean, personal communication, March 5, 2018). The presence of even a small crack (a few cm wide) can ease navigation through a difficult consolidated ice cover (M. Kean, personal communication, March 5, 2018).

2.1.3.2 Divergence

Divergent forces occur when winds and currents combine to reduce ice concentration and release ice pressure (figure 5). When this deformation causes ice floes to become thinner and move apart, cracks open up in the ice, exposing open water (Serreze and Barry, 2005). These cracks, as described above, are called leads or polynyas.

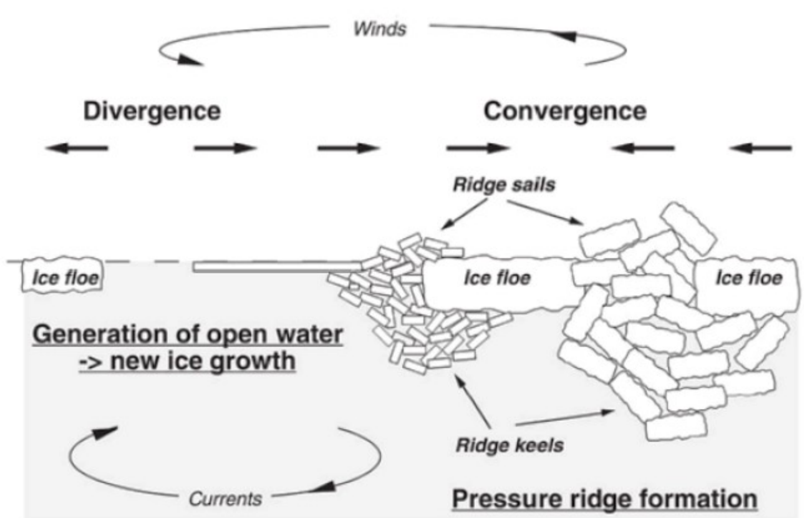

Figure 5. Divergent and convergent ice processes and the formation of pressure ridges (Haas, 2003).

2.1.3.3 Convergence and pressure ridges

Oceanic and atmospheric forces work together to cause the closing, or convergence, of the ice cover resulting in the rafting and piling of ice floes (figure 5)(Kwok, 2001; Serreze and Barry, 2005). The driving forces involved include wind, currents, tide, and swell (Canadian Coast Guard, 2012; Kubat and Sudom, 2008). Convergence increases the ice concentration and creates pressure in the ice, initiating the formation of pressure ridges (Rigor et al., 2002). In addition to atmospheric and oceanic forces, several factors including ice concentration, ice breakup, floe size, and proximity to land play a role in the formation and size of pressure ridges (Kubat and Sudom, 2008). Ridges form by either compression or shear forces, both resulting in ice blocks breaking off at the location of convergence and freezing together over time. The accumulation of ice occurs above and below the waterline creating both a stack of ice above (sail) and a below (keel) the surface (figure 5,6). For first year ridges, the keel of the ridge is usually around 4 times as deep as the corresponding sail (Timco and Burden, 1996). Keel depths of 50 m have been known to occur, but are more commonly found at depths between 10-25m (Wadhams, 2000). Examples of pressure ridges encountered by the MV Arctic while transiting the Hudson Strait can be seen in figures 6-8.

Figure 6. Pressure ridge showing sail above waterline and keel below waterline. (Ogilvie, 2019).

The build up of ice pressure can be greatly influenced by local conditions and coastlines (Kubat et al., 2014). Pressure ridges commonly form where mobile ice comes in contact with landfast ice, such as at a shear zone, or when the ice is forced through a bottleneck as a result of the geography of the area(Kubat and Sudom, 2008). The shear zone is where the mobile pack meets the land fast ice. As the mobile pack moves past the landfast ice, it can grind against it, causing the creation of pressure ridges and deformed ice (Bourbonnais and Lasserre, 2015; Leppäranta, 2011). Over time, the continued motion of the pack ice against the shear zone can create a highly compacted and ridged zone (Bourbonnais and Lasserre, 2015; Mussells et al., 2017). Pressured ice ridges also frequently occur in areas where leads or polynyas have recently refrozen, as the new ice is less strong than the surrounding ice (Wadhams, 2000). When ridges begin to break up, it does not occur all at once; rather they break up slowly by the dislodgement of blocks. The amount of time it can take a pressure ridge to dissipate is variable and influenced by the concentration of the ice sheet and the geography of the area (Kubat and Sudom, 2008).

Figure 7. Pressure ridge beside MV Arctic, while vessel is stuck in shear zone in February 2019. (Ogilvie, 2019).

In areas of seasonal sea ice cover, with rarely any MYI and icebergs that flow through, pressured ice and ridges can present the largest stress that vessels could encounter traveling through the ice. In high ice concentration, regions of heavy ridging, as a result of previous ice pressure, can still be challenging for a ship to pass through after the pressure has released (Mussels et al., 2016; Timco et al., 2000). Pressured ice and ridges are very hazardous challenges to vessels traveling through the ice, and to offshore structures (Kubat et al., 2014; Kubat et al., 2011; Timco et al., 2000).

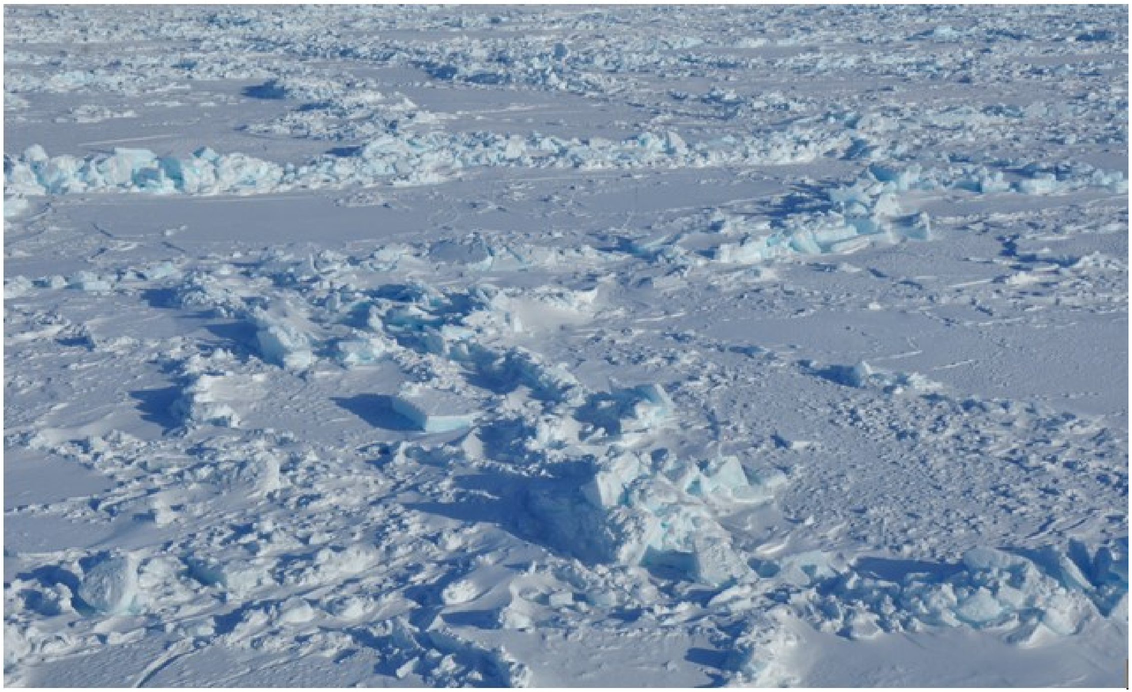

Figure 8. Sea ice ridges in the Hudson Strait, February 2018 (Ogilvie, 2018)

A report created by Vard Marine Inc. (2015) evaluated the risk of ship besetment in the HS and established the risk level of “medium” (figure 9). This risk was defined based on the fact that there is a high likelihood of besetment when navigating through the HS in the winter months, and as well the potential consequences of besetment could be significant. An increase in traffic through the HS, specifically if it were to include less experienced operators or less capable ships, would increase the risk of an accident (Vard Marine Inc., 2015).

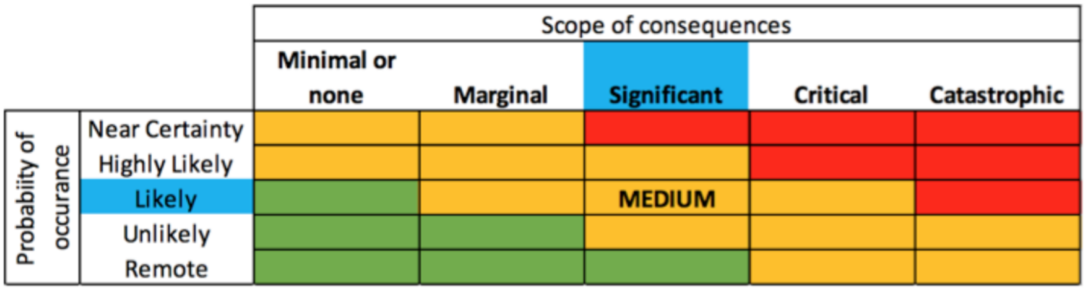

Figure 9. Risk Evaluation of ship besetment in the Hudson Strait (Vard Marine Inc., 2015).

2.2 The impact of sea ice changes on shipping

2.2.1 Changes in shipping activity through the Canadian Arctic

Pizzolato et al. (2016) found significant increases shipping activity, between 1990-2015, in the HS, Beaufort Sea, Baffin Bay, and regions in the southern route of the Northwest Passage (also see Dawson et al. 2018). When comparing increased shipping activity with reductions of sea ice, this study found significant correlations in some regions of the Canadian Arctic. These regions were primarily in multiyear ice-dominant regions (such as the Beaufort Sea) rather than seasonal sea ice regions (such as the HS) (Pizzolato et al., 2016). Although some studies have focused on the increase in opportunity for Arctic shipping due to longer open water seasons (e.g. Barnhart et al., 2015; Smith and Stephenson, 2013), several studies suggest that current changes in shipping patterns are more a result of tourism trends, commodity prices and natural resource development (e.g. Bensassi et al., 2016; Brigham, 2011; Dawson et al., 2014; Pizzolato et al., 2016).

Currently, the majority of commercial shipping in the Canadian Arctic is destinational traffic, rather than through traffic, or transit shipping (PEW, 2018). Two main types of commercial destination traffic in the Canadian Arctic include shipping to and from mining operations and the annual sea-lift, delivering supplies to Arctic communities (PEW, 2018). Tourism vessels visiting locations in the Canadian Arctic also fall under the category of destinational shipping. With climate change, several scientific papers have been published discussing the future possibility of through shipping across the Arctic under the assumption that new transit routes will open up with sea ice decline (Aksenov et al., 2017; Khon et al., 2017; Melia et al., 2016; Smith and Stephenson, 2013; Stephenson et al., 2011). The idea that diminished sea ice in the Arctic could open up Arctic shipping routes such as the Northwest Passage (NWP), the Northern Sea Route (NSR) and Transpolar Sea Route (TSR) has also been widely discussed by the media (Barghout, 2018; Black, 2011; Vidal, 2013; Macalister, 2011; Parfit, 2017;).

The transit distance from North America to Europe or Asia via the Arctic, rather than the Panama or Suez canals, is thousands of kilometers shorter saving fuel, time and costs to shipping companies, in theory (Khon et al., 2017; Melia et al., 2016; Stephens, 2016). In reality, there are many additional complications for ships transiting through Arctic waters, such as sea ice, uncharted seas, extreme weather conditions, and increased risks due to remoteness (Stephens, 2016). In 2018, China published a report on their Arctic policy, highlighting their interest in increased shipping across Arctic waters, and encouraging improved infrastructure in the Arctic to allow for safe international trade through Arctic waters (Ministry of Foreign Affairs of the People's Republic of China, 2018). For Canada to promote shipping through the NWP to China, it would need to make significant investments. This is required to make the route a safer option and to avoid potential liability considering that the route is claimed by Canada as inland waters (Huebert, 2009; Stephens, 2016). The region requires additional investment in Arctic ports, search and rescue services, improved charting and hydrography, and additional clarity on the proposed 'Low Impact Corridors' (LIC) (PEW 2015; Stephens, 2016).

The LIC are routes that are being developed across Arctic Canada, and which are being discussed in other regions of the North American Arctic, where services and infrastructure will be prioritized and where ship traffic is encouraged to transit. In Canada, Transport Canada, the Canadian Coast Guard, and the Canadian Hydrographic Service are leading the initiative, but it has been slow to develop and there has been significant confusion regarding the implementation of the LICs (see PEW 2015; Chénier et al. 2017)(also see Section 2.2.5 for additional detail on the LIC). Given these factors, it is unlikely that through ship traffic through the NWP will increase drastically in the short-term future. However, with climate change and technological developments in ship design, the geopolitical and economic interests in shipping throughout the Arctic will make significant increases in through traffic a distinct possibility in the medium to long-term future.

2.2.2 Necessity for vessels transiting through the Canadian Arctic

Many different types of vessels navigate through Canada's Arctic waters for various purposes (Table 1). With over 100 000 Canadians living in Northern communities, marine transportation of supplies is an essential lifeline to re-supply necessary commodities to these communities (Hodgson, 2013). Alternative methods of re-supply by rail, motor vehicle, or by air are often not available, or too expensive, making marine deliveries indispensable for the livelihood of these people (Hodgson, 2013). An increase in population in Northern communities, or increase in remote workers at new resource extraction operations, would result in a higher demand for marine re-supply voyages. A global demand for natural resources has the potential to increase offshore oil exploration and proposed northern resource extraction projects, both of which would increase shipping activity in the Arctic to support the operations (Hodgson, 2013). Pleasure Craft and Cruise ship activity has been increasing as cruise tourism, one of the fastest growing sectors of Arctic shipping, is servicing a growing global desire to see the Arctic before it is totally transformed by climate change (Dawson et al., 2007, 2014; Hodgson et al., 2013).

Table 1. Description of different vessel types and their associated uses (Compiled from Arctic Council, 2009 (Table 5.2 and 8.1); Dawson et al., 2014).

Classification	Description	Ship Use
Government Vessels and Ice Breakers	Designed to navigate through ice-covered waters with a strengthened hull, and ice-clearing shape and the power to push through ice.	Coast guard vessels, research icebreakers (research, private, government), research vessels
Container Ships	Cargo ships that carry their load in truck-sized containers	Cargo transport
General Cargo	Designed to carry various types and forms of cargo	Community re-supply vessels, roll on/roll off cargo
Bulk Carriers	Designed for bulk carriage of ore but can also carry oil or loose or dry cargo	Timber, merchant, oil, ore, automobile carriers
Tanker Ships	Constructed to carry liquids or compressed gas	Oil tankers, natural gas tankers, chemical tankers
Passenger Ships	Ships that carry passengers	Cruise ships, ocean liners, ferries
Tug/Barge	Tugs are designed for towing and pushing and general work duties while Barges are non-propelled vessels designed to carry bulk or mixed cargoes	Re-supply vessels Bulk cargo transport
Fishing Vessels	Used for commercial fishing. Vessels	Small fishing boats,

	are often small, measuring close to 30m, but can be as large as 100m.	trawlers, whaling boats, fish processing boats
Oil and Gas Exploration Vessels	Designed for the exploration and extraction of natural gas and oil	Seismic, oceanic, and hydrographic survey vessels, oil drilling vessels, oil and gas storage vessels, offshore re-supply, portable oil platform vessels, other oil and gas support vessels
Pleasure Crafts	Small vessels used for personal voyages or small cruise tourism	Personal yachts, small cruise tourism vessels

2.2.3 Risks associated with an increase in Arctic shipping

Significant financial, environmental, ecological, socio-cultural, and governance risks and costs remain when navigating through unpredictable Arctic waters. Some additional financial costs that exist for organizing regular Arctic voyages compared to shipping in the south, include higher ship insurance costs, financing the construction of ice strengthened vessels, and paying the extra cost of hiring icebreaker support (Arctic Council, 2009; Hodgson, 2013). Environmental risks include an increase in heavy fuel oils (HFOs) being burned in the Arctic. HFOs are some of the most polluting fossil fuels and the emissions generated in sensitive Arctic environments can create negative environmental impacts (Yumashev et al., 2017). Ecological risks include introducing invasive species, and having ships pass through ecologically sensitive areas and disrupting or harming wildlife, such as through marine migration paths (Arctic Council, 2009; Hodgson, 2013). Lack of adequate or complete navigational charts can increase the risk of vessel grounding, which can result in both financial costs and environmental disasters from damaged ships (Vard Marine Inc., 2015). Socio-cultural impacts of increased shipping through Arctic waters include contributing to cultural degradation and shipping through traditional hunting grounds or areas of historical or cultural significance (Dawson et al., 2014; Inuit Circumpolar Council, 2008; Vard Marine Inc, 2015). Governance challenges also exist in determining who will be responsible to finance and coordinate the clean up of an environmental disaster or the cost of an emergency rescue mission.

Considering the interdisciplinary complexities involved, it is clear there are many increased safety risks when navigating through remote waters and difficult ice conditions (Arctic Council, 2009). To address some of these issues, the International Maritime Organization (IMO) has spent several years developing an International Code for Ships Navigating in Polar Waters (Polar Code) that went into force on 1 January, 2017. These new regulations are mandatory for all ships certified under SOLAS (International Convention for Safety of Life at Sea) and MARPOL (International Convention for the Prevention of Pollution from Ships). The Polar Code contains rules and regulations to increase environmental protection standards and reduce unpreparedness of vessels traveling through Arctic waters (IMO, 2015).

2.2.4 Regulations to reduce risk of ship accidents

In Canada, federal regulations are in place to dictate which strength a ship must be to travel through different parts of Canada's Arctic waters throughout the year. All shipping activity north of 60°N is regulated by the Artic Shipping Pollution Prevention Regulations (ASPPR) of the Arctic Waters Pollution Prevention Act (Andrews, et al., 2017; Transport Canada, 2010). Under the ASPPR, regulations are set based on permitted entry and exit dates for established shipping zones. This "Zone/Date System" allows ice-strengthened vessels longer access windows in zones otherwise off-limits to ships for that date (Andrews, et al., 2017; Transport Canada, 2010). As discussed by Andrews et al. (2017) the access windows in the “Zone/Date System” are out of date as they are based on sea ice conditions that existed when the ASPPR was developed in 1985. Transport Canada has responded to the need of a more flexible system for shipping regulations in Canadian waters by the implementation of the Arctic Ice Regime Shipping System (AIRSS) (Andrews, et al., 2017; Transport Canada, 2010).

AIRSS is based on a calculation that takes into consideration several factors such as ice conditions and vessel capabilities. The system assigns vessel classes based on a vessel’s strength, displacement and power for breaking ice and are grouped into to “Type” class or “CAC-Canadian Arctic Class” (Figure 8) (Transport Canada, 2003). CAC vessels are able to travel through more difficult ice conditions than Type Class vessels. Determined ice classes, however, do not always guarantee safe transit of a vessel through ice-infested waters. For the Hudson Bay region, a tourism vessel must have a minimum ice class of 1A (Stewart et al., 2010). This vessel is, by definition, permitted to travel through sea ice that is 70-120 cm thick (Figure 10). Sea ice in the Hudson Bay region, however, can be as thick as 2-3m when the ice is deformed and ridges are present (Markham, 1986; Stewart et al., 2010). Ice this thickness is over the established limit for safe transit of 1A class vessels.

Vessel Class	Maximum Allowable Ice Type	Ice Thickness (cm)
CAC1	No Limit	no limit
CAC2	Multi-year	no limit
CAC3	Second-year	no limit
CAC4	Thick First-year	> 120
Type A	Medium First-year	70-120
Type B	Thin First-year (stage 2)	50 - 70
Type C	Thin First-year (stage 1)	30 - 50
Type D	Grey-white	15 - 30
Type E	Open Water / Grey	10 - 15

Increasing ice capability

Figure 10. Vessel Class and Maximum Ice Type they can travel through, as defined by AIRSS (Transport Canada, 2003).

Under the Polar Code (IMO, 2015) there is a new mandatory regulatory system, called POLARIS, for vessels travelling through polar waters. POLARIS, or the Polar Operational Limit Assessment Risk Indexing System, was developed in part based on AIRSS (IMO, 2016). The risk indexing system functions similarly to AIRSS by evaluating the limitations of a ship in different ice regimes, based on the ship's established ice class (IMO, 2016). Following the risk calculation, a level of operation is defined (normal operation, elevated risk operation, or operation subject to special consideration). POLARIS also includes recommended speed limits for each level of operation, based on a ship's established ice class.

2.2.5 The Low Impact Shipping Corridors Initiative

In anticipation of increased shipping through Canadian Arctic waters, the Canadian Coast Guard initiated the Northern Marine Transportation Initiative (NMTI) in 2012 (Andrews et al., 2017; PEW 2016). Since 2016 the NMTI has been referred to as the 'Low Impact Shipping Corridors'. This initiative established voluntary marine corridors, within which vessel traffic is suggested to remain. With vessels transiting through the defined corridors, financial, material, and human support can be focused in these areas to allow increased navigational aid and safer transit, when possible (Andrews et al., 2017; Chénier et al., 2017; PEW, 2016). These shipping corridors were defined based on historical and projected shipping patterns. A report by the PEW Charitable Trusts in 2016, identified key gaps in with the existing corridors established, as they were created without sufficiently accounting for environmental and social complexities that exist in Canada's Arctic waters (PEW, 2016). However, in November of 2016, the Canadian government committed 1.5 billion dollars to the Ocean Protection Plan (CBC News, 2016). As a part of this strategy, establishing Low Impact Shipping Corridors are identified as a priority. This priority involves partnerships with indigenous community members and Artic stakeholders for improved input on establishing these shipping corridors. The initiative also states it will be conscious of respecting the environment as well as community cultures.

CHAPTER 3: Understanding the Factors that Contribute to Pressured Ice and that Cause Winter Ship Besetments in the Hudson Strait, Canada

Abstract

Pressure ice and ice ridges are a significant hazard to navigation through Arctic waters. These sea ice features can cause ships to become beset, or stuck, in sea ice for even days at a time, increasing the costs of operations, and presenting additional environmental risks. Icebreaking cargo ships that transit year round through the Hudson Strait in Canada are often delayed by the difficult transiting conditions present in the Strait as a result of ice ridges. There are few studies investigating the use of meteorological data for understanding the formation and presence of ice ridges in a geographic area. This study identifies periods of heavy ice ridging in the Hudson Strait based on logbooks kept (from 2005-2017) by the MV Arctic, a ship that regularly transits the Hudson Strait in winter months (January – March). Looking at both periods of heavy and minimal ice ridging, based on the observations of the MV Arctic, meteorological variables are investigated to determine any patterns that can be found with periods of heavy ridging. To investigate conditions prior to the ship becoming beset, meteorological data from a land based station is used. The reliability of using land based meteorological data to understand the meteorological conditions in the nearby marine area is investigated, showing positive moderate correlation between the data recorded on land the data recorded on the ship, and there are similar variability. This study did not find strong patterns between the land based meteorological data recorded prior to the ship having a difficult transit through the strait, such as any relationships in the meteorological data that would allow the Salluit weather station data to be used to understand what might have caused significant pressure ridging in the nearby marine area. This study did however find similarities in atmospheric pressure patterns, from reanalysis data, prior to difficult ship transits through the Hudson Strait in the winter. As well, this study found some similarities in wind patterns, from reanalysis, that corresponds with heavier and lighter ice conditions, in the region studied, which likely impacted the difficulty of the transits. This study suggests that using atmospheric pressure patterns and wind data to better understand the influence on ice dynamics in the region is further investigated.

Key words: *Arctic shipping; Hudson Strait; sea ice; ship besetment; pressured ice; ridges*

3.0 Introduction

Air temperature in the Arctic is increasing two times faster than elsewhere in the world (IPCC, 2018) which is associated with a decline in sea ice extent and thickness that has been observable since the beginning of the satellite record in 1979 (Blunden and Arndt, 2017; Lindsay and Schweiger 2015; Serreze and Stroeve, 2016; Serreze et al., 2009; Strove et al., 2011). The decline in sea ice has improved navigational conditions by creating longer open water seasons and an overall thinner and younger ice pack. Since 1990 an increase in tourism, cargo transport, fishing, and tanker activities related to resource extraction is evident in the Canadian Arctic (AMAP, 2012; Dawson et al. 2018; Pizzolato et al., 2014). Although it is predicted by some that shipping activity along major shipping routes of the Northern Sea Route, Transpolar Route, and the Northwest Passage (NWP) will rise in the coming years with climate change (Gascard et al., 2017; Melia et al., 2016; Smith and Stephenson, 2013), it is uncertain to what extent the reduction in sea ice is driving this increase in traffic in Arctic waters. Other factors such as tourism trends, natural resource development and fishing activity could hold a greater influence on the amount of shipping occurring through Arctic waters (Bensassi et al., 2016; Dawson et al., 2014; 2017; Eguiluz et al., 2016; Pizzolato et al., 2016).

For all ships transiting through the Arctic, navigational hazards from sea ice, such as becoming beset or damaging the ship in remote environments, are important to consider (Bourbonnais and Lasserre, 2015). As a result of climate change, the Arctic ice pack has become more mobile causing thicker multi year ice to flow into areas it was less commonly seen before (Barber et al., 2018; Howell et al., 2013; Spreen et al., 2011; Tivy et al., 2011). This increase in mobility could also result in an increase in sea ice deformation and the creation of pressure ridges (Bourbonnais and Lasserre, 2015; Spreen, Kwok and Menemenlis, 2011; Stern and Lindsay, 2009). Sea ice "under pressure" and resulting pressure ridges are hazardous even for highly ice strengthened vessels as they can be a very difficult obstacle for the ships to pass through and can cause ships to become beset. These types of ice formations occur when winds, tides, or currents interact, in regions of high ice concentration, squeezing ice floes together and causing pieces of ice to break off and accumulate into a wall of ice that extends above and below the water surface (Leppäranta, 2011). Landscapes can also increase the likelihood of ice pressure, for example, when ice is pushed through a bottleneck between an island and a coastline (Kubat et al., 2012). In high ice concentration, regions of heavy ridging, created as a result of previous ice pressure, can still be challenging for a ship to pass through after the pressure has released (Mussels et al., 2016; Timco et al., 2000). These ice ridges can pose a significant navigational challenge transiting ships (Kubat and Sudom, 2008; Mussells et al., 2017).

The Hudson Strait serves as an example of a region where pressure ridges create a navigational hazard to icebreaking vessels as pressure events and resulting ice ridges are common in this area during the winter season. Pressure events in the Hudson Strait have been known to cause vessels to become beset and delayed for several days at a time (Mussells et al., 2017). Two icebreaking cargo vessels transit year round through the Hudson Strait to service mines in Deception Bay in Northern Quebec. The *MV Arctic* is an icebreaking Oil, Bulk goods and Oil (OBO) carrier with a PC4 ice class rating (Fednav, 2014), meaning it can safely transit through thick first year ice (>130cm) with old ice inclusions (IACS, 2011). It is one of the two vessels that transits year round through the Hudson Strait to service a mine in Deception Bay, bringing supplies and fuel north from Quebec City and carrying nickel and copper ore concentrate south from Deception Bay (Têtu et al., 2015). While transiting through the HS in the winter months (January – March), the *MV Arctic* encounters ice pressure and ice ridges sometimes causing the ship to become beset for several days at a time (Bourbonnais and Lasserre, 2015; Mussells et al., 2017; Mussells et al., 2016). A ship becomes "beset" when it is stuck in the ice and unable to advance forward or backwards due to ice conditions.

To date, the majority of research on pressure ridges that has been completed has focused on the scale of a few kilometers (Kubat and Sudom, 2008; Kubat et al., 2012) or used satellite imagery to investigate ridge formation (Mussells et al., 2017, 2016). Shipping companies and captains are calling for more detailed and finer resolution research in order to improve the understanding of the formation of pressure and ice ridges at a ship scale, in the hopes of being able to predict their formation and presence in the future.

To respond to the identified need to better understand the formation of pressured ice that causes ship besetment at a finer resolution, this study involved an analysis of selected historic besetting events that occurred in the Hudson Strait. The overarching goal of the study was to identify if a relationship between meteorological variables influenced the creation of pressure ridges, causing delays to the *MV Arctic,* in the Hudson Strait and to investigate if available land based or reanalysis meteorological data could be used to better understand the development of pressure ridges in an area prior to the ship arriving.

The specific project objectives were to:

1) Investigate the reliability of meteorological variables that can be obtained from land-based stations as a proxy for conditions experienced locally by ships transiting the Hudson Strait route near Deception Bay;
2) Conduct a sea-ice climatology in order to better understand the sea ice patterns of the region and the influence they could have on the dynamics of ice conditions for transiting ships throughout the winter season; and
3) Discern the relative role of different meteorological variables, such as atmospheric pressure and wind, in influencing the formation of pressured ice that has caused historic besetments of the *MV Arctic* while transiting near Deception Bay, in the Hudson Strait.

3.1 Winter shipping in the Hudson Strait

The Hudson Strait (HS) is a narrow passage between the Hudson Bay basin and Canadian Arctic Archipelago (via Fury and Hecla Strait) to the North Atlantic Ocean (figure 11). The Strait is bordered by Baffin Island to the north and by northern Quebec and Ungava Bay to the south. Sea ice is present in the HS for about 8 months a year, and the Strait is fully ice covered between December and May (Saucier et al., 2004; Drinkwater, 1986). Sea ice formation generally occurs from west to east in the Strait and from the shores into the center of the Strait (Houser and Gough, 2003; Mussells et al., 2016). Although landfast ice forms along the Baffin Bay and Quebec coasts, the majority of sea ice in the HS remains mobile throughout the winter (Drinkwater, 1986; Mussells et al., 2016). Currents in the HS run in opposite directions with the northwest current flowing into the HBC, along Baffin Island, and the southeast current flowing out of the HBC along the northern Quebec coast (Staneo and Saucier, 2008). In addition to these opposite currents, strong tides and freshwater run-off have an influence on the ice movement and deformation in the Strait (Saucier et al., 2004).

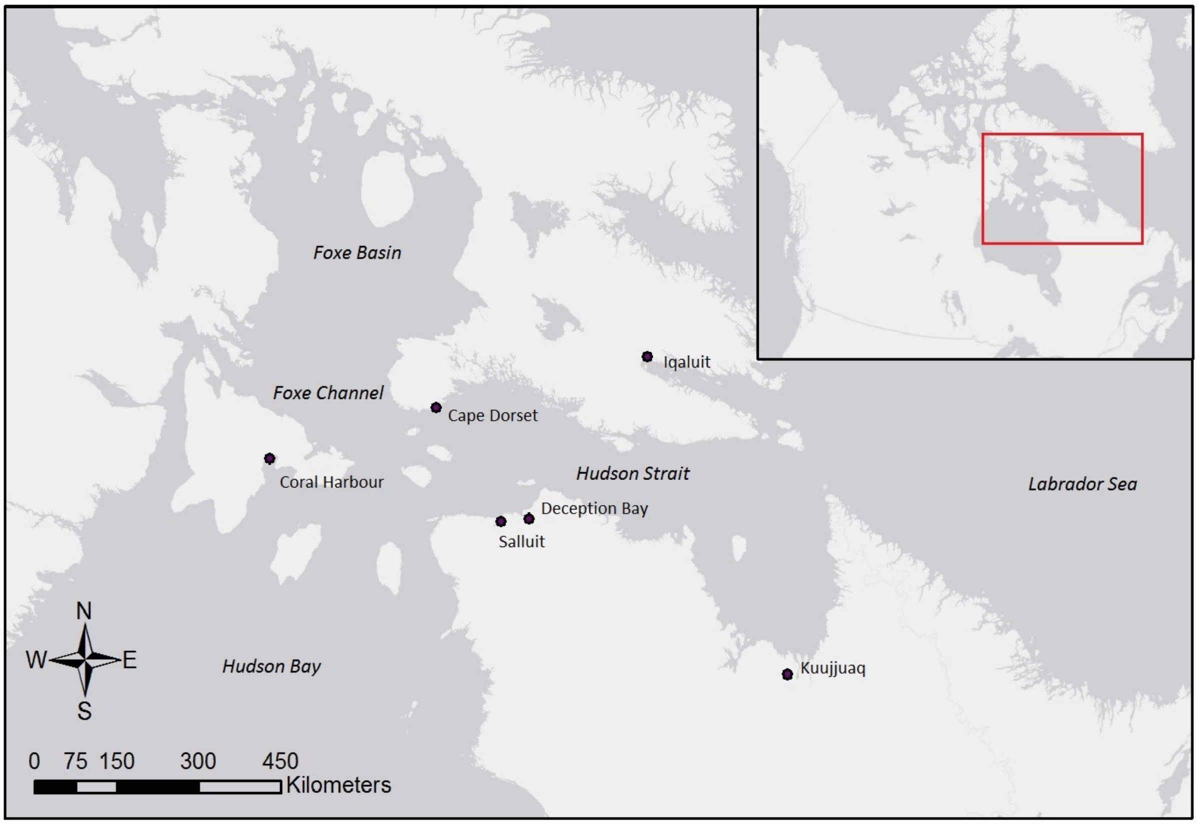

Figure 11. Map of the Hudson Strait and surrounding area. (Ogilvie, 2018).

Although most transits through the HS occur in the summer, the two ice breaking vessels which service the Raglan mine, operated by Glencore mining corp., and the Nunavik mine, operated by Canadian Royalties Inc., are impacted by pressure ridges during their winter transits to and from Deception Bay, QC (Vard Marine Inc. 2015). Mussells et al. (2016, 2017) investigated ridging patterns in the HS from RADARSAT-1/2 and Mussells et al. (2017) found a significant correlation of r^2= 0.5776 between the monthly ridge count in the Hudson Strait and the amount of time the *MV Arctic* spent beset during winter transits (with the month of March in two outlier years removed). Further, specific areas with recurring patterns of besetting events were identified as the shear zone at the entrance to Deception Bay, the entrance to the HS near Resolution Island, and the area between Charles Island and the coastline (Mussells et al., 2016) (Figure 12). A shear zone, where the mobile pack meets the land fast ice, is commonly a difficult zone for ships to pass through (Bourbonnais and Lasserre, 2015; Mussells et al., 2017) because these zones are formed as the mobile pack ice moves past the landfast ice, grinding against it, causing the creation of pressure ridges and deformed ice (Bourbonnais and Lasserre, 2015; Leppäranta, 2011).

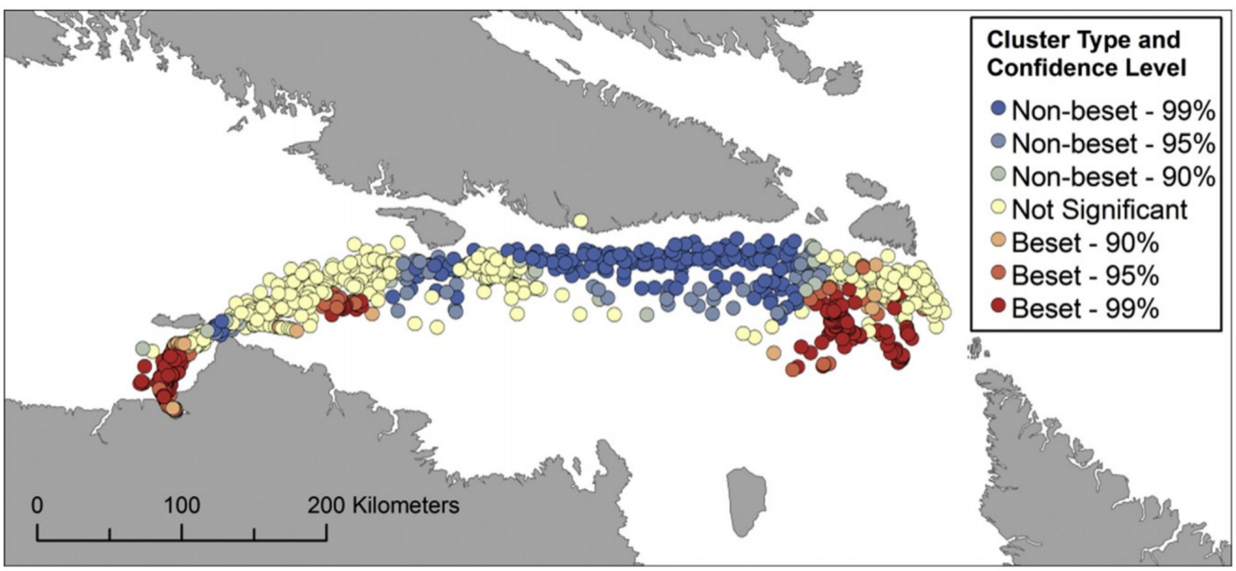

Figure 12. Cluster analysis for besetting events of the MV Arctic in the Hudson Strait from 2005-2014 showing common besetting areas in red of near the shear zone, at the entrance to Deception Bay, between Charles Island and the Quebec coast, again near the entrance to Deception Bay, and near Resolution Island, at the entrance to the Hudson Strait (Source: Mussells et al., 2017).

3.2 Methods and data

The study analyzed 6 transits through the Hudson Strait. First, the spatial and temporal focus was defined, then the research was conducted through a phased approach based on 3 main objectives (table 3). The spatial and temporal focus, and the 3 phases will be discussed in the following sections.

3.2.1 Transit Selection

The MV Arctic typically makes 2 voyages to the Raglan mine in Deception Bay per winter (January-March) from Quebec City. Every voyage is made up of 2 one-way transits. During these 2 eastward transits, and 2 westward transits through the HS, ship logbooks are updated every 2 hours detailing ship location, as well as noontime location. In addition, information on ice conditions and coverage, weather conditions, maintenance activities going on, and details on if the ship became beset are updated in the logbook. These logbook entries were acquired with the permission of the ship operator for the winter months (January, February and March) of 2015 to 2017.

Mussells et al. (2017) created an inventory of completed winter transits, and frequency of besetting events, of the MV Arctic through the HS, between 2005 and 2014 by digitizing and organizing the logbook entries. The same methods were followed to extend the inventory of winter transits to include 2015 to 2017, creating a database of all winter transits from 2005-2017. This dataset was used to determine the total hours spent in the Hudson Strait during each transit, the total time the MV Arctic spent beset in the HS, and the percentage of time the MV Arctic was beset during each transit through the HS (table 2). This information was essential to compare the difficulty that the MV Arctic had on different transits as a result of encountering pressure ridges and becoming beset.

Table 2. All voyage length and time beset for all MV Arctic winter voyages from 2005 -2017 (data from 2005-2014 from Mussells et al., 2016 dataset).

Voyage Name	Month of Voyage	Total Hours in Hudson Strait	Hours Beset	Percentage Time Beset
2005_1_E	Feb	109:32	33:32	30.6
2005_2_W	Mar	119:23	50:23	42.2
2006_1_W	Jan	32:00	3:00	9.4
2006_2_E	Mar	135:17	101:12	74.8
2006_3_W	Mar	79:30	21:20	26.8
2007_1_W **	Jan	10:00	0:00	0
2007_2_E	Jan	230:00	169:54	73.9
2007_3_W	Feb	90:00	39:00	43.3
2007_4_E	Mar	128:00	61:47	48.3
2008_1_E**	Mar	118:00	84:00	71.2
2009_1_W	Jan	66:00	0:00	0
2009_2_E	Jan	56:00	15:00	26.8
2009_3_W	Feb	44:00	4:00	9.1
2009_3_E	Mar	302:00	202:00	66.9
2010_1_E	Jan	42:00	0:00	0
2010_2_W	Jan	40:00	4:00	10
2010_3_E	Feb	100:00	72:00	72
2010_4_W	Feb	92:00	36:00	39.1
2011_1_E	Jan	28:00	0:00	0
2011_2_W	Jan	36:00	0:00	0
2011_3_E	Feb	79:00	44:00	55.7
2011_4_w	Mar	70:00	29:00	41.4
2012_1_E	Jan	76:00	36:00	47.4
2012_2_W	Jan	35:00	6:00	17.1
2012_3_E	Feb	136:00	80:00	58.8
2012_4_W	Mar	112:00	66:00	58.9
2013_1_E	Jan	53:15	14:15	26.8
2013_2_W	Jan	136:00	84:00	61.8
2013_3_E	Feb	220:00	157:00	71.4
2013_4_W	Mar	170:00	100:00	58.8
2014_1_E	Jan	104:00	58:00	55.8
2014_2_W	Jan	58:00	10:00	17.2

2014_3_E	Feb	366:00	302:00	82.5
2014_4_W	Mar	160:00	88:00	55
2015_1_E	Jan	54:00	10:05	18.6
2015_2_W	Jan	48:00	5:30	11
2015_3_E	Feb	54:00	3:00	5.5
2015_4_W	Mar	134:00	70:25	52.4
2016_1_E	Jan	218:00	140:25	64.3
2016_2_W	Feb	284:00	161:00	56.6
2017_1_E	Jan	42:00	0	0
2017_2_W	Jan	56:00	4:30	76.7
2017_3_E	Feb	248:00	4:00	1.6
2017_4_W	Mar	256:00	44:00	17.2

** partial voyage

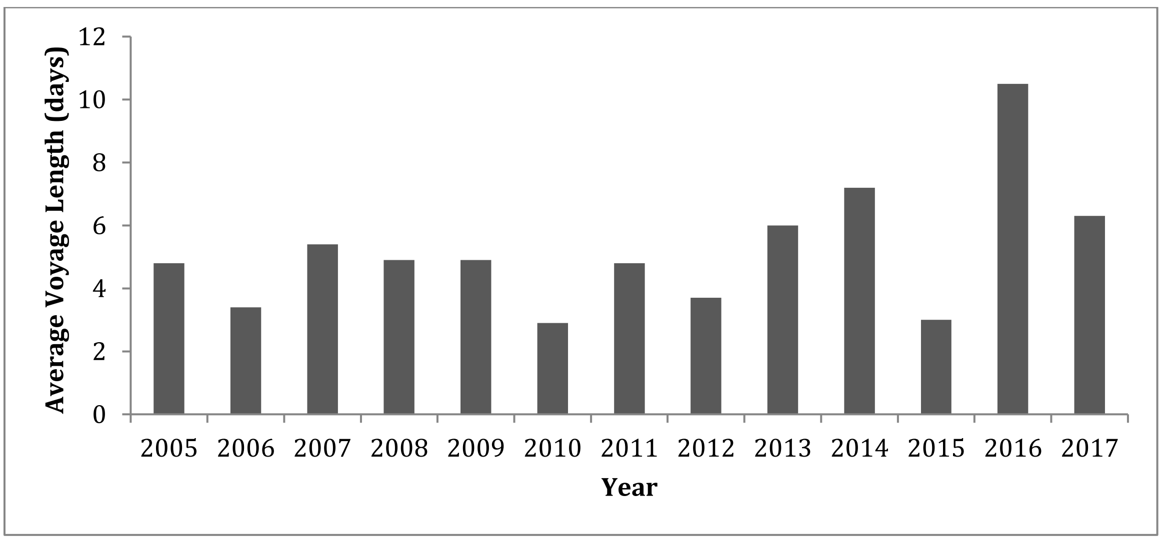

Figure 13. Average length of time (days) spent in the Hudson Strait per year for all MV Arctic winter transits from 2005 -2017

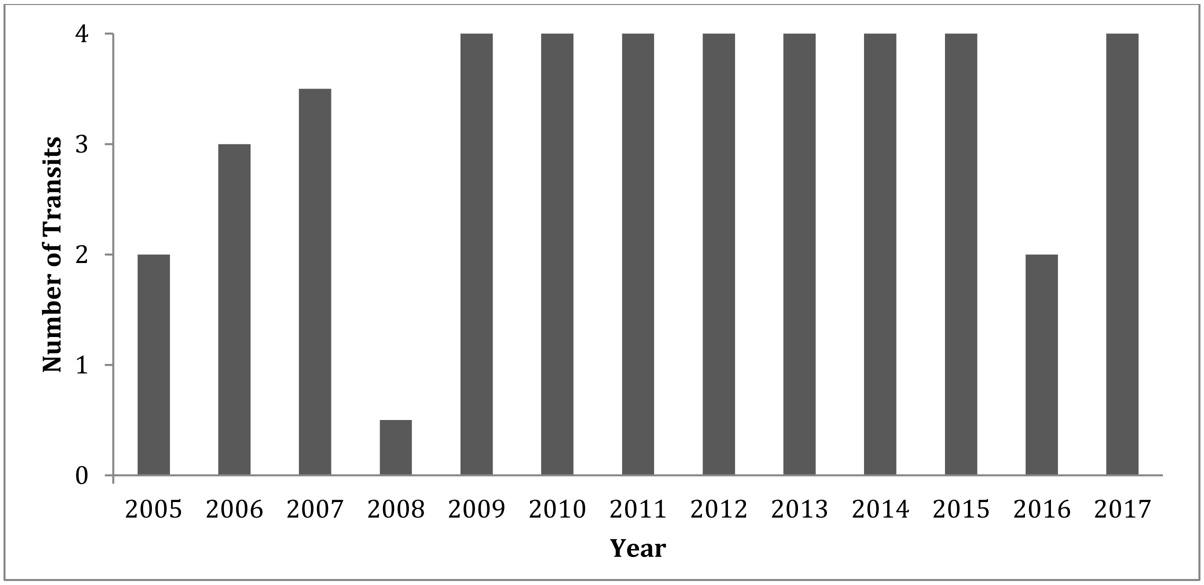

Figure 14. Total number of transits per year (with available logbook entries) by the MV Arctic through the Hudson Strait between January and March from 2005 -2017

For this study, a total of 6 transits (3 fast and 3 slow) were chosen for in-depth investigation. It was decided to investigate both transits during which the MV Arctic ran into little delays due to pressure ridges (fast transits) and transits where the MV Arctic experienced significant delays from besetting events as a result of pressure ridges (slow transits). This decision was made in order to compare any relationship in the meteorological variables recorded during the fast versus the slow transits, in order to better understand possible influencing factors of the slow transits.

Following the methods of Mussells et al. (2017), a slow transit was defined as being beset for over 40% of its transit time, and a fast voyage as being beset for 20% or less of its transit time. The fast and slow transits were then chosen based on the dates that had the most complete meteorological data available. Once the data was investigated, it was observed that several of the transits had missing meteorological data for several days, or in some cases, no data for certain meteorological variables, or for all variables for the entire length of the transit. Sufficient data was defined as not missing several days of data within the selected period of time for any of the meteorological variables investigated. Transit selection was limited due to the fact that meteorological data recorded on board the ship was unavailable or insufficient for the transits that occurred between 2005-2009 and from 2015-2017.

The meteorological variables investigated were determined by what was available from both the land-based station in Salluit and the shipboard weather system. These variables included temperature, wind speed, wind direction, dew point, and sea level pressure (station pressure for land-based station). All available variables were investigated to allow for the observation of any possible relationships. Of the slow voyages that had sufficient meteorological data, the 3 voyages that were beset for the longest amount of time were chosen. Of the fast transits that had sufficient meteorological data the 3 transits that occurred later in the year were chosen, to the reduce the likelihood that light ice conditions at the beginning of the winter season were the most significant reason for the minimal delays and besetments during the transit. The 3 chosen fast transits occurred in 2010, 2012, and 2014. The 3 chosen slow transits occurred in 2010, 2013, and 2014 (see section 3.3.1, table 6).

3.2.2 Spatial focus

The spatial distribution of besetting events of the *MV Arctic* in the HS were investigated by Mussels et al. (2017). They found significant clustering of besetting events occurred in the area between Charles Island and Deception Bay. Based on the findings of Mussells et al. (2017), it was determined that more research should be focused around this area as it was identified as a hot spot for ship besetments (figure 12).

To understand how representative this spatial focus was of the besetting events in the chosen transits (see section 3.2.3.1, figure 15), the besetment locations of the 6 chosen transits were mapped using ArcGIS. The majority of besetments were concentrated in the western region of the Strait, close to Deception Bay (Figure 15), aligning with the findings of Mussels et al. (2017). An exploratory data analysis was also completed to determine the specific distance from the nearby land-based weather station (in Salluit) that would be included in the study area (discussed in section 3.2.3.1). Following this, it was determined that the Zone of Interest (ZOI) would include the area 150km from the Salluit station (Figure 15).

3.2.3 Phased Approach Analyzing Transits

Once the spatial and temporal focus of the study were defined, the analysis involved three linked and largely iterative phases with different methodological approaches that link directly to the study objectives (Table 3). Details on the methodological approach taken in each phase of the study are provided below.

Table 3. Summary of Phased Approach used to reach thesis objectives.

Objective 1	A comparison of meteorological conditions recorded at the Salluit land based station and recorded on board the MV Arctic was completed to investigate how reliable land based data is for understanding the meteorological conditions present along the shipping route near Deception Bay (objective 1).
Objective 2	An ice climatology for the HS was created in order to understand the sea ice patterns of the region and the influence that variable freeze-up dates could have on the ice conditions present at the time of the transits in the years of interest (objective 2).
Objective 3	An investigation into the meteorological variables that could have had an influence on the difficulty the MV Arctic had with pressure ridges and besetting events when transiting through the HS (objective 3).

3.2.3.1 Objective 1: Comparing weather station data and ship based data

To investigate the meteorological conditions that existed prior to the ship becoming beset, and prior to the ship arriving in the ZOI, meteorological data from a nearby weather station was required. The weather station chosen for the metrological analysis was the closest land-based station, located in Salluit, QC (62°19’55”N 75°40’10”W), about 50km from Deception Bay. Although the dataset available from the Salluit weather station is often missing data (Genivar, 2012), it is considered more representative than other remote stations as it is the closest station to Deception Bay and is recorded in a similar coastal environment (Genivar, 2012). It is also the weather station that the ship Captains use to get their weather data when they are in this region.

A meteorological time series for the 6 chosen transits (see Section 3.3.1) was created to investigate how well the land based meteorological data, collected at the Salluit station, represented the data recorded on the board the *MV Arctic* when within the ZOI.

Meteorological data was acquired from the National Centres for Environment Information for the MV Arctic ship-based data (https://www.ncdc.noaa.gov/cdo-web/datatools/marine) and from Environment Canada for the land-based weather station located in Salluit, QC (http://climate.weather.gc.ca/historical_data/search_historic_data_e.html). The meteorological variables available from the Salluit weather station and the ship-based data included temperature, wind speed, wind direction, dew point, and sea level pressure (station pressure for Salluit weather station) (Tables 4 and 5). Since the frequency of meteorological records differed between the Salluit weather station and the ship-based data, the frequency of the weather station's records were used as the standard. The time series included hourly data from 8h00 to 17h00 EST.

Table 4. Example of available meteorological data from the weather station in Salluit, QC, for January 1st, 2010 (Environment Canada).

Date (YY/MM/DD)	Time	Temp (°C)	Dew Point Temp (°C)	Rel Hum (%)	Wind Direction (10's deg)	Wind Spd (km/h)	Stn Press (kPa)
10/01/05	8:00	-9.5	-10.3	94	36	2	100.08
10/01/05	9:00	-9.4	-10.6	91	3	4	100.09
10/01/05	10:00	-9	-10.1	92	3	17	100.12
10/01/05	11:00	-9.8	-11	91	5	13	100.13
10/01/05	12:00	-10	-11.2	91	4	13	100.11
10/01/05	13:00	-10.4	-11.7	90	4	15	100.11
10/01/05	14:00	-10.9	-12.2	90	3	17	100.12
10/01/05	15:00	-11.4	-12.8	89	3	13	100.13
10/01/05	16:00	-11.9	-13.3	89	3	15	100.13
10/01/05	17:00	-11.9	-13.3	89	3	17	100.15

Table 5. Example of available ship-based meteorological data recorded onboard the MV Arctic, QC, for January 1st, 2010 (https://www.ncdc.noaa.gov).

Time of Observation	Sea Level Pressure (mbar)	Temp (°C)	Dew Point Temp (°C)	Wind Direction (°)	Wind Speed (km/h)
2010-01-05T08:00:00	1023.7	-0.5	-0.7	80	46
2010-01-05T08:00:00	1023.7	-0.5	-0.7	80	46

2010-01-05T09:00:00	1023.5	-0.5	-0.7	80	51
2010-01-05T09:00:00	1023.5	-0.5	-0.7	80	51
2010-01-05T10:00:00	1023.3	-0.9	-1.1	70	51
2010-01-05T10:00:00	1023.3	-0.9	-1.1	70	51
2010-01-05T11:00:00	1022.9	-0.9	-1.1	70	57
2010-01-05T11:00:00	1022.9	-0.9	-1.1	70	57
2010-01-05T12:00:00	1022.7	-1.7	-1.9	30	108
2010-01-05T12:00:00	1022.7	-1.7	-1.9	30	108

An exploratory data analysis was then completed to investigate the relationship between the meteorological data from the Salluit weather stations and the ship-based data on the *MV Arctic*. Using the statistical software "R" (version 3.4.3) (R Core Team, 2013), the Salluit meteorological data was compared to the ship-based meteorological data for each of the chosen variables. To first determine the distance from Salluit that the meteorological variables recorded at the Salluit weather station are relatable, temperature data from the weather station and ship-based data records were compared. This was completed by investigating correlations (Pearson) calculated in the statistical software "R" for each transit at the distances of 50, 100, 150, 200km and over 200km from Salluit (50, 100, and 150km distances from Salluit shown in figure 15). Due to data gaps or quick transit over 50km distances, the fast transits could not be compared at these intervals. The three slow transits were investigated. Finally, 200km from Salluit was not included in the comparison as for each voyage the vessel travelled between 150 and 200km either between 2 logbook records, or overnight, which is not included in the analysis due to availability of data at the Salluit weather station. The data was reviewed prior to the correlation to ensure all values were within an acceptable range, i.e. no outliers. When comparing the three slow transits, temperature data within 150km was more highly correlated than over 150km (see section 3.3.1, table 6). This aligns with Beek (1991), that states meteorological variables can be assumed to not vary significantly within the range of 150km.

This study, however, also acknowledges that this is not considering abrupt changes in landscape, and does not assess land-ocean differences. Beek (1991) mentions that coastal environments have the largest gradient for differences in meteorological variables.

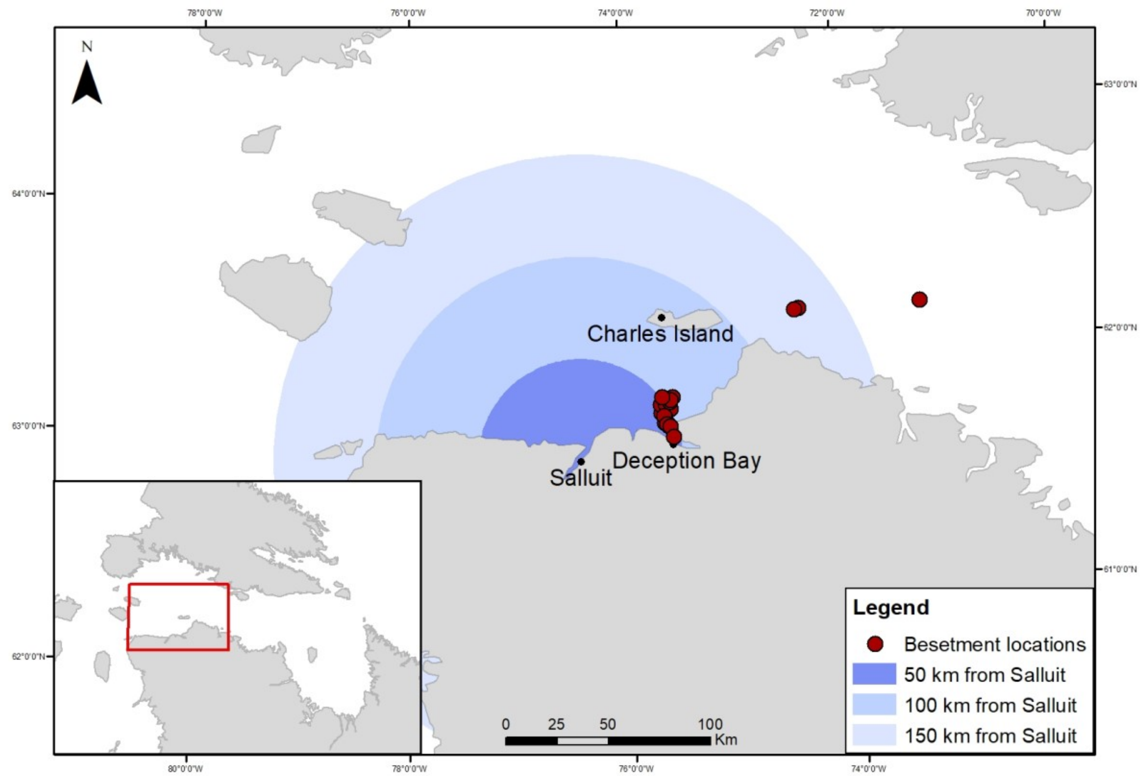

Figure 15. Map of study area, near Deception Bay, with buffers showing distance 50, 100, and 150km from Salluit. Locations of recorded besetments during the 6 chosen transits are displayed over the buffers.

For each transit, each type meteorological data from Salluit weather station was compared against the same type of ship-based meteorological data. This was done for each fast and slow transit for all the records that were available from both the weather station and ship-based data while the ship was within 150km of Salluit, including when the ship was in Deception Bay.

These records were compared against one another through linear regression models. The R^2 coefficient of determination and p-value were extracted from the regression models and compared between meteorological variables. These models were used to provide a quantitative basis for how well the data recorded at the Salluit weather station represented the recorded ship-based data.

3.2.3.2 Objective 2: Creating a sea ice climatology

To gain an understanding of how freeze up patterns and ice conditions present in the HS during the chosen years might have influenced the difficulty that the MV Arctic had during certain transits, an ice climatology was created. Ice charts and ice data from the Canadian Ice Service were downloaded and compared to understand the historical normal freeze-up dates and the variability between the freeze-up patterns in the chosen years.

Historical normal sea ice freeze up

The Canadian Ice Service (CIS) maintains a digital archive for the Northern Canadian Waters covering the time period of 1981-2010, the 30-year Ice Atlas (http://iceweb1.cis.ec.gc.ca /30Atlas). This atlas includes visual representations of statistical compilations of the regional ice charts published by the CIS between 1981 and 2010 (Canadian Ice Service, 2011). Climatic sea ice conditions are shown for the complete Northern Canadian Waters, and as well for various regions, including the Hudson Bay region. The Freeze-up Dates chart of Northern Canadian Waters and the Median Ice Concentration charts for the Hudson Bay region were used to demonstrate the historical normal freeze up patterns of the HS.

Using the CIS IceGraph tool (http://iceweb1.cis.ec.gc.ca/IceGraph/ page2.xhtml), total accumulated ice concentration values were extracted for every week from the beginning of November to the end of July for every winter between 2004/05 and 2017/18. These values were graphed to create a time series demonstrating the variability in freeze up and break up through out the year, between different years. Following this, the annual dates of freeze-up (first date when more than 50% of the Strait was covered by ice) and breakup (first date when less than 50% of the Strait was covered by ice) were determined for all the years that the log books were available in the HS (2005-2017). These definitions of break up and freeze up align with the terminology used by the CIS. The freeze up and break up dates were shown by the specific week's number in the year.

Variability in sea ice conditions in the years of interest

The CIS has issued ice concentration and stage of development data for the HS since 1971. The Canadian Ice Service Digital Archive (CISDA) (http://iceweb1.cis.ec.gc.ca/Archive/) contains a collection of the CIS's daily operational ice charts, regional ice analysis charts, and daily iceberg charts that can be used to better understand the ice conditions that existed at different times of the year, and in different years, for various regions across the Canadian Arctic. For the HS region, available information includes the weekly regional ice charts for the Hudson Bay region (1971 to present). The ice charts are created by the CIS through the integration of information from satellite images, airborne and ship reports, results from operational models, as well as ice forecaster knowledge (Tivy et al., 2011).

To better understand the variability in freeze up patterns in the chosen years, ice concentration (in tenths) during the first week of December for each of the years of interest, based on Ice Charts from the Canadian Ice Service, was displayed for each of the years of interest. The ice charts were loaded into ArcMap 10.6.1 and displayed on a basemap, focused in on the Hudson Strait. Next, using data extracted from the CIS Ice Graph Tool, graphs of the freeze up sequence of the chosen years were created with the total accumulated ice concentration values. The percentage of the HS covered in ice, and percentage of the HS covered in first year ice (≥30cm) were graphed, again, to show the variability in freeze up patterns between the years of interest.

Variability in sea ice conditions during the chosen transits

To compare the difference in ice conditions during the time of the chosen transits, the percentage of ice cover by stage of development was graphed for each of the chosen transits. This data was extracted from the CIS Ice Graph Tool, showing the estimated stage of development of the ice, or estimated (not measured) general thickness. This data was graphed for the week closest to the chosen transits. Following this, for a different visualization of the ice present in the HS during the chosen transits, the weekly ice charts closest to the time of each of the chosen transits was displayed for the fast and slow years. Using ArcMap 10.6.1, ice charts detailing both the ice concentration and the stage of development of the ice was displayed for all the chosen transits, with the ship track for each transit over laying the ice regimes. The ship tracks are based on the locations reported in the log books, and a line was created from the available coordinates in ArcMap 10.6.1. Given the fact that the logbook entries occur every 2 hours, the ship track shown is a simplification of the actual route taken.

3.2.3.3 Objective 3: Investigating how meteorological variables influenced the transits

Following the investigation of how well the Salluit weather station data represented the recorded ship-based data, when it was within 150km of the Salluit station, the meteorological variables were compared between the different voyages. This step was done using the Salluit weather station data from 1 week prior to the vessel being within 150km of Salluit, in addition to when the vessel was within 150km of Salluit. As mentioned, it is important to investigate the meteorological conditions that occurred in the area prior to the ship passing through, as an area with extensive ridging can still be difficult for a ship to pass through, and still cause besetting events, even after the pressure has dissipated. For temperature, dew point, pressure and wind speed, the averages and ranges of the data were calculated for each fast and slow transit. The average and range for each meteorological variable for the three fast transits together and the three slow transits together were calculated. For wind speed, main wind speed direction and the percentage of time that the majority wind direction was recorded was calculated for each of the transits. This was done to investigate if any similarities between the slow transits or the fast transits existed, to provide insight into the variables which were the most influential to the ice conditions that occurred during each transit.

NCEP Daily Reanalysis

To better understand sea level pressure patterns that might have an influence on ridge formation in the HS, daily average (mean) NCEP NARR composites were produced from the

NOAA OAR ESRL (Earth Systems Research Laboratory) PSD (Boulder, Colorado) website (https://www.esrl.noaa.gov/psd/cgi-bin/data/narr/plotday.pl/) (Kalnay et al., 1996). Daily reanalysis composites (average) of the daily mean were extracted for mean sea level pressure (SLP) for the chosen transits. These model outputs were reviewed for all chosen transits for 1 week prior to the ship entering the ZOI. This was completed to observe how the pressure patterns developed and dissipated, and as well, where the main low-pressure pattern was located around the HS region, prior to the ship transiting through the ZOI. For the slow transits, the same observations were made for the days that the ship was within the ZOI. The daily mean sea level pressures over the ZOI in each transit were shown graphically to compare the transits. Daily NCEP NARR composites were also produced with wind vector reanalysis data showing the mean dominant wind direction and speed for the week prior to the *MV Arctic* entering the ZOI for the chosen fast and slow transits.

3.3 Results and Discussion

Study results are presented in three sections. Objective 1 presents a comparison of the meteorological conditions recorded at the Salluit land based station and recorded on board the MV Arctic, discussing if the land based data can be reliably used to understand the meteorological data in the marine area close to Deception Bay. Objective 2 presents an ice climatology of the HS, focusing on the freeze up patterns in the area and investigating the ice conditions in the chosen years in greater detail. Objective 3 presents an investigation into which meteorological variables might have had the greatest influence on the creation of pressure ridges in the ZOI for the chosen transits.

3.3.1 Comparing land-based and ship-based meteorological variables (*Objective 1*)

To first investigate the distance from the Salluit land-based meteorological station up to which the recorded data can be used to understand the marine conditions near Deception Bay, the air temperature data from both the Salluit weather station and recorded ship-based data was compared. This dataset was compared, based on records as the was at different distances from Salluit. If both the weather station data and recorded ship-based data were highly similar within a certain distance, this would increase the confidence in using the Salluit data to understand the meteorological conditions in the marine area, within that distance.

Table 6 shows correlation (pearson), adjusted R-squared, and p-values acquired when comparing temperature values recorded from the *MV Arctic* and from the Salluit station. The values from both data sources are least closely related when data from when the MV Arctic transited across the entire HS was included. These findings show that, over 150km from Salluit, weather variables recorded at the Salluit station are less correlated to the weather recorded on board the vessel. In the three slow transits, there is no clear improvement of the correlation of the data, between the land based data and the ship based data, when looking at the period when the ship was within 50km from Deception Bay to the period when the ship was within 150km from Deception Bay. To increase the amount of data that could be used for the analysis, the area within 150km was determined as the ZOI. The P-values and correlation values show that the comparisons between the land based and ship based temperature data are significant with a moderate positive relationship within 150km.

Table 6. Correlation of temperature values recorded at the Salluit station and on-board the MV Arctic in Deception Bay and to end of Strait, at different distances from Salluit, for the chosen slow transits.

		In Deception Bay	In Deception Bay and within 50km of Salluit	In Deception Bay and within 100km of Salluit	In Deception Bay and within 150km of Salluit	In Deception Bay and until the end of HS
2010	Correlation	0.6295	0.6365	0.6343	0.6114	0.5891
	Adjusted R-squared	0.3871	0.3983	0.3959	0.3674	0.3408
	P-value	8.94E-09	1.56E-11	3.99E-12	1.79E-11	3.08E-11
	Number of observations	68	90	96	99	106
2013	Correlation	0.7503	0.8194	0.8406	0.8702	0.5795
	Adjusted R-squared	0.5539	0.6666	0.7024	0.754	0.3286
	P-value	3.54E-10	< 2.2e-16	< 2.2e-16	< 2.2e-16	9.39E-10
	Number of observations	50	69	71	77	94
2014 **	Correlation	0.9724	0.6109	0.6026	0.5984	0.2852
	Adjusted R-squared	0.9426	0.367	0.3572	0.3522	0.0006081
	P-value	7.96E-13	9.20E-12	4.13E-12	4.02E-12	0.07473
	Number of observations	20	102	109	111	141

**only 2 days of data available when the vessel was in Deception Bay

Following the ZOI being further defined; additional investigation was completed on the other available meteorological data. Looking at air temperature, dew point temperature, wind speed, wind direction, and pressure data, table 7 and 8 show comparisons between the recordings from the Salluit weather station and the ship-based data. From these comparisons, it can be observed that all wind speed correlations were less than 0.45, showing that wind speed from the Salluit weather station is not representative of wind speed conditions that the ship was experiencing when transiting through the marine area, into Deception Bay. The other meteorological variables have higher correlations than wind speed. The ship-based air temperature, dew point temperature and pressure values recorded, when compared to variables recorded at the Salluit weather station, show some positive correlations (Table 7, 8). The correlation for air temperature and dew point temperature between the ship-based and weather station data is between 0.6 and 0.8 (Table 7, 8). Pressure data shows the closest values between the ship-based and weather station data, within 150km, with high correlation values over 0.8 for all voyages examined. As examples, figure 16 and 17 show a visual comparison of the air temperature and pressure data recorded at the Salluit weather station and recorded onboard the ship for the slow chosen transits in 2013 (air temperature) and 2014 (pressure). Looking at examples of the data graphed, it can be observed that although the values are not the same from the two sources, they generally follow the same pattern when compared to one another, within the defined spatial scope (Figure 16,17).

This comparison has shown that data from Salluit weather station does not show the exact same conditions that are experienced in the ZOI, and that, for the specific locality of this study in relation to the Salluit weather station, land based data is not a replacement for data recorded on board the ship. The comparisons between the meteorological values of air temperature, dew point temperature and pressure did, however, show positive moderate to strong statistical significance when compared between what was recorded at the Salluit land based station and what was recorded onboard the ship when it was within 150km of the Salluit station. For the cases investigated, this points to the fact that the Salluit meteorological data (except for wind) can be used to understand the variability of the meteorological conditions in the marine area near Deception Bay. Further investigating the Salluit data, we will explore any relationships between meteorological conditions that existed prior to the ship entering the ZOI that may have influenced the difficulty of the transit.

Table 7. Correlation between meteorological variables recorded on board the MV Arctic and at the Salluit weather station for the days the vessel was within 150km of Salluit, and in port in Deception Bay, for the chosen years of fast transits through the Hudson Strait.

Year	Meteorological variable	Correlation	Adjusted R-squared	P-value
2010	Air Temperature (n=48)	0.794	0.623	1.641e-11
	Dew point Temperature (n=43)	0.774	0.589	1.15e-09
	Wind Speed (n=54)	0.440	0.178	0.000884
	Pressure (n=54)	0.962	0.924	< 2.2e-16
2012	Air Temperature (n=51)	0.798	0.629	2.384e-12
	Dew point Temperature (n=50)	0.796	0.626	4.875e-12
	Wind Speed (n=55)	0.145	0.629	0.2918
	Pressure (n=55)	0.967	0.934	< 2.2e-16
2014	Air Temperature (n=49)	0.637	0.393	8.693e-07
	Dew point Temperature (n=42)	0.665	0.428	1.56e-06
	Wind Speed (n=49)	0.281	0.059	0.05031
	Pressure (n=49)	0.964	0.928	< 2.2e-16

Table 8. Correlation between meteorological variables recorded on board the MV Arctic and at the Salluit weather station for the days the vessel was within 150km of Salluit, and in port in Deception Bay, for the chosen years of slow transits through the Hudson Strait.

Year	Meteorological variable	Correlation	Adjusted R-squared	P-value
2010	Air Temperature (n=99)	0.611	0.3674	1.794e-11
	Dew point Temperature (n=95)	0.627	0.3872	1.018e-11
	Wind Speed (n=99)	-0.030	-0.0094	0.771
	Pressure (n=99)	0.905	0.8172	< 2.2e-16
2013	Air Temperature (n=77)	0.870	0.754	< 2.2e-16
	Dew point Temperature (n=63)	0.689	0.466	4.325e-10
	Wind Speed (n=77)	0.274	0.06247	0.01609
	Pressure (n=77)	0.985	0.9696	< 2.2e-16
2014	Air Temperature (n=111)	0.598	0.352	4.019e-12
	Dew point Temperature (n=68)	0.573	0.3204	8.137e-09
	Wind Speed (n=110)	0.230	0.04655	0.00474
	Pressure (n=110)	0.953	0.9073	< 2.2e-162

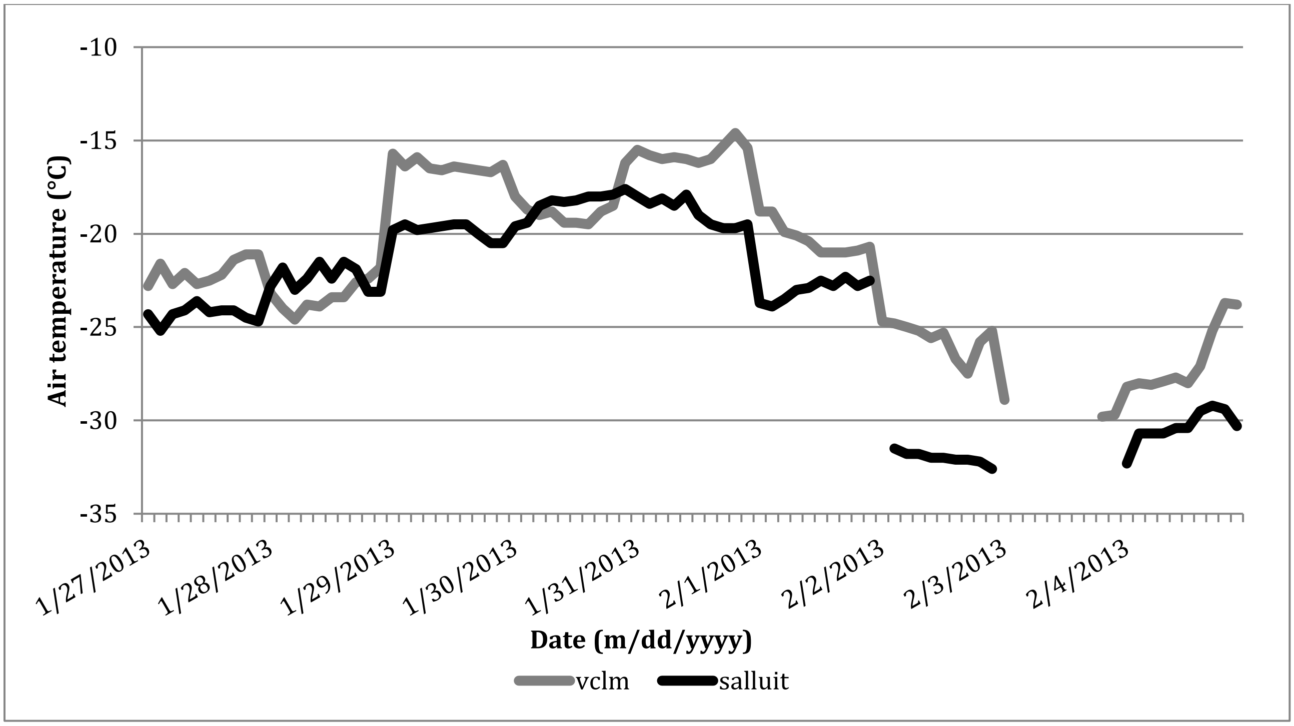

Figure 16. Comparison of air temperature values recorded from the Salluit weather station, and the ship-based data recorded on the MV Arctic *(VCLM) within the ZOI in 2013.*

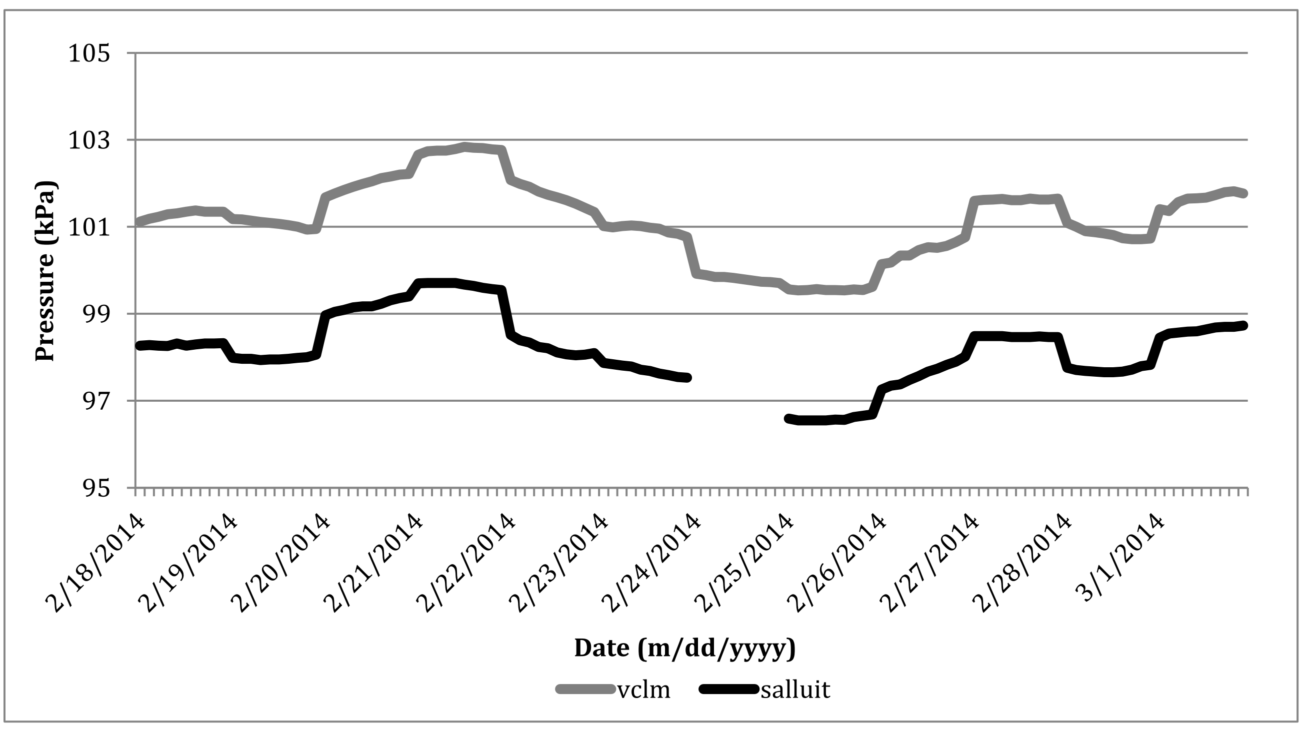

Figure 17. Comparison of pressure recorded from the Salluit weather station, and the ship-based data recorded on the MV Arctic *(VCLM) within the ZOI in 2014.*

3.3.2 Sea ice climatology and variability in freeze-up patterns (*Objective 2*)

Variability in sea ice conditions in the years of interest

There is variability in the freeze up dates in the Hudson Strait from year to year (table 9), as well as variability in the stage of development (estimated general thickness) of the ice cover throughout the winter season. Sea ice progression in a region is defined as the time when sea ice first covers at least 50% (freeze up) or less than 50% (break up). A time series plot of the ice concentration in the Hudson Strait from the beginning of November to the end of July for each winter between 2004/05 and 2017-18 can be seen in Figure 18, with a dotted line at 50% ice coverage showing freeze up in the winter and break up in the summer (break up is shown simply to demonstrate the full variability in ice conditions year to year). Table 9 shows the number of the week in the year that the freeze up and break up occurred each winter season.

The earliest freeze up, in this time series, occurred during the winter of 2015/16, with 50% of the HS being ice covered between the 19 and 26 of November. The latest freeze up occurred during the winter of 2010/11, with 50% of the HS only becoming ice covered between January 8 and 15. This freeze up was almost 2 months later that the early freeze up of 2015/16 (figure 18), and 4.5 weeks later than the mean freeze up of this time series, week 50.6 (table 9). Other winters with early freeze up include 2007/08, 2004/05, and 2013/14. Other years with late freeze up include 2011/12, 2006/07, and 2005/06 (figure 18, table 9). The mean of this time series is week 50.6, while the CIS historical mean (from 1981-2010) is 49.2. On average, freeze up in the Hudson Strait between 2004 and 2017 occurred 0.6 weeks later than the historical mean.

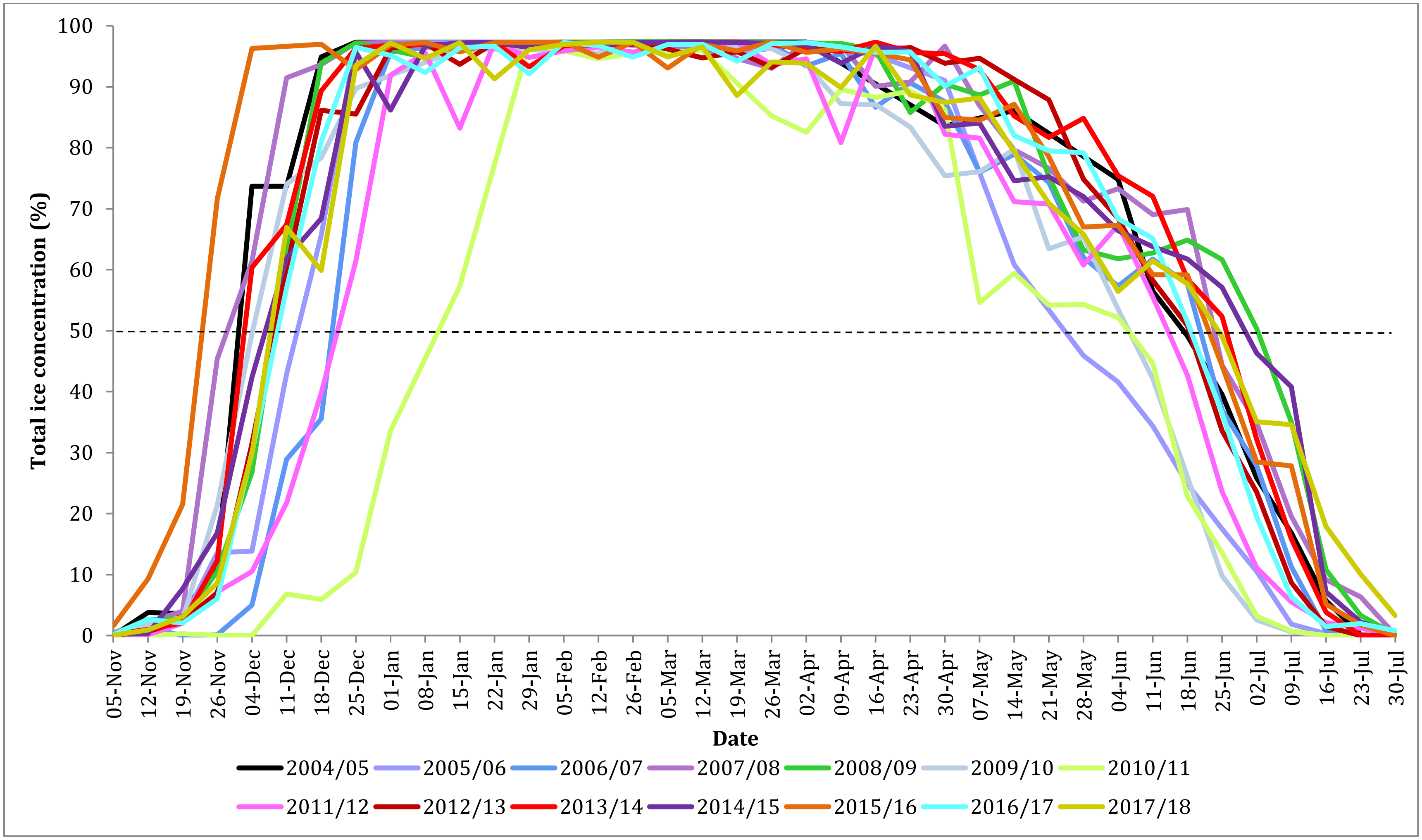

Figure 18. Time series showing the seasonal variations in ice concentrations (%) in the Hudson Strait for the winters between 2004/05 to 2017/18. (Data source: CIS)

Table 9. Freeze up and break up dates for the Hudson Strait for 2004-2017. Freeze-up is defined as when the Strait is first covered with at least 50% ice concentration; break up is defined as when the Strait is first covered with less than 50% ice concentration (CIS, 2011).

Year	Freeze-up week number	Breakup week number
2004-2005	49	25
2005-2006	51	22
2006-2007	52	26
2007-2008	49	26
2008-2009	50	28
2009-2010	50	24
2010-2011	55	24
2011-2012	52	25
2012-2013	50	26
2013-2014	49	27
2014-2015	50	27
2015-2016	48	26
2016-2017	50	26
Mean (2004-2017)	50.6	25.6
Climatological Mean (1981-2010)	49.2	26.9

The variability in ice concentration and stage of development (estimated general ice thickness) between the years of interest is important to investigate to better understand the ice conditions encountered during the chosen transits. Prior to comparing the meteorological conditions surrounding each transit, differences in ice conditions between the years of the chosen transits were compared, starting with the pattern of sea ice freeze-up in the months prior to the transits. Figure 19 demonstrates the presence (% of concentration) of sea ice in the HS during the first week of December prior to the winter season of the years of interest (2010, 2012, 2013, 2014). Figure 20 shows the progressions of freeze up based on the weekly, CIS reported, percent of ice concentration across the Hudson Strait from the first week of November to the first week of March. Figure 21 covers the same period but shows the weekly, CIS reported, percent of first year ice concentration (≥30cm). The data displayed in Figures 20&21 stops after the first week of March as none of the chosen transits continue after this date.

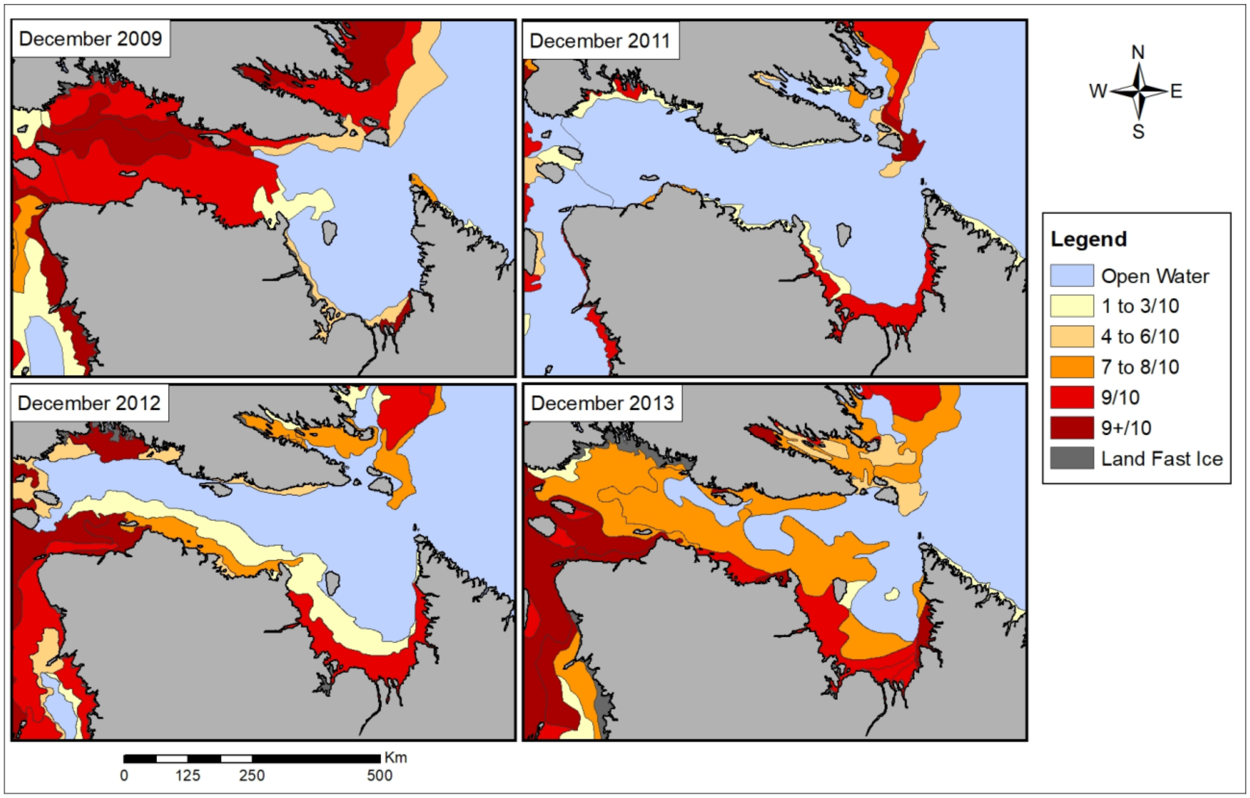

Figure 19. Ice concentration (in tenths) during the first week of December for each of the years of interest based on Ice Charts from the Canadian Ice Service. Published dates of weekly Ice Charts used: December 7, 2009; December 5, 2011; December 2, 2012; December 02, 2013.

Between the 4 years of interest, freeze up occurred earliest in the winter of 2013/14, closely followed by 2009/10. In the first week of December, the Hudson Strait was 60% ice covered in 2012, and 49.5% covered in 2009 (figure 20). These two winters also both had one fast and one slow chosen transit. It is important to note, that the fast transits in both these years occurred in mid-January, and the slow transits for both years occurred in mid-February. Although they both had a similar amount of ice present in the Strait by the first week of December, the development of ice cover between the winters of 2009/10 and 2013/14 followed a slightly different pattern. Freeze up in the Strait normally starts from the western side of the Strait and then extends eastward. The median ice concentration by the first week of December, based on the CIS 1981-2010 sea ice climatology, shows the western side of the strait fully ice covered, with ice cover extending along the coast of Ungava Bay (see section 1.3.3, figure 3). The freeze up in the winter of 2009/10 began from the western side of the Strait and extended to cover the western and central part of the Strait with 9-9+/10 ice coverage, by the first week of December. This is very close to the pattern of the historical median ice coverage, except for the lack of ice cover along the coast of Ungava Bay, and slightly more ice coverage east of Big Island (figure 19). The freeze up pattern in 2013/14, the other year of interest with the earliest freeze up, was also similar to the historical normal freeze in the Strait. The slight difference in freeze up pattern for this winter was the lighter ice concentration across the Strait by the first week of December, mostly 7-8/10 ice coverage with patches of open water near Big Island. The ice cover did however extend slightly farther east in the Strait and from the coast of Ungava Bay this year than the historical median and the winter of 2009/10 (figure 19). By the first week of December there was 9-9+/10 ice coverage between Charles Island and Deception Bay in both years. As the freeze up patterns in these two years were close to the historical normal pattern, it is likely that factors other than the freeze up pattern played a more significant role in defining the difficulty of the transit.

During the other two years of interest 2010/11 and 2012/13, there was less sea ice coverage by the first week of December than the historical median (figure 19). In the first week of December, the Hudson Strait was 31% ice covered in 2012, and only 10.5% covered in 2011 (figure 20). In 2012 by the first week of December, most of the ice present was along the southern shore of the Strait, along the Quebec / Nunavik coastline, including along the coast of

Ungava Bay. At this time there was 9+/10 ice coverage between Charles Island and Deception Bay (figure 19). In the first week of December of 2011, there was only some ice development right along the coast of the Hudson Strait, and along the coast of Ungava Bay, significantly less than the other years at this time (figure 19). The concentration of ice cover in the Strait in the winter of 2011/12 did not catch up to that of the other years of interest until the beginning of January, after which time there was also a dip in ice concentration during the middle of January, from over 95% to 83%, until the following week (figure 20). The later freeze up at the beginning to the season in 2011/12 (figure 19) could have played a role in why the ship was able to quickly pass through the ZOI when it arrived on January 31, 2012 (figure 24), in comparison to the difficulty the ship had passing through the ZOI on January 31, 2013 (figure 26).

Looking at the development of first year ice at the beginning of the winter season for the years of interest, by the first week of January, it was only during the winter of 2011/12 that there was less than 25% estimated first year ice cover. During the winter of 2011/12, the estimated first year ice cover was only slightly over 7% by the first week of January, and the estimated first year ice cover continued to lag behind the other years of interest until the beginning of February (figure 21). The winter of 2013/14, the estimated first year ice cover grew faster than the other years of interest, and remained slightly higher than the other years until the end of the investigated period, the beginning of March (figure 21). The estimated first year ice cover of that year reached 80% during the last week of January, and stayed over 80% for the remainder of the investigated period (figure 21). During the winter of 2009/10, the estimated first year ice cover grew more steadily than the other years, reaching over 70% by the end of January (figure 21). During the winter of 2012/13, the estimated first year ice cover grew in a more varied manner, increasing from around 30% to around 75% between the second and third week of January, then generally stabilizing before a drop to close to 60% during the first week of February (figure 21). Similar to looking at the difference in ice concentration between the years of interest, the only year that stands out as potentially having the development of first year ice as an indicator as to why the ship was able to transit more quickly in the chosen transit is the year 2011/12. This year stands out from the other years of interest as the development of first year ice occurred much later than the other chosen years. This later date of reaching the same level of ice thickness as the other years would not give the ice as much time to thicken by the time the ship was transiting through the Strait in the end of January, in comparison to the other chosen years. This is likely a contributing factor as to why this transit was less difficult than others.

The growth of first year ice, reported in the weekly CIS Ice Charts, is noteworthy to look at between the years of interest even though it is an estimate of the ice thickness rather than an actual measurement. In addition to the amount of time that the ice cover has been developing, such as a year with a late vs. early freeze up, there are other factors which can influence the thickness of the ice that are difficult to capture in forecasts and models, such as wind dynamics. Wind dynamics on a mobile ice cover, such as in the Hudson Strait, will cause the ice cover to ridge and raft, changing the thickness of the ice across the area in a non-uniformed manner. The estimates of the stage of development published by the CIS in their ice charts is used for a better understanding of conditions as the data is consistent and available at the same time frequency for all the chosen transits. Ice thickness (in this cased, estimated as stage of development) is important to investigate, as thicker ice will be more difficult for the ship to navigate through. As well, wind dynamics causing rafting and ridging of thicker ice will cause thicker ridges, again being more difficult for the ship to transit through than thinner ice that is rafted or ridged. Preliminary analysis done by Casey et al. (2018) showed that the MV Arctic's speed slowed down after ice thickness reached over 1m.

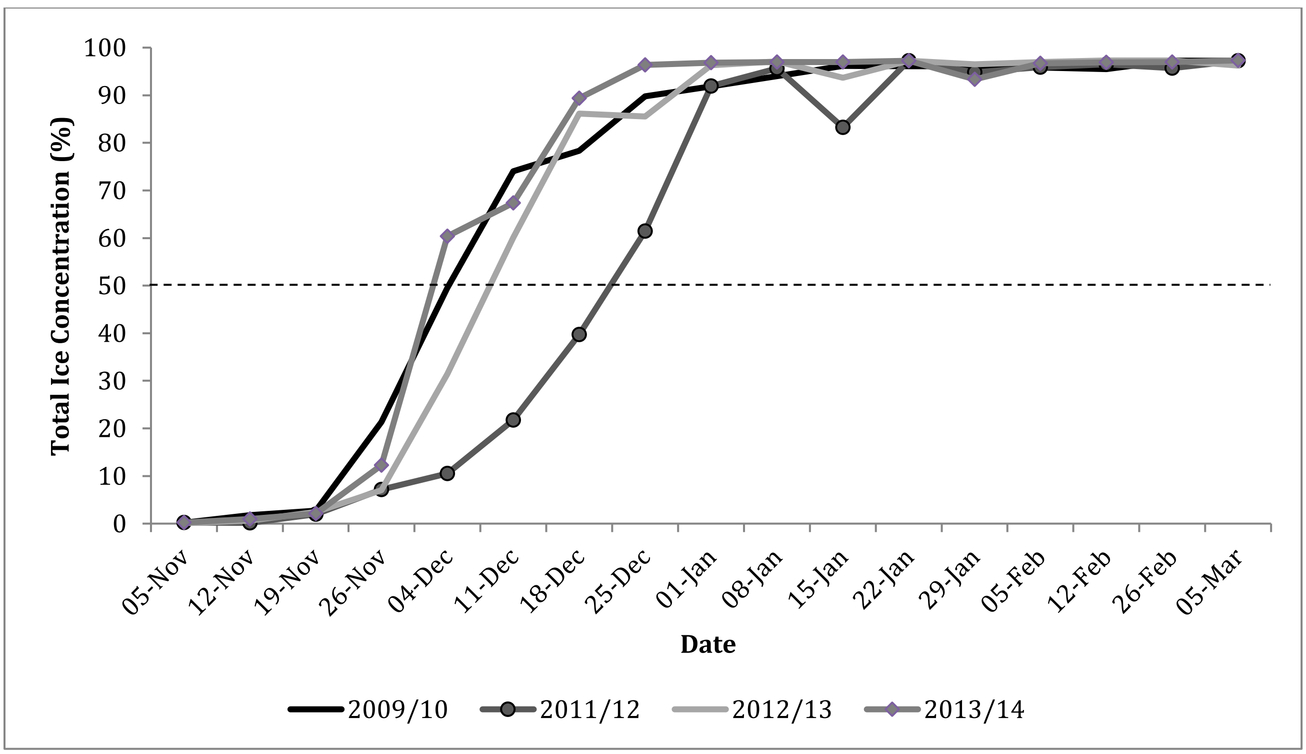

Figure 20. Total ice concentration (%) from the beginning of the winter season to the beginning of March, when all chosen transits had finished. Dotted line showing 50% ice concentration, or freeze up. (Source: CIS).

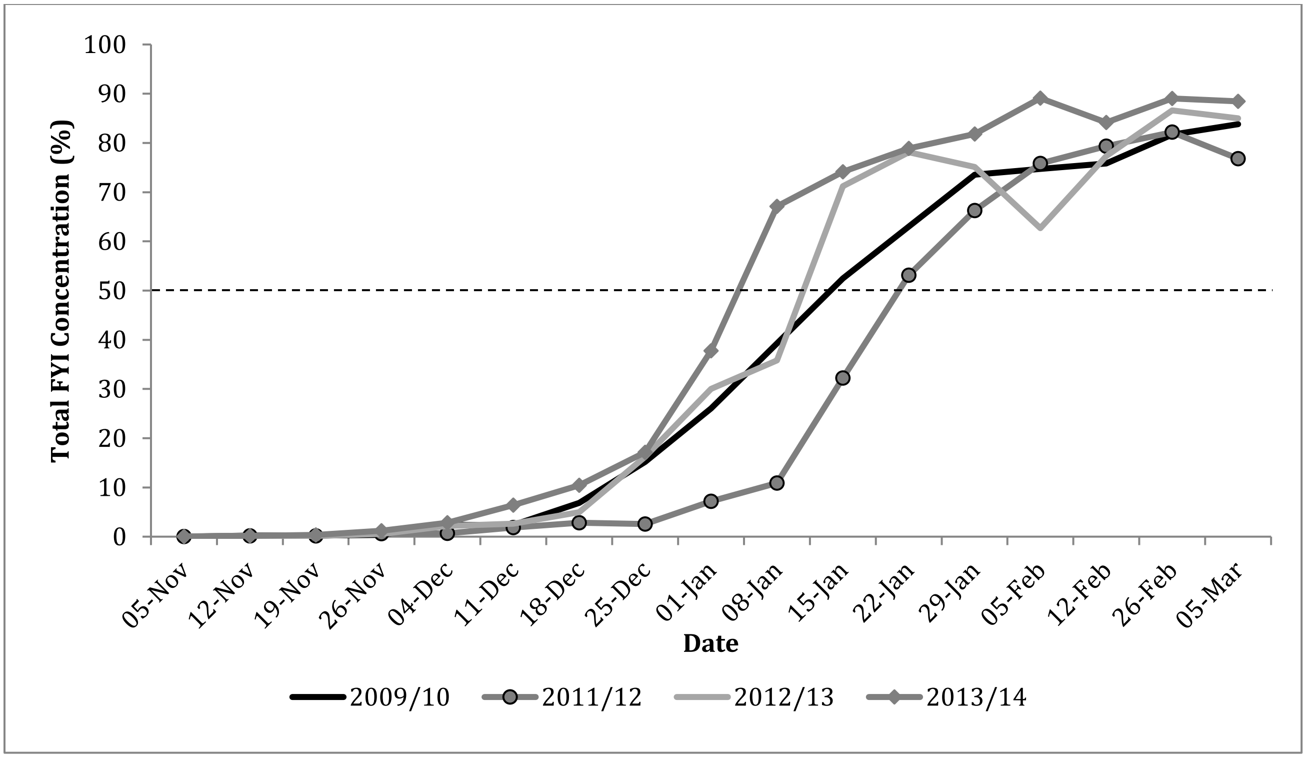

Figure 21. Total concentration (%) of first year ice (≥30cm thick, estimated) from the beginning of the winter season to the beginning of March, when all chosen transits had finished. Dotted line showing 50% ice concentration, or freeze up. (Source: CIS).

Variability in sea ice conditions during the chosen transits

When each of the chosen transits occurred, the Hudson Strait was fully ice covered (figure 22, 24), although there was still variability in the stage of development of the ice across the Strait. Figure 21 shows a summarized visual representation of the percent of stage of development of the ice in the Hudson Strait during the chosen transits. As mentioned, the stage of development shows a general estimation of ice thickness but is not measured thickness. As these are the best information on general thickness available, for all the yeas analyzed, they are discussed relating to the thickness present, however, it should be noted that the values are all estimations.

Since the freeze up patterns were fairly similar in 2010 and 2014, and both years had 1 fast and 1 slow chosen transit, it is interesting to investigate the difference in stage of development of the sea ice between the fast and slow transit each year. In 2010 the fast transit occurred in the middle of January. At this time there was slightly over 50% first year ice (FYI), slightly over 40% young ice, and less than 5% new ice (figure 21). The slow transit in 2010 had 78% FYI concentration; over 25% more than the fast transit. FYI is thicker than young ice (>30cm vs. 10-30cm). This higher concentration of young ice in the HS during the fast transit in 2010 could have played a role in making it as easier and faster transit for the *MV Arctic* through the ZOI. In 2014, the fast transit also had a higher percentage of young ice (20%) than the slow transit that year (10%), however the difference was not as noteworthy. As well, since the fast transit in 2014 had less than 1% concentration of young ice, the concentration of FYI in the fast transit in 2014 was the same concentration as the slow transit in 2010 (78%). This indicates that there are more factors involved in the difficult of a transit through the ZOI than simply sea ice concentration and stage of development.

The other two years with chosen transits, 2012 and 2013, had only 1 chosen transit each year. The interesting comparison between these two years is that the *MV Arctic* entered the ZOI the same day in January both years, the 31st. In 2012, however, the vessel was in the ZOI for 6 hours, while in 2013, the vessel was in the ZOI for 135 hours. Looking closer at the stage of development of the ice during the week of the transit through the ZOI in 2012 and 2013, 75% of the total concentration of ice in the HS was FYI, while only 66% of the total concentration of ice in 2012 was FYI. The difference in ice concentration was made up by more young ice and new ice in 2012 than in 2013 (figure 21). Although this may not be as noteworthy of a difference as between the fast and slow transits of 2010, it is important to note that the thickness of the ice in the HS is not described in greater detail, by this data, than simply being over 30cm. Given than the freeze up date occurred 2 weeks earlier in 2013 than in 2012 (table 9), it is likely that the FYI was able to grow thicker by the end of January. Since these two transits occurred early in the winter season, an extra 2 weeks of freeze up time could have made enough of a difference resulting in a more difficult transit in 2013 than in 2012.

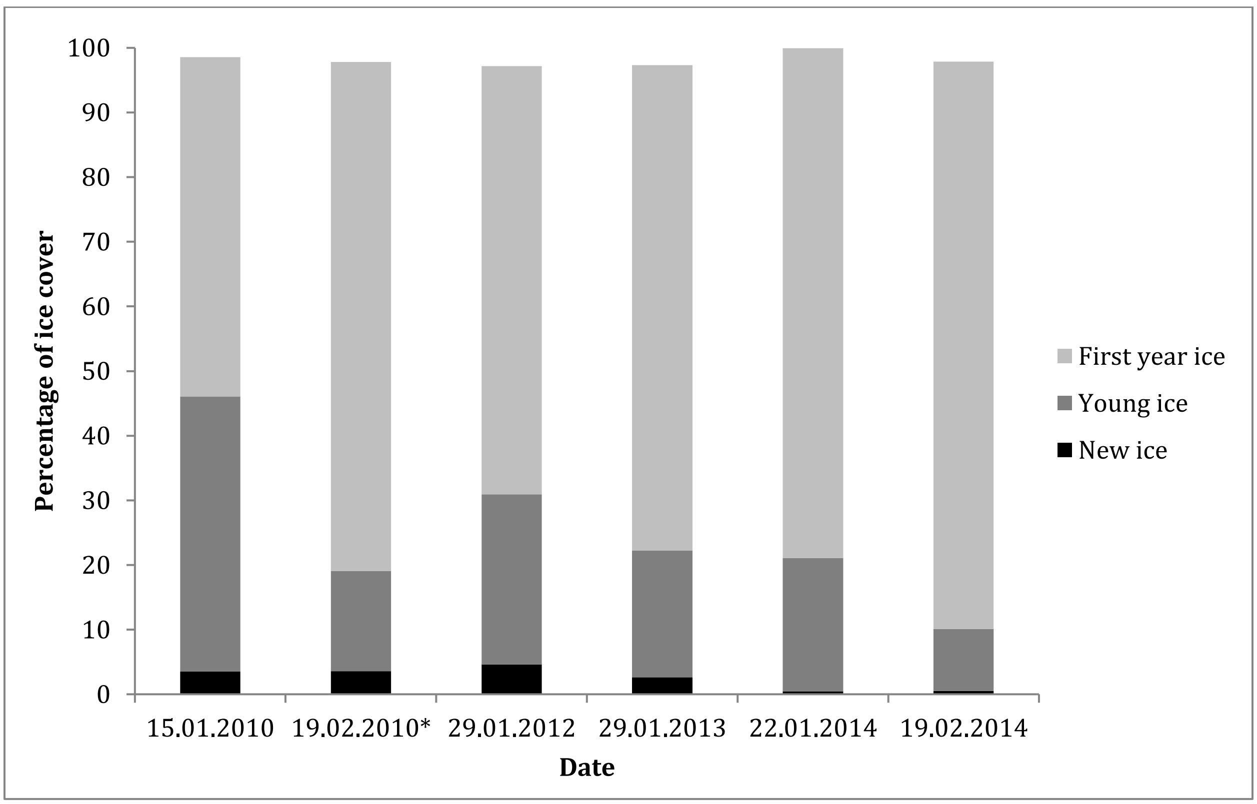

Figure 22. Percentage of ice cover by stage of development for each of the chosen transits (Source: CIS)

*interpolated data

Looking more in depth at the ice conditions during the chosen transits, figures 23 and 25 show the ice regimes across the Hudson Strait, during the time when the ship was transiting the ZOI, with each regime coloured based on the stage of development of the predominant ice type in that regime. Focusing on the ZOI, all chosen transits had 9+/10 coverage during the time the ship was passing through (figure 22, 24). Two of the fast chosen transits occurred at a time when the predominant ice type, leading to the shear zone, was estimated to be lighter. The Ice Chart published January 20th 2012 showed a regime with a predominant amount of (estimated) new ice (>10cm) extending from the northern Quebec/Nunavik shore between Charles Island and Deception Bay. The week of January 20, 2014 showed a regime with a predominant amount of (estimated) grey ice (10-15cm) extending from the coast near Deception Bay (figure 24). These lighter ice conditions, likely cause by prevailing southerly winds, could have played a role in the relative lack of difficulty the ship had transiting through the area. The other chosen fast transit, occurring in January of 2010, was reported as having a regime with a predominant amount of (estimated) thin first year ice (30-70 cm) between Charles Island and Deception Bay. These ice charts do not provide any detail on the amount of ridging or deformation of the ice, nor do they provide information on the direction of the drift of the ice. For 2010, therefore, it is unclear, based on this information, how the general ice conditions influenced the relative ease of the ship's transit through the ZOI.

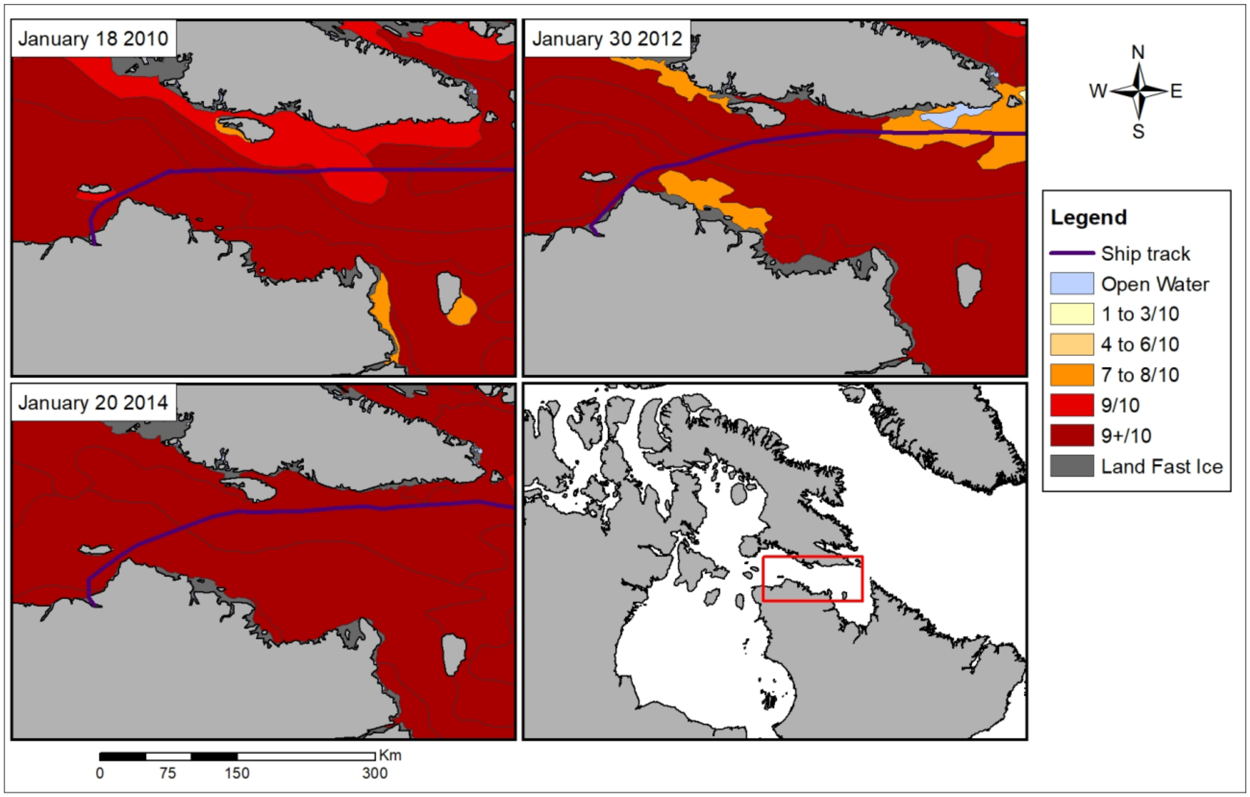

Figure 23. Ice concentration (in tenths) across the Hudson Strait during the chosen fast transits, with the ship track overlaid. (Source, CIS).

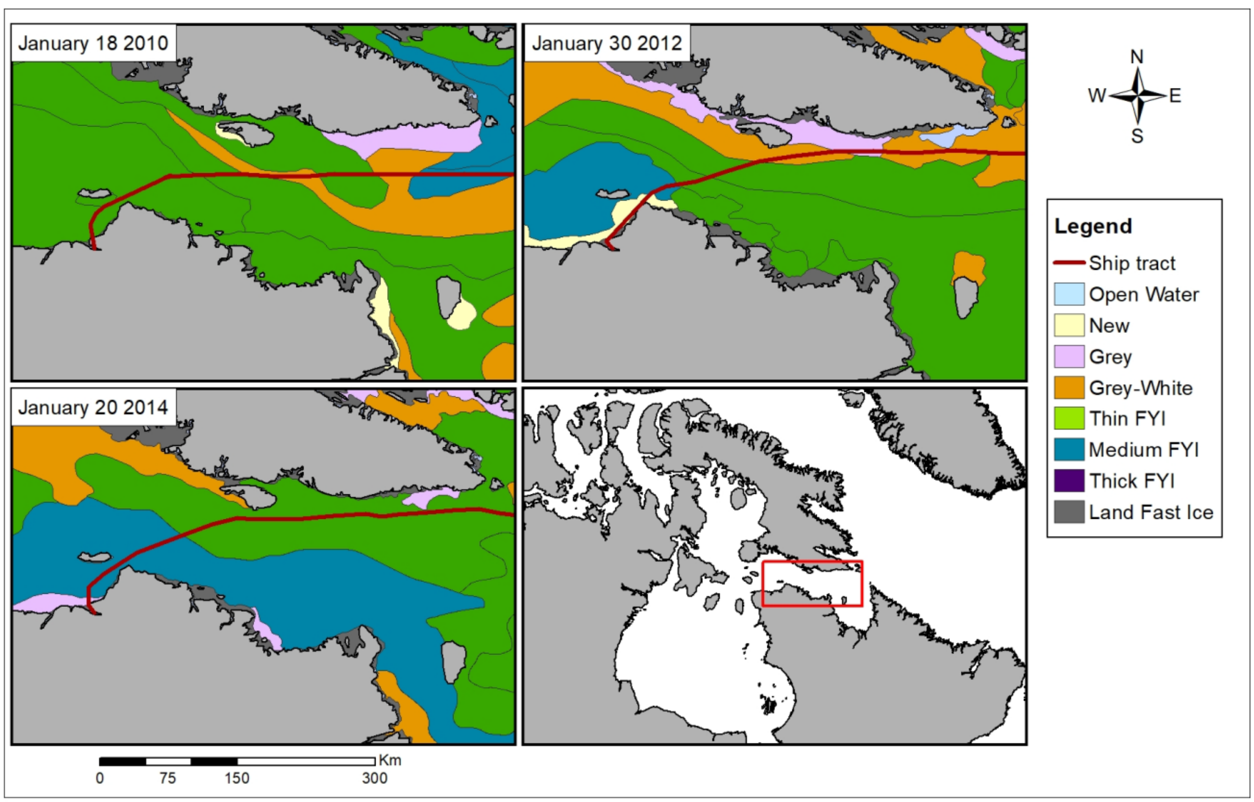

Figure 23. Stage of sea ice development (CIS estimation) across the Hudson Strait during the chosen fast transits, with the ship track overlaid. (Source, CIS).

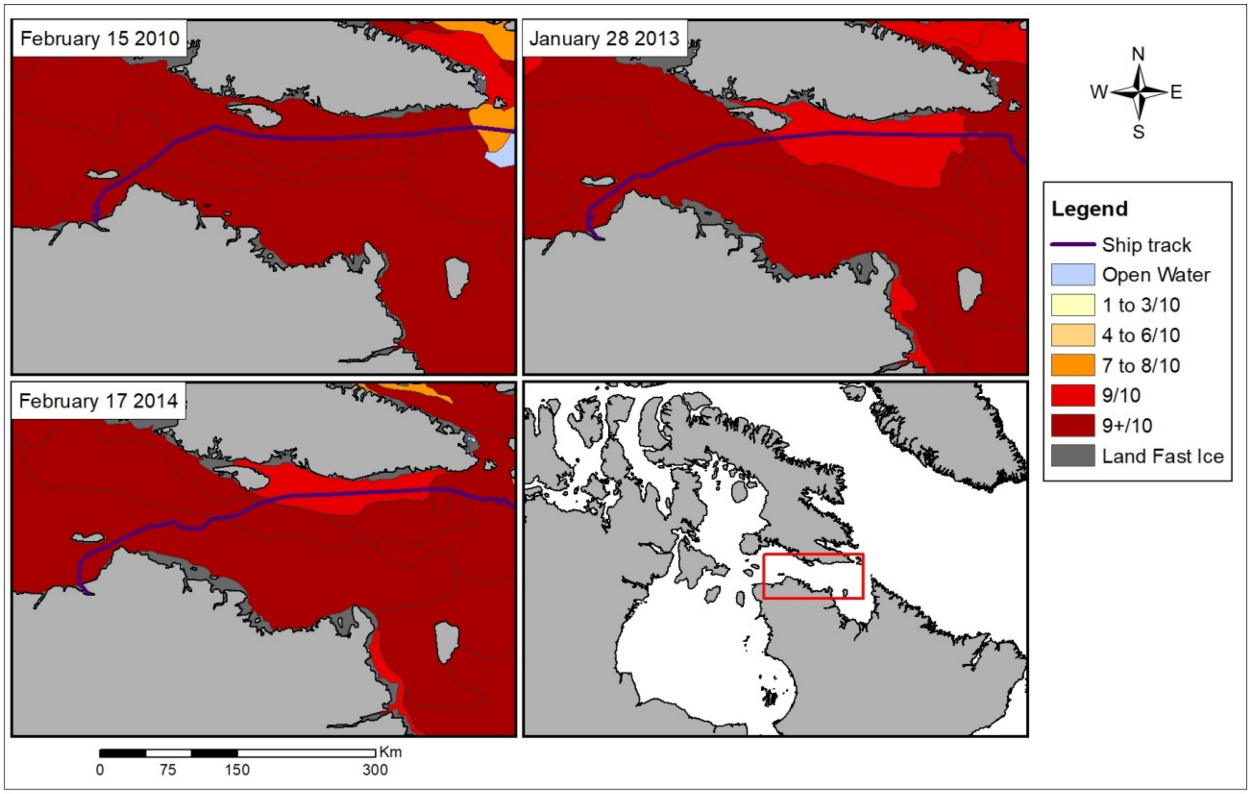

Figure 25. Ice concentration (in tenths) across the Hudson Strait during the chosen slow transits, with the ship track overlaid. (Source, CIS).

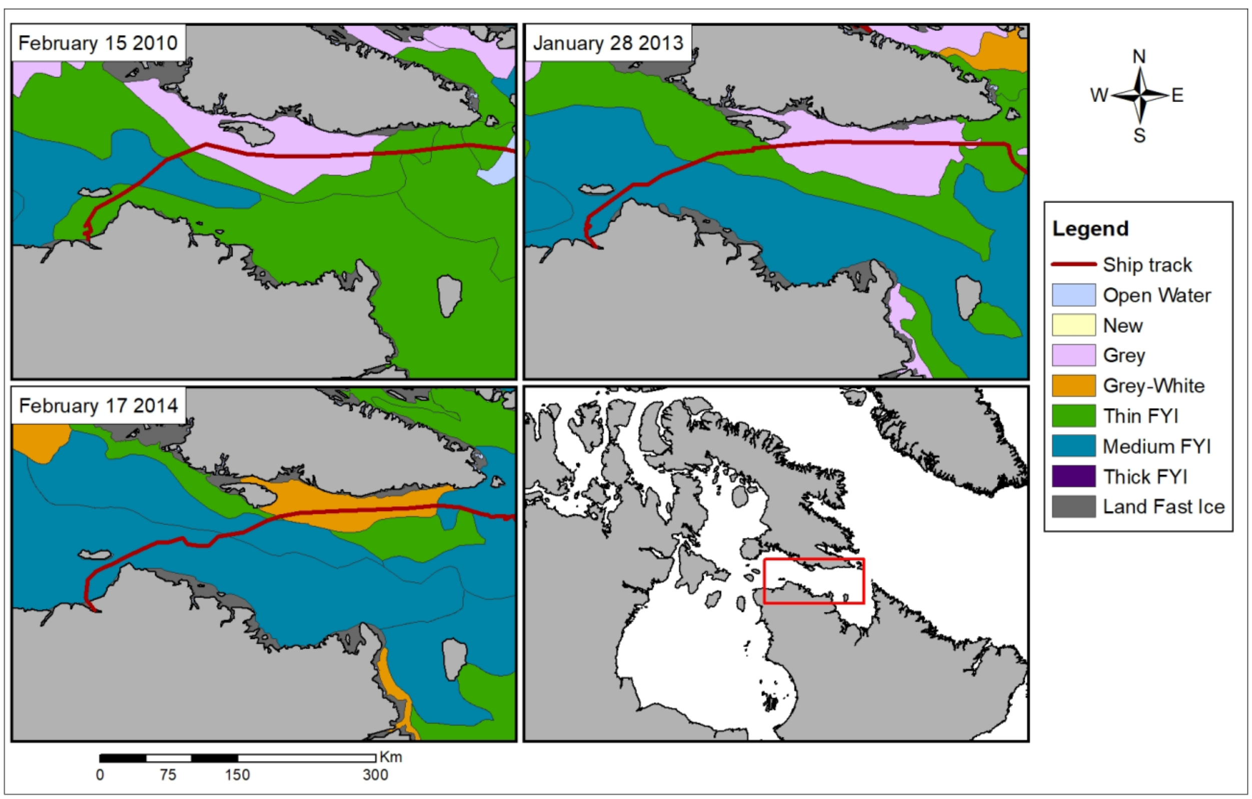

Figure 24. Stage of sea ice development (CIS estimation) across the Hudson Strait during the chosen slow transits, with the ship track overlaid. (Source, CIS).

During the chosen slow transits, focusing on the ZOI, two of the three trips were reported as having a regime with predominantly medium first year ice (70-120cm) (figure 24). Based on these observations, the thicker ice conditions could likely have played a role in the difficult of these transits, in comparison to the three chosen fast transits. The slow transit in 2010, was reported as having the thinnest ice conditions of the three chosen slow transits with a predominantly thin first year ice (30-70) covering the ZOI (figure 24). One interesting comparison is between the chosen fast and slow transits of 2010. The predominant ice type in the ZOI during both of these transits was thin first year ice (30-70cm) (figure 24, 26). This points to the fact that there must be other factors involved, aside from ice thickness that influenced the difficulty of the transit. A possible factor that could have caused the February trip in 2010 to be so much more difficult than the January transit is additional ice ridging.

Mussells et al. (2017) found that between 2005 and 2014, the MV Arctic's winter transits through the Hudson Strait were beset for the greatest percentage of time in March (54%) while in January they were beset for the smallest percentage of time (23%). They also found a significant correlation in the month of travel and the percentage of time the ship was beset. It is important to note, however, that when looking at all the slow transits of the MV Arctic from 2004-2017, five of the slow transits through the HS occurred in January (table 3). Lighter ice conditions, or less freeze up time, cannot be the only factor in determining a difficult transit through the HS. There are many factors that influence the deformation of ice, such as ridging and rafting, and these factors are not depicted in the CIS ice charts.

Mussells et al. (2016) identified ridge counts in the ship track of the MV Arctic through winter months and found that between 1998 and 2012, March was on average the month with the highest ridge counts in the shipping corridor in the Strait, followed by February. This was not always the case however, in some years, such as 2000 and 2008, the month with the highest ridge count identified was January. As well, in some years February had a higher ridge count than March, and in some years, January-March had similar ridge counts, with none of the months having a significant amount of ridges identified compared to the next month. Mussells et al. (2016) identified general similarities and correspondence between areas of high ridge density in the HS and higher levels of besetment of the MV Arctic, they also identified variability in percentages of besetments between transits that could not be described by ridge concentration. To have a greater understanding of what causes one transit through HS to be more difficult that another, other factors must also be considered.

3.3.3 Investigating differences and similarities between fast and slow transits (*Objective 3*)

To investigate the relative role of different meteorological variables on historic besetments during transits of the MV Arctic through the HS, further comparisons with the Salluit meteorological data were completed. Although the Salluit weather station data differed from the data recorded on board the *MV Arctic*, while the ship was in the ZOI, the two were found to have positive moderate statistical significance when compared, and the data was found to have similar variability. The Salluit weather station data is the most related data available to investigate the meteorological conditions that existed prior to the *MV Arctic* arriving in the ZOI. For this analysis, data from the Salluit weather station, starting one week prior to the ship arriving in the ZOI, was considered to capture the conditions that could have influenced ice dynamics prior to the ship arriving in the ZOI. One week prior to the ship arriving in the ZOI was decided to be the period of study, but it is uncertain if this is the proper time frame for analysis. It is possible that weather events that occurred prior to 1 week before the ship entering the ZOI had a greater influence on the conditions at that time, it is also possible that the 1 week period is too long of a period to investigate. Especially in regards to temperature, long-term trends could have played a more significant role than in the week prior to the ship passing through the ZOI. The goal of this work however is to explore the possible influence of the meteorological variables on a shorter timescale.

In table 10 it can be seen that the averages and the range of the investigated meteorological variables for the chosen fast and slow transits are fairly similar. From this comparison, there are no single conditions that seem to stand out between the fast and slow transits to show a clear example of why the slow transits proved much more difficult for the transiting ship. The average air temperature during the fast transits was 1 degree colder and the average range covered a span three degrees larger than the slow transits (table 10). The dew point temperature average during the fast transits was less that 1 degree different than the average in the slow transits. The average range of the fast transits covered a span of almost 5 degrees larger than the slow transits (table 10). It was expected that average dew point temperature and air temperature have a similar difference in average value and range between the fast and slow transits as the two are linked. An increase in air temperature creates an increase in dew point temperature (Ukhurebor et al., 2017).

The pressure values between the fast and slow transits were the closest of the meteorological values, as pressure values do not vary as significantly as the other variables. Average pressure values were 0.4 higher in the slow transits than the fast transits, but this was not consistent between the slow transits, it was more the result of one of the slow transit having a higher average pressure before and during the transit. The range between the average pressure values spanned 0.5 degrees more in the slow transits than the fast transits (table 10).

As determined in the last section, the Salluit wind data is not accurately representative of the wind conditions experienced in the marine area around Deception Bay, based on the comparison to the wind data recorded on the ship while it was in the ZOI. Regardless, the comparison between the slow and fast transits was still completed to see if there were any similarities in the Salluit data that presented themselves between the chosen transits. Following this comparison, reanalysis data was used to further investigate the possible impact of wind on the ice conditions experienced in the ZOI.

From the Salluit data, the average wind speed between the fast transits was within 1 degree of the average wind speed in the slow transits. The average range of the wind speed between the transits was also quite similar, covering only an additional 3.3 degree span in the fast transits (table 10). The average wind direction prior to and during the transits was also compared.

There were 2 chosen fast and 2 chosen slow transits that were dominated by southerly winds, and one transit that was dominated by northerly winds. The percentage that made up the majority wind direction for all the transits was similar, between 24 and 29% (table 10). It was a surprising finding that southerly winds were the dominant direction for 4 of the chosen transits as these winds are more associated with reduced pressure in the ZOI, as they would push the ice away from the shore. Northerly winds, pushing the ice into the shore close to Deception Bay, would likely result in the creation of more pressure ridges, although these were not show as the dominant winds prior to the slow transits, from this data. It has however been discussed that the dominant winds recorded at the Salluit weather station come from the southwest with a frequency of 34% (Genivar, 2012). Although southwest winds have been found to also be prominent in Deception Bay, northwest winds were also found to be more prominent in Deception Bay than in Salluit, likely due to the difference in orientation of the Bay (Genivar, 2012). Later in this section a more in depth investigation into the influence of wind is completed using reanalysis data.

In summary, when comparing the air temperature, dew point temperature, and pressure values recorded 1 week prior to the vessels arriving in the ZOI, outside of Deception Bay, no patterns were found between the weather experienced during the slow transits or the fast transits. In this exploratory analysis, for the restricted timeframe, no relationships between the meteorological data recorded at the Salluit station for 1-week prior and while the ship is in the ZOI have been found to have a significant influence on the creation of pressure ridges. Perhaps if more meteorological conditions were investigated, or if the a longer time scale was used, there would be correlations or some relationships between transits found. Further investigations will need to be completed to gain a deeper understanding of the possible use of Salluit data for understanding sea ice dynamics in the HS.

Table 10. Comparing average and range for each meteorology variable recorded at the Salluit weather station from 1-week prior to, and when, vessel was traveling through the ZOI for the 3 fast and 3 slow chosen transits.

Transit category	Year	Temperature		Dew Point Temperature		Pressure		Wind speed		Wind direction	
		Average	Range	Average	Range	Average	Range	Average	Range	Main direction	% Majority
Fast	2010	-22.4	16.4	-25.6	21.2	98.2	4.1	21.1	48.0	S	26.7
	2012	-19.8	17.1	-21.7	20.5	98.3	2.5	14.7	33.0	N	26.7
	2014	-22	19.8	-25.5	25.8	97.4	1.9	19.9	35.0	S	27.7
	Average	-21.4	17.8	-24.3	22.5	98.0	2.8	18.6	38.7		
Slow	2010	-13.8	7.5	-16.5	10.3	99.4	2.0	4.7	19.0	N	28.9
	2013	-22.7	15.0	-25.3	18.6	97.4	3.2	18.2	52.0	S	24.0
	2014	-24.7	19.4	-28.9	23	98.3	3.2	29.9	55.0	S	27.3
	Average	-20.4	14.0	-23.6	17.3	98.4	3.3	17.6	42.0		

Atmospheric Circulation in the Hudson Strait

The investigated wind data from the Salluit station did not correlate with the wind data recorded on the MV Arctic, nor did the wind data recorded at the Salluit station show any patterns between the slow transits based on the specific spatial and temporal focus of this study. As a continued exploration, larger scale wind patterns from atmospheric pressure systems were investigated. Geostrophic winds have been shown to be important determinants of ice drift on short time scales (Kwok, Pang and Kacimi, 2017; Thorndike and Colony, 1982), and a driving factor in the creation of pressured ice and ridges (Mussells et al., 2016; Kubat et al. 2012). Winds could have played an important role in the difficulty the *MV Arctic* experienced when transiting through the ZOI during the slow transits. Winds causing ice to push against the shoreline in the ZOI would likely result in additional ice being forced into the ZOI, and an increase in the ice pressure in the area, prior to the ship arriving. Winds causing ice to break away from the shore in the ZOI would likely result in ice being forced out of the ZOI, and a reduced ice pressure in the area, prior to the ship arriving. In a short time frame, both these situations could have drastically changed the ice conditions that the MV Arctic would have experienced transiting the ZOI.

In the northern hemisphere, a low pressure system will cause winds in a counter clockwise direction around the center of the low (Munk, 1947). Drinkwater (1986) discussed the impact of atmospheric weather patterns on the wind directions in the HS (table 11). The dominant atmospheric pattern of a low-pressure system over the Davis Strait causes north to north-westerly winds to be prominent in the HS (Drinkwater, 1986). Anomalies in atmospheric circulation have been noted to have an impact on flow of sea ice and its advance and retreat patterns in the HS. An intense low system over the north Atlantic, specifically southwest Greenland and the Davis Strait, has been found to bring northerly winds and an earlier ice advance season. A low centered over south-eastern Baffin Island has been associated with westerly winds over the HS. A low-pressure system centered over Foxe Basin or Northwest Quebec has been associated with southerly winds over the HS, bringing earlier ice retreat dates (Drinkwater 1986). An example of the impact of a low-pressure system on the wind direction through the HS can be seen in figures 27 & 28. In this example a low pressure system can be seen centered over south-eastern Baffin Island, on January 27, 2019. As discussed by Drinkwater (1986) a low-pressure system in this position is associated with westerly winds across the HS. In figure 28, the wind prognosis for the same day shows a forecast of 30 knot westerly winds near Deception Bay in the ZOI area. Mussells et al. (2016) found that most seasons with low ridge densities, between 1997 and 2012, had anomalous wide high-pressure anomalies over HS. These anomalous high pressure systems over the HS could create winds that would encourage the flow of ice through the HS (Mussells et al., 2016).

Table 11. Summary of locations of low pressure systems and associated winds over the Hudson Strait, as discussed by Drinkwater (1986).

Location where low pressure system is centered	**Associated wind direction over the HS**
North Atlantic, specifically southwest Greenland and the Davis Strait	Northerly
South-eastern Baffin Island	Westerly
Foxe Basin or Northwest Quebec	Southerly

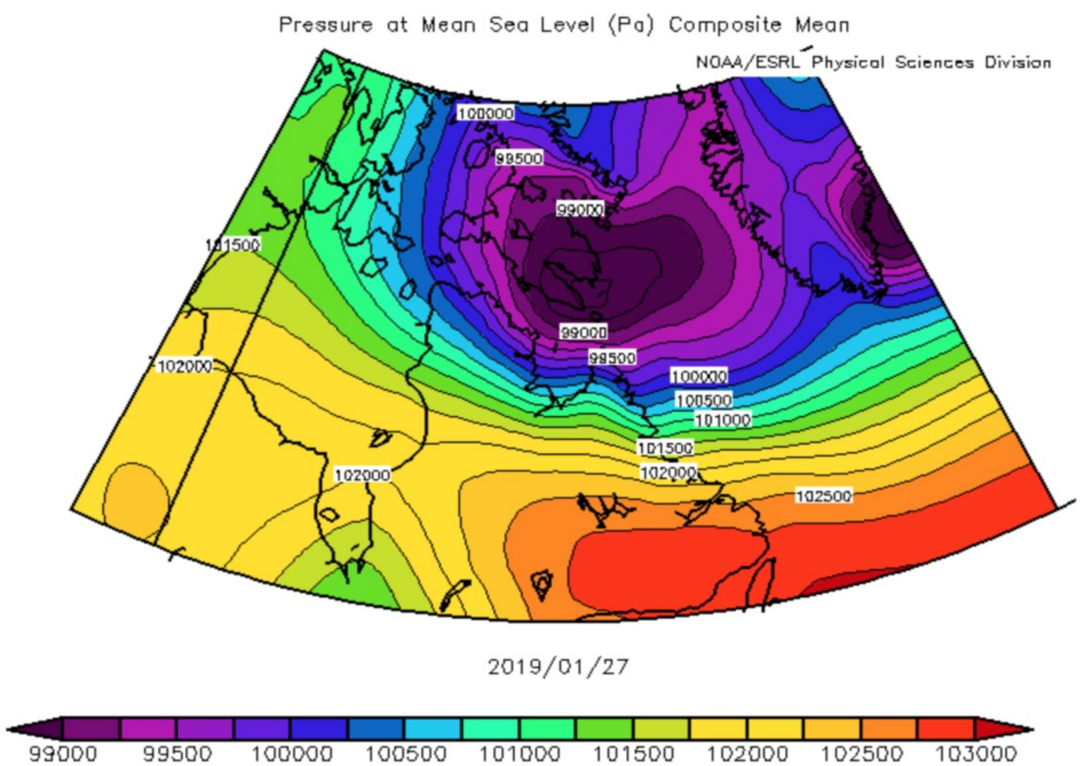

Figure 25. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 27, 2019. (source: ESRL NOAA).

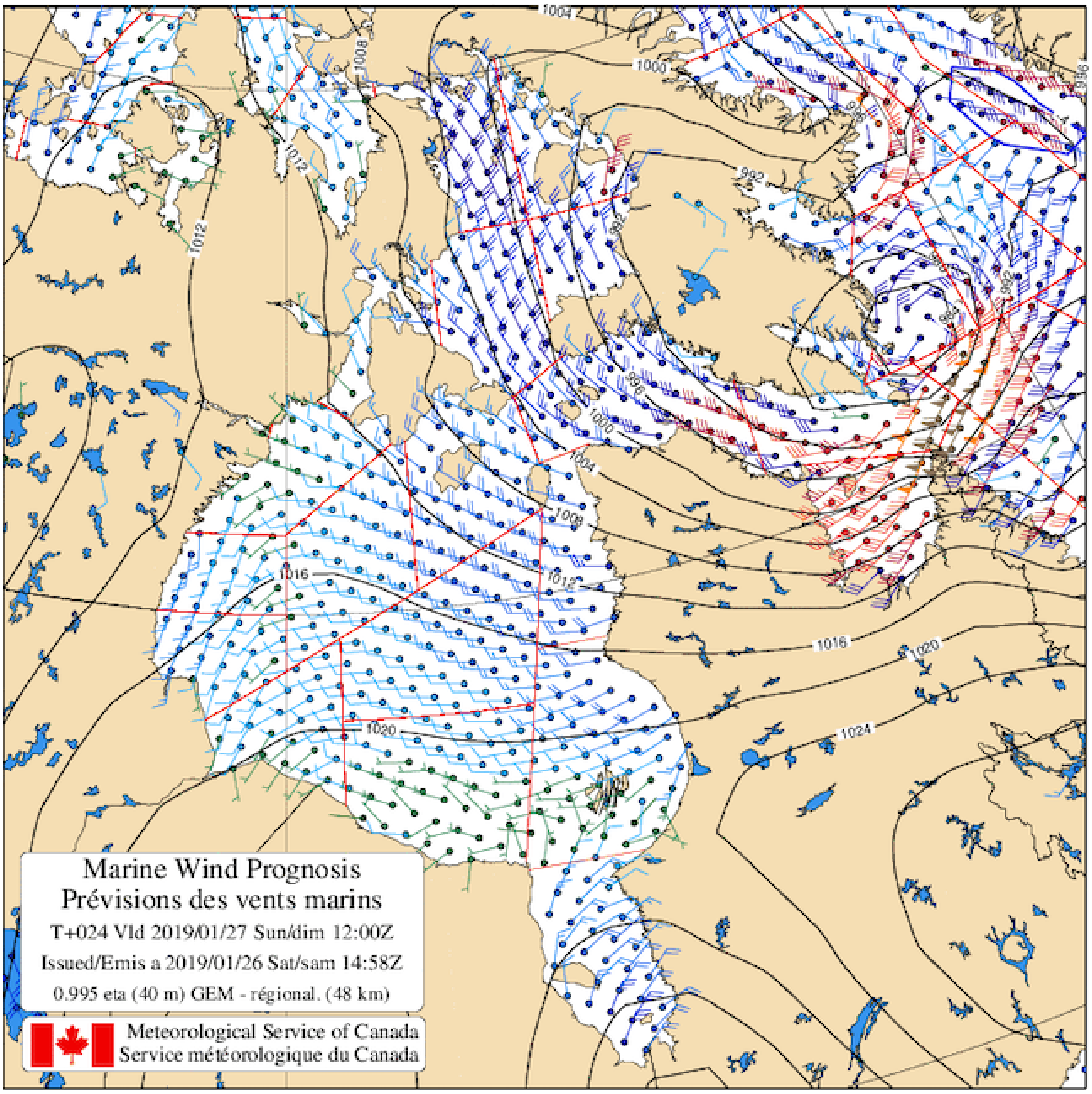

Figure 26. Marine wind prognosis for January 27, 2019. (Source: Meteorological Service of Canada).

The first investigation of the influence of pressure systems in the HS during the chosen transits was completed by looking at the daily mean sea level pressure values over the ZOI, for the week prior to the ship entering the ZOI, during the chosen fast and slow transits (Figure 29). For the chosen time period and for these transits, there is no obvious pattern between the daily mean pressure values and difficulty of transit. The slow chosen transit in 2010 had daily mean pressure values higher than all of the other chosen transits for the entire week prior to the ship arriving in the ZOI. Anomalous high pressure over the HS, however, has been associated with facilitating the flow of ice from the Strait (Mussells et al., 2016). Given this, we would expect that high pressure leading up to the ship passing through the ZOI would allow for a less difficult transit. However, since this was not the case, perhaps the flow of ice through the Strait caused increased ice to be forced through the bottleneck between Charles Island and the Quebec coast, increasing the amount of ice, and the ice pressure in the ZOI. Additionally, an increase in ice flow could cause additional shearing of ice at the shearzone near Deception Bay. It is possible as well that the strength of the wind was not significant to have a substantial impact on the flow of ice in the time frame investigated.

Another noteworthy observation from the comparison between the daily mean pressure values (figure 29) is that during the three fast chosen transits all had relatively low mean sea level pressure over the ZOI, and lower than two of the chosen slow transits, for the 2-3 days prior to the MV Arctic entering the ZOI. Lower sea level pressure could have been the result of a low pressure system near the ZOI. A low pressure system centered over north-western Quebec or Foxe Basin, near the ZOI, is associated with southerly winds (table 11). This could have resulted in ice moving away from the Quebec coast between Charles Island and Deception Bay, and creating more space in the ice pack for the vessel to transit through. When looking at the ice conditions for the chosen fast transits in 2012 and 2014 (see section 3.3.2, figure 24), there is an area of lighter ice along the Quebec coast either near Deception Bay (2014) or between Charles Island and Deception Bay (2012). These conditions align with the hypothesis of southerly winds occurring some days before the ship arrived in the ZOI. It is important to note, however, that the chosen slow transit in 2013 also had similar low mean sea level pressure values for the 2 days prior to the vessel entering the ZOI, however, this did not ease the transit of the vessel into Deception Bay, nor did it appear to push ice from the Quebec coast, based on the ice chart published during the time the ship was in the ZOI (see section 3.3.2, figure 26). In this case, the location of the low pressure system, the strength of the system, or the timescale investigated, could have played a role in its impact on the ice conditions in the area, at that time.

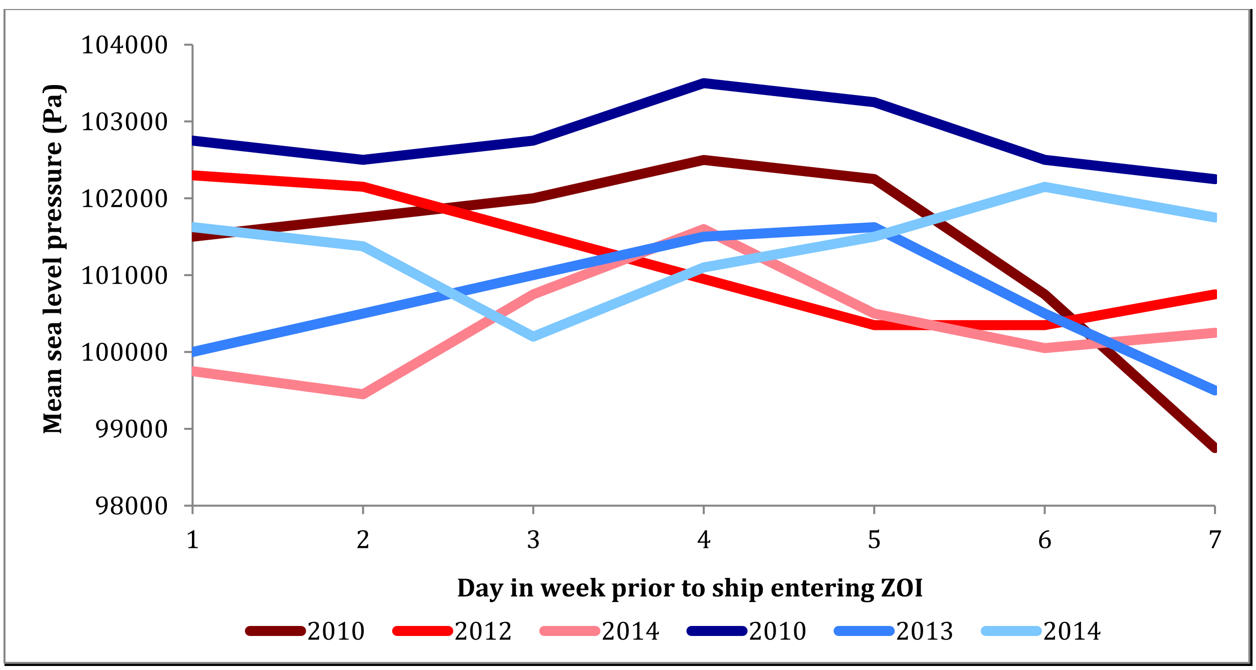

Figure 27. Daily mean sea level pressures (Pa) for the week prior to the MV Arctic entering the ZOI during the chosen transits. Fast transits displayed in red, slow transits displayed in blue. Values from NARR NCEP reanalysis products.

Drinkwater (1986) discussed the influence of the position of the low pressure systems over the HS, rather than the actual values of mean sea level pressure across the Strait (table 11). Table 12 shows a breakdown of the daily location of the low pressure systems centered around the HS, and the associated wind over the HS, for the week prior to the ship entering the ZOI during the chosen transits. Looking at the six chosen transits, it was most common for the low pressure system to be centered over the Davis Strait, specifically often over south western Greenland, and over the North Atlantic. This aligns with Drinkwater (1986) reporting the dominant atmospheric pattern was for a low pressure system centered over the Davis Strait. With a low pressure system over the Davis Strait, closer to SW Greenland, or over the North Atlantic, northern winds are most common (table 11). Northern winds would cause compression of ice into the ZOI, from the northern portion of the HS, into the more southern portion.

Looking at the patterns of the low pressure systems in the chosen transits, it is interesting to see when more southerly winds could have been caused as a result of larger scale atmospheric pressure patterns. For the fast transits in the chosen years, prior to the ship arriving in the ZOI, a low-pressure system was the dominant pressure pattern in the HS. In the three fast chosen transits, there was a minimum of 2 days towards the end of the week, prior to the vessel arriving in the ZOI, that showed the low pressure system was in a position that was associated with southerly winds (table 11). These 2+ days of southerly winds in the fast transits could have resulted in reduce ice pressure in the ZOI, pushing the ice up into the HS, rather than into the coast and the Deception Bay Inlet. Other factors such as wind speed, ice thickness, floe sizes, and ice concentration can all play a role in the impact that the winds could have on the ice pack, however the three fast chosen transits having more consecutive days of atmospheric patterns associated with southerly winds is an interesting connection. Looking at the ice charts available for the dates near the fast chosen transits, in both 2012 and 2014, there are lighter ice conditions close to the Quebec coast in the ZOI, as would be expected from consistent or strong southerly winds (see section 3.3.2, figure 24). For the fast chosen transits in this study, looking at atmospheric pressure patterns provides valuable insight into why these transits could have been faster for the *MV Arctic* to transit through the ZOI than during the other transits.

For the slow transits in the chosen years, when looking at the atmospheric pressure patterns in the area surrounding the Hudson Strait, two of the three slow transits (2013, 2014) had 1 day where the position of the low-pressure system was associated with southerly winds. The rest of the time, the main pattern of low pressure was over Davis Strait, north Atlantic, or south-eastern Baffin Island for the week prior to the ship arriving in the ZOI (table 12). These patterns are associated with bringing northerly winds (or westerly for the case of SE Baffin Island) over the HS, which would likely cause sea ice to be compressed against the Quebec coast near the entrance to Deception Bay, causing an increase in ice pressure in the area. It is likely that having atmospheric pressure patterns associated with northerly winds for the entire week, or majority of the week, prior to the ship entering the ZOI had an influence on the difficulty that the *MV Arctic* had transiting through the ZOI. This points to the fact that, for the chosen slow transits in this study, looking at atmospheric pressure patterns again provides valuable insight into why these transits could have been slower for the *MV Arctic* to transit through the ZOI than during the other transits.

Table 12. Description of mean sea level pressure (hPa) patterns for 1 week prior to the MV Arctic entering the ZOI, for all fast and slow transits, based on NARR NCEP reanalysis products (see Appendix for daily pressure plots)

Trip	Dates	Description of location of low-pressure system for full week prior to MV Arctic entering the ZOI	Associated wind pattern over the HS
F1	01.09.2010 – 01.15.2010	Week begins with low-pressure over Davis Strait, and ends with an additional low-pressure over Hudson Bay, then over Northern Quebec and the Hudson Strait	Day 1-5: Northerly Day 6-7: Southerly
F2	01.25.2012 – 01.31.2012	Week begins with low-pressure system across Davis Strait, then moves to low over North western Quebec, then back to over the Davis Strait	Day 1-3: Northerly Day 4-6: Southerly Day 7: Northerly
F3	01.14.2014 – 01.20.2014	Week begins with low-pressure system over northern Quebec, moving to south-eastern Baffin Island and Davis Strait, then as this low moves eastward, another low pressure system is developing of Foxe Basin. This develops into an intense low-pressure system covering most of the area, but also with a system centered over Quebec.	Day 1: Southerly Day 2-3:Northwesterly Day 4-7:Southerly
S1	02.10.2010 - 02.16.2010	Low-pressure system over Atlantic Canada and the North Atlantic.	Day 1-7: Northerly
S2	01.25.2013 – 01.31.2013	Week begins with a strong low-pressure system over Davis Strait, as this system moves eastward, a low-pressure system moves over northern Quebec towards south eastern Baffin Island the end of the week.	Day 1-5: Northerly Day 6: Southerly Day 7: Westerly
S3	02.11.2014 – 02.17.2014	Week begins with a low-pressure system over the north Atlantic, then as this system moves east, second low-pressure system develops over northern Quebec mid week before moving over to the Davis Strait and the North Atlantic for the rest of the week.	Day 1-2: Northerly Day 3: Southerly Day 4-7: Northerly

Further investigating the slow transits, table 13 shows the main atmospheric pressure patterns and associated wind directions present while the *MV Arctic* was in the ZOI. When looking at the pressure systems in the surrounding area during the slow transits through the ZOI, although there was variation between the locations of the low pressure systems between the 3 transits, the main patterns were still associated with predominantly northerly winds. These northerly winds could likely have influenced more ice flowing into the ZOI, or restricted the flow of ice out of the ZOI, making the transit of the *MV Arctic* more difficult as a result of the greater ice pressure, and resulting pressure ridges in the region.

From the similarities in atmospheric pressure patterns noted, for the week prior to the chosen transits, and for the time the ship spent transiting through the ZOI during the slow transits, it appears that the larger scale atmospheric pressure patterns had an influence on the difficulty of the transits. These findings point to an interesting possibility of atmospheric circulation having an important influence on the creation of pressure ridges in the ZOI, however, this same investigation should be completed for a greater number of fast and slow transits to have a better understanding the strength and influence of the patterns between the transits.

Table 13. Pressure charts during time when the MV Arctic is in the ZOI during slow transits.

Trip	Dates	Description of location of low pressure system for full week prior to MV Arctic entering the ZOI	Associated wind pattern over the HS
S1	02.16.2010 – 02.19.2010	Low pressure in Atlantic Canada, and over the North Atlantic	Northerly
S2	01.31.2013 – 02.04.2013	Low pressure system moves from being centered over south eastern Baffin Island to over the Davis Strait. The final day in ZOI there is a low pressure system developing over Foxe Basin.	North westerly, to southerly on final day
S3	02.17.2014 – 03.01.2014	Low pressure over North Atlantic for entire time the MV Arctic is in the ZOI, however, in addition, there is a second low pressure system that develops over western Quebec and Foxe basin from the 22 to the 25.	17-21: Northerly 22-25: Southerly 26-01: Northerly

Following the investigation atmospheric pressure patterns, weekly reanalysis composite plots from the NCEP NCAR reanalysis dataset were created for wind direction and strength, for the week prior to the *MV Arctic* entering the ZOI for the chosen transits (Figure 30, 31). These plots show the dominant mean wind patterns, locally over Hudson Strait. Figure 30 shows that the fast transits had dominant mean wind directions that would influence sea ice being pushed away from the Quebec coast near Deception Bay. The week prior to the fast transit in 2010 had a mean dominant south-westerly wind of 4-6m/s. The week prior to the fast transit in 2012 had a mean dominant easterly wind of close to 5m/s. The week prior to the fast transit in 2014 had a mean dominant southerly wind of 3-4m/s. Looking at the ice charts for the week of the ship transiting the ZOI during the fast transits, the ice charts show lighter ice conditions in agreement with the predominant wind directions in 2012 and 2014 (section 3.3.2, Figure 24). The average wind speeds do not point to extreme events or stormy weather, the average wind speeds prior to the chosen transits fell between a rating of 3 and 4 on the Beaufort scale. Even though the wind speeds were generatlly calm, these wind patterns are more associated with divergence, and pushing the ice away from the coastline. The dominant consistent wind influencing ice divergence likely had an impact on the relative ease of the fast transits in the ZOI.

The slow transits, in comparison, had dominant mean wind directions that would have influenced sea ice being pushed into the Quebec coast near Deception Bay. In the week prior to the slow transit in 2010, there was a mean dominant northerly wind of around 6m/s. The week prior to the slow transit in 2013 there was a mean dominant northerly wind of around 3m/s. The week prior to the slow transit in 2014 there was a mean dominant westerly wind of 2-3m/s. These wind patterns are more consistent with convergence, and ice being pushed towards the coastline. This was likely a cause of additional ice pressure, influencing slower transits through the ZOI.

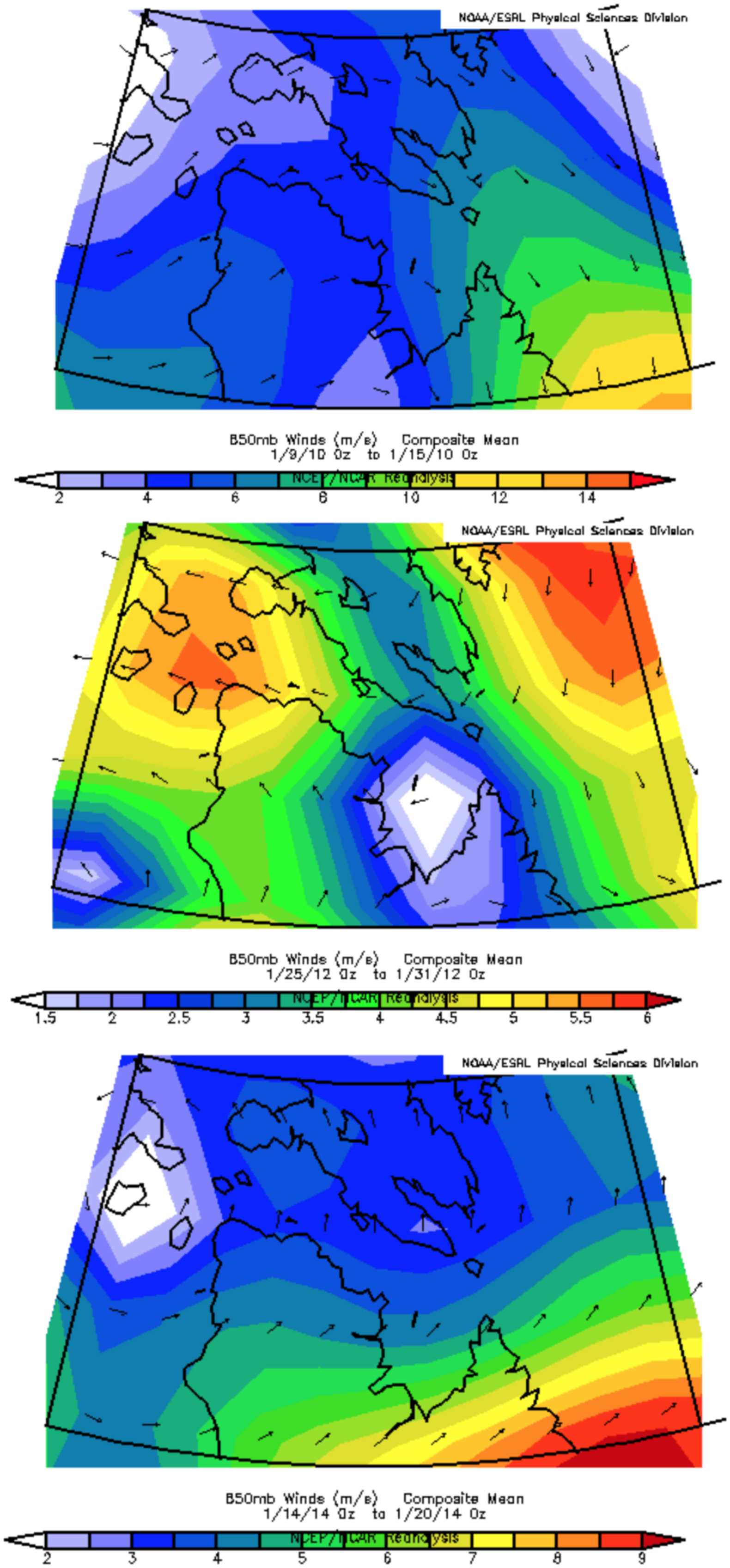

Figure 28. NCEP/NCAR reanalysis composite wind vectors (850mb) showing mean dominant wind direction and speed in the Hudson Strait for the week prior to the MV Arctic entering the ZOI during the fast chosen transits.

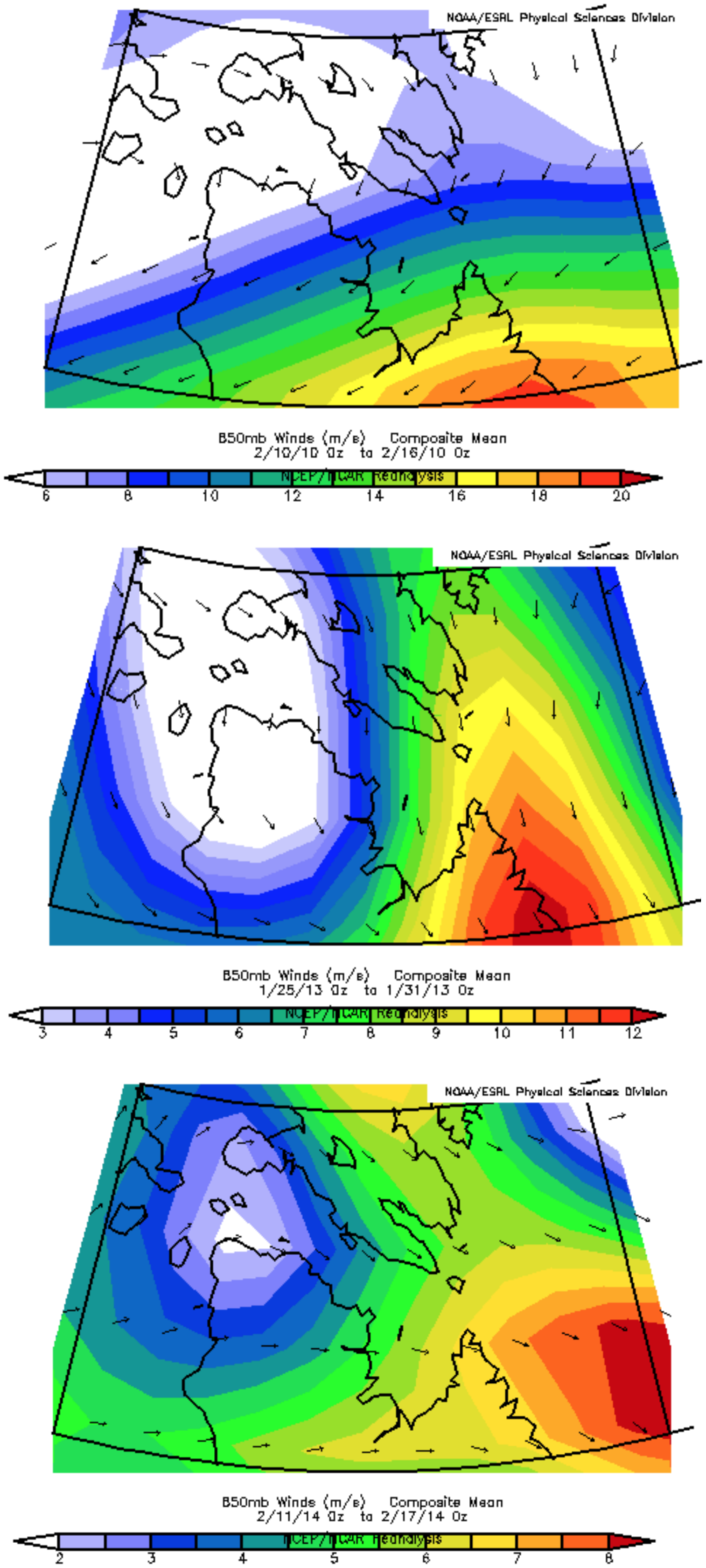

Figure 29. NCEP/NCAR reanalysis composite wind vectors (850mb) showing mean dominant wind direction and speed in the Hudson Strait for the week prior to the MV Arctic entering the ZOI during the slow chosen transits.

Looking at the wind reanalysis data, prior to the ship transiting the ZOI, there is a pattern between the dominant wind direction in the ZOI and the difficulty the ship had when transiting. Although the patterns found agree with the atmospheric pressure analysis, pointing to northerly and westerly winds being more common before slower transits, and southerly and easterly winds being more common before faster transits, the mean dominant wind directions (Figures 30&31) do not perfectly align with the directions assumed from the location of the low pressure systems (Table 12) for the same time period. Further analysis could include daily or hourly wind reanalysis data to better understand what the dominant wind directions over the ZOI are when the low pressure system is located in different areas, and how consistent the relationship is between the two.

Further investigations with reanalysis wind data should be completed with more transits to test the pattern and influence of winds on convergent and divergent ice dynamics. Next steps that would be interesting would be using a pressure model to investigate the ice volume in the ZOI, or between Charles Island and Deception Bay to better understand how much ice is being pushed into the ZOI when the winds are favouring convergence into the coastline. This could also give insight into the importance of ice thickness in relation to the relative difficulty or the ease of the ship transits.

3.4 Conclusions

In areas of high ice concentration, pressured ice and sea ice ridges can cause significant delays to shipping traffic. A better understanding of the meteorological factors involved in the creation of pressured ice and ridges is needed in order to improve the safety of shipping through ice-covered waters. An ice breaking ship, the *MV Arctic*, encounters significant delays during some of the winter transits through the HS in the winter months along its route to service a mine in Deception Bay. This study provides an exploratory analysis investigating for a relationship between meteorological conditions and ship besetments within a specific temporal and spatial scope. This was completed though first examining if meteorological variables recorded at the Salluit land based weather station, near Deception Bay, could be used to understand the weather conditions experienced in the marine area near Deception Bay.

Focusing on 6 transits of the *MV Arctic* through the HS, this study presents a comparison of ice conditions and freeze up patterns for the chosen years to better understand the variability between the years. This study also includes an ice climatology of the HS from the winter of 2004/05 to the winter of 2017/18. Following this, this study includes an investigation of using the available recorded Salluit weather station data, and as well atmospheric pressure data from reanalysis, to better understand the ice conditions encountered by the *MV Arctic* in the marine area along the approaches to Deception Bay, in the HS.

Through the findings of this research, it has been determined that the meteorological data recorded at the Salluit weather station is moderately significant when compared to the meteorological data recorded on board the *MV Arctic* while in the established ZOI. The meteorological conditions of air temperature, dew point temperature and pressure did also follow similar patterns for the chosen transits. Therefore, although the weather station data is not showing the same values as those recorded on the ship while in the ZOI, it can be used with moderate confidence to understand the variability of the weather conditions, and offer insight into the conditions being experienced in the marine area that we otherwise would not have.

The created ice climatology presents the variability that exists between freeze up and break up patterns year to year in the Hudson Strait. Differences in freeze up patterns, ice concentration, and estimated thickness during the chosen transits provides some insight into why some of the chosen transits may have been more difficult for the *MV Arctic* than others. It is clear, however, from looking at the ice conditions during each of the chosen transits, that there is more than just ice concentration and stage of development that play a role in the difficulty of transiting ships. Details of sea ice dynamics, such as those creating pressured ice and sea ice ridges, are not captured in ice charts. Additional investigations, such as this exploratory analysis with meteorological conditions, are important to understand the other factors involved in ice motion and ridging.

The Salluit weather data was used for further analysis of the possible impact the conditions had on the ice dynamics, in relation to the difficulty the *MV Arctic* had transiting through the ZOI. When comparing the Salluit meteorological conditions between the different transits, for prior to when the vessel arrived in the ZOI and when the vessel was transiting through, no significant patterns between the transits were found.

There were patterns found between the three fast and three slow transits when looking at the dominant atmospheric pressure systems from prior to the transits, from NCEP NARR reanalysis data. Although the atmospheric pressure values in the ZOI, prior to ship arriving, showed no patterns with the difficulty that the ship had transiting, the location of the large scale atmospheric low pressure systems near the Hudson Strait did provide insight into the difficulty the ship had transiting through the ZOI. Research has shown that the prevalent winds directions over the Hudson Strait are related to the region over which the predominant low pressure system is located (Drinkwater, 1986). Low pressure systems in the locations that would influence northerly winds were more common prior to and during the slow transits, and low pressure systems in the locations that would influence southerly winds were more common prior to the fast transits. Wind reanalysis data also showed similar results, although slightly different dominant wind directions than were assumed from the location of the low pressure systems. The wind reanalysis data showed, on a larger scale in the ZOI, northerly and westerly winds prior to the *MV Arctic's* slow transits, and southerly and easterly winds prior to the fast transits. Similar analysis should be completed with the atmospheric pressure and wind reanalysis data for a greater number of transits to better identify the strength of the patterns that were found.

More investigations will have to be completed to better understand if the Salluit data can be reliably used to understand the formation of pressure ridges in the ZOI, or if the proper time period or spatial area was not investigated in this study. Although there were some patterns found with reanalysis data, the work presented in this paper shows that more extensive analysis needs to be completed with meteorological data to gain a greater understanding of how the integration of land based meteorological data can be used better understand the creation of pressure ridges at a local scale in the Hudson Strait. It is important to note that because so little is known about pressured ice formation and ship besetment in the Hudson Strait, the approach taken in this paper represents an important first analysis despite no strong patterns found with the recorded land based meteorological data. As patterns in sea level pressure and wind from reanalysis data, over the Hudson Strait, showed some relation to the difference between the difficulties of the transits investigated, more tests should be completed covering a greater number of transits to test the strength of this finding. This could aid in better understanding the dynamics involved in the formation of pressure ridges and perhaps lead to prediction of pressured ice and associated ship delays in the future.

CHAPTER 4: SUMMARY OF WORK AND CONCLUSIONS

4.1 Study Conclusions

Shipping traffic through Canadian Arctic waters is predicted to increase with the reduction of sea ice due to climate change (Gascard et al., 2017; Melia et al., 2016; Smith and Stephenson, 2013), as well as with an increase in tourism and resource extraction initiatives in the Arctic (AMAP, 2012; Pizzolato et al., 2016; 2014). Sea ice is also predicted to continue to become more mobile with climate change, which could increase of the frequency of pressure ridges. These ice ridges cause difficult ice conditions for ships navigating through the ice-infested waters, even highly ice strengthened vessels. Captains have called for more research to be completed to better understand the formation and presence of pressured ice in Arctic waters. A better understanding of their formation could possibly improve our ability to predict their presence in the future. Using the Hudson Strait as the study region, this work has explored this knowledge gap by investigating two main research questions: can land-based meteorological data be used to understand nearby marine weather conditions in the Hudson Strait near Deception Bay; and is there a relationship between land based meteorological variables recorded around the time of significant besetting events of a vessel, the MV Arctic, and such, can these relationships give additional insight into why the vessel was beset more frequently during some transits over others.

In Chapter 3 a sea ice climatology was created to better understand how differences in the freeze up period in the chosen years could have influenced the difficulty the ship had transiting, and the amount of pressured ice and ridges that were encountered. This investigation showed that although a later freeze up season, or a transit occurring early in the ice covered season, may cause lighter ice conditions and less ice pressure and ridges encountered during a transit, this is not the only factor involved. The sea ice analysis, being completed with ice charts, was not able to capture variables that influence sea ice dynamics. This is important to note, as it underscores the need for additional investigations being completed, such as exploratory analyses with meteorological conditions, to better understand the other factors involved in ice motion and ridging. In the ice climatology created, the variability in freeze up and break up patterns and dates were also compared and graphed, between the winter of 2004/05 to the winter of 2017/18. Although there is significant variability in freeze up patterns between some years, the majorities of the years have a similar freeze up and break up week. This is important information for shipping companies who are operating lighter ice class ships and who are looking to navigate the Strait in the shoulder seasons.

Comparing meteorological data recoded at the same time from on-board the *MV Arctic*, and from the nearby weather station in Salluit, QC, showed moderate positive correlations in the data, and similar patterns in the air temperature, dew point temperature, and pressure values when they were graphed. The wind data recorded at the Salluit station and on board the *MV Arctic* was found to show no relation. This could likely be as a result of the different orientation of the land near Salluit in compared to where the ship is in the ZOI. Although, for most meteorological variables investigated, the data recorded from the Salluit land based station and from onboard the ship was not the same, it still showed a positive moderate correlation. The

Salluit data was further analyzed in order to investigate the conditions present in the marine area prior to the ship arriving in the ZOI. Any relationships that existed between the land-based meteorological data recorded prior to and during the *MV Arctic* transiting through the ZOI, during the chosen transits, were investigated, but none were found. This is an important finding as well, as this indicates the study could be repeated with a larger sample size or a different temporal scale. This exploratory work shows but a first step into investigating the use of land based meteorological data for understanding the marine conditions near Deception Bay.

Atmospheric pressure patterns, investigated from reanalysis data, showed some promise for understanding scenarios of pressured ice and sea ice ridge formation, as there were similarities between the locations of atmospheric pressure systems, prior to the *MV Arctic* entering the ZOI, and the difficulty of the transit. The locations of the pressure systems and their associated wind directions over the HS were based off of Drinkwater's (1986) study. Mean local wind directions, derived from reanalysis data, over the ZOI, prior to the ship transiting, were also found to show insight into why some transits were more difficult than others. Additional work should be completed to better understand the reliability of these relationships in order to investigate if pressure patterns can be used to forecast the difficulty that the transiting ship might have when passing through the ZOI.

In response to the first main research question, this work has shown that, based on the cases investigated, the Salluit land based meteorological data can be used to understand the variability of the meteorological data in the marine area in Deception Bay. In response to the third main research question, this work has shown that, based on the cases investigated, there is no relationship that can be found between the land based meteorological variables and the difficulty of the transits of the *MV Arctic* through the ZOI. This work did however show that, using reanalysis data, atmospheric pressure patterns and local winds appeared to have an influence on the difficulty of the *MV Arctic*'s transit through the ZOI. The work competed in this thesis brings light on the fact that little is understood about the formation and prediction of pressure ridges at a local scale, and that more analysis needs to be completed to understand how land-based meteorological data can be used to develop a greater understanding of these ice features.

4.2 Contributions

Chapter 3 makes an original contribution to the research available on meteorological variables, pressured ice and the associated delays to navigating ships in the Hudson Strait. This work, investigating the relationship between meteorological variables recorded at a land based station and onboard a ship in the HS, and investigating any relationships existing between the meteorological variables in relation to fast and slow transits of the *MV Arctic* through the ZOI, is a contribution to a research gap identified by ship Captains and in academic literature (Kubat and Sudom, 2009; Mussells et al., 2016). As shipping through Arctic waters is expected to increase with climate change, and as a result of other factors, (Dawson, 2018; Gascard et al., 2017; Melia et al., 2016), a greater understanding of sea ice dynamics and associated sea ice pressure is necessary to develop a more in depth understanding of safe shipping conditions future transiting ships. This work represents an important first step in exploring the relationships between meteorological variables and ice conditions encountered by the *MV Arctic* while making the voyage to Deception Bay, QC.

Using meteorological observations recorded onboard a ship in the Hudson Strait has allowed for a more in depth local analysis of besetting situations than can be completed simply using meteorological data from models or from gridded reanalysis data. Previous work has been done to explore the factors leading to ice pressure events at a ship scale (Kubat and Sudom, 2008; Kubat et al., 2012; Kubat et al., 2013), however no such work has been done with actual besetting events in the HS. This work provides an important first step into understanding the reliability of using land based meteorological data to understand pressure ridge formation in the Hudson Strait, as encountered by transiting ships.

The work presented in Chapter 3 builds on the foundation presented in Mussels (2017) by providing a longer time period for the summary of the *MV Arctic*'s winter transits and the amount of time beset per transit. This work also provides a sea ice climatology from the winter of 2004/05 to the winter of 2017/18. These two datasets can be used and built upon by future studies investigating sea ice change and ice pressure in relation to winter shipping through the Hudson Strait. This work also presents interesting linkages between the estimated stage of development of the ice (based on CIS Ice Charts) at the time of the transit across the HS and the track of the *MV Arctic*. This allows for a visual understanding of how other dynamics, aside from solely ice thickness, likely play a significant role in the difficulty a ship may have transiting an area with full ice concentration.

Although the results of exploring patterns between meteorological conditions from the land based station between the different transits did not present any statistical relationships, because so little is known about the relationships between meteorological variables and pressured ice on a local scale, the approach taken represents an important first analysis despite limitations of the findings. The exploratory investigation into atmospheric pressure patterns across the HS represents an interesting avenue for continued research as well, as there were patterns found between the location of low pressure systems around the HS and the difficulty of the transit of the *MV Arctic*, for the chosen transits. The location of the low pressure system more common prior to the slow chosen transits of the *MV Arctic* were discussed in by Drinkwater (1986) as pressure patterns associated with northerly and north westerly winds, that would compress ice into the ZOI. The wind reanalysis data investigated over the ZOI prior to and during the chosen transits showed some agreement with the assumptions made from the low pressure patterns, however the assumed dominant wind directions were slightly different. This finding offers a direction for more in depth research regarding the amount we can understand about pressured ice and ridging near Deception Bay, based on the strength and location of atmospheric pressure systems.

4.3 Limitations

There are some limitations to the study that need to be noted. These limitations include the small sample size and the scalability of the study. A goal of this study was to better understand the meteorological conditions that occurred prior to transits with significant besetments in the

ZOI, to possibly understand the why the *MV Arctic* had additional difficulty transiting the ZOI in these specific incidences. The scope of the study reduced the sample size to 6 chosen transits in order to be able to complete a more in depth analysis on specific transits. Completing the study on additional transits would give a better understanding on the reliability of the relationships found. However, considering the timeframe of the study this was not possible.

The temporal scope of the analysis focused on 1 week prior to the *MV Arctic* arriving in the ZOI as the study period. More tests should be completed with a more flexible time scale to investigate what period of time prior to the ship arriving allows for a better understanding of the ice dynamics in the ZOI. With the small sample size and limited meteorological data used in this study, the spatial scope of the study was defined by a quick correlation completed with temperature data, based on 50km stages from Salluit. A more in depth analysis could be completed, if more cases were being investigated, and a variogram could be used in the analysis to understand exactly what the best spatial scale for the analysis would be. As well, given the temporal and spatial specificity of study, the hypothesized causes of pressure may not apply to other times or locations in the HS or outside the HS. Further research of similar test cases is required to understand if this research is relatable to other locations.

The methods of analysis, specifically when investigating the relationships between the meteorological variables, could have been more rigorous. When comparing the relationship between the land based weather station data and the data recorded onboard the *MV Arctic*, more statistical tests could have been completed to better understand the relationship that exists between the datasets. The analysis completed with the meteorological data from the Salluit weather station, when addressing objective 3 could have also been more rigorous. Using a variety of statistical tests to verify the relationships between the meteorological conditions prior to and during the chosen transits would likely have resulted in more definitive results, rather than the results of no relationships found in this portion of the analysis. Given that the meteorological data from the Salluit station and recorded on the MV Arctic was found to be correlated, we believe that it was a result of the analysis completed, for objective 3, that there was no relationship found between the chosen transits for the meteorological variables recorded at the Salluit station, rather than there actually being no relationships to be found.

The methods could have been improved, as well, for objective 2, by defining freeze up differently. In this study freeze up was defined as when ice cover was over 50% of the total area. For this specific study, a more reliable choice could have been defining the freeze up date as when there was first consistent ice cover along the ship's route.. This definition of freeze up could have allowed more insight into the ice conditions along the actual route investigated, allowing for a more detailed understanding of the freeze up progression, rather than investigating the entire larger area.

Further analysis could have been completed for objective 2 by using ice thickness data from the Cryosat 2 dataset. Ice thickness data from this source is only available since 2011, however, using the data for the more recent years would have added additional rigour to the data presented. This additional dataset would have allowed for a more quantitative analysis of the actual ice thickness in the Hudson Strait, rather than simply investigating the stage of development, and estimated ice thickness, as was done in this study. Future analysis completed that includes satellite derived ice thickness data will allow for a more in-depth understanding of how ice thickness impacts the difficulty a vessel experiences as it transits the Strait, and how much of a factor ice thickness is in determining the difficulty a ship might experience during a pressured ice event.

The study was also limited by the data that is available, for example, tidal data for the region is poor, there is no wave data, there is no snow thickness data, and there is a lack of consistent ice thickness measurements for the besetting events investigated. All of this additional data would allow for a better understanding of the actual causes of besetting during the investigated transits, as they could all be influential in the formation of ridges and the dynamics of pressured ice formation. Without this data, it is possible that relationships that exist were unable to be discovered. Finally, this is an exploratory study and therefore the factors that are identified may or may not play a direct causal role in the besetment events. The study approach will not be able to consider the complex dynamics and interactions among various meteorological and environmental factors that may also play a role in pressured ice formation.

4.4 Recommendations for future work

Developing a greater understanding of the formation of pressure ridges is highly important to ensure safe navigation through ice-covered waters. To further develop knowledge on this topic, there are several ways in which the investigations done in this thesis can be the basis for future analyses. Future work should be continued as this work simply explores some of the relations that could influence sea ice dynamics in the HS. More detailed research must be completed to gain a more in depth understanding of the processes involved.

Future work on this topic could be completed in collaboration with the National Research Council, using their sea ice pressure model (Kubat et al., 2009b, Kubat et al., 2012). Introducing actual besetment data, and meteorological data recorded from onboard the MV Arctic, into the model, could improve the quality of the pressure forecasts produced by NRC's model for the ZOI. This would provide additional useful information to Captains when navigating through the ice-infested waters in the HS.

Another way that this work could be continued in the future is through the use of in situ ice thickness measurement data. Sea ice thickness information was collected on the *MV Arctic* during 2 transits through the HS in 2018 and during the majority of 2 transits through the Strait in 2019. This data was collected using a Sea Ice Thickness Measurement System (SIMS) using an electromagnetic induction sounder and a sonic ranger, mounted in front of the vessel during its transit (Casey et al., 2018). Introducing this data into further analysis would add another dimension to the research that was not available at the time of this study. This information could allow for a more in depth understanding of the ice dynamics in the ZOI during and leading up to the time of besetments.

Further research could be completed with land-based data if a weather station were placed in Deception bay, and the data made available to the public. This would allow for land-based data, closer to the area where the ship often becomes beset, to be investigated in a similar fashion to this report. Having land based meteorological data available in Deception Bay could prove to provide insight into the dynamics of sea ice movement in the Hudson Strait, near Deception Bay. This data could be more reliable to better understand the creation of pressure ridges in the area, as this local data may be more representative of the conditions in the nearby marine area than the data recorded at the Salluit land based weather station.

CHAPTER 5: REFERENCES

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APPENDIX

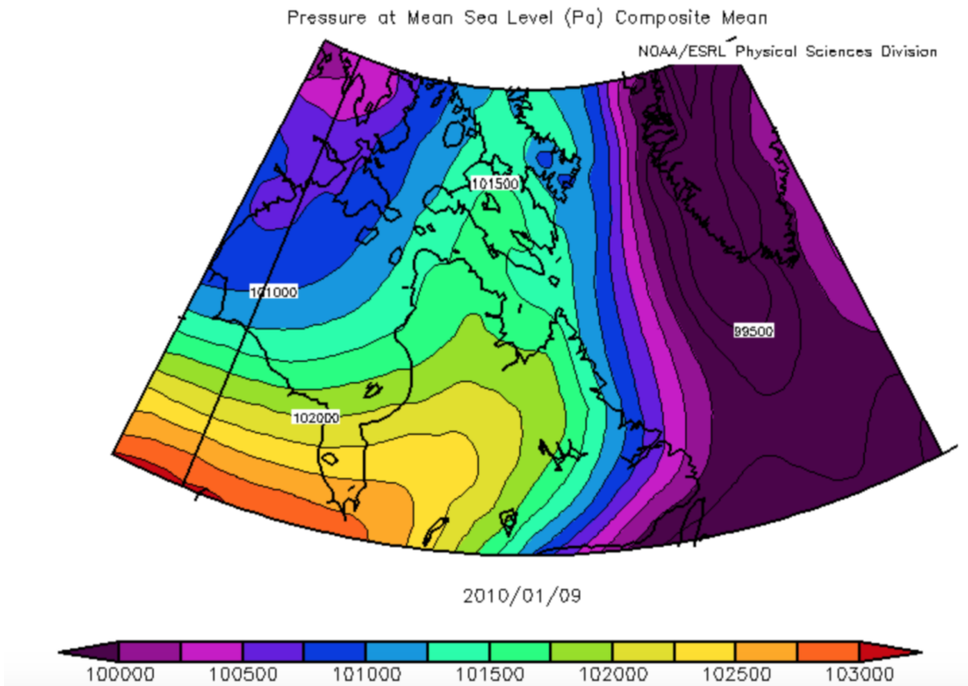

Figure 30. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 9, 2010, prior to fast transit 1. (source: ESRL NOAA).

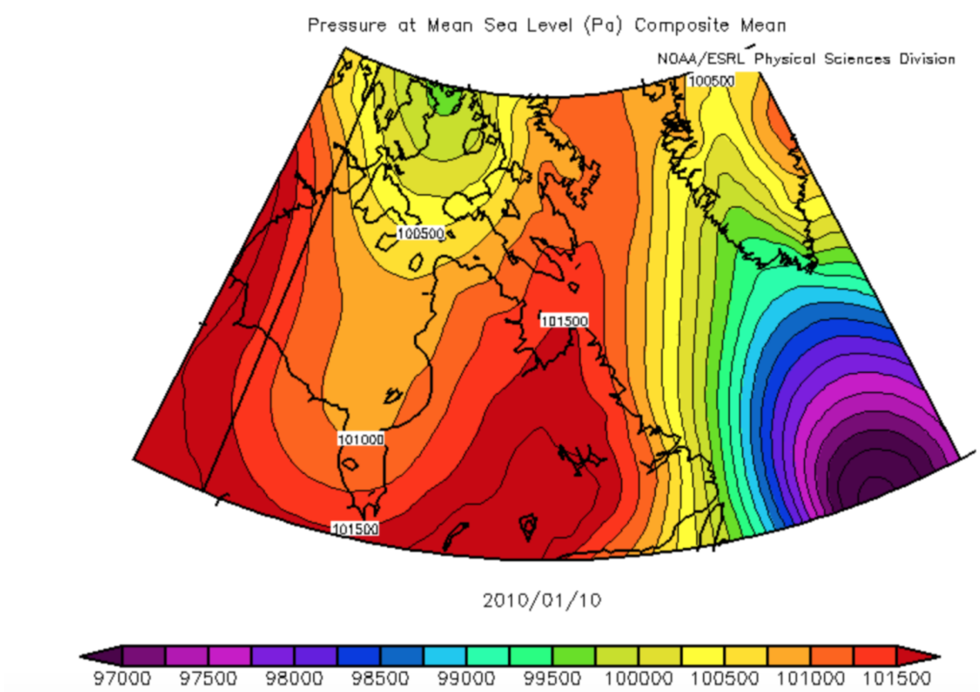

Figure 31. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 10, 2010, prior to fast transit 1. (source: ESRL NOAA).

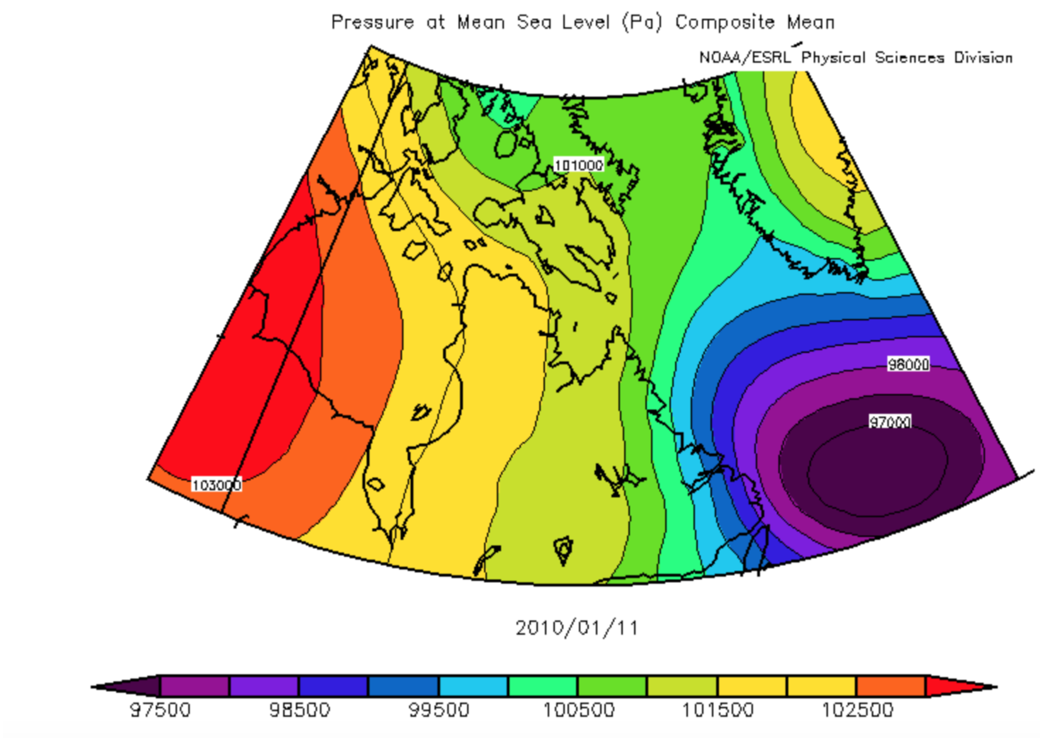

Figure 32. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 11, 2010, prior to fast transit 1. (source: ESRL NOAA).

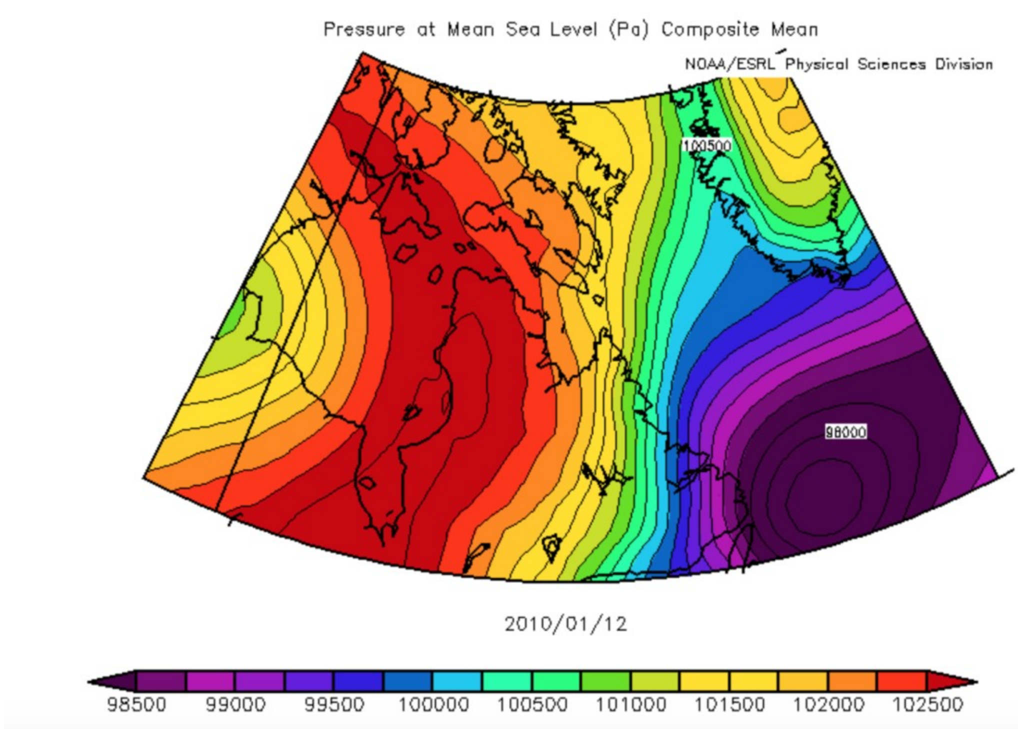

Figure 33. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 12, 2010, prior to fast transit 1. (source: ESRL NOAA).

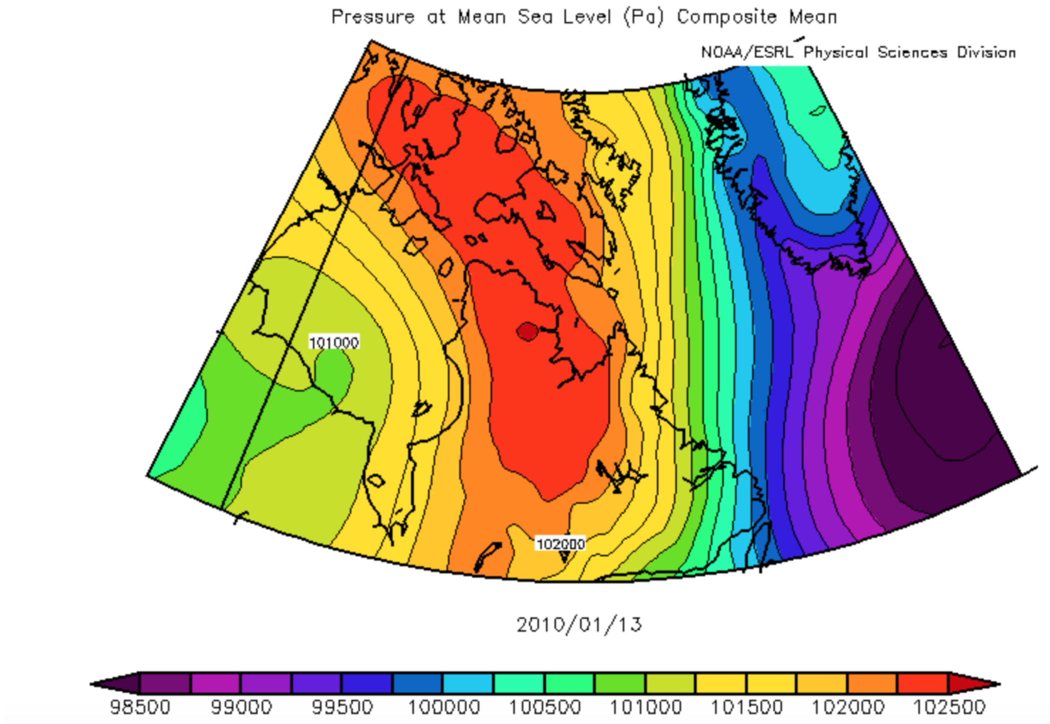

Figure 34. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 13, 2010, prior to fast transit 1. (source: ESRL NOAA).

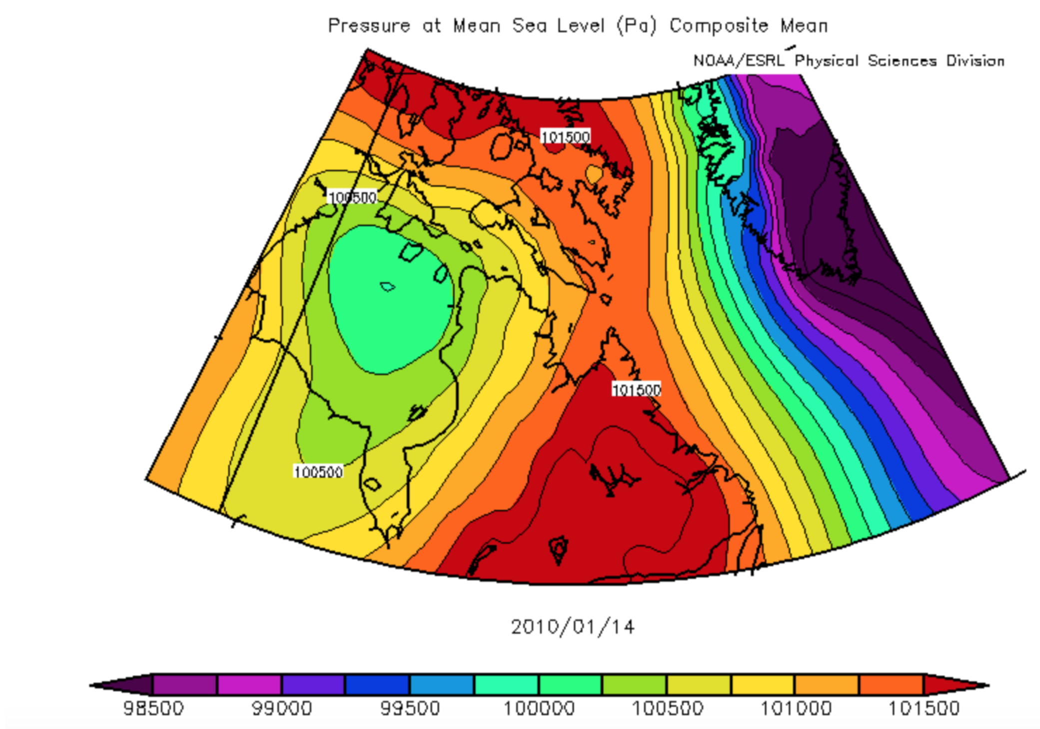

Figure 35. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 14, 2010, prior to fast transit 1. (source: ESRL NOAA).

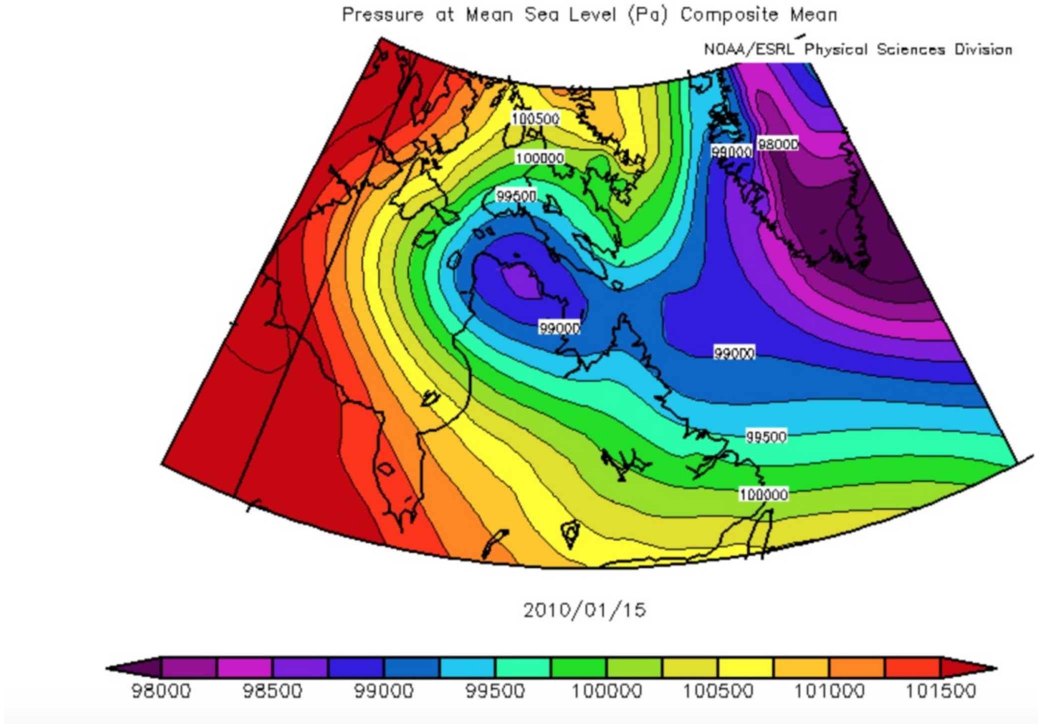

Figure 36. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 15, 2010, prior to fast transit 1. (source: ESRL NOAA).

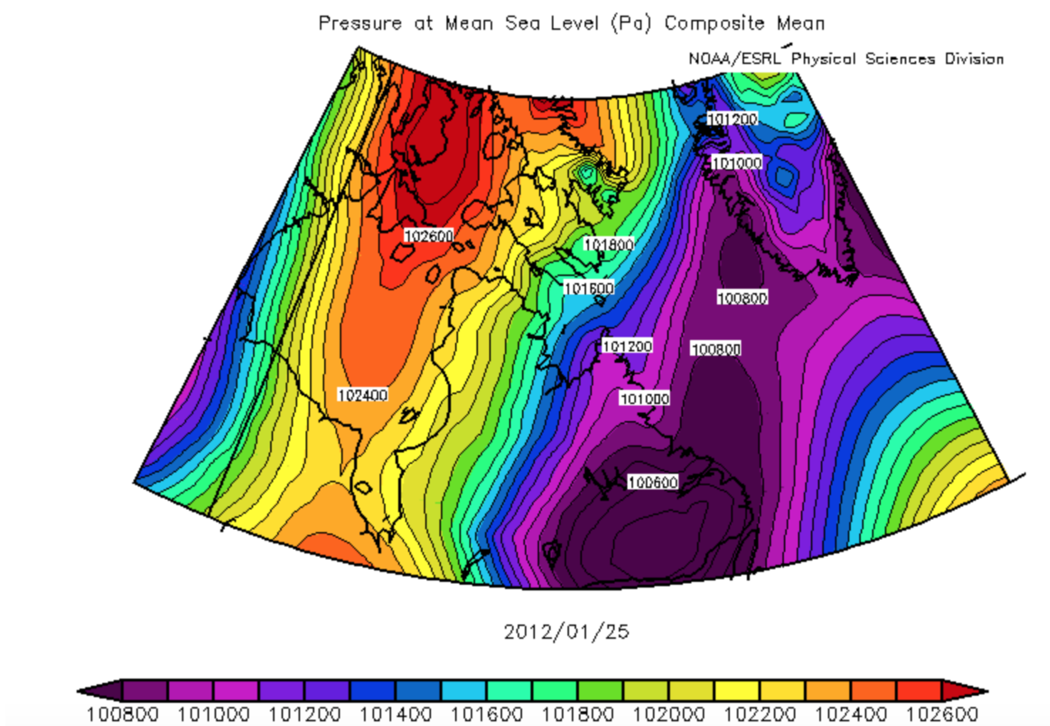

Figure 37. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 25, 2012, prior to fast transit 2. (source: ESRL NOAA).

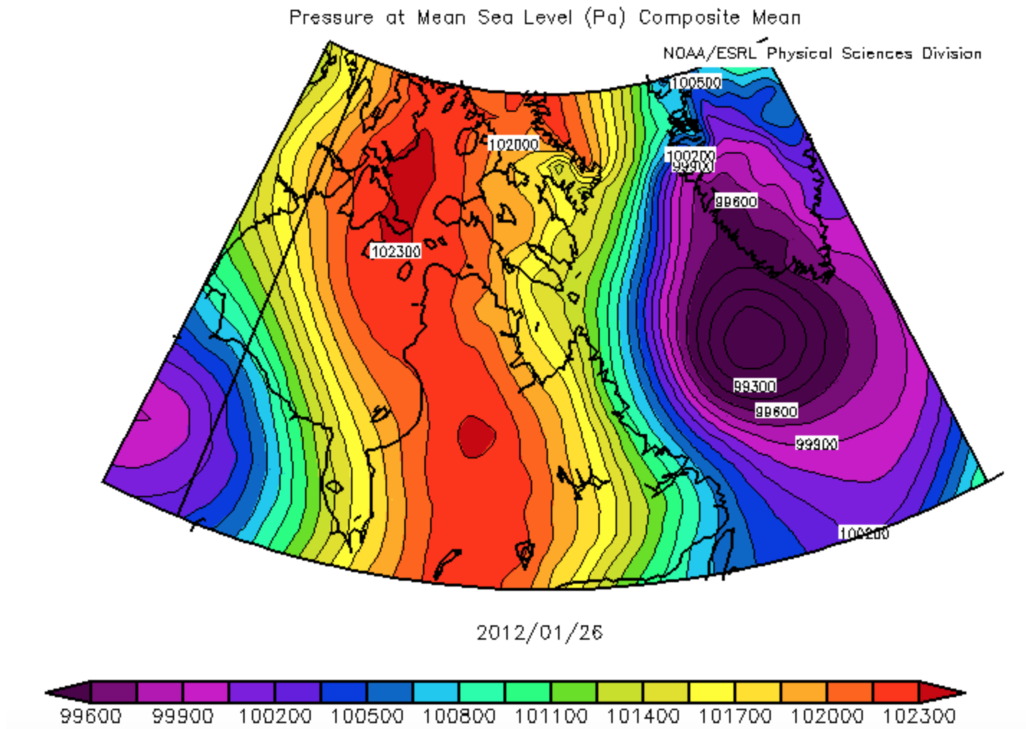

Figure 38. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 26, 2012, prior to fast transit 2. (source: ESRL NOAA).

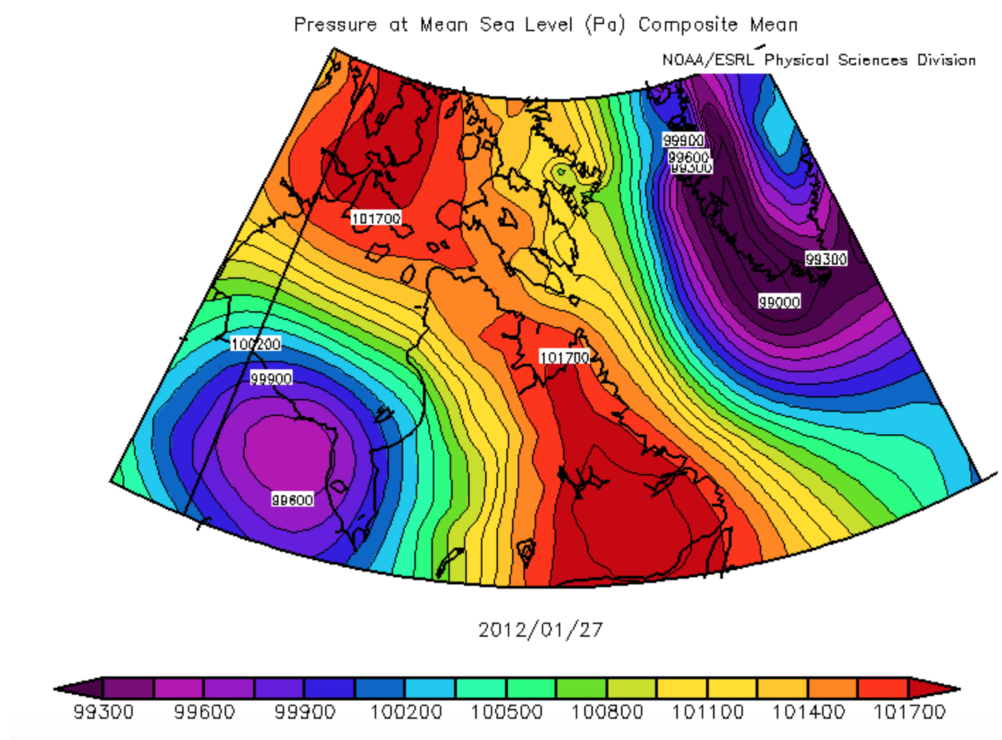

Figure 39. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 27, 2012, prior to fast transit 2. (source: ESRL NOAA).

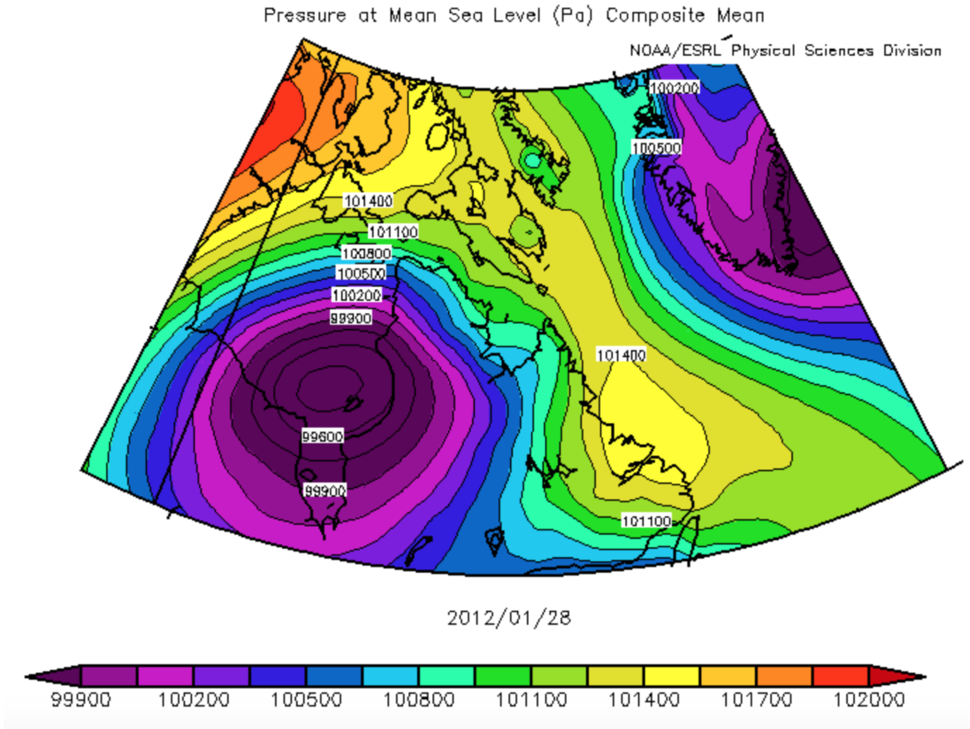

Figure 40. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 28, 2012, prior to fast transit 2. (source: ESRL NOAA).

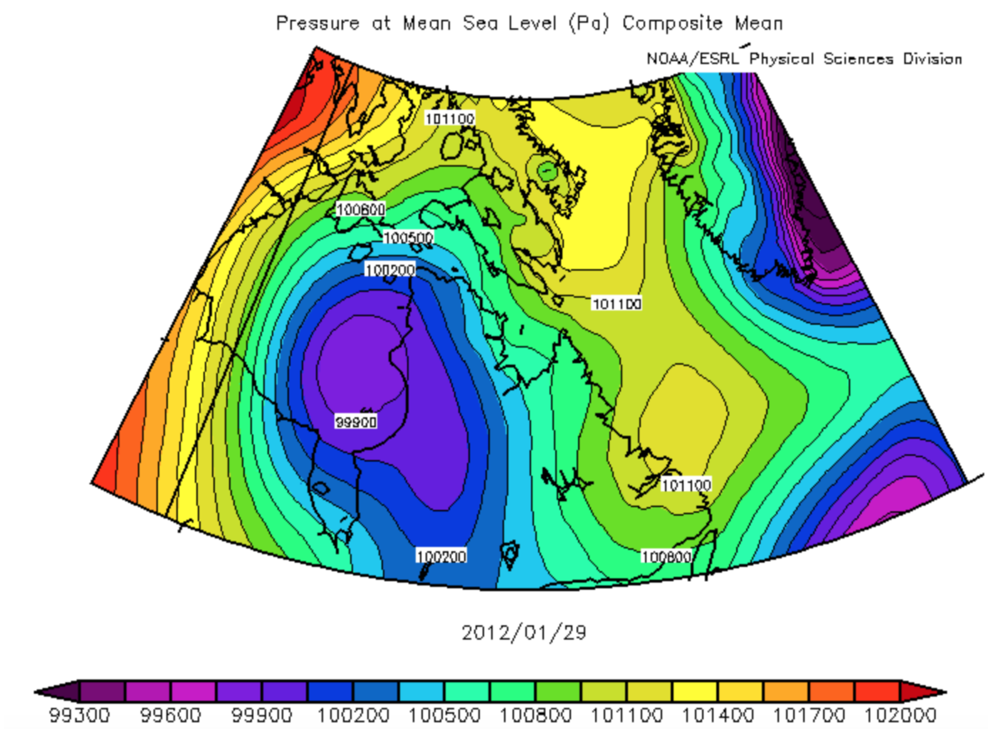

Figure 41. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 29, 2012, prior to fast transit 2. (source: ESRL NOAA).

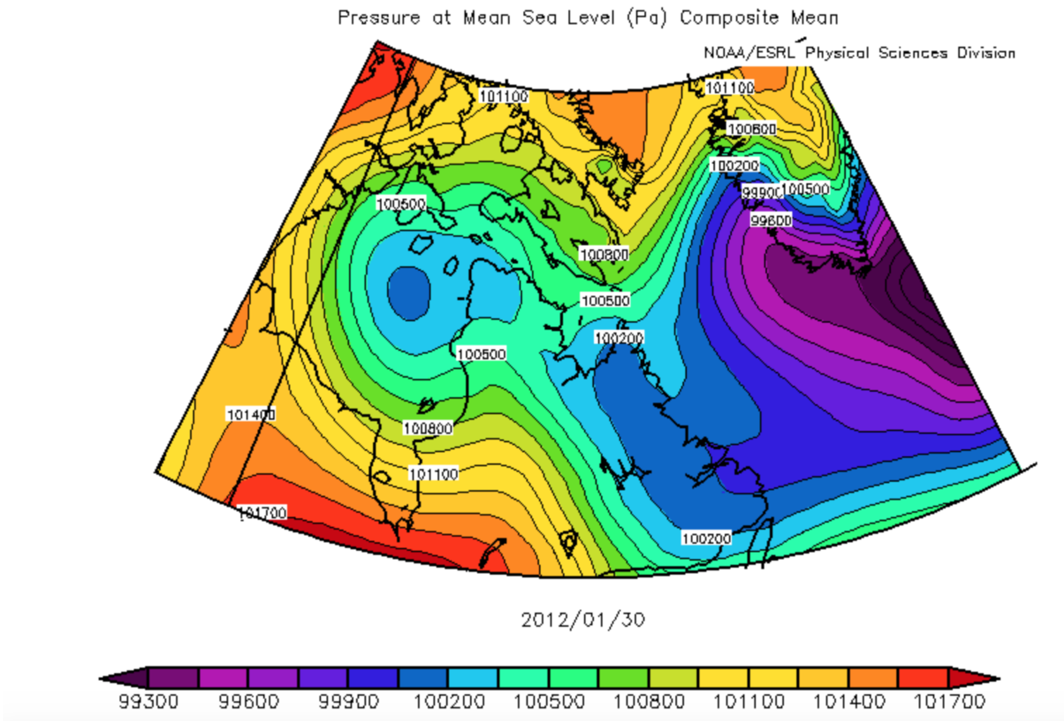

Figure 42. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 30, 2012, prior to fast transit 2. (source: ESRL NOAA).

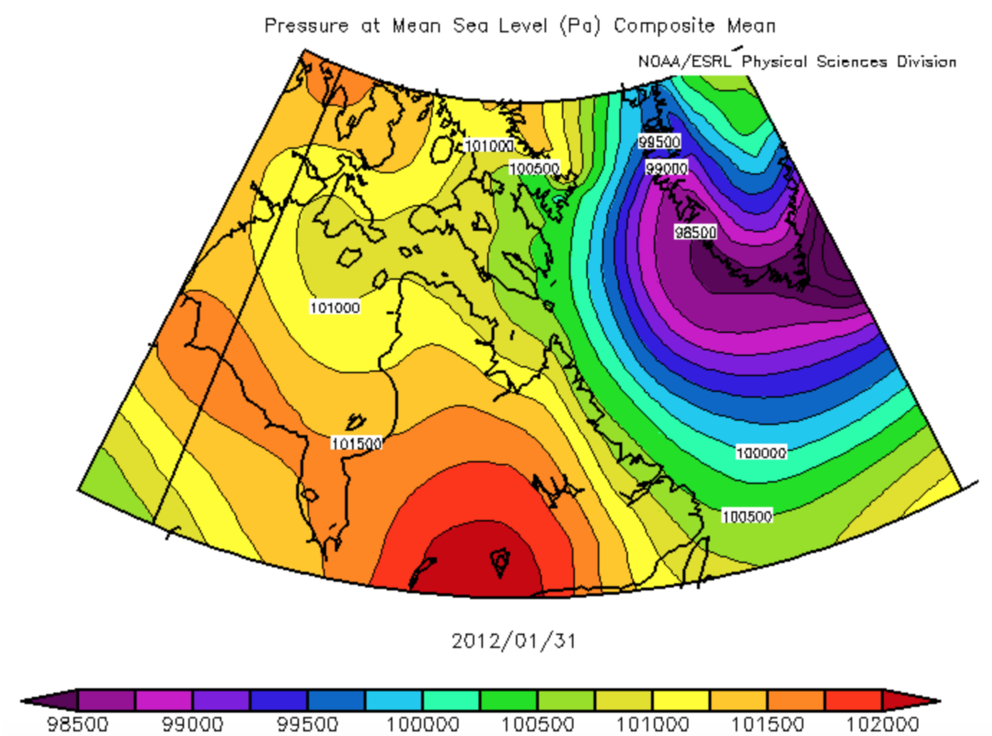

Figure 43. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 31, 2012, prior to fast transit 2. (source: ESRL NOAA).

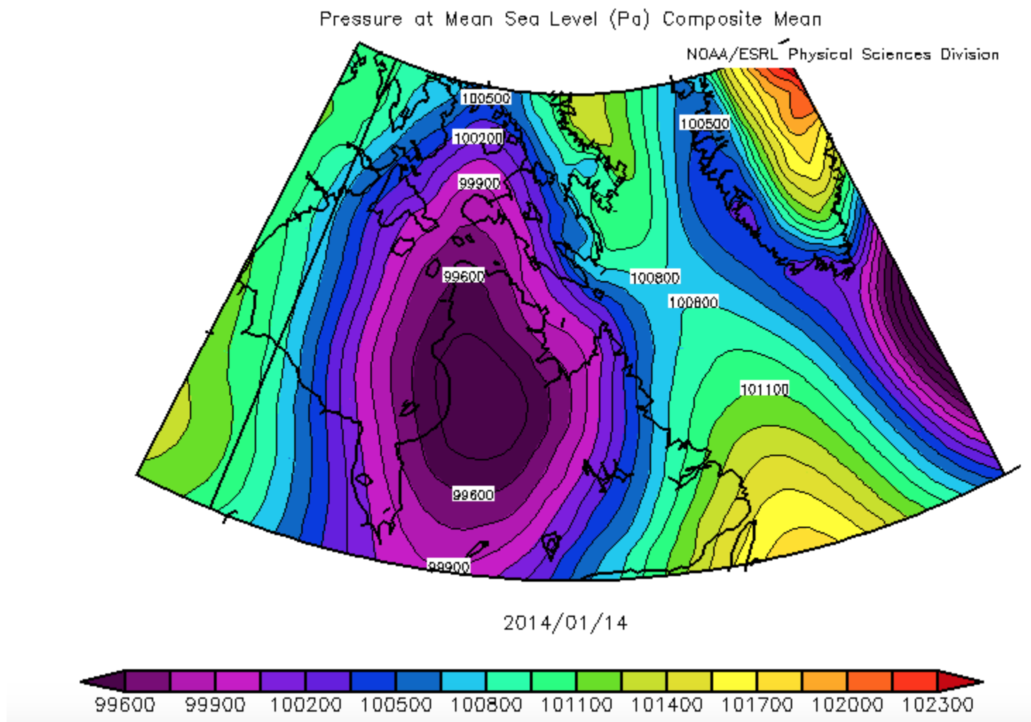

Figure 44. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 14, 2014, prior to fast transit 3. (source: ESRL NOAA).

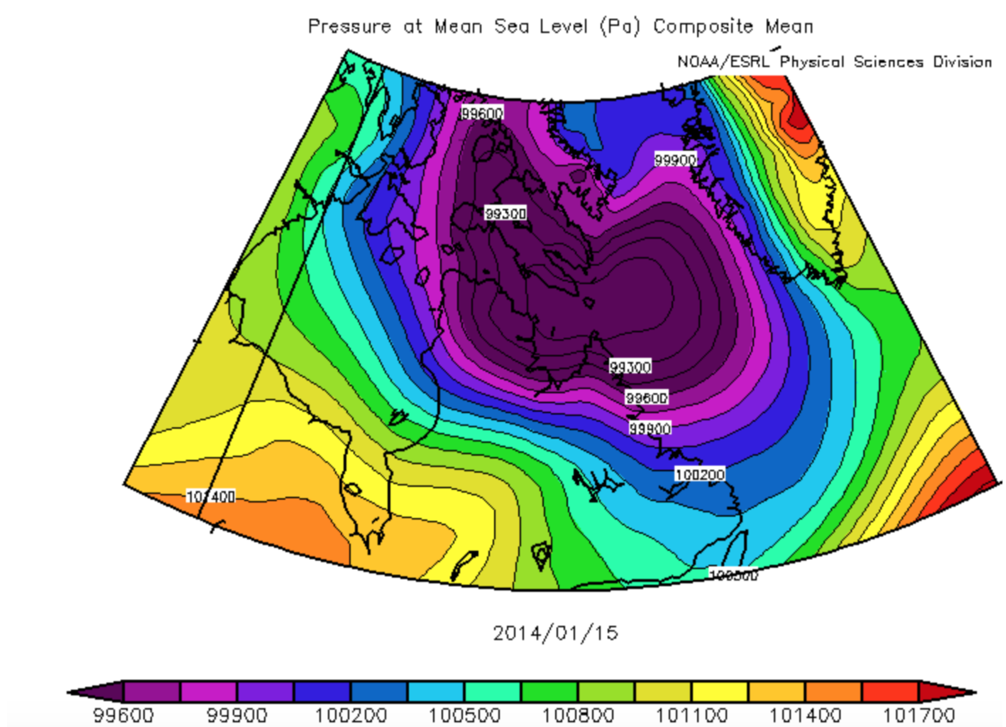

Figure 45. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 15, 2014, prior to fast transit 3. (source: ESRL NOAA).

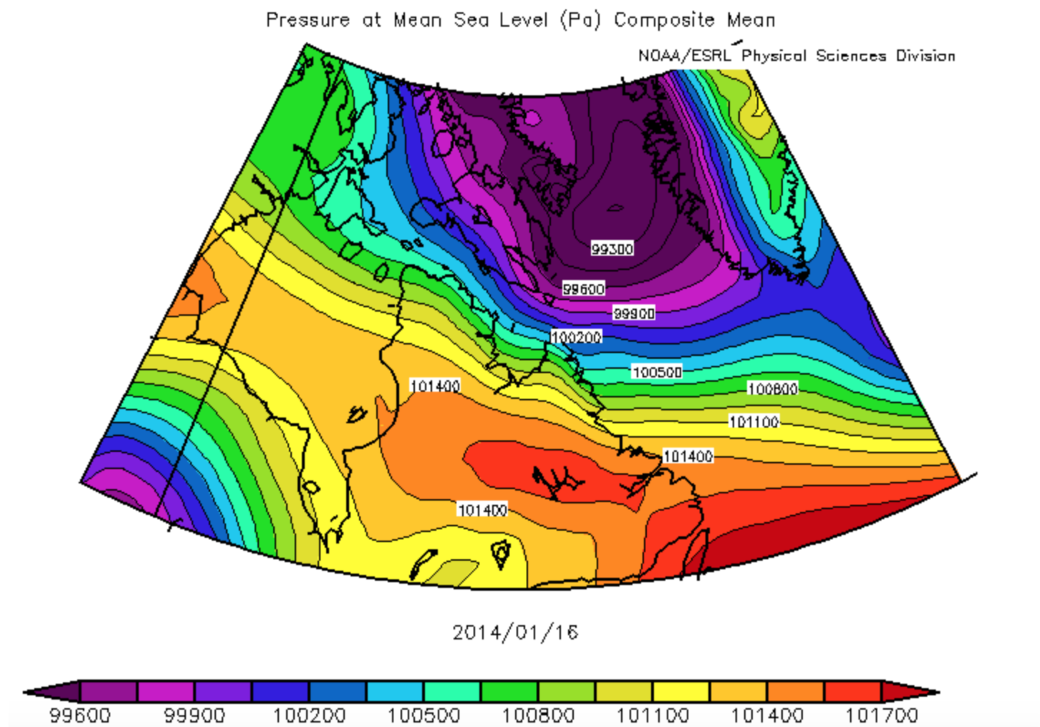

Figure 46. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 16, 2014, prior to fast transit 3. (source: ESRL NOAA).

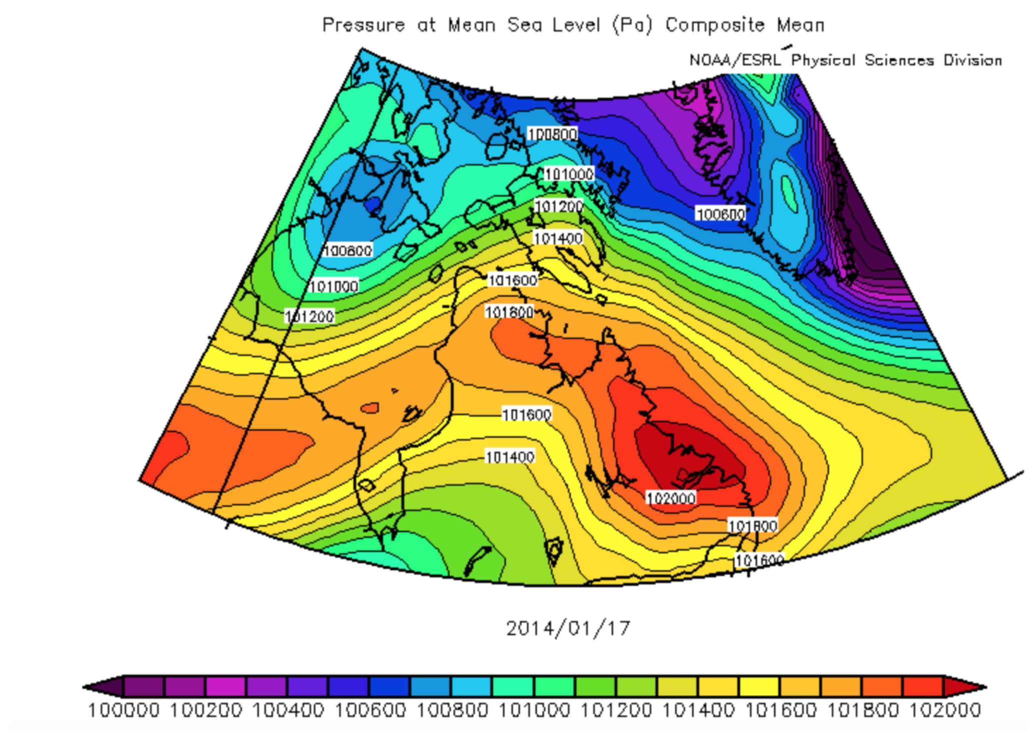

Figure 47. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 17, 2014, prior to fast transit 3. (source: ESRL NOAA).

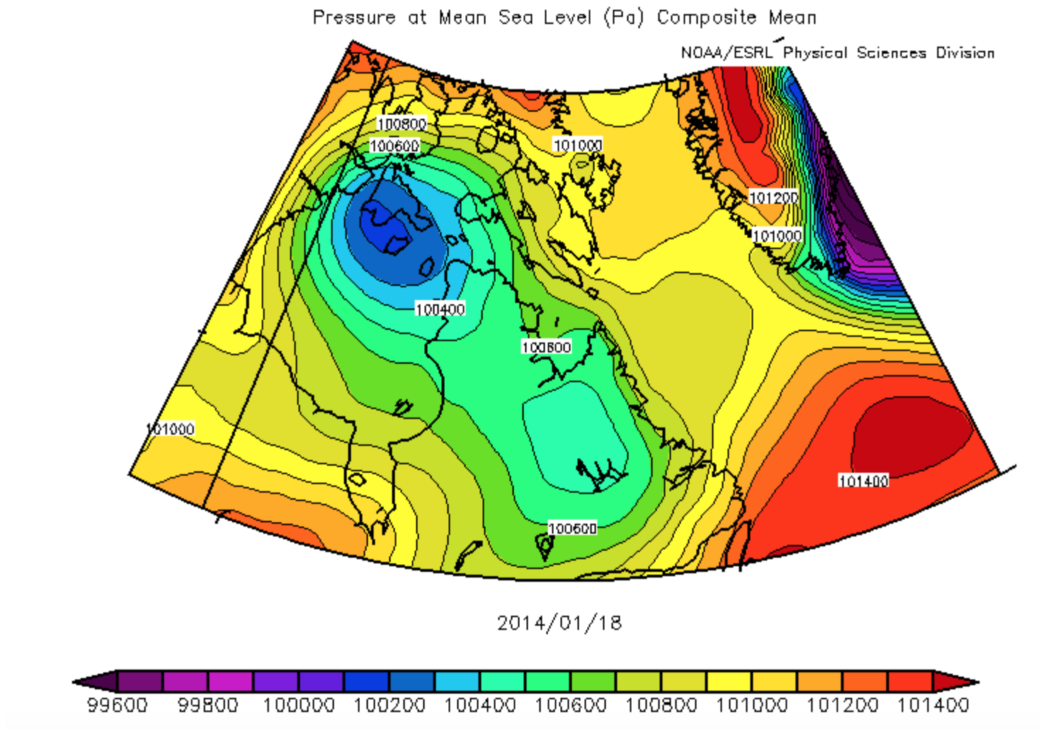

Figure 48. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 18, 2014, prior to fast transit 3. (source: ESRL NOAA).

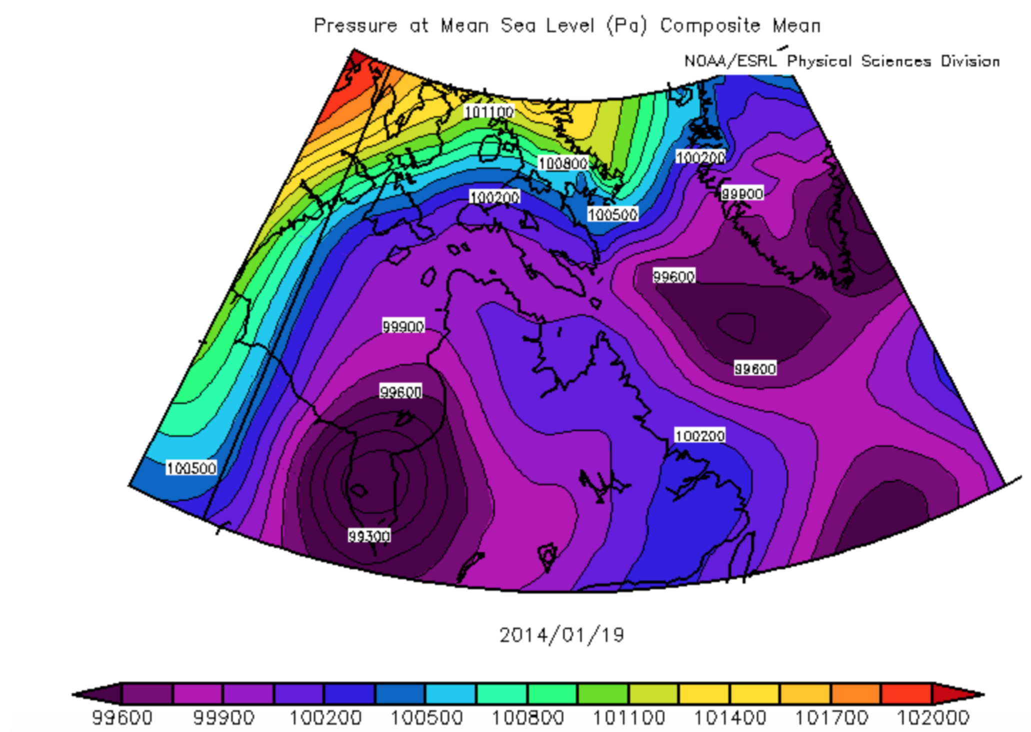

Figure 49. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 19, 2014, prior to fast transit 3. (source: ESRL NOAA).

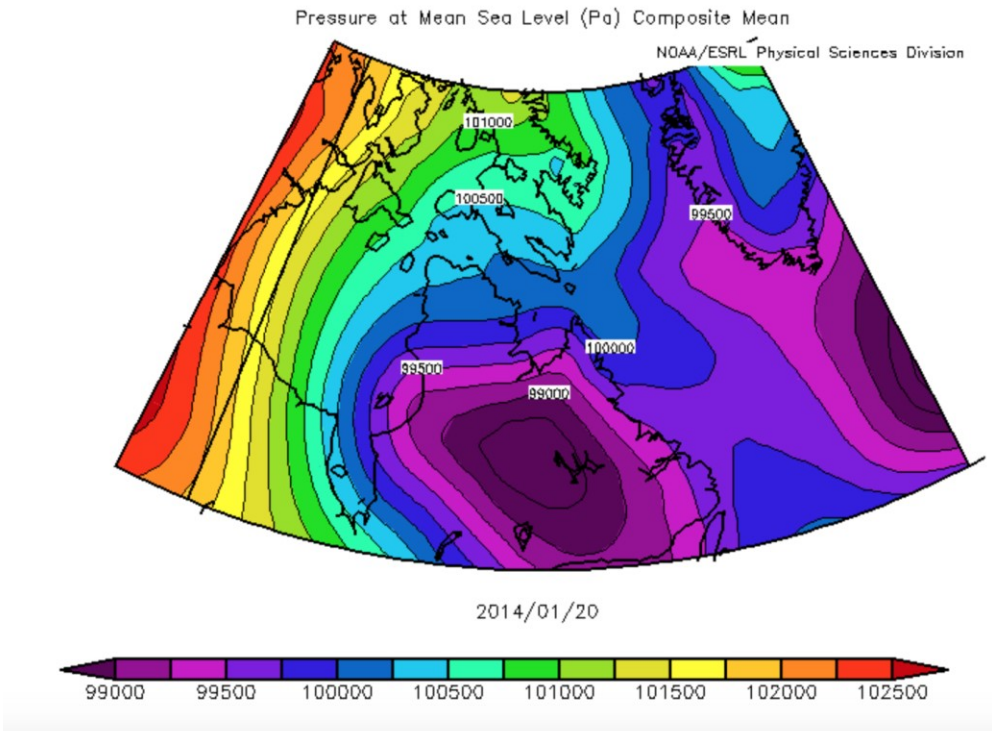

Figure 50. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 20, 2014, prior to fast transit 3. (source: ESRL NOAA).

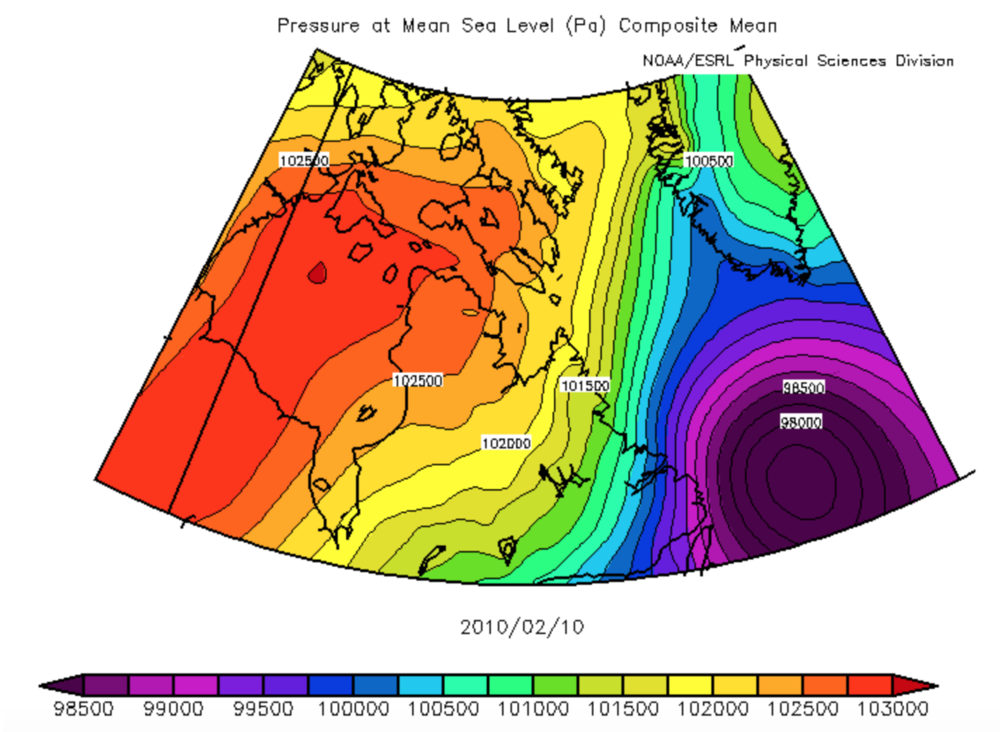

Figure 51. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 10, 2010, prior to slow transit 1. (source: ESRL NOAA).

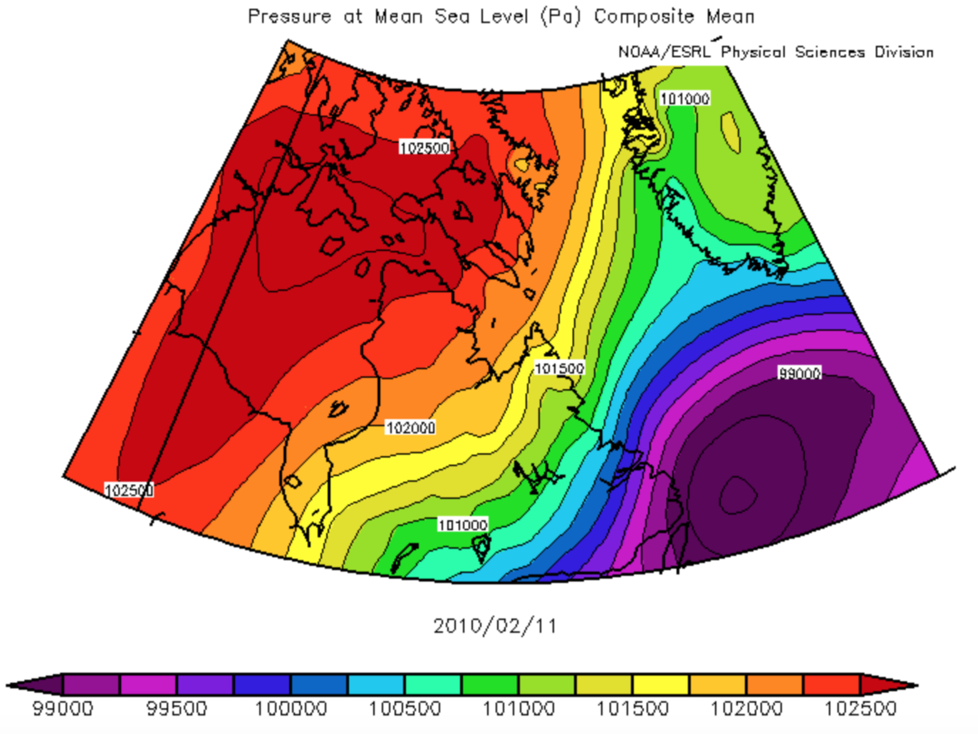

Figure 52. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 11, 2010, prior to slow transit 1. (source: ESRL NOAA).

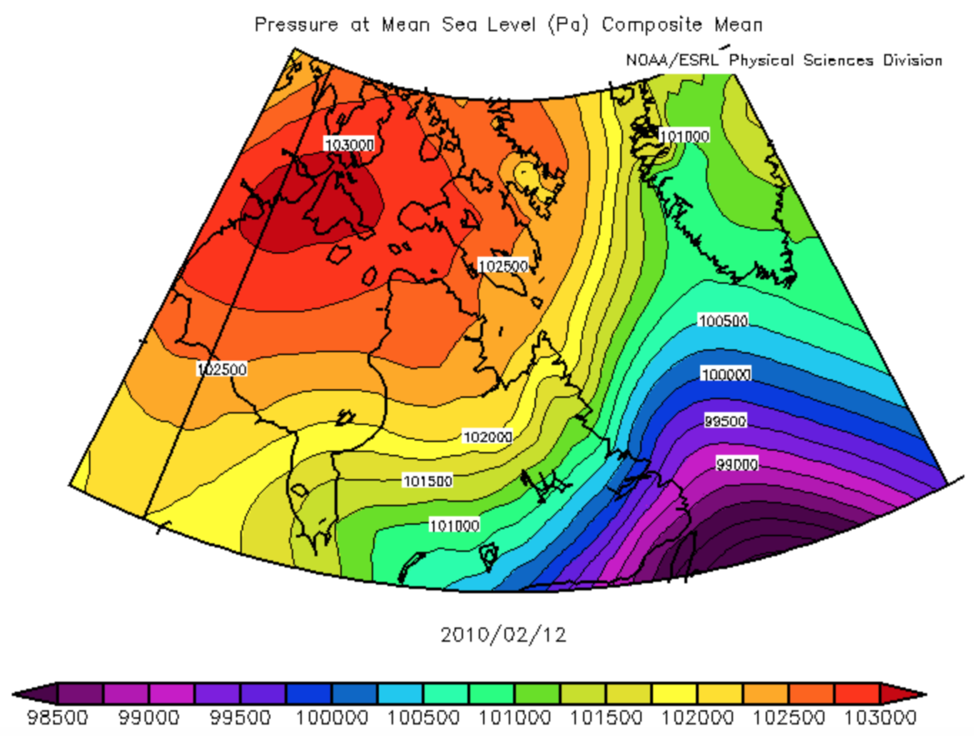

Figure 53. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 12, 2010, prior to slow transit 1. (source: ESRL NOAA).

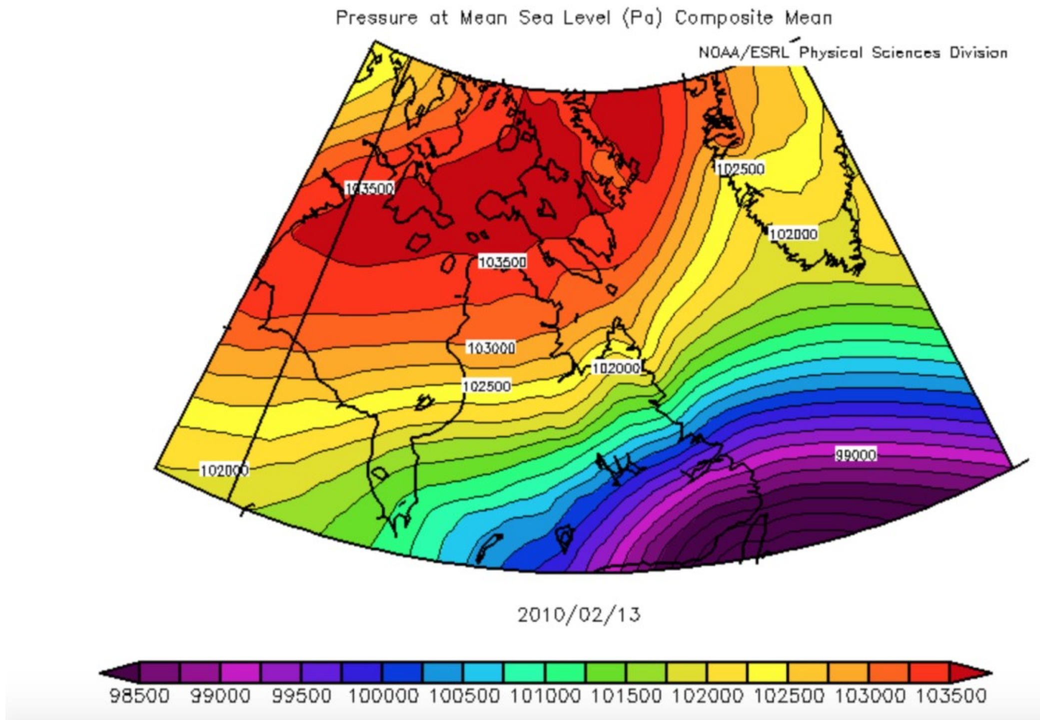

Figure 54. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 13, 2010, prior to slow transit 1. (source: ESRL NOAA).

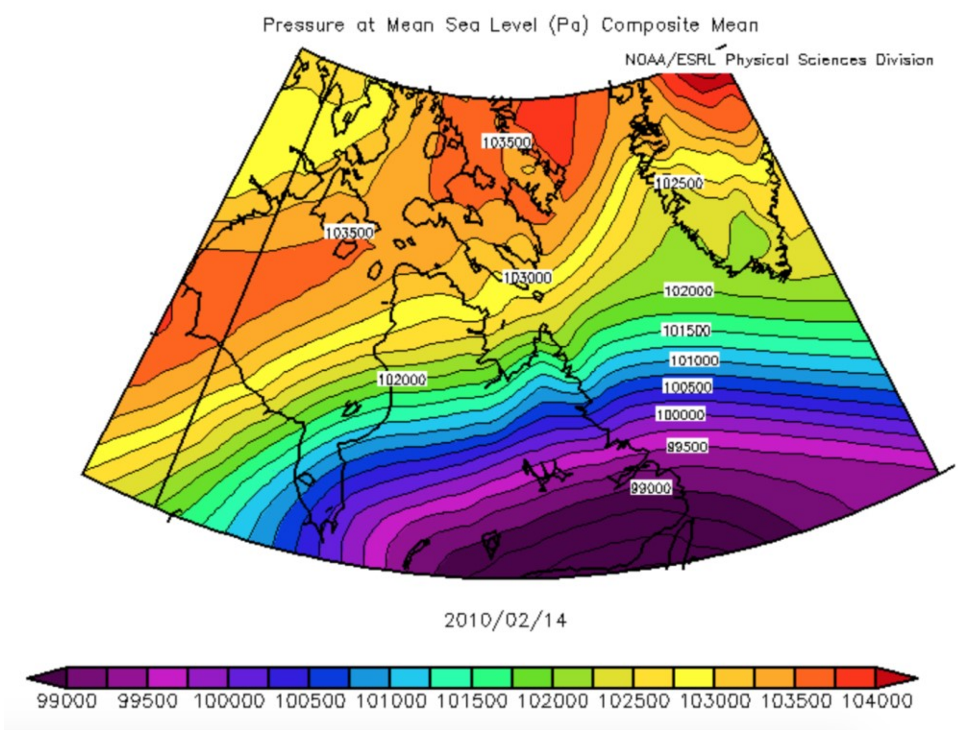

Figure 55. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 14, 2010, prior to slow transit 1. (source: ESRL NOAA).

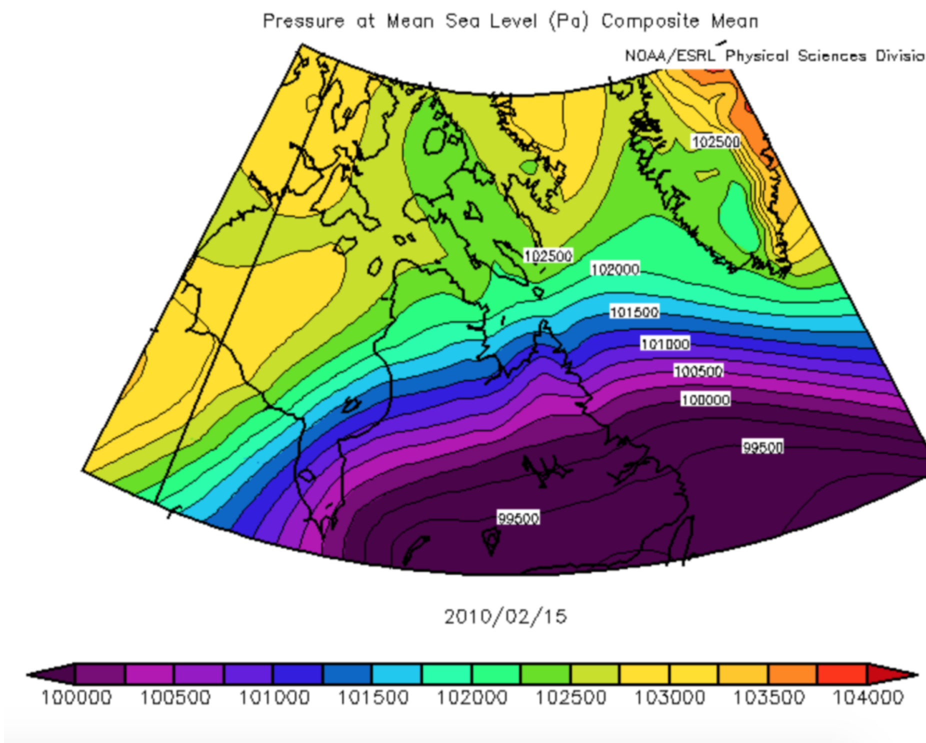

Figure 56. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 15, 2010, prior to slow transit 1. (source: ESRL NOAA).

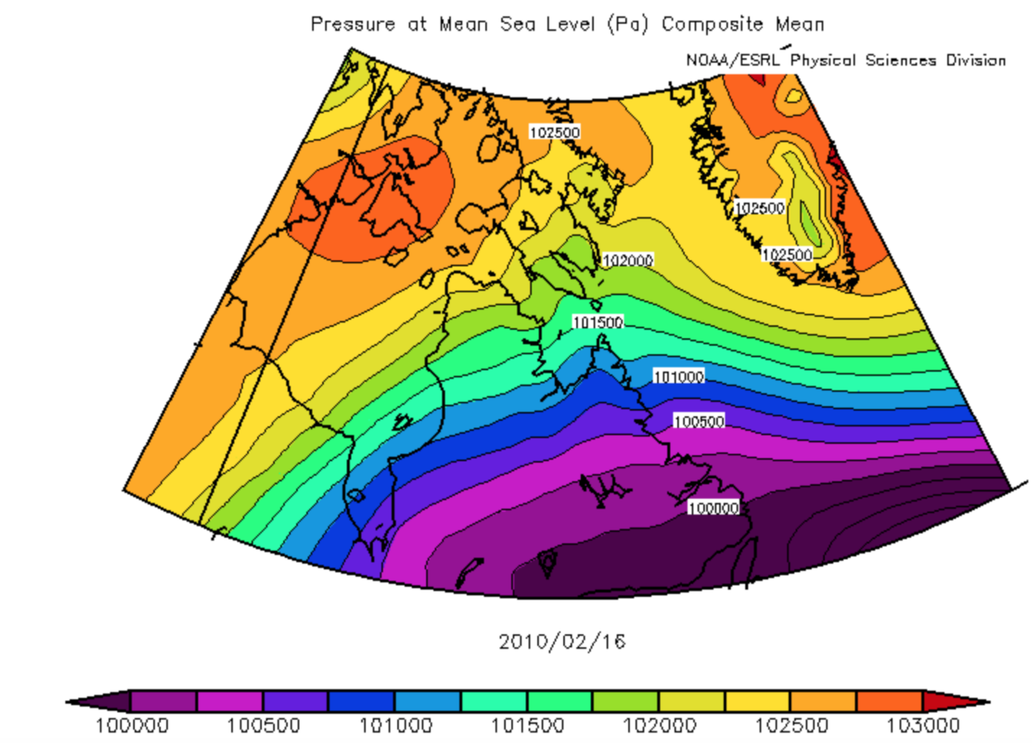

Figure 57. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 16, 2010, prior to slow transit 1. (source: ESRL NOAA).

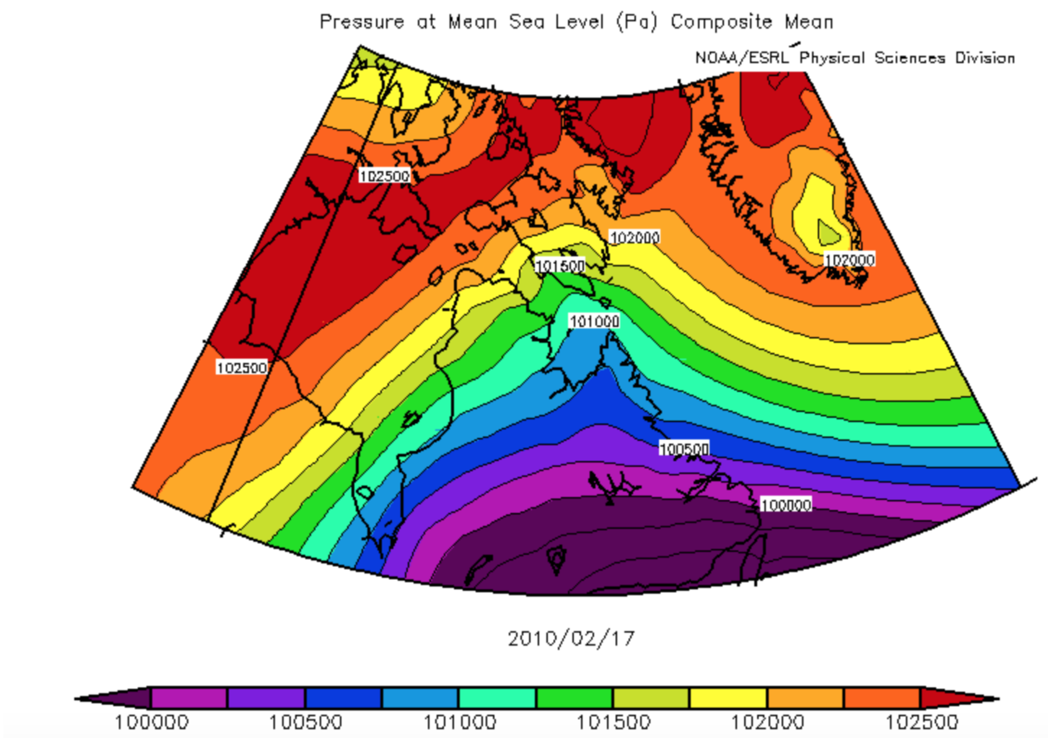

Figure 58. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 17, 2010, during slow transit 1 through ZOI. (source: ESRL NOAA).

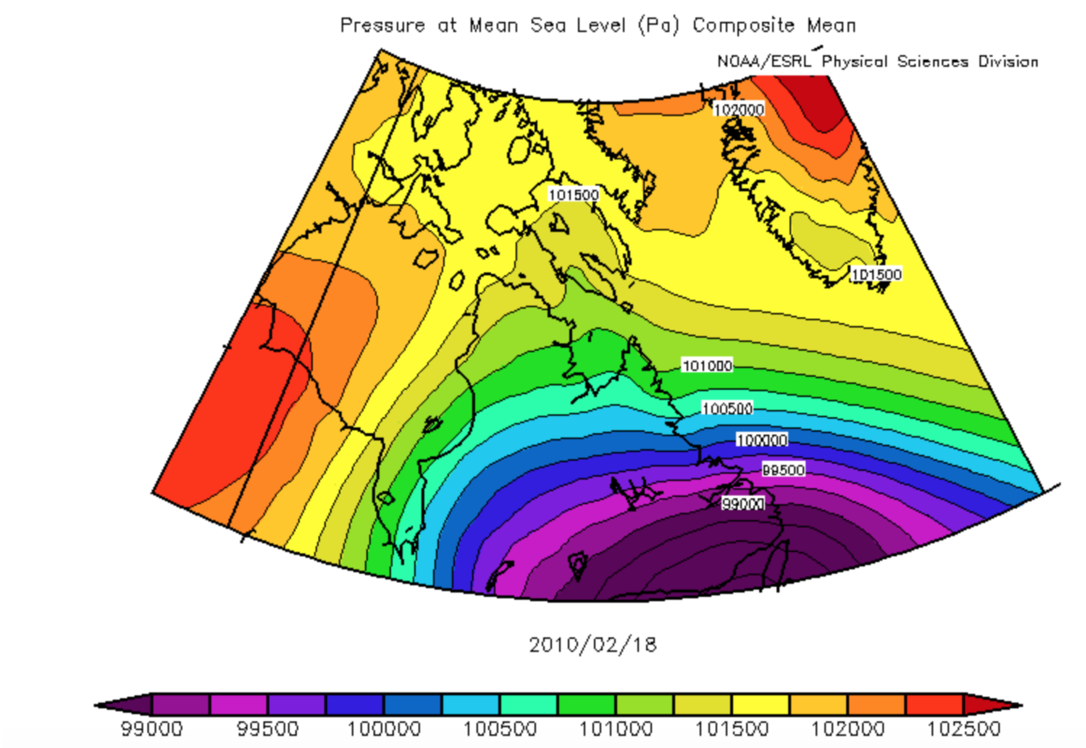

Figure 59. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 18, 2010, during slow transit 1 through ZOI. (source: ESRL NOAA).

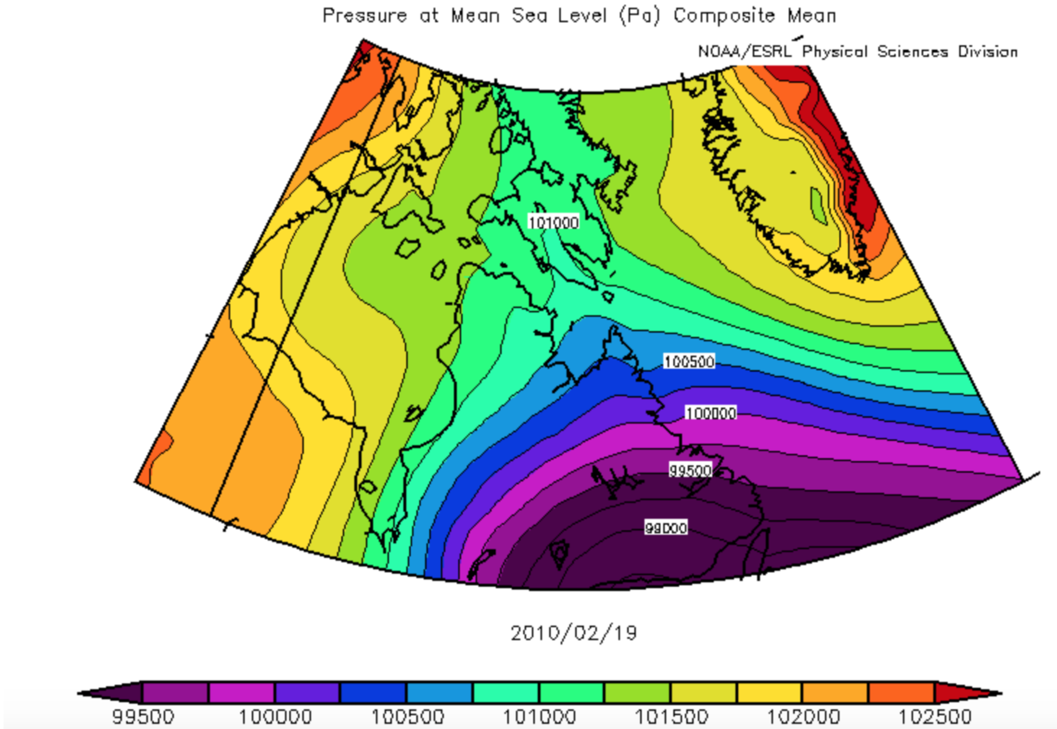

Figure 60. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 19, 2010, during slow transit 1 through ZOI. (source: ESRL NOAA).

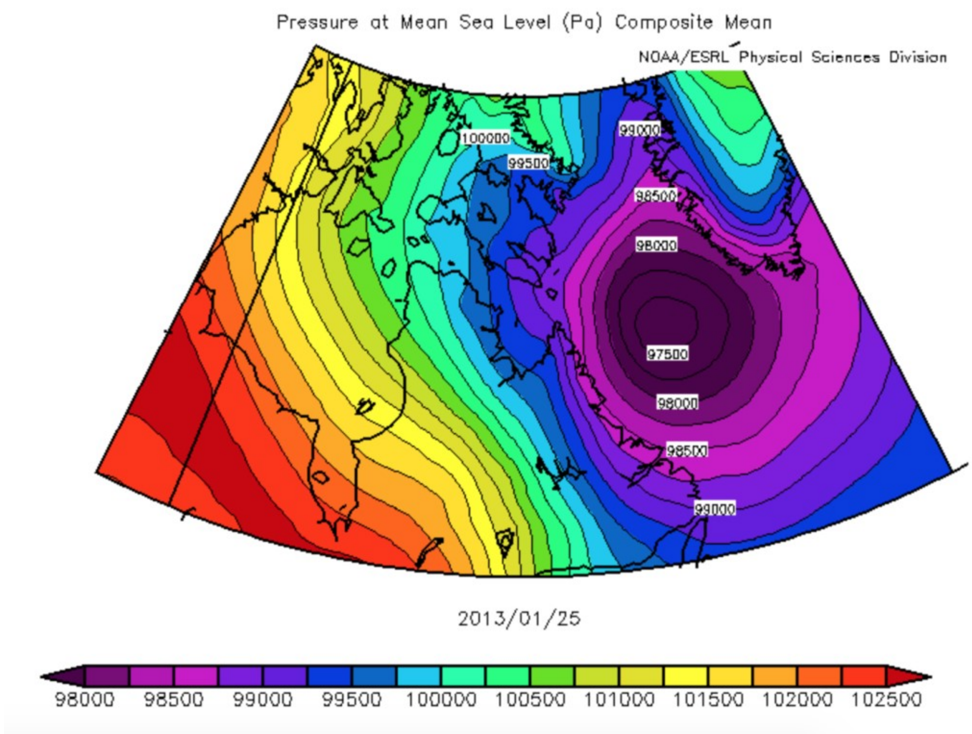

Figure 61. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 25, 2013, prior to slow transit 2. (source: ESRL NOAA).

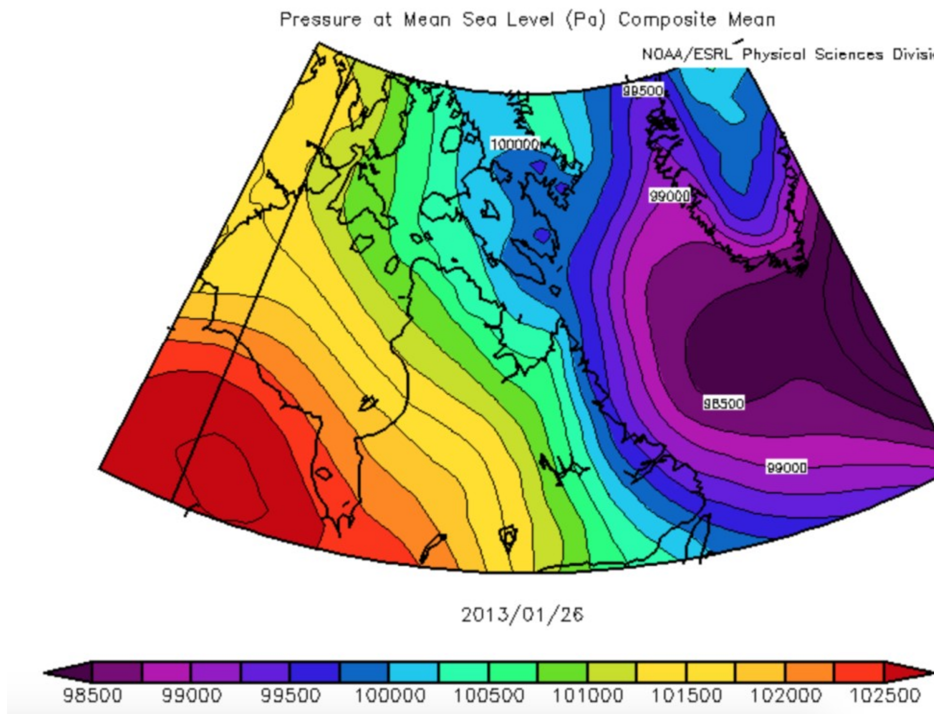

Figure 62. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 26, 2013, prior to slow transit 2. (source: ESRL NOAA).

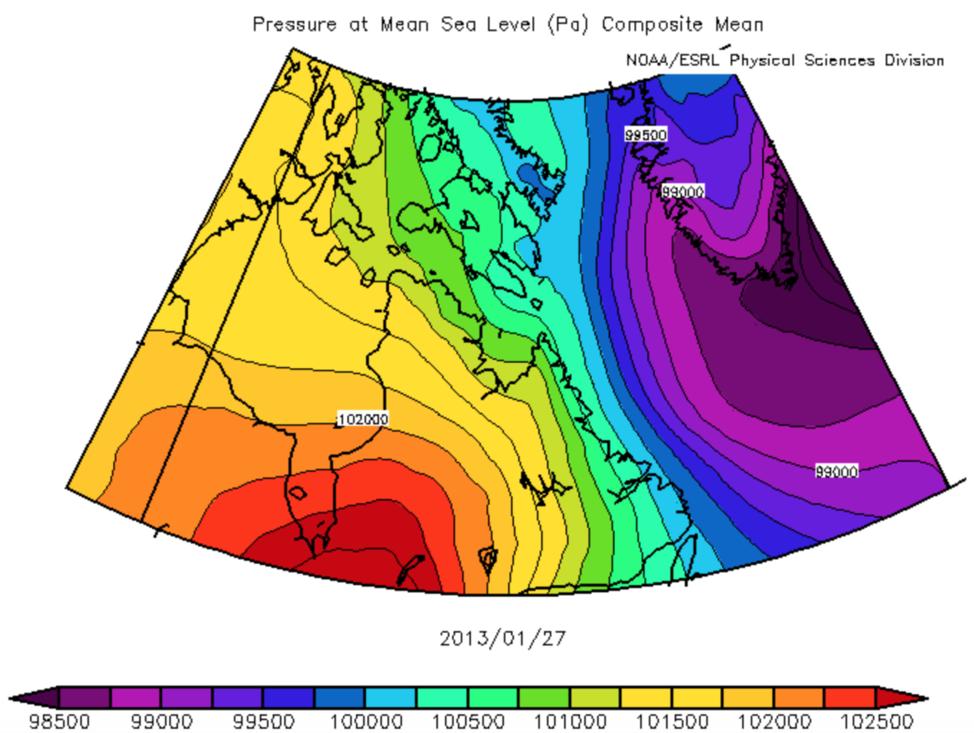

Figure 63. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 27, 2013, prior to slow transit 2. (source: ESRL NOAA).

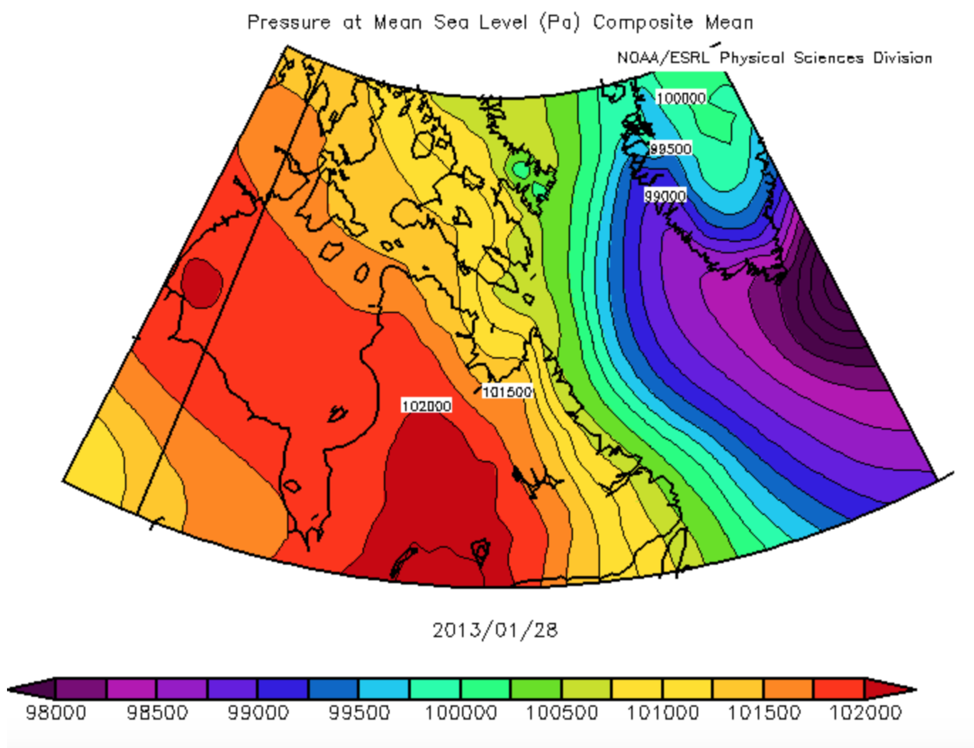

Figure 64. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 28, 2013, prior to slow transit 2. (source: ESRL NOAA).

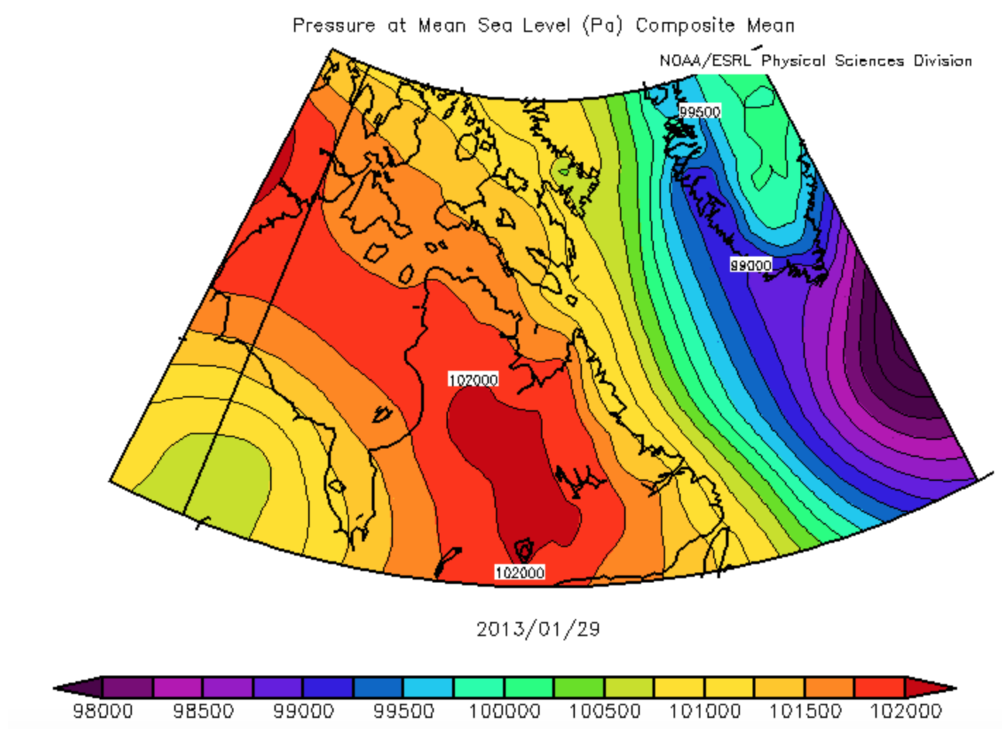

Figure 65. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 29, 2013, prior to slow transit 2. (source: ESRL NOAA).

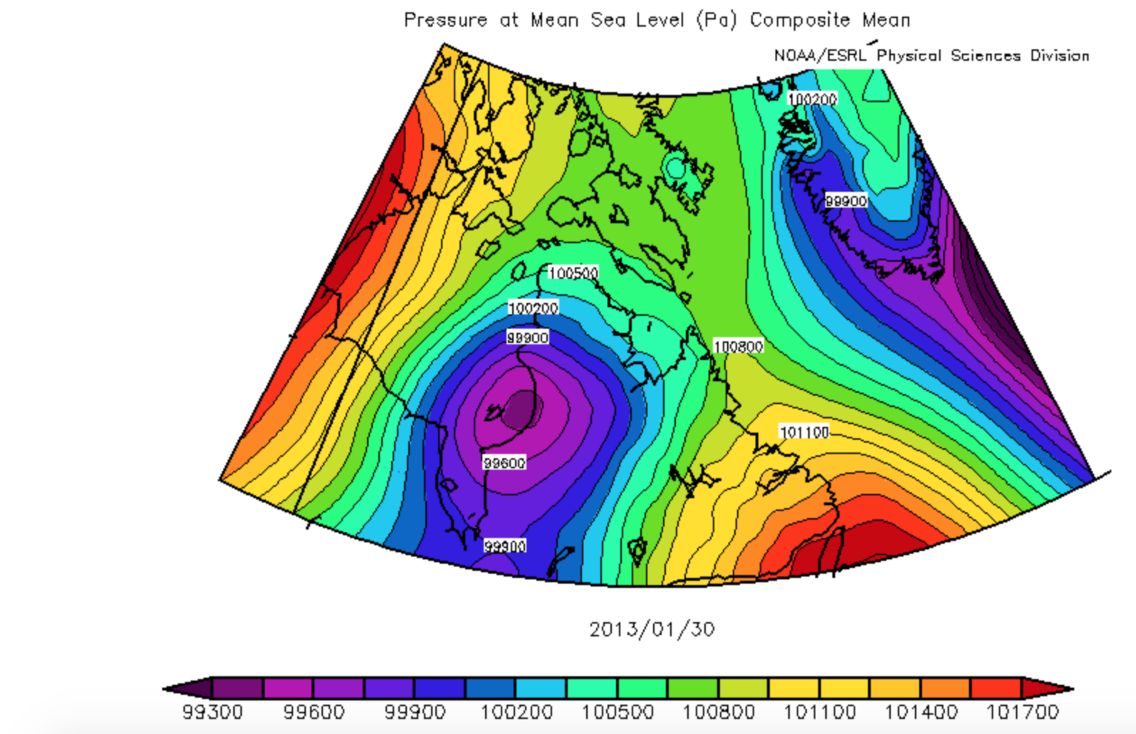

Figure 66. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 30, 2013, prior to slow transit 2. (source: ESRL NOAA).

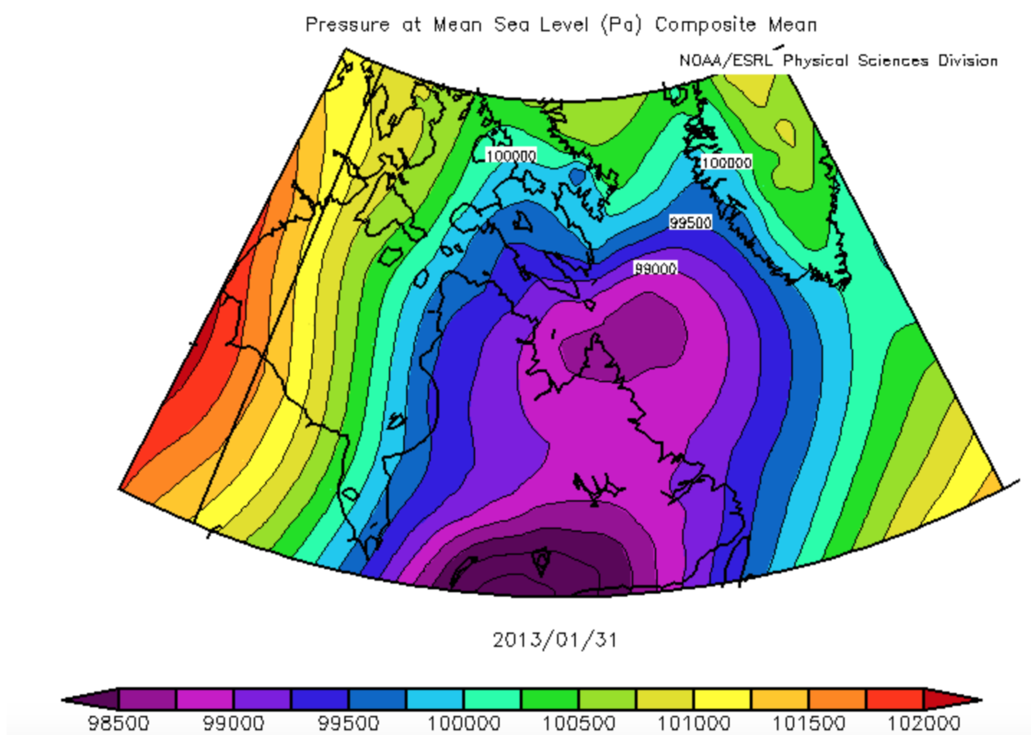

Figure 67. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for January 31, 2013, prior to slow transit 2. (source: ESRL NOAA).

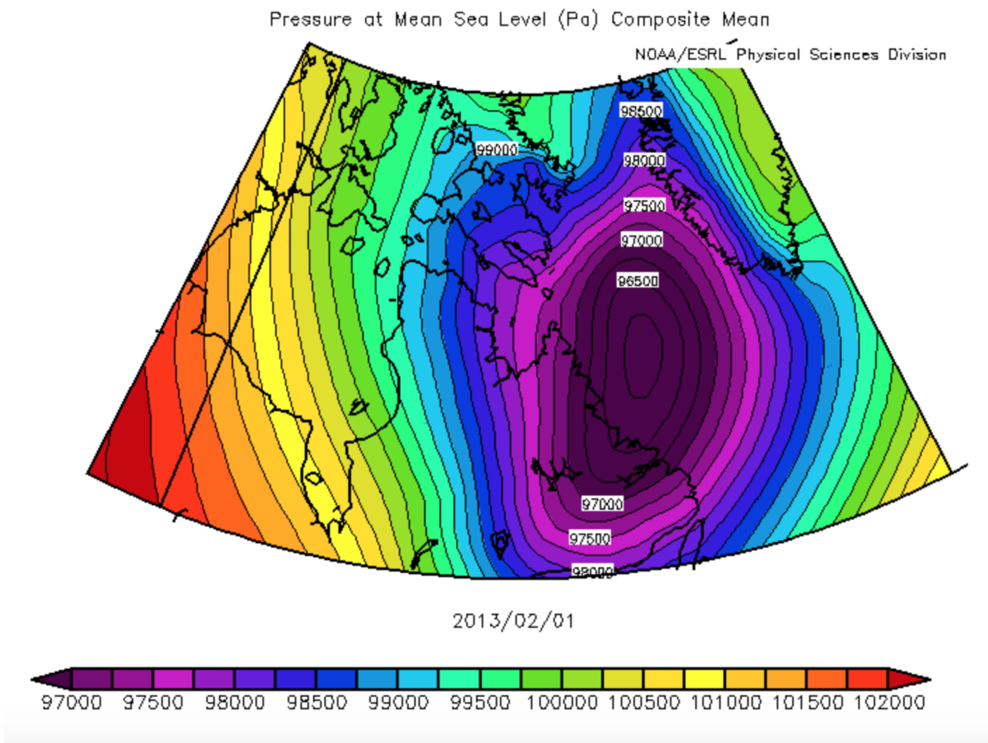

Figure 68. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 1, 2013, during slow transit 2 through ZOI. (source: ESRL NOAA).

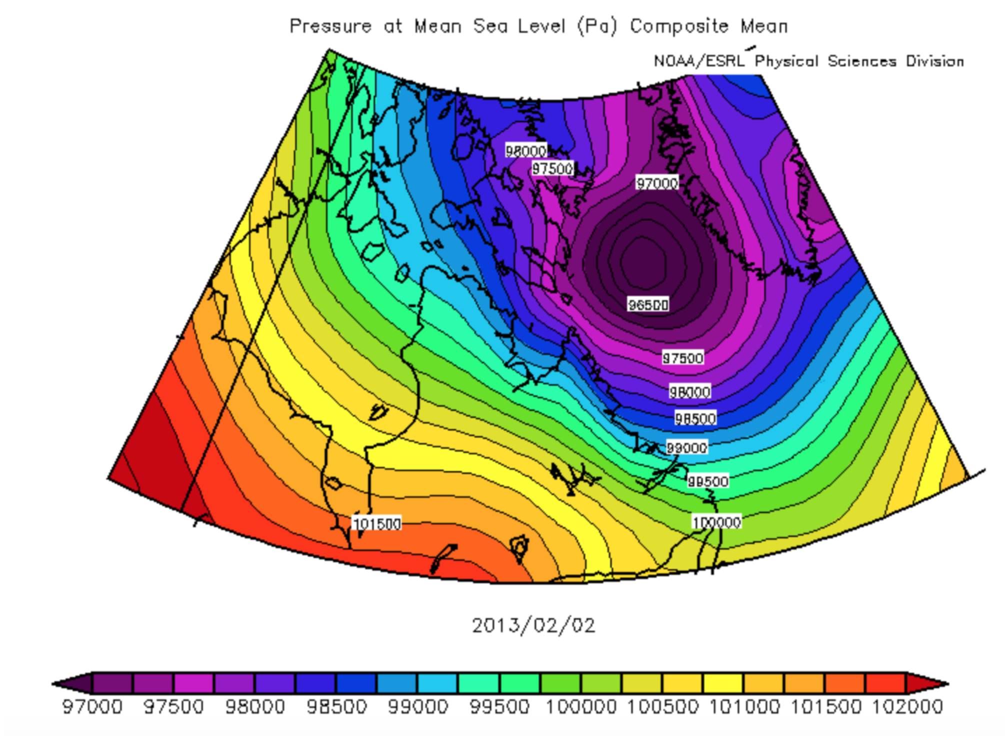

Figure 69. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 2, 2013, during slow transit 2 through ZOI. (source: ESRL NOAA).

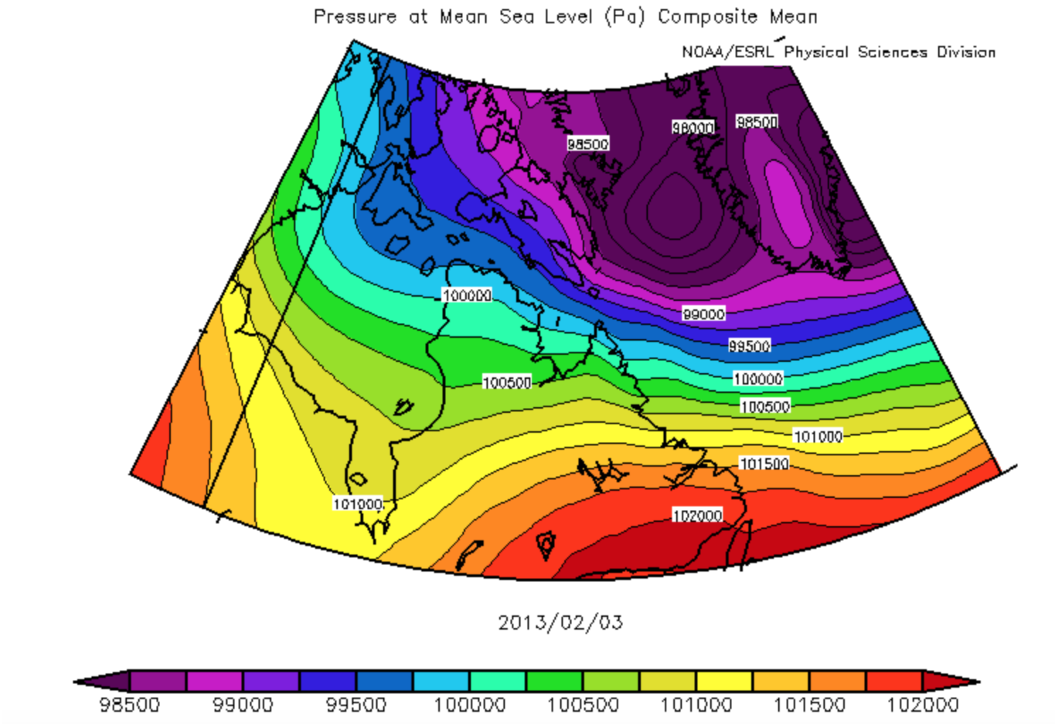

Figure 70. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 3, 2013, during slow transit 2 through ZOI. (source: ESRL NOAA).

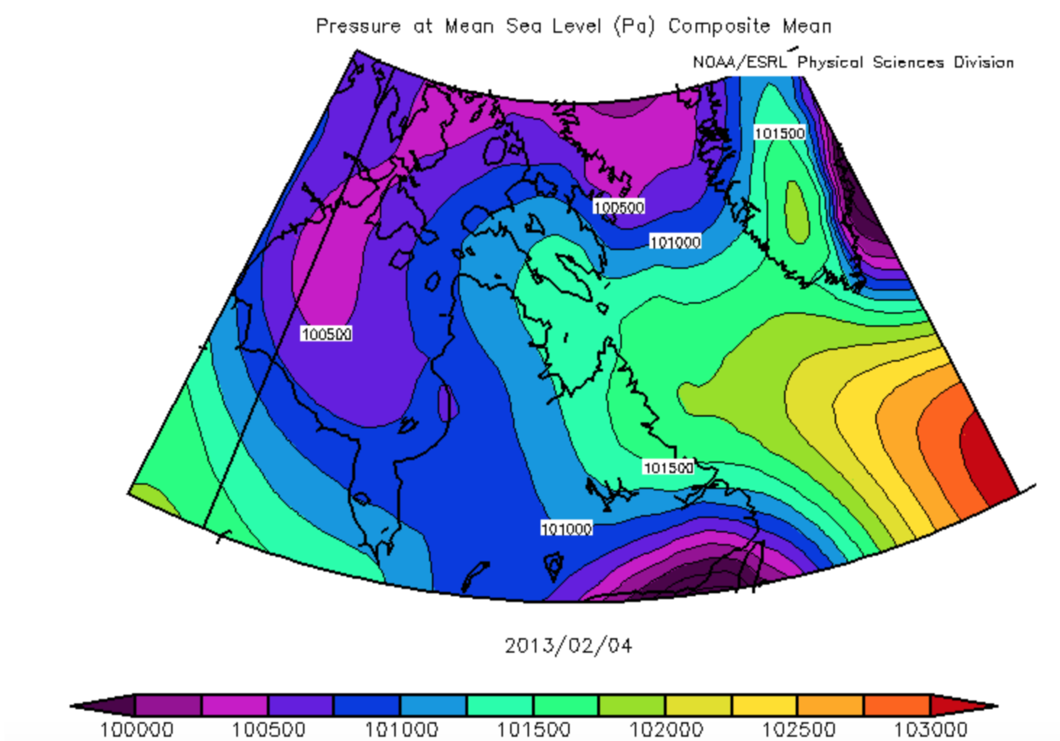

Figure 71. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 4, 2013, during slow transit 2 through ZOI. (source: ESRL NOAA).

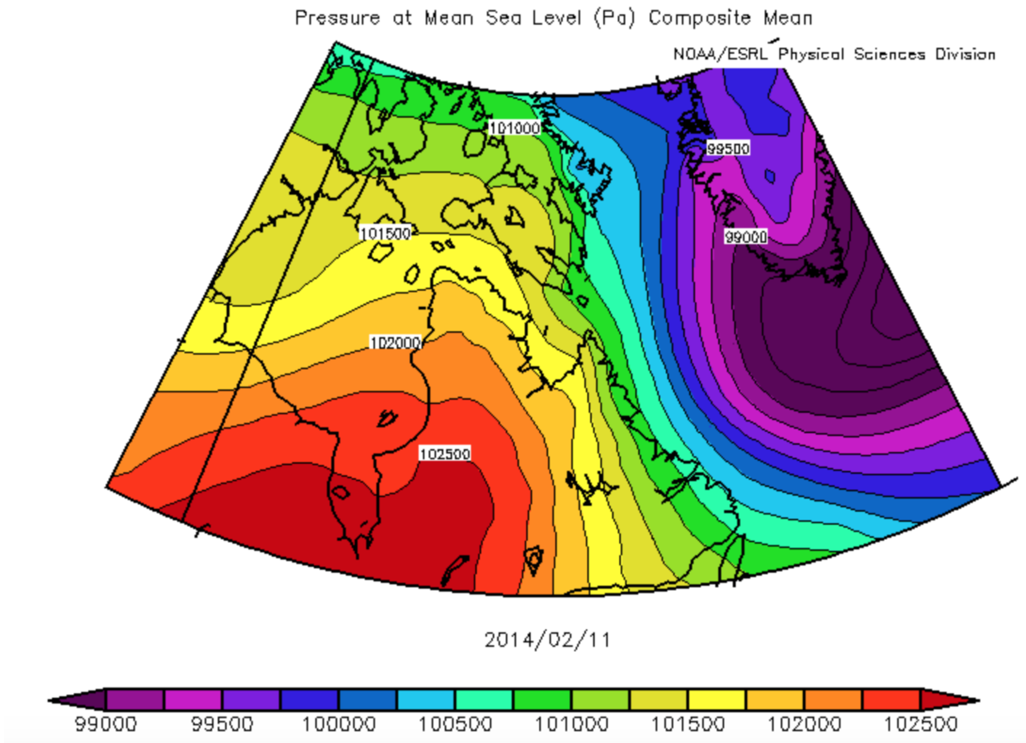

Figure 72. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 11, 2014, prior to slow transit 3. (source: ESRL NOAA).

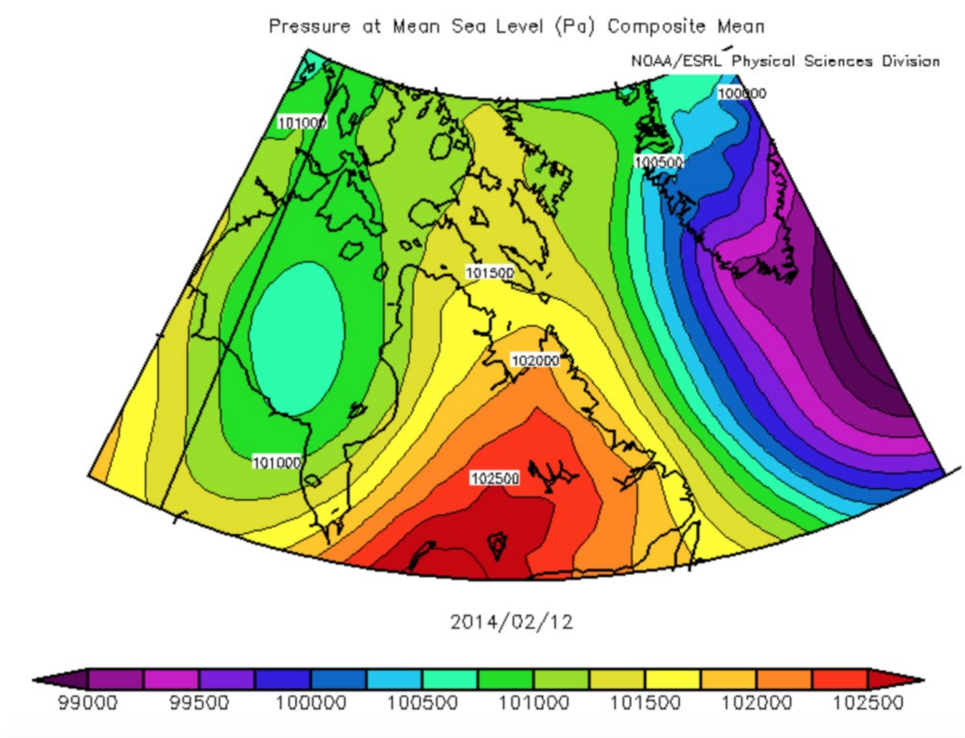

Figure 73. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 12, 2014, prior to slow transit 3. (source: ESRL NOAA).

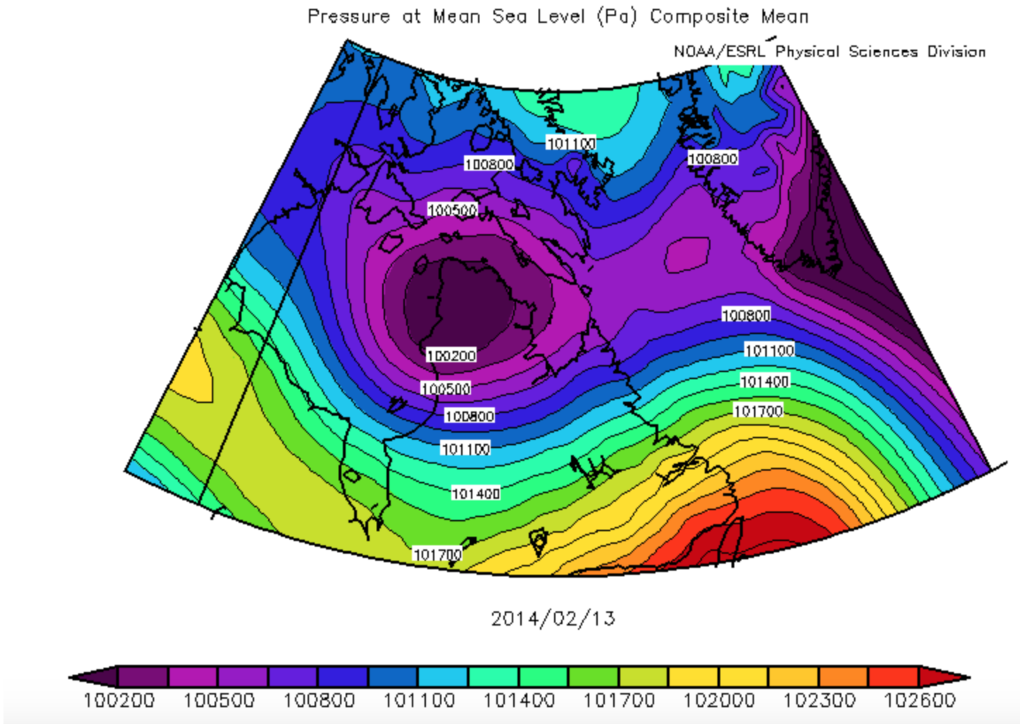

Figure 74. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 13, 2014, prior to slow transit 3. (source: ESRL NOAA).

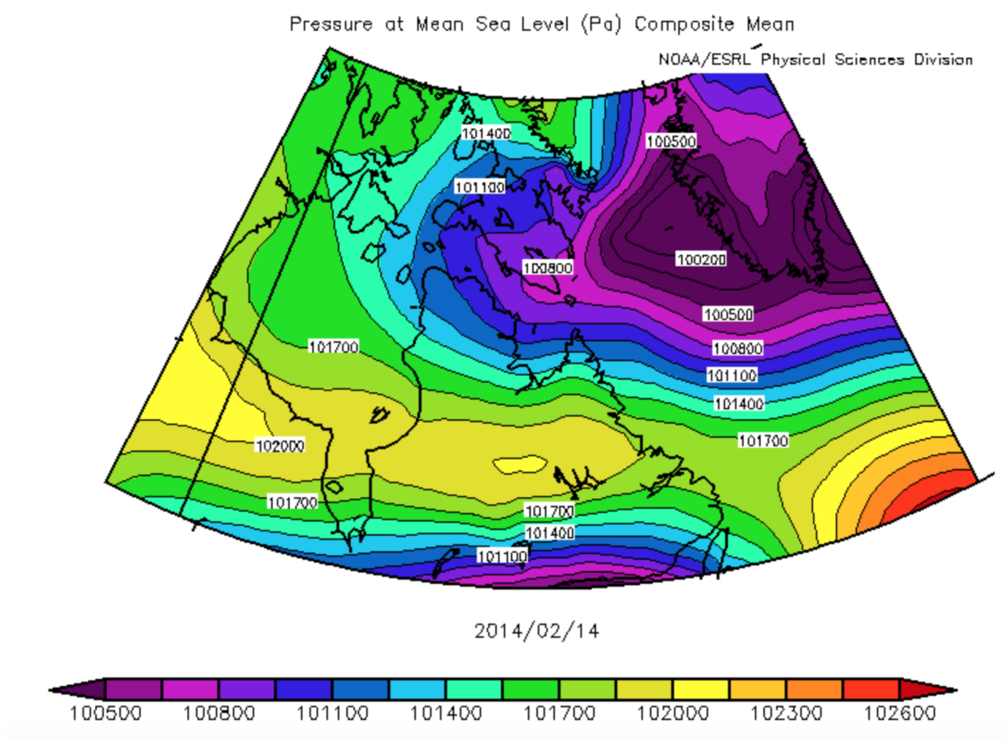

Figure 75. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 14, 2014, prior to slow transit 3. (source: ESRL NOAA).

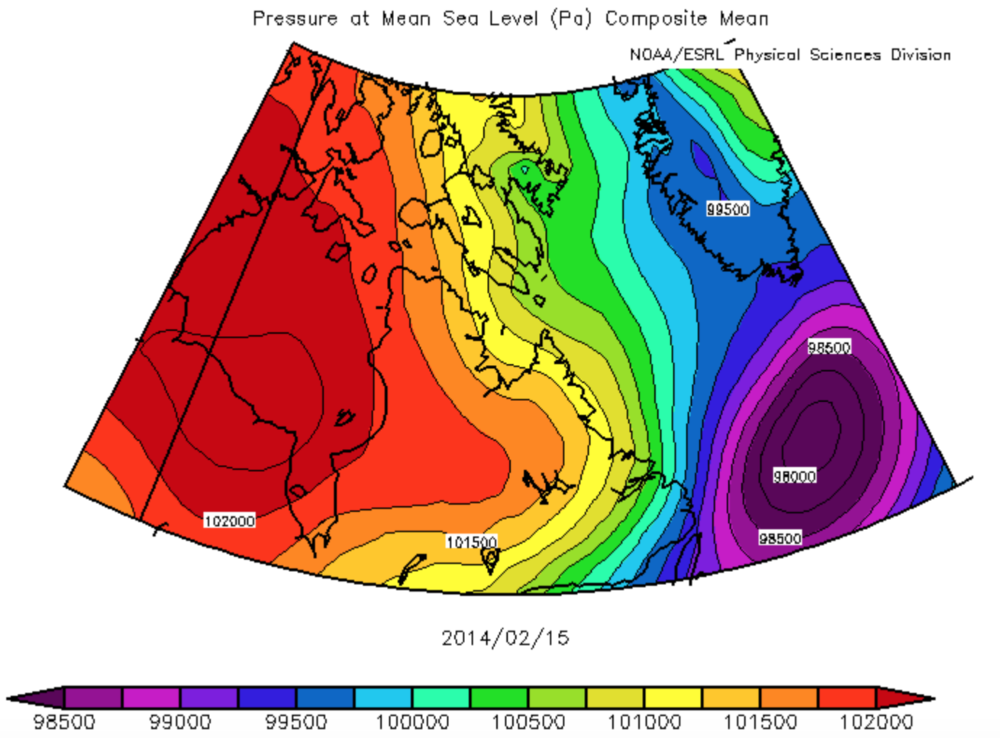

Figure 76. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 15, 2014, prior to slow transit 3. (source: ESRL NOAA).

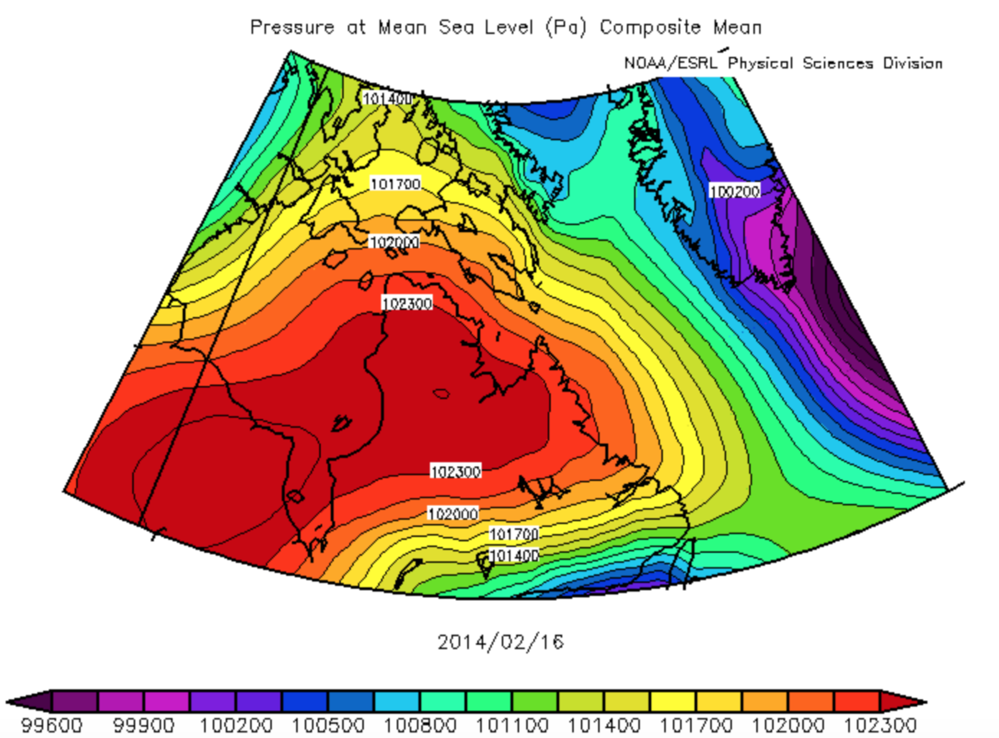

Figure 77. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 16, 2014, prior to slow transit 3. (source: ESRL NOAA).

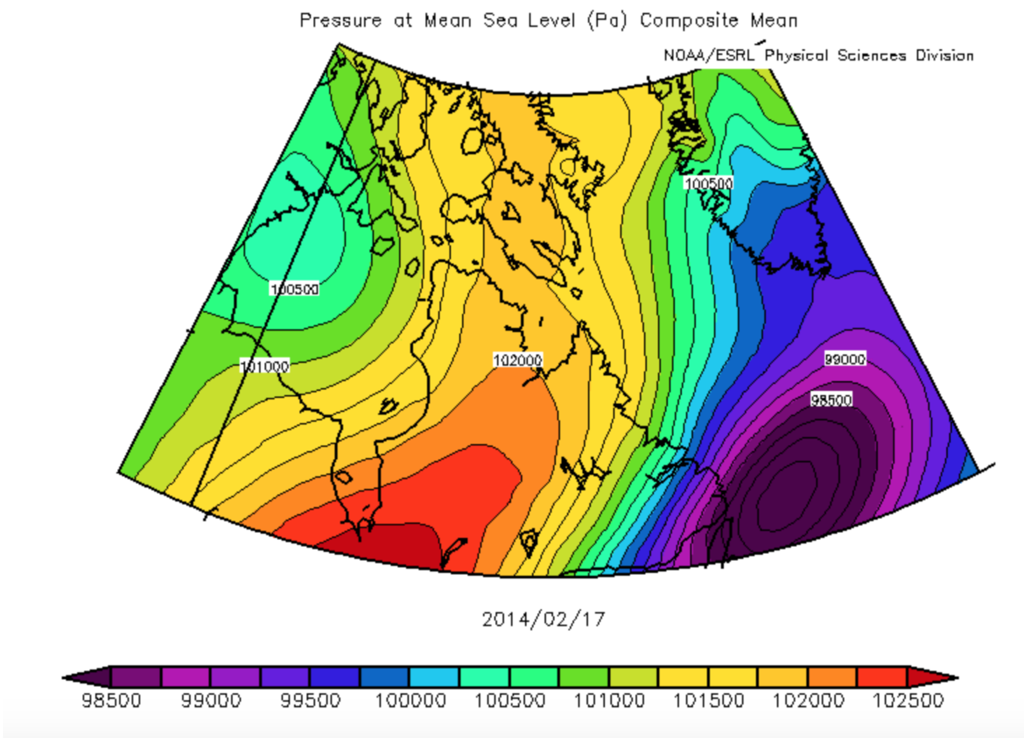

Figure 78. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 17, 2014, prior to slow transit 3. (source: ESRL NOAA).

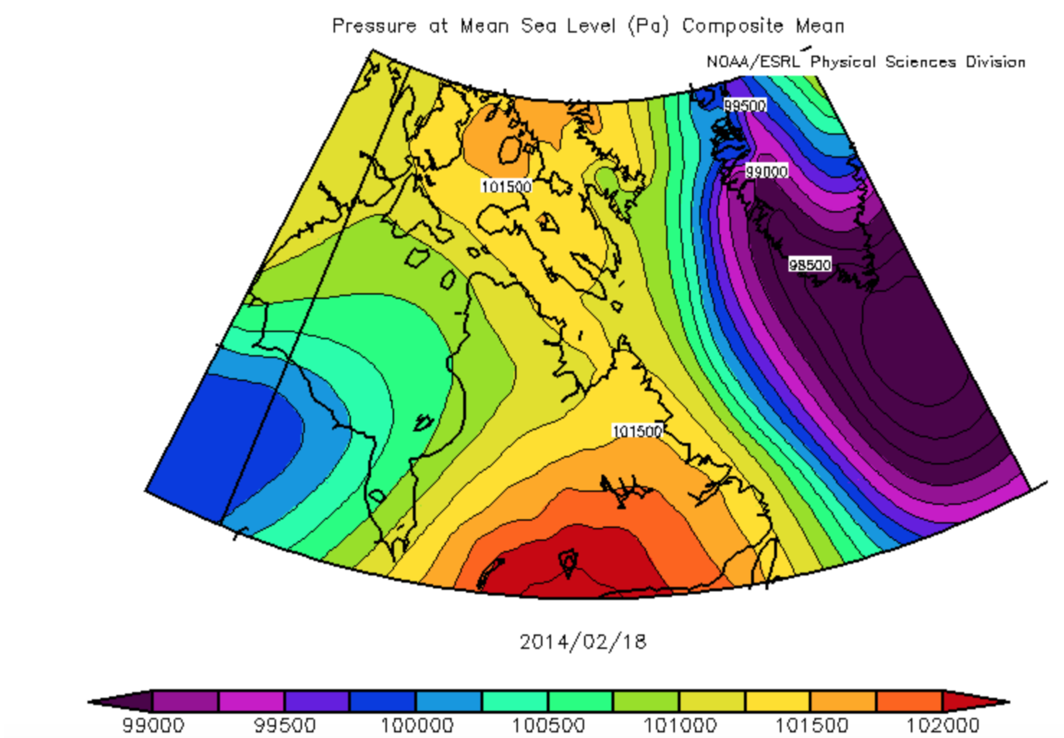

Figure 79. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 18, 2014, during slow transit 3 through the ZOI. (source: ESRL NOAA).

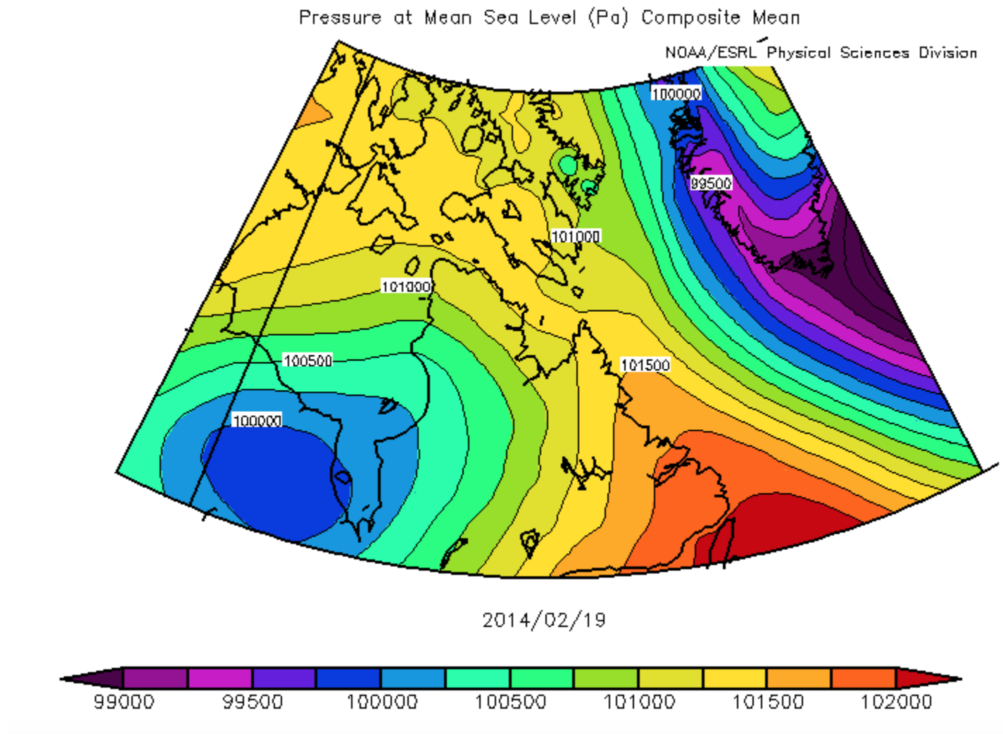

Figure 80. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 19, 2014, during slow transit 3 through the ZOI. (source: ESRL NOAA).

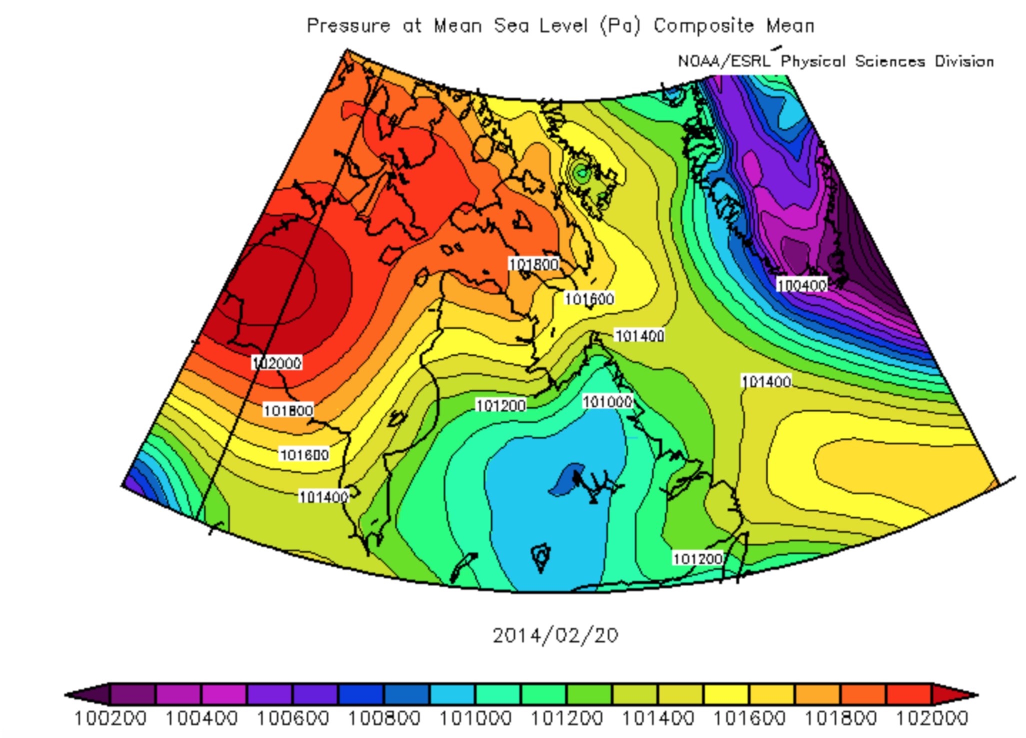

Figure 81. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 20, 2014, during slow transit 3 through the ZOI. (source: ESRL NOAA).

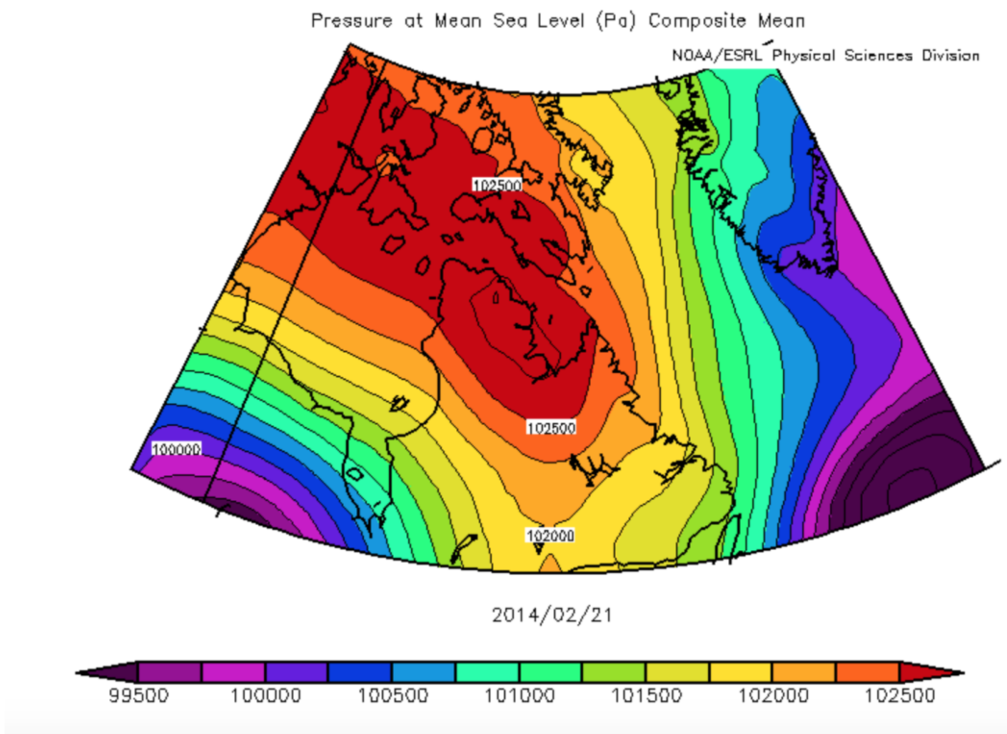

Figure 82. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 21, 2014, during slow transit 3 through the ZOI. (source: ESRL NOAA).

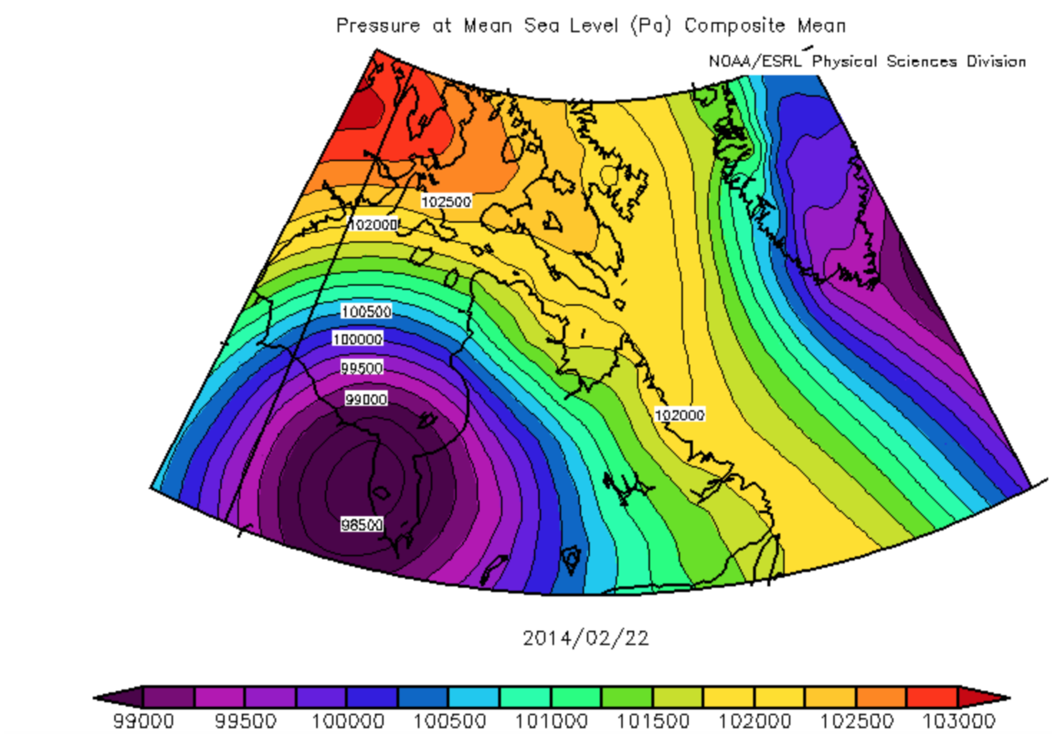

Figure 83. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 22, 2014, during slow transit 3 through the ZOI. (source: ESRL NOAA).

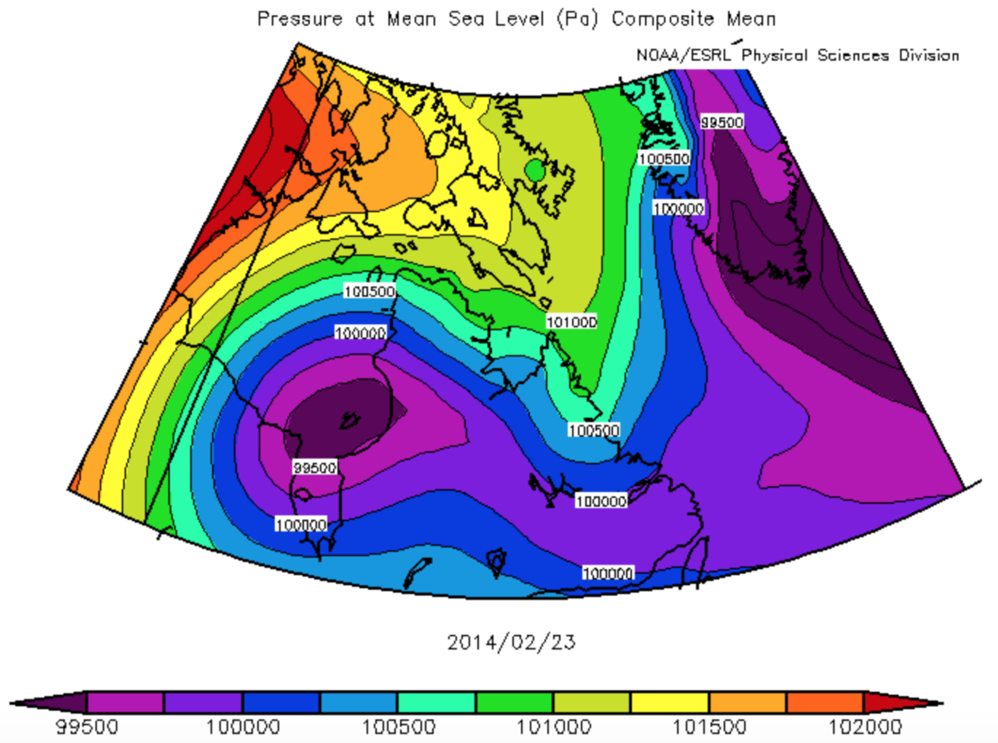

Figure 84. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 23, 2014, during slow transit 3 through the ZOI. (source: ESRL NOAA).

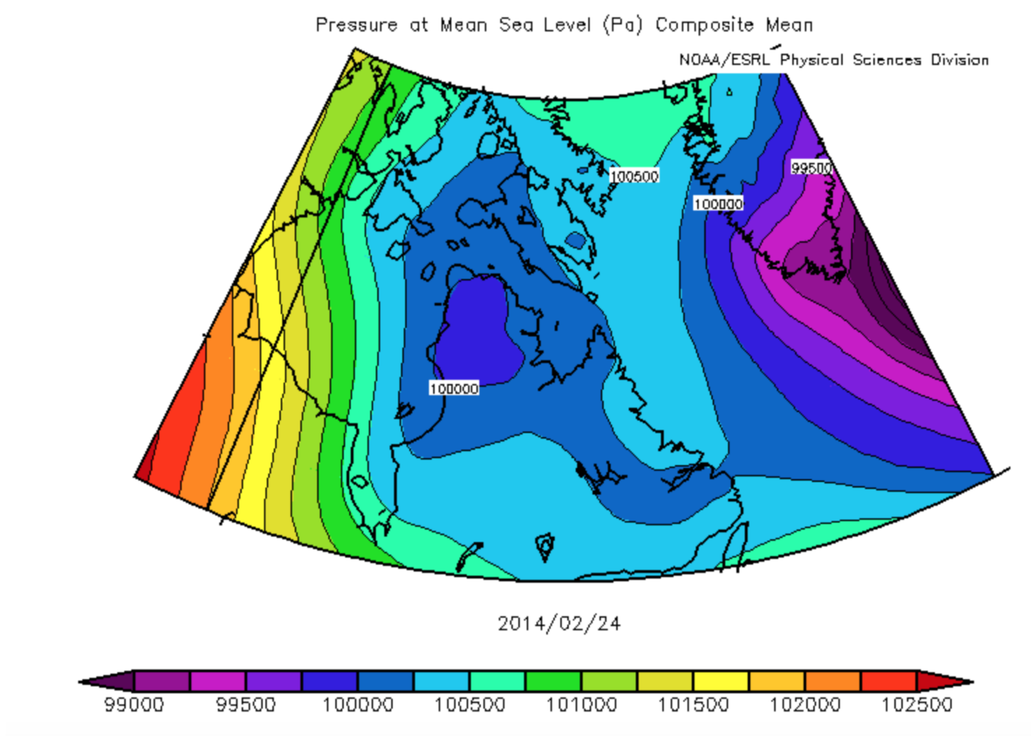

Figure 85. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 24, 2014, during slow transit 3 through the ZOI. (source: ESRL NOAA).

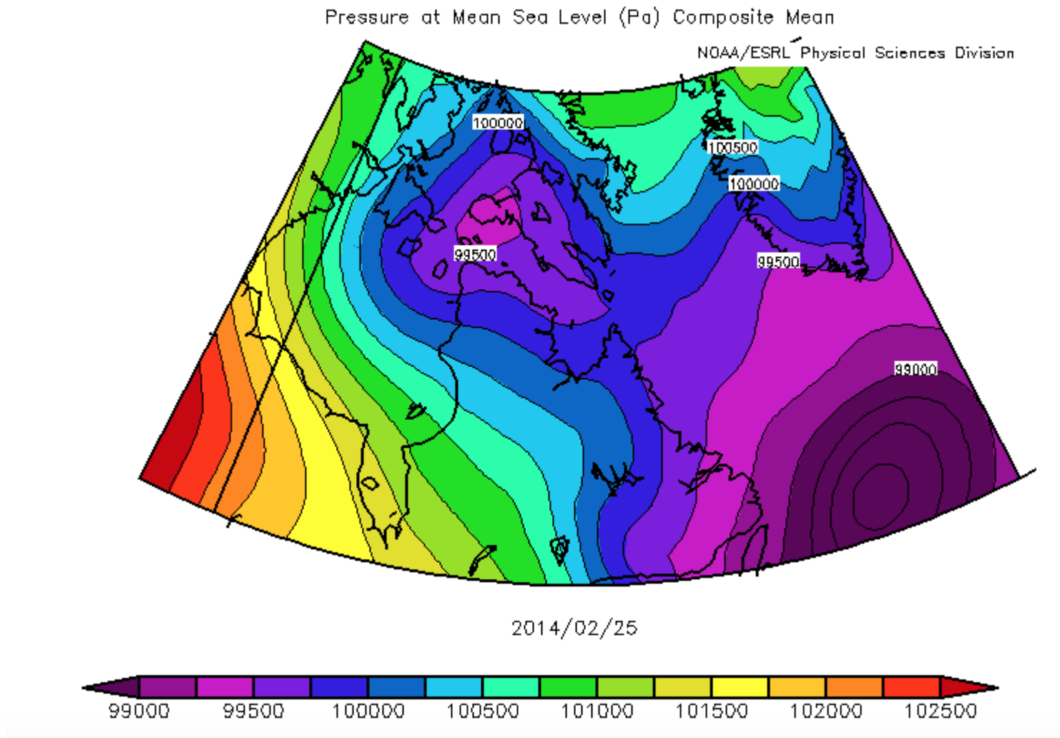

Figure 86. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 25, 2014, during slow transit 3 through the ZOI. (source: ESRL NOAA).

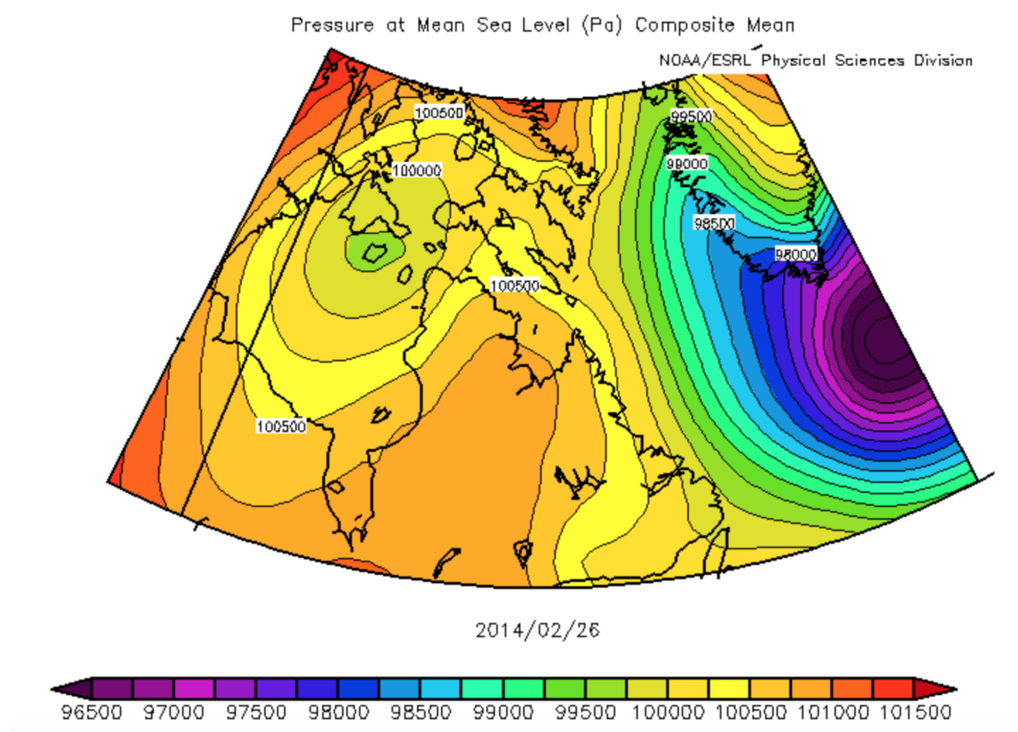

Figure 87. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 26, 2014, during slow transit 3 through the ZOI. (source: ESRL NOAA).

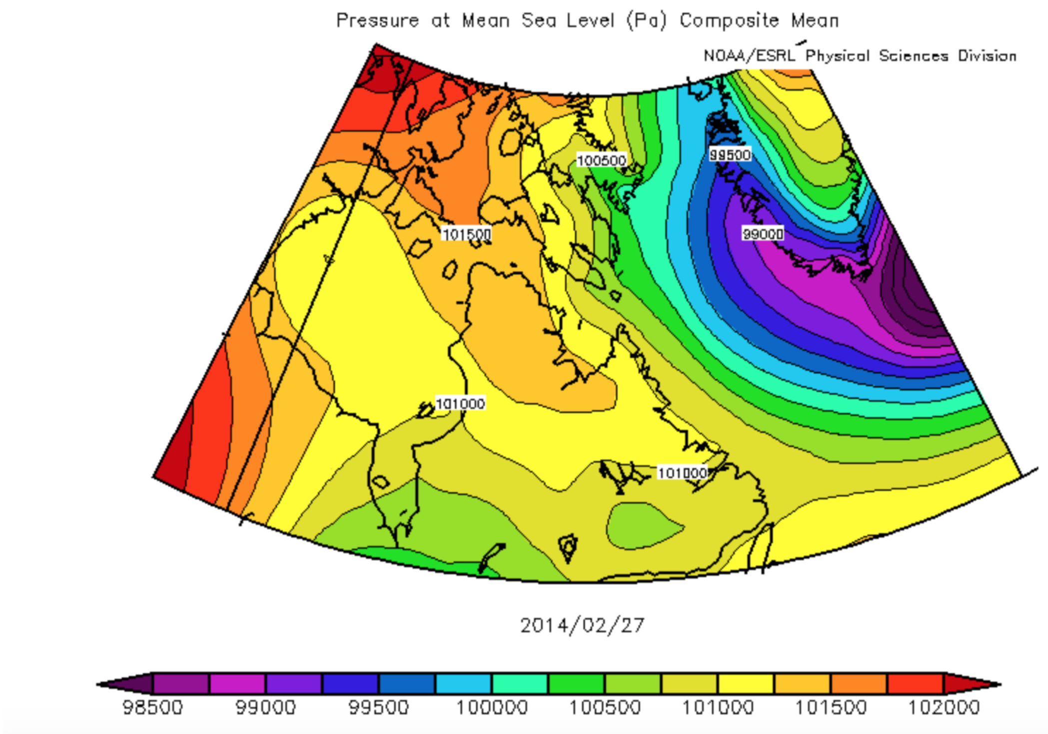

Figure 88. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for February 27, 2014, during slow transit 3 through the ZOI. (source: ESRL NOAA).

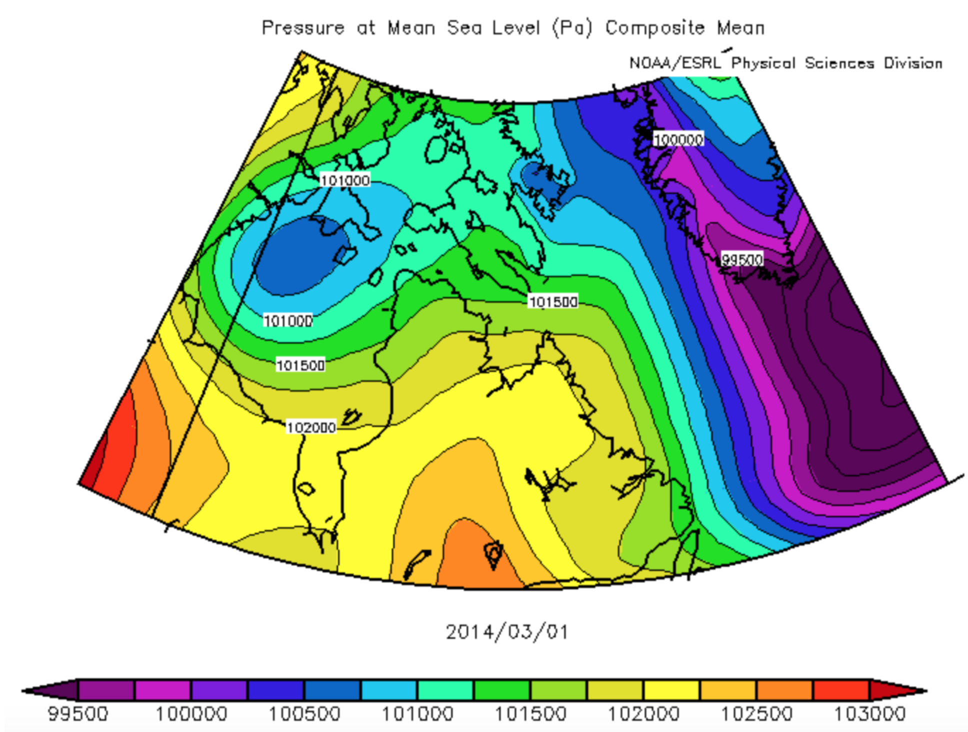

Figure 89. Daily mean (average) sea level pressure (Pa) from NCEP NARR composites, for March 1, 2014, during slow transit 3 through the ZOI. (source: ESRL NOAA).