ARCTIC WEATHER AND ABRUPT SEA ICE LOSS

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ABSTRACT

September Arctic sea ice extent is decreasing rapidly, especially over the past few decades. While the mechanisms contributing to this climate trend are relatively-well understood, the year-to-year variability is not. This study examines 2-d decreases in summer sea ice extent to quantify the year-to-year variability that is due to synoptic time-scale processes and isolate its possible source. It is hypothesized that the abrupt reductions in sea ice are a consequence of synoptic–scale cyclones, and in particular the anomalously strong surface winds over the periphery of the cyclones from a strong pressure gradient.

A spectral analysis of two-day changes in sea ice extent is performed to determine whether events at synoptic time-scales have significant contributions to sea ice loss with respect to red noise. Several significant periods are found at synoptic time-scales, at 5, 6, 8, 10, and 16 days. A Butterworth filter is then applied to high-pass periods shorter than 18 days to isolate the abrupt sea ice loss events corresponding to these high frequencies and compile a set of significant events. Defining the top 1% of the high-pass filtered two-day decrease in sea ice extent, there is found to be two annual maxima: July and December, and only summer cases (June-August) are retained for the present study. Composite sea level pressure of the 25 cases reveals the presence of a 998 hPa mean surface cyclone, which varies in strength from 999 to 978 hPa. While there is always a cyclone, there is often, but not always, a nearby anticyclone that can further enhance the pressure gradient over the sea ice loss region.

1. INTRODUCTION

Arctic sea ice has experienced a dramatic decline over the past few decades. Much of this decrease is due to the overlying climate trend, and the processes behind this trend are reasonably established. Different time-scale processes, such as the surface ice albedo effect (e.g., Hougton et al. 1990; Holland et al. 2008), the Arctic Oscillation (AO; Rigor et al., 2002), and ocean heat transport (e.g., Holland et al. 2006), each contribute to the variability of sea ice in the Arctic. The trend is expected to continue decreasing as global climate models predict accelerating sea ice loss (Holland et al., 2006).

One characteristic of sea ice variability that is not well-understood are the year-to-year differences in minimum September sea ice extent (SIE; Fig.1). Understanding what causes the variability is important because it is believed that ensemble prediction success relies on year to year variability (Stroeve et al., 2004).

Prediction of SIE is important, because as more sea ice melts, the areal coverage of open water in Arctic Ocean increases, increasing the potential for the vertical transfer of heat and moisture into the atmosphere. Several studies have indicated that this may impact global atmospheric circulation patterns during the autumn and early winter (e.g., Budikova 2009; Deser et al. 2010; Jaiser et al. 2012; Francis and Vavrus 2012; Screen et al. 2013; Vavrus 2013). Furthermore, less SIE can open up new trade routes and make it easier to access new natural resources, thereby having a potential economic impact.

Given the possible impacts of sea ice decline, understanding year-to-year variability is becoming more important. Abrupt sea ice loss events do not occur every year, and are unpredictable beyond 1 or 2 weeks as a result of extreme summer atmospheric conditions (e.g., Stroeve et al. 2014). Screen et al. 2011 found that anomalous cyclone activity in the months preceding September is related to loss or gain in sea ice for that month.

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Fewer cyclones corresponded to low September sea ice, while years with more sea ice loss were related to an increased number of cyclones. While Screen et al. 2011 focused on the number of cyclones as a possible factor to explain the September variability, this study looks to see individual cyclone's effects on abrupt sea ice as a possible factor of the September variability.

For example, Simmonds et al. 2012 noted that a single cyclone was associated with a large reduction in SIE during the summer of 2012. This cyclone, now known as the "Great Arctic Cyclone," likely contributed to the 2012 all-time minimum in Arctic SIE. Furthermore, Ogi et al. 2009 noted that wind forcing on sea ice accounted for a 50% variance of September year-to-year SIE, while Rigor et al. 2002 showed that the thin sea ice during the summer over the Arctic is particularly vulnerable to atmospheric winds. Motivated by the observations that a cyclone can have an impact on SIE, this study aims to determine whether individual synoptic events are generally a significant contributor to abrupt sea ice loss.

The paper is organizing as follows: section 2 describes the data used for the study and methods implemented for verification of significance in the synoptic time scales, choosing of the event dates, and overlaid atmospheric composites. Section 3 describes the results of the methods in the same order as the section 2. Section 4 concludes with a discussion of the study and where improvements could be made.

2. DATA AND METHODS

Daily and monthly sea ice extent (SIE) and gridded concentration (SIC) data used in this study are obtained from the National Snow and Ice Data Center passive microwave satellite estimates (Meier et al 2013). Spatial resolution is 25 x 25 km with sea ice extent (SIE) classified as the area of cells with ice coverage greater than 15%. Since SIE is available every 2 days before 1988 and daily after, SIE is linearly interpolated to daily samples. SIE is linearly interpolated between 03 December 1987 and 12 January 1988 due to missing data; results in this study are not sensitive to this missing data. The merged Goddard sea ice concentration was used as the default SIC. When missing, the NOAA/NSIDC climate data record SIC was used instead. The atmospheric data used for this study are from ERA-Interim (Dee et al. 2011) from October 1979 to December 2014.

2.1 Verifying Significance of Synoptic Time Scales

Given that recent sea ice loss events have apparently occurred near the time of synoptic-scale cyclones, we first test whether sea ice loss is generally significant on synoptic time scales. In order to test this, a Fourier transform of the two day change in SIE time series is computed and compared against the 95% confidence interval of the experimental red noise spectrum (Gilman et al. 1963). The 2-d change in SIE on the i^{th} day, or ΔSIE_i, is computed daily by subtracting the net difference in SIE between the present day and the SIE two days prior:

$$\Delta SIE_i = SIE_i - SIE_{i-2} \quad (1)$$

Choosing a 2-d change in SIE allows for the analysis of sea ice change on the shortest time scales that are possible from these data. Furthermore, the 2-d change instead of the 1-d change is necessary to retain a constant sampling rate, since the sampling rate of SIE is every 2 days prior to 1988 and daily thereafter.

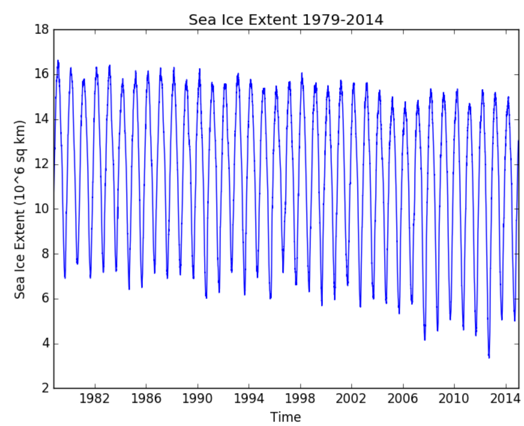

Figure 1: Time Series of Sea Ice Extent, from NSIDC Sea Ice Index Version 2 (1979-2014)

2.2 Choosing Events

Individual SIE events are found by applying a 9^{th} order high-pass Butterworth filter to the 2-d change in SIE time series. This filter removes the low frequency variability that is not associated with individual weather events. A cutoff period of 18 days is chosen because this period lies within a clear spectral gap between variability occurring on days to weeks and the variability from longer time scales.

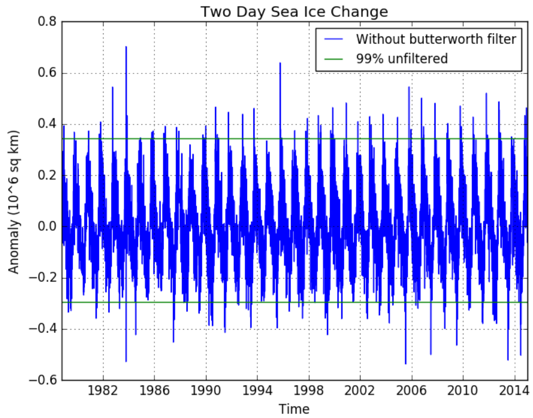

Figure 2: Time series of 2-d change in Sea Ice Extent (1979-2014).

To define a significant event, abrupt changes in SIE events are taken from the bottom 1% of the filtered 2-d time series of ΔSIE. This percentile corresponds a ΔSIE of at about 179,000 sq. km or more. Given the substantial differences in background SIE between summer and winter, and the large seasonal differences in atmospheric dynamics between winter and summer over the Arctic, this study focuses on the summer months of June, July, and August (Fig. 7).

2.3 Overlaying the Atmosphere

A problem that arises from studying the entire Arctic ice pack is the fact that it is not small. A large loss of sea ice could be seen in one area while a large gain can be seen in another, thus defining an abrupt sea ice loss event and finding possible causes requires a more local view. Looking at the local view complements the geographic perspective and a possible understanding of the processes driving the changes.

To address the large geographic area associated with the Arctic, a local reference frame is constructed for each event. A 3000x3000km grid with uniform 30km spacing was imposed on a stereographic projection centered on the event location.

Based on the idea that sea ice motion on the scales of sea ice loss objects has a coherent response to synoptic weather, especially near-surface winds (McNutt & Overland, 2002), we choose to use the maximum wind speed over the largest area of connected sea ice loss as a reference point. The largest sea ice loss area for a given event is found by taking a five day change in SIC (Fig. 3a) and segmenting the individual cells into objects that correspond to connected cells of SIC over 10% (Fig. 3b). A mask is then calculated by nearest-neighbor interpolation of the largest object onto the atmospheric grid (Fig. 3c). The location of the highest 10 m winds over the mask is taken as the reference point. The maximum wind speed can be from any of the five days over which the SIC change was calculated. Each event has a time, latitude, and longitude as a central reference point.

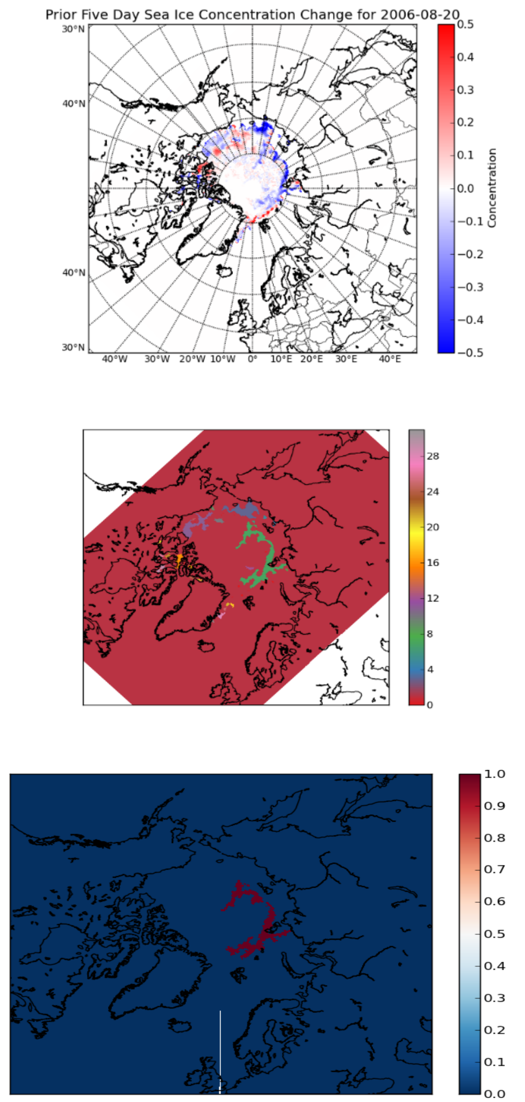

Figure 3: (a) 5 day SIC change for 08-20-2006 event; (b) connected sea ice loss objects individually numbered; (c) nearest neighbor interpolation of largest ice loss object onto the atmospheric grid.

The orientation of the grid is also important to preserve coherent patterns across cases. For reference points based on maximum wind speed, the wind direction at the reference point is oriented so the wind at the reference point flows to the right.

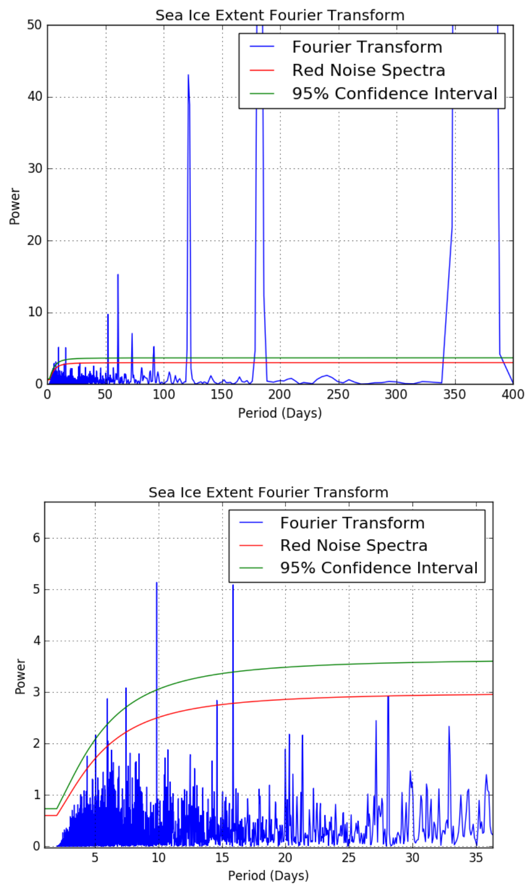

Figure 4: (a) Power spectrum derived from a Fast-Fourier Transform of the 2-d change in SIE time series (Fig 2); (b) zoomed in version focusing on shorter time scales.

3. RESULTS

3.1 Verifying Significance of Synoptic Time Scales

The power spectrum of ΔSIE (Fig. 4a) shows maximum power at a period of 365 days consistent with an annual cycle of freeze and melt (Fig. 2). The shorter-term monthly to semi-annual power may be associated with atmospheric teleconnections, particularly the Arctic oscillation and North American Oscillation (not shown). While there is less power at shorter timescales, periods of 5,6,8,10, and 16 days are significant to 95% confidence relative to a red noise spectrum. Thus, there is significant power in sea ice changes at synoptic timescales.

3.2 Choosing Events

In order to focus on shorter-term sea ice changes, a Butterworth high-pass filter is used to remove seasonal, yearly, and the longer term climate trends (e.g., Fig. 5) Applying the same high-pass filter to ΔSIE, a pattern can be seen between the two time series with reductions in the amplitude of the filtered signal.

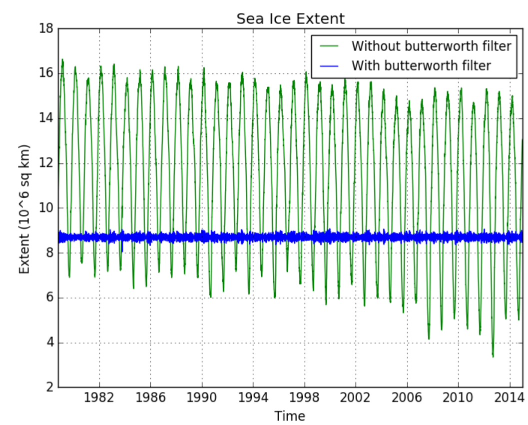

Figure 5: Original (green) and high-pass Butterworth filtered (blue) SIE.

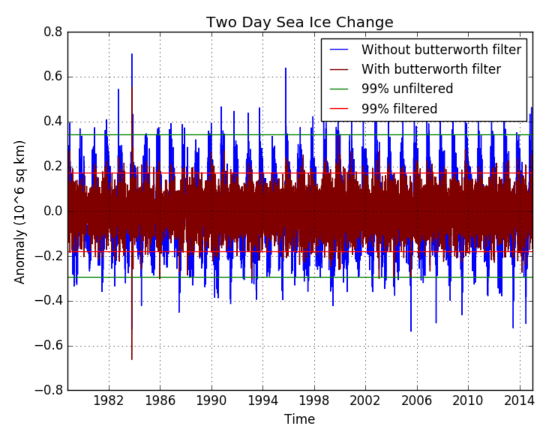

Figure 6: Original (blue) and high-pass Butterworth filtered (maroon) 2-d SIE change. Horizontal lines represent the 1% and 99% bounds of the original (green) and filtered (red) time series.

The months in which the top 1% of two-day SIE events occur are shown in Figure 7. The summer months of June, July, and August were used for the study. To ensure independent events, cases that occur on consecutive dates are removed, leaving 25 summer cases of 28 initial dates. While the summer months are the focus this study, note that the highest peak is in December (Fig. 7).

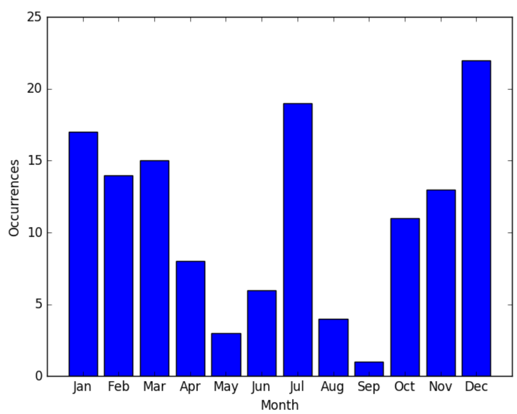

Figure 7: Monthly counts of the largest 1% of high-pass filtered two-day SIE loss events (1979-2014). Summer months of June, July, and August are the focus of this study.

3.3 Overlaying the Atmosphere

A majority of the events occur in the eastern Siberia and the Hudson Bay/Western Greenland areas, but nonetheless vary across the Arctic (Fig. 8). The MSLP composite (Fig. 9a) shows our reference point in a pronounced pressure gradient between a cyclone and anticyclone. Note that it should not be surprising to find strong winds in a tight pressure gradient, so the overall pattern is somewhat by construction.

However, cyclones have a more pronounced anomaly than anticyclones. The plotted anticyclone has a maximum anomaly of around 7 hPa whereas the cyclone reaches to an anomaly of more than -10 hPa. The difference in the mean could be a function of different intensities or varying locations among each case. The spread in MSLP anomaly shows larger ranges of MSLP (Fig. 9c)) over the center of the low in the MSLP anomaly composite from 35-45 hPa. The high on the MSLP anomaly composite has relatively lower spread of about 25 hPa. These differences reinforce the importance of stronger, more variable lows. Importantly, a cyclone is present for each event while an anticyclone is not always present. Note that anticyclones may reinforce weaker cyclones to set up strong, wind-driven conditions for rapid, dynamical sea ice loss. Thus, cyclones can play an important role in driving the conditions for an abrupt sea ice loss event.

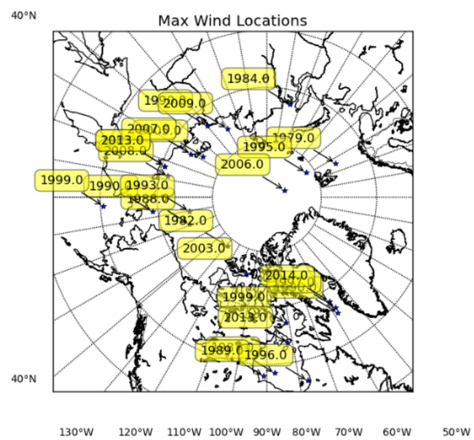

Figure 8: Locations of reference points for the 25 summer events. Each point represents the location of maximum wind over the largest connected ice loss object over a prior 5-d interval ending on the event date.

Considering the mean SIC change (Fig.9), the composite reveals higher loss in concentrations near the point of reference with an average loss of concentration around 30%. This is a substantial loss of sea ice over five days.

The tail of averaged higher concentration loss lining up with the pressure gradient reinforces the importance of the role of wind at driving sea ice loss (Fig. 9b). The main ice loss is angled to the right of the wind, consistent with additional Coriolis forcing. Not all cases show highest concentration loss in a tight pressure gradient or related to high winds throughout the SIC loss, but the overall average does show this tendency. This suggests winds and pressure gradients are important components of cyclones' effects on sea ice loss. This tendency can at least be said for sea ice loss over larger areas, given our reference choice for the local grids.

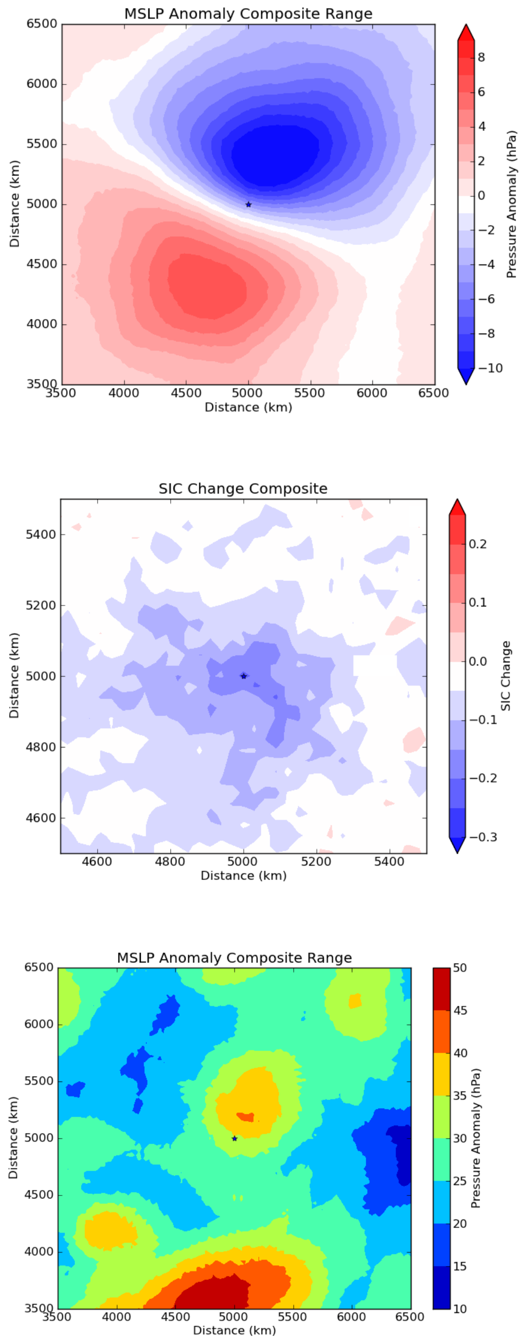

Figure 9: (a) Mean anomalous MSLP over all 25 local grids, with positive pressure anomaly shaded in red and negative anomaly in blue; (b) composite mean of SIC change; (c) Spread (maximum-minimum) of anomalous MSLP.

4. CONCLUSIONS

The causes of year to year variation in sea ice extent are not understood very well, especially for intraseasonal prediction. By looking at synoptic time scales of abrupt sea ice loss, it was believed that a possible link to the year-to-year variability could be made. A spectral analysis found significance in SIE loss at peaks between 4 to 15 days motivating further studies of the synoptic time scales. Abrupt SIE loss events were obtained from the Butterworth filtered two-day change in SIE. The compositing of the anomalous MSLP over local reference frames showed the constructed reference point in a tight pressure gradient between a 7 hPa anomalous anticyclone and an anomalous cyclone with anomalous values under -10 hPa. It was observed that at least one cyclone was within each event grid, and the spread of intensities was greater for cyclones than anticyclones. This result gives reason to believe that cyclones play an important role in setting up conditions for rapid sea ice loss with anticyclones acting as a reinforcement for stronger winds in some cases.

This exploratory study was limited in scope. Several extensions may build a more robust picture of what is happening at abrupt sea ice loss locations. Expanding from the top 1% sea ice loss events, the interval could include the top 5% or 10% to see whether results hold for more cases.

This study also focused on summer months. Incorporating winter months into the events or analyzing them separately to compare to the summer months may add context. Events throughout the year could be integrated to contribute to year-to-year variability.

While we focused on MSLP and surface winds, other atmospheric variables are also important. In particular, tropopause variables will be used to better understand the evolution of the synoptic systems. Preliminary results suggest that constructing a different reference frame may be informative.

Given the importance of cyclones, it is perhaps surprising that the Great Arctic Cyclone of 2012 and several other strong cyclones were not among the most extreme abrupt sea ice loss events. While a conclusive rationale was not developed, the lifetimes of these systems may be long for the criteria used here.

Cyclones appear to be key ingredients in setting up abrupt sea ice loss. It is believed these abrupt sea ice loss events can further the understanding and prediction of year-to-year variability, which may in turn guide modelling and predictions of future climate trends. Although a direct link to year-to-year variability was not made, further investigations into the dynamics of synoptic time scales are warranted.

5. ACKNOWLEDGMENTS

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