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Relationships in Areal Variability:
The Ross Sea Polynya and Ice

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in Geography

by

Jason Michael Ward

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ABSTRACT OF THE THESIS

Relationships in Areal Variability: The Ross Sea Polynya and Ice

by

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Master of Arts in Geography
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Professor Marilyn N. Raphael, Chair

General increases in Antarctic sea ice coverage occur primarily in the Ross Sea. This study investigates the Ross Sea Polynya’s relationship with the Ross Sea ice areal coverage. A unique, relatively long term Ross Sea Polynya area dataset was created through the application of the Polynya Signature Simulation Method (PSSM) onto Special Sensor Microwave Imager (SSM/I) data inputs. Bivariate regression analyses were used to determine the relationships, at the 95% confidence level, between Ross Sea Polynya and ice areal trends, annual seasonalities, and anomalies at the full temporal scale as well as the monthly level. Polynya and sea ice have significant positive relationships in the late austral summer and early spring (February to March), and a significant negative relationship in the late austral winter (August). The areal anomalies only had a significant relationship in February, while the trends were not correlated at any time.
The thesis of Jason Michael Ward is approved.

Yongwei Sheng

Yongkang Xue

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1. Introduction

*Importance of sea ice to regional and global climate*

The presence of sea ice in the Polar Regions has effects on the global climate. Sea ice contributes to processes such as atmospheric carbon sequestration (Arrigo and van Dijken 2003), the ocean-atmosphere gas transfer (Gloersen et al. 1993), the surface heat budget (Ohshima et al. 2003), and the Thermohaline Circulation (Beckmann et al. 1999). In addition, sea ice greatly affects planetary albedo through its relatively high reflectivity (Grenfell 2004). Albedo mitigates temperature increase through the reflection of incoming shortwave radiation back into space. The dominant presence of sea ice, and therefore high albedo, in the Polar Regions creates a negative annual net solar energy flux. This is in contrast to the net annual solar energy flux experienced in the Tropics, which is largely positive. This energy gradient, and subsequent temperature gradient, is the primary driver for equator-to-pole energy transfer processes such as the Hadley Circulation (Hu 2007) and large-scale ocean eddies (Chelton et al. 2007). Polar sea ice extents have strong seasonality, and as a result, the influence of sea ice variability is of particular significance in regards to climatic states (Allison et al. 1993).

The physical properties of sea ice play a great role in influencing the state of global, regional, and local climates. The reduction in heat exchange greatly lowers emission of long wave radiation to the atmosphere. In turn, the polar atmosphere receives significantly more energy in local areas above open water versus areas above the pack ice (Andreas et al. 2002). This affects local and regional temperature, pressure, and wind speed and direction (Adolphs et al. 1995). Sea ice additionally has oceanic linkages to Earth's global system. The process of sea ice formation induces an influx of high-density water to the deep ocean, which feeds the
Thermohaline Circulation (Beckmann et al. 1999). Through its contribution to the Thermohaline Circulation, sea ice is able to extend its influence beyond the Southern Ocean.

This paper focuses on the sites in which sea ice production is continuously possible. These sites are open water areas known as polynyas. Polynyas range in size from tens to hundreds of square kilometers, and are surrounded on all sides by ice (Drucker et al. 2011). They may occur adjacent to the coastline or away from shore (Willmott et al. 1997). Polynyas located along the coast are the ones in which sea ice generation takes place, and are therefore the main focus of this paper (Kern 2009; Marshland et al. 2007). While polynyas are found in both Polar Regions, only in the Antarctic can they be investigated within a sea ice increasing context.

The Antarctic is an interesting place for sea ice research because of the increasing trends in extent, concentration, ice cover duration, and areal coverage (Liu et al. 2004; Comiso 2010; Stammerjohn et al. 2012; Maksym et al. 2012). This observation is a direct contradiction to the story being told in the Arctic, which underwent decreases in these sea ice characteristics over the last four decades. As shown in Figure 1, the change in sea ice extent differs between the Arctic and Antarctic. Mean annual Arctic sea ice coverage has decreased at a rate of ~3% per decade, while Antarctic sea ice coverage has increased approximately 1% per decade (NSIDC 2013). Not only do the northern and southern Polar Regions have dissimilar changes in sea ice coverage, their trends are in opposite directions (Cavalieri and Parkinson 2008). The decline in Arctic sea ice agrees with the anticipated and intuitive effects within a global warming context. The observation of sea ice change in the Antarctic is a counter-intuitive phenomenon.
Figure 1:
Arctic sea ice extent underwent a strong decline from 1979 to 2011, but Antarctic sea ice underwent a slight increase, although some regions of the Antarctic experienced strong declining trends in sea ice extent. Thick lines indicate 12-month moving average, and thin lines indicate monthly anomalies (NSIDC 2013).

Currently, interactions between polynyas and sea ice are not fully understood. As we have seen, sea ice distribution as well as polynyal processes and sizes vary regionally. Having a proper understanding of the links between polynya size and sea ice coverage will give us better insight into polynyas’ susceptibility to and influence on climatic changes. This study investigates the relationship between polynya and sea ice areal variability, particularly within the Ross Sea, Antarctica. To do so, a unique relatively long term polynya size dataset will be created as the first result of this project. Then, the relationship between polynya and sea ice area will be tested for strength and direction of correlation. Also, if polynya contribution to sea ice variability is variable itself, this study will provide the initial steps that will allow us to determine how it can fit into the global picture of change for the Antarctic sea ice field. This will be the first study to
examine a relatively long-term dataset to empirically verify the relationships between polynyas and sea ice.

2. Polynyas

*Areas of Open Water*

Open water regions cover ~1% of the sea ice extent (Smith et al. 1990; Tamura et al. 2008). The study of these areas is of great interest to atmospheric scientists and physical oceanographers (Anderson 1993; Kottmeier and Engelbart 1992; Smith et al. 1990), as they connect the ocean to the atmosphere, which allows interaction between the two mediums (Allison et al. 1993). In particular, they enable the transfer of heat and energy. Considerable contrast between the warm dark ocean, which absorbs and stores heat, and the cold light pack ice, which reflects solar radiation, causes major discrepancies in heat absorption between the two surface types. In turn, there are disparate levels of energy transfer through turbulence and radiation. During winter, the oceanic heat flux is estimated to be up to two orders of magnitude greater than the heat flux from thick pack ice cover. Thus, even when thick pack ice dominates the surface cover of a region, the minimal presence of open water and snow-free thin ice is able to dominate the regional heat budget (Maykut 1978; Ledley 1988; Worby and Allison 1991). During the spring and summer seasons, these areas absorb greater than 90% of incoming solar radiation. Conversely, snow-covered surfaces have a typical albedo of ~0.8 – which means they absorb roughly 20% of solar radiation (Hall and Rothrock 1987).

The open water areas may be identified by two classifications - leads and polynyas. Leads are long narrowly shaped openings in pack ice that form from local divergences caused by drifting ice floes. They reach up to hundreds of meters in width and tens of kilometers in length. The atmospheric processes associated with leads and polynyas are the same. Large air-sea winter
temperature differences between their surfaces and pack ice are typically 20°-40°C. The heat fluxes from them both depend on temperature and wind speed, duration, and horizontal displacement. Creation of coastal polynyas and leads are attributed to the divergence of ice. In this respect leads share important characteristics with polynyas (Smith et al. 1990). Even with these similarities, there are salient differences between leads and polynyas.

Though leads assume a certain level of locational predictability, they are very mobile features that typically only last up to weeks at a time (Marko and Thomson 1975; 1977). They are most prevalent in areas of thinner ice and marginal ice zones (Smith et al. 1990). They have been observed as close as 5 km to each other and as far as 275 km apart (Wadhams et al. 1985).

In the winter season, newly formed leads are able to freeze over in less than 24 hours (Bauer and Martin 1983). They may also close as a result of converging ice floes (Smith et al. 1990). When a lead freezes over, the new ice is thin and more susceptible to fracturing. In this situation, convergence of ice drifts may result in the opening of a lead. When the young ice is compressed from the sides, it ruptures leaving floating blocks of ice, which later freeze and create an ice ridge (Parmeter and Coon 1972).

Unlike leads, polynyas are areas of open water and thin ice that are surrounded by pack ice and occur in virtually the same locations at all times. Polynyas are primarily winter features that appear when air temperatures are far below the freezing point for sea water. They are typically rectangular or elliptical in shape and range from hundreds of meters to hundreds of km in length (Smith et al. 1990). Figure 2 displays three distinct polynyas. These polynyas (dark blue) are significantly darker than the surrounding cryosphere (white).
Figure 2:
Image of western Ross Sea region. Three distinct coastal polynyas are visible – Terra Nova Bay Polynya (left), Ross Sea Polynya (right), and McMurdo Sound Polynya (bottom) (NASA 2011).

The reoccurring nature of polynyas makes them important biological habitats, which make them important in biological studies (Anderson 1993; Kottmeier and Engelbart 1992; Smith et al. 1990). They are reliable when it comes to providing the first open water sites for biological activity to take place in the spring season, which allows them to house the greatest biological activity in the Southern Ocean. They also provide large animals with access to aquatic environments from the ice surface for hunting (Arrigo and van Dijken 2003). Even human populations have used polynyas in hunting 3,000 years ago (Smith et al. 1990).

Polynyas are found within the Arctic and Antarctic because the temperatures there are constantly low enough for formative processes to occur. Within these regions, the surface of the ocean reaches temperatures of -2°C, at which point sea water freezes. There are two mechanisms responsible for polynya development – sensible heat convection and latent heat transfer, which cause advection (Arrigo and van Dijken 2003). Figure 3 displays the spatial distribution of Antarctic coastal polynyas. The colored polygons about the continent represent approximately evenly distributed coastal polynyas.
Figure 3:
Map of the Antarctic showing locations of 37 coastal polynyas. Variable colored areas indicate polynya areas (Arrigo and van Dijken 2003).

Processes in Polynya Formation

Sensible Heat Processes

Sensible heat polynyas are formed through the transport of sensible oceanic heat to the ocean’s surface in sufficient quantities to reduce local ice cover and prevent new ice from forming. The heat moves down the gradient of energy caused by the relatively lower atmospheric temperatures. As a result, energy is transferred upward from the ocean to the atmosphere. The loss of energy from the surface is balanced by energy transported from the ocean below. The inflow of energy maintains the local open water surface area. Upward heat transfer may come about either through vertical mixing of the ocean layers or through convection of heat through upwelling. A significant temperature gradient between the ocean surface and the deeper ocean causes heat to quickly transfer through the water. Also, wind-transported water at the surface is replaced by water from below. The displaced surface water is cool, while the deeper water is relatively warmer and therefore holds more energy. With vertical mixing, oceanic heat is made available to erode the underside of the ice cover. As ice floes drift into a sensible heat polynya, they are melted by the warm water convection. The transfer of sensible heat through the oceanic
environment is significant enough to stabilize polynyas over sizeable areas. They can be as small as 1 km$^2$ (Smith et al. 1990), such as the Dundas Island Polynya. While more rare, the right oceanic and atmospheric conditions may stabilize a sensible heat polynya of 200,000 km$^2$ in area, as with the Weddell Polynya (Holland 2001; Smith et al. 1990).

The Weddell Polynya is a prime example of a sensible heat polynya (Smith et al. 1990). It was present from 1974 to 1976 (Carsey 1980; Parkinson 1983; Zwally et al. 1985), and has not returned since. It was caused by widespread divergence and resultant upwelling of warm water. The regional conditions that allowed the persistence of the Weddell Polynya created a very unstable water column and sensible heat convection ensued. While not always at a magnitude sufficient enough for a Weddell Polynya sized feature, these conditions are far more typical in the Southern Ocean than in the Arctic (Smith et al. 1990).

*Latent Heat Processes*

Latent heat transfer within polynyas is the result of temperature and moisture gradients between atmospheric and oceanic environments. Unlike the Arctic, the Antarctic has relatively warm sea surface temperatures and below freezing atmospheric temperatures. As a result, the directionality of vertical heat transfer is towards the atmosphere. The loss in energy from the ocean surface results in the production of frazil ice crystals. Frazil ice is the most typical type of sea ice produced in the Antarctic. The process associated with frazil ice formation is the prevalent in the Antarctic due to the water turbulence caused by frequent storms (Stammerjohn et al. 2012).

Continuous frazil ice formation eventually leads to coalescence and development of pancake ice, which are disk-shaped ice features. The agglomeration of pancake ice into ice sheets allow for snow ice to develop as precipitation falls onto the ice cover (Stammerjohn et al. 2012).
For open water areas to be maintained under freezing climatic conditions energy must be added to the ocean surface through convection or advection processes. Advective processes are more prevalent in areas of sea ice production. As the ice forms it is simultaneously advected away by wind and water currents. Equilibrium between ice formation and ice advection maintains the size of the open water area.

Certain groups of polynyas are found to be areas where latent heat transfer and ice formation processes are regular. These polynyas are called “latent heat polynyas”. A prime example of a latent heat polynya is the Terra Nova Bay Polynya found in the Ross Sea, Antarctica (Bromwich and Kurtz 1984). As the climate cools the temperature gradient between the Ross Sea surface and the atmosphere increases and latent heat is transferred from the water. As ice is produced, winds transport it northward. With the positioning of the Drygalski Ice Tongue, the other ice floes are blocked from flowing into the bay, which leaves the bay surface clear (Bromwich and Kurtz 1984).

*Combination of Heat Transfer Processes in Polynya Formation*

The two distinct processes of polynya formation are not mutually exclusive. In fact, in many cases, they both contribute to the formation and maintenance of polynyas (Smith et al. 1990). Wind advection and sensible heat transfer through upwelling may act in tandem upon a single polynya. In which case, one mechanism may establish an environment in which the other mechanism is then able to develop. For instance, when heat exchange across the air-water boundary is directed towards the atmosphere, the oceanic surface layer undergoes a decrease in temperature (Smith et al. 1990; Gordon et al. 2007). The absence of an adequate alternative heat source to replace the heat lost over a sufficient duration of time leads to the eventual freezing of the ocean surface. Accompanied by ice formation is the rejection of brine back into the ocean. As
the surface layer becomes cooler, it also becomes more saline, and its density increases. The continuation of this process allows for the increasingly dense water to become denser than water at lower depths and lose buoyancy (Smith et al. 1990; Fiedler et al. 2010). The surface layer water sinks while deeper water is entrained upward to take its place. Through this upwelling process, less saline, warmer water is transported to the surface. The introduction of a new heat source locally melts ice at the surface (Smith et al. 1990). With the exposure of the open water, the polynya is maintained by continual heat flux to the polynya surface. However, the polynya may also be maintained by currents, which advect ice from the polynya. The combination of vertical mixing and wind advection worked to produce the Weddell Polynya and other polynyas like it (Smith et al. 1990).

*Offshore Polynyas*

There is a relationship between the dominant formative mechanism used in polynya development and its location. Offshore polynyas are groups of polynyas that are located away from a shoreline (Gordon et al. 2007). They are typically smaller and occur less frequently than their coastal counterparts (Zwally et al. 1985). These polynyas arise from convection of sensible heat (Gordon 1981). Sensible heat polynyas normally occur away from any coastline because out in the open ocean the water column is relatively warm compared to locations adjacent to a coastline. When the surface temperatures fall and surface water loses its buoyancy, vertical heat transfer or mass exchange takes place between the dense surface water and the buoyant warmer water at lower depths. For this reason, these polynyas are also known as “deep water” or “open ocean” polynyas.
**Coastal Polynyas**

Coastal polynyas are rectangular or elliptical-shaped stationary features that persist year-round. When the continental shelves still have ice covering them, the coastal polynyas remain and expand northward. As they do so, they extend closer to the northern ice edge boundary (Comiso et al. 2011). The mark of coastal polynyas is that they are established near a fixed coastline, usually within 1 km of a land mass, ice shelf, or ice berg that exists within the pack ice (Drucker et al. 2011). The coastlines form the southern boundaries of coastal polynyas, while wind strength and direction determine the position of the other polynya boundaries (Adolphs and Wendler 1995). For coastal polynya development, winds and oceanic currents move pass the fixed coastline boundary and advect sea ice away from the shore, which is the process associated with latent heat polynyas. Therefore, the primary mechanism for coastal polynya development is sea ice advection. The stability of latent heat polynyas relies on rates of sea ice export from wind and water currents that are greater than rates of sea ice formation through latent heat release (Smith et al. 1990). While there may be a sensible heat component, these polynyas are not primarily driven by this mechanism because in typical cases, particularly with larger, more prominent polynyas, the subsurface cooling provided by ice shelves influences the water column. The water columns are relatively shallow and consist of cooler, dense water (Tamura et al. 2007). Therefore, upward convection from greater ocean depths is not initiated.

Coastal polynyas depend greatly on ice advection via katabatic winds to extend and maintain the polynya boundaries (Bromwich et al. 1984). Katabatic winds are downslope, seaward directional thermal winds. During the cold season, a strong atmospheric pressure gradient forms between neighboring continental and marine environments (Renfrew et al. 2002). The pressure gradient is caused by unequal amounts of radiation emission, and sensible and
latent heat transfer from the surface. In the warmer part of the year, the difference in heating between the sea surface and the land environment is smaller and less significant (Renfrew et al. 2002). When katabatic winds move seaward they transfer momentum onto the sea ice and create northward advection. Separation of the sea ice from the fixed shoreline creates and maintains an opening within the ice cover (Arrigo and van Dijken 2003). Due to the fact that these wind systems are the driving forces behind ice advection and coastal polynya formation, spatial and temporal differences in wind intensities cause variability in polynya area (Adolphs et al. 1995).

Katabatic winds act in part to reduce areas of sea ice concentration. They are stronger in the Adelie Land region than any other place throughout the Antarctic continent, and because of this polynyas in that region are able to grow to relatively large sizes (Adolphs et al. 1995). Katabatic winds normally reach 10 to 20 km offshore (Kurtz and Bromwich 1985), but in the Adelie Land region they extend much farther. As a result of the comparatively strong katabatic winds in Adelie Land, areas of reduced ice cover were found over 100 km from the shore in the winter (Zwally et al. 1985).

The intensity of katabatic winds may be heightened due to synoptic scale processes. For instance, a persistent northward flowing geostrophic wind will greatly impact offshore propagation of katabatic wind, and therefore coastal polynya development. Not only do relatively larger scale processes affect wind strength, but they affect wind direction as well. However, the influence of the large scale processes are much greater on wind strength compared to direction (Parish et al. 1993).

In the past, popular thought backed the notion of a virtually one-way link between the atmosphere and sea ice, with the direction of influence leading towards the sea ice. However, sea ice morphology is able to create changes in atmospheric conditions as well (Cavalieri and
Parkinson 1981). The presence of open water and thin ice in the winter allow a significantly greater surface temperature than the surface of the Antarctic land ice and continent. As a result, a large temperature gradient is formed between the continental ice and the open water. Thus, a thermal wind is generated, which causes a positive feedback on katabatic wind strength. With thermal winds augmenting katabatic wind intensity, the offshore winds are better able to advect sea ice northward and maintain the meridional temperature gradient (Adolphs et al. 1995).

The temperature gradient between the continent surface and open water coastal areas is greatest in winter due to minimal insolation incident upon the continental surface, which augments katabatic wind strength. In austral spring and autumn seasons, the circumpolar trough around the Antarctic continent experiences minimum barometric levels. This directly enhances katabatic winds by increasing the pressure gradient between the continental surface and the open water (Adolphs et al. 1995).

**Sea Ice and Water Mass Modification**

While polynyas are of great interest for their roles in macro- and micro- biological activities, local and regional heat budgets, small scale human activities, and more, their greatest geographical influence is seen in their contribution to modulating global oceanic temperatures. This is accomplished via sea ice generation and bottom water formation. For this research, the contribution of polynyas to Antarctic sea ice formation is explored.

Simply stated, sea ice forms from freezing ocean water. The surface freezes as heat is transferred from the ocean to the atmosphere causing surface water temperature to drop. Major ice production primarily occurs in shallow shelf regions because the entire water column is near freezing (Tamura et al. 2007). Offshore polynyas are able to balance heat lost to the atmosphere with heat added from below (Goosse and Fichefet 2001). Since the water column is cooler along
the coast, heat lost from coastal polynyas is not balanced from a source below. Instead, it is balanced from release of latent heat at the surface. This causes the bonds in water molecules to strengthen and freeze into ice (Adolphs et al. 1995).

Many polynyas serve as sites for sea ice production. In particular, the coastal polynyas bordering Antarctic’s lee coastlines during winter are known as “ice factories” (Barber and Massom 2007). Tamura et al. (2008), Kern (2009), and others measure polynya sea ice productivity in terms of areal measurements. Tamura et al. (2008), in particular, declares that polynya-produced sea ice constitutes approximately 10% of the ice in the Southern Ocean. This is calculated using sea ice extent, which is a 2-dimensional measure. Due to the spatial inconsistencies in sea ice thickness, the proportion of sea ice coverage from polynyal activity may not equate to the proportion of actual sea ice produced in polynyas. A greater understanding of the degree of sea ice presence and the proportion of sea ice generated through polynyal processes can be attained through identifying sea ice thickness and including the 3-dimentional spatial measures in polynya-sea ice analyses.

3. Antarctic Ice Geography

Antarctica is a place like no other on the planet. It consists of a large landmass at the pole covered by a 3.2 km thick ice sheet. About 10% of the continental ice sheet extends beyond the land, creating shallow overhanging ice shelves. Figure 4a shows the distribution of the major Antarctic ice shelves. Beyond the shelf and land ice the open ocean. The continent is surrounded by the Southern Ocean, which is the result of the subtropical convergence of the Pacific, Atlantic, and Indian Oceans (de Blij 1978). Along the continental margins exist smaller scale bodies of water. Figure 4b is a schematic of the Antarctic continent and the major water bodies in the Southern Ocean. It displays three oceans that converge to form the Southern Ocean – the
Pacific, Atlantic, and Indian – and five major seas – the Ross, Weddell, Amundsen, Bellingshausen, and Cosmonaut.

**Figure 4a:** Antarctic ice shelves and their distances covered along the coastline (NSIDC 2010).

**Figure 4b:** Major water bodies – oceans and seas – within the Antarctic Polar Region (Comiso and Steffen 2001).

Every year, the Southern Ocean partially freezes over and essentially extends the boundary of the Antarctic continent (de Blij 1987). Sea ice covers a significant portion of the earth’s ocean. Its variability in spatial and temporal coverage, thickness, and concentration allows it to elicit pronounced effects in local, regional, and global climates. Particularly in the Southern Ocean, it drives many physical processes. Its spatial distribution has a strong seasonal pattern due to the disparate levels of insolation during the austral winter and summer seasons.
Unlike in the northern hemisphere, the expansion of Antarctic sea ice towards the equator is not limited by land boundaries. In addition, Antarctic sea ice is located in relatively low latitudes (60° – 70° south), which situates it in a relatively warmer climate, as compared to the true poles (90° north and south). With its open-ended northern extent and latitudinal location, Antarctic sea ice is located in relatively low latitudes (60° – 70° south), which situates it in a relatively warmer climate, as compared to the true poles (90° north and south). With its open-ended northern extent and latitudinal location, Antarctic sea ice is greatly influenced by seasonal temperature changes with yearly melting in the austral spring and summer succeeded by refreezing in the austral winter. In fact, the ice pack expands up to ~19 million km² during the September winter maximum from ~3 million km² during the February summer minimum (Maksym et al. 2012). The ~16 million km² areal fluctuation alters the surface properties of an area comparable to the size of South America (Allison et al. 1993). With an areal fluctuation of this magnitude sea ice possesses substantial influence on large-scale climates.

This massive Antarctic winter ice sheet is not homogeneous. Rather, it is a dynamic hybrid of water, ice, and snow at different stages of development (Allison et al. 1993). For example, in the east Antarctic, spring sea ice concentration is 80% to 100%. However, much of it is thin, young ice that is less than 0.3 meters in thickness, and is dynamic with drifting floes (Allison 1989). Contrasted to the sea ice thickness that reaches up to 1.5 meters in the Weddell Sea (Zwally et al. 2008). There are also areas of varying sea ice coverage, extent, and concentration. As shown in Figures 5a and 5b, the Bellingshausen/Amundsen sector has experienced the most significant decrease in sea ice concentration. This is not only countered, but also surpassed by the significant increase in sea ice observed in the Ross Sea.
**Figure 5a:**
The spatial trends of the Antarctic sea ice concentrations (%; shaded) spanning 1979-2002 derived from the SMMR/SSMI. Contours give the trends above the 95% confidence level. The maximum positive (negative) ice trend is marked by P (N) (Liu et al. 2004).

**Figure 5b**
Trends (days/year) over 1979/80 to 2010/2011 in ice season duration for the Antarctic. The black solid contour delineates the sub-regions reported in Table 1 – the Antarctic Peninsula and Bellingshausen (AP/B) region and the western Ross (wR) region, while the black dotted contour delineates those trends with significance at the p<0.01 level, with standard error determined using the effective degrees of freedom present in the regression residuals. The upper and lower ranges on the colorbars are designated as >= and <=, respectively (Stammerjohn et al. 2012).

The distribution of Antarctic sea ice characteristics and their long-term changes are spatially variable (Cavalieri and Parkinson 2008). Through the previous three decades, the Ross Sea has experienced the greatest positive trend in sea ice concentration, extent, and duration, while the Bellingshausen and Amundsen Seas have experienced the most significant decrease in concentration, extent, and duration. The trends of these sea ice characteristics are statistically
significant in both regions. During the same time period, the Weddell Sea and Indian Ocean sectors have experienced slight increases in concentration, extent, and duration. The Western Pacific Ocean sector has experienced a slight increase in concentration with virtually no change in extent and duration (Liu et al. 2004; Comiso 2010; Stammerjohn et al. 2012; Maksym et al. 2012). Figure 5a and 5b and Table 1 show 20 to 30 year trends for sea ice concentration, extent, duration, respectively.

<table>
<thead>
<tr>
<th>Sector/season</th>
<th>Trend in extent km²/yr (%/decade)</th>
<th>Error in extent km²/yr (%/decade)</th>
<th>Trend in area km²/yr (%/decade)</th>
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<td>2,520 (0.2)</td>
<td>19,100 (1.9)</td>
<td>2,360 (0.2)</td>
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<td>1,920 (0.5)</td>
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<td>1,080 (0.6)</td>
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<td>Western Pacific Ocean</td>
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<td>895 (0.7)</td>
<td>2,500 (2.7)</td>
<td>758 (0.8)</td>
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<td>1,700 (0.6)</td>
<td>13,700 (5.7)</td>
<td>1,520 (0.6)</td>
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<td>-10,300 (-7.1)</td>
<td>-1,290 (-0.9)</td>
<td>-8,120 (-6.8)</td>
<td>1,130 (0.9)</td>
</tr>
<tr>
<td>Maximum</td>
<td>13,260 (0.7)</td>
<td>7,320 (0.4)</td>
<td>20,400 (1.2)</td>
<td>6,650 (0.4)</td>
</tr>
<tr>
<td>Minimum</td>
<td>5,650 (2.0)</td>
<td>7,456 (2.6)</td>
<td>6,300 (3.1)</td>
<td>6,010 (2.9)</td>
</tr>
<tr>
<td>Winter</td>
<td>12,140 (0.8)</td>
<td>6,190 (0.4)</td>
<td>19,990 (1.4)</td>
<td>5,910 (0.4)</td>
</tr>
<tr>
<td>Spring</td>
<td>12,870 (0.7)</td>
<td>6,350 (0.4)</td>
<td>18,470 (1.2)</td>
<td>6,350 (0.4)</td>
</tr>
<tr>
<td>Summer</td>
<td>6,420 (1.0)</td>
<td>8,820 (1.4)</td>
<td>9,660 (2.1)</td>
<td>7,520 (1.6)</td>
</tr>
<tr>
<td>Autumn</td>
<td>21,980 (3.1)</td>
<td>9,400 (1.3)</td>
<td>27,430 (4.7)</td>
<td>9,070 (1.5)</td>
</tr>
</tbody>
</table>

**Table 1: (Thomas and Dieckmann 2009)**

The Ross Sea houses three regularly occurring polynyas – the Ross Sea Polynya, McMurdo Sound Polynya, and the Terra Nova Bay Polynya. Between 2003 and 2008 the Ross Sea polynyas produced an annual mean net ice export of ~737 km³. The Terra Nova Bay and McMurdo Sound polynyas contributed 88 km³ and 47 km³, respectively. The final 82% of ice produced along the Ross Sea coast is attributed to production from the Ross Sea Polynya. From 1992 to 2008 ice production in the Ross Sea has increased at a rate of ~21 km³ year⁻¹ (Drucker et al. 2011). Due to the polynyal origin of much of the sea ice in the Southern Ocean, researchers have theorized a relationship between polynyal activity and sea ice characteristics. In theory,
polynya surface area changes influence sea ice coverage within their regions. Greater sea surface area provided by larger polynyas allow for the generation of greater amounts of sea ice. Conversely, smaller polynyas provide less surface area for ice formation to occur. (Tamura et al. 2007; Tamura et al. 2008) So, regions surrounding relatively large polynyas are expected have relatively high sea ice concentrations. Also, periods of anomalously large polynya coverage should be associated with relatively high sea ice concentration.

There are several different atmospheric and oceanic phenomena linked to climate and sea ice variability. In sea ice studies, researchers have attempted to explain some of the variability of various sea ice characteristics with reference to atmospheric circulation processes such as the Southern Annular Mode [SAM] (Hall and Visbeck 2002; Stammerjohn et al. 2008; Maksym et al. 2012), also known as the Antarctic Oscillation [AAO]; El Nino-Southern Oscillation [ENSO] (Carleton 2003; Kwok and Comiso 2002; Maksym et al. 2012); the Semianurnal Oscillation [SAO] (Stammerjohn et al. 2008); the Antarctic Circumpolar Wave [ACW] (White and Peterson 1996); and Zonal Waves 1, 2, and 3 (Venegas 2003; Raphael 2007). More recently, researchers have put polynyal activity as a focus of sea ice studies (Tamura et al. 2008). With the majority of the Ross Sea ice originating within the Ross Sea polynya (Kimura and Wakatsuchi 2011), sea ice areal variability is expected to be a partial function of the polynya area.

4. Data

Two datasets were acquired for this study – sea ice and polynya area. Areal sea ice data were acquired from the Met Office’s Hadley Centre. The sea ice dataset consists of monthly averaged sea ice areal extent on a one-degree latitude/longitude grid. The observed extent was determined from sea ice concentration climatologies. Temporal coverage of sea ice concentration data ranges from January of 1870 to the present. Spatial coverage is global, which allows for the
determination of sea ice extent in both Polar Regions (Rayner et al. 2003). However, spatiotemporal subsets of sea ice extent were created to properly analyze against available polynya data. The temporal limitation of the polynya data and the spatial coverage of the statistically significant long-term sea ice extent trend in the Ross Sea establish the spatiotemporal parameters for this study. Figure 6 displays the continental and sea ice extents in the Antarctic during the winter maximum (left) and summer minimum (right). The region within the red box is the Ross Sea, the region of interest for this study.

Figure 6:
Maximum 2008 (left) and minimum 2009 (right) Antarctic sea ice distribution. Antarctic sea ice reaches its maximum and minimum extents in September and February, respectively. The red box indicates location of satellite image subset used to create polynya dataset. (NASA 2013).

The areal polynya data had to be created due to limited availability of temporally significant data coverage. Using the Polynya Signature Simulation Method [PSSM] (Markus and Burns 1995) applied to SSM/I input satellite data, daily polynya surface area measurements were obtained. These daily areal measurements were then aggregated to monthly means. The 625 km²
SSM/I images were acquired from the National Snow and Ice Data Center (NSIDC). Available SSM/I images limit the temporal range of the polynya data generated. SSM/I availability began in July, 1987 and ceased April, 2009. While spatial coverage of SSM/I data spans the entirety of both Polar Regions, the Ross Sea, Antarctica is the region of interest for this study, and Ross Sea Polynya measurements are employed.

5. Methodology

Processing of Ross Sea Polynya Dataset

In order to extract open water areas from SSM/I data, the Polynya Signature Simulation Method [PSSM] was employed. In 1995, Markus and Burns released the alternative method for illuminating open water regions within polar pack ice. Studies prior to the development of the PSSM employed usage of visible imagery (Bromwich and Kurtz 1984), and coarse microwave imagery (Zwally et al. 1985), which presented problems of atmospheric moisture interference and pixel resolution too large to identify relatively small polynyas (Markus and Burns 1995). The PSSM essentially involves 7 stages of image processing.

Stage 1: Input Data

The input data used are from dual polarized 37.0 GHz and 85.5 GHz frequency images. Spatial coverage at both frequencies spans the entire Southern Polar Region. Figure 7 is a representation of the spatial extents. Each corner of the SSM/I image extent is labeled with geographic coordinates. The spatial resolution of the 37.0 GHz frequency images is 25x25 km with its columns and rows spanning 316 and 332 pixels, respectively. The 85.5 GHz frequency images have a spatial resolution of 12.5x12.5 km, doubling the width of 37.0 GHz images in both directions, and so also doubling the number of columns and rows to 632 and 664, respectively. Data availability from the SSM/I sensor began July 9, 1987, and is still continuing
to date. However, data collection at 85.5 GHz frequency ceased after April 29, 2009. The availability of data at 85.5 GHz constitutes the temporal range of the data analyzed in this paper. All SSM/I data are sampled daily. Southern Hemisphere SSM/I data images are provided by the NSIDC on a southern polar stereographic projection with the projection grid tangent to the Earth’s surface at 70 degrees south latitude. Placing the projection plane tangential to the surface at 70 degrees eliminates distortions in the marginal ice zone (NSIDC).

Figure 7: SSM/I Southern Hemisphere data frame extent (NSIDC 2013).

The aim of the PSSM is to distinguish areas of open water from other surface types. To do so, the polarization ratio (PR) of the 85.5 GHz data is calculated using the following formula:

Stage 2: Polarization Ratio

**Formula 1:**

$$PR_{ss} = \frac{85_v - 85_H}{85_v + 85_H}$$  \[1\]
As seen in Figure 8a, PR$_{85}$ differentiates open water from ice-covered pixels at a relatively high resolution. Figure 8b displays the polarization ratio of 85.5 GHz with a land mask applied.

**Figure 8a:** Image displaying polarization ratio of 85.5 GHz. The red arrow indicates Ross Sea Polynya.

**Figure 8b:** Image displaying polarization ratio of 85.5 GHz data. A Land mask has been applied to better distinguish between open water and the solid surfaces. The red arrow indicates Ross Sea Polynya.

*Stage 3: Classification*

Three classifications are applied to the PR$_{85}$ image to identify land and shelf ice, sea ice, and open water. A land mask is applied to the image, which classifies the land and shelf ice pixels. Of the remaining unclassified pixels, the higher PR values represent open water pixels, while the lower PR values represent sea ice pixels.
Due to the relatively large amount of water vapor escaping into the atmosphere from open water areas, polynyas and other ice-free regions are associated with overlying fog and clouds. Particularly, at the 85.5 GHz frequency, the SSM/I sensor cannot distinguish between the two dominant land cover types (ice and open water). This reduces the level of certainty for water-ice distinction, particularly at the ice-water edge. To correct for this confusion, a series of simulated images were generated, each with an increasingly greater PR value threshold to delineate the sea ice and open water classifications. The simulations were tested against the observed data at 37.0 GHz frequency.

The use of 37.0 GHz data is the principal improvement made by Markus and Burns upon previous polynya detection methods. The 37.0 GHz frequency data was employed because of its insusceptibility to atmospheric interference. However, its relatively coarse resolution requires the continued use of the 85.5 GHz frequency data as well.

*Stage 4: Synthesize*

To achieve fair comparisons between the 85.5 GHz and the 37.0 GHz images, $PR_{85}$ had to be converted to 37.0 GHz values and resampled to a comparable resolution. To do so, synthetic vertically and horizontally polarized 37.0 GHz images were generated. Mean vertically and horizontally polarized sea ice pixel values from the vertical and horizontal 37.0 GHz images were calculated. All sea ice classified pixels in the $PR_{85}$ image were assigned new values: the mean sea ice pixel values calculated from the 37.0 GHz resolution images. Since open water pixel values do not vary across polarizations, the mean values will be the same for both synthetic vertical and horizontal images. This reassignment of classified pixel values will result in two images, one vertical (Figure 9a) and one horizontal (Figure 9b). All mean values calculated from the $PR_{85}$ images used only pixels within the same day and image subset.
Figure 9a: Synthetic vertical 37.0 GHz image. Black, grey, and white represent land and shelf ice, open water, and sea ice, respectively.

Figure 9b: Synthetic horizontal 37.0 GHz image. Black, grey, and white represent land and shelf ice, open water, and sea ice, respectively.

Stage 5: Simulation

After synthetic vertical and horizontal 37.0 GHz images were created, they were resampled to a more coarse resolution comparable to the measured 37.0 GHz images at 25x25 km. Then, a 21x21 pixel Euclidian distance matrix was generated and convolved with the antenna pattern of the satellite’s sensor using Formula 2 and Table 1 of Markus and Burns (1995). The convolved distance matrix was then applied to the upper left 21x21 pixel subset from the synthetic 37.0 GHz image. This 21x21 pixel weighted average was calculated at every 5th pixel. The resultant weighted mean pixel values were used to generate a new simulated 37.0 GHz image. A series of simulated 37.0 GHz images are created as in stages 3 through 5.
**Stage 6: Comparison**

Once again, to improve the distinguishability between open water and sea ice, the polarization ratio must be calculated for the measured 37.0 GHz images and the simulated 37.0 GHz images from stage 5. This produces measured PR$_{37}$ (Figure 10a) and simulated PR$_{37}$ (Figure 10b) images. Then the simulated images were validated against the measured data using two methods of comparison. The absolute mean difference between each simulated PR$_{37}$ and the measured PR$_{37}$ was calculated. This validates the particular data values within the open water classification of the simulated images. Also, the correlation coefficient for every simulated PR$_{37}$ and the measure PR$_{37}$ was calculated. The correlation coefficient validates the shape of the open water areas generated in the simulations. The simulation with the lowest absolute mean difference and greatest correlation uses the most accurate PR threshold value to delineate open water and sea ice pixel values. Using that PR threshold value, a new PR$_{85}$ image is generated and a three level classification is applied to it. As in stage 3, land and shelf ice pixels are masked out. Pixels not masked and containing values less than the PR threshold are classified as sea ice. Pixels with values equal to or greater than the PR threshold are classified as open water.

*Figure 10a:* SSM/I data image displaying polarization ratio of observed 37.0 GHz data. Notice reduced resolution contrasted to 85.5 GHz data. Red arrow indicates Ross Sea Polynya.
**Figure 10b:** SSM/I data image displaying polarization ratio of best simulation of vertical and horizontal 37.0 GHz data. Black, white, and grey represent land and shelf ice, open water, and sea ice, respectively. Red arrow indicates Ross Sea Polynya.

**Stage 7: Areal Calculation**

To obtain the total area covered by the open water classification, the open water pixel count is multiplied by the area of one pixel. Images commonly contain multiple open water regions as shown in Figure 11a. For this project, only the open water regions identified as the Ross Sea Polynya were included in the surface area calculation (Figure 11b). Since the Ross Sea Polynya is a coastal polynya in the western Ross Sea, only open water areas within that region are included. The reliable, stationary character of coastal polynyas lends confidence to the location of the Ross Sea Polynya (Markus and Burns 1995).

**Figure 11a:** PSSM image output displaying all open water features detected by method. Black, grey, and white represents land and shelf ice, sea ice, and open water, respectively.
Figure 11b: PSSM final image output. Black, grey, and white represents land and shelf ice, sea ice, and open water, respectively. Polynya pixel count equals 746; polynya area equals 18,650 km$^2$.

The PSSM is repeated for each day that all four necessary SSM/I images are available. The resulting daily time series is provided in Figure 12. The blue line represents the monthly average of the Ross Sea Polynya area time series created above, while the red line represents monthly mean Ross Sea Polynya area created by Arrigo and van Dijken (2003). The 2003 dataset validates the dataset created for this study. Discrepancies between the two series result from differences in Ross Sea delineation. The SSM/I image subset used during the data production for this study is more inclusive of greater sea area than that used for the Arrigo and van Dijken 2003 polynya data series. As a result, during the warm season, when vast open water regions and minimal sea ice covers the Ross Sea, the Ross Sea Polynya lacks a northern boundary. Therefore, for application purposes, the polynya’s northern extent is entirely dependent upon the location of the SSM/I image Ross Sea subset definition. Since the SSM/I images in this study include a greater expanse of the sea than in the 2003 study, the Ross Sea Polynya is larger during the austral summer in the data series created for this study. As seen in Figure 12, mean polynya area in January and February in particular is much less in the 2003 study.
**Figure 12:** Monthly average Ross Sea Polynya area time series created for this study (blue) overlain with monthly mean of Arrigo and van Dijken’s (2003) Ross Sea Polynya time series (red).

In order to make proper use of the monthly Ross Sea Polynya data series, several months were removed from the dataset due to sensor errors through the entirety of 1990 and 1991, and from April to June, 2008 (NSIDC 2010) (Figure 13a). The time series decomposition of the Ross Sea Polynya monthly area reveals a trend in size over time, albeit not statistically significant (Figure 13b). The Ross Sea Polynya reaches its minimum area during the winter season, and its maximum area during the summer months, particularly in February (Figure 13c). While the open water area in the Ross Sea is relatively large in the summer, the actual classification of the open water area in the Ross Sea as a polynya falters during the summer because then the open water area is boundless in its northern reach. However, the major open water area will be included in the analysis because its relationship to short term sea ice change may offer information about the ice-water system in this region, and in the Antarctic in general.
Both polynya and sea ice time series (Figures 13a and 14a) can be modeled with a simple additive time series model composed of three parts – the trend (Figures 13b and 14b), cyclical (Figures 13c and 14c), and irregular components (Figures 13d and 14d) (Formula 2).

**Formula 2:** \[ \text{Areal Time Series} = \text{Trend} + \text{Seasonal Cycle} + \text{Anomaly} \] [2]

Subtracting the trend and cyclical components from the model leaves the irregular component. The irregular component is the anomaly of the cyclical component and is defined as the difference between the detrended observed area and the cyclical component (Formula 3).

**Formula 3:** \[ \text{Anomaly} = \text{Detrended Area} – \text{Seasonal Cycle} \] [3]

Detrended area is defined as the difference between observed area (Figures 14a and 15a) and the centered moving average (CMA(12)) (Formula 4).

**Formula 4:** \[ \text{Detrended Area} = \text{Observed Area} – \text{CMA(12)} \] [4]

The CMA(12) is employed in place of the constant linear trend because the general trends are not constant throughout the time series. The cyclical component exists due to the seasonality of polynya and ice area. The regular seasonal cycle is defined as the successive mean of means for each set of individual monthly areal measurements. For example, the mean January polynya area is calculated from the sum of all January areal measurements throughout the detrended data series. The same is done for each month, which constitutes the regular seasonal cycle of the detrended time series (Figures 13c and 14c).
Figure 13a: Complete Ross Sea Polynya monthly mean surface area. Time series ranges from July, 1987 to April, 2009. Data from 1990 to 1991 and April to June, 2008, have been removed due to sensor error.

Figure 13b: Trend in Ross Sea Polynya monthly mean surface area. Average monthly decrease is 33.03 km$^2$. Trend is not statistically significant.
Figure 13c: Ross Sea Polynya area seasonality. Maximum polynya area is found in February, while the minimum is found between April through October when there is virtually no change in area.

Figure 13d: Anomalous monthly mean Ross Sea Polynya surface area.
Ross Sea Ice Dataset

Figure 14a: Complete Ross Sea monthly mean ice surface area. Time series ranges from July, 1987 to April, 2009.

Figure 14b: Trend in Ross Sea monthly mean ice surface area. Average monthly increase is 912.56 km$^2$. Trend is not statistically significant.
Figure 14c: Ross Sea ice area seasonality. Ice area minimum and maximum are found in February and August, respectively. However, ice area is virtually unchanged from July through October.

Figure 14d: Anomalous monthly mean Ross Sea ice surface area.

Statistical Analysis:

The relationship between the polynya size and ice area in the Ross Sea will be determined using a 95% confidence level of Pearson’s correlation and simple linear regression modeling. To examine changes in their relationship through different stages of the year, a monthly analysis will be performed in addition to the full-range time series analysis. Both full
range and monthly analyses will be performed on the observed polynya and ice data, anomalous areal data, and centered moving average (CMA(12)) values for the polynya and ice area. CMA(12) will be employed to analyze the effects of trend. It is an adequate representation of trend for this study because it identifies the normal baseline measure for each 12 month time span, and highlights shifts in the normal values of polynya and sea ice area.

When conducting monthly analyses, the seasonal effects are removed because only one monthly mean value from each year is included in the analysis. Therefore, the annual polynya and ice cycles are not factors in determining the monthly relationship. Since the areal time series can be modeled as additive compositions of trend, cyclical, and anomalous components (Formula 2), each detrended monthly analysis results in the relationship between polynya and ice anomalies.

6. Results

As seen in Figure 15, there is a statistically significant negative relationship between Ross Sea Polynya and sea ice area. With an $R^2$ of .5945, the areal variability in the Ross Sea Polynya is associated with 59.45% of the variability in the Ross Sea ice area. Relatively large polynyas are expected to be associated with less sea ice, and relatively small polynyas are expected to be associated with more sea ice areal coverage. This is contrary to what is expected from other work and is due to the seasonal effect. More heat is available during the warm season, which causes polynyas to grow and sea ice to melt. Less heat is available during the cool season, which allows the sea ice to grow and polynyas to become smaller. With that said, most of the variability in sea ice and polynya area can be attributed to the variability in heat provided during the warm season, and the lack of heat during the cool season. The two variables’ differing areal dynamics cause more months to experience relatively large expanses of sea ice associated with
relative small polynya area. In general, the seasonality of sea ice and polynya area are inversely related. However, Figures 13c and 14c show that the ice growth season (February to August) far exceeds the duration of the polynyal decay season (February to April). The four month difference in seasonal phases cause clustering of lower-end polynya area observations associated with relative large sea ice coverage.

**Figure 15:** Negative statistically significant relationship between monthly mean Ross Sea ice area and monthly mean Ross Sea Polynya area from July 1987 to April 2009.

While the general relationship between mean polynya and sea ice area is strongly negative, the strength and direction of their relationship are dependent upon the time of year. Their relationship is only significant in 3 months of the year, during the summer/early autumn and the late winter. Figures 16a-c show the results of linear regression models for the Ross Sea Polynya and ice areas during February, March, and August. Figures 16a-b show negative relationships with an increasing correlation as the late winter/early autumn months progress. The relationships in January, April, May, June, July, September, October, November, and December are not statistically significant. While the relationship in the warm season is negative, it is
positive in the cool season. During the cool season, relatively large Ross Sea Polynya area is associated with relatively large sea ice area (Figure 16c).

These results suggest that different processes are dominant during different parts of the year. During the warmer season, heat availability is dominant, and expansive polynya area corresponds with low sea ice coverage. When sea surface temperatures are relatively warm, above -2°C, sea ice is production is halted. The sea ice development system breaks down due to above freezing sea surface temperatures. However, during the cool season, ice production in coastal polynyas is substantial. Figure 16c shows the positive relationship between monthly mean polynya and sea ice area during August. In August, 20.8% of the variability in the mean sea ice area can be attributed to the variability in monthly mean Ross Sea Polynya area. So, heat availability is not the primary force behind the significant coastal polynya-sea ice relationship. Because sea ice production mechanisms are effective during the cold season, relatively large polynya area is associated with relatively large area of sea ice coverage.

**Figure 16a:** Negative statistically significant relationship between observed February monthly mean Ross Sea Polynya and ice area.
Figure 16b: Negative statistically significant relationship between observed March monthly mean Ross Sea Polynya and ice area.

Figure 16c: Positive statistically significant relationship between observed August monthly mean Ross Sea Polynya and ice area.

To account for seasonal effects, anomalous monthly means for polynya and sea ice area are analyzed (Anomalies calculated from Formula 3). Figure 17a displays the negative relationship between anomalous polynya and ice area in the Ross Sea. While negative, this relationship is not statistically significant. Months with anomalously large monthly mean polynya area are associated with low sea ice area anomalies. While this is the case, the
relationship is expected to be variable through different times of the year, as seen in Figures 16a-c. In the summer season, sea ice production ceases and open water area is at its largest extent during the summer, both in the Ross Sea and around the entire Antarctic. With the large polynya size and no ice production, the relationship does not hold true during this part of the year. To determine the varied relationship between the Ross Polynya and sea ice on a shorter time scale, simple linear regression models are applied to the data for each individual month of the year.

![Ross Sea Polynya and Ice Area Anomalies](image)

**Figure 17:** Negative, not statistically significant relationship between monthly mean Ross Sea Polynya and ice anomalous area. Anomalies are the result of detrended and deseasonalized time series.

Figure 18 shows the results of the linear regression model. The relationship between anomalous monthly mean Ross Sea Polynya and ice area is statistically significant in February. Figure 18 shows there is a negative relationship between the polynya and sea ice in February, which is expected in the summer season because the large polynya area is not accompanied by sea ice production due to overwhelming temperature forcing. In February, the variability within the Ross Sea Polynya area can account for 45.77% of the sea ice area variability within the Ross Sea. The relationship between anomalous monthly mean Ross Polynya and sea ice area in all
other 11 months of the year is not statistically significant at the 95% confidence level. Therefore, the overall relationship between anomalous monthly mean Ross Sea Polynya and ice area is primarily driven by the summer season effects.

Figure 18: Negative statistically significant relationship between anomalous monthly mean Ross Sea Polynya and ice area in February.

To determine the effects of trend on the Ross Sea Polynya-ice relationship, the CMA(12) used in Formula 4 to detrend the data series is analyzed. Figure 19 shows the CMA(12) for both the Ross Sea Polynya and Ross Sea ice area.

Figure 19: 12 month centered moving averages (CMA(12)) for Ross Sea Polynya and ice monthly mean surface area.
The positive and negative trends in the Ross Sea Polynya and ice monthly mean area, respectively, are apparent in Figure 19. Figure 20 shows there is no association between the two CMA(12) series. Therefore, the significant relationship between the observed polynya and ice area (Figure 15) is not driven by the change in the normal states of monthly mean polynya and ice area. Also, none of the individual monthly CMA(12) relationships are significant. When the CMA(12) is observed over time, the trend is not significant in any months for polynya area, but it is significant in every month for ice area.

![Ross Sea Polynya and Ice CMA(12)](image)

Figure 20: Negative, but not statistically significant relationship between 12 month centered moving averages (CMA(12)) for Ross Sea Polynya and ice monthly mean surface area.

From these results, it is expected that removing the trend from the observed areal measurements will not have an effect on the significance levels of the Ross Sea Polynya-ice relationship. Figure 21 shows the relationship between the Ross Sea Polynya and ice monthly mean area with the CMA(12) removed. Just as in Figure 15, the relationship displayed in Figure 21 shows a clustering of relative small polynya areas associated with relatively large expanses of sea ice, which is due to the incongruous duration of the sea ice growth and polynya decay seasons.
Figure 21: Negative statistically significant relationship between detrended Ross Sea Polynya and ice monthly mean area data series. Note: values do not represent observed areal measurements, but instead areal measurements over time with the trend (represented by the centered moving average) removed. Therefore, negative values are permissible.

Variability within normal yearly polynya and sea ice levels also contribute to the variability in the polynya-ice relationship throughout the year. The monthly relationships of the observed areal measurements are significant in February, March, and August. Once the CMA(12) is removed, these relationships are changed greatly in nonuniform ways. When the CMA(12) is removed, the relationship in February is virtually unchanged – from an $R^2$ of .4428 (Figure 16a) to .4577. The relationship in March is greatly weakened from an $R^2$ of .7086 (Figure 16b) to .2263. The relationship in August is also weakened, from an $R^2$ of .2082 (Figure 16c) to .0302. Accounting for trend effects not only weaken the relationship in March and August, but the relationship is no longer statistically significant in either of those months. However, it cannot be concluded that the positive significant relationship between the polynya and ice area in March and August is due to the negative relationship in their trends. Figures 22a-b show the negative relationship between polynya and ice area trends in March and August months.
Figure 22a: Non-statistically significant relationship between 12 month center moving average of monthly mean Ross Sea Polynya and ice area in March.

Figure 22b: Non-statistically significant relationship between 12 month center moving average of monthly mean Ross Sea Polynya and ice area in August.

7. Conclusion

This study has produced a unique polynya area dataset that is the first to estimate Ross Sea Polynya surface area over an approximately 22 year period (July 1987 to April 2009). The dataset will allow for analysis of relatively long term area dynamics and relationships. Initial results show that the Ross Sea Polynya has a slight general decreasing trend in it size. However,
this seemingly negative trend in Ross Sea Polynya area is not statistically significant. The polynya’s maximum areal extent is reached in February, after which it rapidly decreases until the onset of the ice growth season in late autumn. There is virtually no change in size from April through October.

With the new Ross Sea Polynya dataset, the relationship between the polynya and ice in the Ross Sea was analyzed. The relationship between observed monthly mean Ross Sea Polynya area and Ross Sea ice area is negative and statistically significant. This is primarily due to the distinct annual cycle of both the polynya and sea ice surface areas. When accounting for the seasonal behavior of the two features, there is no longer an association ($R^2$ of .0655). Neither are there any associations between Ross Sea Polynya area and Ross Sea ice extent trends or anomalies.

However, the polynya-ice relationship in the Ross Sea is not constant throughout the year, but is variable from month to month. In particular, the late austral summer to early autumn (February to March) and the late winter (August) seasons are of great significance, statistically. These monthly relationships change in distinctive manners when accounting for the different components of the time series model. Analyzing monthly relationships inherently requires removal of the annual cycle. When this is done, statistically significant associations are only found during February, March, and August. The negative relationship in February is weaker than that of the full range data series, while the negative relationship in March is stronger than that of the full range data series. The positive relationship in August is much weaker than that of the full range data series, and is of opposite direction. When the trend is accounted for through the removal of the 12 month centered moving average, there is a very slight increase in the relationship in February, and large decreases in the relationships in March and August. The
weakened relationships in March and August are no longer statistically significant at the 95% confidence level.

The statistical significance of the Ross Sea Polynya – Ross Sea ice area relationship in February is driven by the anomalous behavior in that month. The statistical significance of the relationship in March is partially due to the anomalous behavior in that month, but is primarily due to the relatively long term trends, even though the relationship of their 12 month centered moving averages are not statistically significant in any individual month. The statistical significance of the relationship in August is also governed by both the anomalous activity and trend. However, the relationship of the trends in August is negative, therefore it cannot be concluded that the trends influence the positive significant relationship between observed polynya and ice areas.

Since ice production ceases during the warm season, and ice melt produces boundless open water area in the Ross Sea, the general negative relationship between polynya area and sea ice extent is most likely due to the variability in heat. During the cold season, ice production is linked to polynyal activity. Particularly in August, sea ice coverage is significantly influenced by polynya area. In August, larger polynyas are associated with greater sea ice coverage.

The bulk of the work done here is the creation of the unique polynya area dataset. Further work using a more limited sea ice area specification will be done to get a more accurate sense of the role of polynyas in Antarctic sea ice. The analysis presented here represents a first look at the dataset and its potential relationship with ice area. The ice area used extends from the continental boundary to the sea ice edge, and is therefore probably too extensive to reveal from relationships between polynya area and ice area.
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