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

Hamish Jelleyman

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Abstract

Acknowledgements

Contents

Chapter 1

Introduction

For this thesis, the key question we are attempting to ask is this:

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

Our motivation for asking this is as follows. 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.

In order to answer our 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

This can be like Figure 1.1 or the next section of this introduction. Finish this at end of project when we know what we did.

of analysis and methods.pdf of analysis and methods.pdf

Figure 1.1: Option one

1.3 Structure of the methods used

Below we will go into more detail about how each of the procedures mentioned here work and are implemented, however first, let's take a moment to outline the processes carried out on the data for our analysis.

1. **Data Wrangling**. First we had to manipulate the raw data for analysis.

   (a) **Standardise the data**. The data came from a variety of sources. The idea here is that regardless of the source, we can process everything in the same manner.

   (b) **Change the resolution**. By lowering the resolution of the data we can speed up our computation. Higher resolutions return better quality results. We did this both temporally and spatially.

(c) **Regridding**. In some of the computations, we required the data to represent set coordinates.

(d) **Temporal decomposition**. We performed analysis for both standard time series and anomalous time series for each set of data.

(e) [WIP] **Smoothing of data**. In order to make the analysis easier to analyse, we applied band-pass filters and moving averages to a variety of time series.

2. **Correlation analysis**. Our first analysis technique revolved around Pearson correlation coefficients between different time series.

   (a) **Correlations**. The primary output here is the correlation between the different time series we are analysing.

   (b) **P-values**. In order to identify how significant our results are we used p-values from a Student's t-test (confirm this).

   (c) **Compare time series**. As a visual check for the validity of results, we also plotted example time series of the different correlated variables used.

   (d) [WIP] **Time-lagged correlations**.

3. [WIP] **Regressions**. In order to quantify the impact different variables have on each other we turned to a multivariate regression analysis.

4. [WIP] **Temporal breakdown**. In order to identify specific patterns in the data we broke the temporal scale up in a number of ways.

   (a) [WIP] **Extreme events**. By taking times when the SIE was at extreme values, we can look at patterns seen in different variables and indices and link what is observed to physical processes.

1.4 Our key findings

Our final point of importance before launching into the main body of this thesis is a quick summary of our key findings.

- Temperature statistically accounts for the majority of trends and variability in Antarctic Sea Ice.

- Local temperature does not statistically account for the trends and variability in Antarctic Land Ice, however remote temperatures seem more promising.

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.

- Skin Temperature [SKT]
- 2 metre Temperature [T2M]
- 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 negligibly in compared to the utility 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 presence 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 satellite data, but in the absence 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

We can validate the quality of our temperature data sourced from the ERA5 reanalysis by comparing the reanalysis with measured station temperature data. This is included below

2.3 Climate Indices

The Southern Annular Mode

The Southern Annular Mode (SAM), is a pattern of variability in climate which exists in the lower lattitudes of the southern hemisphere. SAM

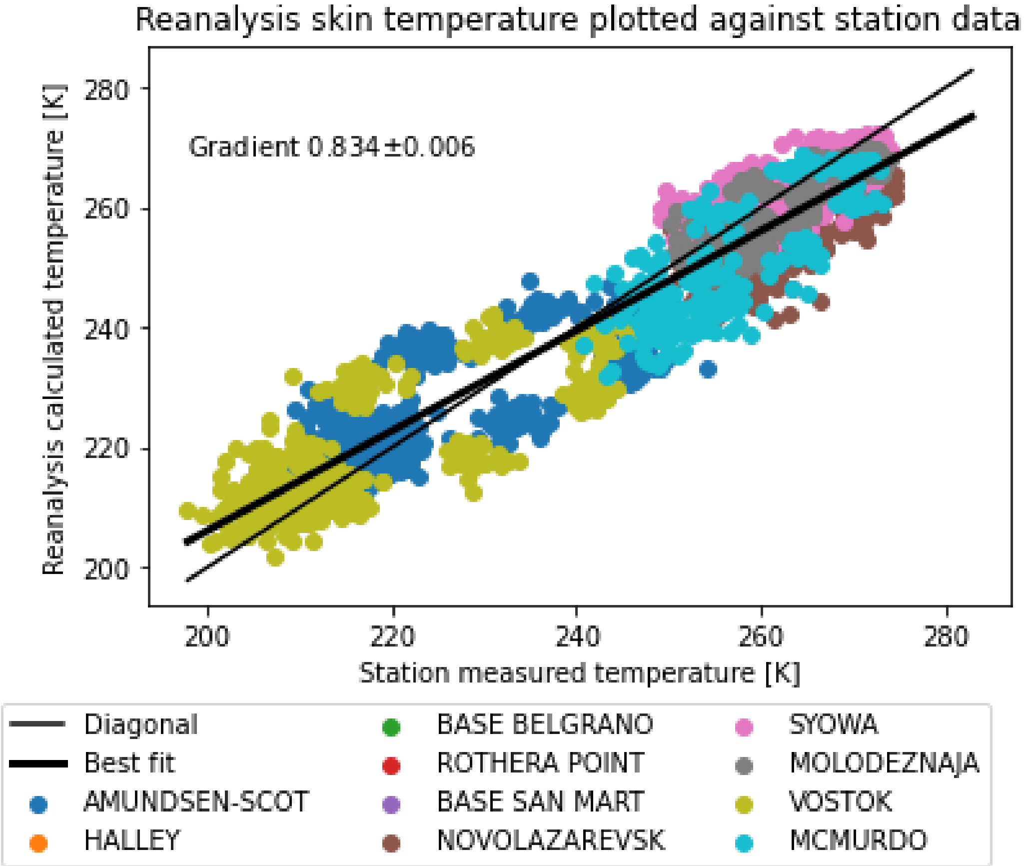


Figure 2.1: Reanalysis and measured temperature scatter plot.

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

Methods

3.1 Correlation analysis

In this following section, we will set out the methods used and some of the motivations behind them for calculating and analysing the correlations between different variables and SIE and SIC in Antarctica.

3.1.1 Pearson correlation coefficient

One comparison which we used for identifying connections between two different time series or different time series components is the Pearson correlation component. Taking a time series x, and a time series y, with elements x_i and y_i, and means denoted by $\bar{x}$ and $\bar{y}$; we can calculate the Pearson correlation coefficient r_{xy}.

$$r(x,y) = \frac{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)\left(y_i - \overline{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}\sqrt{\sum_{i=1}^{n}\left(y_i - \overline{y}\right)^2}} \tag{3.1}$$

The magnitude of the coefficient indicates how well correlated the data is and the sign represents the nature of the relationship. A large positive coefficient is indicative of a strong directly proportional correlation between the two variables, whereas a small negative coefficient indicates a weak correlation where the variables are approximately correlated to each other.

One thing to be careful of when interpreting these results is that the correlation is indicative of a relationship between two variables, it does not imply that a relationship directly exists. To determine that further analysis is required. Additionally, as will be explained in a little more detail below, a high correlation does not necessarily indicate a significant correlation between two variables, yet again, more analysis is required for that.

3.1.2 P-values and significance of correlation

In order to identify the significance of the calculated correlations, it is not sufficient to simply use the strength of correlation. Instead we used a p-value from a two tailed test with a threshold value of 0.05, giving us a confidence level of 95%.

The p-value approximately represents the probability of an uncorrelated system producing the correlation which has been calculated. For a more detailed description of how the p-value is calculated see the documentation for scipy. cite this, also do I need to describe it more?

3.1.3 Comparing time series by eye

As a test beyond simply calculating the correlations and looking at their spatial distributions, for each set of calculations we plotted example time series against each other to give an visual indication on the validity of the calculated correlations.

3.1.4 [WIP] Time-lagged correlations

When plotting the different time series, specifically the time series of temperature and ice extent in Antarctica link this to the results section, it was noticed that there was a time lag between the different time series, which caused a decrease in the correlation between these clearly related variables. Other researchers cite this, solved this by introducing a time lag of one month before computing their correlations. We wanted to take this further by investigating at what time lag, maximal correlations are found spatially, regionally, and overal for each variable.

3.2 Regression analysis

After computing a bunch of correlations We want to establish to what extent we can contribute the behaviour of SIE to the different circulations. We can do this with regression analysis. The first step is to compare the indices individually with SIE. So we take a linear regression of each index with Antarctic Sea ice extent with the following model.

$$\overline{\mathrm{SIE}_{i,j} = m_{i,j}}\mathrm{IND} + b_{i,j}$$

Where i and j are index values for each gridpoint. SIE is the time series of concentration of sea-ice at that gridpoint and IND is the time series for the index in question. b is a bias term which we will generally ignore as we are more interested in the value for $m_{i,j}$, the regression coefficient of seaice concentration against the index in question. It is worth noting that the index timeseries only come as a single time series and will not include a spatial distribution which needs to be indexed.

3.2.1 Contribution of a single index

We can extend the results from the above regression analysis to estimate the contribution of each index to the change in seaice over our time period. We do this by multiplying $m_{i,j}$ by the temporal derivative we can gain an estimation for the extent to which we expect seaice to increase or decrease at the gridpoint over our time period soley on the influence of the single index time series.

$$\left.\frac{\overline{d\ \mathrm{SIE}_{i,j}}}{dt}\right|_{\mathrm{IND}} = \frac{d}{dt}\left(m_{i,j}\mathrm{IND} + b_{i,j}\right) = m_{i,j}\frac{d\ \mathrm{IND}}{dt}$$

This will give us a spatial distribution of the contribution of each index to the trends in Antarctic sea ice concentration based on a linear regression model. If we normalise this by the true trend in SIC at each gridpoint we can gain further understanding of what this means in relation to what has actually happened over the last 40 years. This also stands as a method we can use to verify the validity of our model.

3.3 Multiple Regression

We can extend this analysis to more complicated models. The first step in this direction is a linear regression where we consider multiple indices at the same time. This hopefully should be more comprehensive than running each linear regression separately and individually. The model we use to predict the concentration time series of sea ice at each gridpoint is as follows.

$$\overline{\mathrm{SIC}_{i,j}\left(t\right)} = a_{i,j}\mathrm{SAM}\left(t\right) + b_{i,j}\mathrm{ENSO}\left(t\right) + c_{i,j}\mathrm{IPO}\left(t\right) + d_{i,j}\mathrm{DMI}\left(t\right) + e_{i,j}$$

Where the index time series are SAM(t), ENSO(t), IPO(t), and DMI(t) respectively. a, b, c, and d are the regression coefficients at each gridpoint i, j. $\overline{\mathrm{SIC}_{i,j}\left(t\right)}$ is the predicted behaviour of Antarctic Sea ice at each gridpoint over the entire time period. We have to be particular with our calculations here because while each index and SIC dataset has a time component, it is not being used as part of the regression, but is used to work out the expected amount of sea ice at a given year or season.

3.3.1 Contribution of a single index

Like when we compute a single regression we are interested in the individual contribution of each index to the change in Antarctic SIC. We compute this in a similar way using the regression coefficient which corresponds to the specific index of interest and treating it like the gradient of a single regression.

$$\left.\overline{\frac{d\ \mathrm{SIE}_{i,j}}{dt}}\right|_{\mathrm{IND}} = \frac{d}{dt}\left(m_{i,j}\mathrm{IND} + b_{i,j}\right) = m_{i,j}\frac{d\ \mathrm{IND}}{dt}$$

If we normalise this by the true change in Antarctic SIC over time at each gridpoint we can gain an understanding of what proportion of what we see happening in SIC over time can be contributed to each index over time.

3.4 Verification of Regression Analysis

In order to validate the quality of our regression analysis we can use a few measures. Firstly we can use the covariance of the fitting which is output with the regression calculation. If the coefficients are more than two standard deviations from 0, we can say with 95% confidence that there exists a meaningful relationship between the index in question and the SIC at that gridpoint.

Additionally, we can compute the correlation of the predicted SIC change at each location with the actual behaviour of SIC at each location. If this is a large correlation or has a significant p-value we can use this as an indication of the quality of the fitting.

Finally, we can sum over the entire continent and generate a time-series of the expected SIE over the entire continent and compare that to what actually happened. This can be done visually as it will only be two time series.

We can estimate how good the linear regressions are by comparing the expected sea ice extent for each time point predicted by the regression with the actual extent of sea ice in Antarctica at that time. First we can compare this just visually by plotting the two timeseries together along with the different components. In this case we are particularly interested in the overall trend in sea ice and what proportion of it can be contributed to global atmospheric circulations. We can Take this a step futter and consider the extent to which the sea ice extent variability can be contributed to variability of the different atmospheric circulations which we are interested in. We do this by considering the expected sea ice extent if our linear model was entirely accurate and computing the correlation this has with the actual behaviour of sea ice. By computing a regression of this we can establish what proportion of the variability seen in the the true behaviour of sea ice in Antarctica can be contributed to the different circulations in our model.

Chapter 4

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 **?**.

4.1 Sea ice trends and variability in Antarctica

Sea Ice Extent (SIE) in Antarctica has changed over the last few years as discussed by **?**. They discuss in detail the behaviour of ice between 1979 and 2018. There has been a steady, although slow increase over the majority of the time period. Despite this steady increase in SIE, we see a dramatic decrease in

SIE between 2014, where we have our maximum ammount of SIE of get value and 2017, where we see the minimum ammount of SIE. This decrease is larger than any trends seen even in the Arctic, where large decreases in sea ice has been observed. The exact drivers of this are uncertain, although a number of theories have been proposed. This will be discussed in more detail later in this literature review.

Spatial variability is also important for understanding ice in Antarctica fully. Parkinson expands on this by calculating the trends and behaviours seen in different geographic regions of sea ice concentration. It is worth noting that the only region where we see a decreasing trend in Antarctic Sea Ice is in the western Antarctic Peninsula check geography. **?** discusses this as well. Finding that the Ross Sea Region (RSR) is the only region in Antarctica where we see a statistically significant increase in SIE over the entire time period.

It is important to consider the seasonality of the variability we see in Antarctic SIE as well. **?** discuss this in some detail. Large-scale climate circulations such as SAM and El Niño Southern Oscillation (ENSO) have negilible impact on the longterm trends in SIE, however they remain significant, at least on a statistical level, on short-term or seasonal variability.

Sea ice thickness

It has been much more dificult to measure the thickness of Antarctic Sea ice, and as such we do not have the same breadth of products for this. The best datasets available at the moment are not continuous and only extend as far back as 2002 double check this. Consequently there is significantly less research which deals with this as a variable, as opposed to SIE which is no more than an area measure which is easily taken via satilite.

4.2 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.

4.3 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.

4.4 Land Ice in Antarctica

In the chapter 2 of this thesis, we discus the usage of GRACE data sourced from NASA to represent the changes in Antarctic land ice over the last couple of decades. Now, we will discuss what the relevant literature has to say regarding the behaviour of Land ice in Antarctica in the context of this dataset. **?** run a statistical analysis of the trends in Antarctic and Greenland land ice masses. They identify regions of significant changes in ice mass and accelerations in the change of ice mass over time. They identify that the majority of mass lost in Antarctica is in the Amundsen Sea and Antarctic peninsular regions. With a total loss of 67 ± 44 Gt/yr of land ice mass. Below Figure 4.1 from the paper check I can include this.

This paper links the changes to ice mass with ice dynamics. **?** discusses this in some detail with examples of glaciers in western Antarctica, the location with the largest amount of ice change. Essentially, glaciers in this region are flowing faster which is causing them to thin. This is linked to warming ocean temperatures which have thinned the ice shelf and ice plain as discussed by **?**.

Clouds and the impact they have on the radiative energy balance which in turn has an impact on the Ice-Sheet mass balance could also be another factor to consider. **?** discuss this in some detail. By looking at a 4-year

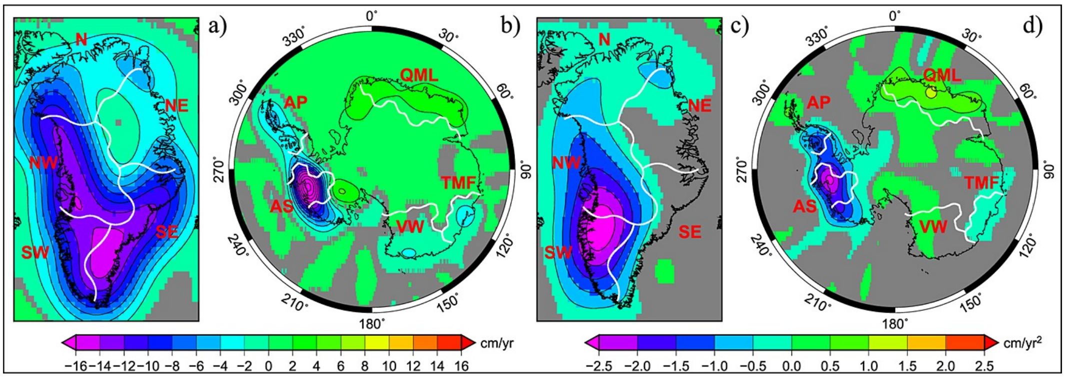


Figure 4.1: (a, b) GRACE-derived Greenland and Antarctica ice mass balance linear trends, dM(t)/dt, in cm/yr of water. (c, d) Accelerations, d2M/dt2, in cm/yr2 for January 2003 to December 2013. Contour interval is 2 cm/yr for the linear trend (Figures a and b) and 0.5 cm/yr2 for the acceleration (Figures c and d). White lines define regions for which time series are calculated in Figure .

record of cloud observations and surface radiation measurements they quantify the West Antarctic Ice Sheet (WAIS) radiation budget and investigate the meteorological link between clouds and the trends seen in the ice sheet.

Chapter 5

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.

5.1 Sea ice

5.1.1 Sea ice concentration

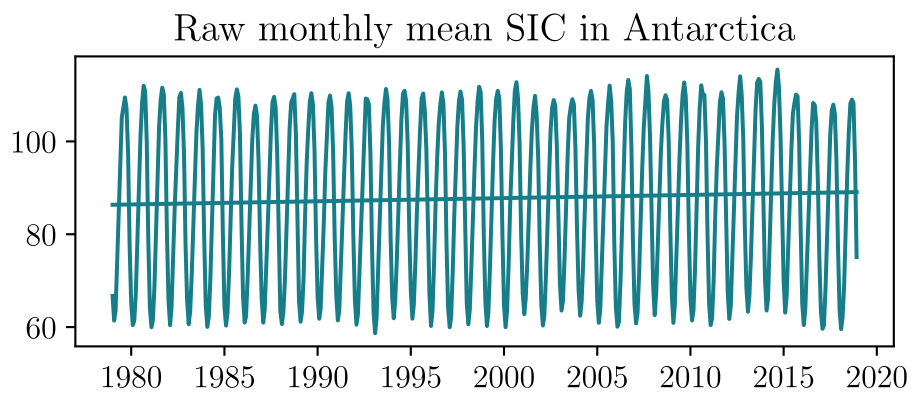


Figure 5.1: Raw mean Antarctic Sea Ice concentration from 1979 to 2019.[WIP update with new plot

5.1.2 Sea ice thickness

5.1.3 Sea ice volume

5.2 Land Ice

5.2.1 Land Ice thickness

5.2.2 Land Ice volume

5.3 Combined Ice dataset

5.4 Implications for further research

5.5 Limitations

Chapter 6

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 (SKT) as discussed before Write up different temperatures.

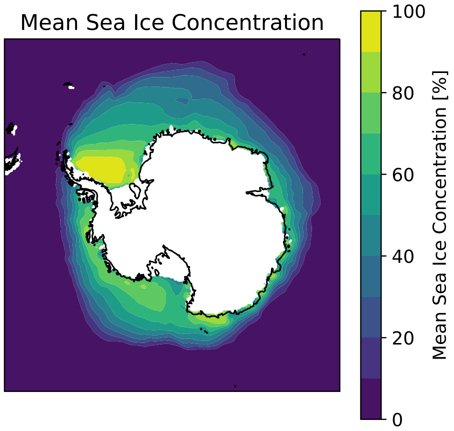
6.1 Temperature and ice anomalies

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

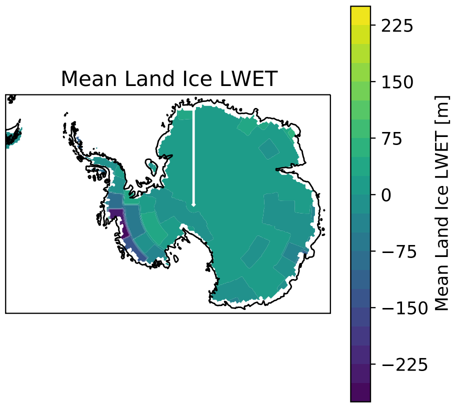
Let $y(t, x, y)$ be our time-series of measured values. x and y are spatial coordinates. For the purposes of this exercise the spatial coordinates are arbitrary as we apply the calculations separately for each time-series found at each location. For each month we take the average value of our variable 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 6.1).

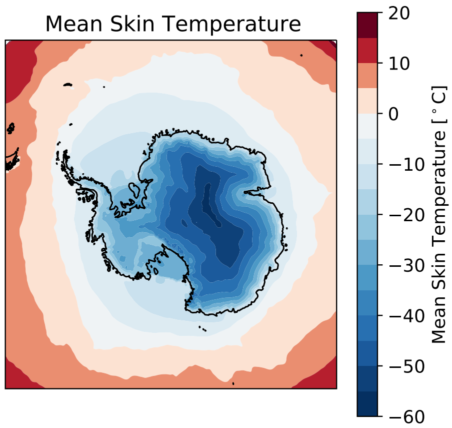
Below in figure 6.1 we have plotted the mean values of Sea Ice Concentration (SIC), SKT, and Land Ice Liquid Water Equivalent Thickness (LILWET).



(a) Mean SIC over Antarctica.



(b) Mean LILWET over Antarctica.



(c) Mean SKT over Antarctica.

Figure 6.1: Spatial distributions of the mean values of different variables used in this chapter.

Looking at these plots, it is worth noting that the mean SKT 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.

6.2 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. For this we will plot 4 2-dimensional histograms of

The top row contains all the gridpoints over land, the corresponding ice values being 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).

This plot (Figure 6.2) tells us an interesting story. For sea ice, we can observe a significant relationship between SKT 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.

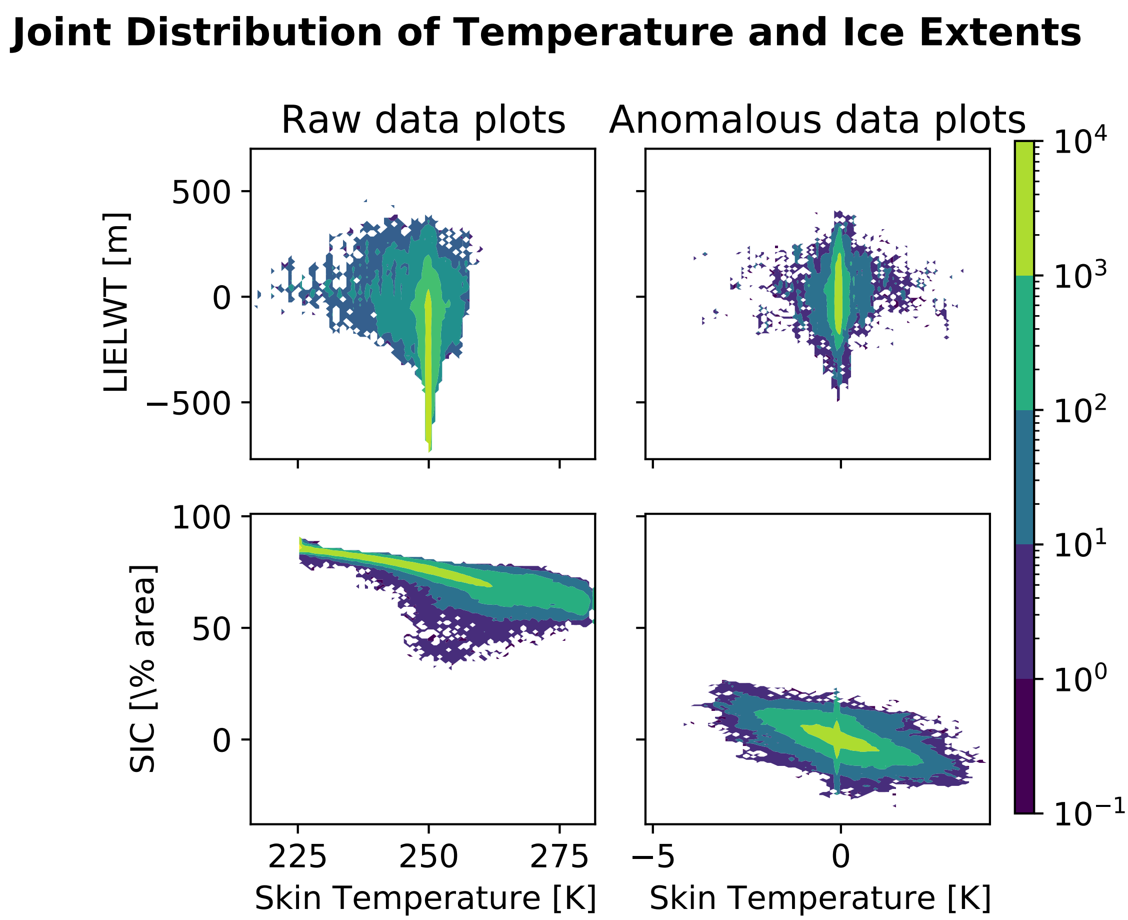
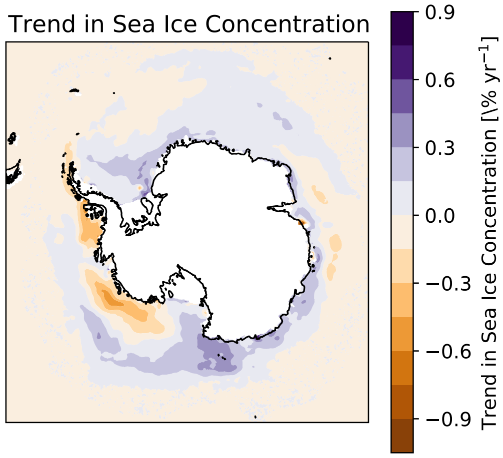


Figure 6.2: Distribution of SKT against ice. Colour represents the number of data points in our dataset with a given histogram box of temperature and ice amounts.

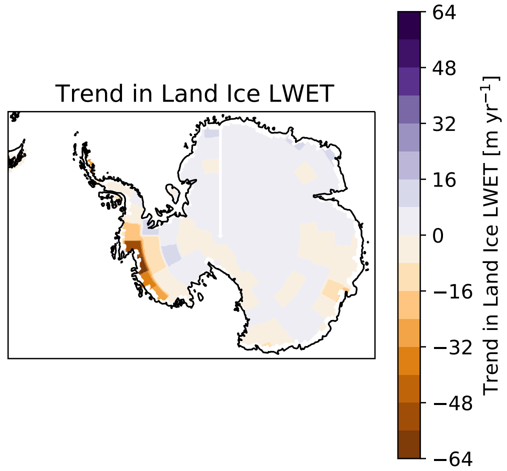
We can learn more about this relationship by looking at the spatial and temporal variability and trends for each of the variables.

6.3 Spatial distribution of trends in Antarctic ice and temperature

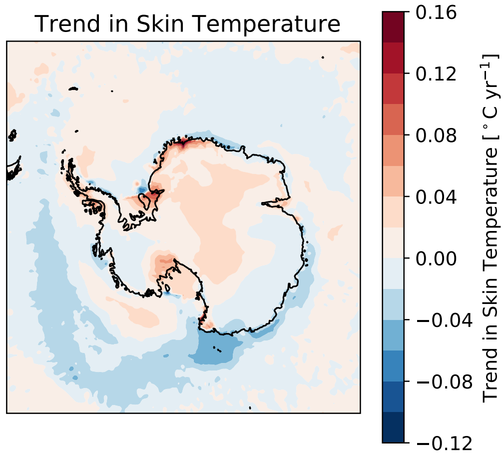
Our next step in unpacking the relationship between ice in Antarctica and temperature is to look at the trends we see in the different variables



(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 SKT over Antarctica.

Figure 6.3: Spatial distributions of the mean values of different variables used in this chapter.

Looking at these plots (Figure 6.3) 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 6.5 and 6.6). Before doing that however, we should look at the temporal variability in our variables to see if there are any notable similarities or differences.

6.4 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 6.4. 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. Looking at figure 6.4 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. Sea Surface Temperature (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 6.2 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 2m Temperature (T2M) are values for estimated temperature above any sea ice, and as such we expect SST to exhibit less variability than the other

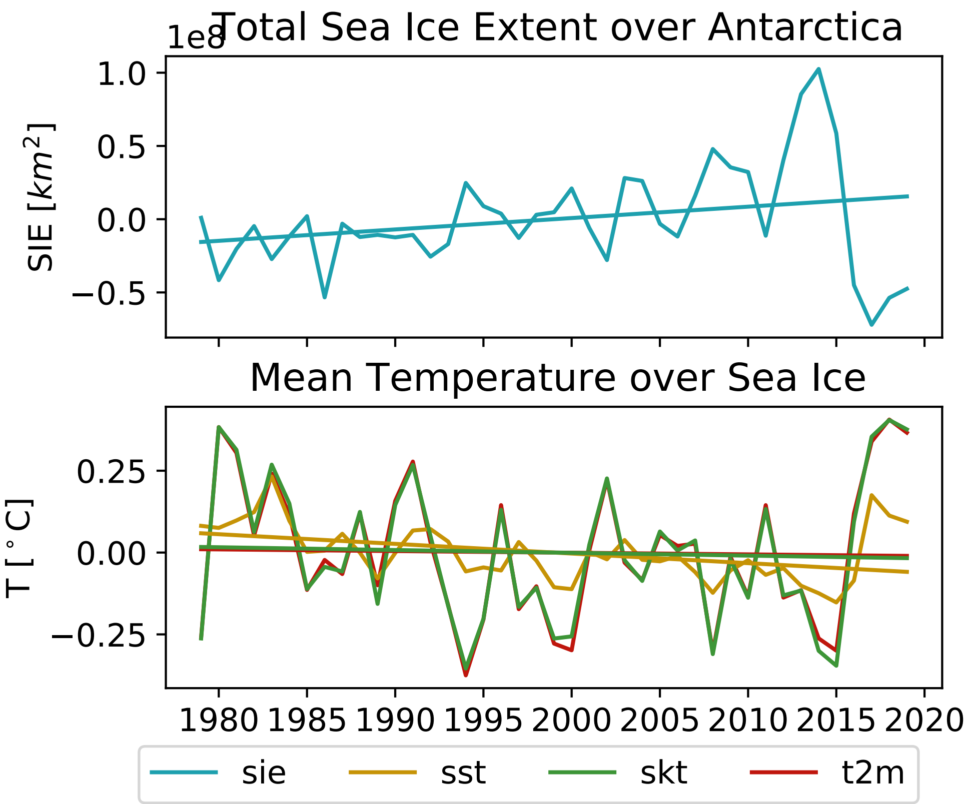


Figure 6.4: Time-series for the total SIE over Antarctica and the mean temperature over sea ice from 1979 to 2019.

measures of temperature whilst having similar patterns of variability. This is what we observe in figure 6.4.

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 6.5. 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.

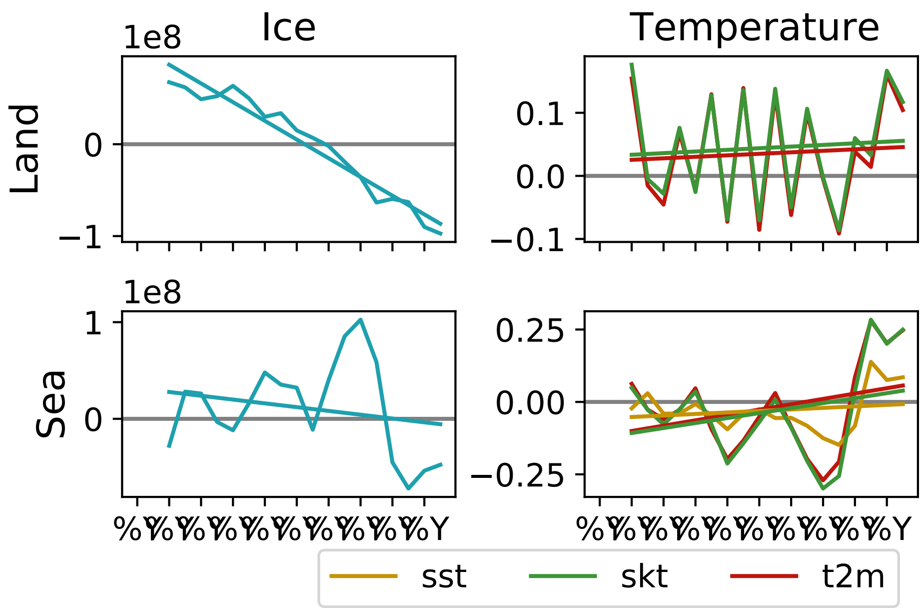


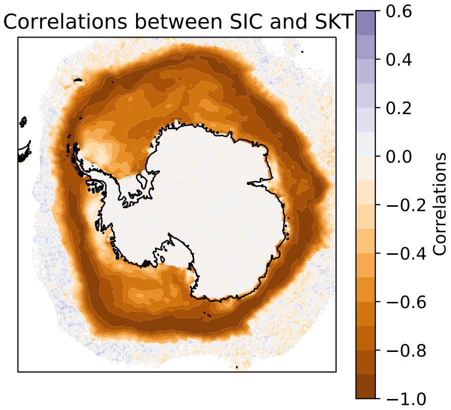
Figure 6.5: Time-series for the Ice and temperature quantities 2002 to 2019. The top row contains values over land, the bottom row contains values over the sea. The left column contains Ice variables (Land Ice Liquid Water Equivalent and Sea Ice Extent), and the second column contains plots for temperature.

6.5 Correlations

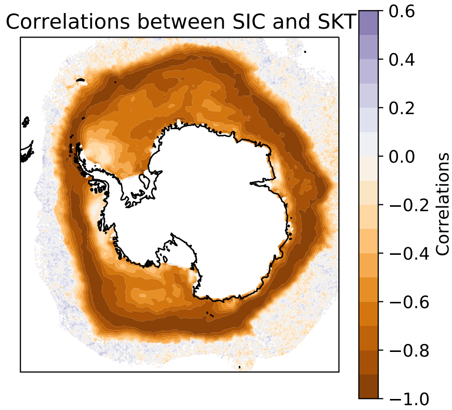
6.6 Regressions using temperature to predict Antarctic ice

6.7 Statistics for Antarctic ice and temperature

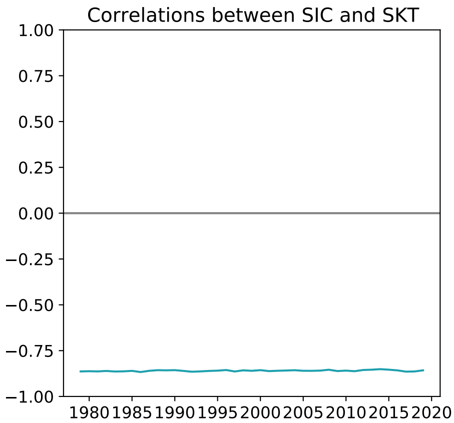
6.8 Implications for our understanding of Antarctic ice



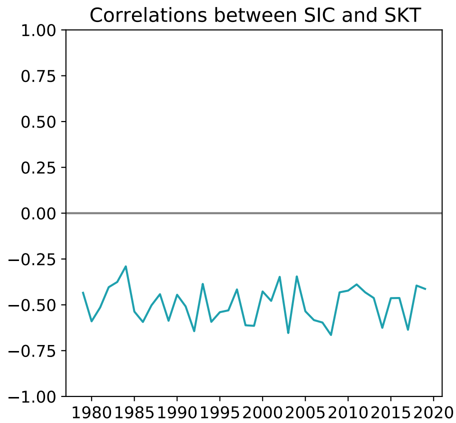
(a) Spatial distribution of correlations of SIC and SKT.



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



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

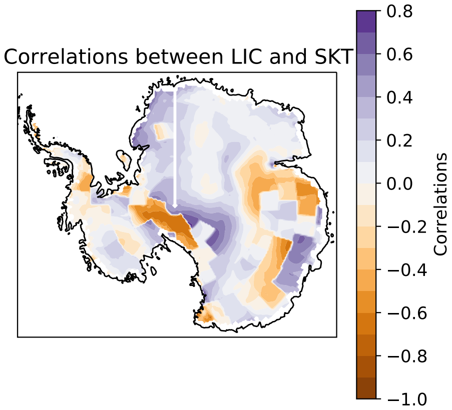


(d) Temporal distribution of correlations of anomalous SIC and SKT.

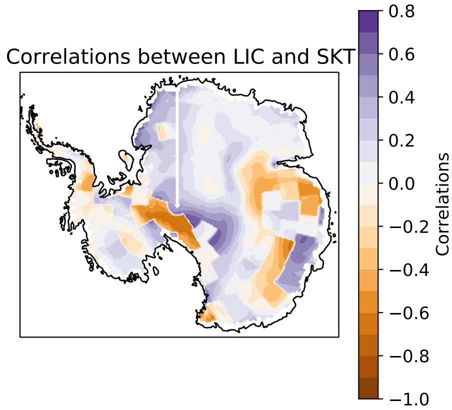
Figure 6.6: Correlations between SIC and SKT. The left column contains correlations for raw data time-series and the right column contains the correlations for anomalous time-series. The top row contains correlations for individual time series. The bottom row contains pattern correlations between the two variables and how that changes over time.

Things still to do for this Chapter

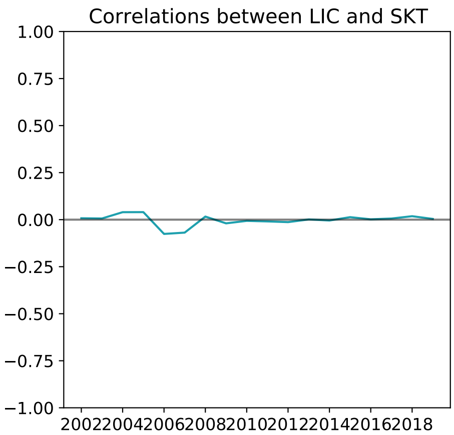
1. Correlations
2. Temporal Aggregations
    - Trend lines to ice.



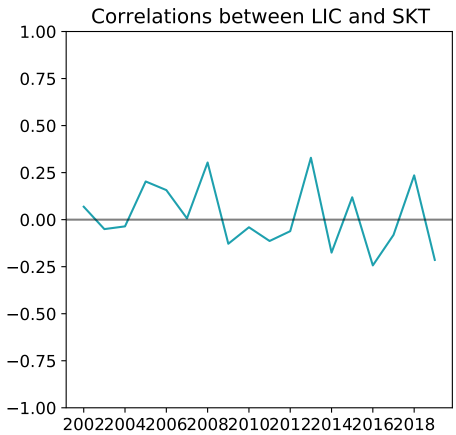
(a) Spatial distribution of correlations of LILWET and SKT.



(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 6.7: 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.

- 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.

Chapter 7

Drivers of Antarctic Land Ice

In chapter 6, we found that temperature is significant for our understanding of the trends in Antarctic SIC over the last 40 years. However we found that the relationship between temperature and land ice is not as strong. To understand this we will have to do some more calculations.

We want to consider a range of variables which could be impacting land ice in Antarctica. We will include temperature again for completeness. Wind speed is linked to atmospheric circulations which move clouds and thermal energy around the continent. Cloud cover has also been linked to behaviours in the land ice. add appropriate citations here.

Let's start by looking at the behaviour of land ice.

7.1 Land ice trends and variability

Figure 7.1: Mean value of LILWET from 2002 to 2019.

The simplest thing we can do at this point is to compare the mean time series of this with different variables.

7.2 Comparing land ice with different variables

For the first step in analysis here we plotted the mean values for both land ice and other environmental variables, considering only the grid points where we have data for land ice.

7.3

Chapter 8

Short term variability of Antarctic Ice and its drivers

Chapter 9

Conclusion

intro to conclusion chapter.

9.1 Summary of thesis

9.2 Implications for further research

9.3 Closing statement

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Supplementary Figures