**Quantifying Ecologically Significant Feeding Areas for Marine Mammals and Seabirds in the Arctic**

by

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May 2017

Masters Project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment of Duke University

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# EXECUTIVE SUMMARY

The Arctic marine ecosystem is highly dynamic and sensitive to environmental change, experiencing the impacts of climate change at a rate at least twice as fast as other areas of the world. Arctic organisms are adapted to the strong seasonality of the Arctic marine ecosystem, making them sensitive to changes in phenology. While it has already been shown that phenological shifts are occurring with relation to sea ice and primary production in this region, it is necessary to further quantify what species and key ecological zones will be most impacted. In an effort to assess potential changes to these key ecological areas, I analyze satellite remote sensing data for sea ice concentration and chlorophyll *a* concentration in ecologically significant feeding areas in the Arctic. This provides for a clearer view of what species stand to gain or lose the most as the Arctic transitions to a more temperate marine environment.

The goal of this research is to analyze sea ice concentration and primary production (chlorophyll *a* concentration) within ecologically significant feeding areas for marine mammals and seabirds. Diminishing sea ice impacts the timing and magnitude of primary productivity in the ocean, and shifts in primary productivity have impacts that cascade through the Arctic food chain.

My analysis integrates the work published in the Arctic Council report, *"Identification of Arctic marine areas of heightened ecological and cultural significance: Arctic Marine Shipping Assessment (AMSA) IIc" (2013).* In this report, feeding areas across the Arctic are mapped and defined qualitatively, with a total of close to 120 feeding areas included for marine mammals and seabirds. The analysis in this study complements the work done in the *AMSA IIc* report by further quantitatively defining these ecologically significant foraging areas.

In this study, feeding areas are categorized into three main species groups: 1) cetaceans, 2) pinnipeds, and 3) seabirds. Species groups are designated based on the unique life histories of the three groups listed. For example, foraging habits of cetaceans (toothed and baleen whales) differ greatly from pinnipeds (seals and walruses). Additionally, species groups utilize sea ice in different ways in relation to foraging and other life cycle processes. Analysis includes a spatiotemporal analysis of study environmental variables with respect to 1) the Pan-Arctic and 2) ecologically significant feeding areas for species groups. Trends are identified across two temporal ranges: 1) 1979 through 2015 for monthly and annual trends and 2) 1979 and 2012 for 8-day trends.

In general, the results of this analysis show that trends within feeding areas are highly correlated to trends across the Arctic, as well as moderately correlated with one another. Ecologically significant feeding areas for all three species groups experience declines in sea ice concentration of between five to ten percent between 1979 and 2012 for summer and early fall months, with the largest changes experienced in September, where sea ice extent reaches its annual minimum. Open water days, characterized as areas where sea ice concentration is less than 15 percent, steadily increase across the Arctic and feeding areas, with a large amount of variation annually. Measuring phenological shifts in sea ice extent across the Arctic shows an increase in the length of time between sea ice retreat and advance.

Chlorophyll *a* concentration data show a stark contrast when comparing trends in 1979 to 2012. Across the Arctic and within feeding areas, the peak in chlorophyll *a* concentration flattens out between study years. In 1979, a clear peak is seen in June with a short four-week range between peak bloom initiation and end (as defined by a pre-determined threshold for the year) across the Arctic, with similar trends in species group feeding zones. By 2012, there is a clear flattening out of the peak bloom in chlorophyll *a* concentration across the Arctic, with an earlier onset in peak bloom initiation from June to April, and an overall longer peak range. The flattening trend is seen both across the Arctic and within

cetacean and seabird feeding areas on average; however, the changes in onset of peak bloom initiation are different across species groups.

In conclusion, there are distinct trends occurring with respect to both study variables – sea ice concentration and chlorophyll *a* concentration. As sea ice continues to decrease across the Arctic, primary production is likely increasing, though the season for peak chlorophyll *a* concentration has changed from a short window in summer to stretching from early spring into autumn months for many areas across the Arctic and within foraging areas.

If both endemic and migratory marine animals are adapted to a high density of prey availability in summer months, with respect to both primary and secondary consumers, the changes in primary production indicate that prey distribution moving up the food chain may be shifting, which is likely to affect upper trophic species in the Arctic. The change in timing and the potential reduced density of prey availability across a longer time period may benefit some species, such as sub-Arctic baleen whales that will enjoy a longer foraging summer, while some species – with lower plasticity in their foraging and life cycle processes – may stand to lose a lot as the Arctic marine ecosystem transitions to a new normal. Further research should be done, implementing other data and methodologies, to further investigate specific implications and potential adaptability of species across the Arctic.

# INTRODUCTION

*Statement of Objectives*

The Arctic is a rapidly changing marine ecosystem. Historically, the Arctic is an important destination in the summertime for peak foraging, attracting marine animals from across the world. As environmental variables are shifting at an accelerated rate of change in the Arctic, what are the implications for foraging marine animals, both migratory and endemic?

The goal of this research is to analyze sea ice concentration and phytoplankton primary production (using chlorophyll *a* concentration as an indicator variable) within ecologically significant feeding areas for marine mammals and seabirds. My analysis will integrate the work done by a number of Arctic Council working groups and published in the report, *"Identification of Arctic marine areas of heightened ecological and cultural significance: Arctic Marine Shipping Assessment (AMSA) IIc"* (AMAP/CAFF/SDWG 2013).

In particular, my interest lies in the timing of how these changes are occurring across the Arctic. Small timing mismatches between biological processes and the environment could have significant implications for upper trophic species in the future (Ji et al. 2013).

This study includes *three main objectives*:

1) To determine the overall changes occurring across the Arctic with respect to study variables through geospatial analysis of satellite remote sensing data;
2) To determine changes happening within the designated feeding areas for select species groups; and
3) To differentiate between species groups and draw conclusions about which foraging species in the Arctic may be more or less impacted now and in the future.

*The Changing Arctic*

The Arctic marine ecosystem comprises the Arctic Ocean, including the Eurasian and Canadian Basins, and the surrounding continental shelf seas – Barents, Kara, Laptev, East Siberian, Chukchi, and Beaufort Seas – and the Canadian Archipelago. The Arctic marine ecosystem is a complex and dynamic environment and one of the most rapidly changing ecosystems on the planet. While the consequences of climate change affect terrestrial and marine ecosystems across the globe, the Arctic is experiencing the

impacts of climate change at a rate at least twice as fast as most other areas of the world (Arrigo et al. 2011).

Over the past few decades the changes in the Arctic have been creating a "new normal" (Moore & Stabeno 2015), marking environmental shifts that will permanently alter the Arctic marine ecosystem. While the Arctic Ocean displays a distinct natural climate variability on time scales ranging from seasonal to multi-decadal, the dramatic changes occurring in recent decades have happened at a speed and scale that is unprecedented with historical fluctuations (Haug et al. 2017).

In a report released at the end of last year by the National Oceanic and Atmospheric Administration (NOAA), changes occurring in the Arctic were summarized, including the following highlights:

- *New records in surface air temperature* were observed in the Arctic in 2016.
- *Sea ice extent* reached its *second lowest minimum* ever in September 2016, with sea ice extent at 4.14 million $km^2$ , a 33 percent reduction compared to the average minimum for the time period 1981 to 2010 (Perovich et al. 2016).
- Ongoing *reductions in multi-year ice* were observed, as well, as first-year ice now dominating the composition of sea ice in the Arctic. Younger sea ice is more vulnerable to atmospheric and oceanic forcing, and therefore, sea ice in the Arctic is less resilient now than ever before (Perovich et al. 2016).
- Estimates of *ocean primary productivity* showed *widespread positive anomalies* across the Pan-Arctic for 2016, except for the western (North American) Arctic (Frey et al. 2016).
- Finally, an overall *northward shift of Sub-Arctic species* is occurring as the Arctic warms, increasing biodiversity and potentially dramatically changing Arctic marine and terrestrial food webs (NOAA 2016).

### *Sea Ice*

The rapid loss of sea ice in the Arctic is one of the most striking manifestations of climate change. While most change occurring within ocean systems is less visible, disappearing sea ice is very discernible evidence of the effects of current climate warming on our oceans. Not only is sea ice extent decreasing across all seasons, the thickness and, therefore, resilience of sea ice is diminishing, as well (Moore & Stabeno 2015).

Sea ice is integral to this marine ecosystem, and its disappearance has biological and ecological consequences. Sea ice habitat not only plays an important role in biological processes in the ocean

system, also it is a key component of the life histories of most marine mammals and seabirds in the region.

In particular, my analysis aims to look at how sea ice is changing in areas that are known to be ecologically important for feeding for marine mammals and seabirds. The retreat of sea ice can impact the ability of ice-dependent animals to forage efficiently, forcing animals, such as seals or diving seabirds, to travel farther to reach the same feeding grounds as before. Additionally, changes in the sea ice regime in the Arctic impact the distribution of prey sources for marine animals.

In the summertime, the Arctic attracts a wide range of species that migrate large distances to take advantage of the peak foraging season. Scientific modeling indicates that the Arctic may be ice-free in the summer months within the next three to four decades, as we continue to experience accelerated sea ice loss (Wang & Overland 2012). Identifying what areas and species might be most impacted provides an important step in prioritizing marine protection policy and management measures.

*Primary Productivity*

In addition to the impacts that sea ice loss has directly on marine animal behavior, the question is raised of the link between shrinking ice coverage, earlier sea ice retreat, and the change in timing and scale of primary production pulses in the Arctic (Ji et al. 2012). Primary production is inherently limited by sea ice in the Arctic. Ice restricts the amount of light that allows photosynthesis to take place in the ocean, and it limits the length of the season for primary production. Therefore, it is reasonable to ask that, given the thinning and areal reduction of sea ice in recent years, what is the effect on ocean primary productivity (Moore & Stabeno 2015)?

As sea ice has been on the decline in recent decades, primary production in the Arctic has been steadily increasing – between 1998 and 2009, for example, satellite measurements revealed a 20 percent overall increase in phytoplankton primary production (Arrigo et al. 2011, Jeffries & Overland 2013). This spike in productivity, which occurred mostly on the Eurasian side of the Arctic Ocean, is connected to the increase in extent and duration of open water, showing the not-so-surprising link between diminishing sea ice and increasing primary production.

Not only is overall net primary productivity increasing across the Pan-Arctic, there have been other phenomena occurring in the region related to primary production. First, massive under-ice phytoplankton and algal blooms have been observed in the Arctic in recent years (Arrigo & van Dijken 2015). For example, in 2011, a large under-ice bloom was observed in the Chukchi Sea, and similar

reports have been made about areas in the Beaufort Sea, Barents Sea, and Canadian Arctic Archipelago (Arrigo & van Dijken 2015).

Secondly, regions in the Arctic, as a result of sea ice loss, are now developing a second phytoplankton bloom in fall months, coinciding with a delayed freezing and increase in open water extent (Ardyna et al. 2014). The shift from one to two phytoplankton blooms in the Arctic signals a significant shift in a core component of the ecosystem. At temperate latitudes, the occurrence of two blooms per year is normal, so this transition may indicate the shift of some lower-latitude Arctic regions from a polar to a more temperate ocean environment (Ardyna et al. 2014).

Several studies in recent years look at the relationship between sea ice and primary production timing in the Arctic (Ardyna et al. 2014, Arrigo & van Dijken 2015, Ji et al. 2012). My aim is to translate these changes to how they relate to ecologically significant areas for different groups of species. Phytoplankton are the foundation of the marine food web. So, when analyzing feeding areas for top predators, such as whales or seabirds, looking at chlorophyll *a* satellite imagery helps to get an idea of how and where things are changing across the Arctic.

### *Phenology: Why Timing is Everything*

Arctic organisms are adapted to the strong seasonality that corresponds with the Arctic marine ecosystem (Ji et al. 2013). A mismatch in the timing of biological processes could have significant implications for upper trophic species in the food web. While it has already been shown that phenological shifts are occurring with relation to sea ice and primary production in the Arctic (Ji et al. 2013, Wassmann 2011, Arrigo & van Dijken 2015), it is necessary to further quantify what species and what key ecological zones will be more or less impacted by these changes.

The unparalleled transformation of the Arctic marine ecosystem will have implications for marine animals throughout the Arctic food web. Species that are endemic to the Arctic – such as the narwhal, ringed seal, and the polar bear – have life histories that tie them closely to certain biological and ecological characteristics of the northern latitudes (Moore & Huntington 2008). Additionally, many animals travel thousands of miles to the Arctic in summer months for peak foraging. Tracking migratory patterns for certain species, such as beluga whales, has already shown a shift in the timing and duration of migration to the Arctic (Bailleul 2012, Moore & Huntington 2008, Moore 2016).

However, the adaptability of species to these changes is still largely unknown. As Moore and Huntington note in their analysis of marine mammal resiliency to climate change, "Recognition that the

biogeography of life on earth can change with climate is not new" (2008). The concept of adaptation is well understood. Still, what is different in the current climate of environmental change is the rate of environmental change, specifically in the Arctic.

This rapid and permanent shift is likely to have consequences for higher trophic species (Ji et al. 2013). If the timing is off for peak foraging, species traveling long distances to the Arctic may expend a lot of energy for a smaller return. Take seabirds as an example: the AMSA IIC report clearly describes that birds spend a lot of energy on the long migration and are "critically dependent on feeding to replenish their depleted energy stores" once they reach the Arctic (AMAP/CAFF/SDWG 2013).

For marine mammals, which are long-lived, highly derived species, their adaptability to severe environmental changes could go both ways. Cetaceans, such as baleen whales like fin and humpback whales, have been shown to be fairly adaptive to phenological shifts in the ocean system, altering the timing of their migrations (Ramp et al. 2015). However, pinnipeds such as seals and walruses – which are usually much more tied to sea ice – may not have the adaptive capacity to deal with the rapid changes occurring in the icy waters that they call home. Finally, the northward encroachment by Sub-Arctic species into warming Arctic waters could also create crowding, increased competition for food, and increased predation on certain species (Moore 2016).

Overall, the continuing drastic changes to the Arctic marine environment may seriously threaten the population viability of certain species and the overall ecosystem structure across the Arctic.

# MATERIALS AND METHODS

*Study Areas*

The reference areas for my analysis originate from a report published in 2013 by a number of Arctic Council Working Groups: *"Identification of Arctic marine areas of heightened ecological and cultural significance: Arctic Marine Shipping Assessment (AMSA) IIc"* (AMAP/CAFF/SDWG 2013).

In the report, ecologically significant areas are defined and mapped for marine mammals, seabirds, and fish. The areas are defined by their use for the given species; for example, feeding or breeding. A number of other qualitative characteristics, also, are provided. In the case of my analysis, I will specifically focus on feeding or foraging areas for marine mammals and seabirds. There are 118 feeding areas defined in this dataset, though several were too small in size for use in this analysis due to the resolution of the satellite imagery data used.

Marine mammals will be differentiated between cetaceans and pinnipeds, due to the drastic differences in their life histories and how these two groups of marine mammals utilize sea ice. Specifically, foraging patterns for cetaceans and pinnipeds vary greatly, as pinnipeds rely on the ice as a platform for various life cycle processes, including feeding. Seabirds were kept in one group, for simplicity, and because I did not see as much of a difference in the life histories of the different groups of seabirds. Examples of the species represented in the AMSA IIc foraging areas include:

- *Cetaceans:* Narwhal, Beluga Whale, and Bowhead Whale
- *Pinnipeds*: Ringed Seal, Walrus, and Bearded Seal
- *Seabirds:* Eiders, Murres, and the Black-Legged Kittiwake

A comprehensive list of all species can be found within the attribute table for the ArcGIS data used for this analysis (**Appendix A**). Species are specified for each of the individual feeding zones.

As outlined in the report, 'areas of heightened ecological significance' are taken to mean areas that are ecologically important and possess a heightened ecological significance, relatively, in comparison to other areas. The areas are evaluated using the International Maritime Organization (IMO) Particularly Sensitive Sea Areas (PSSA) criteria. The set of standards are part of the revised guidelines for the identification and designation of PSSAs, adopted in December 2005 (AMAP/CAFF/SDWG 2013).

In the case of the areas of ecological significance identified for Canadian waters, Ecologically and Biologically Significant Areas (EBSAs) – a term and standard created by the United Nations Convention on Biological Diversity (CBD) – were identified based on a set of national criteria, the "National Framework for the Identification of Ecologically and Biologically Significant Areas" (AMAP/CAFF/SDWG

2013). The criteria highly resemble the standards created by CBD, but it should be noted that ecologically significant feeding areas in Canadian waters were created under a different process, though still peer-reviewed by the same panel of scientific experts.

On a related note, the number of feeding areas in the Canadian and American Arctic heavily outweigh those defined for the Eastern Arctic, bordering Europe and Russia. This spatial disparity in study areas could represent differences in where these animals are actually feeding across the Arctic, but more likely it may be related to sampling error in the process of creating the AMSA IIc ecologically significant areas. It is likely that there is less availability or public accessibility of data in the Eastern Arctic.

While the AMSA IIc report from 2013 successfully outlines important areas for marine mammals and seabirds, aside from the spatial component of the areas, most of the analysis is qualitative. The aim of this study is to quantify these areas, in order to describe, not only their significance for different species, but the significance of changes occurring in these areas. By calculating changes to important environmental variables within these areas, we can make educated guesses about what species may be more or less impacted by a warming Arctic. Since we know the changes happening across the Arctic are not uniform, species will be impacted differently, depending on their distribution.

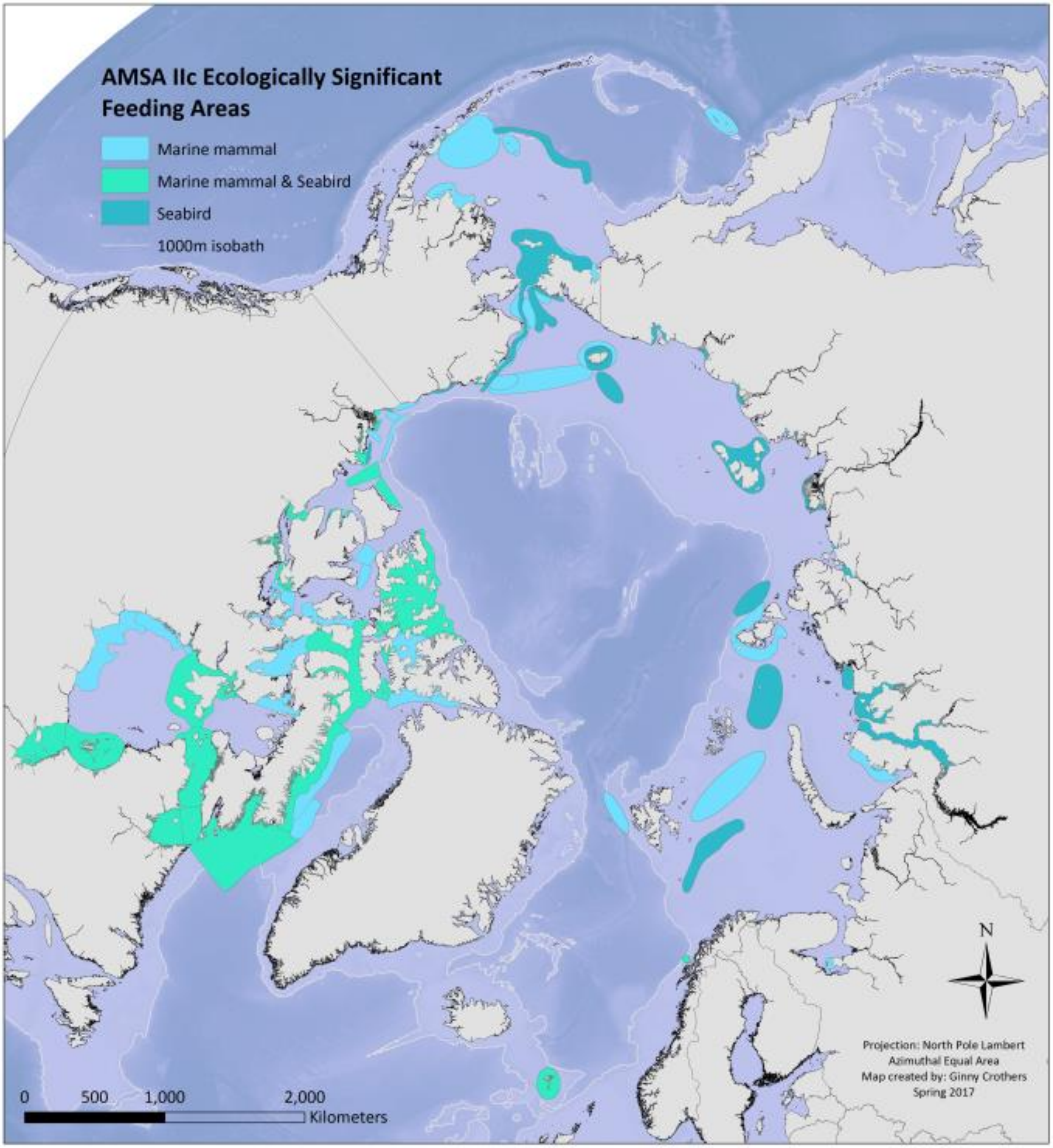



**Fig. 1.** Ecologically significant feeding areas, defined for marine mammals and seabirds (with some feeding areas assigned to both), are used as the basis for zonal statistical analysis of static and dynamic variables. The feeding areas originate from the report, *"Identification of Arctic marine areas of heightened ecological and cultural significance: Arctic Marine Shipping Assessment (AMSA) IIc"* (AMAP/CAFF/SDWG 2013).

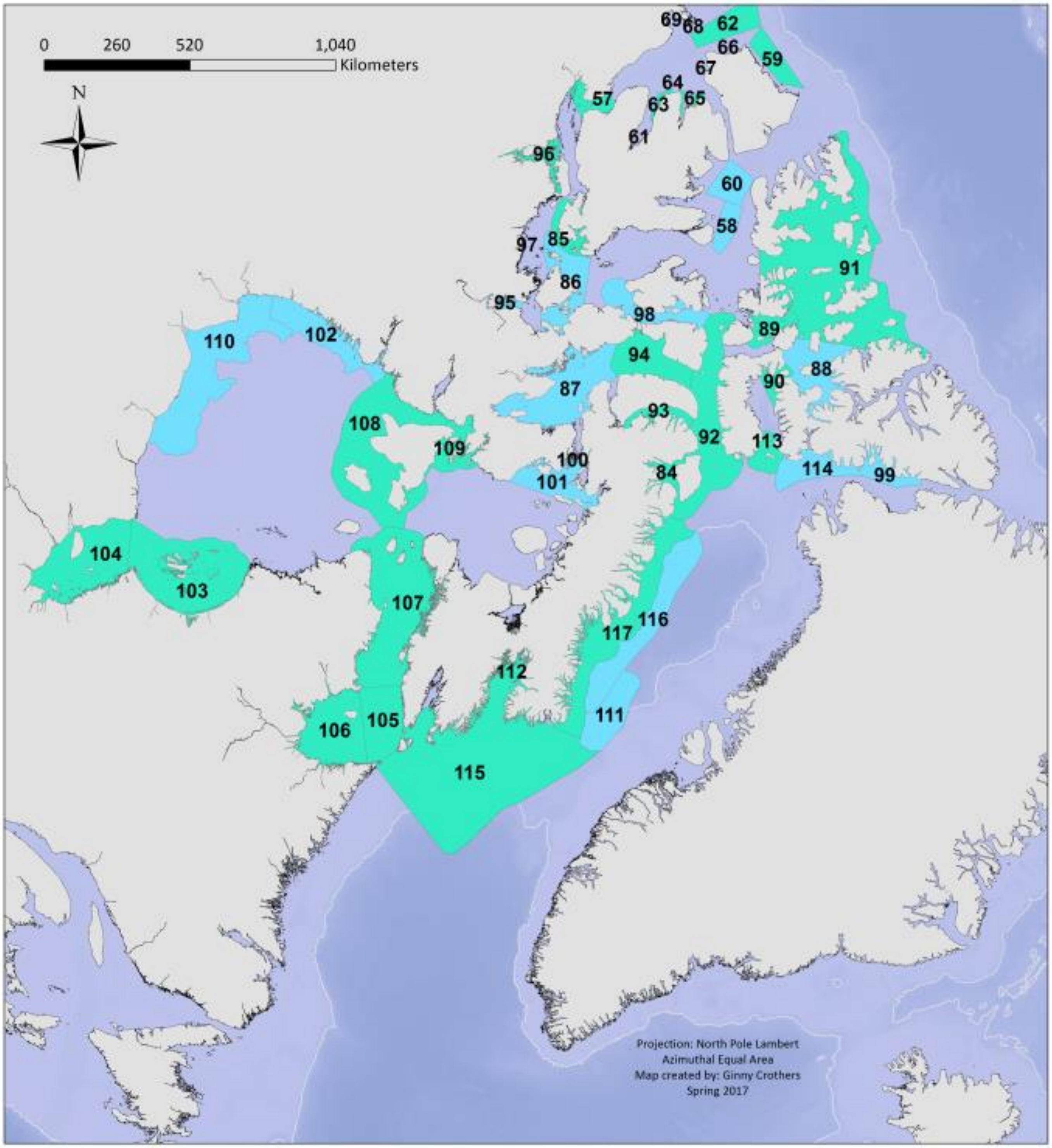



**Fig. 1a.** Subset study area map, showing ecologically significant feeding areas in the Baffin Bay-Davis Straight, Hudson Bay Complex, and the Canadian Arctic Archipelago Large Marine Ecosystems (LMEs). Reference Figure 1 for Legend. Labels represent FID numbers for each feeding area. Please reference attribute table in Appendix A for further information on a given feeding zone.

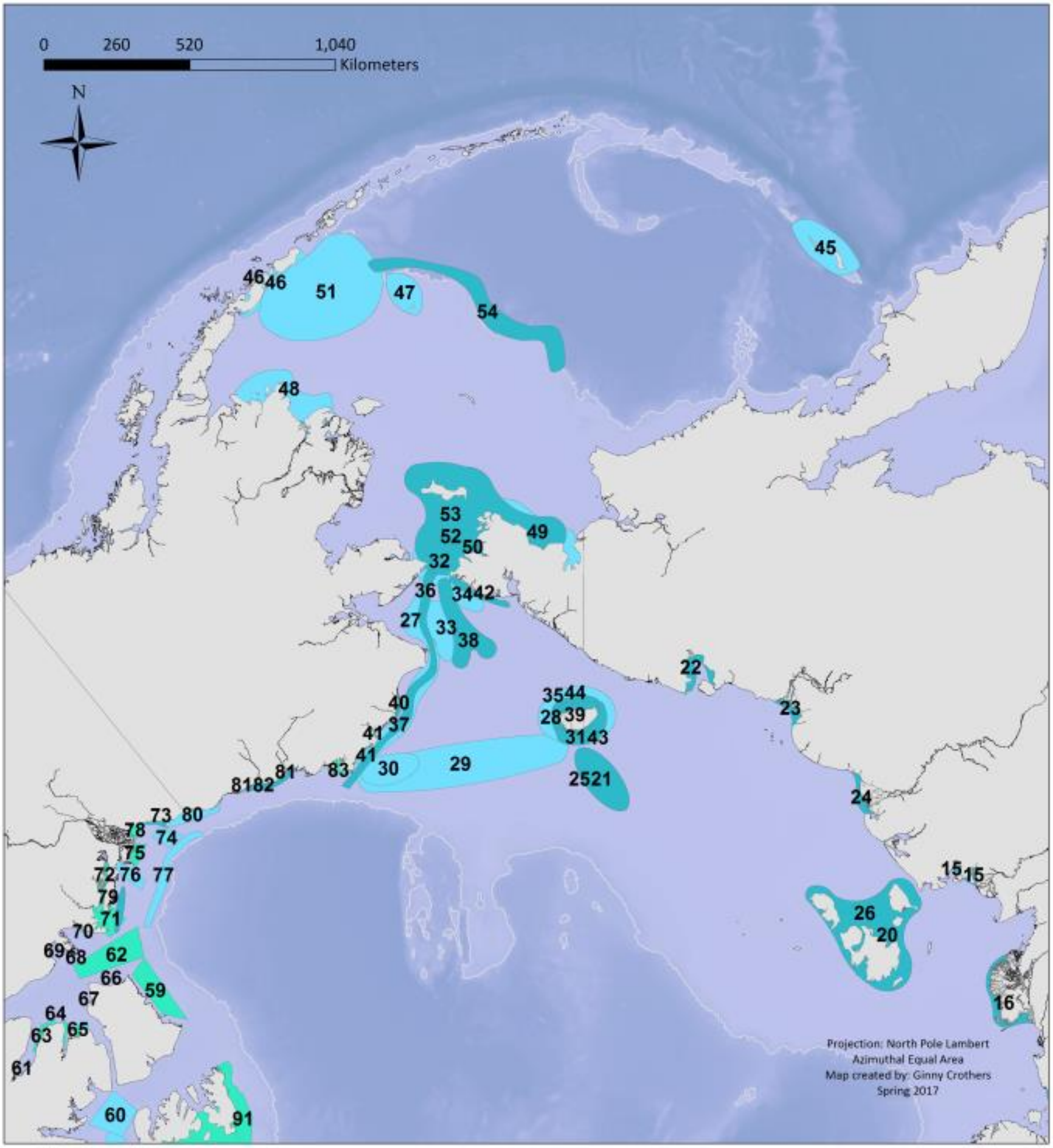



**Fig. 1b.** Subset study area map showing feeding areas in the Beaufort Sea, Chukchi Sea, Bering Sea (East and West), and East Siberian Sea LMEs. Labels represent FID numbers for each feeding area. Please reference attribute table in Appendix A for further information on a given feeding zone.

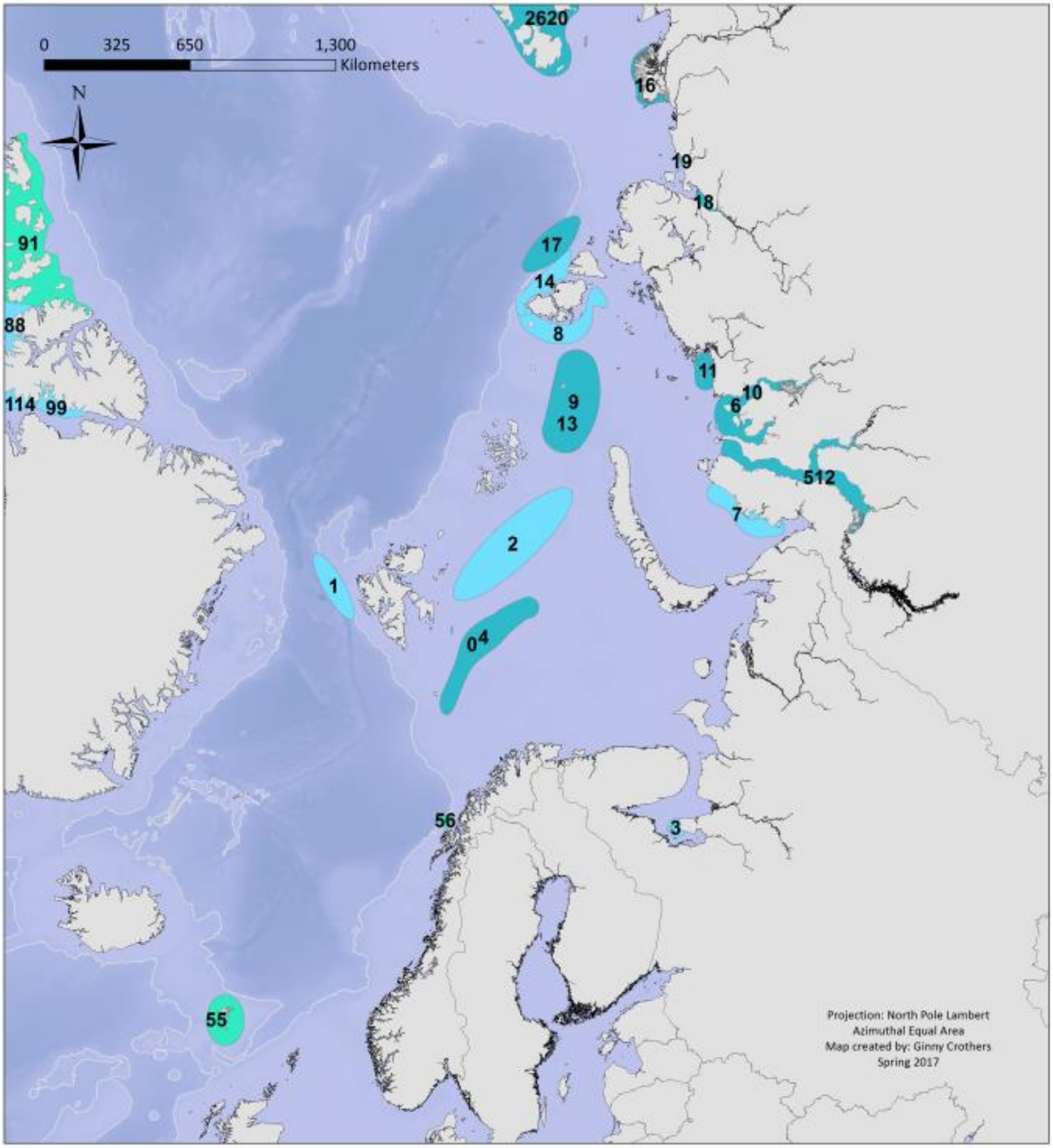



**Fig. 1c.** Subset study area map, showing feeding areas in the Laptev Sea, Kara Sea, Barents Sea, Norwegian Sea, Greenland Sea, and Iceland Shelf and Sea LMEs. Labels represent FID numbers for each feeding area. Please reference attribute table in Appendix A for further information on a given feeding zone.

The following are variables used in this study. The parameters are broken into two categories: *static* and *dynamic*.

*Static Variables*

In order to successfully protect important ecological areas, first we have to understand what defines areas that are ecologically or biologically significant for a given species. Running statistics on certain static or fixed parameters helps to get a sense of what features define important feeding areas for different species, prior to identifying changes related to the dynamic variables in this study.

These variables all have in common that they do not change temporally. However, forces such as sea level rise and coastal erosion may minimally impact these variables in the long term. For all of these static variables, the average or mean of each variable is calculated for each individual polygon, representing an individual feeding area from the AMSA IIc report (2013). The bulk of the analysis is completed through Python programming and the ArcPy module of Python that allows for processing ArcGIS tools directly through the Python interface. Please see **Appendix B** for attached Python scripts.

| Data Product | Data Source | Resolution |
|---|---|---|
| **Average depth (m)** | International Bathymetric Chart of the Arctic Ocean (IBCAO) 3.0 (Jakobsson et al.) and adapted by Jesse Cleary, MGET, Duke University | Spatial: 500m x 500m |
| **Average slope (degrees)** | International Bathymetric Chart of the Arctic Ocean (IBCAO) 3.0 (Jakobsson et al.) | Spatial: 500m x 500m |
| **Average distance to shore (km)** | Esri Continent Shapefile (2013) | Polygon Shapefile |
| **Average distance to 1,000m shelf break (km)** | 1,000m isobath contour (created from IBCAO) | Polyline Shapefile |

**Table 1.** Static variables calculated for each marine mammal and seabird feeding area.

<u>Depth</u>

In studying the behavior of marine animals, including cetaceans, pinnipeds, and different types of seabirds, bathymetry is an important indicator. Especially in the case of deep diving animals, depth is a critical factor in predicting and identifying important feeding habitat for different upper trophic species in marine ecosystems.

The bathymetric chart used in analyzing ocean bottom features was adapted from the International Bathymetric Chart of the Arctic Ocean (IBCAO) 3.0 (Jakobsson et al.). Because the IBCAO does not extend into southern Sub-Arctic latitudes, where some of the feeding study areas exist, I used an adapted version

of this chart that was created by Jesse Cleary of the Duke University Marine Geospatial Ecology Lab (MGEL). The chart stitches together other bathymetric charts around the globe to allow for analysis in areas below the Arctic Circle (60 degrees North).

### Slope

Equally important, if not more important, is bottom slope or steepness of seabed topography. Historically, bathymetric slope has been a determining variable in predicting the spatial distribution of foraging marine mammals and seabirds (Amélineau et al. 2016, Laidre et al. 2008). Shallow shelves make up a large part of the ocean bottom floor in the Arctic and often are zones where nutrients mix well in the water column, therefore, promoting primary production (Laidre et al. 2008). Species prefer different foraging depths, but for the most part, marine mammals and seabirds are attracted to areas of benthic complexity, because these topographic features – such as canyons, shelf breaks, and ridges – attract or direct prey into small, dense areas.

Areas of high slope or variation in slope, for example, near the continental shelf break – often prove to be highly linked to feeding for marine mammals and seabirds. Not only is benthic complexity a fundamental characteristic of feeding habitat for many Arctic marine species, the way in which these areas interact with changing dynamic variables – specifically sea ice – is of interest, because sea ice is a platform used by many species, especially seabirds and pinnipeds, for foraging. As sea ice retreats, that platform for feeding may be moving further away from these densely productive feeding areas.

### Distance to Shore

Distance to shore was calculated for all of the feeding areas, using a high-resolution continent shapefile from ESRI (2013). Distance to the coast can be a valuable, mostly static statistic to look at, especially when analyzing feeding areas. For species such as pinnipeds and diving seabirds, their attachment to land and landfast ice is a big part of what makes these species so vulnerable to retreating sea ice. Many species use landfast ice for feeding, as well as breeding and hauling out.

Many of the ecologically significant feeding areas outlined in the AMSA IIC report, and utilized in this analysis, are coastal areas. Obtaining an average of distance to shore provides an idea of the distance and duration of feeding trips for different ice-dependent animals, depending on their connection to land and sea ice. Distance to shore may be less telling for cetaceans, because they are not dependent on ice for resting or hauling out.

Distance to 1,000m Shelf Break

Finally, distance to the continental shelf break was calculated for the given study areas. Once determining that 500-meter and 1,000-meter isobaths define the shelf break in the Arctic Ocean, I created those bathymetric contours in ArcGIS prior to calculating average distance for the feeding areas (Amélineau et al. 2016).

In the case of distance to shore and distance to shelf break, prior to running the Zonal Statistics As Table tool through the Arcpy module in Python, I created a Euclidean Distance raster for the continent polygon shapefile (for distance to shore) and for the 1,000m contour polyline shapefile (for distance to shelf break). From there, I was able to calculate zonal statistics on each of the feeding zones to obtain an average within each zone.

It should be noted that the Zonal Statistics As Table tool was run iteratively in a for loop in Python in order to avoid the merging of overlapping polygon features in the process of extracting zonal statistics. Please see appendix to reference Python scripts used for analysis.

*Dynamic Variables*

While obtaining statistics on fixed variables for key feeding areas is useful in describing these areas in a way that is not related to temporal change, dynamic variables provide the story of what and how things are changing in these important foraging zones across the Arctic.

On both land and sea, satellite remote sensing is a powerful tool for measuring, monitoring, and assessing biological resources. Especially in marine ecosystems, satellite remote sensing is a way of looking at spatiotemporal changes across regions of open ocean.

For the purposes of analyzing environmental changes to feeding areas in the Arctic, as mentioned in the previous section, I am mainly interested in the intersection of changes to sea ice and primary productivity in the AMSA IIC ecologically significant feeding areas. The different products for analysis aim to look at changes in the areas and, additionally, the phenology or timing of how these variables may be shifting.

Due to availability of data, there are some differences in the temporal scale of the data used for sea ice and chlorophyll *a* concentration. The National Snow and Ice Data Center (NSIDC) provide very consistent daily data available for sea ice concentration (SIC) between 1979 and 2015. However, the NASA Ocean Color data for chlorophyll *a* is less consistent and, due to the nature of the data, have less overall spatial coverage. Especially in the Arctic, where cloud cover and ice interfere in obtaining ocean color data via

satellite imagery, the data are much less consistent. I will discuss this issue more in the Results section below.

Sea Ice

Sea ice is a hugely important, changing environmental variable when it comes to the life histories of both marine mammals and seabirds. More than any other environmental variable in the Arctic, the rapid changes in sea ice concentration, extent, and resilience have the potential to alter marine ecosystems permanently. In my analysis, I aim to gauge how sea ice concentration is changing within my study areas, by looking at the following metrics:

| Data Product | Data Source / Method | Resolution |
|---|---|---|
| **Average sea ice concentration (SIC)** | Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data (Cavalieri et al. 1996) | Spatial: 25 x 25km<br>Temporal: monthly, 1979 and 2012 |
| **Open water days** | Adapted from SIC data by creating binary daily data files for "sea ice" (0) or "no sea ice" (1)*<br><br>*No sea ice defined as SIC < 15%, per NSIDC standards for sea ice extent | Spatial: 25 x 25km<br>Temporal: annual, 1979-2015 |
| **Sea ice range (retreat and advance)** | Calculated by looking at daily sea ice extent or area (sq km) for cells with SIC > 15%.<br><br>*Sea ice threshold value calculated as 50% of maximum annual area (sq km) for sea ice extent. Threshold used to create time range. | Spatial: 25 x 25km<br>Temporal: annual, 1979 and 2012 |

**Table 2.** Data products created from sea ice concentration data. From these data products, the zonal mean was found for each feeding area, and more broadly, across each species group.

Following NSIDC standards for defining a sea ice concentration threshold, I use 15 percent as the threshold for sea ice or no sea ice. This is similar to how NSIDC creates their sea ice extent data files. Other academic research has used different thresholds for sea ice concentration. For example, 50 percent is another threshold used as a proxy because of the thermo-dynamic and hydrodynamic induced change that occurs in sea ice at that level of concentration (Ji et al. 2013).

Upon setting a threshold for sea ice or no sea ice, I transformed my sea ice raster files into binary files for sea ice (Pixel Value = 0) or no sea ice (Pixel Value = 1). Defining no sea ice as a value of one then enabled me to add binary files for an entire year. If every year for the time range from 1979 to 2015 had 365 data files, I would not have converted the data to percent rasters. However, in earlier years ranging from 1979 to 1988, daily sea ice data files are not available and instead is available on an every-other–day basis. Additionally, leap years throw off the ability to compare open water days across years. So, after creating open water day rasters, I adapted those rasters by dividing each one by the number of data files in the given year.

Subsequently, I ran a Python script to iterate through every feeding area feature polygon and every year to obtain the percentage of open water days per year for every feeding area in my study areas and across a long time range of 1979 through 2015. The aim of calculating this statistic across a relatively long time range was to assess the natural variation in open water days across the Arctic and the variation or change in open water days within select feeding areas. Due to dynamic ocean circulation patterns, wind and storm systems, and other variables that shift frequently, sea ice moves around a lot. Assessing variation within these feeding areas may give clues into how adaptive marine animals already are to a dynamic sea ice regime.

While the overall warming Arctic and diminishing extent of sea ice is, no doubt, problematic, it is important to quantify how much change these animals experience on a short time scale and how that may lead us to make assumptions about their future adaptability to a rapidly changing Arctic.

## Primary Productivity

Diminishing sea ice cover in the Arctic is changing biological processes in the Arctic Ocean system, including primary production. By analyzing chlorophyll *a* concentration satellite imagery, I aim to identify how primary production may be shifting in key feeding areas across the Arctic. Additionally, I will examine how the timing of these processes is changing and how this may impact different species.

While satellite imagery for estimating chlorophyll *a* concentration has its limitations, it provides "the only holistic perspective of productivity in marine ecosystems worldwide" (Suryan et al. 2012). One issue with satellite data can be the patchiness or gaps in data due to different variables, mostly cloud or ice cover in this case. Additionally, because of the limitations for the depth at which satellite imagery can perceive chlorophyll in the water column, phytoplankton production is usually slightly underestimated with satellite imagery and, in areas where sea ice is prevalent, under-ice primary production is not usually detected.

| Data Product | Data Source / Method | Resolution |
|---|---|---|
| **Average chlorophyll *a* concentration** | NASA Ocean Color Chlorophyll *a* Concentration, L3 8-day binned (NASA et al.)*<br><br>*Satellites differ across years. | Spatial: 9 x 9km<br>Temporal: 8-day, 1979 and 2012 |
| **Peak bloom initiation date** | NASA Ocean Color Chlorophyll *a* Concentration, L3 8-day binned (NASA et al.)<br><br>The method for detecting the date (or 8-day date range) for peak bloom initiation is drawn from the Threshold Method outlined in Brody et al. 2016 | Temporal: annual, 1979 and 2012 |
| **Peak bloom range** | NASA Ocean Color Chlorophyll *a* Concentration, L3 8-day binned (NASA et al.)<br><br>Range found using initiation threshold value to create time range. | Temporal: annual, 1979 and 2012 |

**Table 3.** Data products created from NASA Ocean Color chlorophyll *a* concentration data. Obtaining zonal statistics from the chlorophyll data was more difficult due to patchiness in the data, which will be discussed later on.

The majority of data processing was done through the Pythonwin 2.7 interface. Initially data for chlorophyll *a* concentration was downloaded using the Marine Geospatial Ecology Tools (MGET) tool, “Create Rasters for NASA OceanColor L3 SMI Product” (Roberts et al. 2010). This tool allowed me to download the data I needed only for the specified spatial extent: (50N, 90N, -180, 180).

After obtaining primary data products, zonal statistics were calculated (iteratively) for all of the marine mammal and seabird feeding areas using the ArcPy module in Python. By querying the feeding areas into groups based on broad species groups, I was able to further quantify what kinds of Arctic animals are seeing more or less change within key feeding areas. Because a large number of species were listed under these feeding areas, grouping them into species groups enabled me to make sense of the statistical outputs from the data processing. Further processing could be done to look specifically at individual species.

In addition to looking at change within the study area feeding zones, I was interested in looking at the Arctic as a whole and how a broader look at the entire Arctic might help in identifying those phenological shifts in primary production. To gauge how the timing of primary production might be changing, I

calculated peak bloom initiation date, using a Threshold Method (outlined in Brody et al. 2016) to 1) identify the peak bloom initiation threshold and 2) find where that threshold is met by starting at the peak concentration value and moving back in time, in order to avoid confusion with minor blooms earlier in the year. The peak initiation threshold, under the Threshold Method (Brody et al. 2016) is equal to the median chlorophyll concentration for the year, plus five percent of the median. This method performs particularly well for marine phenology studies, and it is shown that the method is relatively insensitive to the percentage above median used.

The limitations of the data and my methods of analysis should be noted. I have addressed the sometimes patchiness of satellite data, which is amplified in the Arctic, especially during winter months. For this reason, my analysis of the ocean color data for the Arctic is limited to months February through October (excluding November, December, and January, where data are very sparse).

In addition to the issue of patchy satellite data in the Arctic, there is some skepticism around the idea of relating changes in primary productivity to its impacts on secondary and tertiary productivity, spatially (Suryan et al. 2012). Because of the time lag in the responses of secondary and tertiary consumers to primary production, there is likely an inherent spatial and temporal mismatch between chlorophyll *a* concentration and upper trophic species distribution related to foraging (Suryan et al. 2012). While this could be an issue when studying these feeding areas, the spatial extent of the AMSA IIc feeding areas is relatively large, with feeding areas averaging approximately 30,000 square kilometers.

# RESULTS

*Static Variables*

The statistical results calculated for the study feeding areas provide background information on the characteristics that depict ecologically significant foraging areas for the select species groups. While there is not a lot of variation between species groups, the slight differences clearly correspond to different life histories of the species groups in this study.

While the map of the study areas can be somewhat fooling, the extent of these feeding areas is quite large, especially considering the extent of the Arctic as a whole. On average, each feeding area has an area of approximately 30,000 square kilometers. Considering that the spatial resolution of the NSIDC sea ice data have grid cells measuring 625 square kilometers, larger study areas enables better sampling of the data. Still it should be noted that a small number of the feeding areas failed to calculate statistics using the Zonal Statistics As Table tool due to small spatial extent.

When looking at mean distance to shore, which ranged between 30 and 40 kilometers (**Table 4**), unsurprisingly cetaceans show the highest mean distance to shore. While pinnipeds and seabirds, for many life cycle processes including foraging, utilize land or landfast ice as a foraging platform, cetaceans are much less tied to the shoreline. Additionally, cetaceans typically possess the ability to forage at deeper depths – which is shown in the mean depth values – allowing them to feed at farther distances from the coast. Pinnipeds and seabirds show similar preferences in terms of how their feeding habitat relates to Arctic shorelines.

Mean distance to the shelf break ranges between approximately 465 and 500 kilometers (**Table 4**). While, again, there is not a lot of variation between the species groups, cetaceans show a divergence in their feeding habitat preferences in relation to the 1,000-meter continental shelf break. Pinnipeds and seabirds are both slightly more tied to feeding areas in some proximity to the continental shelf break. Regardless, though, in general the numbers for distance to shelf break are high.

Mean depth of the study feeding areas show a much more stark difference across the three species groups. As mentioned earlier, cetaceans unsurprisingly favor feeding areas with a deeper average depth. Physiologically, cetaceans usually have higher maximum diving depths and times when compared to pinnipeds and seabirds. Seabirds possess the lowest mean depth, while pinnipeds fall somewhere in the middle.

Interestingly, pinnipeds show a preference for feeding habitat with a higher mean slope, though cetaceans closely follow. Seabird feeding areas, overall, reveal a preference for a lower bathymetric slope,

though the difference is not significant. The mean slope for feeding areas, though, is likely correlated to mean depth, since the same trends are seen across species groups for both variables.

Overall, cetacean and pinniped feeding areas correspond more closely to one another, while statistics for static parameters are more differentiated for seabird feeding zones. While a higher level of statistical analysis was outside of the scope of my analysis, it would be useful to identify the degree of dependence across species groups – since some of the feeding areas correspond to two or more species groups – and to identify if any of the differences among the static statistics calculated are statistically significant.

| | Mean area (sq km) | Mean distance to shore (km) | Mean distance to 1,000m shelf break (km) | Mean depth (m) | Mean slope (degrees) |
|---|---|---|---|---|---|
| **ALL** | 30,179 | 40.39389 | 487.90765 | -183.13493 | 0.61980 |
| **Cetaceans** | 34,123 | 38.33612 | 493.76418 | -227.55119 | 0.78027 |
| **Pinnipeds** | 31,282 | 30.09391 | 469.79792 | -196.87522 | 0.83381 |
| **Seabirds** | 31,144 | 32.39595 | 465.18500 | -151.52287 | 0.64684 |

**Table 4.** Static statistics for feeding areas based on the three species groups: cetaceans, pinnipeds, and seabirds. Statistics were calculated by finding the zonal mean for each feeding area and finding the average across each species group.

### *Dynamic Variables*

#### Sea Ice

Before looking specifically at how sea ice concentration – and, conversely, open water days – are changing within the given study areas, I familiarized myself with the data by looking at overall changes across the time range 1979 to 2015. Because the time range is large, I used monthly (rather than daily) sea ice concentration data from NSIDC (Cavalieri et al. 1996) and created five-year bins to capture longer-term trends across this time period. In **Figure 2a**, there is a clear shift between 1979 and the present in the Arctic sea ice regime, with continuously diminishing concentration of sea ice across the Arctic.

Aside from the clear negative trend in sea ice concentration between 1979 and 2015, there is a stark contrast between study years 1979 and 2012. These two years were chosen as representative years because typically 1979 represents a historically "normal" sea ice regime and 2012 represents the "new normal". Across the Arctic, sea ice concentration decreases marginally in winter months and significantly in summer and early fall months. For example, in September, sea ice concentration drops by nearly 50 percent between 1979 and 2012.

Within feeding areas, the change in sea ice concentration between 1979 and 2012 is lower overall (**Figures 2d** and **2e**). In winter months, surprisingly there is little change in average sea ice concentration between 1979 and 2012. This contrasts the changes occurring across the Pan-Arctic. However, change

within feeding areas in sea ice concentration in summer and fall months is significant. September sea ice concentration values drop from approximately 30 percent to 20 percent between 1979 and 2012 in ecologically significant feeding areas.

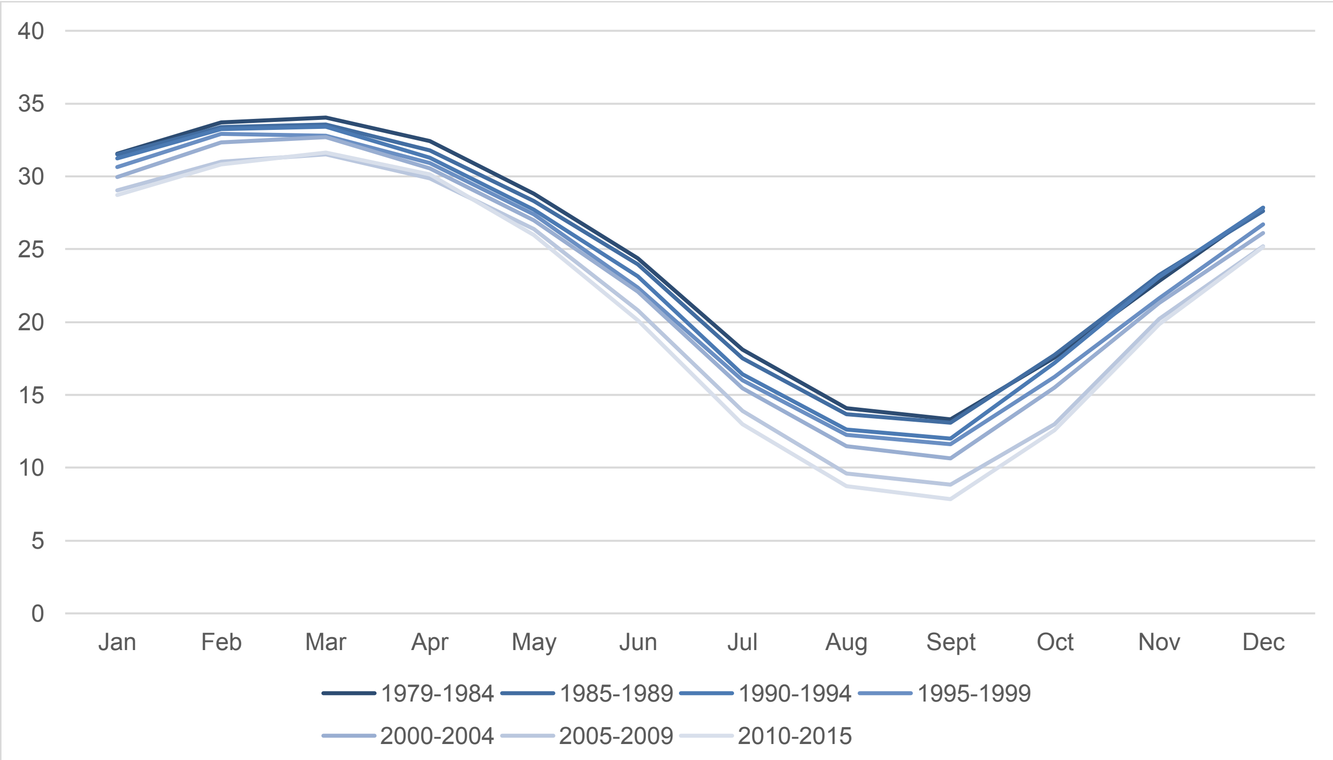



**Fig. 2a.** Monthly mean sea ice concentration (percent) for 5-year climatologies, 1979-2015.

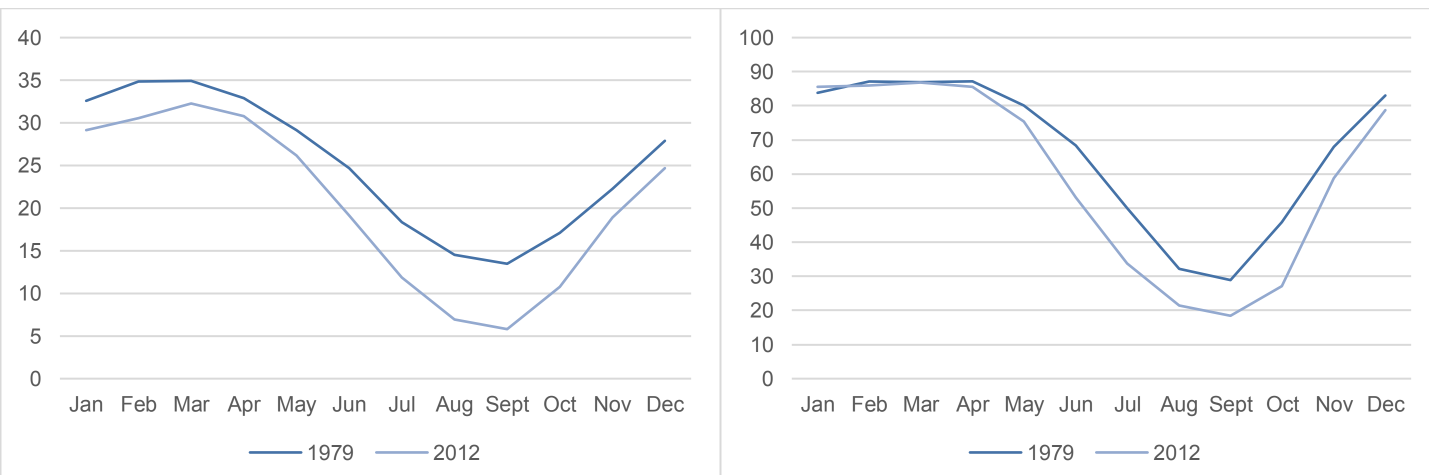



**Fig. 2b & c. (b)** Monthly mean sea ice concentration (percent) comparison for study years 1979 and 2012.
**(c)** Monthly mean sea ice concentration (percent) comparison for study feeding areas for 1979 and 2012.

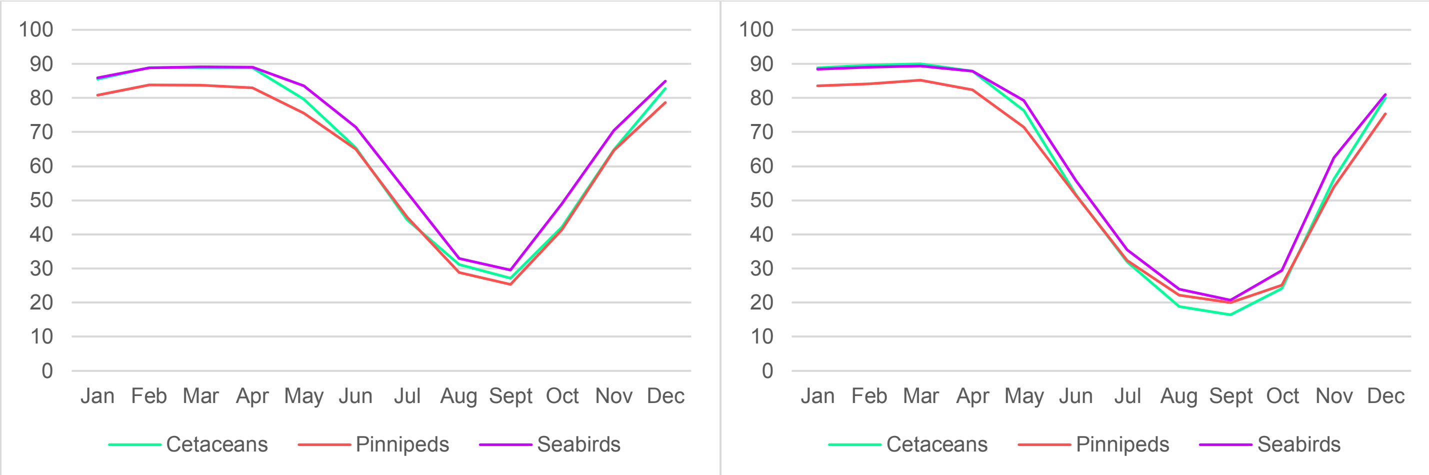



**Fig. 2d & e. (d)** Monthly mean sea ice concentration (percent) for 1979 for study feeding areas, categorized by species group. **(e)** Monthly mean sea ice concentration (percent) for 2012 for study feeding areas, categorized by species group.

<u>Open Water Days</u>

By creating raster files showing the percentage of open water days per year for each grid cell in my study area, I am able to show the change in sea ice concentration between 1979 and 2015 both spatially and temporally. In **Figure 3**, change in open water days is shown as a difference grid between 1979 and 2012. Here, several anomalies in sea ice concentration are represented in: 1) the Bering Sea, 2) the Russian Arctic (Kara and Laptev Seas), and 3) Baffin Bay west of Greenland. Curious at these results, I looked at trends for both years to find that 1979 and 2012 experienced opposing anomalies in sea ice concentration in those areas. These areas tend to experience anomalies on an annual basis, showing the variability of these regions of the Arctic marine ecosystem.

The number of open water days is calculated for each pixel for each given year and the mean is calculated across the Arctic region for each year. Note: The spatial coverage for this analysis is equivalent to the NSIDC data coverage (N: 90, S: 30.98, E: 180, W: -180). Because the spatial extent extends beyond the Arctic Circle, percentage of open water days per year is inflated across the entire Arctic.

Both negative and positive trends can be seen between 1979 and 2015. The time series in **Figures 4a** and **4b** show the increase in open water days between 1979 and 2015. **Figure 4b** displays the change specifically within feeding areas, across the three species groups, whereas **Figure 4a** represents the entire Arctic.

In **Figures 4c** and **4d**, the annual rate of change is shown for both the entire Arctic (**4c**) and the study feeding areas (**4d**). Both charts display the variation, year to year, in open water days. Across the Arctic, the rate of change is much less variable than within the feeding areas.

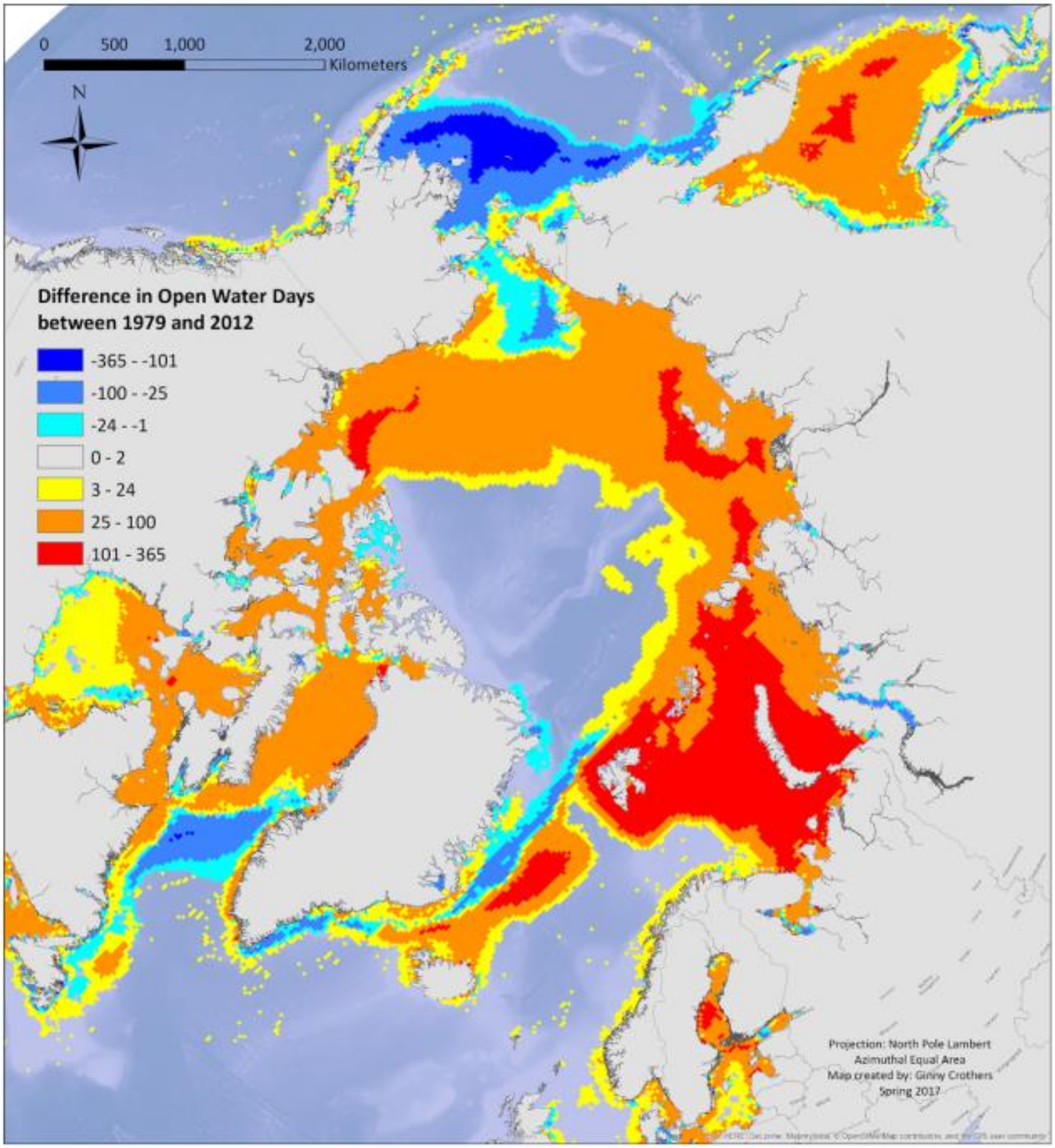



**Fig. 3.** Change in open water days between 1979 and 2012. Here, the number of days is the unit of measure. Negative numbers indicate areas where open water days decreased (or sea ice increased). Positive numbers indicate areas where open water days increased (or sea ice concentration decreased).

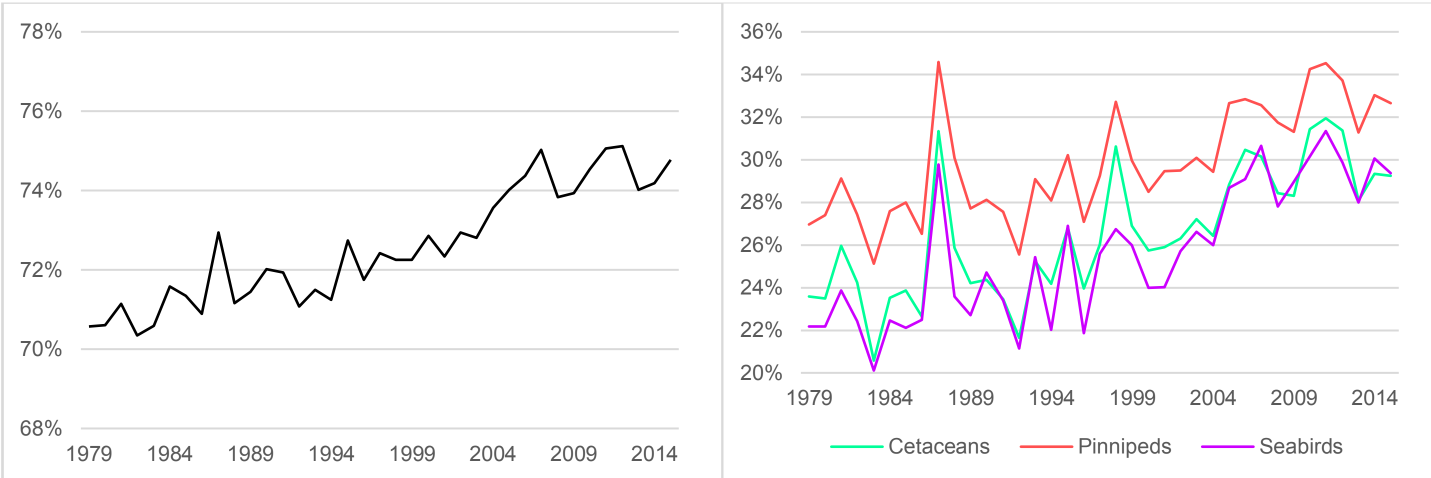



**Fig. 4a & 4b. (a)** Annual time series displaying change in open water days (percentage per year) between 1979 and 2015. **(b)** Annual time series for feeding zones grouped into three species groups: cetaceans, pinnipeds, and seabirds.

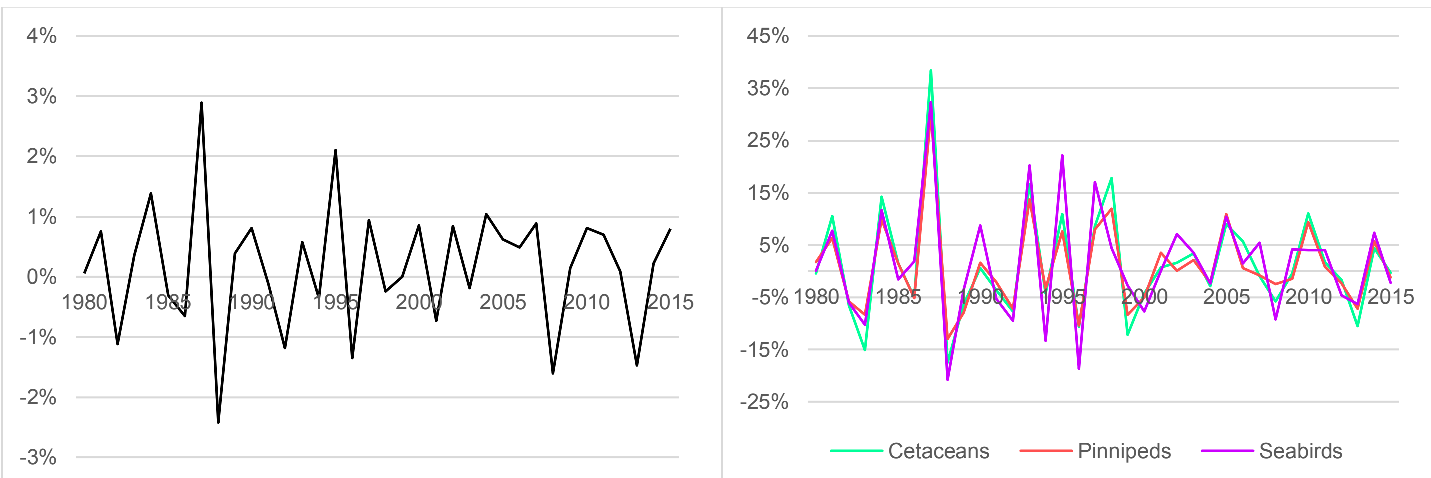



**Fig. 4c & 4d. (c)** The annual rate of change in open water days (mean percentage per year) is calculated for 1979 through 2015. **(d)** Annual rate of change in open water days (mean percentage per year) is also calculated for feeding zones for three species groups.

Primary Productivity

Below are annual time series, for the months February through October, for key years between 1979 and 2015 (**Figures 5a** and **5b**). In **Figure 5b**, I extract only 1979 and 2012, the two study years used in my analysis for comparison. Please also see the following table (**Table 5**), showing statistics for chlorophyll *a* concentration for given years and the peak bloom initiation threshold and time period. A Threshold Method, developed at Duke University (Brody et al. 2016), is used to identify the peak bloom period.

**Figures 6a** and **6b** show the time series for chlorophyll *a* concentration for both **(a)** 1979 and **(b)** 2012 for ecologically significant feeding areas, broken up by species group. The following tables (**Tables 6a** and **6b**) present statistics for the study years for species group feeding areas. More analysis on the timing of peak blooms will be shown in the following section on Phenology.

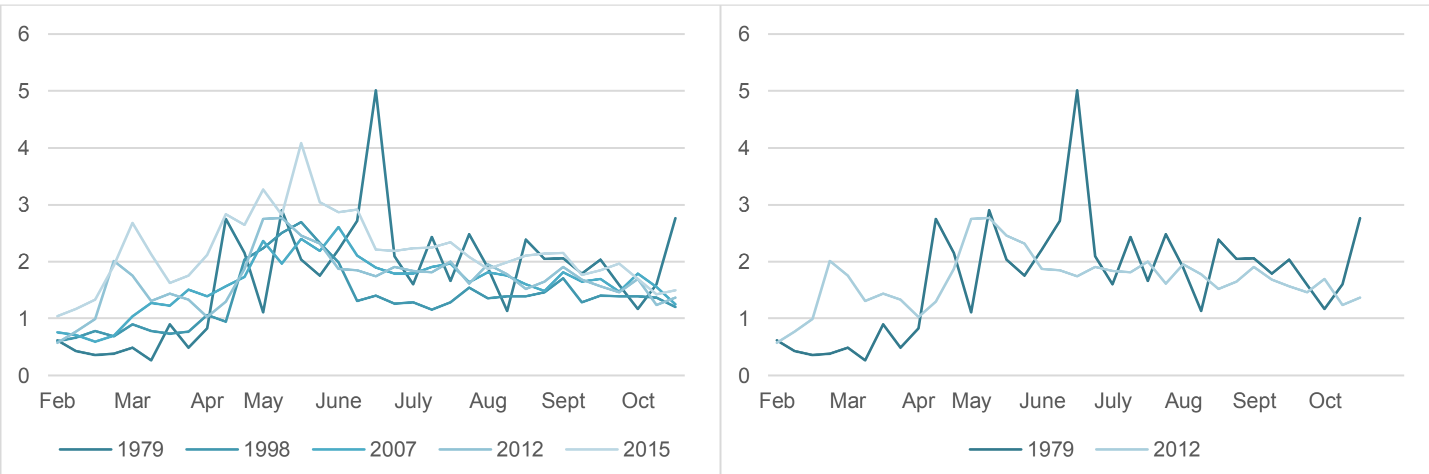



**Fig. 5a & 5b. (a)** Times series of chlorophyll *a* concentration (mg/m3) for select years between 1979 and 2015 for months February through October. **(b)** Comparison of chlorophyll *a* concentration for study years 1979 and 2012.

| | **1979** | **1985** | **1998** | **2000** | **2003** | **2007** | **2012** | **2015** |
|---|---|---|---|---|---|---|---|---|
| **Mean** | 1.712 | 2.627 | 1.364 | 1.382 | 1.609 | 1.619 | 1.681 | 2.178 |
| **Maximum** | 5.011 | 18.125 | 2.696 | 2.742 | 3.031 | 2.610 | 2.769 | 4.083 |
| **Standard deviation** | 0.987 | 3.223 | 0.531 | 0.479 | 0.538 | 0.480 | 0.484 | 0.634 |
| **Median** | 1.774 | 2.091 | 1.334 | 1.381 | 1.600 | 1.673 | 1.723 | 2.125 |
| **Peak initiation threshold** | 1.863 | 2.196 | 1.401 | 1.451 | 1.680 | 1.757 | 1.809 | 2.230 |
| **Peak range (weeks)** | 4 | 2 | 6 | 7 | 10 | 11 | 12 | 13 |
| **Peak initiation month** | June | June | April | April | April | May | April | April |

**Table 5.** Statistics for chlorophyll *a* concentration for given years. Additionally the peak bloom threshold and length of period is included. Not all of these years are included in the figure above.

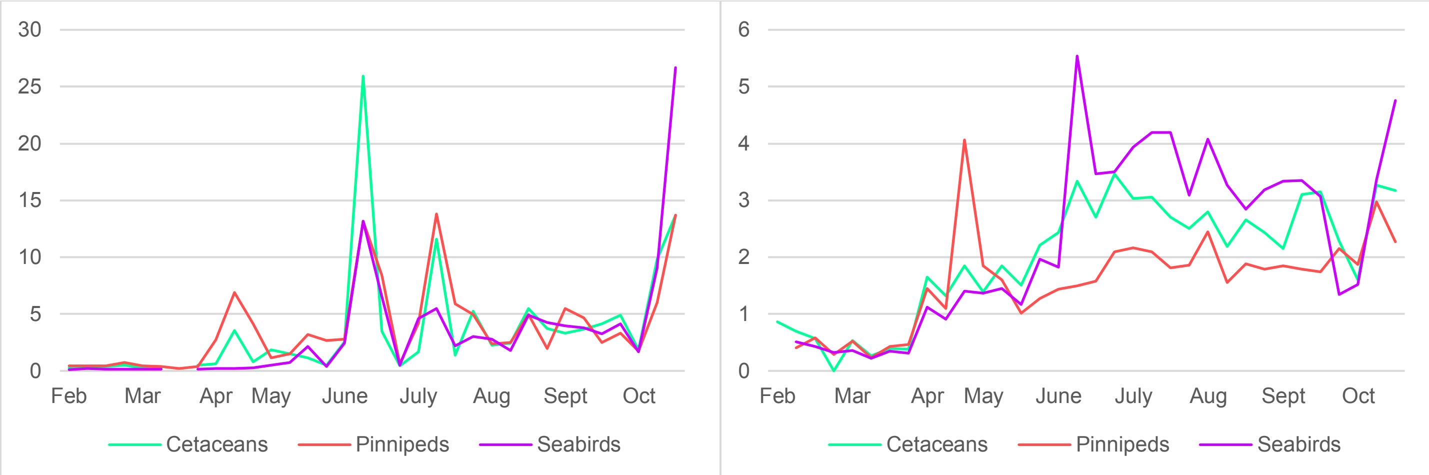


**Fig. 6a & 6b. (a)** Chlorophyll *a* concentration (mg/m3) time series for 1979 for species group feeding areas. Values based off 8-day data files. **(b)** Chlorophyll *a* concentration (mg/m3) time series for 2012 for species group feeding areas.

| 1979 | **Mean** | **Maximum** | **Standard deviation** | **Median** | **Peak initiation threshold** | **Peak range (weeks)** |
|---|---|---|---|---|---|---|
| **Cetaceans** | 3.63849 | 25.92785 | 5.15587 | 1.82906 | **1.92052** | 4 |
| **Pinnipeds** | 3.78845 | 13.80459 | 3.74711 | 2.67935 | **2.81332** | 3 |
| **Seabirds** | 2.59939 | 13.19146 | 2.97248 | 1.96830 | **2.06671** | 4 |

| 2012 | **Mean** | **Maximum** | **Standard deviation** | **Median** | **Peak initiation threshold** | **Peak range (weeks)** |
|---|---|---|---|---|---|---|
| **Cetaceans** | 2.04603 | 3.46397 | 0.98822 | 2.21252 | **2.32315** | 9 |
| **Pinnipeds** | 1.57970 | 4.06328 | 0.81645 | 1.74092 | **1.82796** | 8 |
| **Seabirds** | 2.29538 | 5.53929 | 1.52205 | 1.96673 | **2.06506** | 15 |

**Tables 6a & 6b. (a)** Statistics for chlorophyll *a* concentration for 1979 for feeding areas, categorized by species group. **(b)** Statistics for chlorophyll *a* concentration for 2012 for feeding areas, categorized by species group.

Phenology

Calculating the timing of sea ice and chlorophyll *a* concentration proved to be somewhat difficult for the study feeding areas. For sea ice, I was unable to calculate statistics on sea ice retreat and advance for feeding areas, but the results in **Tables 7a** and **7b** show the change in sea ice retreat and advance for the Pan-Arctic for study years 1979 and 2012.

Between 1979 and 2012, the minimum extent for sea ice in the Arctic drops by nearly 50 percent from approximately 7 million square kilometers to about 3.5 million square kilometers. Unsurprisingly, the length of the period between sea ice retreat and advance increases from 1979 to 2012. This can also be seen in the area of the time series that falls below the red line in **Figures 7a** and **7b**.

Phenology of chlorophyll *a* concentration is shown in **Figures 8a** and **8b**. Time series for chlorophyll *a* for 1979 and 2012 are included, as well as vertical red lines representing the peak bloom range. I include sea ice extent in **Figures 8a** and **8b** for a visual comparison of the overlap in both dynamic variables.

| 1979 | |
|---|---|
| **Maximum (sq km)** | 17,253,593.75 |
| **Minimum (sq km)** | 6,915,468.75 |
| **Threshold (sq km)** | 8,626,797 |
| | |
| **Date of retreat (Julian range/month)** | 217-224 / Aug |
| **Date of advance (Julian range/month)** | 289-296 / Oct |

| 2012 | |
|---|---|
| **Maximum (sq km)** | 15,708,750.00 |
| **Minimum (sq km)** | 3,543,281.25 |
| **Threshold (sq km)** | 7,854,375 |
| | |
| **Date of retreat (Julian range/month)** | 193-200 / Jul |
| **Date of advance (Julian range/month)** | 305-312 / Nov |

**Tables 7a & 7b. (a)** Sea ice extent (sq km) statistics for study year 1979 for the Pan-Arctic. **(b)** Sea ice extent (sq km) statistics for study year 2012 for the Pan-Arctic.

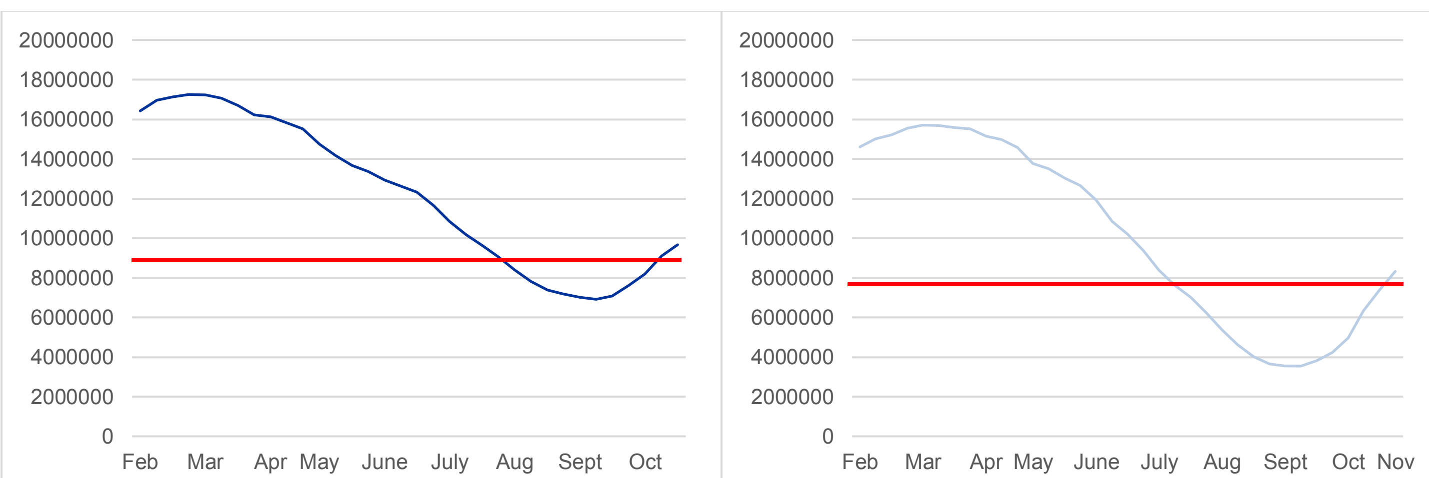


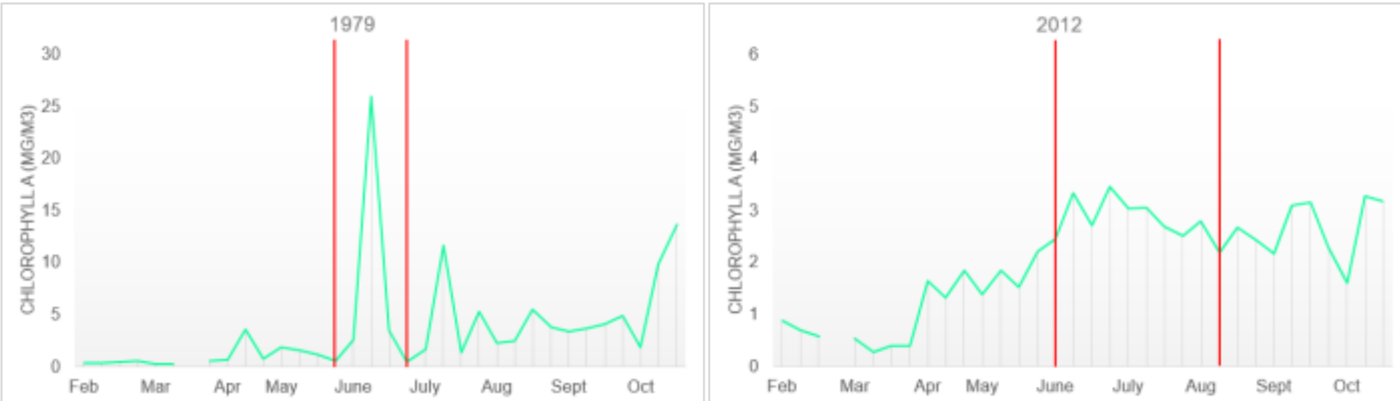

**Fig. 7a & 7b.** Sea ice extent (sq km) for **(a)** 1979 and **(b)** 2012. Red horizontal lines represent sea ice threshold values for the given year, and intersecting points with the sea ice extent time series represent points of sea ice retreat and sea ice advance.


**Fig. 8a & 8b.** Sea ice extent (sq km) and chlorophyll *a* concentration (mg/m3) for study years **(a)** 1979 and **(b)** 2012. Left axis measures sea ice extent in square kilometers and right axis measures chlorophyll *a* concentration in milligrams per meter cubed. The time series is measured across the months February through October and the red vertical line represents the point where chlorophyll *a* reached the peak initiation threshold value, based off the maximum chlorophyll value for the given year. Dotted linear trend lines are included for both variables.

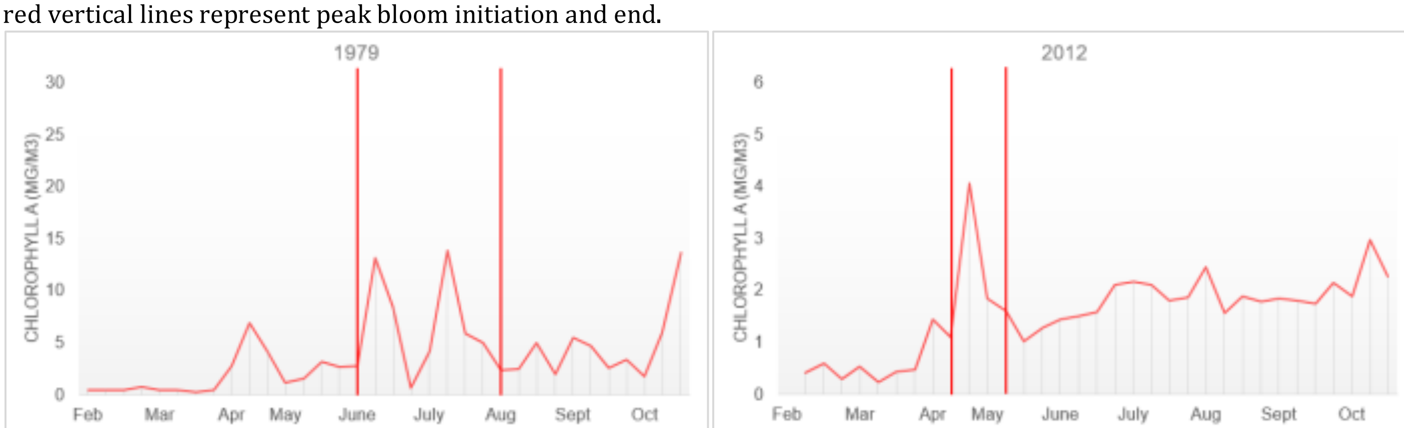
| 1979 | **Mean** | **Maximum** | **Standard deviation** | **Median** | **Peak initiation threshold** | **Peak range (weeks)** |
|---|---|---|---|---|---|---|
| **Cetaceans** | 3.63849 | 25.92785 | 5.15587 | 1.82906 | **1.92052** | 4 |
| **Pinnipeds** | 3.78846 | 13.80459 | 3.74711 | 2.67935 | **2.81332** | 8 |
| **Seabirds** | 2.59936 | 13.19146 | 2.97248 | 1.96830 | **2.06671** | 4 |

| 2012 | **Mean** | **Maximum** | **Standard deviation** | **Median** | **Peak initiation threshold** | **Peak range (weeks)** |
|---|---|---|---|---|---|---|
| **Cetaceans** | 2.04603 | 3.46397 | 0.988224 | 2.212523 | **2.32315** | 9 |
| **Pinnipeds** | 1.579703 | 4.063275 | 0.816447 | 1.740916 | **1.82796** | 3 |
| **Seabirds** | 2.295375 | 5.539291 | 1.522048 | 1.966725 | **2.06506** | 15 |

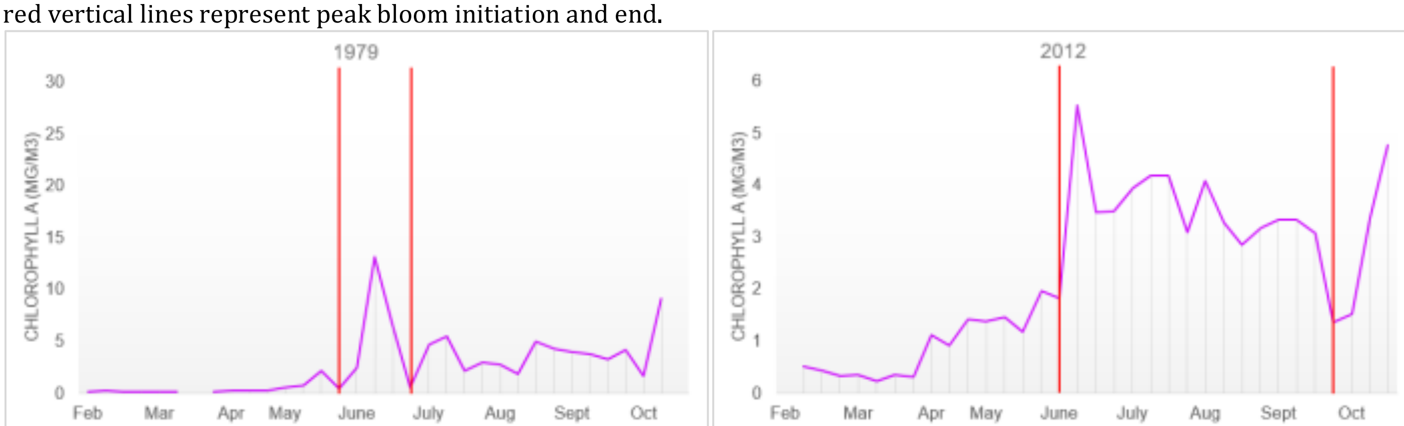
**Tables 8a & 8b.** Statistics for chlorophyll *a* concentration for ecologically significant feeding areas, categorized by species group. Additionally the peak bloom threshold and length of period is included.




**Figures 9a & 9b.** Chlorophyll *a* concentration (mg/m3) time series for Cetacean feeding areas for **(a)** 1979 and **(b)** 2012. The red vertical lines represent peak bloom initiation and end.




**Figures 9c & 9d.** Chlorophyll *a* concentration (mg/m3) time series for Pinniped feeding areas for **(c)** 1979 and **(d)** 2012. The red vertical lines represent peak bloom initiation and end.




**Figures 9e & 9f.** Chlorophyll *a* concentration (mg/m3) time series for Seabird feeding areas for **(e)** 1979 and **(f)** 2012. The red vertical lines represent peak bloom initiation and end.

# DISCUSSION

*Sea Ice*

When assessing overall changes across the Arctic, there is a clear shift occurring with respect to both sea ice concentration and primary production. Sea ice, since 1979, is steadily diminishing – though, in recent years, it is evident that the annual rate of change has accelerated. In **Figure 2a**, it is evident that the Arctic has experienced a consistent negative decline in sea ice concentration since 1979.

Seen in **Figures 2b** through **2e**, we can see that feeding areas experience less change in sea ice concentration overall between 1979 and 2012. In the summer and early fall months, declines in sea ice concentration of around 10 percent are seen for both the Pan-Arctic (**Figure 2b**) and the feeding areas as a whole (**Figure 2c**). In winter and early spring months, there is a divergence in the changes happening within the study areas compared to the Arctic as a whole. Whereas declines of up to 5 percent are seen in winter months between 1979 and 2012, feeding areas experience less change in sea ice concentration in winter months. Looking at statistics for feeding areas for the species groups – Cetaceans, Pinnipeds, and Seabirds – the trends are similar across all groups (**Figures 2d** and **2e**).

Conversely, it makes sense that the percentage of open water days is steadily increasing across the Arctic and within the feeding areas used in this study (**Figures 4a** and **4b**). While this is not surprising, it is interesting to look at the spatial component**.** Clearly, certain parts of the Arctic more than others are experiencing an accelerated decline in sea ice and, as I learned through outside research, more annual variation in sea ice concentration. The map shown in **Figure 3** demonstrates these spatial differences, as we see increases in open water days concentrated in the Eastern Arctic in the Barents and Kara Seas. Moderate increases in open water days between 1979 and 2012 are seen Arctic-wide, though, as well. The Bering and Chukchi Seas are experiencing decreases in open water days. Additionally, the Baffin Bay-Davis Straight region between Canada and Greenland is experiencing moderate decreases in open water days. As mentioned before, these regions seem to represent areas experiencing more annual variation, so the trends seen in **Figure 3** are more of a snapshot of the differences between 1979 and 2012.

When looking at the annual rate of change in open water days, both across the Arctic and within the study areas, there is a lot of variation year to year. Especially within the study areas, the variation ranges up to 35% change in open water days from a given year to the next, possibly showing that Arctic marine species are already used to a fair bit of variation when it comes to short-term changes and movement of sea ice.

*Primary Productivity*

As mentioned in the Introduction, the changes occurring in the Arctic marine ecosystem have the potential to shift the patterns of primary productivity in the region. In the Arctic, historically, there has been one peak bloom per year in the summer. However, recently, a second spring bloom has been occurring within the region. This marks the transition of the Arctic marine ecosystem to a more temperate marine ecosystem biological cycle for primary production.

Consequently, these changes have had the effect of flattening out the peak in primary production, so that it is more of a hill or plateau. In **Figures 5a** and **5b**, the movement of the timing of the peak chlorophyll *a* bloom is evident across peak years from 1979 to 2015. In 1979, we see a huge peak in late June or early July. In following years, the peak moves earlier in the year and decreases substantially in magnitude. In 2012, the peak bloom is seen in early May, nearly two months earlier than is identified as the "normal" peak bloom timing seen in 1979. Finally, the flattening out of the peak is very evident moving from 1979 to the present.

The plateau in primary production means that prey sources up the food chain, whether zooplankton or fish, may not be available in the same density. As is discussed in the introduction, if marine animals are migrating large distances to get to the Arctic to feed off this short, but highly productive feeding period, there will be significant implications for different upper trophic species – including cetaceans, pinnipeds, and seabirds – if there is a lower density of prey available when they get there. For pinnipeds, which are generally less migratory or not migratory, this may be less of an issue, but cetaceans and seabirds stand to lose a lot if they are not able to adapt to an earlier onset of primary production in the Arctic. Some research shows species already altering their migratory timing and patterns in relation to changing environmental variables, though (Bailleul et al. 2012).

In addition to looking across the entire Arctic, an objective of this study was to gauge the changes occurring specifically within feeding areas in the Arctic. In **Figures 6a** and **6b**, time series are shown for species groups feeding areas for 1979 and 2012. Here, again, there is a clear flattening out of chlorophyll *a* concentration in 2012, when compared to 1979. Additionally, the peak range (shown in **Tables 6a** and **6b**) increases substantially for all species groups between 1979 and 2012. The range changes from three to four weeks in 1979 to up to 15 weeks in 2012.

There is considerable variation in the peak range for 2012. While pinnipeds and cetaceans see a peak range between eight to nine weeks, seabird feeding areas, on average, experience a peak range time period of 15 weeks.

*Phenology*

My analysis shows that, not only is sea ice decreasing in magnitude, but the timing of sea ice is also shifting dramatically. Between 1979 and 2012, the date of sea ice retreat shifts earlier from Julian Range 217-224 (August) to Julian Range 193-200 (July) (**Tables 7a** and **7b**). Additionally the date of sea ice advance shifts later in the year between 1979 and 2012 from mid-October to early November. Overall, this indicates an increase in the amount of time when sea ice extent (sq km) is lower than the given threshold. While the threshold used in my analysis was relatively simple (50 percent of annual maximum amplitude), the analysis still gives an idea of how sea ice is shifting temporally.

Because sea ice advance and retreat was a particularly challenging component to calculate within feeding areas, I do not have a sense of the temporal scale of changes happening within feeding areas. However, from other pieces of my analysis, I would assume that the changes happening within feeding areas would be similar to those occurring on a Pan-Arctic scale, if not slightly reduced.

The interplay of sea ice and chlorophyll *a* concentration is one of the main concepts that drove my interest in this research. Changes in sea ice phenology influence the phenology of primary production (Ji et al. 2013), and those changes can greatly impact foraging success of marine animals in the Arctic. In **Figures 8a** and **8b**, sea ice and chlorophyll *a* concentration time series for the Pan-Arctic are combined for study years. Additionally, the timing for peak bloom is graphed to give an idea of how the temporal component of that variable is shifting.

Some of the notable differences in these graphs include:

- The change in slope for sea ice extent between 1979 and 2012. The slope increases negatively in 2012, showing a larger range in sea ice extent, as the minimum value of sea ice extent drops considerably between those years.
- The peak in the chlorophyll *a* concentration curve decreases between 1979 and 2012, showing the flattening out of the peak bloom.
- The peak bloom range increases dramatically between study years. In 1979, the peak bloom is contained within the month of June. In 2012, the average chlorophyll *a* concentration values show a peak range stretching from mid-April until late July.

While representing these temporal changes within feeding areas for sea ice extent was a part of my analysis that I was unable to include, the timing differences in chlorophyll *a* concentration for the feeding areas (**Figures 9a** through **9f**) show notable changes. We see across the board that the magnitude of chlorophyll *a* concentration is much lower in 2012 than in 1979. The maximum values of chlorophyll *a*

were up to 30 mg/m3 in 1979, whereas maximum values did not exceed 6 mg/m3 in 2012 for any of the feeding area species groups.

In **Figures 9a** and **9b**, chlorophyll *a* concentration for cetacean feeding areas shows a flattening in the peak bloom and a widening of the peak range. While the peak initiation date does not stray from the beginning of June between 1979 and 2012, the length of the peak range is much larger in 2012, extending into August.

Interestingly, the trends seen in seabird feeding areas (**Figures 9e** and **9f**) relate closely to cetacean feeding areas in that the peak initiation date does not move from late May/early June. The differences seen in the peak bloom for seabird feeding zones is 1) the lower maximum value for chlorophyll *a* in 1979 and 2) the even longer peak bloom range, extending to late September. In 2012, the peak range for seabird feeding areas was 15 weeks.

The chlorophyll *a* time series for pinniped feeding areas shows interesting results. While the magnitude of chlorophyll *a* is larger in 1979 by nearly three-fold, the peak range for primary production is actually longer in 1979 than in 2012. Additionally, the peak initiation date shifts greatly between study years from early June in 1979 to mid-April in 2012. This is the only species group where the peak bloom shifts greatly in timing.

Overall, the shifts in chlorophyll *a* concentration for ecologically significant feeding areas reinforce the idea that timing mismatches in primary production could have implications for these upper trophic species. The widening of the peak range, similarly, is cause for concern for species where timing really, really matters – such as migratory species or species that are tied tightly to life cycle schedules (for example, pinniped breeding).

*Limitations and Future Research Opportunities*

The limitations of the study relate both to the data utilized in my analysis, as well as the limitations of the overall scope of the project.

The data used in the study has qualifications that create challenges when successfully drawing results from the analysis. The study areas, taken from the AMSA IIc ecologically significant areas, have a high percentage of overlap between the species study groups that I was interested in looking at – cetaceans, pinnipeds, and seabirds. Because of the dependence of the study variables, the results were highly correlated, making it more difficult to draw separate conclusions about different species groups.

However, there is truth to the high correlation across these species groups. It is very likely that cetaceans, pinnipeds, and seabirds are utilize many of the same areas for foraging. In a further analysis, I

think it would be interesting to pull out specific species – for example, the ringed seal or the black-legged kittiwake or bowhead whales – and base the analysis on indicator species within the species groups. Narrowing down the focus of the analysis may lead to more compelling findings on specific species.

In addition to some issues in analyzing the study areas used for my research, the satellite imagery for sea ice and chlorophyll *a* concentration, at times, proved problematic for this analysis. For one, the often-coarse resolution of satellite imagery makes it hard to calculate reliable and compelling results about relatively small zones, such as the feeding areas used in this analysis. In addition to the coarse resolution of the data, satellite imagery in the Arctic can be very patchy, due to frequent cloud cover (especially in winter months) and sea ice cover.

While the sea ice data was very consistent from 1979 to the present, the chlorophyll data was harder to process for zonal statistics due to the patchy nature of the data. In fact, in that way, drawing any real conclusions from the zonal statistics of the feeding areas was nearly impossible.

One method for dealing with coarse or inconsistent satellite data is to create methods for supplementing those datasets or interpolating those datasets to fill in the gaps. In several studies, model data was a secondary component in analyzing primary production.

The work done in this research study only skims the surface of studying:

- The changes occurring with respect to sea ice concentration and primary productivity,
- The overlap and timing mismatches occurring in these processes and the possible consequences of such changes, and
- Implications for marine mammals and seabirds that rely on the Arctic for foraging.

# CONCLUSION

This is just one piece of the story. While changes are clearly being seen in these foraging areas, it is still necessary to further identify the significance of these changes and the potential adaptability or resilience of the impacted species groups to these shifting variables. A follow-up literature review assessing the life cycles of different species in these species groups would aid in identifying how these changes may harm or benefit certain Arctic marine animals.

The spatiotemporal analysis of sea ice and chlorophyll *a* concentration data for Arctic feeding areas was done in an effort to get a better idea of what species may be more or less impacted by shifting environmental variables in this ecosystem. While negative trends in sea ice concentration are consistent

across the three species groups (cetaceans, pinnipeds, and seabirds), the results are more variable when looking at chlorophyll *a* concentration. Across all species groups, 1) a decrease in the magnitude of the peak bloom is observed between 1979 and 2012 and 2) a widening of the peak range is observed between 1979 and 2012. Pinniped feeding areas seem to experience the most change in the timing of the peak bloom, with a shift forward in peak bloom initiation from June in 1979 to mid-April in 2012.

While the analysis done in this study is not conclusive, it indicates a clear shift occurring in the Arctic with respect to sea ice concentration and chlorophyll *a* concentration. Diminishing sea ice concentration clearly impacts the makeup and the magnitude of primary production pulses in the Arctic, and here, it seems that these changes may indicate the transformation of the Arctic marine environment to a more temperate marine ecosystem. This transformation, no doubt, is affecting and will continue to affect the foraging behavior of Arctic marine animals in the future.

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# APPENDIX A: Supplementary Data

*Attribute Table for AMSA IIc Feeding Areas (adapted from original version)*

| ID | Activity | Species | Season | Location | Area (sq m) | AMSA ID | LME | Index No. |
|---|---|---|---|---|---|---|---|---|
| 0 | Feeding | Polar bear, Harp seal | Spring, Summer | Western and Central Barents Sea | 63249100000 | M6 | 5 | |
| 1 | Feeding | Bowhead whale, Blue whale, Minke whale | | Svalbard Archipelago | 24526000000 | M16 | 5 | |
| 2 | Feeding | Polar Bear | Summer, Autumn | Northern Barents Sea Marginal Ice Zone | 109070000000 | M7 | 5 | |
| 3 | Feeding | Beluga whale | Summer | White Sea (Kandalaksha, Onega, Dvina Bays) | 4020940000 | M13 | 5 | |
| 4 | Feeding | Thick-billed murre, Black-legged kittiwake, Northern fulmar | Summer | Western and Central Barents Sea | 63249100000 | B18 | 5 | |
| 5 | Feeding | Beluga whale | Summer | Ob Estuary | 51943200000 | M5 | 6 | |
| 6 | Feeding | Beluga whale | Summer | Yenisey Estuary | 34268600000 | M6 | 6 | |
| 7 | Feeding, Haul-out | Walrus | Summer | Baydaratskaya Inlet - Western Yamal | 27062700000 | M7 | 6 | |
| 8 | Feeding | Polar bear | Spring, Summer | Western Severnaya Zemlya | 36720500000 | M3 | 6 | |
| 9 | Feeding | Polar bear | Summer, Autumn | Northern Kara Sea Marginal Ice Zone | 86332200000 | M8 | 6 | |
| 10 | Molting, Feeding | King eider, Long-tailed duck | Summer, Autumn | Yenisey Estuary | 34268600000 | B6 | 6 | |
| 11 | Molting, Feeding | King eider, Steller's eider, Long-tailed duck, Black scoter, White-winged scoter, N. pintail, Bewick's swan, Dark-bellied brent goose | Summer, Autumn | Pyasina Estuary | 12053800000 | B7 | 6 | |
| 12 | Molting, Feeding | King eider, Steller's eider, Long-tailed duck, Black scoter, White-winged scoter, N. pintail, Bewick's swan, Dark-bellied brent goose | Summer, Autumn | Ob Estuary | 51943200000 | B5 | 6 | |
| 13 | Feeding | Black-legged kittiwakes, Ivory gull, Black guillemot, Skuas, Larus species (gulls) | | Vilkitskij Strait | 86075100000 | B11 | 6 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 14 | Feeding, Migration | Beluga whale, Walrus | Spring | Baydaratskaya Inlet - Western Yamal | 21461600000 | M2 | 7 | |
| 15 | Feeding, Moulting, Staging | King eider, Spectacled eider, Steller's eider, Long-tailed duck, Black scoter, Dark-bellied brent goose, Black brant, Tundra swan, Divers, Red phalarope | Summer, Autumn | Yana Delta | 1645050000 | B8 | 7 | |
| 16 | Feeding, Moulting, Staging | King eider, Spectacled eider, Steller's eider, Long-tailed duck, Black scoter, Dark-bellied brent goose, Black brant, Tundra swan, Divers, Red phalarope | Summer, Autumn | Lena Delta | 9079770000 | B8 | 7 | |
| 17 | Feeding | Dovekie, Black-legged kittiwake, Ivory gull, Larus species (gulls) | Summer, Autumn | Northwestern Laptev Sea | 32660500000 | B3 | 7 | |
| 18 | Feeding, Moulting, Staging | King eider, Spectacled eider, Steller's eider, Long-tailed duck, Black scoter, Dark-bellied brent goose, Black brant, Tundra swan, Divers, Red phalarope | Summer, Autumn | Khatanga Delta | 4215030000 | B8 | 7 | |
| 19 | Feeding, Moulting, Staging | King eider, Spectacled eider, Steller's eider, Long-tailed duck, Black scoter, Dark-bellied brent goose, Black brant, Tundra swan, Divers, Red phalarope | Summer, Autumn | Anabar Delta | 1088740000 | B8 | 7 | |
| 20 | Feeding, Moulting | Long-tailed duck, Pacific eider, King eider, Red phalarope | Summer, Autumn | New Siberian Islands | 57785600000 | B6 | 7 | |
| 21 | Feeding | Beluga whale, Bowhead whale | Summer, Autumn | Ice Zone on the Northern Shelf | 25941700000 | M3 | 8 | |
| 22 | Feeding, Moulting, Staging | Waterfowl, Shorebirds | Summer, Autumn | Chaun Bay | 5970340000 | B6 | 8 | |
| 23 | Feeding, Moulting, Staging | King eider, Spectacled eider, Steller's eider, Black brant, Tundra swan, Red phalarope | Summer, Autumn | Indigirka and Kolyma Deltas and Estuaries | 3150520000 | B5 | 8 | |
| 24 | Feeding, Moulting, Staging | King eider, Spectacled eider, Steller's eider, Black brant, Tundra swan, Red phalarope, Short-billed dowitcher | Summer, Autumn | Indigirka and Kolyma Deltas and Estuaries | 3906030000 | B5 | 8 | |
| 25 | Feeding | Ivory gull, Ross's gull, Thick-billed murre, Black-legged kittiwake, Skuas | Summer, Autumn | Ice Zone on the Northern Shelf | 25941700000 | B4 | 8 | |
| 26 | Feeding, Moulting | Long-tailed duck, Pacific eider, King eider, Red phalarope | Summer, Autumn | New Siberian Islands | 57785600000 | B1 | 8 | |
| 27 | Feeding | Polar bear | | Alaska - Northeast Coastal Area | 37573400000 | M1a | 11 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 28 | Feeding | Polar bear | Summer | Wrangel / Herald Islands Area | 22287400000 | M2 | 11 | |
| 29 | Feeding | Polar bear | Summer, Autumn | Chukchi Shelf - Marginal Ice Zone | 97646700000 | M3 | 11 | |
| 30 | Feeding | Pacific walrus | Summer | Chukchi Shelf - Hannas Shoal | 17879600000 | M5 | 11 | |
| 31 | Feeding | Pacific walrus | Summer | Wrangel / Herald Islands Area | 37926400000 | M6 | 11 | |
| 32 | Feeding | Bowhead whale | Summer | Bering Strait | 19834100000 | M10 | 11 | |
| 33 | Feeding | Gray whale | Summer | Alaska - Northeast Coastal Area | 22920600000 | M13a | 11 | |
| 34 | Feeding | Gray whale | Summer | Northern Chukchi Peninsula | 10534000000 | M14 | 11 | |
| 35 | Feeding | Thick-billed murre, Common eider, Red phalarope | Spring | Wrangel / Herald Islands Area | 10482800000 | B2 | 11 | |
| 36 | Feeding, Migration | Thick-billed murre, Common murre, Pacific eider, King eider, Long-tailed duck, Red phalarope, Red-necked phalarope | Spring | Southeastern Chukchi Sea | 9773920000 | B1 | 11 | |
| 37 | Feeding, Staging | King eider, Common eider, Red phalarope | Spring | Alaska - Northeast Coastal Area | 15024200000 | B3 | 11 | |
| 38 | Feeding | Least auklet, Crested auklet, Parakeet auklet, Black-legged kittiwake, Short-tailed shearwater | Summer, Autumn | South-Central Chukchi Sea | 25349300000 | B8 | 11 | |
| 39 | Feeding | Kittliz's murrelet (Critically Endangered) | Summer, Autumn | Wrangel / Herald Islands Area | 16488800000 | B11 | 11 | |
| 40 | Feeding, Staging | Dunlin phalarope, Red phalarope | Spring, Autumn | Alaska - Northeast Coastal Area - Kasegaluk Lagoon | 934163000 | B15 | 11 | |
| 41 | Feeding, Staging | Red phalarope | Summer, Autumn | Alaska - Northeast Coastal Area - Peard Bay | 470406000 | B19 | 11 | |
| 42 | Feeding, Migration | Red phalarope, Red-necked phalarope | Summer | Northern Chukchi Peninsula | 4729970000 | B20b | 11 | |
| 43 | Feeding, Migration | Red phalarope, Red-necked phalarope | Summer | Wrangel / Herald Islands Area | 9968930000 | B20a | 11 | |
| 44 | Feeding, Migration | Red phalarope, Red-necked phalarope | Summer | Wrangel / Herald Islands Area | 2479010000 | B20a | 11 | |
| 45 | Feeding, Breeding | Northern fur seal, Seal | Spring, Autumn | Komandorsky Islands | 25708400000 | M3 | 9 | |
| 46 | Feeding, Breeding, Haul-out | Sea otter, Pacific walrus | | Bristol Bay and Southeastern Bering Shelf / Northern Alaska Peninsula | 10470600000 | M1 | 9 | |
| 47 | Feeding, Breeding | Northern fur seal | | Continental Southeastern Shelf and Shelf Break | 13990800000 | M2 | 9 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 48 | Feeding, Haul-out | Walrus | | Northern Bristol Bay | 27831700000 | M8 | 9 | |
| 49 | Feeding, Haul-out | Walrus | | Gulf of Anadyr | 25737600000 | M9 | 9 | |
| 50 | Feeding, Haul-out | Walrus | | Bering Strait - Chukotka Peninsula | 13486700000 | M10 | 9 | |
| 51 | Feeding | North pacific right whale (Critically Endangered) | | Bristol Bay and Southeastern Bering Shelf / Northern Alaska Peninsula | 117784000000 | M13 | 9 | |
| 52 | Feeding | Gray whale | | Bering Strait - Chirikov Basin | 21300600000 | M14 | 9 | |
| 53 | Feeding, Migration | Seabird, Waterfowl: Least auklet, Thick-billed murre, Common murre, Crested auklet | | St Lawrence Island area including St Lawrence Polynya | 104786000000 | B7a | 9 | |
| 54 | Feeding | Seabird: Short-tailed albatross, Fork-tailed storm petrel, Red-legged kittiwake | | Contiental Southeastern Shelf and Shelf Break | 43739400000 | B8 | 9 | |
| 55 | Feeding, Breeding | Northern fulmar, Atlantic puffin, European storm-petrel, Black-legged kittiwake, Common murre, Common eider, Harbor seal, Gray seal | | Norwegian Coast and Shelf | 28480600000 | 1 | 3 | |
| 56 | Feeding | Feeding habitat (eg. Sperm whale) | Spring, Summer | Canyon (Bleiksdjupet) | 2427410000 | BH2 | 4 | |
| 57 | Breeding, Feeding, Staging | Ringed seal, Polar bear, Common eider, Loon, Seabird | Winter, Spring | Lambert Channel / Union and Dolphin Strait (?) | 9669130000 | 2.3 | 12 | B-3.1 |
| 58 | Feeding, Rearing | Beluga whale, Polar bear | | Viscount Melville Sound | 11228200000 | 4.1 | 12 | B-3.24 |
| 59 | Feeding, Staging | Beluga whale, Bearded seal, Ringed seal, Polar bear, Seaducks, King eider | Spring | Bank's Island Flaw Lead | 14973600000 | 1.2 | 12 | B-3.15 |
| 60 | Feeding, Rearing | Beluga whale, Polar bear | | Viscount Melville Sound | 15330200000 | 4.1 | 12 | B-3.24 |
| 62 | Migration, Feeding, Staging | Bowhead whale, Beluga whale, Ringed seal, Polar bear, Seabird, Seaduck | Summer | Cape Bathurst Polynya | 20643500000 | 1.1 | 12 | B-3.14 |
| 63 | Feeding, Breeding | Ringed seal, Bearded seal, Polar bear, Seabird, Seaduck | | Prince Albert Sound | 1958140000 | 2.1 | 12 | B-3.18 |
| 64 | Breeding, Feeding | Ringed seal, Bearded seal, Polar bear, Seaduck, Seabird | | Minto Inlet | 925182000 | 2.2 | 12 | B-3.20 |
| 65 | Breeding, Feeding | Ringed seal, Bearded seal, Polar bear, Seaduck, Seabird | | Walker Bay | 1038440000 | 2.2 | 12 | B-3.21 |
| 70 | Breeding, Feeding, | Ringed seal, Polar bear, Beluga whale, Bowhead whale, Thick-billed murre, Black | Winter, Spring | Horton River | 169308000 | 1.4 | 12 | B-3.25 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Migration | guillemot | | | | | | | |
| 71 | Feeding, Migration, Nesting, Staging | Bowhead whale, Polar bear, Seabird, Seaduck, Geese | | | Liverpool Bay | 7685480000 | 3.8 | 12 | B-3.26 |
| 72 | Nursing, Feeding, Migration | Marine mammal, Seabird, Seaduck | | | Husky Lakes | 1931470000 | 3.7 | 12 | B-3.12 |
| 73 | Breeding, Feeding, Molting | Black guillemot, Waterfowl | | | Herschel Island / Yukon North Slope | 1369360000 | 5.2 | 12 | A-3.7 |
| 74 | Migration, Feeding, Breeding | Bowhead whale, Beluga whale, Ringed seal, Polar bear | | | Mackenzie Trough | 4248380000 | 3.4 | 12 | A-3.8 |
| 75 | Molting, Feeding, Migration | Beluga whale, Ringed seal, Seabird, Seaduck, Geese | | | Beluga Bay | 2919530000 | 3.2 | 12 | A-3.11 |
| 76 | Migration, Feeding | Ringed seal | | | Kugmallit Corridor | 4520130000 | 3.3 | 12 | A-3.13 |
| 77 | Feeding, Migration | Polar bear, Beluga whale, Bowhead whale | | | Beaufort Shelf Break / Outer Mackenzie Shelf | 10550100000 | 3.6 | 12 | A-3.9 |
| 78 | Molting, Feeding, Migration | Beluga whale, Ringed seal, Seabird, Seaduck, Geese | | | Shallow Bay | 1708870000 | 3.2 | 12 | A-3.10 |
| 79 | Staging, Feeding, Molting | Seaduck: Common eider, Long-tailed duck, others | Spring, Summer | | Mackenzie Shorelead | 3598680000 | 3.5 | 12 | |
| 80 | Feeding | Bowhead whale | | | Shelf areas | 5735600000 | 5.3 | 12 | |
| 81 | Nesting, Feeding, Rearing, Nesting, Molting, Staging | Geese, Shorebird | Summer | | Colville and Sagavanirktok river deltas and estuaries | 635103000 | 6.1 | 12 | |
| 82 | Breeding, Molting, Rearing | Common eider, Seabird, Long-tailed duck, Seaduck | | | Simpson Lagoon and Stefansson Sound | 3833720000 | 6.2 | 12 | |
| 83 | Feeding, Staging, Migration | Seabird: Ross's gull, Waterfowl: Common eider, King eider, Shorebird: Phalarope, Bowhead whale | Autumn | | Elson Lagoon and Dease Inlet | 1512540000 | 6.3 | 12 | |
| 84 | Migration, | Narwhal, Beluga whale, Killer whale, | Summer | | Eclipse Sound / Navy Board | 5850820000 | 3.1 | 14 | B-2.1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Feeding, Staging, Breeding | Ringed seal, Harp seal, Seabird | | Inlet | | | | |
| 85 | Migration, Feeding, Staging, Breeding | Narwhal, Beluga whale, Killer whale, Ringed seal, Harp seal, Seabird | Summer | Southern Victoria Island Coastline / Eclipse Sound - Navy Board Inlet | 9665740000 | 2.2 | 14 | B-3.6/2.1 |
| 86 | Feeding | Ringed seal, Polar bear | | King William Island | 26173000000 | 2.1 | 14 | B-3.5 |
| 87 | Migration, Nursing, Rearing, Feeding | Narwhal, Bowhead whale, Polar bear | | Gulf of Boothia | 60661500000 | 4.2 | 14 | B-2.4 |
| 88 | Feeding, Rearing | Polar bear (genetically differentiated) | | Norwegian Bay | 31310300000 | 8.2 | 14 | B-5.4 |
| 89 | Haul-out, Nesting, Breeding, Feeding | Walrus, Seabird, Seaduck | | Wellington Channel | 12354700000 | 6.1 | 14 | B-2.7 |
| 90 | Haul-out, Feeding, Summering, Breeding | Walrus, Beluga whale, Killer Whale, Seal, Seabird | Year-round, Summer | Cardigan Strait / Hell Gate | 6412900000 | 7.1 | 14 | B-2.16 |
| 91 | Feeding, Rearing, Nesting | Polar bear, Ivory gull, Ice-dependent species | | Archipelago Multi-Year Pack Ice | 162891000000 | 8.1 | 14 | B-5.3 |
| 92 | Migration, Feeding, Staging, Breeding, Aggregation | Polar cod, Beluga whale, Bowhead whale, Narwhal, Polar bear, Seabird, Seaduck, Ivory gull | | Lancaster Sound | 69571700000 | 3.2 | 14 | B-2.6 |
| 93 | Feeding, Breeding | Narwhal, Bowhead whale, Ringed seal, Harp seal, Seabird | Summer | Admiralty Inlet | 8615220000 | 3.3 | 14 | B-2.2 |
| 94 | Migration, Feeding, Molting | Narwhal, Bowhead whale, Beluga whale, Seabird, Seaduck | | Prince Regent Inlet | 32022000000 | 4.1 | 14 | B-2.3 |
| 95 | Feeding, Habitat | Ringed seal | Summer | Chantrey Inlet | 3186370000 | 1.3 | 14 | B-3.4 |
| 96 | Feeding, Habitat | Ringed seal, Seabird | Summer, Year-round | Bathurst Inlet | 9025060000 | 1.1 | 14 | B-3.2 |
| 98 | Aggregation, | Narwhal, Beluga whale | Summer | Peel Sound | 24455500000 | 5.1 | 14 | B-2.5 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Feeding | | | | | | | |
| 99 | Feeding, Haul-out | Narwhal, Seal, Walrus | | Princess Maria Bay | 12952800000 | 9.3 | 14 | B-5.5 |
| 100 | Migration, Feeding, Haul-out | Bowhead whale, Narwhall, Killer whale, Beluga whale, Walrus | | Igloolik Island | 4837670000 | 1.2 | 15 | C-1.2 |
| 101 | Migration, Habitat, Haul-out, Feeding | Bowhead whale, Narwhal, Beluga whale, Killer whale, Walrus | Year-round | Rowley Island | 20668500000 | 1.3 | 15 | C-1.3 |
| 102 | Migration, Aggregation | Polar bear, Beluga whale | Autumn | Western Hudson Bay Coastline | 37700600000 | 3.1 | 15 | C-1.6 |
| 103 | Feeding, Overwintering, Summering, Aggregation, Haul-out | Polar bear, Beluga whale, Bearded seal, Walrus, Common eider | Summer, Winter | Belcher Islands | 92223000000 | 6.1 | 15 | C-1.9 |
| 104 | Haul-out, Feeding, Overwintering, Molting, Critical staging | Walrus, Polar bear, Beluga whale, Seaduck, Shorebird, Waterfowl | Summer, Winter | James Bay | 66749600000 | 5.1 | 15 | C-1.8 |
| 105 | Migration, Overwintering, Haul-out, Nesting, Feeding, Aggregation | Beluga whale, Bowhead whale, Narwhal, Walrus, Seabird, Ivory gull | | Eastern Hudson Strait | 35624400000 | 7.2 | 15 | C-1.12 |
| 106 | Summering, Rearing, Breeding, Feeding | Beluga whale, Polar bear, Seabird, Seaduck | Summer | Ungava Bay | 52258900000 | 8.1 | 15 | C-1.13 |
| 107 | Migration, Overwintering, Feeding | Beluga whale, Bowhead whale, Narwhal, Killer whale, Walrus, Seabird, Seaduck | | Western Hudson Strait | 106354000000 | 7.1 | 15 | C-1.11 |
| 108 | Migration, Feeding, Haul-out, Breeding | Bowhead whale, Beluga whale, Polar bear, Walrus, Seabird, Seaduck | Spring, Autumn, Summer, Winter | Southampton Island | 93177200000 | 2.2 | 15 | C-1.5 |
| 109 | Feeding, | Bowhead whale, Narwhal, Walrus, | Summer, | Repulse Bay / Frozen Strait | 17084200000 | 2.1 | 15 | C-1.4 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Habitat, Breeding | Seabird, Iceland gull | Year-round | | | | | |
| 110 | Aggregation, Feeding, Rearing, Migration | Beluga whale, Polar bear, Harbor seal | Summer | Southwestern Hudson Bay Estuaries | 95127200000 | 4.1 | 15 | C-1.7 |
| 111 | Overwintering, Feeding | Narwhal, Bowhead whale | | Southern Baffin Bay | 30181100000 | 4.1 | 16 | D-2.12 |
| 112 | Feeding, Breeding | Beluga whale, Seabird, Iceland gull | Summer | Cumberland Sound | 6542430000 | 3.2 | 16 | D-2.9 |
| 113 | Feeding, Breeding, Staging | Walrus, Beluga whale, Ringed Seal, Polar bear, Seabird | Summer, Year-round | Eastern Jones Sound | 11733700000 | 1.3 | 16 | D-2.15 |
| 114 | Feeding, Migration, Haul-out, Staging, Breeding, Overwintering | Beluga whale, Bowhead whale, Narwhal, Ringed seal, Bearded seal, Harp seal | Summer, Winter, Year-round | North Water Polynya | 22478300000 | 1.1 | 16 | D-2.14 |
| 115 | Migration, Feeding, Staging, Breeding, Overwintering | Beluga whale, Bowhead whale, Narwhal, Polar bear, Killer whale, Harp seal, Hooded seal, Seabird | Winter, Summer | Hatton Basin - Labrador Sea - Davis Strait | 231839000000 | 3.1 | 16 | D-2.8 |
| 116 | Migration, Feeding | Bowhead whale, Narwhal, Ringed seal, Bearded seal, Harp seal, Hooded seal | | Baffin Bay Shelf Break | 53510100000 | 2.2 | 16 | D-2.11 |
| 117 | Migration, Nursery, Haul-out, Feeding, Breeding | Bowhead whale, Narwhal, Walrus, Polar bear, Seabird | | Baffin Island Coastline | 79166500000 | 2.1 | 9 | D-2.10 |

# APPENDIX B: Python Scripts

*Daily Sea Ice Concentration Data Download Python Script*

```
##---------------------------------------------------------------------------------------
## SeaIceConcentrationDownloadDaily.py
## Downloads NSIDC daily Sea Ice Concentrations Data
## from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data
## and converts Binary files to ArcGIS-ready TIFF files through a series of steps
##
## Created: January 2017
## Author: Ginny Crothers -- virginia.crothers@duke.edu
##
## Reference: https://github.com/johnpfay/ArcticIce/blob/master/Scripts/GetNSIDCData.py
##
##---------------------------------------------------------------------------------------

# Import necessary modules
import sys, os, urllib, glob, arcpy, datetime

# Set working directory folders via relative paths
scriptDir = os.path.dirname(sys.argv[0])
rootDir = os.path.dirname(scriptDir)
scratchDir = os.path.join(rootDir, "Scratch")
dataDir = os.path.join(rootDir, "Data")
enviDir = os.path.join(dataDir, "Environmental_Data")
seaIceDir = os.path.join(enviDir, "sea_ice_concentration")
dailyDir = os.path.join(seaIceDir, "Daily")
    # Daily directory must be created ahead of time because header template file must be
    # located in this folder for data file conversion
    # Header template is described in User Guide for data: http://nsidc.org/data/nsidc-0051
tiffDir = os.path.join(seaIceDir, "TIFF_rasters_daily")
if not os.path.exists(tiffDir): os.mkdir(tiffDir)
tiffFinal = os.path.join(seaIceDir, "TIFF_final_daily")
if not os.path.exists(tiffFinal): os.mkdir(tiffFinal)

# Define monthly data source ftp site and filename format
# httpdailyURL =
'https://daacdata.apps.nsidc.org/pub/DATASETS/nsidc0051_gsfc_nasateam_seaice/final-
gsfc/north/daily/'
dailyURL = 'ftp://sidads.colorado.edu/pub/DATASETS/nsidc0051_gsfc_nasateam_seaice/final-
gsfc/north/daily/'
dailyFN = 'nt_YYYYMMDD_SSS_v1.1_n.bin'

# Set geoprocessing environments
arcpy.env.scratchWorkspace = scratchDir
arcpy.env.workspace = dailyDir
arcpy.env.overwriteOutput = True

#---------------------------------------------------------------------------------------

# Define input start and stop years for data download
inputStartYr = 1979
inputStopYr = 2015

# Compile data year range
# Must add 1 to stop year due to range tool formatting
allYears = range(inputStartYr,(inputStopYr + 1))

# Define default start day as first day of every month
inputStartDay = 01
```

```
# Create else/if statement so that the correct starting day is selected for each year
# NOTE: some of the older NSIDC SIC data was not recorded daily and instead was every other day
# This accounts for those disparities between data years
if inputStartYr == 1979 or inputStartYr == 1982 or inputStartYr == 1984 or inputStartYr == 1985 or
inputStartYr == 1987:
    inputStartDay = 02
elif inputStartYr == 1980 or inputStartYr == 1981 or inputStartYr == 1983 or inputStartYr == 1986:
    inputStartDay = 01
if inputStartYr == 1988:
    inputStartDay = 13

# Parse dates
d = datetime.date(inputStartYr,01,inputStartDay)
td = datetime.timedelta(days=1)
nextDay = d

# Create date ranges to account for the change in sensors
# The sensor is a component of filename so must change according to date
startn07 = datetime.date(1979, 1, 2)
endn07 = datetime.date(1987, 8, 20)
startf08 = datetime.date(1987, 8, 21)
endf08 = datetime.date(1991, 12, 18)
startf11 = datetime.date(1991, 12, 19)
endf11 = datetime.date(1995, 9, 29)
startf13 = datetime.date(1995, 9, 30)
endf13 = datetime.date(2007, 12, 31)
startf17 = datetime.date(2008, 1, 1)

#-------------------------------------------------------------------------------------

# Print status to interactive window
print "Beginning data download from {}...".format(dailyURL)

# Download data files inside of a loop
for year in allYears:
    while nextDay.year == year:
        try:
            # Define date inputs for use in filename formatting
            yr = str(nextDay.year)
            mnth = str(nextDay.month)
            mnth = str(mnth).zfill(2)
            dy = str(nextDay.day)
            dy = str(dy).zfill(2)

            # Define the date
            date = datetime.date(int(yr), int(mnth), int(dy))

            # Define satellite sensor ID to include in data filename
            # Satellite sensor changes depending on date
            if date >= startn07 and date <= endn07:
                sens = 'n07'
            elif date >= startf08 and date <= endf08:
                sens = 'f08'
            elif date >= startf11 and date <= endf11:
                sens = 'f11'
            elif date >= startf13 and date <= endf13:
                sens = 'f13'
            elif date >= startf17:
                sens = 'f17'

        except Exception:
            pass

        # Build the new daily filename and full download URL
        dailyFN = 'nt_' + yr + mnth + dy + '_' + sens + '_v1.1_n.bin'
```

```
        theURL = dailyURL + yr + '/' + dailyFN

        # Create the output filename and account for files that may already exist
        outFN = os.path.join(dailyDir, dailyFN)
        if os.path.exists(outFN):
            print "-->{} exists; skipping".format(dailyFN)

        # Write data to local file
        print "...saving"
        try:
            urllib.urlretrieve(theURL, outFN)
        except Exception:
            pass
            print "File: {0} does not exist in directory or failed to download;
skipping".format(dailyFN)

        # Tell the loop to jump to the next day
        nextDay = nextDay + td

print "Raw data download complete"

#-----------------------------------------------------------------------------------------

print "Changing file extensions for all files in {}...".format(dailyDir)

# Loop through filenames to change file extensions from .bin to .bil
# and shorten filename to create consistent format across all months and years
for filename in glob.iglob(os.path.join(dailyDir, '*.bin')):
    os.rename(filename, filename[:-15] + '.bil')

print "Successfully changed all file extensions"

#-----------------------------------------------------------------------------------------

print "Creating header.txt files in preparation for TIFF file conversion..."

# Create matching header text files for conversion to TIFF file format
# Header template file included in Daily folder in order to be accessible for conversion
# Information in file found at:
# http://nsidc.org/support/21680984-How-do-I-import-the-0051-sea-ice-concentration-data-into-
ArcGIS-
headerFile = dailyDir + "\\headerTemplate.txt"
for filename in glob.iglob(os.path.join(dailyDir, '*.bil')):
    def copy(File1, File2):
        opener1 = open(File2, 'w+')
        opener2 = open(File1, 'r')
        reader = opener2.read()
        opener1.write(reader)
        opener1.close()
        opener2.close()
    copy(headerFile, dailyDir + '\\headerTemplateTwo.txt')
    newHeaderFile = dailyDir + '\\headerTemplateTwo.txt'
    os.rename(newHeaderFile, filename[:-4] + '.hdr')
    if os.path.exists(newHeaderFile):
        pass
        print "-->{} exists; skipping".format(newHeaderFile)

print "Header.txt files created for all files"

#-----------------------------------------------------------------------------------------

# Loop through files and convert them to TIFF format rasters
print "Converting all files in {} to TIFF format...".format(dailyDir)

for filename in glob.iglob(os.path.join(dailyDir, '*.bil')):
```

```
    # Convert files to raster format
    arcpy.RasterToOtherFormat_conversion(filename, tiffDir, "TIFF")

print "All files have been converted to TIFF format and exported to {}".format(tiffDir)

#-------------------------------------------------------------------------------------

# Define projection to custom coordinate system created per NSIDC parameters found here:
# http://nsidc.org/support/21680984-How-do-I-import-the-0051-sea-ice-concentration-data-into-
ArcGIS-

print "Defining projection for files..."

prjFile = scriptDir + "\\Sea_Ice_North_PCS.prj"
spatialRef = arcpy.SpatialReference(prjFile)

for filename in glob.iglob(os.path.join(tiffDir, '*.tif')):
    arcpy.DefineProjection_management(filename, spatialRef)

print "Projection has been defined for all files in {}".format(tiffDir)

#-------------------------------------------------------------------------------------

# Import necessary modules
from arcpy import env
from arcpy.sa import *

# Check out the ArcGIS Spatial Analyst extension license
arcpy.CheckOutExtension("Spatial")

# Set workspace in environmental settings
env.workspace = tiffFinal

print "Converting rasters to percentage values for sea ice concentration..."

# For loop to run raster division on all sea ice concentration TIFFs
# Dividing by 2.5 converts sea ice concentration to percentage values
for rast in glob.iglob(os.path.join(tiffDir, '*.tif')):
    outFN = os.path.basename(rast)
    inRaster = Raster(rast)
    outRaster = inRaster / 2.5
    outRaster.save(outFN)

#-------------------------------------------------------------------------------------

print "All requested files successfully retrieved, downloaded, projected and converted to
percentage value for sea ice concentration; ready for use in ArcGIS"
```

## *Monthly Sea Ice Concentration Data Download Python Script*

```
##-------------------------------------------------------------------------------------
## MonthlySeaIceConcentrationDownload.py
## Downloads NSIDC Sea Ice Concentrations Data
## from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data
## and converts .bin files to .tiff files for use in ArcGIS through a series of steps
##
## Created: January 2017
## Author: Ginny Crothers -- virginia.crothers@duke.edu
##
## Reference: http://nsidc.org/data/NSIDC-0051#
##-------------------------------------------------------------------------------------

# Import necessary modules
import sys, os, urllib, glob, arcpy

# Set working directory folders via relative paths
scriptDir = os.path.dirname(sys.argv[0])
rootDir = os.path.dirname(scriptDir)
scratchDir = os.path.join(rootDir, "Scratch")
dataDir = os.path.join(rootDir, "Data")
enviDir = os.path.join(dataDir, "Environmental_Data")
seaIceDir = os.path.join(enviDir, "sea_ice_concentration")
monthlyDir = os.path.join(seaIceDir, "Monthly")
    # Monthly directory must be created ahead of time because header template file must be
    # located in this folder for data file conversion
tiffDir = os.path.join(seaIceDir, "TIFF_rasters")
if not os.path.exists(tiffDir): os.mkdir(tiffDir)
tiffFinal = os.path.join(seaIceDir, "TIFF_final")
if not os.path.exists(tiffFinal): os.mkdir(tiffFinal)

# Define monthly data source ftp site and filename format
monthlyURL = 'ftp://sidads.colorado.edu/pub/DATASETS/nsidc0051_gsfc_nasateam_seaice/final-
gsfc/north/monthly/'
monthlyFN = 'nt_YYYYMM_SSS_v1.1_n.bin'

# Set geoprocessing environments
arcpy.env.scratchWorkspace = scratchDir
arcpy.env.overwriteOutput = True

#-------------------------------------------------------------------------------------

print "Beginning data download from {}...".format(monthlyURL)

# Define input start and stop years for data download
inputStartYr = 1979
inputStopYr = 2015

# Compile data year and month range
allYears = range(inputStartYr,(inputStopYr + 1))
allMonths = [1,2,3,4,5,6,7,8,9,10,11,12]

# Define start and end ranges for change in satellite sensors
# The satellite sensor is a component of the sea ice filename
startn07 = datetime.date(1979, 1, 1)
endn07 = datetime.date(1987, 8, 31)
startf08 = datetime.date(1987, 9, 1)
endf08 = datetime.date(1991, 12, 31)
startf11 = datetime.date(1991, 1, 1)
endf11 = datetime.date(1995, 9, 30)
startf13 = datetime.date(1995, 10, 1)
endf13 = datetime.date(2007, 12, 31)
startf17 = datetime.date(2008, 1, 1)
```

```
# Loop through years and months to download data
for year in allYears:
    for month in allMonths:
        try:
            # Define year and month strings for filename
            strYear = str(year)
            strMonth = str(month).zfill(2)
            strDay = str(1)
            date = datetime.date(int(strYear), int(strMonth), int(strDay))

            # Define sensor string for filename
            if date >= startn07 and date <= endn07:
                strSens = 'n07'
            elif date >= startf08 and date <= endf08:
                strSens = 'f08'
            elif date >= startf11 and date <= endf11:
                strSens = 'f11'
            elif date >= startf13 and date <= endf13:
                strSens = 'f13'
            elif date >= startf17:
                strSens = 'f17'

            # Update the filename strings for current year
            yearFN = monthlyFN.replace("YYYY", strYear)
            monthFN = yearFN.replace("MM", strMonth)
            sensFN = monthFN.replace("SSS", strSens)
            finalFN = sensFN

            # Update FTP address
            theURL = monthlyURL + finalFN

            # Create the output file
            outFN = os.path.join(monthlyDir, finalFN)
            if os.path.exists(outFN):
                print "-->{} exists; skipping".format(finalFN)

            # Retrieve the file
            print "Downloading {}".format(outFN)
            response = urllib.urlopen(theURL)

            # Write to local file
            print "...saving"
            with open (outFN, 'wb') as outFile:
                for line in response:
                   outFile.write(line)

        except Exception:
            pass
            print "Failure to save file: ".format(outFN)

print "Raw data download complete"

#-------------------------------------------------------------------------------------

# Loop through filenames to change file extensions from .bin to .bil
# and shorten filename to create consistent format across all months and years
print "Changing file extensions for all files in {}...".format(monthlyDir)
for filename in glob.iglob(os.path.join(monthlyDir, '*.bin')):
    os.rename(filename, filename[:-15] + '.bil')
    if os.path.exists(filename):
        print "-->{} exists; skipping".format(filename)
        continue

print "Successfully changed all file extensions"

#-------------------------------------------------------------------------------------
```

```
print "Creating header.txt files in preparation for TIFF file conversion..."

# Create matching header text files for conversion to TIFF file format
# Header template file included in Monthly folder
# Information in file found at http://nsidc.org/support/21680984-How-do-I-import-the-0051-sea-ice-
concentration-data-into-ArcGIS-
headerFile = monthlyDir + "\\headerTemplate.txt"
for filename in glob.iglob(os.path.join(monthlyDir, '*.bil')):
    def copy(File1, File2):
        opener1 = open(File2, 'w+')
        opener2 = open(File1, 'r')
        reader = opener2.read()
        opener1.write(reader)
        opener1.close()
        opener2.close()
    copy(headerFile, monthlyDir + '\\headerTemplateTwo.txt')
    newHeaderFile = monthlyDir + '\\headerTemplateTwo.txt'
    os.rename(newHeaderFile, filename[:-4] + '.hdr')

print "Header.txt files created for all files"

#-------------------------------------------------------------------------------------

# Loop through files and convert them to TIFF format rasters
print "Converting all files in {} to TIFF format...".format(monthlyDir)
for filename in glob.iglob(os.path.join(monthlyDir, '*.bil')):

    # Convert files to raster format
    arcpy.RasterToOtherFormat_conversion(filename, tiffDir, "TIFF")

print "All files have been converted to TIFF format and exported to {}".format(tiffDir)

#-------------------------------------------------------------------------------------

print "Defining projection for all files in {}".format(tiffDir)

# Define projection to custom coordinate system created per NSIDC parameters found here:
# http://nsidc.org/support/21680984-How-do-I-import-the-0051-sea-ice-concentration-data-into-
ArcGIS-

prjFile = scriptDir + "\\Sea_Ice_North_PCS.prj"
spatialRef = arcpy.SpatialReference(prjFile)

for filename in glob.iglob(os.path.join(tiffDir, '*.tif')):
    arcpy.DefineProjection_management(filename, spatialRef)

print "Projection has been defined for all files in {}".format(tiffDir)

print "All processes complete; data for years {} downloaded and converted to raster
format".format(allYears)

#-------------------------------------------------------------------------------------

# Import necessary modules
from arcpy import env
from arcpy.sa import *

# Check out the ArcGIS Spatial Analyst extension license
arcpy.CheckOutExtension("Spatial")

# Set workspace in environmental settings
env.workspace = tiffFinal

print "Beginning raster division for all .tif files"
```

```
# For loop to run raster division on all sea ice concentration TIFFs
for rast in glob.iglob(os.path.join(tiffDir, '*.tif')):
    outFN = os.path.basename(rast)
    inRaster = Raster(rast)
    outRaster = inRaster / 2.5
    outRaster.save(outFN)

print "Raster division complete for all files"

#-------------------------------------------------------------------------------------

print "All requested files successfully retrieved, downloaded, projected and converted to
percentage value for sea ice concentration"
```

*Binary Sea Ice or No Sea Ice Raster Python Script*

```
##---------------------------------------------------------------------------------------
## BinarySeaIceNoSeaIce.py
## Creates binary rasters that give grid cell values for sea ice or no sea ice
## with a threshold value for sea ice concentration (SIC) at 15%;
## Subsequently adds binary rasters for all days for each year to create rasters
## that show for each grid cell the # of "open water" days for the given year
##
## Created: February 2017
## Author: Ginny Crothers -- virginia.crothers@duke.edu
##
##---------------------------------------------------------------------------------------

# Import necessary modules
import sys, os, arcpy, glob, shutil
from arcpy.sa import *

# Set working directory folders via relative paths
scriptDir = os.path.dirname(sys.argv[0])
rootDir = os.path.dirname(scriptDir)
scratchDir = os.path.join(rootDir, "Scratch")
dataDir = os.path.join(rootDir, "Data")
enviDir = os.path.join(dataDir, "Environmental_Data")
seaIceDir = os.path.join(enviDir, "sea_ice_concentration")
tiffDir = os.path.join(seaIceDir, "TIFF_final_daily")
tiffYearDir = os.path.join(tiffDir, "1979")  ## Change for each run to reflect given year
binaryDir = os.path.join(seaIceDir, "Binary")
binYearDir = os.path.join(binaryDir, "1979")  ## Change for each run to reflect given year
if not os.path.exists(binYearDir): os.mkdir(binYearDir)
outputDir = os.path.join(dataDir, "Output")
openWaterDir = os.path.join(outputDir, "open_water")

# Check out the ArcGIS Spatial Analyst extension license
arcpy.CheckOutExtension("Spatial")

# Set environmental parameters
arcpy.env.overwriteOutput = True

# Define environmental workspace for arcpy operations
arcpy.env.workspace = tiffYearDir

#---------------------------------------------------------------------------------------

# Create binary rasters from sea ice concentration rasters
for filename in glob.iglob(os.path.join(tiffYearDir, '*.tif')):
    inRaster = Raster(filename)
    outFN = os.path.basename(filename)
    outCon = Con((inRaster < 15), 1, 0)

    arcpy.env.workspace = binYearDir
    outCon.save(outFN[:-4] + '_bin.tif')

print "All binary rasters created and saved to {}".format(binYearDir)

#---------------------------------------------------------------------------------------

# Define input workspace and create list of binary rasters
# Change workspace in order to save output TIFF file to ideal directory
arcpy.env.workspace = binYearDir
rasters = arcpy.ListRasters()

# Run cell statistics to add binary rasters for each year
calc = arcpy.sa.CellStatistics(rasters, statistics_type = 'SUM')
calc.save('1979_openwaterdays.tif')  ## Change for each run to reflect given year
```

```
#---------------------------------------------------------------------------------------

print "All binary rasters for directory: {} have been added and saved to an output raster
file".format(binYearDir)
```

*Get Raster Properties Python Script*

```
##--------------------------------------------------------------------------------------
## GetRasterPropertiesChlor.py
## Retrieves information from descriptive statistics of rasters in database
## in order to create a monthly time series of sea ice and chlorophyll-a
##
## Created: February 2017
## Author: Ginny Crothers -- virginia.crothers@duke.edu
##
##--------------------------------------------------------------------------------------

# Import necessary modules
import sys, os, urllib, glob, arcpy, csv
from arcpy import env
from arcpy.sa import *

# Set working directory folders via relative paths
scriptDir = os.path.dirname(sys.argv[0])
rootDir = os.path.dirname(scriptDir)
scratchDir = os.path.join(rootDir, "Scratch")
dataDir = os.path.join(rootDir, "Data")
enviDir = os.path.join(dataDir, "Environmental_Data")
seaIceDir = os.path.join(enviDir, "sea_ice_concentration")
tiffDir = os.path.join(seaIceDir, "TIFF_final_daily")
chlorDir = os.path.join(enviDir, "chlor_a")
outputDir = os.path.join(dataDir, "Output")
tableDir = os.path.join(outputDir, "Tables")

# Check out the ArcGIS Spatial Analyst extension license
arcpy.CheckOutExtension("Spatial")

# Set geoprocessing environments
arcpy.env.scratchWorkspace = scratchDir
arcpy.env.overwriteOutput = True

# Create variables for temporary lists
dateList = []
meanList = []

# Define input year and CSV filename based on directory and input year
inputYr = 2012
csvFile = tableDir + r'\chlor_a_' + str(inputYr) + '_stats.csv'

#--------------------------------------------------------------------------------------

print "Beginning batch raster statistics..."

# Define database where raster files are stored and set that to environmental workspace in arcpy
settings
inputDir = chlorDir + '\\8_day\\' + str(inputYr) + '\\'
arcpy.env.workspace = inputDir

# Create list of rasters from input directory
rasterList = arcpy.ListRasters()

# Iterate through all files in database to retrieve raster cell properties
# and input them to output table
for raster in rasterList:
    try:
        inRaster = Raster(raster)

        # Get the geoprocessing result object using Get Raster Properties tool in arcpy
        chlorMeanResult = arcpy.GetRasterProperties_management(inRaster, "MEAN")
```

```
        # Get the chlor-a mean raster value from geoprocessing result object
        chlorMean = chlorMeanResult.getOutput(0)

        # Write raster mean and date to temporary lists
        meanList.append(chlorMean)

        date = os.path.basename(raster)
        dateList.append(date)

    except:
        pass
        print "Unexpected error: Raster {0}".format(raster)

#-------------------------------------------------------------------------------------

print "Merging all tables and writing to output .csv file {}".format(csvFile)

# Import necessary module for creating CSV file
from itertools import izip

# Merge list values into output CSV file
with open(csvFile, 'wb') as file:
    writer = csv.writer(file)
    newList = izip(dateList, meanList)
    for item in newList:
        writer.writerow(item)

#-------------------------------------------------------------------------------------

print "All operations complete; Final output table created and stored in table directory"
```

*Zonal Statistics As Table Python Script: Sea Ice data*

```
##---------------------------------------------------------------------------------------
## ZonalStatisticsAsTableSeaIce.py
## Iterates through polygons in a shapefile to run Zonal Statistics as Table
## in order to avoid merging of overlapping polygons in feature class
##
## Created: January 2017
## Author: Ginny Crothers -- virginia.crothers@duke.edu
##
##---------------------------------------------------------------------------------------

# Import necessary modules
import sys, os, arcpy, glob
from arcpy import env

# Set working directory folders via relative paths
scriptDir = os.path.dirname(sys.argv[0])
rootDir = os.path.dirname(scriptDir)
scratchDir = os.path.join(rootDir, "Scratch")
dataDir = os.path.join(rootDir, "Data")
enviDir = os.path.join(dataDir, "Environmental_Data")
amsaDir = os.path.join(dataDir, "AMSAIIC_Sub_Areas")
bathyDir = os.path.join(enviDir, "bathymetry")
seaIceDir = os.path.join(enviDir, "sea_ice_concentration")
monthlyDir = os.path.join(seaIceDir, "TIFF_final")
outputDir = os.path.join(dataDir, "Output")
tableDir = os.path.join(outputDir, "Tables")

# Check out the ArcGIS Spatial Analyst extension license
arcpy.CheckOutExtension("Spatial")

# Set geoprocessing environments
arcpy.env.scratchWorkspace = scratchDir
arcpy.env.workspace = dataDir
arcpy.env.overwriteOutput = True

arcpy.env.cellsize = 25000

# Define input and output variables for Zonal Stats
# Field for extraction from each row in cursor iteration
field = ['FID']
inputZones = amsaDir + '\\AMSAIIC_Sub_Areas_all.shp'

# Define parameters for start year and day for data processing
inputYr = 2012  # Change for each run

# Define FID #'s for different subgroups in order to extract desired values from DBF file
# Switch out list name in "if" statement below in order to run through certain lists
FIDcetacean =
[1,3,5,6,14,21,32,33,34,51,52,56,58,59,60,62,70,71,72,74,75,77,78,80,83,84,85,86,87,90,92,93,94,98,
99,100,101,102,103,104,105,106,107,108,109,110,111,112,113,114,115,116,117]
FIDpinniped =
[0,7,14,30,31,45,46,47,48,49,50,55,57,59,62,63,64,65,70,72,74,75,76,78,84,85,89,90,93,94,95,96,99,1
00,101,103,104,105,107,108,109,110,113114,115,116,117]
FIDseabird =
[4,10,11,12,13,15,16,17,18,19,20,22,23,24,25,26,35,36,37,38,39,40,41,42,43,44,53,54,55,56,57,59,62,
63,64,65,70,71,72,73,75,78,79,81,82,83,84,85,89,90,91,92,93,94,103,104,105,106,107,108,109,112,113,
115,117]

#---------------------------------------------------------------------------------------

print "Beginning zonal statistics iterations..."

# Iterate through every row/attribute in input feature class
```

```
# Make shapefile into a layer in order to select below
arcpy.MakeFeatureLayer_management(inputZones, "AMSA_Sub_Areas")

# For loop to iterate through zonal statistics as table tool
# This process needs to be done iteratively to avoid merging overlapping polygons

for file in glob.iglob(os.path.join(monthlyDir, '*.tif')):
    with arcpy.da.SearchCursor(inputZones, field) as cursor:
        for row in cursor:
            if row[0] in FIDpinniped:
                try:
                    dateBN = os.path.basename(file)
                    date = dateBN[3:9]

                    # Create select statement for given row
                    selectStatement = '"FID" = {0}'.format(row[0])
                    print selectStatement

                    # Define file pathname for temporary DBF file
                    tempTable = r'C:\\Temp\\FID_{0}_{1}_seaice_summary.dbf'.format(row[0], date)
                    print tempTable

                    # Define file pathname for temporar raster
                    # To ensure better accuracy and because zonal stats can have issues creating
                    rasters
                    # "on the fly" in the zonal stats tool, rasters are created for select zones
                    prior to running tool
                    tempRaster = r'C:\\Temp\\AMSAIIC_Sub_Areas_raster_{0}.img'.format(row[0])

                    # Select feature in layer using select statement above
                    selection = arcpy.SelectLayerByAttribute_management("AMSA_Sub_Areas",
                    "NEW_SELECTION", selectStatement)

                    # Convert input zone to raster before running zonal statistics
                    arcpy.PolygonToRaster_conversion(selection, "FID", tempRaster)

                    arcpy.env.snapRaster = file

                    # Run zonal statistics, this case calculating the mean of the value raster
                    within that zone
                    arcpy.sa.ZonalStatisticsAsTable(tempRaster, "Value", file, tempTable, "DATA",
                    "MEAN")

                    # An exception clause is included because some input zones were creating errors
                    in zonal stats
                except:
                    pass
                    print "Unexpected error: Feature FID {0}".format(row[0])

    #-------------------------------------------------------------------------------------

# Merging files for the same 8-day period into one .dbf file within loop as the
# Search Cursor loops through each 8-day binned data file within the year
print "Merging all tables and writing to new file"

#Set env workspace to temp folder, since that's where tables are located
arcpy.env.workspace = 'C:\\Temp\\'

# Merge all "temp tables" to output final table using arcpy Merge tool
finalTable = tableDir + '\\' + str(date) + 'monthly_seaice_zonal_stats_pinniped.dbf'

files = arcpy.ListFiles('*_seaice_summary.dbf')
arcpy.Merge_management(files, finalTable)

print "Zonal statistics complete for Value File: ".format(file)
```

```
# Delete temporary files once they have been merged
for filename in glob.iglob(os.path.join(r'C:\Temp\\', '*.dbf')):
    os.remove(filename)
for filename in glob.iglob(os.path.join(r'C:\Temp\\', '*.dbf.xml')):
    os.remove(filename)
for filename in glob.iglob(os.path.join(r'C:\Temp\\', '*.cpg')):
    os.remove(filename)

del row, cursor

#--------------------------------------------------------------------------------------

print "All operations complete"
```

*Zonal Statistics As Table Python Script: Chlorophyll a data*

```
##-------------------------------------------------------------------------------------
## ZonalStatisticsAsTable.py
## Iterates through polygons in a shapefile to run Zonal Statistics as Table
## in order to avoid merging of overlapping polygons in feature class
##
## Created: January 2017
## Author: Ginny Crothers -- virginia.crothers@duke.edu
##
##-------------------------------------------------------------------------------------

# Import necessary modules
import sys, os, arcpy, glob
from arcpy import env

# Set working directory folders via relative paths
scriptDir = os.path.dirname(sys.argv[0])
rootDir = os.path.dirname(scriptDir)
scratchDir = os.path.join(rootDir, "Scratch")
dataDir = os.path.join(rootDir, "Data")
enviDir = os.path.join(dataDir, "Environmental_Data")
amsaDir = os.path.join(dataDir, "AMSAIIC_Sub_Areas")
bathyDir = os.path.join(enviDir, "bathymetry")
seaIceDir = os.path.join(enviDir, "sea_ice_concentration")
chlorDir = os.path.join(enviDir, "chlor_a")
outputDir = os.path.join(dataDir, "Output")
tableDir = os.path.join(outputDir, "Tables")

# Check out the ArcGIS Spatial Analyst extension license
arcpy.CheckOutExtension("Spatial")

# Set geoprocessing environments
arcpy.env.scratchWorkspace = scratchDir
arcpy.env.workspace = dataDir
arcpy.env.overwriteOutput = True

# Add supplemental toolbox that contains Zonal Statistics As Table 2
# This new tool deals with the issue of overlapping polygons
# The folder for the toolbox is stored in the Data directory
# arcpy.AddToolbox("SpatialAnalystSupplementalTools//Spatial Analyst Supplemental Tools.pyt")

# Define input and output variables for Zonal Stats
# Field for extraction from each row in cursor iteration
field = ['FID']
inputZones = amsaDir + '\\AMSAIIC_Sub_Areas_all.shp'

# Define parameters for start year and day for data processing
inputYr = 1979  # Change for each run
allDays =
[33,41,49,57,65,73,81,89,97,105,113,121,129,137,145,153,161,169,177,185,193,201,209,217,225,233,241
,249,257,265,273,281,289,297]
            # Excluding winter months that have little to no data coverage
            # Date range is February through October

# Define FID #'s for different subgroups in order to extract desired values from DBF file
# Switch out list name in "if" statement below in order to run through certain lists
FIDcetacean =
[1,3,5,6,14,21,32,33,34,51,52,56,58,59,60,62,70,71,72,74,75,77,78,80,83,84,85,86,87,90,92,93,94,98,
99,100,101,102,103,104,105,106,107,108,109,110,111,112,113,114,115,116,117]
FIDpinniped =
[0,7,14,30,31,45,46,47,48,49,50,55,57,59,62,63,64,65,70,72,74,75,76,78,84,85,89,90,93,94,95,96,99,1
00,101,103,104,105,107,108,109,110,113114,115,116,117]
FIDseabird =
[4,10,11,12,13,15,16,17,18,19,20,22,23,24,25,26,35,36,37,38,39,40,41,42,43,44,53,54,55,56,57,59,62,
```

```
63,64,65,70,71,72,73,75,78,79,81,82,83,84,85,89,90,91,92,93,94,103,104,105,106,107,108,109,112,113,
115,117]

#-------------------------------------------------------------------------------------

print "Beginning zonal statistics iterations..."

# Iterate through every row/attribute in input feature class

# Make shapefile into a layer in order to select below
arcpy.MakeFeatureLayer_management(inputZones, "AMSA_Sub_Areas")

# For loop to iterate through zonal statistics as table tool
# This process needs to be done iteratively to avoid merging overlapping polygons
for day in allDays:
    try:
        dy1 = day
        dy1 = str(dy1).zfill(3)
        dy2 = day + 7
        dy2 = str(dy2).zfill(3)

        valueFN = chlorDir + '\\8_day\\' + str(inputYr) + '\\' + 'c' + str(inputYr) + dy1 +
str(inputYr) + dy2 + '.L3m_8D_CHL_chlor_a_9km.img'
                # NOTE: THE FILENAME MAY CHANGE SUBTLY BETWEEN YEARS, i.e. the singular letter
before the date
        arcpy.env.snapRaster = valueFN

    except:
        pass
        print "Unexpected error with Filename: {0}".format(valueFN)

    with arcpy.da.SearchCursor(inputZones, field) as cursor:
        for row in cursor:
            if row[0] in FIDcetacean:
                try:
                    # Create select statement for given row
                    selectStatement = '"FID" = {0}'.format(row[0])
                    print selectStatement

                    # Define file pathname for temporary DBF file
                    tempTable = r'C:\\Temp\\FID_{0}_{1}{2}{3}_chlor_summary.dbf'.format(row[0],
                    inputYr, dy1, dy2)
                    print tempTable

                    # Define file pathname for temporary raster
                    # To ensure better accuracy and because zonal stats can have issues creating
                    rasters
                    # "on the fly" in the zonal stats tool, rasters are created for select zones
                    prior to running tool
                    tempRaster = r'C:\\Temp\\AMSAIIC_Sub_Areas_raster_{0}.img'.format(row[0])

                    # Select feature in layer using select statement above
                    selection = arcpy.SelectLayerByAttribute_management("AMSA_Sub_Areas",
                    "NEW_SELECTION", selectStatement)

                    # Convert input zone to raster before running zonal statistics
                    arcpy.PolygonToRaster_conversion(selection, "FID", tempRaster)

                    # Run zonal statistics, this case calculating the mean of the value raster
                    within that zone
                    arcpy.sa.ZonalStatisticsAsTable(tempRaster, "Value", valueFN, tempTable, "DATA",
                    "MEAN")

                 # An exception clause is included because some input zones were creating errors in
                 zonal stats
                except:
```

```
                    pass
                    print "Unexpected error: Feature FID {0}".format(row)

#--------------------------------------------------------------------------------------

        # Merging files for the same 8-day period into one .dbf file within loop as the
        # Search Cursor loops through each 8-day binned data file within the year
        print "Merging all tables and writing to new file"

        # Set env workspace to temp folder, since that's where tables are located
        arcpy.env.workspace = 'C:\\Temp\\'

        # Merge all "temp tables" to output final table using arcpy Merge tool
          finalTable = tableDir + '\\' + str(inputYr) + str(dy1) + str(dy2) +
       '_cetacean_chlor_summary.dbf'  # Change for each zonal stats
        files = arcpy.ListFiles('*_chlor_summary.dbf')

        arcpy.Merge_management(files, finalTable)

        print "Zonal statistics complete for Value File: ".format(valueFN)

        # Delete temporary files once they have been merged
        for filename in glob.iglob(os.path.join(r'C:\Temp\\', '*.dbf')):
            os.remove(filename)
        for filename in glob.iglob(os.path.join(r'C:\Temp\\', '*.dbf.xml')):
            os.remove(filename)
        for filename in glob.iglob(os.path.join(r'C:\Temp\\', '*.cpg')):
            os.remove(filename)

del row, cursor

#--------------------------------------------------------------------------------------

# Merge all temporary tables for each 8-day data file (that lists zonal stats for all FID's)
# into one final table using Merge tool
arcpy.env.workspace = tableDir

finalfinalTable = tableDir + '\\' + 'chlor_a_' + str(inputYr) + '_cetacean.dbf'
files2 = arcpy.ListFiles('*cetacean_chlor_summary.dbf')
arcpy.Merge_management(files2, finalfinalTable, "Value")

#--------------------------------------------------------------------------------------

print "All operations complete"
```