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 Environmental variables

2.2.1 Describing the environmental variables

For this project we use ERA5 reanalysis data produced by ECMWF cite this as our source of data for the environmental variables listed below.

1. Skin Temperature [SKT]
2. 2 metre Temperature [T2M]
3. Sea Surface Temperature [SST]

This data comes in a regular check resolution 0.25 degrees grid which covers the entire globe. For our analysis which involves looking at weather in Antarctica we projected this data onto the standard South Polar Stereographic projection as defined by NSIDC link this here. This means that the data we use for analysis is interpolated which lowers the quality slightly, but negilibly in compared to the utillity we gain from having it in the same projection and coordinates as our other sources of data.

Next we should consider the different variables we used from this dataset. Listed above, we will now go through them one by one and explain how they are calculated and what this may mean for the project and any results we may generate.

For a full technical description of how any and all variables are calculated for the ERA5 reanalysis you can refer to cite report. We will briefly summarise the most relevant points here for convenience of the reader.

Skin Temperature [SKT]

The skin temperature is the theoretical temperature that is required to satisfy the surface energy balance. It represents the temperature of the uppermost surface layer, which has no heat capacity and so can respond instantaneously to changes in surface fluxes. Skin temperature is calculated differently over land and sea because of the difference in dynamics in each type of terrain.

In the presense of sea ice, skin temperature is taken as the temperature on the upper surface of the ice.

2 metre Temperature [T2M]

2 metre temperature is the temperature measurement which is most often used in literature because of its regularity. 2m temperature is calculated by interpolating between the lowest model level check what pressure this is and the Earth's surface, taking account of the atmospheric conditions.

Sea Surface Temperature [SST]

SST is usually calculated directly from satilite data, but in the absense of that it is calculated using data from NEMO forecasts cite this. Sea surface temperature is masked to be only over sea and as such we can only use it when doing calculations over the ocean. Nonetheless it is still useful. When the ocean is exposed this will be very similar to skin temperature, however when sea ice is found, SST is usually set to -1.65°C, the freezing point for salt water.

2.2.2 Example plots

2.2.3 Validation

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×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

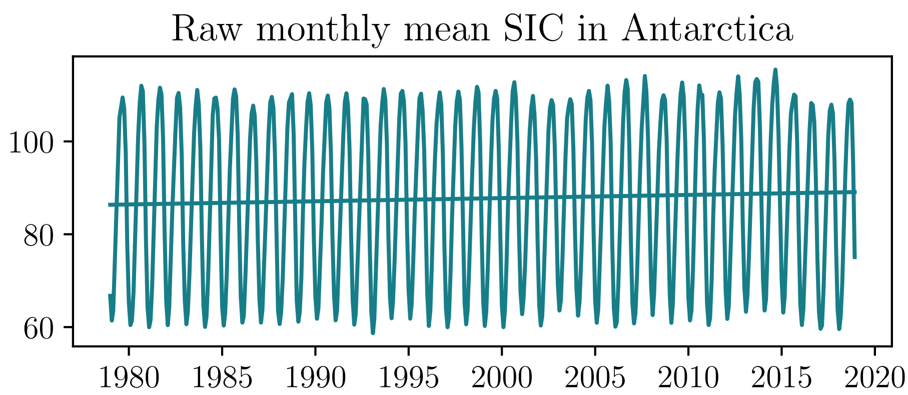


Figure 4.1: Raw mean Antarctic Sea Ice concentration from 1979 to 2019.[WIP update with new plot

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 Antarctica 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.

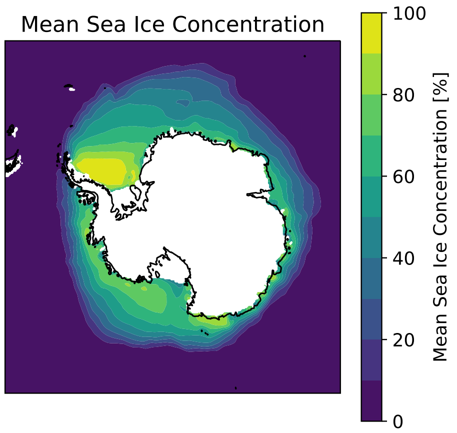
For the purpose of this chapter, when we use temperature we will use skin temperature as discussed before Write up different temperatures.

5.1 Temperature and ice anomalies

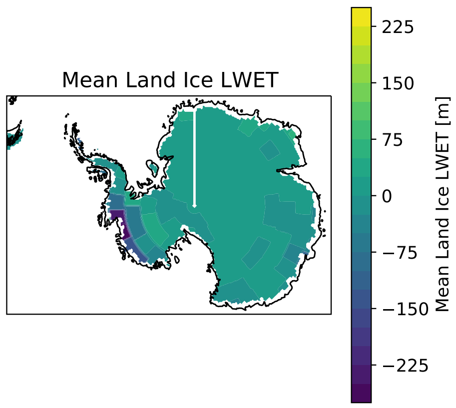
In this chapter we will be looking at both anomalous and raw datasets. We define anomalous values as follows.

Let $y(t, x, y)$ be our time-series of measured values. x and y are spatial coordinates. For the purposes of this exercise the spatial coordinates are arbitrary as we apply the calculations separately for each time-series found at each location. For each month we take the average value of our variable y

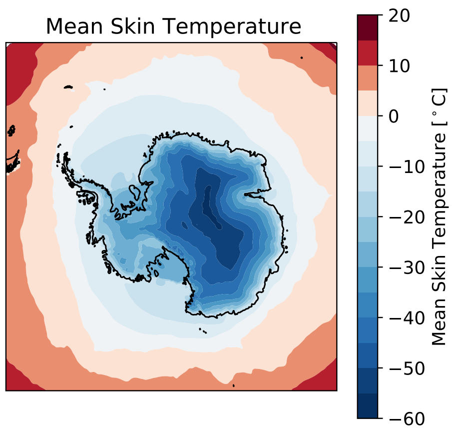
and subtract that from every instance of that month in the time-series. In the case of annual data there is only one mean value for each time-series. In order to demonstrate the spatial variability in the data which is lost by finding the anomalous values, we have plotted the mean value for the variables used in this chapter below (Figure 5.1).



(a) Mean SIC over Antarctica.



(b) Mean Land Ice Liquid Water Equivalent Thickness over Antarctica.



(c) Mean Skin Temperature over Antarctica.

Figure 5.1: Spatial distributions of the mean values of different variables used in this chapter.

Looking at these plots, it is worth noting that the mean skin temperature over the ocean is around 0 degrees close to Antarctica, and so in this region we expect to see a large amount of melting and refreezing of ice as the temperature shifts above and below the freezing point, whereas over land, the temperature tends to be much colder. As such we don't expect temperatures to be above freezing often, so while temperature change may be related to variability in ice change it will not necessarily be the predominant driving factor.

5.2 Visually comparing temperature and ice

Before we get into any aggregation let's compare the amount of ice at each time and space coordinate in our dataset with the temperature at the associated grid point.

This plot (Figure 5.2) tells us an interesting story. For sea ice, we can observe a significant relationship between skin temperature and SIC. This relationship matches with our intuition, which is great. However land ice doesn't exhibit the same strong relationship as sea ice. This is interesting as it suggests that it is driven by a different set of processes. We will have to be careful about this in our ongoing analysis. The anomalous plots tell us a similar story in regards to the relationship between the two variables, however as the overall shape for both land and sea ice plots changed, we expect there to be some spatial variation in how we see the relationship between ice and temperature expressed.

One thing we need to remember with this plot is that it will be exhibiting some spatial bias because some locations will have higher values of ice and lower temperatures. Additionally these plots only contain data points from 2002 because the land ice data only has values from then due to it being based on an later mission.

We can learn more about this relationship by looking at the spatial and temporal variability and trends for each of the variables.

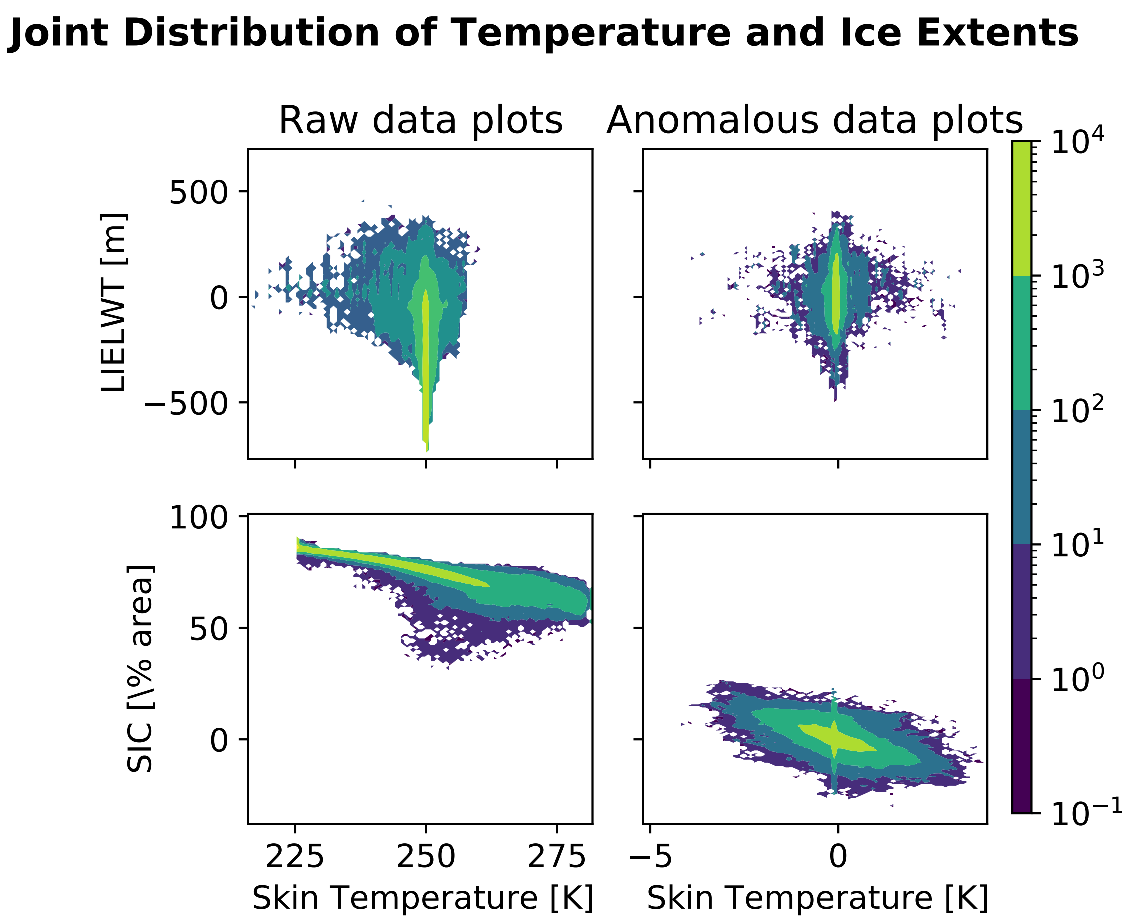
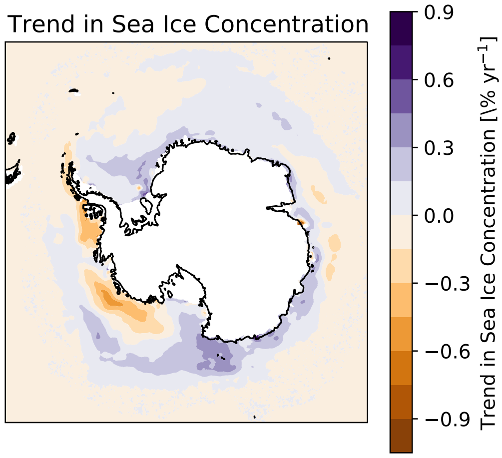


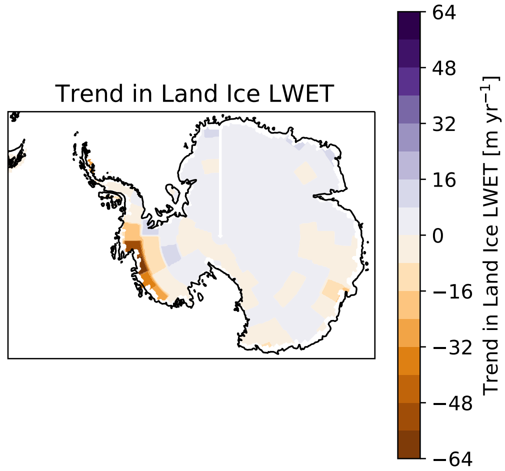
Figure 5.2: Distribution of skin temperature against ice. This is a 2 dimensional histogram where the colour represents the number of points in our dataset with a given temperature and amount of ice. The top row contains all the gridpoints over land, the corresponding ice values being Land Ice Liquid Water Equivalent Thickness (LILWET). And the row subplot contains all the gridpoints over the sea, with Sea ice concentration (SIC) plotted on the y-axis. The left column contains the raw values for each measurement and the right column has the anomalous values where the mean value of each variable is removed for each spatial location. (The values for this is plotted below).

5.3 Spatial distribution of trends in Antarctic ice and temperature

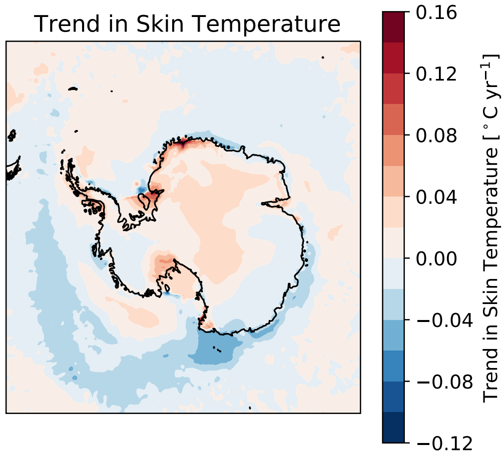
Our next step in unpacking the relationship between ice in Antarctica and temperature is to look at the trends we see in the different variables



(a) Distribution of trends in SIC over Antarctica.



(b) Distribution of trends in Land Ice Liquid Water Equivalent Thickness over Antarctica.



(c) Distribution of trends in Skin Temperature over Antarctica.

Figure 5.3: Spatial distributions of the mean values of different variables used in this chapter.

Looking at these plots (Figure 5.3) we can see a clear similarity between the trends in SIC and SKT, the regions to the left of the Antarctic Peninsular (Bellingshausen and Amundsen Seas) with decreasing SIC appear to correspond with an increase in temperature over our time period. We notice that To get a better understanding of how good this relationship is we will need to do further analysis (see section 5.5 and 5.6). Before doing that however, we should look at the temporal variability in our variables to see if there are any notable similarities or differences.

5.4 Temporal variability of Antarctic ice and temperature

Before looking at land and sea ice on the shorter timescale, let's look at the temporal variability of sea ice and different temperatures over our entire time period from 1979 to 2019. This is plotted below in figure 5.4. Looking at figure 5.4 the first thing to note is that while we see an increase in SIE over time, the mean temperatures above ice do not have much of a gradient if any. SST does have a negative gradient, however that may be due to its minimum temperature being set to -1.65 °C when covered with ice. When we see more ice we expect the average SST to decrease because the sea surface will spend more time in a year at its minimum temperature.

Despite the lack of trend in temperatures, we should note that there is a potential relationship between the variability of temperature and SIE. We often see peaks in temperature at the same time as dips in SIE, and conversely dips in temperature when we see peaks in SIE. This fits with the distribution plots (see figure 5.2 above) but will require a more rigurous statistical analysis to confirm.

We should also acknowledge the difference between SST and the other temperature variables. As discussed in greater detail in chapter 2 check this, SST is the estimated temperature at the sea's surface underneath the ice, whereas SKT and T2M are values for estimated temperature above any sea ice, and as such we expect SST to exhibit less variability than the other measures

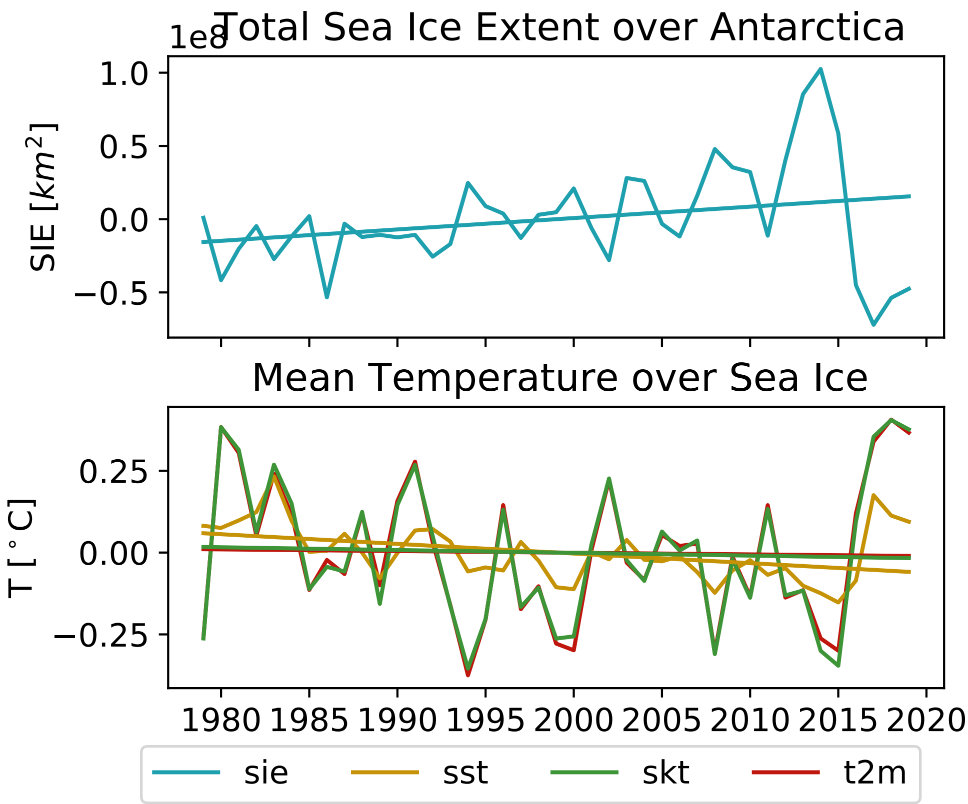


Figure 5.4: Time-series for the total SIE over Antarctica and the mean temperature over sea ice from 1979 to 2019. Both time-series were generated by first averaging annually, then removing the mean value at each grid point, then aggregating (by sum in the first plot, by mean in the second). Any and all aggregations are area adjusted to account for the spatial variability of grid size. Linear trend lines have been plotted with each time-series.

of temperature whilst having similar patterns of variability. This is what we observe in figure 5.4.

Now let's consider our shorter timescale (2002-2019) and look at the temporal variability of land ice, sea ice and temperature. This is plotted in figure 5.5.

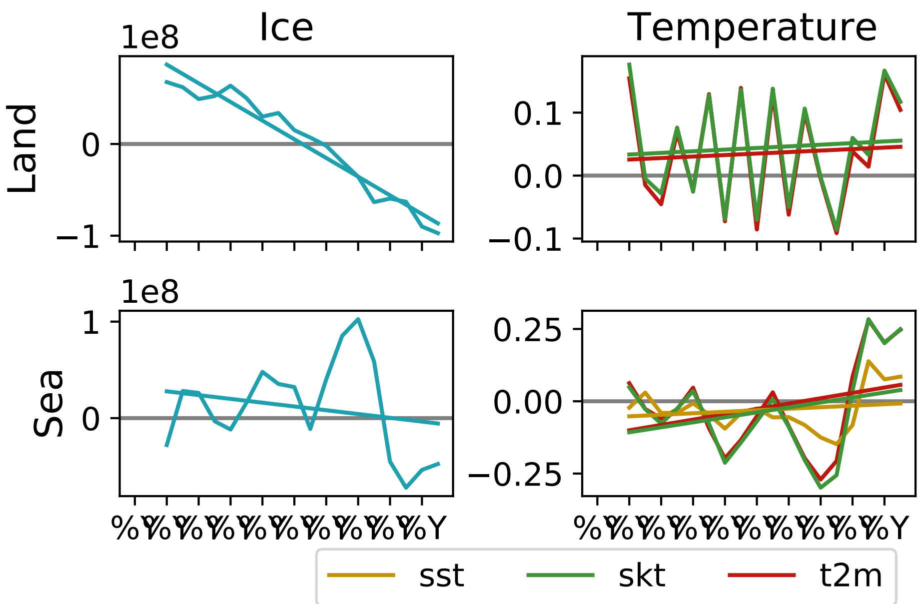
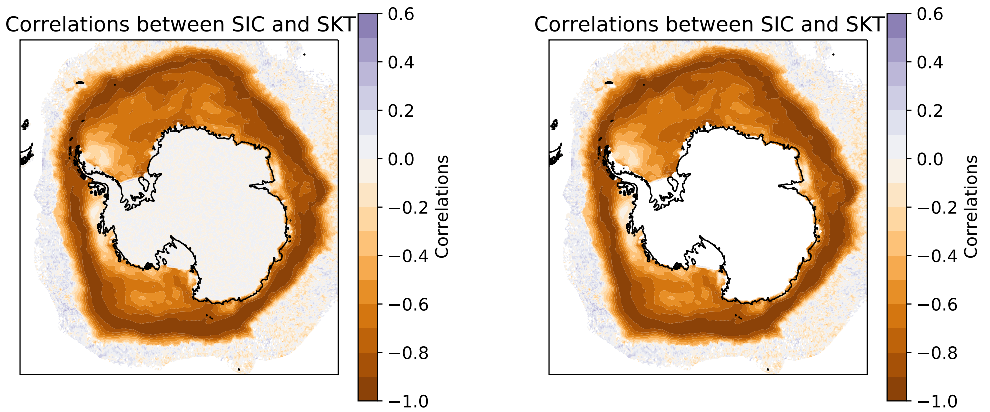
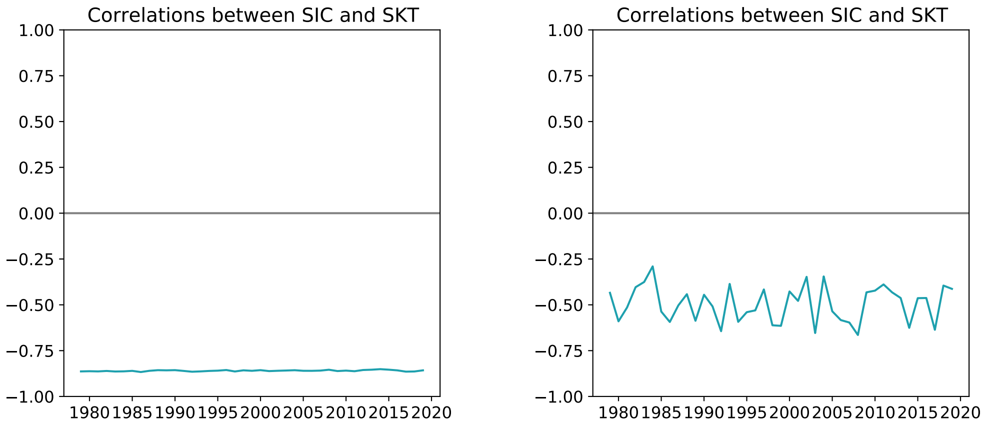


Figure 5.5: Time-series for the Ice and temperature quantities 2002 to 2019. The top row contains values over land, the bottom row contains values over the sea. The left column contains Ice variables (Land Ice Liquid Water Equivalent and Sea Ice Extent), and the second column contains plots for temperature. All time-series were generated by first averaging annually, then removing the mean value at each grid point, then aggregating (by sum for ice, by mean for temperature). Any and all aggregations are area adjusted to account for the spatial variability of grid size. Linear trend lines have been plotted with each time-series.



(a) Spatial distribution of correlations of SIC and SKT.

(b) Spatial distribution of correlations of anomalous SIC and SKT.



(c) Temporal distribution of correlations of SIC and SKT.

(d) Temporal distribution of correlations of anomalous SIC and SKT.

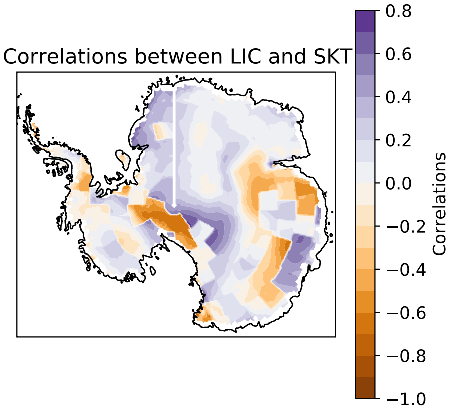
Figure 5.6: Correlations between SIC and SKT. The left column contains correlations for raw data time-series and the right column contains the correlations for anomalous time-series. The top row contains correlations for individual time series. The bottom row contains pattern correlations between the two variables and how that changes over time.

5.5 Correlations between temperature and Antarctic ice

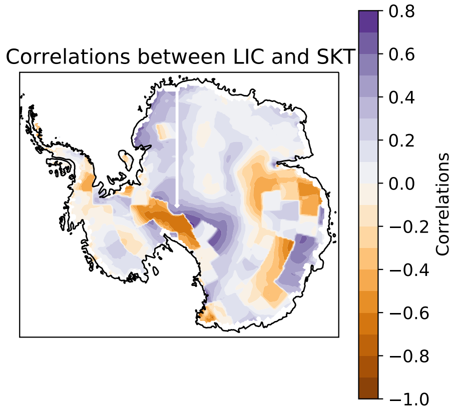
5.6 Regression using temperature to predict Antarctic ice

5.7 Statistics for Antarctic ice and temperature

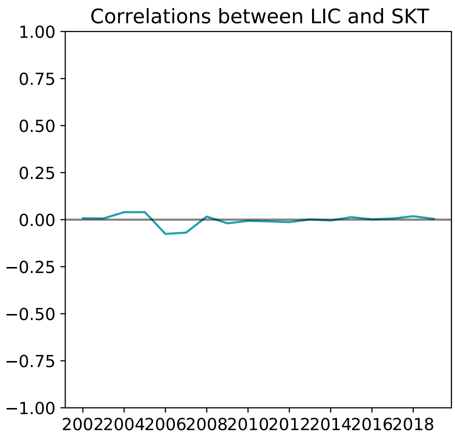
5.8 Implications for our understanding of Antarc-



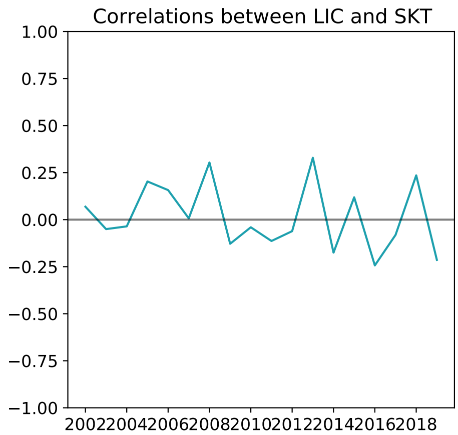
(a) Spatial distribution of correlations of LILWET and SKT.



(b) Spatial distribution of correlations of anomalous LILWET and SKT.



(c) Temporal distribution of correlations of LILWET and SKT.



(d) Temporal distribution of correlations of anomalous LILWET and SKT.

Figure 5.7: Correlations between LILWET and SKT. The left column contains correlations for raw data time-series and the right column contains the correlations for anomalous time-series. The top row contains correlations for individual time series. The bottom row contains pattern correlations between the two variables and how that changes over time.

Things still to do for this Chapter

1. Correlations

2. Temporal Aggregations

    - Trend lines to ice.

- Remove total ice row for now (until we have volume data).

3. Regress temperature onto ice.
4. Fill out red citation notes in the text.
5. Generate relevant statistics.
6. check comment made at the end of the mean distribution plots.

Appendix A

Appendices