The Shrinking of the West Antarctic Ice Sheet

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Key Points

- This paper investigates the West Antarctic Ice Sheet's susceptibility to rising global temperatures in recent years.
- The Community Earth System Model was used to model surface temperature, snow depth, and sea ice concentration over the West Antarctic Ice Sheet.
- Results show a correlation between all mentioned variables and can be used to make predictions about the stability of the ice sheet.

Abstract

With the rise of global warming, this research aims to see what rising temperatures means for the Antarctic --the largest ice mass in the world. This paper focuses on the western domain of the Antarctic. The melting of this ice body can lead to many consequences such as rising sea levels, which would cause the displacement of millions of people if it reaches high enough levels. This research aims to observe and project the stability of the ice sheet moving forward. The main variable in analyzing this is surface temperature, however, it is also important to take ice sheet depth, wind directions, and sea ice density into account when producing model output. With this model output, this research seeks an ultimate trend or proxy that explains the shrinking of the West Antarctic Ice Sheet and how these results will change or continue in the future.

Plain Language Summary

This research aims to find if there is a relationship between rising temperatures and the melting of ice sheets in Antarctica, the Earth's largest ice mass. The West Antarctic Ice Sheet is one of its biggest areas, and this study will uncover what will happen to its ice mass in the coming future. It will primarily use modeling technology, namely the Community Earth System Model (CESM) to analyze and compare the changes in the ice sheet over the years and use this information to produce model output that could predict its future. In doing this, one can uncover what factors other than climate change are causing the shrinking of this ice sheet, and what consequences will come if this trend is allowed to keep going. Understanding this trend and what affects this ice sheet change is crucial to predicting sea level changes. This will allow us to create mitigation strategies and spread awareness to communities, especially along the coastlines about the dangers of shrinking glaciers.

1 Introduction

The West Antarctic Ice Sheet (WAIS) has become a focal point for scientific study, especially in the context of its susceptibility to rising global temperatures and consequential impacts on sea level rise. This introduction provides a comprehensive overview of past research on the WAIS, positioning the study with respect to past work.

1.1 Modeling

When looking into modeling for the WAIS, it is necessary to first find what factors would be most beneficial in using one. Ferrari et al. (2020) dove into model resolution and boundary conditions in simulating Earth. Their findings suggest that optimizing resolution based on surface and water distinctions can enhance model efficiency. Additionally, the distinction between analysis and forecast data reveals the significance of accurate boundary forcing, a concept that is important for the study's modeling framework. This study highlights how exact regional boundaries and specific domains are quite tedious when it comes to truly getting accurate output. Global system models are a good solution and avoid potential mistakes or inefficiencies with using boundary forcing. CESM is a global system model that facilitates getting model output during research. Pollard and DeConto (2009) delve into the historical changes of the WAIS over thousands of years, providing insights into the factors influencing its growth and collapse. By integrating mass influx, scaled equations, and long-term trends, their model serves as a valuable resource for understanding past dynamics, which can be incorporated into modern simulations for predicting future changes. Another modern technology to incorporate into the CESM simulations is satellite data. Rignot et al. (2008) employ satellite data to observe recent Antarctic ice mass loss, particularly in response to climate change. The integration of radar technology highlights the increasing relevance of observational data in understanding the interactions between the WAIS and climate change. This approach aligns with this research's intention to reference existing models and observational data.

In many previous models for observing changes in ice sheets, there have been many numerical factors that have not been taken advantage of to create accurate and reliable models. However, Pattyn et al. (2017) explores the progress in numerical modeling of Antarctic ice-sheet dynamics, highlighting the integration of new technologies and factors once overlooked. Their emphasis on the evolution of modeling techniques resonates with the current intended approach, as the aim is to utilize these advancements to improve predictions of the WAIS's contribution to rising sea levels. This is especially relevant since over time, it has been shown that the WAIS's stability has worsened over time. Oppenheimer (1998) investigates the impact of global warming on the stability of the WAIS, predicting the consequences of its melting on sea levels. The paper not only serves as a reference for understanding the historical stability of the WAIS but also contributes valuable insights into predicting the timeline for climate-related impacts, which is a crucial aspect of this research.

1.2 Factors

Carbon dioxide emissions may be a big factor in determining ice sheet mass over the years, however, there are many more to account for to create accurate predictions. For example, ocean temperatures. Shepherd, Wingham, and Rignot (2004) contribute to the understanding of the warm ocean's role in eroding the WAIS. By utilizing satellite data, they analyze changes in surface elevation, emphasizing the interconnectedness of climate variables in influencing ice sheet dynamics. This approach aligns with this methodology, where one considers various factors, including oceanic influences, in this modeling and analysis. There is also the trend where the ice sheets have gone down but also up over the years, even with a constant trend of increasing global temperature. Alley and Whillans (1991) investigated this, and found that there are internal processes in the WAIS, revealing both thinning and thickening. Their study suggests that the near-future impact on global sea level is predominantly influenced by internal processes, rather than external climate-related changes. This underscores the importance of understanding internal factors in predicting the overall future behavior of the ice sheet. As ice sheets melt, they also erode the area around them affecting other ice sheets. This has implications over time, which is necessary to account for as well. Budd, Jenssen, and Smith (1984) looked into this, and presented a three-dimensional time-dependent model of the WAIS, incorporating variables such as melting speed and gravitational effects. This model's detailed analysis of ice sheet dynamics serves as a foundational reference for this modeling, providing insights into the complex interactions influencing the WAIS.

1.3 Ice Sheet Trends

When analyzing data over the years about the WAIS, there appears to be trends in the ice sheets based on its interactions with factors over the years. For example, the last global cycle caused a portion of the WAIS to thin in some spots and thicken in others. This can be linked to the ocean forcing this interaction. Alley et al. (2015) discuss the primary control exerted by ocean-ice interactions on the WAIS, emphasizing threshold behavior in response to increasing marine melting. Their work highlights the potential for rapid and delayed shifts to a reduced state, with significant implications for sea-level rise. The uncertainties surrounding these thresholds underscores the challenges in predicting the worst-case scenario. There also comes the ice stream flow as ice sheets melt over time, leaving spots in the WAIS vulnerable. Hughes (1981) explores the vulnerability of the WAIS, particularly its weak underbelly, to various destabilizing factors. The article's use of numerical models to calculate changes in ice density furthers understanding of the intricate processes leading to ice sheet disintegration.

1.4 Goal

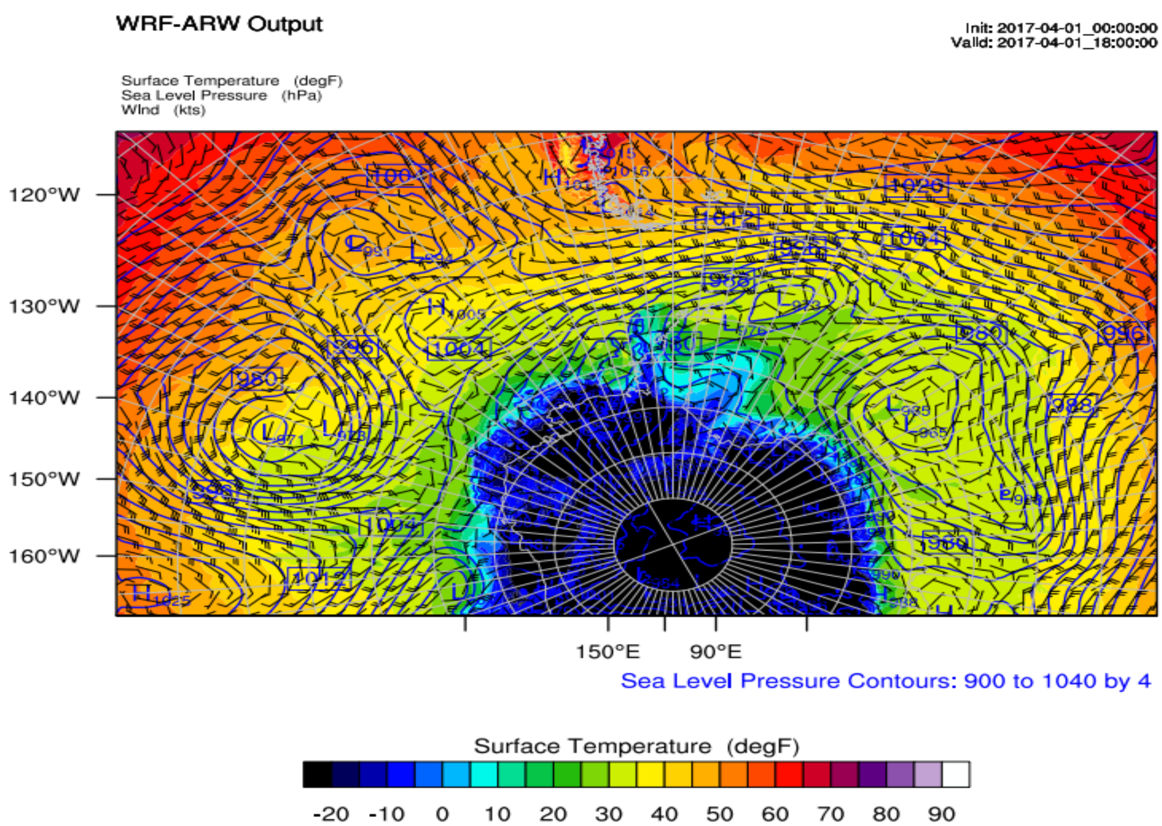
This research aims to build upon these foundations, using advanced modeling techniques to generate output of the WAIS in the face of climate change. Being able to find correlations between multiple variables over the WAIS will be crucial to applying these correlations to ice sheet mass trends. By considering historical trends, observational data, and integrating various climate variables, this study contributes to the ongoing dialogue surrounding the impacts of global warming on the WAIS.

2 Data, Materials, and Methods:

Aside from the output displayed in Figure 1, this research employed Community Earth System Model version 2.1 (CESM2.1) to simulate the dynamics of the WAIS. To conduct simulations pertinent to this study, Cheyenne, a high-performance computing system, was employed to run CESM simulations. The scope of the model encompassed latitudes ranging from -90 to 90, hence the global model, and longitudes from -55 to 55, specifically targeting variables such as Ice Sheet Surface Temperature and Sea Ice Concentration. The Weather Research & Forecasting Model (WRF) was used to generate model output for Surface Temperature, Sea Level Pressure, and Wind. In order to assure an accurate simulation, precise boundary forcing and physics manipulation was incorporated in the modeling. The data for the study was sourced from servers hosted by the National Center for Atmospheric Research (NCAR). Python served as a vital analytical tool throughout the research, aiding in the refinement and enhancement of visualizations derived from CESM model outputs associated with the behavior and dynamics of the WAIS. This utilization of Python was instrumental in comprehending the intricate dynamics of the ice sheet and its broader implications within the context of climate change. Within the CESM framework, the research utilized specific commands tailored for this study, employing the T1850G compset and a resolution set to f_19_g17_gl4, corresponding to a global spatial resolution of 2 degrees by 2 degrees. The T1850G compset is used due to its high-resolution functionality and compatibility with the Community Sea Ice Model (CSIM).

3 Results:

Figure 1

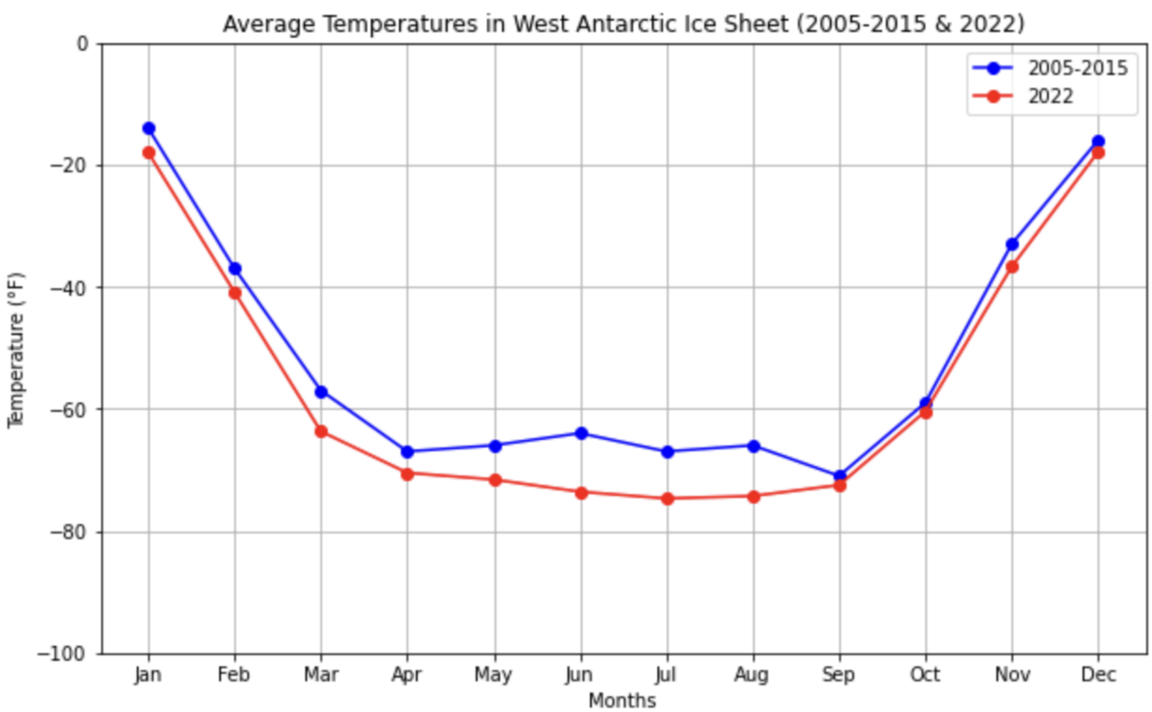


This model was generated through running a WRF program through Cheyenne. In order to achieve this, there had to be edits to the &time, &domain, and &physics sections. This specific output compares the temperatures of the WAIS between 2017-04-01 00:00:00 to 2017-04-01 18:00:00, and also how wind and sea level pressure may affect the ice mass. The domain section was specifically edited using the corner coordinates 55^{o}W 77^{o}S ; 55^{o}W 62^{o}30'S ; 105^{o}W 62^{o}30'S ; 105^{o}W 77^{o}S to show the Western section of the Antarctic. To accommodate the fact that this is an arctic domain, $physics was edited to specific parameters for this polar case.

This graph shows surface temperature, sea level pressure, and wind over the WAIS and surrounding ocean on 2017-04-01. This model output shows how the ocean water temperature affects the WAIS ice sheets.

This model includes sea level pressure. This shows wind directions and can be compared to the surface temperature output. Wind moves from high to low pressure. If the wind is coming from the sea, it will be warmer air and can cause melting in the ice sheet and sea ice. If wind is coming from the inner ice sheet, it will be colder and can lead to increased sea ice concentration and ice sheet volume.

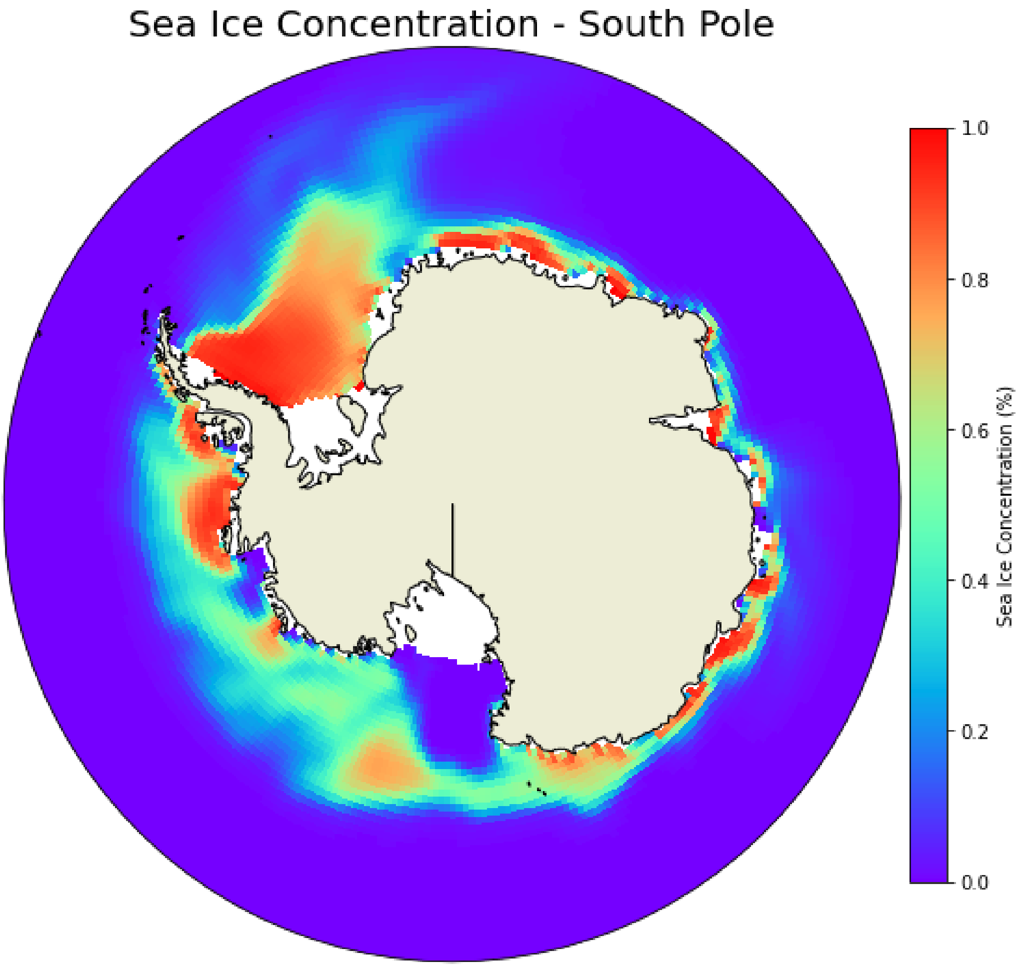
Figure 2



The generated plot illustrates the average temperatures in the WAIS during the period of 2005-2015 and specifically for the year 2022. It employs Matplotlib to display the data using distinct line graphs for each dataset. The blue line graph represents the average temperatures from 2005 to 2015, with temperature values ranging from approximately -14°F to -16°F across the months. Simultaneously, the red line graph represents the average temperatures in 2022, depicting a broader temperature range from around -18°F to -75°F throughout the year. The x-axis displays the months of the year (January to December), while the y-axis shows temperature values in degrees Fahrenheit.

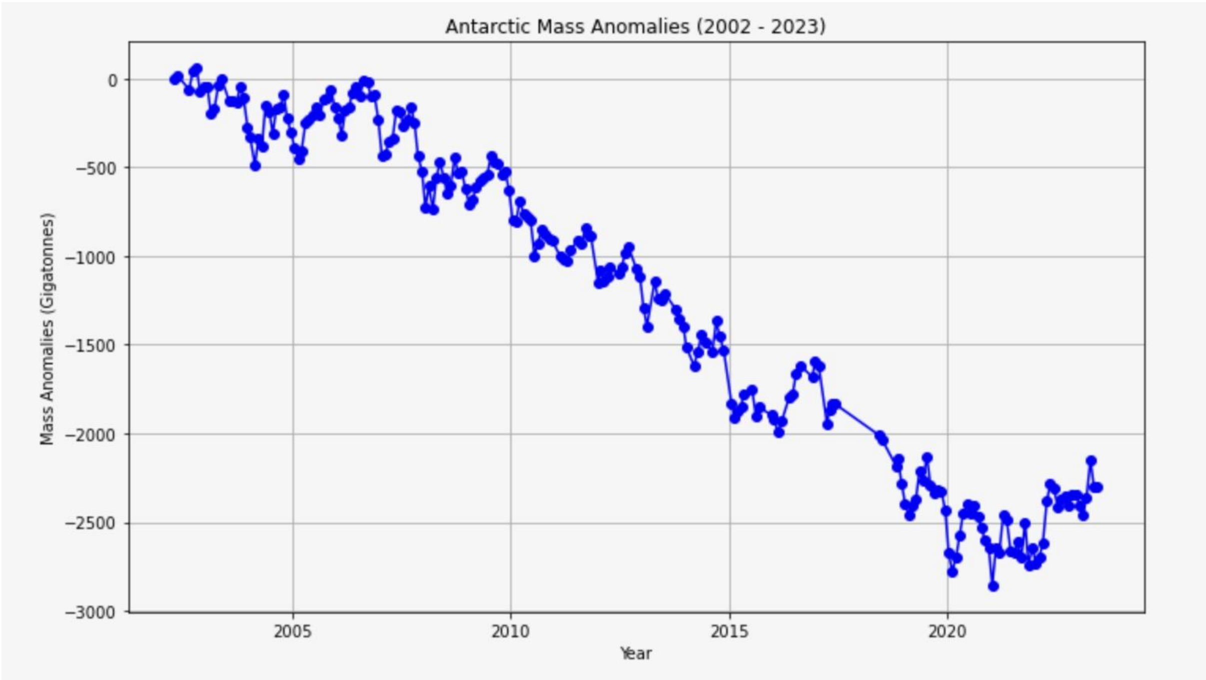
The plot offers a comparative view of temperature trends between the selected periods, allowing observation of potential variations in temperature within the WAIS over time. The gridlines enhance readability, and the legend clarifies the distinction between the datasets, aiding interpretation. The plotted data aids in understanding the temperature fluctuations in the WAIS across different periods, offering insights into potential climate variations over the years.

Figure 3



The figure is a polar stereographic plot representing sea ice concentration in the South Pole region using Matplotlib and Cartopy libraries. This visualization utilizes a circular boundary to denote the South Polar Stereographic projection and incorporates land features for context. The plot depicts the first time-slice of sea ice concentration data over the region, utilizing a color gradient ('cmap='rainbow'') to indicate varying concentrations. The color bar displays the range of sea ice concentration percentages, aiding interpretation. The latitude/longitude boundaries for the South Pole region are set accordingly, offering a focused view. This visualization technique effectively presents the spatial distribution of sea ice concentration in the South Pole area, enabling observation of the initial snapshot and potential variations over time, crucial for understanding the dynamics of polar sea ice.

Figure 4



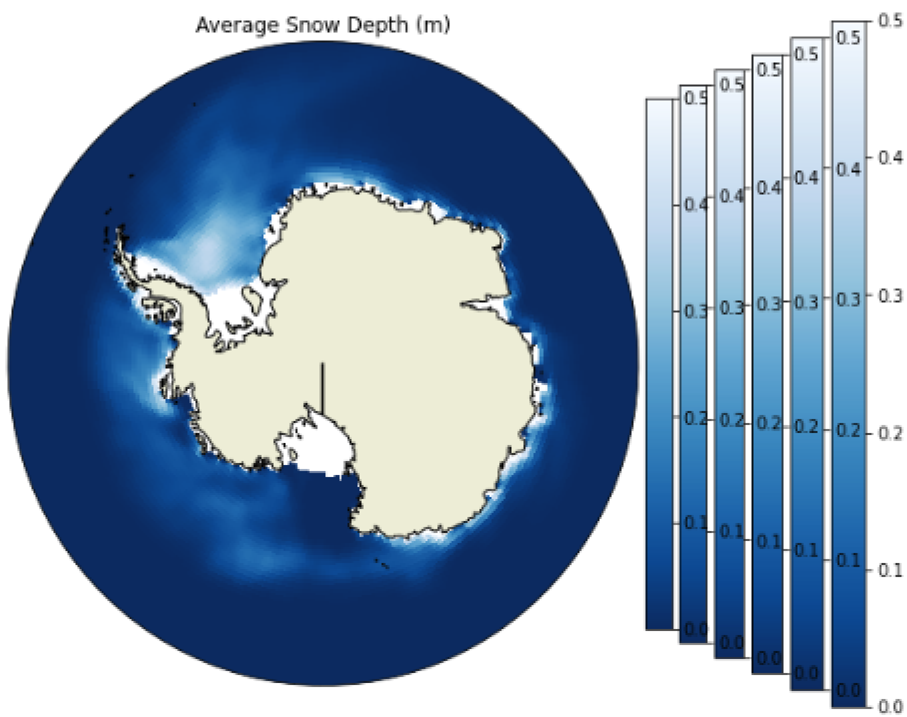
Script:

```
data = [
    [2002.29, 0.00, 178.90],
    # ... (all the data)
    [2023.45, -2298.12, 64.28]
]

# Extracting columns from the data
years = [row[0] for row in data]
mass_anomalies = [row[1] for row in data]

# Creating the line graph
plt.figure(figsize=(10, 6))
plt.plot(years, mass_anomalies, marker='o', linestyle='-', color='b')
plt.title('Antarctic Mass Anomalies (2002 - 2023)')
plt.xlabel('Year')
plt.ylabel('Mass Anomalies (Gigatonnes)')
plt.grid(True)
plt.tight_layout()

# Show plot
plt.show()
```

The provided Python code uses Matplotlib to showcase annual fluctuations in Antarctic mass anomalies from 2002 to 2023. This dataset comprises three columns: decimal-year values indicating time, recorded Antarctic mass anomalies measured in gigatonnes, and their corresponding measurement uncertainties. This data has been taken from NASA. The code organizes the data into separate 'years' and 'mass_anomalies' lists, facilitating the creation of a line graph using 'plt.plot()' to illustrate mass anomalies against time. Stylistic attributes like 'marker', 'linestyle', and 'color' enhance the graph's clarity, while labels ('xlabel', 'ylabel') and gridlines ('plt.grid(True)') aid interpretation.

This graph visually represents annual changes in Antarctic ice mass, crucial for understanding WAIS dynamics and predicting sea-level rise. By delineating shifts in ice mass due to melting or accumulation, these anomalies provide vital insights into WAIS stability and behavior, fostering a better comprehension of ongoing trends in the Antarctic ice sheet.

Figure 5



The figure illustrates a polar stereographic circular plot depicting the average snow depth across grid cells in the Antarctic region. Utilizing Matplotlib and Cartopy, the plot highlights variations in snow depth, showcasing the average snow depth distribution across the area. Employing a circular boundary to denote the South Polar Stereographic projection and integrating land features, the plot effectively visualizes the spatial patterns of average snow depth. The color bar aids in interpreting snow depth levels. This visualization provides valuable insights into the average snow depth across the Antarctic grid cells, offering a comprehensive perspective on the region's snow accumulation patterns.

4 Conclusions:

Before 2000, it was marked that the WAIS was growing, with potential instability appearing in some model outputs (Oppenheimer, 1998). With the observable (Figure 2) higher averages of summer temperatures between 2005 and 2015, the stability of the ice sheet is at question. This increase in temperature is potentially due to the increase in CO2 in the atmosphere. However, it is observed in Figure 2 that the summer temperature in the WAIS in 2022 was lower and more constant compared to the 2005-2015 average. This is potentially due to the decrease in carbon emissions during the COVID lockdowns mainly in 2020 and partially in 2021. In Figure 1, it can be observed that the surface temperature around the WAIS is colder where there is more edge surface area. This is also observable in Figure 3 and Figure 5, where the sea ice concentration and average snow depth is higher around the WAIS. Figure 1 shows higher sea level pressure in the sea south of the WAIS (left side) and lower sea level pressure in the sea north of the WAIS (right side). This means wind is coming from the sea into the WAIS from the south and coming out from the WAIS to the sea in the north. This observation matches the results of Figure 3, showing greater sea ice concentration in the north and lesser sea ice concentration in the south. After connecting each variable, it is crucial to mark the connection between Figure 2 and Figure 4. The greater average temperatures between 2005-2015 correlates with decreasing Antarctic mass during the same time frame. Looking then to 2022, when temperatures in the WAIS were lower than 2005-2015 (Figure 2), the Antarctic mass is on a positive increase that began around 2021 (Figure 5). It is likely that the COVID lockdowns, leading to fewer CO2 emissions, leading to more stable temperatures, can have led to a more stable ice sheet. It must be noted that determining the true stability of the WAIS is difficult because major changes take ~10,000 years to take noticeable effect (Oppenheimer, 1998).

Future Work:

Future work includes continuing to analyze the effects of CO2 emissions on the WAIS in the future. Additionally, it will be crucial to track how this research's variable data changes over the course of the next decade. Next, further comparing these findings to previous records and predictions will strengthen the confidence in the result output figures. Lastly, determining if the data of the examined variables followed a specific trend post-lockdown will strengthen the conclusion of this research.

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Figure 1. WRF 2017-04-01 TIME surface analysis (a) with T2 in Fahrenheit, (b) sea level pressure in hPa, and (c) wind barbs in kts.

Figure 2. Average Temperature Analysis: Comparison between 2005-2015 and 2022 (a) showcasing months on the x-axis and (b) temperature in Fahrenheit on the y-axis.

Figure 3. CESM Sea Ice Concentration Analysis (a) displaying sea ice concentration with a color bar representing the concentration levels.

Figure 4. Antarctica Mass Anomalies Analysis: Line graph of the anomalies in antarctic mass from 2002-2023 (a) with year on the x-axis and (b) mass anomalies on the y-axis.

Figure 5. CESM Avg Snow Depth Analysis (a) displaying average snow depth with a colorbar with shades blue representing depth in meters.