Quantifying the Impact of Atmospheric and Oceanic Processes on the behaviour of Sea Ice in Antarctica

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Abstract

Acknowledgements

Contents

Chapter 1

Introduction

Ice in Antarctica is critical for our understanding of global climate patterns and climate change. It has a high albedo and stores massive amounts of both energy and water, being intrinsically linked with both the water cycle and energy balance for the Southern Hemisphere. Sea ice melts and reforms around the continent each year, trapping extra $C0_2$ in the Ocean. It is also shown to affect the salinity of the ocean and ocean circulations. The extent of ice is additionally linked to the state of the climate in Antarctica, and therefore by extension, the state of our global climate. Understanding the processes which have driven its behaviours and which could potentially drive the trends and variability we see in both land and sea ice in Antarctica in the future is therefore important for our understanding of the changing climate of Earth. For this thesis, the key question we are attempting to ask is this:

What drives the trends and variability we see in Antarctic ice?

In order to answer this question we will make use of statistical techniques such as linear regressions and Pearson correlations to determine the relationships which we can observe between ice in Antarctica, different environmental variables such as temperature, Ozone concentration, and surface pressure, and climatic patterns which are known to drive global and southern hemisphere climate such as the El Niño Southern Oscillation and the Southern Annular Mode.

This introduction will include details about the data we have used in this project, followed by a brief overview of the analysis carried out on the data and a discussion of our key findings. The rest of the thesis will cover the analysis and results in more detail alongside a literature review which should introduce the key ideas which you need to know to understand the state of contemporary research on ice in Antarctica and its relationship with global climate.

1.1 Data used in this project

For this project we used a wide variety of data sources, detailed in more detail in the Data chapter of this thesis. We will briefly comment on what sources were used for each dataset and variable here.

For sea ice, we used concentration from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive microwave data, provided by NSIDC. For the thickness of sea ice we use data from where?. For land ice thickness and volume, we sourced data from the NASA GRACE mission.

Additionally to the variety of sources for Antarctic ice, we also used data for a number of "environmental variables" such as temperature and ozone concentration. These are almost entirely sourced from the ECMWF ERA5 reanalysis. Temperature values are verified against station data around Antarctica to ensure that it is of high quality. (See the Data chapter of this thesis for more detail.)

1.2 Planning the analysis

Input flow chart of methods carried out at the end of completing this thesis.

1.3 Our key findings

Chapter 2

Data and Data Processing

This will be a summary of the data we use in this project and some data which we don't (but is used by other researchers) How is it collected? What format is it in? How reliable is it? This chapter will also contain a brief overview of some of the preprocessing methods carried out on the variety of datasets used for this project.

2.1 Antarctic Ice

Sea Ice

Thickness of sea ice

For this project we are also interest in using the thickness of Antarctic Sea Ice to aid our analyses. This is complicated because measuring the thickness of ice in Antarctica involves a number of technical challenges. Satellites have been used since the late 90s for measuring ice concentration, as described above this involves measuring the albedo of regions with ice and using the measured values as a proxy for the amount of ice. A number of satellite missions have been used to carry this out. We cannot use the same data as for land ice thickness (described below) because that data includes all liquid water in its thickness calculations as well as frozen ice. So we have to turn to other sources of data. These sources are varied, and none of great quality for Antarctica, so we will pick one which seems to give us reasonable values and use it for qualitative rather than quantitative understanding of the behaviour of ice in Antarctica.

One we settled on is collected by NASA's Ice, Cloud, and land Elevation Satellite (ICEsat). This data has been processed by Kurtz and Markus cite. It is freely available online (insert website here)[]. Limitations we have to consider are that the time period for the data is limited to between 2003-2008. As such we cannot reliably use it for extended periods of time but will use it briefly in our research. Additionally they only have data for Spring, Summer and Autumn, not winter, so we are missing the time of year with the thickest amount of ice. For use in this project, we will treat this data as a rough indicator for how thick ice can be around Antarctica and treat any calculations using it as rough estimates which can be used to indicate potential relationships but require better data.

The data is in our standard polar stereographic projection of 25km x 25km, link this here so no interpolation is necessary. In order to obtain an approximate thickness of ice on an annual scale, we will average these three datasets together and use this as our value for the thickness of ice. Because the data is limited in nature this is for qualitative understanding only.

Land Ice

Standardising Ice values

We can try to standardise the different ice datasets so we can use them as one variable without comparing them separately.

The NSIDC data comes in a concentration % with an associated area data file. We can therefore calculate the total area of ice which changes from year to year, or leave the data as a %.

The GRACE data

2.2 Temperature and other environmental variables

2.3 Climate Indices

SAM

ENSO

DMI

IPO

Non-Pacific Climate Modes

2.4 Pre-processing

Temporal Averaging

Spatial Regridding

Because we use a variety of datasets which come in a variety of structures, it is important that standardise the spatial dimensions of each data source. One way we do this is by interpolating each dataset to have a consistent spatial arrangement. This allows for better quality results and makes it easier to calculate measures such as the correlation between 2m temperature and sea ice concentration.

We do the interpolation using the python package Scipy, which makes use of a piece-wise cubic, continuously differentiable (C1), and approximately curvature-minimising polynomial surface to determine the value of our given variable at a chosen location.

We converted the temperature data to the projection the sea ice data is provided in; a south polar stereographic projection with regular grid cells of 25km$\times$25km. We found this resolution to have a good balance between reasonable run-times and good quality results.

Temporal Anomalies

Erroneous Values

Chapter 3

Literature Review

In this literature review, we aim to tell you a story of research which has been done in this area of research before this point in time. In doing this we hope to provide the reader of this thesis an understanding of the strengths and weaknesses of relevant literature. What has and what hasn't been done by other researchers. We also will take some time to delve into the papers most relevant to this project by discussing methods and results which we at least considered using in the process of doing our research.

This literature review will be structured to look at specific topics which are somehow related to the research we carried out. These topics are included in the left hand column of the table below, alongside with the counts for the numbers of papers we looked at for each topic.

If the reader is looking for a good overview of recent climate science it is worth reading **?**

3.1 Sea ice trends and variability in Antarctica

This section of the literature review will discuss the research papers which we looked at regarding the trends and variability of sea ice extent and area around Antarctica.

Sea ice thickness

For measurements on the thickness of Antarctic sea

3.2 Atmospheric trends and variability in Antarctica

This section of the literature review will discuss the research papers which we looked at regarding the trends and variability of atmospheric conditions around Antarctica.

3.3 Oceanic trends and variability in Antarctica

This section of the literature review will discuss the research papers which we looked at regarding the trends and variability of oceanic conditions around Antarctica.

3.4 Sea ice and atmospheric processes

This section of the literature review will discuss in some detail, the research which has been carried out to investigate the relationship between sea ice and atmospheric processes in Antarctica and globally.

Comiso et al look with some detail at the relationship between sea ice in Antarctica and surface temperature **?**. While their dataset ends in 2015, just before the amount of ice in Antarctica experiences a rapid decrease in concentration, their research intent and their methods are still relevant to us as we look at sea ice in Antarctica today. They provide a good commentary on the quality of the satellite measurements from different sensors, before moving into a correlation analysis, looking at the relationship between surface temperature and sea ice in Antarctica. One thing they do is to break the continent into sections and look at how the correlation changes in each region. Likewise they break the temporal scale into seasons while keeping the overall picture. When looking for other environmental influences they found smaller than expected correlations with patterns like the Southern Annular Mode (SAM), however they speculate that ENSO may be a major contributing factor to the patterns in sea ice in Antarctica. On the whole, they found a positive correlation between the SIE in Antarctica and surface temperature in the same region, with an even larger correlation when you introduce a time-lag.

In 2016 we saw a record low in Antarctic Sea ice extent. Wang et al **?** discuss some of the physical processes which could be a cause of this extreme event. Their results indicate to them that this was largely due to naturally occurring variability, nonetheless they are unable to discount a possible role of anthropogenic forcing. They link the extreme concentrations of ice to a anomalous atmospheric circulation over the Indian and western Pacific oceans and unusual internal atmosphere-ocean variability. Of interest to us here are the different atmospheric circulation indices they argue has an impact on the patterns of sea ice concentration in Antarctica. The look at the Indian Ocean Dipole (IOD), Madden Julian Oscillation (MJO), ENSO and SAM, as contributors to this event.

? wrote one of the key papers for our project so we will use it as a starting point. And explore the literature using its references which seem relevant to this topic. The paper focuses on the impacts on the sudden sea ice retreat in 2016 where we saw record low SIE. The first detail of point is that they classify the sections of their SIE time series by when IPO is positive and negative with a 13 year low-pass Lanczos filter. They associate IPO with acceleration or slowdown of global warming, thus relating it to long term trends in sea ice. (Acceleration in positive phase and slowing in negative phase) They say that the acceleration off antarctic sea ice growth was predominantly driven by negative convective heating anomalies in the tropical Pacific.

They also discuss the sudden decrease seen in 2016. They claim this occurred because of a zonal wave number 3 pattern enhancing meridional flow, and negative SAM values towards the end of the year. The DMI index caused positive SST anomalies in the tropical eastern Indian Ocean and the far-western Pacific. This enhanced convection during SON and indicated by record low OLR for the area 90 E - 150 E and an associated precipitation anomaly.

The main takeaway can be drawn from the end of their introduction; First, teleconnections from strong tropical convection in the eastern Indian Ocean produced surface wind anomalies. They say that a negative phase of IPO and positive phase of SAM associated with strengthened westerlies moved warm subsurface water upwards due to Ekmann suction (On the long term). Third, a negative phase of SAM and transition to a positive IPO produced warm SSTs to complete a warming of the upper 600m of the ocean.

? discuss in some detail, some of the impact of SAM on the Antarctic SIE seasonal cycle. Their primary finding is that positive SAM anomalies in summer result in cold SST and anomalous ice growth in the following summer, while negative anomalies in SAM can be associated with a reduction in SIE on the following Autumn. The increase in SAM is notably largest in summer and has been linked to the depletion of stratospheric ozone over Antarctica. They note that other papers have found some evidence of the SAM affecting Antarctic SIE in the Indian Ocean during MJJ, but that it is not well explained by SAM. They mention a two time scale response which can be used to explain this relationship. This is explored by **?** in some detail and may be related to our research. **?** use composites and regression analysis to look at the relationship between SAM and SIE on a seasonal basis finding the results described above. They find the same signal in the raw and detrended datasets.

? and **?** discuss with some technical analysis the impact of long term behaviours between Antarctic SIC with ENSO and SAM.

? establish a link between tropical modes of atmospheric climate and surface air temperature (SAT) over the internal Antarctic region. While this isn't directly Sea ice, it is good physical evidence that these relationships exist which supports our hypothesis that SAM impacts the long term variability of Antarctic SIE.

? Detail some physical reasons for the decrease in Antarctic SIE in 2016.

3.5 Sea ice and oceanic processes

This section of the literature review will discuss in some detail, the research which has been carried out to investigate the relationship between sea ice and oceanic processes in Antarctica and globally.

3.6 Statistical Methods

This section of the literature review will cover a number of the statistical methods used in different papers which we looked at using for this project.

One such technique we may want to use is change-point analysis as discussed by Beaulieu, Chen, and Sarminento **?**. This is used for looking at changes in temporal regimes for time series, they propose it for the purposes of detecting abrupt climate variations. We will also use it for this purpose. The paper provides a good overview of different types of change-points which exist Include figure? and a good overview of different ways in which people go about detecting them. They set out to describe and extend an informational approach to this problem, making use of the Schwartz information criterion to identify change points for a variety of fitting models.

Chapter 4

Trends and variability in Antarctic Ice

Before we get into any complicated analysis we will start with the simplest thing we can. Describing and understanding the trends in Antarctic Ice in our datasets. We will start this by looking at Antarctic sea-ice, first looking at concentrations and extents before briefly discussing the thickness and volume of the ice. Then we will discuss in some detail, our understanding of land ice in Antarctica. And finally we will compare the two datasets and look at the trends and variability's of the two datasets combined.

For each dataset we look at we want to look at the following things. How the total ice has changed over time. How this changes with different temporal frequencies. How this also changes if we remove seasonal patterns or trends. What the seasonal patterns and trends we see in Antarctic Ice are. How significant these behaviours are. And how this all might impact the way we carry out further research. Finally we will want to acknowledge any shortcomings in our understanding of Antarctic ice and what the associated ramifications might be.

4.1 Sea ice

4.1.1 Sea ice concentration

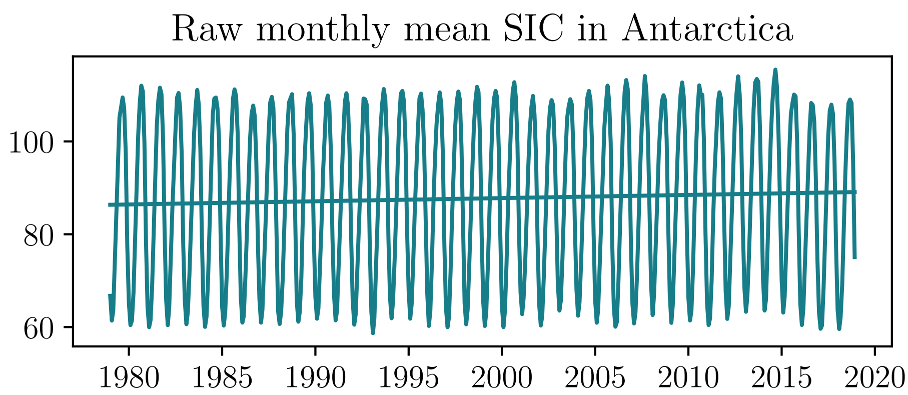

Figure 4.1: Raw mean Antarctic Sea Ice concentration from 1979 to 2019.[WIP update with new plot

4.1.2 Sea ice thickness

4.1.3 Sea ice volume

4.2 Land Ice

4.2.1 Land Ice thickness

4.2.2 Land Ice volume

4.3 Combined Ice dataset

4.4 Implications for further research

4.5 Limitations

Chapter 5

The Impact of Temperature on Antarctic Ice

The variable which we found had the largest impact on the behaviour of ice in Antarcica is temperature. This follows naturally from the basic thermodynamics of phase change. As the temperature increases we see lower concentrations of sea ice, and as the temperature increases we see lower concentrations of sea ice. The extent of this relationship will be explored in detail in this chapter. We will first look at the relationship through density plots Check name of plots. Before calculating correlations and looking at the similarities and differences of the two different variables.

5.1

Appendix A

Appendices