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**ICE MOTION DYNAMICS IN THE 1998 NORTH WATER POLYNIA (NOW)
SEASON: VALIDATION AND MONITORING USING
RADARSAT-1 SCW DATA AND THE CANADIAN ICE SERVICE ICE
TRACKING ALGORITHM**

by

KATHERINE JEAN WILSON, B.A.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Arts
Department of Geography

Carleton University
Ottawa, Ontario

August, 2000

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SEASON: VALIDATION AND MONITORING USING RADARSAT-1 SCW DATA
AND THE CANADIAN ICE SERVICE ICE TRACKING ALGORITHM”

submitted by KATHERINE J. WILSON
B.A. (Hons), Carleton University
in partial fulfilment of the requirements for
the degree of Master of Arts.

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September, 2000

ABSTRACT

RADARSAT-1 ScanSAR Wide imagery (January-December 1998), was collected for Northern Baffin Bay and processed by an automated ice tracking algorithm (Tracker) currently used at the Canadian Ice Service (CIS). The intent of this study is to 1) examine the accuracy of the Tracker ice motion vectors and 2) investigate the utility of these maps in monitoring ice motion, and their relative contributions in the analysis of formation and maintenance theories of the North Water polynya. Results found that Tracker ice motion compared favorably to in-situ beacons. High levels of ice export are found, supporting the theory that winds or ocean currents continually remove ice from the polynya. Also found is the northward import of ice into the polynya along the Greenland coast, recycling ice through the polynya. A comparison of weekly ice motion with wind shows that ice motion in the region is strongly influenced by atmospheric pressure systems.

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CHAPTER 1

INTRODUCTION

1.1 Sea Ice

In winter, sea ice covers all of Canada's navigable waters in the regions of the Arctic, Labrador, Newfoundland, Gulf of St. Lawrence and the Great Lakes regions. In summer, melting in southern latitudes reduces the sea ice cover, while much of the waters in the Arctic remain frozen. Even though most Canadians do not recognise its presence in their day-to-day lives, sea ice is a constant obstacle for mariners. Ensuring the safe navigation of fishing vessels, import/export shipping and offshore hydrocarbon development is an essential role of the Canadian Ice Service (CIS), part of Environment Canada's Meteorological Service of Canada. Daily ice conditions, warnings and forecasts are provided by CIS for the public good and in support of the Canadian Coast Guard (CCG) Ice Breaking operations, escort, re-supply and rescue services. Water transport and related service industries contributed approximately \$2 billion dollars (1992 prices) towards the Canadian Gross Domestic Product in the first quarter of 1999 alone (Statistics Canada, 1999).

Globally, sea ice plays an important role in balancing our climate system. The large expanse of sea ice around the poles reflects massive amounts of solar energy back to the atmosphere, maintaining average winter temperatures of approximately -30°C in the Arctic (Barry, 1993). The cold polar regions aid in driving global circulation by drawing

warmer air and ocean currents from the equatorial regions towards the poles, and re-circulating cooler air and ocean currents back towards the equator. Without atmospheric circulation, temperatures would be approximately -110°C at the poles and 70°C at the equator (Smith, 1998 Pers. Comm.).

The controlling climate factors in the Arctic are based on a series of feedbacks between the ocean and the atmosphere (thus through the sea ice). The best known feedback in the system is the sea ice-albedo feedback. It has been hypothesized that because of these strong feedbacks, the effects of climate change will be amplified in polar regions and thus are expected earlier in polar regions than other parts of the globe (IPCC, 1996). Early signs of atmospheric warming may either result in a seasonal decrease in aerial extent (Maykut, 1978) or an increase in seasonal extent in certain areas because of the complexities of the ice-albedo feedback (D. Barber, Pers. Comm)

1.2 Remote Sensing of Sea Ice

The remote locations and frigid conditions of polar regions have meant that operational and scientific work is difficult and costly. In the past, the CIS and researchers monitored sea ice using visual aircraft observations. The areal coverage obtained by aircraft was on the order of $100\text{-}200\text{ km}^2$ due to the low-level flights necessary for visual reconnaissance. Poor weather conditions and polar darkness meant many long and dangerous hours for pilots, scientists and ice analysts. For these reasons, our knowledge

about Arctic ice was relatively limited until satellite data became readily available in the 1970's. The large areal coverage (500 - 3000 km²) and polar orbits of the RADARSAT-1 satellite have meant that areas of interest can be continuously monitored, allowing for improved ice observations and climate studies in remote Arctic regions. Logistical problems have meant that tides, currents and bathymetry have still not been adequately mapped in many regions of the Arctic. Scientists and mariners must still rely on extrapolated point data and forecasted meteorological data from distant weather stations.

The introduction of satellite radar systems has made a significant impact in sea ice applications. Radar sensors use the microwave portion of the electromagnetic spectrum. These systems can acquire images independent of light conditions and the longer wavelengths are able to penetrate through most cloud cover. Sea ice can now be consistently monitored all year round including periods of polar darkness and in most weather conditions. Canada's first earth observation satellite, RADARSAT-1, was launched in November 1995. Its polar orbit provides almost daily coverage for northern Arctic regions. The frequency and consistency in repeat coverage of RADARSAT-1 images are valuable tools for ice analysts and forecasters at the CIS. The increased availability of RADARSAT-1 images has also meant that the amount of data visually analyzed at CIS has almost doubled. Computer assisted algorithms are currently being researched and implemented to aid forecasters in analyzing the large amount of data received daily.

The CIS automated ice tracking algorithm (Tracker) compares RADARSAT-1 images of the same geographical region, separated by a small time difference, and then calculates the change in ice position. Vectors are calculated and overlaid on top of the RADARSAT-1 images to describe the direction and magnitude of the ice motion (Fig.1.1). Tracker images provide CIS ice analysts with an overview of the most recent ice motion for their daily analysis and forecasting.

Tracker data have many potential uses. On short time scales, ice motion is affected by winds, while over longer periods ocean currents dominate the ice movement. By monitoring regional ice motion, we can potentially map wind conditions and ocean currents in regions where these data are not readily available.

Analysing regional Tracker data in comparison to atmospheric and oceanic data may aid in determining the influence of these forces on ice motion for regional-scale climate studies. Monitoring changes in the

Fig. 1.1 Example of Tracker Image
© Canadian Space Agency, 1998

annual import and export of ice volumes in a region using Tracker data may also provide indications of climate change.

Sea ice models play an important part in climate research. By reviewing and isolating all the forcing mechanisms required to model the growth and movement of sea ice, researchers are continuously learning more about Arctic climate systems. Sea ice models are also important for providing historical and forecasted trends in sea ice for monitoring climate change. Tracker data can be used as input to, or in validating sea ice models.

1.3 Research Objectives

Prior to using the Tracker algorithm in further studies, it is important to address the accuracy of the Tracker results and the limitations. This was done within the context of an ongoing research study on the North Water (NOW) polynya in Canada's Baffin Bay region.

A polynya is a polar phenomenon in which areas of open water or thin ice appear in regions where climatic conditions alone would normally lead to the formation of ice 1 to 2 metres thick. Polynyas can vary in size from only tens of metres across to over 80,000 km², lasting for a few days or up to 9 months, (Muench, 1975). It has been theorized that the NOW polynya is formed and maintained by a combination of strong winds and

ocean currents that continually remove ice from the region as it forms, and/or due to the upwelling of warm ocean currents melting the underside of the sea ice.

For this research, approximately 148 Tracker ice motion images were produced during the period of January to December 1998 to monitor the seasonal evolution of the NOW polynya. The research presented here was conducted as one component of the International North Water Polynya Experiment, which took place during the spring of 1998 on board the CCG ice breaking vessel, the Pierre Radisson, in the region of Baffin Bay. The objectives of the thesis are to: 1) determine the accuracy of the Tracker ice motion vectors derived from RADARSAT-1 data, and 2) investigate the utility of the Tracker ice motion maps in monitoring ice motion in the region, and their relative contribution in the analysis of formation and maintenance theories of the NOW polynya.

1.4 Thesis Organization

Chapter Two presents the background theory and concepts for the two major components of this thesis: 1) the physical processes of sea ice and polynya formation and maintenance, and 2) the technologies of microwave imaging and automated ice motion tracking that are utilized in this research.

Chapter Three describes the NOW study site and provides background information on previous research on ice drift in the region. Chapter Four describes the data collected, methods and results of validating Tracker in the NOW region. Chapter Five analyses the physical processes of the NOW polynya based on the ice motion maps and its uses in understanding the formation and maintenance processes in the NOW region. Chapter Six synthesizes the significant results of the research, presents conclusions and makes recommendations for future research.

CHAPTER 2

BACKGROUND

This chapter reviews the mechanisms of sea ice formation, its stages of development and the coding of sea ice for mapping ice conditions. Background information on the processes of sea ice movement and previous studies done in this field will be provided as well as an overview of Arctic polynyas and their formation and maintenance. A review of radar concepts and sea ice interpretation from radar images will follow. The chapter will conclude with a detailed description of the CIS ice tracking algorithm.

2.1 Sea Ice Physical Properties

Several forms of ice can be encountered at sea, including fresh water ice from rivers and harbours, icebergs from the calving of glaciers, and most commonly, ice that results from the freezing of sea water. The following sections deal primarily with salt water ice of the Arctic regions.

2.1.1 The Formation of Sea Ice

Ice formation is strongly linked to the thermodynamic processes of sensible and latent heat transfer. Heat is energy that is transferred from one body or system to another as a result of temperature difference (Uvarov and Isaacs, 1986). If the addition or subtraction of energy to a body can be measured as a rise or fall in its temperature, then this is referred to as *Sensible Heat*, (Oke, 1987). Several difference scales of measurement

exist for measuring sensible heat. The most common are Celsius, Fahrenheit and Kelvin, (Pidwirny, 2000).

Latent heat is the energy required to change a substance to a higher state of matter (Pidwirny, 2000). In order for phase changes to occur, substantial amounts of energy are required. Latent heat energy is absorbed during a change of phase from solids to liquids to gases. This same energy is released from the substance when the change of state is reversed, gases to liquids to solids (Fig. 2.1). Thus when ice forms, latent heat is released, whereas when it melts, the water absorbs latent heat. When water vapour condenses or water freezes, by conservation of energy, the same quantity of energy will be released that was originally used in the reverse phase change (Barry and Chorley, 1987).

Fig 2.1 Latent heat exchanges of energy involved with the phase changes of water (Adapted from Pidwirny, 2000)

The presence of salt in ocean water increases its density and depresses freezing temperatures to -1.8°C , lower than in freshwater conditions (0°C). As small ice crystals form, they sink because of their higher density than the surrounding water. As they sink in the shallow surface layers, warmer less dense water is pushed to the surface. As this warmer less dense water is brought to the surface, sensible heat is released to the atmosphere and the sea water cools to temperatures at which ice can form.

Brine (salt in a liquid form) does not fit into the crystalline structure of the ice. Some of the brine is rejected during the freezing process, creating a further mixing of the surface ocean layer. The rejected low temperature, high-density brine sinks and is replaced by warmer, less dense water at the surface (Barry, 1993). The brine rejection enhances the surface mixing and the formation of sea ice by bringing low salinity sea water to the surface where it can cool to temperatures at which ice formation can occur (Thurman, 1983). As ice crystals bond together, the molecular volume expands causing the ice to float. By the time water freezes, the density of ice is only about 0.9 times that of water at 4°C (Thurman, 1983).

2.1.2 Stages in the Development of Sea Ice

New Ice Types

The first stage of sea ice formation consists of small plates up to 2.5 cm thick floating on the water surface, known as *frazil ice*. As cooling continues

the frazil ice plates freeze together to form *grease ice*.

In RADARSAT-1 images these new forms of ice have an oily, slushy appearance (Fig 2.2). With further cooling, sheets of thin ice up to 10 cm thick called *nilas* form.

Fig. 2.2 Example of new ice types in RADARSAT-1 SCW imagery (Approximately 50 km in width)
© Canadian Space Agency, 1998

Young Ice Types

The action of wind and waves break up nilas ice into *pancake ice*, circular pieces of ice 30 cm to 3 m in diameter with rough edges. Pancake ice will freeze together to form a consolidated ice cover and

Fig. 2.3 Cross-section example of ice growth
(Adapted from Onstott, 1992)

will continue to thicken by the direct freezing of sea water to the underside of the ice sheet, called *congelation growth* (Fig. 2.3). This additional ice grows typically as columnar shaped crystals creating the next stage of ice 10-30 cm in thickness

called *grey* and *grey white* ice. *Grey* and *grey white*

Fig. 2.4 Example of young ice types in RADARSAT-1 SCW imagery. (Large Grey ice floes approximately 25 -50 km)
© Canadian Space Agency, 1998

ice are distinguishable in RADARSAT images by their smooth edges which have been rounded out from continuous friction with other ice floes (Fig. 2.4).

First, Second and Multi-Year Ice

The next stage of development is known as *First Year Ice* and it is divided into three categories: thin, medium and thick. At the end of the winter season, first year ice may reach a thickness of up to 2 – 2.5 metres due to congelation growth. Water can no longer freeze to the underside of the ice because of the reduced temperature gradient between the ocean and the atmosphere, especially if an insulating snow layer is present. If the ice survives the summer melt season, it is then designated as *Second Year Ice* at the beginning of the next winter season. As ice melts in the spring and summer seasons, gravity drains the brine from the sea ice leaving channels of air pockets. Ice that survives subsequent seasons is called *Multi-Year*

Ice, which reaches a maximum thickness of approximately 4m (Fig 2.5), (Canadian Hydrographic Service, 1994).

The de-salinization of sea ice over subsequent seasons results in ice that is almost pure water. The removal of brine increases the hardness and strength of this ice. Multi-year ice is distinguishable in RADARSAT-1 imagery because of its bright appearance.

Fig. 2.5 Example of first and multi year ice types
In RADARSAT-1 SCW imagery.
(Large first-year floe approximately 50 km in width)
© Canadian Space Agency, 1998

2.1.3 World Meteorological Organization (WMO) Coding of Ice Concentrations

Using a symbol called an 'egg code', areas of similar ice regimes are mapped based on total concentration, main stages of development, and floe sizes (Figure 2.5).

Fig. 2.6: Key to Sea Ice Symbols (Adapted from CIS MANICE, 1994)

Concentrations are reported in tenths with 10/10 being consolidated ice and 1/10 being mostly open water. Egg codes are numerical so foreign vessels can interpret them without language barriers.

2.2 Sea Ice Kinematics

Sea ice is divided into two main types according to its movement. *Fast Ice*, despite its name, does not move but is held fast to coasts, attaching itself to land and then spreading outward (Fig. 2.7). Beyond this, lies *Drift Ice* that is mobile and moves under the action of wind and ocean currents. Within the context of this research, the following section discusses the motion of drift ice only.

Fig. 2.7 Example of Fast Ice in RADARSAT-1 SCW imagery (Fast Ice Approximately 200 km in Width)
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The velocity of ice motion due to wind varies with wind speed, but also with the concentration of the ice. In low concentrations of 1/10 - 3/10, ice responds more to the influence of wind than in higher concentrations of 7/10 - 10/10, where movement space is very limited (Canadian Hydrographic Service: 1994). On daily to weekly time frames, wind directed ice is deflected to the right, or east, in the northern hemisphere due to the rotation of the Earth (the Coriolis effect). Over the course of months, regional ocean

currents dominate ice motion. Ice can move at the full current velocity as long as it is not jammed in narrow channels. When the wind blows in the same direction as the ocean currents, considerable velocities can be achieved (Canadian Hydrographic Service, 1994).

As sea ice moves, there are three general processes at work. **Compacting** occurs when ice is forced together by winds and ocean currents or due to the presence of land that impedes movement. This increases ice concentrations and/or produces stress by forcing ice to pile up in **ridges** resulting in ice deformation, also called **rumble ice** (Fig. 2.8). **Divergence** occurs when ice fields or floes move apart, reducing ice concentration and/or relieving stress. **Shearing** occurs when two ice fields move in opposing parallel directions. For example, the zone between land fast ice and drift ice, or perhaps when one ice field is compacting and the neighboring field is experiencing divergence.

Fig. 2.8 Processes of Ice Motion
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Winds and ocean currents manipulate and redistribute the sea ice boundary layer, thereby affecting the transfer of energy between the ocean and the atmosphere. In high ice motion regions, exported ice is constantly being replaced by new ice growth, termed an 'ice factory'. High ice accretion rates cause considerable salt fluxes in the ocean surface, influencing thermohaline circulation, resulting in substantial turbulent fluxes across the ocean - sea ice - atmospheric interface (Stephan and Ohmura, 1985). Areas of low ice motion generally consist of thick pack ice types that impede energy fluxes between the ocean and the atmosphere. Consolidated sea ice regions with large forcing from winds and ocean currents often become high-pressure areas, thick with rubble ice.

2.3 Polynyas

In the Arctic, winter temperatures average -30°C due to the long periods of polar darkness. During summer months, northern latitudes receive large amounts of incoming solar radiation capable of warming the Arctic. The high albedo effect of sea ice (up to 80% in May) means that a majority of the incoming solar radiation is reflected back to the atmosphere. This albedo feedback maintains average summer air temperatures of approximately 5°C (Rouse, 1993). These low temperatures do not allow significant melting, allowing a large portion of the sea ice to remain in the Arctic Ocean year round.

as ocean ridges force deep ocean currents to the surface. In both situations, the deep ocean currents are warm enough to erode the underside of the sea-ice allowing a polynya to form.

As the polynya opens, surface ocean layers will rapidly lose sensible heat and begin to cool. If upwelling is sufficient, cooling will not continue to temperatures at which ice formation can occur. The melting of the underside of the sea ice by deep water also results in an increase of low salinity fresh water. This fresh water creates a low density layer floating on top of the denser, more saline deep water. The fresh water surface layer absorbs large amounts of radiation in the springtime and quickly becomes warmer than the deep ocean water. This stratification ensures the maintenance of a sensible heat polynya by inhibiting vertical mixing and allowing the surface layers to warm. The open water of the polynya then expands as the warm surface layers melt the polynya ice margins (Fig. 2.10).

Fig. 2.10 Sensible and Latent Heat Polynya Formations
(Lewis, 1996)

2.3.2 Latent Heat Polynyas

In a latent heat polynya, winds and or ocean currents continually export sea ice as it forms. The constant removal of sea ice by winds and or ocean currents aid in the freezing of sea water by mixing the upper layers of the water column, preventing surface layers from warming (Smith et al., 1990). Brine rejection from the continual formation of ice in a latent heat polynya creates dense saline water that sinks. The brine rejection and the mixing of the surface layers inhibits the water column from becoming stratified. The sinking of dense saline water returning less saline water to the surface creates a vertical circulation and conditions suitable for the freezing of sea water (Fig. 2.10). The continuous formation of ice also reduces the loss of sensible heat from the oceans to the atmosphere.

The export of ice maintains the open water of the polynya but also means that a greater amount of ice is formed in the region than if it was ice covered. Pease (1995) calculated that the sea ice cover in the Bering Sea region could be regenerated two to six times when ice is continually removed from the region. The large amount of ice that is formed means that a great amount of latent heat is being released to the atmosphere (when water freezes, latent heat is released), hence the term latent heat polynya.

Latent heat polynyas can often have short time spans. They open up when winds blowing offshore move existing ice away from the region, and they close up when winds move pack ice towards the shore. Longer term latent heat polynyas tend to

exist when the drift of ice into the polynya is inhibited by other factors. Narrow channels can become ice jammed or the presence of grounded glacial ice can also inhibit ice motion.

The sensible and latent heat processes are not mutually exclusive. In some cases, as in the NOW polynya, they are theorized to work in combination.

2.3.3. Polynyas and Climate Change

Although polynyas only cover a small fraction of the Arctic Basin, they make a large contribution to the Arctic energy budget and the atmosphere of the region. The area of open water in a polynya may provide heat exchanges between the atmosphere and the ocean up to two orders of magnitude greater than that of the surrounding pack ice (Maykut, 1978).

Understanding polynya formation and maintenance will improve our understanding of regional climate systems of the Arctic. Monitoring changes in size, formation and break-up dates of polynyas may give early indications of climate change. Polynyas could also be used as a model system to forecast the effects of climate change in the Arctic (Barber, 1997).

2.4 Sea Ice - Microwave Radiation Interactions

This section summarizes the concepts of radar imaging and interactions of the radar signal with sea ice that are relevant to the thesis. For a more comprehensive presentation see Carsey (1992).

2.4.1 Radar Sensors

A radar system consists of a transmitter and a receiver. The transmitter sends pulses of microwave energy towards the earth's surface; the reflected energy, called *backscatter*, is captured by the receiver and converted into an image. Side Looking Aperture Radar's (SLAR) consist of an antenna mounted on the underside of an airplane or satellite. Resolutions for SLAR's are dependent on the sensor altitude and the length of the antenna. Generally, lower altitudes and longer antennas provide better resolutions. In order to provide high resolution data from space borne platforms, antennas kilometres in length would be needed. Synthetic Aperture Radar (SAR) is a technique in which antennae only several metres long and associated signal processing are used to synthesize longer antennae. For more information on SAR, the series by Ulaby, Moore and Fung (Ulaby et al., 1981; Ulaby et al., 1982) are recommended.

2.4.2 Radar System Parameters

The strength of the returned backscatter is a function of radar system parameters and surface characteristics. Aspects critical in reviewing SAR sensors for specific applications are frequency, polarization and imaging geometry. The wavelength used

can affect the backscatter return of a target because shorter wavelengths tend to reflect off near-surface elements and enhance the surface geometry while longer wavelengths respond less to the surface and more to sub-surface elements. In previous research it has been found that X-band (~3.25 cm) radar has been the most useful for ice related studies because it enhances the surface characteristics of various sea ice types (Onstott, 1987). In contrast, L-band (19-77 cm) penetrates into sea ice providing information concerning the sub-surface structure. In identifying sea ice types, surface characteristics are of primary interest and shorter wavelengths are generally used. However X-band is scattered more by the atmosphere and clouds and is not useful in the variety of applications that radar platforms are designed for. Consequently, C-band (5.2-7.7cm) was selected as a compromise for RADARSAT and ERS-1 and 2. It reflects mostly surface characteristics of sea ice but can provide some sub-surface backscatter, depending on ice porosity.

Radar systems emit signals at an angle to the earth's surface. This angle fans out to create a line of imagery perpendicular to the sensor flight direction called a *swath*. ***Incidence angles*** in the near range are closer to the platform and are therefore smaller than incidence angles in the far range of the swath. As the angle of incidence increases with range, the intensity of backscatter decreases. This means that similar targets will have a decrease in signal return across the swath. Data processing techniques can then be used to normalize the data across the swath.

Foreshortening occurs if the slope of the terrain is less than the incidence angle, the radar signal will reach the base of the slope first and the top of the slope last as shown in Figure 2.10. When this happens, the slope is displaced away from the sensor, causing the slope to appear compressed. This type of distortion tends to occur more in the far ranges of the swath where the incidence angles are larger (Lillesand and Kiefer, 1999).

Layover occurs if the slope of the terrain is greater than the incidence angle of the radar platform. The radar pulse will reach the top of the terrain slope first and the bottom of the slope last (Fig. 2.11). When this happens, the top of the slope is received by the sensor before the bottom of the slope. The top of slope will overlap the bottom of the slope and cause objects to be displaced towards the direction of the sensor on the image. This type of distortion tends to occur more in the near ranges of the swath where the angles of incidence are smaller, (Lillesand and Kiefer, 1999).

Fig. 2.11 Example of Foreshortening and Layover Displacements in Radar Imagery
(Adapted from Lillesand and Kiefer, 1999)

High and steep hills may also block some of the signal from reaching the ground behind, and a *shadow* may occur, resulting in a loss of image data. Sea ice has relatively minimal relief in comparison to land applications, and therefore layover and foreshortening are insignificant in most sea ice images. The presence of shadow in very large ice ridges is rare.

Radar signals can be transmitted in vertical (V) or horizontal (H) planes. Signals sent out and received in the same plane (HH) and (VV) are termed *like-polarizations*. Signals sent out in one polarization and received in another (HV) and (VH) are termed *cross-polarizations*. Generally, like-polarization provides the strongest signal return and a wider image brightness range (Lillisand and Keiffer, 1999). Targets with high surface areas show little difference in like-polarizations, whereas a definite difference is apparent for targets with low surface areas, such as sea ice. HH is preferred in ice applications because VV has been found to cause ambiguous ice-water discrimination in the near range of the swath. VV polarizations are sensitive to small waves in areas of open water with minimal amounts of wind, thus causing high radar returns (Kwok et al., 1992). Cross-polarizations have been found to provide stronger returns for multi-year ice types showing the effects of multiple scattering from brine drainage channels and dielectric discontinuities (see section 2.3.4 on dielectrics) (Onstott, 1992). Classification of sea-ice types can be aided by using more than one of these polarizations, yet research in this area is still fairly limited (Flett, 1997).

2.4.3 Microwave Sea Ice Target Parameters

The RADARSAT imagery used in this work can be considered, for the most part, a representation of the amount of incident C-band energy reflected back to the sensor from the sea ice and/or ocean surface. The strength of the received backscatter will result in a bright (high backscatter) or a dark (low backscatter) tone in the radar image. Tones in the RADARSAT-1 imagery used in this thesis are represented as pixels with 8 bit grey levels. The appearance of sea ice in these data is a function of the sea ice volume's (including snow layer) electrical properties and surface roughness.

How a sea ice volume transmits, scatters and/or absorbs the radiation incident from the sensor is largely dependent on the electromagnetic properties of its constituent materials: ice, air, water (liquid and frozen) and brine. Each constituent in the sea ice volume will have different electrical properties (described here as dielectric constants (ϵ^*)) and these will affect how well the radar energy will penetrate and or be reflected. The degree at which radar will reflect or be absorbed at the earth's surface is dependant on the ϵ^* ratio between the transmission material (air, $\epsilon^* \sim 1$) and a volume on the earth's surface. For example, air has a $\epsilon^* \sim 1$, and open water has a $\epsilon^* \sim 80$ resulting in a ratio of 1: 80. This high contrast in dielectrics will result in little radar energy penetrating into the surface volume. The ratio of air and first year ice ($\epsilon^* \sim 3.5$ at -5°C) has a ratio of 1: 3.5, resulting in the radar signal penetrating the volume. Since the atmosphere is relatively transparent at C band, the first potential interaction is with the target surface. Generally a volume with a high ϵ^* will result in less penetration into the material by the radar signal. An overall dielectric constant can be estimated for a sea ice volume by summing the ϵ^* weighted by the relative proportions of each material that make up the

volume, and it has been shown to be sensitive to time of year (season). (Barber et al., 2000).

Surface Scattering

The radar signal will scatter depending on the dielectric constant of the volume and the magnitude of the surface roughness. Generally, the greater the surface roughness of a target the greater the scattering. For an air-open water interface, the large contrast in ϵ^* will make the open water impermeable causing surface scattering. If this open water is relatively calm, the smooth surface will reflect nearly all of the energy away from the sensor resulting in a loss of backscatter. This is called *specular reflection*. (Fig 2.12).

First year ice has a high brine volume (salinity) and its dielectric constant is less than that of open water. By comparing an air / first year ice ($\epsilon \sim 3.5$ at -5°C) interface, there is less of a contrast in ϵ^* and penetration of up to a few centimeters into the ice surface will result in near surface scattering. When surface scattering occurs on objects with high surface roughness, energy is reflected in all directions isotropically, allowing some of the backscatter to be returned to the sensor. This type of surface scattering is called *diffuse reflection* (Fig. 2.12).

Corner reflection is another type of surface scattering that occurs in areas where perpendicular or near perpendicular surfaces meet (Fig 2.12). The double or multiple reflection caused by the corners returns a significant amount of backscatter back to the sensor that is very intense and *bright in tone*. This can occur at the edges of floes, or along ridges.

Volume scattering

As ice ages, brine drainage occurs resulting in multi-year ice floes having a lower salinity and thus a lower dielectric constant, $\epsilon \sim 2.7$ at -5°C . At the air / multi-year ice interface an even smaller contrast in ϵ^* results in more penetration into the ice surface allowing more scattering to occur within the volume. As brine drains out of the sea ice it leaves channels of air pockets. The microwaves scatter within these air pockets in the upper few centimeters of multi year ice, allowing some of the backscatter to be reflected back to the sensor resulting in a bright signature (Fig 2.12) (Barber et al.; 2000, Lewis, 1987).

Fig. 2.12 Backscatter Interactions for Multiyear Ice, First Year Ice, and Smooth Open Water. (Adapted from Onstott, 1992)

2.4.4 Microwave Sea Ice Image Parameters

Visual interpretation of radar images is based on the backscatter image elements of tone, texture, shape, size and association. The word *tone* refers to the brightness at a point in the image. The tone or 8-bit grey value of an object in a digital radar image is related to the amount of backscatter received from an object. At one extreme, a black tone (e.g. nilas or calm open water) indicates that the sensor received little or no reflected

radiation, while at the other extreme a white tone represents a strong reflection towards the antenna (Fig 2.2).

Texture is used to describe the spatial variation of tones (Werle, 1992). A surface can appear rough due to a wide range of tones, or smooth due to an even distribution of tones. Like differences in grey tones, varied image texture between ice types or conditions is useful in classification. For example, (Fig. 2.4) shows different textures of first and multi-year ice types.

Knowledge of an object's *shape* increases our ability to visually interpret Radar. For example, roads and streams are distinguished by differences in geometric complexity, even though both are linear features. In ice applications, new ice (Fig 2.2) and young ice (Fig 2.4) can be distinguished due to their differences in shape and size. The *size* of an object, or its spatial extent relative to other surface features, allows differentiation of ponds from lakes, hills from mountains, etc. *Association* is based on our previous knowledge of the study area, surface processes, or human impacts. In analysis of sea ice in radar imagery, for example, we can infer from the knowledge of consistently low temperatures that what may appear as open water in an image is probably smooth nilas (Lillesand and Kieffer, 1999).

2.5 Previous Studies Tracking Sea Ice Motion

2.5.1 Historical Techniques

In 1881 the US vessel *Jeannette*, in attempts to reach the North Pole, was crushed by ice and abandoned near *Ostrov Bennetta* (north of Siberia, Russia). Three years later, pieces of the wreck were discovered near the southernmost tip of Greenland, over 3000 miles away from Ostrov (Peele, 1971). This inspired a Norwegian explorer Fridtjof Nansen to set his ship the *Fram* in the ice east of *Severnaya Zemlya* (Russia). The ship exited the ice near *Spitsbergen* in 1896 and proved the existence of a transpolar drift of sea ice (Daida, 1991).

Forty-two years later in 1937, the former Soviet Union set up the first Arctic ice station on a multi-year floe near the North Pole called *Severnyy Polus-I* (North Pole-I). Oceanographic and meteorological information was collected until the ice floe broke up a year later after drifting 3300 miles to Scoresby Sound in east Greenland. Into the mid-1980's over 30 ice islands have been occupied by the Soviet Union and the United States to collect scientific data.

2.5.2 Technological Advances

Capabilities to monitor ice kinematics have improved significantly with the launch of telecommunication and remote sensing satellites. Ice beacons removed the need for occupied ice stations to monitor ice drift. Beacons deployed onto ice floes transmit hourly signals to global positioning satellites. With positional accuracies of up to 150 metres, they can provide real ice motion data in remote areas. Limitations to studying sea ice

motion using beacon data are primarily expense-related. The cost of the instrument, satellite communications and helicopter or aircraft deployment means that a limited number of beacons can be deployed in large areas of study. Beacons may malfunction and the results from beacon-derived ice motion are biased towards larger, thicker ice floes because of deployment requirements. Ice beacon data have been successfully interpolated for monthly and yearly ice motions as well as inferred ocean currents at a synoptic scale in the Arctic (Peterson and Prinsenburg 1989, 1996; Overland 1985; Pease (1995)). What ice stations and ice beacon data failed to define was a finer spatial variability of ice motion due to the limited ice motion points available.

Remote sensing data provides the ability to monitor ice motion at a greater spatial detail than could be previously observed using beacon data (Kwok et al., 1998) although the revisit periods of most satellites are still inferior to the temporal detail provided by the hourly beacon signals. The earliest work was done by manually drawing the ice motion fields through visual comparisons of remotely sensed imagery. Dunbar (1979) provided one of the first North American accounts of manually extracting ice motion from SLAR imagery in the NOW polynya region. These data were not geo-rectified and therefore suffered from problems in accuracy. Ito and Müller (1982) also used the manual technique to track ice motion in the NOW polynya using geo-rectified Landsat images providing accuracies of +/- 2km.

Manually extracting ice motion fields from remotely sensed imagery was tedious and time consuming. Work on computer aided ice motion analysis began in the late 1980's with

Carsey and Holt (1987) who introduced an ice motion algorithm to increase the speed of obtaining ice information from several person-days to person-hours. The launches of ERS-1, JERS-1 and RADARSAT, planned for the early to mid 1990's, increased the urgency to create ice motion algorithms. Filey et al. (1987) worked on a technique called hierarchical correlation (see section 2.6) that has been the basis for the operational ice algorithms available at the Alaskan SAR Facility (Kwok et al., 1998) and the Canadian Ice Service (Noetix, 1997).

A majority of automated ice motion studies have been performed at global scales due to the historically low resolution of satellite sensors. Agnew and Le (1996) using SSM/I 85.5 GHZ, 12 km resolution, found displacement errors of 3.5 km in comparison to in-situ beacon data. Kwok et al. (1998) also using SSM/I found displacement errors of 5 km (85-GHz, 12 km resolution) and 12 km (37-GHz, 25 km resolution) in comparison to beacons. Heacock et al. (1993) utilizing NOAA AVHRR 1 km resolution optical data found errors of approximately 2.45 km. Sea ice tracking results using optical systems were also problematic due to large gaps in the imagery from cloud cover and polar darkness.

The launch of the ERS-1 (July 1991), ERS-2 (April 1995), and RADARSAT-1 (November 1995) satellite SAR systems provided operational ice application users with consistent repeat coverage during polar darkness and through most atmospheric conditions. The increased spatial resolutions offered by these SAR sensors also meant that smaller scale regions could now be monitored and meso-scale Arctic phenomena such as polynyas could now be studied.

Presently, ERS-2 (C-VV) provides data in a sun-synchronous orbit with at 100 metre swath and 25 m pixel spacing. The Canadian Ice Service uses RADARSAT-1 as its operational satellite. The C-HH polarizations are preferable in ice applications and the polar orbit of RADARSAT-1 provides a daily revisit period over Canadian regions north of 60° N, allowing for frequent temporal sequences capable of capturing diurnal ice motion. RADARSAT-1 provides many different beam modes, each with different spatial coverages, resolutions, and incidence angles. ScanSAR Wide and Narrow (SCW, SCN) are the beam modes of choice at the CIS, with 25 and 50 m pixel spacing and 300-500 km swath width respectively (Table 2.1), allowing ice motion to be monitored at regional scales with moderate resolution suitable for polynya-scale observations.

Table 2.1 RADARSAT-1 ScanSAR Satellite Beam Specifications

Beam Mode	Incidence Angle (Degrees)	Nominal Resolution (m)	Pixel Spacing (m)	Nominal Swath Range from Nadir (km ²)
ScanSAR Narrow A	20 - 46	50	25	0 - 300
ScanSAR Narrow B	31 - 46	50	25	145 - 440
ScanSAR Wide A	20 - 49	100	50	0 - 500
ScanSAR Wide B	20 - 46	100	50	0 - 450

(Adapted from RADARSAT International, 1995)

With the CIS receiving over 4000 RADARSAT-1 images annually, an operational ice tracking algorithm was implemented to aid ice forecasters in analyzing this large amount of data.

2.6 The CIS Automated Ice Tracking Algorithm

The CIS ice tracking algorithm (Tracker) was designed by Noetix Research Inc. of Ottawa and jointly funded by the CIS and the Canada Centre for Remote Sensing (CCRS), Natural Resources Canada. Tracker calculates ice displacements from spatially overlapping, time sequential RADARSAT-1 image pairs. The basic strategy is to calculate cornerity coefficients to map the crude ice motion first from highly averaged images, and to then improve these displacements with images at higher resolutions (Filey et al., 1987) (Fig. 2.13). The algorithm uses an image correlation point matching technique to find points on ice floes common in the two images, and then calculates the magnitude and direction of their movement (Heacock et al., 1993). Ice tracking vectors (ITV) are overlaid on the RADARSAT-1 pairs, describing the ice motion field (Fig. 1.1). The geographical coordinates of the ITV may also be exported in an ASCII format for statistical analysis, or as input into ice models. Case studies of the Tracker accuracy in RADARSAT-1 images conducted by Noetix (1998) found displacement errors averaging less than 1 km in CIS operational areas.

2.6.1 How the Tracker Algorithm Works

Fig. 2.13 Data flow of Hierarchical Correlation

Phase One. Two RADARSAT-1 images are geocoded to a map projection. Using a low pass 3x3 mean filter and then sub-sampling every other pixel the images are re-sampled in order to reduce processing times. The resolution of the imagery using SCW data would now be 1000m.

Phase Two. The objective of phase two is to identify pixels on the edges of floes that will be easily identified in other images. Each pixel is assigned a 'cornerity' value (Eq. 2.1) calculated using its immediate neighbour values in a 3x3 grid, in four different directions

(Fig. 2.14). Cornerity values that are high in multiple directions will account for changes in the viewing direction of the SAR and for the rotation of ice floes.

Fig. 2.14 Directions for Calculating Cornerity Values

Cornerity is calculated using Equation 2.1

$$\text{Cornerity Function: } |(A-B)| + |(B-C)| \quad (2.1)$$

(Noetix: 1993).

Each neighbouring pixel on either side of the central pixel is subtracted from the central pixel and the absolute values of the results are then added together. This is then repeated for all four directions (Fig. 2.14).

Fig. 2.15 Calculating Cornerity Values

In Fig. 2.15 (a), the calculated cornerity values in each grid are quite high in several directions. Fig. 2.15 (b) shows an example of a uni-directional grid with one large digital number (DN's) value in the bottom left hand corner. The lowest cornerity value from all four directions is selected to represent the worst case cornerity of the pixel. The lowest cornerity values are chosen because if the largest cornerity values were selected, the data set could be biased with uni-directional cell values.

The image is then divided into 30x30 pixel subsections. Then the highest cornerity value (based on the low 3x3 grid cornerity values) is selected from each sub-section, forcing an even distribution of initial matches over the entire images. By selecting the highest cornerity value in each subsection the algorithm is selecting the best omni-directional candidates for finding Tracker matches.

The cornerity values on the first image (the reference) are compared to those on the second image (the match image) within similar geographic areas to determine which pixels have the most similar cornerity. The geographic areas are based on a search radius from the location of the cornerity value on the reference image. This search radius is a user definable parameter that can be set based on known maximum ice drift in the region. For example the search radius is set to 20 km/day for tracking ice in the Gulf of St. Lawrence and 50 km/day for the NOW region.

Area correlations are used to verify these cornerity matches by comparing their respective image digital numbers through image correlation. The correlations are based on a 9 x 9 window, centred around the high cornerity values on both images. If the correlation values are greater than 0.7, the pixels are accepted as a match. Vectors are then drawn from the x, y location of the pixel on the reference image to the x, y location of the pixel on the match image.

Phase Three. Vectors from phase two are used to help guide more matching at the pixel level. Cornerity values are calculated at the pixel level but are first compared to the direction and displacement of the vectors from Phase 2. This process uses *guided area correlation* (Filey et al., 1987). In (Fig. 2.16) pixel C_1 is compared to vectors A and B that were found within the predefined search radius. The displacement of A was +5 pixels in y and 0 pixels in x, and the displacement of B was + 4 pixels in y and + 4 in x. Pixel correlation values are calculated from point C_1 on the reference image to C_2 on the match image (+5 pixels in y and 0 in x), the same displacement as

vector A. It also calculates correlation values from point C_1 on the reference to C_3 on the match (+4 pixels in y and +4 in x) the same displacement as vector B. The best correlation value over 0.7 is accepted for point C and a vector is created, based on a predetermined assumption that there is consistency in the motion of the neighbouring locations.

Fig. 2.16 Guided Area Correlation

Phase 3 finishes with an error correction procedure that ensures that the matches are consistent with the vectors in their neighborhood. If a vector does not move roughly parallel to the surrounding vectors, it is removed.

Phase Four. Phase 3 processing is repeated but with correlation coefficients relaxed to 0.5, allowing a greater number of matches to be identified.

Phase Five. The vectors are scaled back to the original resolution of the RADARSAT-1 images, and overlaid on top of the imagery

This chapter outlined the principal concepts of sea ice development and motion, Arctic polynyas, radar concepts in regards to sea ice applications and ice tracking ice motion in satellite imagery. These concepts have been introduced as a prerequisite for Chapter Three, which describes in detail the North Water polynya and the questions and problems that arose in previous research that have resulted in the objectives for this thesis.

NORTH WATER SITE DESCRIPTION & BACKGROUND

The largest re-occurring Canadian Arctic polynya is the North Water (NOW) Polynya. At its maximum extent it is double the size of Lake Superior (Aber and Vowinkel, 1972). The NOW Polynya is located in Baffin Bay between the east coast of Ellesmere Island and the west coast of Greenland (74° - 79° N and 70° - 78° W) (Fig. 3.1).

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The NOW region is characterized by higher air temperatures and precipitation than in other areas of the Arctic. Temperature differences can be 10-15 °C higher in the NOW region than in other parts of the Arctic Archipelago (Müller et al., 1975). Reasons for higher temperatures and precipitation in this region are many. First, low pressure systems dominate the Baffin Bay area in March and April as the open water of the polynya increases (Barry et al., 1975), resulting in a high frequency of spring storm systems. A majority of these storms track north from Labrador and Davis Strait bringing warmer maritime air masses into the Baffin Bay regions (Hanesiak and Cummine, 1997). As the open water of the polynya expands, this allows sensible heat from the oceans to escape, warming the surrounding atmosphere. The presence of cloud cover means that oceanic sensible is absorbed and re-radiated back towards the ocean surface. During cloud free periods, higher temperatures can also be related to the substantial heat gain caused by the lower albedo of the open water, thereby allowing more solar radiation to be absorbed by the surface waters of Baffin Bay (Müller et al., 1975). Warmer maritime air also has the ability to retain more atmospheric vapour than dry polar continental air masses. With the large expanses of open water and the presence of maritime air masses, average precipitation in the area is about 30% greater than in surrounding regions (Hanesiak and Cummine, 1997).

Ocean circulation in the NOW region is dominated by the Baffin Bay counter-clockwise circulation (Fig. 3.2). This comprises a warm current moving north along the coast of Greenland meeting a cold current moving south from the Arctic Basin along the coast of

Baffin Island. The ocean currents for the Baffin Bay region have still not been adequately mapped and the maps available are based on interpolated and estimated data. Oceanographers working in the region do not feel that these maps truly represent the ocean currents in the NOW region, but they are all that are currently available (Barber, Pers. Comm, 2000).

Fig 3.2 Surface Currents of the Eastern Arctic
(Canadian Hydrographic Service, 1994)

3.2.1 NOW Polynya Extents & Seasons

The open water of the NOW Polynya was well known to Inuit hunters from Thule and the Danish that settled in Greenland. The North Water was first recorded by William Baffin during his voyages in 1616 and was used extensively in the 18th

century by whalers who followed the ice break-up along the western Greenland coast near the end of July. Its physical extents and duration of open water were not fully established or documented until the late 1960s.

Dunbar (1969) was one of the first to examine the phenomena of the NOW Polynya. Its location was confirmed using air reconnaissance data (1950-1962) and weather satellite data (1966-68). It was hypothesized that ice exported from the Arctic Ocean became congested in the narrow channel of Kane Basin, creating a barrier at the head of Smith Sound (called an ice bridge) initiating polynya formation. Dunbar established the existence of this fast ice bridge in northern Smith Sound and its formation was estimated to be some time in October, but satellite data were lacking during the dark months of October to February so this could not be confirmed. Break up of the ice bridge was observed between July and August and initial estimates of the southern polynya extents were also established (Fig 3.3).

Dunbar (1973) used airborne Radar Scope Photography to monitor polynya conditions during the winters of 1970-71 and 1971-72. The existence of the ice bridge and the presence of the polynya during winter months were observed.

Muench, (1975) collected weather satellite imagery from the spring of 1969 and 1970, and oceanic cruise data from the summers of 1968, 1969 and 1970 to map the surface area of the NOW Polynya. This study agreed with Dunbar's findings on freeze up and break up periods, as well as the southern extents of the polynya.

Smith and Rigby (1981) mapped the location and sea ice conditions of Canadian Arctic Polynyas using NOAA AVHRR 4 and 5 visible and infrared satellite imagery. Data were gathered from January 1975 until December 1979 on a bi-weekly basis. The NOAA 2000 km swath width and 1 km pixel spacing meant that only coarse-scale characteristics of the polynyas were visible, but coverage was available during the winter periods using the infrared channels. Typical times of freeze up, polynya sizes, basic ice types and the break up patterns were established over a 5 year period.

Steffan and Maslanik (1988) used the LANDSAT visual analysis of ice types provided by Ito and Muller (1981) to validate automated ice concentrations derived from the Nimbus-7 scanning multichannel microwave radiometer (SSMR) data. The VV and HH 18 GHz and 37 GHz frequencies had a 60 x 60 km and 30 x 30 pixel spacing, respectively. The hemispheric coverage and year round availability of the SSMR passive microwave system, provided a better alternative to mapping the NOW polynya than with optical and infrared data. Periods of pre-melt (March 2-April 12), onset of melt (May 5-May 17), and melt (June 8) were identified based on changes in the brightness of the SSMR data along with corresponding gridded air temperature data.

Based on the above research, a summary of polynya extents follows. Smith and Rigby (1981) found that congestion in Kane Basin can occur as early as October, but the resulting ice bridges usually lasted for only a few days. The stable ice bridge that induces polynya formation generally occurs late in the winter near the end of March or in early April, but has been known to form as early as January. During the same time frame, ice bridges form in Devon and Lancaster Sounds, preventing ice from the Queen Elizabeth Islands from entering Baffin Bay, thus allowing the polynya to expand southwards. Even without the import of ice into the NOW region, why cold winter conditions do not encourage the growth of ice 1-2 metres thick is still not fully understood.

The presence of the Smith Sound ice bridge means that the northern bounds of the polynya are fairly constant but the southern extent varies from year to year (Smith and Rigby, 1981). The NOW Polynya expands greatest along the western coast of Baffin Bay down to Lancaster Sound in mid-June (Fig. 3.3). At its height in late June, early July, the NOW Polynya covers an area of about 80,000 km² (Müller et al., 1977).

By late July or early August, the polynya collapses when the ice bridge breaks. Ice from the Arctic Ocean and Kane Basin drains through Smith Sound into Baffin Bay. The large open water expanse created by the polynya continues to absorb large amounts of solar radiation, contributing to continued melt into the summer season (late August – mid October), (Smith and Rigby, 1981).

Fig. 3.3 Southern Extents of the NOW Polynya
(Adapted from, Dunbar, 1969)

Freeze-up begins in mid-September as waters in Kane Basin freeze to the shore on the eastern and western sides, creating land fast ice. A central corridor remains where mobile ice from the Arctic basin exits through Smith Sound, until the formation of the ice bridge occurs again in late winter.

3.2.2 Previous Studies in Oceanic (Sensible) Heat

The upwelling of warm oceanic water (see section 2.3.1 on sensible heat theory) is another theory behind why the NOW polynya does not encourage the growth of sea ice.

Muller et al., (1975) measured ice and water surface temperature using an airborne radiation thermometer and a Super 8 movie camera to capture sea ice types. Three flights in March 30/31, April 22 and June 8 were conducted and compared with meteorological data. During the North Water project (1972-1981) meteorological data was collected at Cobourg Island, Carey Island and Cape Hershel, known as the NOW research stations. It was found that there was a warming trend from south to north in the North Water area, becoming more pronounced throughout the season until disappearing with full melt in June. Areas of warmer surface temperatures persisted around Carey Island.

Steffan (1986) and Steffan and Lewis (1988) conducted low level aircraft flights from November to March, 1978-1979 and 1980-1981, gathering ice surface radiant temperatures. Based on studies by Maykut (1978) who found that surface radiant temperatures could be related to the thickness of first year ice types, Steffan and Lewis used the thermal data to map ice types and surface temperatures. Visual characteristics were also recorded during these flights on 16 mm film illuminated by search lights. It was found that the temperatures increased from west to east in the range of 10 to 15 °C. The largest temperature anomaly was found around Cape

Alexander, on the western side of Greenland, where the temperatures were 20 °C warmer than the surrounding pack ice. It was speculated that these results were due to winds off the Greenland ice cap, moving ice and surface water away from the coast, allowing the upwelling of warmer water.

3.2.3 Previous Studies in Ice Motion (Latent Heat)

The presence of winds and/or ocean currents may continually remove ice out of the region as it forms, maintaining the open water of the polynya, (see section 2.3.2, latent heat theories).

Aber and Vowinkel (1972) used weather satellite images from March – September 1969, 1970 to monitor ice motion in the NOW polynya. Distinguishable ice features were manually mapped and the ice was found to move towards the north and west along the eastern side of the polynya, and to the south along the western side of the polynya in accordance with the mapped ocean currents (Fig. 3.2).

Table 3.1 Aber and Vowinkel (1972) Results

Month	1969		1970	
	No. of Cases	Mean Speed km/day	No. of Cases	Mean Speed km/day
April	10	8.2	6	9.1
May	4	5.5	7	9.9
June	5	21.5	4	12.4
Average		11.8		10.5

The evaluation required clear sky conditions resulting in an over-representation of high-pressure systems with low wind speed situations. This in combination with the limited number of data sets resulted in ocean currents dominating the ice motion.

Dunbar (1973) during the winters of 1970-71 and 1971-72 visually estimated ice drift to be 6 km per day between January and July through Nares Strait.

Muench, (1975) collected weather satellite imagery from the spring of 1969 and 1970, and oceanic cruise data from the summers of 1968, 1969 and 1970, to map the surface area of the NOW Polynya. Muench noted some interesting visual observations in the data:

- winds and/or ocean currents swept ice southwards out of the polynya as it formed.
- the westward expansion of open water into Jones and Lancaster sounds may be due to the transport of ice by water currents.
- the eastward expansion was theorized to occur due to westerly winds that developed during the spring of 1969 and 1970.

No ocean current measurements were taken to validate Muench's observations but it was anticipated that short term variations in ice motion would show some correlation with wind data. Geostrophic wind speeds and directions were compared to those at Thule Greenland finding correlations $R = 0.4$ for 1969 and negligible for 1970. Poor correlations were again probably due to an over-estimation of anti-cyclonic activity

using weather data with low winds speeds resulting in the ice motion being dominated by the ocean currents.

Comparisons were then made between surface area and air temperature, dew point and cloud cover observed at Thule. Expectations were to find correlations of high temperatures and low cloud cover with an increase in the surface area of the polynya and the melting of ice. However, again poor correlations resulted. It was concluded that data from the weather station at Thule do not represent the meteorological conditions of the entire polynya.

Ito and Müller (1977) established that the fast ice edge did not move, preventing the influx of ice into the polynya. Measurements were made with field markers in Kane Basin during the springs of 1974 and 1975 and in Jones Sound during the spring of 1976. They also speculated that the ice bridge appears to break in the spring due to the force of storms moving north from Labrador and Davis Strait.

Dunbar (1979) used SLAR from three flights between 19 – 26 October 1976 to manually track autumn ice drift. Dunbar noted that:

- day-to-day variations in wind appeared to be the controlling factors in ice drift, especially with the high coasts of Nares Strait having a funneling effect.
- In the Kane Basin region, dominant westerly winds may have increased velocities, enhanced as they blow down the Humboldt Glacier (Katabatic winds) and across the basin.

- Ocean currents appeared to play a large role in the ice drift by greatly enhancing the effect of a northerly wind and reducing that of a southerly.
- Remarkable ice drift distances were achieved with a maximum distance of 402 km in one week and speeds of up to 0.83 m/s. The greatest speeds were found in Kennedy Channel and the lowest speeds were found in Kane Basin. This is expected as ice begins to refreeze to the shores (fast ice) in Kane Basin during the Fall period.

Table 3.2 Dunbar (1979) Results

Area	Max Velocity (m/s)	Typical Velocity (m/s)
Robeson Channel	0.39	0.24
Kennedy Channel	0.76	0.51
Kane Basin N	0.83	0.59
Kane Basin S	0.32	0.22
Smith Sound E	0.50	0.42
Smith Sound W	0.41	0.26

Dunbar's observations were made on a limited data set of ice motion, 3 ice drifts in a one week period during the fall. The small data set combined with inexact wind data and inadequate knowledge of ocean currents made it difficult to draw any firm conclusions.

Dey (1980) used NOAA Thermal infrared imagery to monitor the North Water during the dark polar winters of 1974-75, 1975-76, and 1976-77. Dey found it difficult to distinguish between large single floes and compact fields made up of a number of smaller floes. The average displacement rates for the three winter seasons were 3 km/day - 21 km/day, averaging around 12 km/day. The dominant motion was southward.

Ito and Muller (1982) observed the movement of pack ice in Smith Sound using LANDSAT bands 6 and 7, from March to September 1973-1981. Directions and magnitudes were determined by visually tracking floes in the 80m resolution imagery. Ice motion was compared with winds collected at the NOW research stations. Results indicated that short term sea ice motion was under the direct influence of local winds but this could not be inferred for the entire polynya. Mean ice velocities of 4 km/day and at a direction of 183° were estimated between March and September. Ice export was calculated to be at rates of 600 km^2 per day in the NOW region.

To summarize, the previous studies of ice motion in the NOW region found that the ice bridge was indeed fast and that the overall dominant motion was south, but whether the dominant southward motion is a result of winds and/or ocean currents is still not known.

3.2 Statement of Problem

It has been theorized that the sensible and latent heat processes do not occur in isolation but in some cases work together to maintain open water in the NOW polynya. Smith et al. (1990) speculated that 20 % of the NOW polynya is maintained through latent heat and 80% is due to sensible heat. Previous research on the NOW polynya has not been able to validate this.

Prior studies in ice motion could only focus on certain seasons due to fieldwork and aircraft expenses. Large gaps in the data sets were due to cloud cover in optical data, and past remote sensing data were at scales too large to capture the polynya-scale ice motion and visual tracking techniques meant that most data sets were not geo-rectified. Because of this, previous studies lacked the accuracy, scale and consistency needed to monitor the polynya through different seasons. Monitoring ice motion in the NOW polynya using the validated RADARSAT-1 ice tracking technique (Tracker) will provide for the first time a full year of coverage over the NOW polynya at a scale capable of capturing polynya dynamics. Latent heat mechanisms are directly related to the export of ice, and thus regions of sustained directional ice movement would be of interest as areas where latent heating mechanisms predominate. In the case of sensible heating the relationship with ice motion is more circumspect. Relatively small ice velocities and perhaps the presence of divergent or moderately convergent ice fields would characterize areas prone to sensible heating. The ice motion fields could also be helpful in understanding polynya dynamics through the identification of spatial regions and seasonal variability of export, import and redistribution within of ice within the polynya.

Previous research could not provide any conclusive answers as to how ice motion was influenced by winds, ocean currents, or a combination of the two. These previous studies were limited to wind data collected at distant weather stations in Thule and Alert or at the micro-scale of the NOW research stations, neither of which can be extended over the entire polynya. Even today, the tides and ocean currents in the region still have not been adequately mapped. The meteorological data collected during the International North Water polynya project are the best to-date (see description in section 5.2) and in combination with the RADARSAT-1 derived ice motion may provide the best indicators of the influence of wind on ice motion in the NOW polynya.

CHAPTER 4

AUTOMATED ICE TRACKING VALIDATION

4.1 Introduction

The first objective of this research is to assess the potential and limitations of the Canadian Ice Service Tracker algorithm. In this chapter, section 4.2 outlines the methods and data collection involved in the Tracker validation and section 4.3 describes the Tracker displacement and directional validation results. Section 4.4 compares the NOW validation results with previous studies and section 4.5 provides a summary and conclusion.

4.2 Methods

The International North Water Polynya Study was an inter-disciplinary field experiment that occurred on board the Canadian Coast Guard (CCG) Ice Breaker, the Pierre Radisson. A large group of ice scientists and graduate students from Canada participated in the field study during the summer of 1998. Being invited to participate in this cruise provided an excellent opportunity to study the ice dynamics of the polynya using Tracker. It also allowed for in-situ field validations of the Tracker algorithm by comparing ship deployed ice beacons drifts with the Tracker results.

4.2.1 Initial Tracker Testing

In preparation for the 1998 field campaign, RADARSAT-1 images of the NOW polynya were collected using the daily data received at CIS (Appendix A). Nine Tracker pairs from April until June 1997 were processed to determine:

- If Tracker could track the dynamic ice conditions of the NOW polynya in its seasonal state.
- The “best” time interval between RADARSAT-1 images to successfully track ice motion in the NOW polynya.
- The temporal frequency of the RADARSAT-1 imagery required for ice tracking during the 1998 polynya season.

The initial Tracker results were very successful in capturing ice motion in the NOW region. The Tracker ice drift parameter (section 2.4.1) was increased to 40 km (from 20 km based on Gulf of St. Lawrence ice motion) to capture the larger ice dynamics in the NOW region. Initial visual results found that prior to the formation of the polynya, the best tracking results between image pairs were estimated to be obtained using an interval of 3-4 days. During, and after the formation of the polynya, best results were attained with intervals of 12 - 36 hours, as ice motion became more dynamic.

4.2.2 Data Collection

RADARSAT-1 SCW data over the NOW region were collected from January 1998 until December 1998. Scenes were collected on a bi-weekly basis from January until February 1998, and then increased to provide tracking pairs 2 to 3 times a week until the break up of the Ice Bridge around June 20, 1998. Data collection then resumed on a bi-weekly basis until the end of the year. Three quarters of the data were used to support the Canadian Coast Guard in their summer Arctic operations. Approximately 170 RADARSAT-1 images were collected from which 148 Tracker pairs were produced (Appendix B).

Ice Beacon data for the NOW study were shared by several researchers and generously donated by the following:

- Bedford Institute of Oceanography – 5 beacons
- University of British Columbia – 3 beacons
- National Ice Center, Washington – 2 beacons
- Canadian Ice Service – 2 beacons

Nine out of the 11 ice beacons survived aircraft, helicopter and ship deployment in the NOW region between April and June 1998. In December 1998 the CIS deployed another beacon in the region as part of their ice-monitoring program (Fig. 4.1). This provided 10 working beacons for which the hourly positions were downloaded each day at CIS and archived for the validation of Tracker. Table 4.11 lists the ice beacon deployment schedule and their lifetimes.

Fig. 4.1 Beacon deployment locations around the North Water Region

Table 4.1 NOW Beacon Deployment

	Beacon #	Start Date	End Date	Days	Comments
CIS	47551	April 12	April 12	0	air deployed in early March from ice camp and failed
NIC	48573	June 2	June 10	8	Deployed from ice camp
	48575	June 7	June 11	4	Deployed from ice camp
BIO	47543	May 11	June 12	32	Heli-deployment on the ice bridge
	47548	April 27	Aug 31	126	Ship deployed, center of the polynya
	47550	May 2	Aug 31	121	Ship deployed, center of the polynya
	47554	May 11	May 11	0	Heli-deployment on the ice bridge
	47559	June 9	July 15	36	Heli-deployment near the ice bridge
Mc Gill	47553	June 9	June 11	2	Ship deployed
	47552	June 20	June 23	3	Deployed on the Greenland side
	47555	June 20	June 27	7	Deployed on the Greenland side
MLI	47557A	April 14	May 9	26	Picked up May 9 th
	47557B	May 28	July 21	54	re-deployed
CIS	47556	Nov 3	Jan 9/99	67	air deployed

4.2.3 Ice Motion Data Manipulation

To quantitatively compare Tracker and beacon ice motion directions and magnitudes, the latitude and longitude displacements were converted into magnitude (kilometers) and direction (bearing from North) using the following equations.

Tracker and beacon distances were calculated from latitude and longitude coordinates using the great circle equations 4.1- 4.3 (Patterson, 1994).

$$\text{Speed} = \text{Distance} / \text{Time} \quad (4.1)$$

$$\text{Distance} = 2\pi r\alpha/360 \quad (4.2)$$

Where r = radius of the earth (6370 km) and α = the great circle route as defined by equation 4.3

$$\cos\alpha = \sin\phi_A \sin\phi_B + \cos\phi_A \cos\phi_B \cos\Delta\lambda \quad (4.3)$$

Where ϕ = latitude, A = start position,
B = stop position, $\Delta\lambda$ = difference in longitude

Beacon and ice motion vector angles were then calculated using the latitude and longitude coordinates of equation 4.4 (Robinson et al. 1995).

$$\tan\alpha = \cos\phi_A \tan\phi_B \cdot \arcsin\Delta\lambda - \sin\phi_A \cdot \arctan\Delta\lambda \quad (4.4)$$

Equation 4.4 provides angles based on +/- 0 to 90 degrees. To convert this to a bearing from North, the Tracker and beacon angles were changed to 0 - 360 degrees by comparing the angle with its x,y positions and determining in which quadrant they belonged:

- +, + = Quadrant 1, no change
- +, - = Quadrant 2, 180 degrees + angle (negative)
- , - = Quadrant 3, 180 degrees + angle (positive)
- , + = Quadrant 4, 360 degrees + angle (negative)

Traditional methods for calculating averages cannot be used when dealing with vectors. The angle and length of each vector must be considered and therefore the vector addition techniques of equation 4.7 and 4.8 were used. All vectors were first converted to their x and y components based on equations 4.5 and 4.6.

$$\text{x component} = V_m \cdot \cos V\theta \quad (4.5)$$

$$\text{y component} = V_m \cdot \sin V\theta \quad (4.6)$$

Where V_m = Vector magnitude and $V\theta$ = Vector angle.

$$\text{Average Magnitude} = \text{SQRT} ((\sum x/N)^2 + (\sum y/N)^2) \quad (4.7)$$

$$\text{Average Direction } \tan\theta = \sum y / \sum x \quad (4.8)$$

(Campbell Scientific Canada, 1994)

When calculating the average vector angle using the x and y components, the mathematical reference point (0°) is from the x-axis (East). Angles were again provided as +/- 90 degrees. The Tracker and beacon directions were converted to 0-360° by determining in which mathematical quadrant they belonged and the reference angle (East) was adjusted to North based on the following logic:

+, + = Quadrant 1, 90 degrees - averaged direction angle
 +, - = Quadrant 2, 90 degrees + averaged direction angle
 -, - = Quadrant 3, 90 degrees - averaged direction angle + 180 degrees
 -, + = Quadrant 4, 270 degrees - averaged direction angle

Standard deviations for vectors must also be calculated differently by using equations 4.9 and 4.10.

$$\text{Standard Deviation for Vectors} = \arcsin(\alpha)[1 + 0.157\alpha^3] \quad (4.9)$$

$$\text{Where, } \alpha = \text{SQRT} [1 - (\cos V\theta)^2 + (\sin V\theta)^2] \quad (4.10)$$

(Campbell Scientific Canada, 1994)

4.2.4 Positional Accuracy of Reference Ice Beacons

The beacon data were downloaded via the GTS (Global Telecommunication System) satellite. These real-time data are delivered as single positional fixes with respect to the ARGOS satellites with relative positional accuracies of 150 to 1000 metres (Service ARGOS, 1996). Prior to the Tracker validation, the single positional beacon accuracy was re-evaluated by averaging 325 hourly positions

for a single beacon deployed in the Kane Basin ice bridge prior to break up in June (May 11 to May 28, 1998. Since the beacon deployed on the ice bridge was stationary, it allowed the single position beacon to be examined to determine the potential absolute error. Geographic coordinates received from the ice bridge should have shown that there was no ice movement, but average errors on the order of 315 metres with a standard deviation of 210.6 metres were found (Table 4.2).

Table 4.2. Beacon #47543 Displacement (metres) on the Smith Sound Ice Bridge

Date	# of samples	Daily Displacement (m)				
		Mean	Median	Min.	Max.	Std. Dev.
11-May	2	338.29	338.29	274.63	401.95	90.03
12-May	13	254.52	230.21	0.00	857.13	270.17
13-May	22	351.57	255.51	0.00	987.66	273.19
14-May	18	358.69	402.15	20.93	602.94	169.12
15-May	14	301.30	246.62	62.79	668.38	190.49
16-May	15	286.11	218.72	62.79	831.56	204.41
17-May	20	313.00	296.10	104.65	1029.03	205.86
18-May	22	381.96	284.31	62.79	817.75	250.55
19-May	20	265.83	221.05	20.93	626.75	149.28
20-May	23	330.66	266.28	62.79	1100.96	251.73
21-May	15	223.53	231.05	118.79	351.39	68.25
22-May	23	286.39	200.99	20.93	1211.47	280.21
23-May	18	270.06	258.93	83.73	549.37	120.50
24-May	18	365.27	401.98	20.92	855.69	223.87
25-May	15	373.72	401.98	20.92	855.69	212.95
26-May	21	349.29	351.39	0.09	766.06	214.85
27-May	19	291.22	293.98	20.93	574.86	142.40
28-May	19	351.94	274.67	118.80	805.89	219.60
Results for Entire Sample	317	314.9	251.2	0	1211.5	210.6

In addition to this analysis, three of the ten ice beacons were reprocessed by ARGOS for improved accuracies. Using the multiple fixes from several ARGOS satellites and from a specific reference point on the earth (called relative or differential positioning) provides improved relative accuracies in the following classes; 1 = <1000 metres, 2 = < 350 metres and 3 = < 150 metres (Service ARGOS, 1996). Three single position beacons were compared to three reprocessed beacons for the same dates and times, to determine what percentage of the single fix beacon data fell within the improved accuracies of the multiple fix beacon classes. For the single fix data, 67% fell into ARGOS Class 3 (<150 m), 18.5% into Class 2 (151 - 350 m) and 14.5% into Class 1 (351 - 1000 m) (Table 4.3). By combining Class 2 and 3, 85.5% of the original data had positional errors of less than 350 metres. Since the single fix stationary beacon on the ice bridge averaged 315 metres and 85.5% of the single fix beacon data fell into the multiple fix accuracy of 0 - 350 metres, it was assumed that the single fix beacon data had an 85.5% probability of having an accuracy of better than 350 metres. With this level of beacon accuracy, when comparing the beacon to the Tracker vector, displacements were measured to the closest 100 metres.

Table 4.3. Percentage of Single Position Beacons for each Reprocessed Beacon Class

Beacon #	47555	47553	47552	Total %
Class 1 = <1000 m	10	11	23	14.5
Class 2 = < 350 m	35	11	10	18.5
Class 3 = < 150 m	55	78	68	67
# of samples	40	18	31	100

4.2.5 Validation of Tracker Ice Motion

In validating Tracker motion, the beacon data were used as a best reference to represent true ice motion. Beacon latitude and longitude positions were imported into PCI EASI/PACE and overlaid as vectors on top of the SCW Tracker imagery pairs, (Fig. 1.1).

Ice conditions are very dynamic and are not considered homogenous surfaces. With only one beacon representing the ice regime for a specific area, the closest Tracker vector within the same ice regime (based on CIS ice charts) was visually selected (Fig. 4.2). Comparing the means of the closest Tracker vectors within a specified distance to the beacon vector was not done because distance does not always correspond to similar ice regimes.

There are Tracker pairs in which the beacon positions are not available within the overlapping area of the RADARSAT-1 pairs, and therefore these Tracker pairs could not be used. Beacons that were no longer drifting and had become lodged in landfast ice were also removed from this analysis. Beacon positions within +/- 2 hours of the RADARSAT-1 acquisition times were selected and this provided 40 Tracker pairs in which 54 beacon positions were available for validation. Tracker and beacon vectors were imported into an Excel spreadsheet (Appendix C) where magnitudes and bearings were calculated using equations 4.1 – 4.10.

Linear regressions were performed, and the 95 per cent confidence intervals computed to examine the relationship between the ice Tracker vectors (ITV's) and ice beacon vectors (IBV's) magnitude and bearing.

Fig. 4.2 Example of Visual Selection Techniques.
(The thick white arrow represents the beacon vector
in comparison to the Tracker vectors)

A problem arose when comparing circular numbers such as bearings. For example, an ITV with a bearing of 355° compared to an IBV with a bearing of 5° will show a scalar difference of 350° when it actually has a circular difference of 10° . In order to perform linear regressions on bearings, the ITV bearings were recalculated from circular to comparable scalar units based on the following steps (see also Table 4.4).

1. $ITV - IBV = \Delta$
2. If Δ is ≥ -180 and ≤ 180 , then ITV remains unchanged
3. If Δ is ≥ 180 , then adjust by subtracting 360 from ITV
4. If Δ is ≤ -180 , then adjust by adding 360 to ITV

(Vachon: Pers. Comm., 2000)

Table 4.4 Example of Converting Circular to Scalar Numbers for the Statistical Analysis of Bearing

A	B	C	D	E	F	G
ITV	IBV	Δ	Changes to ITV	New ITV	IBV	New Δ
175	190	-15	no change	175	190	-15
355	5	350	-360	-5	5	-10
5	355	-350	+360	365	355	10

The new ITVs were then regressed against the IBVs to determine their relationship (example, Appendix C). Ice Tracker magnitude and bearing errors were then compared with RADARSAT-1 image separation times to determine if there was a relationship between Tracker errors and image intervals. In addition, an analysis of Tracker error by month was conducted to determine if ice conditions affected vector accuracy.

4.2.6 Determining an RMS Tracking Error

The overall RMS Tracker error in km was calculated using (4.11). It calculates a displacement error based on the distance between two vectors (Fig. 4.3), using the cosine rule.

$$\text{TE (metres)} = \sqrt{[A^2 + B^2 - 2AB \cos(p1 - p2)]} \quad (4.11)$$

Where,

A = mean beacon magnitude

B = mean Tracker magnitude

p1 = mean beacon bearing

p2 = mean Tracker bearing

(Heacock et al., 1993).

Fig. 4.3 Illustration of Error Calculated between two vectors

Georeferencing errors in the RADARSAT data are inherent in the RMS Tracking errors. Mean georeferencing errors in the RADARSAT-1 imagery were calculated by comparing known coastal positions in eight RADARSAT-1 image pairs (Table 4.5).

Table 4.5 RADARSAT-1 Georeferencing Errors

Tracking Pairs	Georeferencing Coastline Errors in metres (pixels)
May 14_14	45.6 (0.9)
May 18_21	233.3 (4.7)
May 21_21	302.5 (6.1)
May 21_24	253.6 (5.1)
May24_24	316.4 (6.3)
May24_26	316.5 (6.3)
May26_27	136.7 (2.7)
May27_28	194.5 (3.9)
Mean	224.9 (4.5)
Std	96.0 (1.9)

It was assumed that the average georeferencing error of 225 m with a standard deviation of 96 m was representative of the RADARSAT-1 images used in this study.

4.3 Results and Discussion

4.3.1 Validation of Tracker Ice Motion

Magnitude

A comparison of Tracker and beacon distances found magnitudes of 15.5 km and 16.6 km respectively (Table 4.6). Both the Tracker and the beacons have similar standard deviations of 12.5 and 13.8 km respectively, indicating the wide range of ice motion found in the polynya during the validation period.

The Tracker data values are plotted as discrete intervals (± 1 standard deviation) in the frequency distribution of Figure 4.4. The values are skewed to the right in this frequency distribution. This graph could be biased since there are no negative distances but it may represent the large magnitudes that can be achieved in the polynya. The magnitudes in the Tracker data are concentrated at and above the mean, or between 15.5 and 28 km. The data in the ice beacon frequency distribution, (Fig. 4.5) has a larger positive skew towards higher distance values between 16.6 and 30.4 km. The regression equation $y = 1.06x + 0.1$ indicates that ice motion magnitudes are slightly underestimated by Tracker in comparison to the beacons.

Table 4.6 Tracker vs. Beacon Magnitude Results (km)

	ITV	IBV	Delta	R	R ²	Std Error	P-value	Count
Mean	15.5	16.6	1.1	0.96	0.93	3.6	0.91	54
Std	12.5	13.8	1.3					
Min	0.3	0.3	0					
Max	56.2	61.9	5.7

Fig. 4.4 Tracker Magnitudes (km) Frequency Distribution

Fig. 4.5 Beacon Magnitudes (km) Frequency Distribution

Regression of Tracker and beacon displacements produced a strongly significant relationship $R^2 = 0.93$, with a Standard Error (SE) = 3.6 km (Fig. 4.6). These are considered good results since much of the difference in magnitude could be due to the inherent beacon errors (85.5% probability of up to 350 metres), the RADARSAT georeferencing error of 225 metres and the inability of the algorithms to capture displacements smaller than the 100 metre

Fig. 4.6 Regression of Tracker versus Beacon Ice Motion Magnitudes (km)

Fig. 4.7 Standardized Residual Plot of Magnitudes

resolution of the SCW data. Plotting out the standardized residuals (Fig. 4.7) can further ensure that the residuals are normally distributed (assumption of the statistical model). Equal variance is indicated by the spread of values about the x-axis (between ± 2) and if the mean of the standard residual is equal to zero (Kleinbaum and Kupper, 1978).

Bearing

Tracker and beacon bearings had similar means at 200.8° and 208.6° respectively (Table 4.7). Both the Tracker and the beacons again have large standard deviations of 101.4° and 94.1° , indicating the wide range of ice motion found in the polynya during the validation period.

The Tracker bearing values as plotted in the frequency distribution (Fig. 4.8) are slightly skewed to the right. This indicates that the directions of the Tracker data are concentrated around Southwest (200.8°) to Northwest (302.1°). The ice beacon bearings in the frequency distribution, (Fig. 4.9) have a similar positive skew. A majority of the beacon ice direction is concentrated between Southwest (208.6°) and Northwest (302.7°), but also towards the North (360°). The slope and intercept of the regression equation (Fig. 4.10) is $y = 0.86x + 30.02$ which indicates that the beacon ice motion direction is also underestimated by Tracker.

Table 4.7. Tracker vs. Beacon Bearing Validation Results

	ITV degrees	IBV Degrees	Delta	R	R ²	Std Error (degrees)	P-value	Count
Mean	200.8	208.6	7.8	0.89	0.79	38.8	0.017	54
Std	101.4	94.1	7.3					
Min	25.0	25.3	0.3					
Max	351.5	358.7	7.2

Fig. 4.8 Tracker Bearing Frequency Distribution

Fig. 4.9 Beacon Bearing Frequency Distribution

Regression of the two bearings produced a significant relationship, $R^2 = 0.89$, $SE = 38.8^\circ$, (Fig. 4.10). These are also considered good results with almost 90 percent of the ice direction captured by Tracker in comparison to the beacon data. The large outlier (Fig. 4.10) which is greater than 360 degrees is due to converting circular numbers to scalar (see table 4.4).

Fig.4.10 Regression of Tracker versus Beacon Ice Motion Direction (Degrees)

Fig. 4.11 Standardized Residual Plot of Bearings

The standardized residuals in Fig. 4.11 are plotted to examine the distribution of the bearing data. Equal variance about the x axis is not present and the mean standard residual is equal to 0.14 degrees. It appears that there are three outliers in this data set and so the data were re-examined. There was no reasonable explanation to remove these outliers and data transformation techniques would not correct for this. For this analysis it was felt that an error of 0.14 degrees was insignificant.

4.3.2 Tracker Validation Results: Temporal Factors

Magnitude

In comparing the Tracker magnitude error in respect to beacons, the overall average error was 2.8 km (Table 4.8). These errors were analyzed as a function of RADARSAT-1 image separation times. The error ranges

between 2.2 and 3.8 km with a tendency for larger error with great image separation times (Fig. 4.12).

Table 4.8. Monthly Averaged Magnitude Errors (km)

	< 12 hours	12-24 hours	24-36 hours	36-48 hours	48-60 hours	> 72 hours	Average	# of Samples
April				3.2			3.2	2
May	1.7	1.8	3.7	3.5	2.0	3.7	2.3	25
June	0.2	2.5	1.9		2.0	1.1	1.9	10
July	6.0	2.7			2.0	8.4	4.6	8
Nov	1.5	0.6		2.2	9.1		3.7	7
Dec		2.8				0.4	1.6	2
Average	2.4	2.2	2.6	3.2	3.8	3.5	2.8	
# of Samples	15	15	5	6	8	5		54

Fig. 4.12 Image Temporal Effects on Tracker Magnitude Errors

Analysis of Tracker errors as a function of month (Table 4.8) revealed a strong relationship with ice conditions. During the May-June period, when the ice remained fairly consolidated, average displacement errors were between 1.9 to 2.3 km (April was removed because of limited data points, $n=2$). Displacement errors increased in July to 4.6 km after the break up of the ice bridge causing ice to drain through Kane Basin and Smith Sound at high velocities. The displacement errors remained high (3.7 km in November) until freeze up started again in December. When error as a function of month is combined with increased image separation time, the largest errors are found in July (> 72 hours = 8.4 km error), and in November (48-60 hours = 9.1 km error). The lowest errors were found during the spring (April-June) and winter (December) months with the lowest error in magnitude equal to 0.2 km for the month of June with an image separation time of less than 12 hours.

Tracker errors in magnitude were also analysed as a percentage of the Tracker vector length. For example, a 4 km error is very significant on a 5 km vector in comparison to a 40 km vector. The overall error in Tracker magnitudes as a percentage of vector length was 25.6 % for an average Tracker vector of 15.5 km (Table 4.9). When analysed as a function of image separation times, the largest errors ranged from 39.8%

to 27.1 % in the smaller time intervals of 12 – 24 hours. Magnitudes are easier to calculate over longer distances and in the shorter image separation times, the distances are indeed smaller, 7 km – 10.2 km.

Table 4.9 Percentage of Tracker Magnitude Error with Vector Length

		Hours														# of samples
		< 12		12-24		24-36		36-48		48-60		> 72		Average		
		%	km	%	km	%	km	%	km	%	km	%	km	%	km	
April							6.5	40.8					12.9	40.8	2	
May		27.0	5.6	14.8	10.6	9.8	33.0	21.2	20.3	15.3	14.6	15.0	23.0	19.7	13.4	25
June		9.0	1.9	31.4	8.0	13.1	14.2			4.5	45.4	8.8	13.0	18.7	13.5	10
July		109.6	7.4	53.9	6.4					8.2	25.0	23.4	36.0	65.2	12.8	8
Nov		18.3	12.5	10.1	6.2			11.1	19.9	40.3	23.0			22.4	15.7	7
Dec				8.7	32.5							0.9	42.1	4.8	37.3	2
Average		39.8	7.0	27.1	10.2	11.8	21.7	14.6	27.1	19.3	21.9	12.6	27.4	25.6	15.5	
# samples		15		15		5		6		8		5				54

In comparing these errors to month, the strong relationship with ice conditions is still apparent with errors increasing to 65.2 % in July as ice concentrations diminish after the breaking of the Smith Sound ice bridge.

Bearing

Tracker ice motion bearing errors were also analyzed as a function of RADARSAT-1 image separation times. In Fig. 4.13 a trend is evident showing that errors are larger with smaller image separation times (Table 4.10).

Table 4.10 Monthly Average Angle Errors (Degrees)

	< 12 hours	12-24 hours	24-36 hours	36-48 hours	48-60 hours	>72 hours	Average	# of Samples
April				7.24			7.24	2
May	39.17	22.11	5.98	9.34	6.72	11.83	22.14	25
June	6.36	15.46	10.12		8.97	7.25	11.76	10
July	12.54	22.49			7.15	2.70	14.37	8
Nov	57.98	12.44		9.26	23.81		34.75	7
Dec		10.50				0.79	5.64	2
Average	35.65	18.77	8.46	8.63	11.33	6.88	2.34	
# of Samples	15	15	5	6	8	5		54

Fig. 4.13 Image Temporal Effects on Tracker Bearing Errors

Analysis of Tracker bearing error as a function of month (Table 4.10) found a strong relationship with ice conditions in November, but this was biased by a large 12-hour error in November. When reviewing the November errors for all the other image separation times, the November

average is 17.33° . As ice concentrations decrease in the summer months, winds and ocean currents are now able to move ice greater distances, which are difficult to track. Yet the Tracker algorithm is still able to capture the direction of the ice motion even with changes in ice conditions.

4.3.3 RMS Tracking Error

To derive an absolute measure of Tracker error, a RMS error was calculated using equation 4.11. This equation calculates the vector difference between the Tracker and Beacon vectors (Fig. 4.3). The Tracking errors will be larger than those seen in the validation regression results because displacement and bearing are no longer being separately analyzed, but are combined.

A weighted RMS error was determined in which equation 4.11 was calculated using all 54 points and then averaged. The weighted RMS Tracker error was 4.7 km (Table 4.11). Another way of calculating the RMS error is to take the mean of the Tracker and beacon displacements and bearings using all 54 data points and calculate equation 4.11 using the means only. The un-weighted RMS error of 1.3 km (Table 4.11) is not considered statistically valid, but was computed in order to compare with other Tracker validations done by Noetix Research Inc. discussed later in this section.

When looking at the RMS error by month, the largest errors are again a function of ice conditions. For example as the ice in the NOW region begins to reach summer conditions in July, the weighted RMS error is 6.1 km and remains large until freeze-up begins in late November (7.6 km). When reviewing the weighted RMS Tracker error for the winter/spring months of April, May, June and December, errors vary between 3.5 km and 7.73 km. Considering the April and December data sets consist of only 2 data points each, it was expected that the months of May and June truly represented the winter/spring validation period with 25 and 10 data points respectively. Thus, a maximum weighted RMS error of 3.8 km is expected in the winter/spring period while a maximum RMS error of 6.8 km can be expected in Summer and Fall ice conditions for the North Water region.

Table 4.11. RMS Tracking Errors (km)

	April-Dec Mean	April Mean	May Mean	June Mean	July Mean	Nov Mean	Dec Mean	Winter Spring May/June Mean	Summer Fall July/Nov Mean
A (beacon mean)	15.5	43.3	13.7	13.2	16.5	18.6	35.7	10.6	17.5
B (Tracker mean)	16.6	40.8	13.4	13.5	12.8	15.7	37.3	10.4	14.1
A-B	-1.1	2.5	0.3	-0.3	3.7	2.9	-1.6	0.1	3.3
p1 -2	2.3°	7.2°	22.1°	11.8°	14.4°	34.8°	5.6°	19.1°	23°9
RMS Tracker Error	1.3	5.9	5.2	2.8	5.2	10.6	3.9	3.5	7.3
Weighted RMS Tracker Error	4.7	7.6	3.9	3.5	6.1	7.6	3.5	3.8	6.8
Count	54	2	25	10	8	7	2	35	15

4.3.5 Summary

Tracker and beacon magnitudes are highly correlated with R^2 of 0.93 and SE of 3.6 km over the entire validation period. Tracker displacement errors increase slightly with image separation and significantly with ice conditions. They varied between 1.9 km – 2.3 km until the ice began to melt in the summer season with average errors increasing up to 4.6 km in the summer months.

For bearing, the R^2 was 0.79 and SE was 38.8° for the entire validation period. Errors in bearing are largest (35.6°) with small image separation times of < 12 hours, and vary over the validation period between 6.9° and 18.7° . An increase in bearing error did not occur as the ice conditions changed temporally.

The weighted RMS errors give an idea of what the combined Tracking errors are in direction, magnitude and due to the georeferencing errors in the RADARSAT-1 data. The Weighted RMS error over the entire validation period was 4.7 km. When reviewing this on a seasonal basis, the average weighted RMS error in the Winter/Spring periods was 3.8 km while in the Summer/Fall period it was about 6.8 km.

Mean tracker displacement errors cannot be quantified better than 350 metres due to the accuracy provided by the beacon data, and the SCW georeferencing errors are also a contributing factor in the RMS Tracker error. These errors are considered acceptable for the dynamic ice conditions of the NOW region covering an area over 80,000 km² in size, but may be considered too large for navigational purposes. In providing operational ice motion data, the best Tracker results would be achieved during winter conditions only and in less dynamic ice environments such as the Gulf of St. Lawrence and the Beaufort Sea.

4.4. Comparison to other Tracker Validations

When comparing the NOW validation results to those done by Noetix Research Inc. (1992, 1998), these errors seem quite large. Table 4.12 shows a list of the validation results for various sensors and regions during freeze up and winter time conditions only.

When comparing the NOW data to the 1998 Noetix study a comparison can be made only of the weighted Tracker errors since an evaluation of the georeferencing errors was not done for the 1997 RADARSAT-1 data. Combining all the points used in the 1997 Noetix validation study ($n=32$, $R^2=0.98$, $Se=0.5$ km, using 4 image pairs), results in an average displacement error of 0.1 km and an average angle error of 17.08°. The 1997 validation results range between 0.2

– 0.8 km, less than half of the NOW errors. Reasons for this difference arise from differences in the ice environments. The 1997 ice displacements averaged 4 km while in the NOW region during winter conditions, displacements average 15.5 km. In the Queen Maud and the Beaufort Sea regions visual comparisons were done in which validations were performed down to the 50 metre pixel level. In the NOW region our validation accuracies are limited to a maximum accuracy of 350 metres. The 1997 validation may be somewhat biased in the fact that the validations were done on single scenes only, but it is quite reasonable to accept that in other regions RMS Tracker error can be less than 1 km. This is important to note, because the regions used in the 1997 study are operational regions used by the Canadian Coast Guard.

The Noetix validations of 1992 were performed using Seasat and NOAA AVHRR imagery (Table 4.12). Georeferencing errors were calculated, but not presented in the 1992 report. The Seasat data should be comparable to the RADARSAT data because of the similar 4-look processing, but Seasat Tracker errors are significantly lower at 0.2 – 0.3 km. Perhaps the Seasat data are not comparable after all, or perhaps the Seasat validation results are seriously understated. The 1992 Noetix study was again performed in operational regions where the ice conditions are less dynamic, and during winter conditions in which the ice was fairly consolidated. The Noetix validation work was based on visual comparisons at the pixel level, providing better accuracies than the 350 metres

provided in the NOW validation. It is not known if the samples were collected from just a few scenes or a variety of images. Unfortunately, the Noetix 1992 validation raises more questions than answers and therefore their results were not evaluated further within the context of this research.

Table 4.12. Tracking Errors for Various Sensor Types in km
(Freeze Up / Winter Conditions Only)

Location	Sensor	Pixel Size Metres	RMS Tracker Error	Weighted RMS Tracker Error	Geo-ref Error	Total Points
North Water, Baffin Bay 1998	RADARSAT-1 ScanSAR Wide	50	3.5	3.8	0.2	35
Gulf of St. Lawrence February 25-26 1997	RADARSAT-1 ScanSAR Wide	50	1.6	0.8		8
Gulf of St. Lawrence March 4-5 1997	RADARSAT-1 ScanSAR Wide	50	0.3	0.4		9
Ψ Queen Maud October 13-14 1997	RADARSAT-1 ScanSAR Wide	50	0.3	0.3		8
Ψ Beaufort Sea October 13-14 1997	RADARSAT-1 ScanSAR Wide	50	0.1	0.2		7
Ψ Bank's Island, Arctic January 1992	Seasat-1	25	0.2			40
Ψ Beaufort Sea January 1992	Seasat-2	16	0.3			70
Ψ Grand Banks, Nfld. January 1992	NOAA AVHRR	1000	6.9			43

Ψ (Using visual validation methods: From Noetix 1992, 1998)

4.5 Conclusion

The first objective of this research was to assess the accuracy of the Canadian Ice Service Tracker algorithm outlined in this chapter. The Tracker ice motion data compared favorably to the representative ice motion of the beacon data in the NOW region. Significant regression results in magnitude and bearing provide us with the confidence that ice motion in the NOW region can be accurately measured using Tracker. Overall errors were somewhat larger in Tracker pairs with small image separation times and during summer/melt conditions. The best agreement was found in the spring (April-June) and winter (December) months of 1998. Knowing the potential and limitations of Tracker means that the data can be examined further in understanding the links between ice motion and polynya dynamics.

CHAPTER 5

NOW ICE MOTION ANALYSIS

5.1 Introduction

Having completed the quantitative analysis of the Tracker ice motion accuracy in the NOW region, this chapter will analyze motions derived from Tracker in relation to the spatio-temporal distribution of ice motion during the 1998 polynya season and compare this to wind data collected during the 1998 NOW International Study. The objective is to provide insight into the influence of atmospheric and oceanic forces on ice motion and thus the contribution of latent and sensible heating to polynya thermodynamics (Barber, NOW Science Plan: 1997, Unpublished).

5.2 Methods

5.2.1 Ice Motion Map Production

Monthly and weekly ice motion maps were created to aid in the spatial representation of ice dynamics over the 1998 cycle of the NOW polynya. The ice motion data were averaged into weekly and monthly time frames to remove the effects of tides. Little is known about tides in the eastern Arctic and available tidal charts are based on interpolated data from remote locations. Monthly and weekly maps were created to review longer term ice motion over the course of 1998.

The Tracker ice motion vectors were imported into Arcview 3.1. All Tracker vectors for each specific month were overlaid on a 60 by 60 cell grid covering the NOW region. The grid cell size used was 20 km x 20 km, based on average magnitudes calculated during the Tracker validation (~15.5 km). Ice motion vectors were tagged to specific grid cells if the geographic centre point of the vector fell inside the grid cell. All the vectors tagged to the grid cell were averaged speeds in m/s (equation 4.3) and bearing (equation 4.4). Monthly averages were not computed using the weekly averages, but with all the Tracker data for that month. The vector data were then converted to raster and averaged into monthly maps. A 9x9 nearest neighbour filter was applied to fill in the data gaps for map production purposes only.

The georeferencing errors found on land (225 m) were compared to the Tracker displacements on the ice bridge (322 m) and were found to be within a pixel (Table 5.1). This indicates that the ice bridge was truly immobile as found by Ito and Müller (1977). Therefore, ice displacements under 350 m (0.025 m/s) were considered to be georeferencing errors and/or fast ice and were removed from the analysis.

Table 5.1 Comparison of Georeferencing Errors and Tracker Vectors on the Smith Sound Ice Bridge

Tracking Pairs	Georeferencing Coastline Errors in metres (pixels)	ITV's on the ice bridge in metres (pixels)
May 14_14	45.6 (0.9)	118.8 (2.4)
May 18_21	233.3 (4.7)	779.4 (15.6)
May 21_21	302.5 (6.1)	305.4 (6.1)
May 21_24	253.6 (5.1)	305.4 (6.1)
May24_24	316.4 (6.3)	401.4 (8.0)
May24_26	316.5 (6.3)	336.1 (6.7)
May26_27	136.7 (2.7)	118.8 (2.4)
May27_28	194.5 (3.9)	209.2 (4.2)
Mean	224.9 (4.5)	321.8 (6.4)
Std	96.0 (1.9)	211.0 (4.2)

5.2.2 NOW Polynya Seasonal Evolution

An overview of the Tracker monthly mean speeds and bearings for the year was produced. Ice motion was analysed by comparing seasonal evolution mechanisms and the ice types and concentrations derived from the CIS monthly ice charts covering the Eastern Arctic (January - September 1998), and the 1998 CIS Seasonal Summary of the Eastern Arctic (June - September 1998).

The monthly maps are reviewed further for evidence of latent and sensible heat influences. Since the Tracker algorithm calculates ice displacements based on recognizable floes, it should be noted that new ice types in the polynya cannot be tracked and are therefore not represented in this 1998 NOW polynya review. This will affect the study by underestimating the import/export of new ice types

from Smith Sound from the emergence of the polynya into the summer period. Although new ice types forming in the polynya cannot be tracked, older ice from the Arctic basin or new ice that has thickened into rubble ice as it moves through the NOW region can be. This will provide indications of the directions and velocities of ice motion (latent heat) moving through the polynya and being exported out of this region.

Oceanic sensible heat would result in areas that are predominantly ice-free. It is assumed that sensible heat would be evident in the maps as consistent areas of negligible ice motion. Finally, these results are then compared to previous studies of ice motion in the region.

5.2.3 Tracker Ice Motion and Wind Correlation Analysis

Several meteorological data sets were collected during the International NOW Polynya project. The University of Miami collected ship data from March - August 1998 (Fig. 5.1).

Fig. 5.1 Example of Monthly Ship Tracks for Ship Meteorological data collection (March – August 1998). (Adapted from NOW Web Site)

The University of Manitoba collected data from March - July 1998 for six remote stations around the polynya (Fig. 5.2) and (Table 5.2).

Fig. 5.2 Geographic Locations of Remote Meteorological Stations. Numbers refer to those listed in Table 5.1 (Adapted from NOW Data Report, 1999)

Table 5.2 NOW Remote Weather Stations 1998

	Site Name	Location	Duration (in Julian Days)
1	Cape Herschel - Ice Camp	78°36'57.1" N 74°40'33.5" W	94 - 123
2	Rosse Bay	78°39'45.3" N 74°34'42.7" W	80 - 156
3	Smith Sound	78°35'51.78" N 74°29'31.62" W	103 - 121
4	Herschel Bay	78°35'18.9" N 74°40'36.7" W	126 - 141
5	Goding Bay	77°57'54" N 76°19'28" W	99 - 140
6	Rensselaer Bay	78°39'09.6" N 70°43'13.9" W	102 - 140

(Adapted from: NOW Data Report, 1999)

Weather station data were collected by CIS from January – August 1998 (Fig. 5.3).

Fig. 5.3 Geographic Locations of the Weather Station Data Collections
(Adapted from NOW Data Report, 1999)

John Heinrichs with the Department of Geosciences at Fort Hay's University in Kansas interpolated all of the above data into a NOW meteorological database. These data were interpolated using a Global Environmental Multi-scale Model (Côté et al., 1997). Radii were established to estimate the size of the area for which the station data would be representative. This radius was set to 30 km for the shipboard data and all other data sources were given a radius of 6 km. The data were re-sampled to a 4 km grid for the following times of 00:00, 06:00, 12:00 and 18:00 UTC (January-August 1998).

Using a series of Excel 97 macros, the centre lat./long position of each 4 km grid, the u (wind speeds in the north-south axis) and v (wind speeds in the east-west axis) meteorological data were extracted. The 6-hour u,v components were averaged into daily u,v and then averaged into weekly u,v . The weekly data were averaging using the daily u,v because weekly averaging using the 6-hour data was too CPU intensive. The u,v components were then converted into weekly wind speeds (m/s) using equation 5.1.

$$\text{Speed} = \text{SQRT}(u^2 + v^2) \quad (5.1)$$

To import this data as wind vectors into Arcview, the start and stop lat./long coordinates of the wind vectors needed to be calculated. The centre lat./long of the 4km grid was used as the start lat./longs. Equations 5.2 - 5.5 were used to calculate the stop lat./longs.

$$\text{Lat2} = \sin^{-1} (\sin(\text{lat1}) \cdot \cos(\text{distance}) + \cos(\text{lat1}) \cdot \sin(\text{distance}) \cdot \cos(\text{tc})) \quad (5.2)$$

(Williams, 2000)

$$\text{Long2} = \text{mod}(\text{long1} - \text{asin}(\sin(\text{tc}) \cdot \sin(\text{distance}) / \cos(\text{lat2})) + \pi, 2 \cdot \pi) - \pi \quad (5.3)$$

If $\cos(\text{lat2}) = 0$, then $\text{lat2} = \text{lat1}$
(Williams, 2000)

$$\text{tc} = \text{atan}(u, v) - \pi/2 \quad (5.4)$$

(Williams, 2000)

Where tc = true course, the angle between the starting point and ending point (true indicating north as the reference) and mod = the standard mathematical function modulus, which returns the remainder from a division of two numbers.

(Carrierres, Pers. Comm, 2000)

$$\text{Distance} = \text{Speed} \cdot \text{Time} \quad (5.5)$$

Where, Time = 6 hours

Once in Arcview, the wind vectors were then converted to the same 60 x 60 grid (1 grid cell = 20 x 20 km) used for the ice motion maps. The vectors were then averaged into the 20 km raster cells and regression analyses were performed by comparing the weekly ice motion to the weekly wind data. Weekly mean speed and bearing values for wind and ice motions were calculated for the entire NOW region. Only the Winter and Spring seasons were selected for this analysis because of the increase in Tracker errors into the summer seasons found during the validation and to focus in on the Polynya season only. Wind bearings were converted from circular to scalar numbers (see Table 4.2) in order to correlate

with ice motion directions. Correlations were performed from weeks 4 – 26 for the entire NOW region and by season.

5.3 Results and Discussion

5.3.1 Now Polynya Seasonal Evolution Overview

The ice speed and bearing fields over the 1998 annual cycle of the NOW polynya are presented as monthly ice motion maps (Figure 5.4a - l). The following discussions will refer to approximate seasons of the NOW polynya used by Mundy and Barber (2000), which are based on temperatures and ice conditions outlined below.

- **Winter** (January-February), temperatures and solar radiation inputs are their lowest. Congelation ice growth continues and regions are fairly consolidated.
- **Spring** (March-May), the ice bridge forms in Smith Sound initiating polynya formation. The polynya will continue to expand until the break-up of the ice bridge.
- **Summer** (June-September), the ice bridge breaks. High solar radiation and temperatures are absorbed by the large expanse of open water from the polynya contributing to full melt.
- **Fall** (October-December), as temperatures and solar radiation inputs decrease, new ice types begin to form and older ice begins to re-freeze.

Fig. 5.4a January 1998 Tracker Ice Motion

Fig. 5.4b February 1998 Tracker Ice Motion

Fig. 5.4c March 1998 Tracker Ice Motion

Fig. 5.4d April 1998 Tracker Ice Motion

Fig. 5.4e May 1998 Tracker Ice Motion

Fig 5.4f June 1998 Tracker Ice Motion

Fig. 5.4g July 1998 Tracker Ice Motion

Fig. 5.4h August 1998 Tracker Ice Motion

Fig. 5.4i September Tracker Ice Motion 1998

Fig. 5.4j October 1998 Tracker Ice Motion

Fig. 5.4k November 1998 Tracker Ice Motion

Fig. 5.41 December 1998 Tracker Ice Motion

The monthly ice motion maps capture the annual progression of the NOW polynya very well. In the **winter** maps (Figs. 5.4a - b), ice motion speeds average 0.07 m/s or 6.1 km/day (Table 5.3). The maps show that speeds in Kane Basin decrease as ice becomes congested in the narrow channel and concentrations increase in Smith Sound. The East Coast of Baffin Bay and Lancaster Sound are dominating the south-easterly export of ice.

The **spring** maps (Figs. 5.4c - f) show that with the formation of the ice bridge (early March) ice movement ceases in Kane Basin. In March, ice speeds decrease in Jones and Lancaster Sounds as ice bridges form in these regions. Ice motion speeds south of the ice bridge slowly increase in Smith Sound and Baffin Bay as the polynya reaches its maximum southern extent in May. The majority of the ice export occurs along eastern Baffin Bay and speeds are high around Lancaster Sound in May as this region begins to break up. Average ice movement is again to the Southeast and speeds increase to 0.11 m/s or 9.5 km/day towards the end of May (Table 5.3).

The ice bridge breaks at the end of June and the polynya disappears in the **summer** maps (Figs. 5.4g - i). The ice motion is highly variable as melting ice and open water dominate the region. The high speeds of older floes being exported from the Arctic Basin through Kane Basin, Jones and Lancaster Sounds into Baffin Bay are captured, and average speeds peak in August at 0.46 m/s or 39.7 km/day. The direction of ice motion is highly variable as summer storms frequent the region

causing ice directions to vary between Northeast to Southwest. Also the increase in Tracker errors during the summer months must also be considered.

Evidence of freeze-up in the **fall** maps (Figs. 5.4j - l) is identified as ice speeds decrease to 0.20 m/s or 17 km/day by the end of December. The growth of fast ice along the coasts re-creates the narrow corridor through Kane Basin, and increased ice concentrations in Smith Sound reduce speeds further (November). As freeze-up continues, the ice motion directions return to south-easterly by early December.

Table 5.3 provides an overview of the regional mean ice speeds (excluding fast ice) and bearings by season. Figure 5.5 illustrates this seasonal overview of the ice motion through the NOW region and outlines the geographical locations of the regions.

Table 5.3 Regional/Seasonal Mean Ice Speed
(m/s and (km/day)) and Direction

	Winter		Spring	
	Speed	Direction	Speed	Direction
Now Polynya	0.07 (6.1)	SE	0.11 (9.5)	SE
Kane Basin	0.05 (4.3)	SW	0.04 (3.5)	SW
Smith Sound	0.06 (5.2)	S	0.08 (6.9)	W
Baffin Bay	0.08 (6.9)	SE	0.10 (8.6)	SE
Greenland	0.07 (6.1)	SE	0.08 (6.9)	SE
	Summer		Fall	
	Speed	Direction	Speed	Direction
Now Polynya	0.52 (44.9)	S	0.27 (23.3)	S
Kane Basin	0.15 (12.96)	S	0.10 (8.6)	SW
Smith Sound	0.32 (27.7)	W	0.24 (20.7)	SW
Baffin Bay	0.65 (56.16)	S	0.31 (26.8)	S
Greenland	0.82 (70.9)	S	0.24 (20.7)	S

Fig. 5.5 Geographic Locations of Regions
Showing Mean Ice Speeds and Bearing by Season

Previous ice drift estimates in the NOW region for the winter period found 12 km/day (Dey, 1980) and 6 km/day in Kane Basin (Dunbar, 1973), (Table 5.4). While Dunbar's findings compare with the Tracker estimates of 4.3 km/day, Dey's findings are doubled in speed. Aber (1972) found speeds of 10.48-11.77 km/day during the spring, which are comparable to the Tracker findings of 9.5 km/day. Ito and Muller (1982), for the same period, estimated ice speeds at 4 km/day in Smith Sound, just under the 6.9 km/day found in this study. Dunbar's (1979) Fall data set consists of 3 image pairs, showing an overestimation of ice speeds in Kane Basin (19-51 km/day) and Smith Sound (9-37 km/day) in comparison to the Tracker estimates of 8.6 km/day and 20.7 km/day respectively.

Table 5.4 Seasonal Comparison of Tracker Ice Speeds (km/day) vs. Previous Studies
(Tracker speeds are indicated in red).

Winter				Spring					Fall		
Dunbar		Dey		Aber			Ito & Muller		Dunbar October 19-26		
1970-72		1974-77			1969	1970	1973-1981		1979		
Kane Basin	6 (4.3)	NOW Region	12 (6.1)	NOW Region	11.8 (9.5)	10.5 (9.5)	Smith Sound	4 (6.9)	Kane Basin N	50.98	(8.6)
									Kane Basin S	19.01	(20.7)
									Smith Sound E	36.60	
									Smith Sound W	9.00	

Not all of the Tracker results compare favourably with the previous studies. The limited data sets used in past studies resulting from cloud saturation, polar darkness and accuracy related problems from visual tracking techniques and geo-rectification problems should mean that the 1998 Tracker data set provides the best estimate of ice motion in the NOW region to date.

5.3.2 Evidence of Latent and Sensible Heat Mechanisms

Based on the positive results of Tracker capturing the seasonal evolution of the polynya, the monthly ice motion maps from Tracker were investigated further for evidence in support of latent and sensible heating mechanisms in the regime of the NOW polynya.

Latent Heat Export

The review of the annual cycle of ice motion in the polynya shows that an overall southward export of ice dominates the NOW region. This supports latent heat export theories in which winds or ocean currents maintain the open water and thin ice types of the polynya. After the ice bridge breaks in June, an increase in the level of ice export is apparent until full melt in September. During the summer season, average speeds reach 45 km/day over the entire polynya region while average speeds along the Greenland coast average 71 km/day (Table 5.3). The tracking errors in the months of July, August and September increase as recognizable ice floes decrease, causing variable results with limited regional patterns. The monthly ice motion maps do indicate how large ice export and ice speeds can be in this region.

Latent Heat Import

Although the dominant pattern is a southerly export of sea ice, it is also evident from the results that there are regions of ice import and or re-circulation in the NOW polynya. In January - March (Figs. 5.4a - c), ice is imported along the Greenland coast and re-circulated back into Kane Basin at low speeds of less than 0.05 m/s. In April (Fig. 5.4d) one large circular pattern in Baffin Bay dominates the ice motion, recycling ice back into Smith Sound along the coasts of Greenland at rates of 0.05 to 0.2 m/s. In the May subset, (Fig. 5.4e) ice is still being imported back into Smith Sound and towards Devon Sound at lower speeds of 0.05 – 0.1 m/s. In June, (Fig. 5.4f) the circular motion expands

southwards recycling ice from Lancaster Sound and Baffin Bay back into Smith Sound. Although this import region covers a larger area, the speeds are small at rates of 0.05 to 0.1 m/s. Mundy (2000) speculated that medium first year ice dominating the eastern coast of the polynya during the spring emerges in southwestern Greenland due to recycling by Baffin Bay ocean currents. The April, May and June ice motion maps tend to confirm Mundy's recycling theory, but we do not know if this influence is due to winds or ocean currents. This point will be re-visited in section 5.3.3 when the influence of winds on ice motion will be examined.

Ice motion was too variable in the **summer** months to determine or visualize regional patterns. During late **fall** freeze-up in the November and December subsets, (Figs. 5.4k – l) several small circular patterns appear in the region with minimal import of ice into Smith Sound on the Greenland side. The ice motion returns back to a similar motion as in the January, February maps prior to polynya formation. It is not known if this motion occurs seasonally or the magnitude of the negative feedback on the sensible and latent heat mechanisms at work in the polynya. Without knowing how long this recycling period takes, how long the ice remains in the gyre and how much ice is being imported back into the polynya region we can only speculate on its significance. Overall, the import of ice into Smith Sound is slow, except in April. It is assumed that the import of this ice does not significantly impact the polynya or else the expansion

of open water in the polynya would not occur and this motion would be indicated in the seasonal summary (Fig. 5.5).

Sensible Heat Import: Oceans

Steffan (1986) documented the consistent occurrence of warm water cells along the Greenland coast of Smith Sound. It was speculated that winds off the Greenland ice cap (katabatic winds) during the fall period were strong enough to export surface ocean layers and allow the upwelling of warm (0°) Atlantic water. Mundy and Barber (2000) found an extension of open water appearing along the Greenland coast during the fall period (October-December) utilizing ice types and concentrations from the same RADARSAT-1 data used in this study. They inferred that this could be due to warm water upwelling from the Atlantic current impeding ice formation in the fall. Although this is not a classic case of a sensible heat polynya, the transfer of energy retarding the growth of sea ice may in fact result in thinner ice in this region, thus promoting earlier melting of this ice in the spring. In the November ice motion map (Fig. 5.4k) a strong northerly flow along the Greenland coast at high speeds is apparent, but whether this is related to the fall sensible heat input is not known.

The analysis in this chapter found many indications of the latent heat mechanism in the maintenance of the polynya, with no evidence of oceanic sensible heat.

Summary

This research has presented the first consistent ice motion results at the polynya-scale over the seasonal cycle of the polynya. The monthly ice motion maps show a significant export of ice from the polynya influenced by eastern Baffin Bay and a minimal amount of ice import from along the Greenland coast. In the summer months, average speeds reached up to 45 km/day with a maximum of 71 km/day (Table 5.3), showing a high level of ice export in this region not found in previous studies. The monthly Tracker results provide insight into the contribution of the latent heat mechanism at work in the NOW polynya.

5.3.3 Tracker Ice Motion, Wind Correlation Analysis

In the previous section, the seasonal evolution of the polynya derived from Tracker measurements indicated a latent heat influence, but whether winds or ocean currents maintain this is not known. Relations between wind and ice motion can be analysed by comparing the Tracker ice motion to the NOW meteorological data set.

Mean wind and ice speed / bearings maps were compared on a weekly basis from January to June 1998 (see example Fig 5.6), all weekly maps are available in Appendix D. A statistical analysis of the influence of winds on ice motion is performed for the NOW area and by region (see Fig. 5.5 for regions).

Fig. 5.6a Week 10: March 1 - 7 1998

A time series analysis of the weekly ice motion versus the weekly winds in the NOW region is presented in Figure 5.7. After the formation of the ice bridge (week 12), drift speeds for the entire NOW region begin to decrease. Unfortunately, week 15 was not captured by Tracker because of a lack of RADARSAT-1 coverage. Ice speeds increase in May as the polynya expands until a sudden drop at Week 22. Ice and wind speeds continue to be low into June until the ice bridge breaks at the end of week 25. The frequency of Northerly winds increases at week 24 and 25, possibly aiding in the break-up of the ice bridge, (Ito and Müller, 1977).

Fig 5.7 Now Polynya Wind and Ice Drift Speeds (m/s) and Bearings

Table 5.5 NOW Region Ice Motion and Wind Regression Results

		Weeks 4-12			Weeks 13-26			All Weeks		
		R^2	P-value	# of weekly means	R^2	P-value	# of weekly means	R^2	P-value	# of weekly means
NOW Region	Speed	0.59	0.016	9	0.15	0.197	13	0.22	0.026	23
	Bearing	0.98	2.16E-07		0.92	1.79E-07		0.93	3.02E-13	

* Speeds in m/s, bearing in degrees

The regression (R^2) results for the NOW region in Table 5.5 show that in all weeks the winds play a dominant role in ice direction ($R^2=0.93$), but have less of an influence on speed ($R^2=0.22$). Regression results with a P-value of less than or equal to 0.05 are considered significant and are highlighted in Table 5.5. The bearing R^2 value of 0.93 is significant in that it tells us that a majority of the ice motion direction variance is accounted for by winds. The speed coefficients of determination prior to

Fig 5.8 Kane Basin Wind and Ice Drift Speeds (m/s) and Bearings

the ice bridge in Smith Sound are highest at $R^2=0.59$ compared to an $R^2=0.15$ after the bridge formation.

Table 5.6 Kane Basin Region Ice Motion and Wind Regression Results

		Weeks 4-12			Weeks 13-26			All Weeks		
		R^2	P-value	# of weekly means	R^2	P-value	# of weekly means	R^2	P-value	# of weekly means
Kane Basin	Speed	0.21	0.360	6	0.918	0.06	6	0.006	0.800	12
	Bearing	0.61	0.011		0.067	0.78		0.50	0.019	

The influence of winds on ice motion differs considerably by region. The speed regression for Kane Basin (Table 5.6) was the most insignificant of all regions ($R^2 = 0.006$), but before the ice bridge a small amount of the ice motion variation in the region is influenced by winds ($R^2 = 0.21$).

The Kane Basin bearing regression (Table 5.6) for all weeks ($R^2=0.50$) shows that 50% of the ice motion bearing is accounted for by winds and prior to ice bridge formation the relationship is even stronger ($R^2=0.61$). The number of data points available for the Kane Basin time series is small because of the dominant occurrence of fast ice, limiting ice motion in the region (Fig. 5.8). These data points were not interpolated. Even with limited data points, the P-value of 0.019 is ≤ 0.05 and therefore the hypothesis that there is no relation between winds and ice motion speeds in the NOW region can be rejected. At week 26 (Fig. 5.8), the wind and ice motion directions are opposite. Although the winds are blowing to the northeast, the ice cannot move in that direction because it is consolidated to the north. Although

influenced by winds, the ice motion in Kane Basin results in speeds and directions that do not always correspond with winds due to internal ice pressures.

Fig. 5.9 Smith Sound Wind and Ice Drift Speeds (m/s) and Bearings

Table 5.7 Smith Sound Region Ice Motion and Wind Regression Results

		Weeks 4-12			Weeks 13-26			All Weeks		
		R ²	P-value	# of weekly means	R ²	P-value	# of weekly means	R ²	P-value	# of weekly means
Smith Sound	Speed	0.25	0.664	9	0.016	0.173	13	0.04	0.367	23
	Bearing	0.48	0.002		0.09	0.040		0.38	0.294	

In Smith Sound, the influence of wind speed on ice drift is also low for all weeks ($R^2=0.04$), before ($R^2=0.25$) and after the ice bridge ($R^2=0.016$). There is a trend towards higher ice speeds by the end of the polynya season, not evident in the wind

speeds (Fig. 5.9). Prior to ice bridge formation, ice speeds are fairly low due to high concentrations of ice in the region. After the formation of the ice bridge ice concentrations decrease and the open water of the polynya increases allowing the ice motion in Smith Sound to increase. These higher ice motion speeds do not always correlate well with areas of high wind speeds, (see week 23, Appendix D).

The Smith Sound bearing coefficients of determination prior to the ice bridge are $R^2=0.48$, after $R^2=0.09$ and for all weeks $R^2=0.38$. The regression results indicate that before the ice bridge almost 50% of the variation in ice motion could be accounted for by winds, while after the ice bridge the influence of winds was insignificant.

Fig. 5.10 West Baffin Bay Wind and Ice Drift Speeds (m/s) and Bearings

Table 5.8 Baffin Bay Region Ice Motion and Wind Regression Results

		Weeks 4-12			Weeks 13-26			All Weeks		
		R ²	P-value	# of weekly means	R ²	P-value	# of weekly means	R ²	P-value	# of weekly means
W. Baffin Bay	Speed	0.30	0.128	9	0.05	0.045	13	0.05	0.33	22
	Bearing	0.44	0.052		0.17	0.158		0.20	0.036	

On the West Coast of Baffin Bay the coefficient of determination for speed is $R^2=0.30$ prior to polynya formation, $R^2=0.05$ afterwards and $R^2=0.05$ for all weeks (Table 5.8). Again the results show that winds have a greater influence on ice motion prior to presence of the ice bridge as can be seen in the time series (Fig. 5.10).

Bearing regression results for Baffin Bay prior to, after ice bridge formation, and for all weeks are $R^2=0.44$, 0.17 and 0.20 respectively. These are the lowest regressions in bearing for all the regions.

Fig. 5.11 Western Greenland: Wind and Ice Drift Speeds (m/s) and Bearings

Table 5.9 Western Greenland Region Ice Motion and Wind Regression Results

		Weeks 4-12			Weeks 13-26			All Weeks		
		R^2	P-value	# of weekly means	R^2	P-value	# of weekly means	R^2	P-value	# of weekly means
Greenland Coast	Speed	0.30	0.124	9	0.40	0.021	13	0.37	0.003	22
	Bearing	0.06	0.511		0.74	0.000		0.58	3.47E-05	

In the Greenland region the ice motion and wind speed regression results are $R^2 = 0.30$, 0.40 and 0.37 (Table 5.9). The higher regression results of $R^2 = 40$ for weeks 13-26 indicates that the ice bridge has less impact on ice speeds in comparison to the other regions. Overall wind speeds are higher in April, May and June than in the other regions (Fig. 5.11). At weeks 18 and 20 there is significant ice motion along the Greenland coast in accordance with high winds (Appendix D).

The bearing regression for Greenland is low before the ice bridge at $R^2 = 0.06$ but is much higher after the ice bridge $R^2 = 0.74$ with an $R^2 = 0.58$ for all weeks (Table 5.9). With the formation of the ice bridge, the influence of winds on ice direction is greater in the Greenland region.

Summary

The coefficient of determination of 0.93 for all the weeks in the NOW region shows that ice drift directions are significantly influenced by winds. At the regional level, results were also significant in Kane Basin ($R^2 = 0.50$) and along the Greenland Coast ($R^2 = 58$). The effect of winds on ice motion speeds for all the weeks in the NOW

region was not significant with an $R^2=0.22$. This was the case for most regions except in Greenland where winds showed some influence on ice speed ($R^2=0.37$).

Overall the regression results indicate that winds have a greater influence on ice motion variance prior to polynya formation, except in the Greenland region where regression results improved after the presence of the ice bridge. It is expected that ice concentrations play a significant role in how responsive winds are to ice motion. Generally, high ice motion velocities occur in regions of low ice concentrations and low ice motion velocities occur in consolidated ice regions. Therefore, wind speed and bearing are not the sole factors that determine ice motion. The relationship between wind speed and ice motion might be improved by incorporating the 1998 NOW ice types and concentrations into the analysis, done by (Mundy 2000).

5.4 Conclusion

It is evident that winds play a role in the export of ice in the NOW polynya. The import and or recycling of ice is apparent (see, Fig. 5.4d) along the Greenland coast. This import appears to be due to the directional influence of winds along the Greenland coast (see weeks 14 – 17, Appendix D).

The export of ice from the NOW polynya may also be partly controlled by ocean currents. It was believed that during periods of low wind speeds, ice motion could remain high due to the influence of the ocean currents. This possibly occurred in week

23 for Smith Sound (Appendix D) and may be responsible for the unexplained ice motion of weeks 9 and 18 (Appendix D).

Evidence of sensible heat was not apparent in the weekly analysis. The polynya does expand along the Greenland coast (weeks 16-20, Appendix D) and speeds in this region are higher, possibly due to the presence of sensible heat thinning the ice.

There is a seasonal shift evident in the Smith Sound springtime weekly ice motion (Fig. 5.9). In early spring the ice motion is predominantly south until week 18 when it changes to westerly. This change may be due to the northerly retreat of the Arctic front in the spring, allowing storms from the Labrador and Davis Straits into the region (Barry, 1973). Ito and Müller (1977) also speculated that during the spring of 1974-76, an increase in northerly storms might weaken the ice bridge. The frequency of this northward ice motion in association with winds was apparent towards the end of June 1998 as the ice bridge was starting to break up (Fig. 5.9), which supports Ito's observations.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

In this research, a unique data set of 148 RADARSAT-1 derived ice Tracker pairs (January – December 1998) for the North Water region have been examined. The intent of this study was to determine how useful RADARSAT-1 Tracker derived ice motion products were in studying the dynamics and thermodynamics in the NOW polynya. The specific questions that were addressed to achieve these goals were:

1. How accurate is Tracker in capturing ice motion in the NOW region?
2. Can the Tracker ice motion capture the seasonal evolution of the polynya found in other studies?
3. Do the ice motion speeds and bearings compare with other research results?
4. Can latent and sensible heat mechanisms, theorized to be responsible for polynya maintenance, be inferred from this data set?
5. Is wind a driving force for ice motion in the NOW polynya?

6.2 Conclusions

Tracker derived ice motion compared very well to in-situ beacon measurements showing that Tracker can produce spatially extensive, accurate estimates of the ice motion fields in this region. Significant regression results in magnitude and bearing provide us with the confidence that ice motion in the NOW region can be accurately measured using Tracker. Overall errors were larger in Tracker pairs with small image separation times and during summer/melt conditions. Average RMS Tracking errors were less than 3.8 km in winter/spring ice conditions and 6.8 km during summer/fall conditions. The best agreement was found in the spring (April-June) and winter (December) months of 1998 with an image separation time of 24-48 hours.

The monthly ice motion maps provided a spatial visualization of the NOW region over the different seasons of 1998 at the polynya scale. These Tracker derived monthly maps captured the seasonal evolution of the polynya and compared reasonably well to previous studies. The limited data sets used in past studies resulting from cloud cover and polar darkness, and accuracy related problems from visual tracking techniques and geo-rectification problems means that the 1998 Tracker data set provides the best estimate of ice motion in the NOW region to date.

The monthly Tracker derived speed and bearing maps provided insight into the contribution of latent heating mechanisms at work in the NOW polynya. Large amounts of ice being exported through Baffin Bay were evident, supporting latent heat export theories. A review of the Baffin Bay ice motion found that ice was being imported back

into the Smith Sound region along the Greenland coast, but this was not expected to have a significant impact on polynya maintenance. Sensible heat mechanisms could not be confirmed from this analysis. The polynya does expand along the Greenland coast (weeks 16-20, Appendix D) and speeds in this region may be a result of the presence of sensible heat thinning the ice.

Winds were found to be significantly related to ice direction, especially before the Smith Sound ice bridge was formed. An exception was along the Greenland coast where the effect of wind speed on ice motion was only apparent after the formation of the ice bridge. A closer examination of the latent heat import along the Greenland coast revealed that the import and or recycling of ice is due to the directional influence of winds (see weeks 14 – 17, Appendix D). Smith et al. (1990) speculated that sensible and latent heat contributed 80% and 20%, respectively, to polynya thermodynamics. The large export of ice shown in the ice motion maps indicates that latent heat likely plays more of a role than previously expected in the NOW polynya.

6.3 Recommendations

The Tracker algorithm is dependent on the surface roughness of radar sea ice signatures to calculate cornerity values and find successful matches. This results in the inability to capture the motion of new ice types in the polynya that lack coherent floes. Also, since new ice is continually changing its shape, finding matching cornerity values in subsequent images is extremely difficult. As the new ice is exported from Smith Sound, it continues to thicken through continued freezing and or convergence and results in ice that is trackable. This trackable ice did provide indications that large amounts of ice are being exported from the polynya, but it definitely underestimates new ice motion in the region. This should be noted if this data set is intended for future studies in the region. At present, there are no immediate recommendations for overcoming the current problem of tracking new ice types in satellite imagery.

A comparison of the ice velocities (this work) with RADARSAT-1 derived ice concentrations (Mundy and Barber, 2000) is currently being conducted to estimate the sea ice budget (volumes of ice being exported, imported and recycled into the NOW polynya) during 1998. The use of ice concentrations should provide a good representation of the new ice types not available in the ice motion data set. A multiple regression evaluation of the winds, ice motion and ice concentrations may provide further insight into the influence of winds on ice motion. Oceanographic data from the concurrent NOW cruises may also provide further insight into the influences of sensible heat in the NOW polynya and hopefully an updated surface currents map of the region will aid in the further analysis of ice motion in the North Water polynya.

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Appendix A

1997 RADARSAT-1 Data

1997 NOW Tracker Testing Processed RADARSAT-1 Passes

Date	Start Time UTC hh:mm	Frame # in the Swath	Product Type	Receiving Station	Orbit	Production Order #	Tracker Pairs	Comments
April 1	11:56	2,3	SCW B	OBR	7345	M0109864	Yes	
April 3	21:22	3,4	SCW A	PASS	7365	M0109256		
April 27	21:24	1,2	SCW A	PASS	7708	M0112032		
April 30	21:36	1,2	SCW A	PASS	7751	M0112295	Yes	
June 10	21:10	1,2	SCW A	PASS	8351	M0115698	Yes	
June 12	21:51	1,2	SCW A	PASS	8380	M0116563		
								atellite anomaly
								atellite anomaly
								atellite anomaly
								atellite anomaly
June 26	21:50	2,3	SCW A	PASS	8580	c000622701	Yes	
June 27	21:20	2,3	SCW A	PASS	8594	M011755904f		
June 29	22:05	3,4,5f	SCW A	PASS	8623	M0119082		
July 2	22:15	2,3	SCW A	PASS	8666	c000627	Yes	
								at M0116563 - frame over NOW
								frame added to previous pair
July 13	21:55	2,3	SCW A	PASS	8823	c0006405	Yes	
July 14	21:25	3,4	SCW A	PASS	8837	M0119794		
July 16	22:05	2,3	SCW A	PASS	8866	c0006446		
July 17	21:35	2,3	SCW A	PASS	8880	c0006457	Yes	
July 20	22:20	4,5	SCW A	PASS	8909	M0121479	Yes	
July 25	21:35	4,5,6	SCW A	PASS	8980	M0122409		
July 28	21:41	2,3	SCW A	PASS	9023	M0121520		
July 31	21:55	2,3	SCW A	PASS	9066	M0122845- c006581		
Aug 4	21:45	1,2	SCW A	PASS	9123	M0123780	Yes	
Aug 7	21:55	1,2	SCW A	PASS	9166	M0123855		
Aug 18	21:35	1,2	SCW A	PASS	9323	M0125736		
Aug 21	21:45	1,2	SCW A	PASS	9366	M0126480		
Total								

Appendix B**1998 RADARSAT-1 Data**

1998 NOW SCW Data Collection and Tracker Pairs.

Date	Approx. UTC Time	PO #	Tracker Pair	# of frames
RSAT 21-Jan-98	21:51	c0008551		2
RSAT 24-Jan-98	22:03	c0008642	jan21_24	2
RSAT 28-Jan-98	21:47	M0152813	jan 24_28	2
RSAT 02-Feb-98	12:44	c0008727	jan28_fb2	3
RSAT 04-Feb-98	21:42	c0008746	feb3_4	3
RSAT 07-Feb-98	21:55	M0152768	feb4_7	2
RSAT 10-Feb-98	22:07	c0008835	feb7_10	2
RSAT 14-Feb-98	21:51	c0008874	feb10_14	2
RSAT 17-Feb-98	22:03	M0154050	feb14_17	2
RSAT 24-Feb-98	21:59	M0157353	feb17_24	2
RSAT 28-Feb-98	21:42	M015582	feb24_28	2
RSAT 03-Mar-98	21:55	M0156147	feb28_mar3	2
RSAT 06-Mar-98	22:07	c0009127	mar3_6	2
RSAT 10-Mar-98	21:51	M0157846	mar6_10	2
RSAT 13-Mar-98	22:03	M0159749	mar10_13	2
RSAT 17-Mar-98	21:47	M0160062	mar13_17	2
RSAT 18-Mar-98	21:46	M0160368	mar17_18	3
RSAT 20-Mar-98	21:59	M0160535	mar18_20	2
RSAT 24-Mar-98	21:42	M0159676	mar20_24	2
RSAT 27-Mar-98	21:55	M0160068	mar24_27	2
RSAT 30-Mar-98	22:07	M0161234	mar27_30	2
RSAT 03-Apr-98	21:51	M0161539	data error	2
RSAT 04-Apr-98	21:20	M0160916	mar30_apr4	2
RSAT 08-Apr-98	12:48		apr4_8	2
RSAT 10-Apr-98	21:47	M0162154	apr8_10	2
RSAT 11-Apr-98	21:18	M0162040	apr10_11	3
RSAT 12-Apr-98	12:31	M0162331	apr11_12	2
RSAT 13-Apr-98	12:02	M0162377	apr12_13	2
RSAT 13-Apr-98	21:59	M0162395	apr13_13	2
RSAT 15-Apr-98	12:44	M0162483	apr13_15	2
RSAT 17-Apr-98	21:42	M0162629	apr15_17	2
RSAT 18-Apr-98	21:13	M0162643	apr17_18	2
RSAT 20-Apr-98	11:58	M0162935	apr18_20	2
RSAT 20-Apr-98	21:55	M0162084	apr20_20	2
RSAT 23-Apr-98	22:07	M0162611	apr20_23	2
RSAT 24-Apr-98	21:38	M0162447	apr23_24	2
RSAT 27-Apr-98	11:53	M0162592	apr24_27	3
RSAT 27-Apr-98	21:51	M0162597	apr27_27	2
RSAT 28-Apr-98	21:20	M0163407	apr27_28	3

RSAT 30-Apr-98	22:03	M016295	apr28_30	2
RSAT 02-May-98	12:48	M0163561	apr30_may2	2
RSAT 04-May-98	21:47	c0009664	may2_4	2
RSAT 06-May-98	12:31	M01638601	may4_6	2
RSAT 07-May-98	12:02	M0163898	may6_7	2
RSAT 07-May-98	21:59	M0163369	may7_7	2
RSAT 10-May-98	12:14	c0009711	may7_10	2
RSAT 11-May-98	21:42	M0163502	may10_11	2
RSAT 14-May-98	11:58	M0164199	error	3
RSAT 14-May-98	21:55	M0163710	may14_14	3
RSAT 17-May-98	22:07	M0163917	may14_17	2
RSAT 18-May-98	21:38	M0163951	may17_18	3
RSAT 21-May-98	11:53	M0164572	may18_21	2
RSAT 21-May-98	21:51	M0164120	may21_21	2
RSAT 24-May-98	12:06	M0164808	may21_24	2
RSAT 24-May-98	22:03	M0164186	may24_24	2
RSAT 26-May-98	12:48	M0164867	may24_26	2
RSAT 27-May-98	12:19	M0164878	may26_27	2
RSAT 28-May-98	21:47	M0164995	may27_28	2
RSAT 31-May-98	12:02	c0009855	may28_31	3
RSAT 31-May-98	21:59	M0165209	may31_31	2
RSAT 02-Jun-98	12:44	M0165310	may31_jn2	2
RSAT 03-Jun-98	12:14	M0165368	jun2_3	2
RSAT 04-Jun-98	21:42	M0165017	jun3_4	2
RSAT 07-Jun-98	21:55	M0164932	june4_7	2
RSAT 10-Jun-98	12:10	M0165851	jun7_10	2
RSAT 10-Jun-98	22:07	M0165221	jun10_10	2
RSAT 11-Jun-98	21:38	M0165289	jun10_11	2
RSAT 14-Jun-98	21:51	M0165399	jun11_14	2
RSAT 17-Jun-98	12:06	M0166508	jun14_17	3
RSAT 17-Jun-98	22:03	M0165644	jun17_17	2
RSAT 18-Jun-98	21:33	M0166595	jun17_18	3
RSAT 19-Jun-98	12:48	M0166623	jun18_19	2
RSAT 20-Jun-98	12:19	M0166653	jun19_20	4
RSAT 21-Jun-98	21:47	M0166735	jun20_21	3
RSAT 24-Jun-98	12:02	M0166913	jun21_24	3
RSAT 24-Jun-98	21:59	M0166926	jun24_24	2
RSAT 26-Jun-98	12:44	M0167036	jun24_26	4
RSAT 28-Jun-98	21:42	M0167105	no overlap	2
RSAT 01-Jul-98	11:58	M0167117	no overlap	3
RSAT 01-Jul-98	21:55	c0010233	jul1_1	2
RSAT 02-Jul-98	21:25	M0166856	jul1_2	3
RSAT 04-Jul-98	22:07	M0166915	jul2_4	3
RSAT 05-Jul-98	11:40	c0010255	jul4_5	3
RSAT 05-Jul-98	21:38	M0166961	error	5

RSAT 08-Jul-98	11:53	M0167668	no overlap	3
RSAT 08-Jul-98	21:51	M0167696	jul18_8	3
RSAT 11-Jul-98	22:03	M0167320	jul18_11	3
RSAT 12-Jul-98	21:32	M0167369	jul11_12	4
RSAT 13-Jul-98	12:48	M0167964	no overlap	2
RSAT 13-Jul-98	21:06	M0167964	jul13_13	4
RSAT 14-Jul-98	12:19	M0168064	jul13_14	2
RSAT 15-Jul-98	21:47	M0168228	jul14_15	3
RSAT 18-Jul-98	12:02	M0168523	jul15_18	3
RSAT 19-Jul-98	21:30	M0168581	jul18_19	2
RSAT 22-Jul-98	21:42	M0168829	jul19_22	3
RSAT 23-Jul-98	21:13	M0168916	jul22_23	2
RSAT 27-Jul-98	12:38	M0169096	jul23_27	3
RSAT 28-Jul-98	12:10	M0169143	no overlap	4
RSAT 29-Jul-98	21:38	c00010522	jul28_29	3
RSAT 01-Aug-98	11:53	c00010557	jul29_aug01	2
RSAT 04-Aug-98	12:06	M0169758	aug01_04	2
RSAT 08-Aug-98	21:46	M0170193	aug04_08	3
RSAT 10-Aug-98	12:31	M0170249	aug08_10	2
RSAT 11-Aug-98	12:02	M0170329	aug10_11	2
RSAT 14-Aug-98	12:15	M0170543	aug11_14	2
RSAT 18-Aug-98	11:57	M0170795	aug14_18	2
RSAT 21-Aug-98	12:10	M0170978	aug18_21	2
RSAT 24-Aug-98	12:23	M0171118	aug21_24	2
RSAT 28-Aug-98	12:06	M0171405	aug24_28	2
RSAT 01-Sep-98	21:46	M0171747	aug28_sept1	2
RSAT 04-Sep-98	12:02	M0171909	sept01_04	2
RSAT 05-Sep-98	21:30	M0171953	sept4_5	2
RSAT 08-Sep-98	21:42	M0171581	sept5_8	2
RSAT 11-Sep-98	21:55	M0171697	sept8_11	3
RSAT 14-Sep-98	12:11	M0172391	sept11_14	2
RSAT 21-Sep-98	12:05	M0172749	sept14_21	3
RSAT 24-Sep-98	12:19	M0172862	sept21_24	2
RSAT 27-Sep-98	12:30	M0173064	sept24_27	3
RSAT 28-Sep-98	12:01	M0173116	sept27_28	3
RSAT 28-Sep-98	21:42	n/a	sept28_28	2
RSAT 01-Oct-98	12:15	M0173613	sept28_oct01	2
RSAT 02-Oct-98	21:42	M0173160	oct1_2	2
RSAT 04-Oct-98	12:26	M0173172	oct2_4	3
RSAT 05-Oct-98	11:59	M0173849	oct4_5	2
RSAT 05-Oct-98	21:55	c0011143	oct5_5	2
RSAT 06-Oct-98	21:25	M0172983	oct5_6	2
RSAT 09-Oct-98	21:38	M0173649	oct6_9	3
RSAT 11-Oct-98	12:22	M0174291	oct9_11	3
RSAT 12-Oct-98	11:53	M0174343	no overlap	3

RSAT 13-Oct-98	21:21	M0173719	oct12_13	2
RSAT 14-Oct-98	12:36	M0174455	oct13_14	2
RSAT 15-Oct-98	12:06	M0174473	oct14_15	2
RSAT 15-Oct-98	22:03	M0173864	oct15_15	2
RSAT 17-Oct-98	12:48	M0174616	oct15_17	2
RSAT 17-Oct-98	21:04	M0174663	oct17_17	2
RSAT 18-Oct-98	22:15	M0173986	oct17_18	3
RSAT 19-Oct-98	11:50	M0174795	oct18_19	2
RSAT 19-Oct-98	21:46	M0174835	oct19_19	3
RSAT 20-Oct-98	21:18	M0174115	oct19_20	2
RSAT 22-Oct-98	12:02	M0175058	oct20_22	2
RSAT 22-Oct-98	22:00	M0174657	oct22_22	2
RSAT 23-Oct-98	21:29	M0174694	oct22_23	2
RSAT 25-Oct-98	12:14	M0175306	oct23_25	3
RSAT 26-Oct-98	11:45	M0175332	no overlap	2
RSAT 26-Oct-98	21:43	M0174677	oct26_26	2
RSAT 29-Oct-98	21:56	M0174826	oct26_29	2
RSAT 30-Oct-98	21:25	M0175869	oct29_30	2
RSAT 01-Nov-98	12:09	M017592301	oct30_nov1	4
RSAT 02-Nov-98	21:38	M017509401	nov01_02	3
RSAT 05-Nov-98	11:54	M017621901	nov02_05	2
RSAT 05-Nov-98	21:49	M017532501	nov05_05	3
RSAT 06-Nov-98	21:20	M017552301	nov05_06	4
RSAT 08-Nov-98	12:05	M017647001	nov06_08	3
RSAT 08-Nov-98	22:03	M017583801	nov08_08	3
RSAT 09-Nov-98	21:33	M017585301	nov08_09	3
RSAT 11-Nov-98	22:15	M017634001	nov09_11	3
RSAT 12-Nov-98	21:46	M017678501	nov11_12	3
RSAT 14-Nov-98	12:31	M017701801	nov12_14	3
RSAT 15-Nov-98	21:59	M0176297	bad data	3
RSAT 19-Nov-98	21:42	M017678001	bad data	2
RSAT 21-Nov-98	12:26	M017736301	bad data	4
RSAT 22-Nov-98	11:58	M017742101	bad data	2
RSAT 22-Nov-98	21:54	M017671801	bad data	3
RSAT 23-Nov-98	21:25	M017678701	nov22_23	3
RSAT 26-Nov-98	11:42	M017732801	no overlap	2
RSAT 26-Nov-98	21:38	M017717301	nov26_26	2
RSAT 29-Nov-98	11:53	M017793901	nov26_29	3
RSAT 03-Dec-98	21:34	M017786501	nov29_dec3	2
RSAT 06-Dec-98	21:46	M017839901	dec3_6	3
RSAT 07-Dec-98	21:16	M017841701	dec6_7	3
# of frames				411
# of swaths				170
Tracker pairs				148

Appendix C

Tracker and Beacon Magnitudes and Direction

Tracker Pair	Beacon #	# of Days Between Images	Tracker Distance (m)	Tracker Distance (km)	Absolute Beacon & Tracker Difference in km	Tracker Angle from North (degrees)	Tracker Angle from North (degrees)	Absolute Beacon & Tracker Difference in degrees
Apr28 30w	47548	2	56.18	61.86	5.68	215.44	202.72	12.72
Apr30 m2	47548	1.5	25.48	24.76	0.71	194.46	196.23	1.77
May2 4	47548	2.5	16.42	16.30	0.12	210.08	210.91	0.83
May2 4w3	47550	2.5	18.52	16.32	2.21	143.32	142.03	1.29
May4 6w	47548	2	13.75	10.32	3.43	310.50	321.02	10.52
May4 6	47550	2	38.54	33.76	4.78	340.39	341.72	1.33
May6 7	47548	0.5	0.33	0.27	0.06	269.99	325.42	55.43
May7 7	47550	0.5	12.02	14.43	2.42	206.27	198.73	7.54
May7 7	47548	0.5	1.56	1.68	0.12	175.29	173.87	1.42
May10 11	47548	1.5	28.52	28.62	0.10	186.27	187.90	1.63
May10 11w	47550	1.5	37.51	44.73	7.21	177.11	187.44	10.33
May 14 14	47548	0.5	2.28	1.45	0.83	193.03	185.33	7.70
May 14 14	47550	0.5	7.71	7.78	0.07	164.94	166.33	1.39
May 14 17	47550	3	20.76	21.82	1.06	165.63	167.91	2.28
May 14 17	47548	3	25.29	31.61	6.31	242.63	221.24	21.39
May 17 18	47550	1	12.11	12.75	0.64	310.14	310.36	0.21
May 17 18	47548	1	18.79	26.00	7.22	287.53	248.59	38.94
May 21 21	47550	0.5	7.94	10.41	2.47	186.42	186.81	0.39
May 21 24	47550	2.5	11.98	11.09	0.89	198.87	205.62	6.75
May 24 24	47548	0.5	4.03	3.67	0.36	52.57	68.61	16.04
May 24 24	47550	0.5	1.79	1.73	0.07	244.33	205.78	38.55
May 24 26	47548	1.5	8.64	10.92	2.28	57.17	40.98	16.19
may27 27w	47548	1	4.07	4.37	0.29	249.28	262.76	13.47
May 27 28	47550	1	17.56	16.79	0.77	319.09	321.58	2.48
May28 3b1	47550	2.5	11.53	6.80	4.73	216.04	234.03	18.00
May31 31b	47550	0.5	7.22	1.10	6.13	189.94	307.53	117.59
May31 31a	47548	0.5	5.83	8.75	2.91	86.63	248.50	161.87
Jun2 3	47548	1	10.36	13.57	3.21	158.96	192.89	33.93
Jun2 3	47550	1.5	7.55	9.19	1.64	189.31	207.99	18.67
Jun3 4	47550	1.5	17.31	16.90	0.41	138.52	138.40	0.12
June4 7	47550	3	13.04	11.90	1.14	351.49	358.74	7.25
June10 10	47550	0.5	1.92	1.75	0.17	79.96	86.32	6.36
June10 11	47550	1	4.05	5.41	1.37	24.99	25.34	0.35
June18 19	47559	0.5	10.10	6.16	3.94	279.08	287.99	8.91
June20 21	47550	1.5	10.45	10.02	0.43	178.87	167.39	11.48
June20 21	47559	1.5	14.75	9.92	4.84	174.06	192.81	18.76
June21 24	47559	0.5	45.35	47.38	2.03	333.54	324.58	8.97
Jul1 1	47548	0.5	3.63	11.31	7.68	222.75	224.32	1.57
Jul1 1	47550	0.5	3.13	5.10	1.97	112.97	111.67	1.29
Jul1 1	47559	1	15.40	23.72	8.33	163.72	128.95	34.77
Jul1 2	47550	0.5	6.19	4.85	1.35	229.84	258.18	28.34
Jul4 5	47548	0.5	9.34	11.95	2.61	76.08	50.62	25.46
Jul4 5	47548	3	3.64	7.71	4.07	45.36	31.70	13.66
Jul8 11	47550	2.5	35.99	44.43	8.44	124.41	127.11	2.70
Jul 15 18	47550	2.5	25.03	22.99	2.04	275.50	282.65	7.15
Nov2 5	47556	2.5	21.01	30.90	9.89	236.17	193.85	42.32
Nov5 5	47556	0.5	16.83	17.80	0.96	236.07	259.48	23.41
Nov8 8	47556	0.5	15.10	16.65	1.55	123.33	117.64	5.68
Nov11 12	47556	1	6.24	5.61	0.63	90.92	78.48	12.44
Nov12 14	47556	1.5	19.94	22.15	2.21	133.97	143.23	9.26
Nov26 26	47556	0.5	5.49	3.35	2.14	510.50	354.36	156.14
Nov26 29	47556	2.5	25.05	33.44	8.38	134.26	139.57	5.31
Dec3 7	47556	3	42.14	41.74	0.40	144.53	145.32	0.79
Dec7 7	47556	1	32.50	29.66	2.84	152.17	141.67	10.50
54								
Mean		1.4	15.5	16.6	1.1	200.8	208.6	7.8
Std		0.9	12.5	13.8	1.3	101.4	94.1	-7.3
Min		0.5	0.3	0.3	0.0	25.0	25.3	0.3
Max		3.0	56.2	61.9	5.7	351.5	358.7	7.2
Converted from scalar to linear, see Table 4.4.								
Values calculated using equations 4.8 - 4.10								

Appendix D

1998 NOW Ice Motion and Wind Maps (Weeks 4-26)

Fig. 5.6b Week4: January 18 – 24 1998

Fig. 5.6c Week 5: January 25 – 31 1998

Fig. 5.6d Week 6: February 1 – 7 1998

Fig. 5.6e Week 7: February 8 – 14 1998

Fig. 5.6f Week 8: February 15 – 21 1998

Fig. 5.6g Week 9: February 22- 28 1998

Fig. 5.6h Week 10: March 1 - 7 1998

Fig. 5.6i Week 11: March 8 - 14 1998

Fig. 5.6l Week 14: March 29- April 4 1998

Fig. 5.6m Week 15: April 5- 11 1998

Fig. 5.6n Week 16: April 12 - 18 1998

Fig. 5.6o Week 17: April 19 - 25 1998

Fig. 5.6p Week 18: April 26 – May 2 1998

Fig. 5.6q Week 19: May 3 - 9 1998

Fig. 5.6r Week 20: May 10 - 16 1998

Fig. 5.6s Week 21: May 17 - 23 1998

Fig. 5.6t Week 22: May 24 - 30 1998

Fig. 5.6u Week 23: May 31 - June 6 1998

Fig. 5.6v Week 24: June 7 – 13 1998

Fig. 5.6w Week 25: June 14 – 20 1998

Fig. 5.6x Week 26: June 21 – 27 1998