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Utilising ARIMA models to predict the mass balance of the Antarctic ice sheet and comprehend its fluctuations

Yijun Gao

Maths School, University of Birmingham, Birmingham, B15 2TT, United Kingdom

yxg199@student.bham.ac.uk

Abstract. The mass balance of the Antarctic Ice Sheet is forecasted in this study using ARIMA models, with a particular emphasis on the distinct regions of East and West Antarctica. The research endeavours to forecast the trends in ice mass balance over the next 12 years by examining data from 1992 to 2021, thereby elucidating the potential impacts of climate change on these critical regions. The ARIMA model, which is renowned for its capacity to capture and predict time series data, has identified substantial trends that indicate a persistent loss of ice mass, particularly in West Antarctica, which has experienced substantial declines in recent decades. The model's predictions suggest that, despite the potential for a reduction in the rate of loss, the overall trend is consistent with the ongoing reduction of ice mass. These results underscore the pressing necessity for ongoing research and monitoring to gain a more comprehensive understanding of the consequences of these developments. The study also emphasises the necessity of enhancing predictive models by incorporating supplementary environmental variables to provide more comprehensive insights into the future of the Antarctic Ice Sheet and its global impacts, thereby increasing their accuracy.

Keywords: Antarctic ice sheet, ARIMA models, mass balance forecasting, climate change impact.

1. Introduction

The melting of glaciers is a significant environmental crisis that necessitates an immediate response due to global warming. Antarctica is the southernmost continent on Earth, spanning nearly all longitudes and primarily located south of 60 degrees south latitude. It encompasses 14 million square kilometres and is one of the seven continents. Antarctica, which spans 12 million square kilometres and is 50% larger than the United States, is abundant in water [1, 2]. In Antarctica, the summer temperature rarely exceeds -20°C, while winter temperatures can drop to below -80°C. Most locations are covered by ice sheets that are 1.9 kilometres thick, which contain 60% of the world's fresh water. Antarctica, which spans 12 million square kilometres and is 50% larger than the United States, is abundant in water [2]. In recent years, Antarctica has experienced an increase in positive temperature anomalies [1].

What is the cause of the melting of Antarctica? In a warmer climate, the Antarctic ice sheet would not melt unless global temperatures rise by at least 4–5°C, precipitation on the continent would increase due to ocean evaporation, and the ice sheet would only grow and gain mass, according to simplified numerical ice sheet models that are influenced by global climate simulations [2]. This notion has been prevalent for decades [3]. However, there has been an increasing body of evidence suggesting that the

Antarctic ice sheet is not expanding and is not in mass equilibrium since 1998 [4, 5]. Substantial, independent studies have validated this concept in the past 3–4 years by measuring the mass balance of the ice sheet (i.e., whether it is increasing or decreasing) using a variety of methods [6, 7]. As the ice sheets lose bulk to the ocean, Antarctica is melting rapidly, as evidenced by these research and surveys.

The melting of ice will undoubtedly have a variety of consequences. To provide further clarification, the melting of glaciers will result in an increase in sea levels and the initiation of a sequence of events. Ocean circulation is disrupted by the melting of glaciers into the ocean. This could potentially harm the marine ecosystem by altering the salinity and temperature of the water [8, 9]. Secondly, the thawing of glaciers will result in the release of substantial quantities of greenhouse gases, including carbon dioxide and methane, which will contribute to the acceleration of global warming [10]. The melting of glaciers will result in an increase in surface temperatures, which will accelerate the melting process and establish a vicious cycle. The complexity and urgency of climate change are exacerbated by chain reactions.

Autoregressive Integrated Moving Average Models (ARIMA Models), which are frequently employed to forecast and analyze time series values, are among the most effective statistical tools [11]. This will be described in the Methods and Materials section, which will also compare the ARIMA to other models.

The ARIMA model is employed in the article to forecast the mass balance of the ice sheets over the next 12 years, thereby revealing potential impacts on this critical region. The findings and observations should have a significant impact on future research and policy-making, emphasizing the importance of prediction methodologies and promoting environmental preservation.

2. Methodology

2.1. Data source

The article estimates the total mass change, uncertainty, and mass change rates of the Antarctic Ice Sheet by utilizing databases from the UK Polar Data Centre [12]. Mass balance estimations from satellites are reconciled through the use of input-output methods, gravimetry, and altimetry (Table 1).

Table 1. An example of datasets that includes four components that illustrates the bulk of the ice sheet

Year	Mass balance (Gt/yr)	Mass balance uncertainty (Gt/yr)	Cumulative mass balance (Gt)	Cumulative mass balance uncertainty (Gt)
1992	22.5333	127.4965	1.8778	36.8051
1992	22.5333	127.4965	3.7556	52.0502
1992	22.5333	127.4965	5.6333	63.7483
1992	-138.422	118.0717	-5.9018	72.2882
1992	-138.422	118.0717	-17.437	79.9208
1992	-63.229	102.8949	-22.7061	85.2620
1993	-63.229	102.8949	-27.9752	90.2878
1993	-63.229	102.8949	-33.2442	95.0483
1993	-63.229	102.8949	-38.5133	99.5814
1993	-63.229	102.8949	-43.7824	103.9169
1993	-63.229	102.8949	-49.0515	108.0787
1993	-63.229	102.8949	-54.3206	112.0861

The extensive original datasets consist of West Antarctica, East Antarctica, the Antarctic Peninsula, the Greenland Ice Sheet, and their aggregate between 1992 and 2020. Furthermore, Gigaton (Gt) and micrometre (mm) are units of measurement. Locations and units are illustrated as the important elements. Additional precise discoveries. The illustration considers West and East Antarctica in accordance with their respective sizes. while serving as Gigaton.

The file 'imbie_all_2021_Gt.csv' is used to illustrate data processing. Initially, the table 1 displays four components that illustrate the bulk of the ice sheet. The article exclusively focuses on mass balance (Gt/yr) for prediction purposes, as it clearly analyses the yearly change in mass balance, rendering it the most critical statistic for predicting future trends. This variable is crucial for prognosis because it reveals the immediate dynamics of mass gain or loss. The annual mass balance is more sensitive and transparent for modelling and predicting ongoing changes, despite the fact that cumulative measurements may reduce short-term fluctuations. Additionally, it streamlines the prediction model by emphasizing a single critical variable. The prediction variable "Mass balance (Gt/yr)" provides a variety of advantages over other variables. The "Mass balance (Gt/yr)" is a critical factor in predicting the development status of glaciers or ice, as it directly reflects fluctuations in ice mass. Nevertheless, the "Mass balance uncertainty (Gt/yr)" metric only denotes the accuracy or error range of the mass balance, not the changes in ice mass. In contrast to "Mass balance (Gt/yr)," "Cumulative mass balance (Gt)" is a historical accumulation of mass balance. It is beneficial for comprehending long-term trends, but it is less precise for short- or medium-term predictions. Additionally, the cumulative mass balance error is quantified by the "Cumulative mass balance uncertainty (Gt)" metric. It is necessary to assess the accuracy of the model, despite the fact that it does not immediately predict changes in ice mass. Therefore, "Mass balance (Gt/yr)" is a predictive variable that is particularly useful for prediction applications due to its ability to rapidly display yearly glacial mass fluctuations. Uncertainty and cumulative balance are becoming increasingly significant in the context of long-term trend analysis and result evaluation.

Another distinction is that decimals are used to represent months, and the values of neighbouring mass balances are identical. January and February are associated with 1992 and 1992.0833, which have a mass balance of 22.5333. To solve it, divide it by the number of mass balance values that are associated with the same year without decimals. In 1992, the mass balance was 22.5333, -138.422, and -63.229, as illustrated in the table 2. Although the value of a single month is processed to be more comprehensible, disregarding it can result in misvalues and issues in the final results, as will be elucidated in the discussion.

Table 2. The dataset after the processing and optimisation

Year	Mass Balance (Gt/yr)	Mass Balance Uncertainty (Gt/yr)	Cumulative Mass Balance (Gt)	Cumulative Mass Balance Uncertainty (Gt)
1992	22.5333	127.4965	1.8778	36.8051
1992	-138.422	118.0717	-5.9018	72.2882
1992	-63.229	102.8949	-22.7061	85.262
1993	-63.229	102.8949	-27.9752	90.2878
1993	-104.549	103.9689	-63.033	116.0348
1994	-104.549	103.9689	-115.308	137.3639

2.2. Model introduction

Error Trend and Seasonality Models (ETS), Autoregressive Integrated Moving Average Models (ARIMA), and Long Short-Term Memory Models are among the numerous statistical strategies [13]. The context of the forecast, the availability of historical data, the threshold for model accuracy or inaccuracy, the time period, the cost to the company, the value/benefit, and the time required to complete the analysis are all factors that must be taken into account when selecting a time series forecasting method.

The ARIMA Model, which stands for Auto-Regressive Integrated Moving Average, is a potent instrument for forecasting time series [14]. It is frequently employed to forecast and analyze future values by utilizing historical data. Three critical components are integrated into the model:

Autoregression (AR): This component encapsulates the relationship between an observation and a number of lagged observations (i.e., prior values in the time series). The autoregressive process in ARIMA models the dependence of the current value on its previous values [15].

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Integration (I): This process entails the differencing of the data to achieve stationarity, a critical component of dependable time series forecasting. Stationarity refers to the fact that the statistical properties of the time series, including the mean and variance, remain consistent over time. Differencing is the process of stabilizing a time series by removing seasonal structures or trends by subtracting the current observation from the previous one.

Moving Average (MA): The moving average component represents the relationship between a residual error and an observation in a moving average model that is applied to lagged observations. In essence, it smooths the data by averaging out the fluctuations over a specific number of prior periods, thereby reducing the impact of random noise or errors in the data.

For example, if there is a time series Y_t that is applied an ARIMA (1,1,0) model, the series would be firstly differed:

$$Y_t^{'} = Y_t - Y_{t-1} \tag{1}$$

Then, the AR (1) model would predict the current value $Y_t^{'}$ based on the previous value $Y_{\{t-1\}}^{'}$ using the equation $Y_t^{'} = \alpha + \phi Y_{\{t-1\}}^{'} + \epsilon_t$, where α is a constant, ϕ is the coefficient for the lagged term, and ϵ_t is the error term.

In summary, the ARIMA Model integrates these three components to predict and model time series values. The autoregression order, degree of differencing, and moving average order (p, d, q) are frequently used to represent the ARIMA configuration [16]. The ARIMA Model is a forecasting tool that is widely used and versatile due to its ability to be customized to various time series data.

3. Results and discussion

3.1. East Antarctica

The results and analysis of the Antarctica forecast, as well as comparisons, will be included in this section. To start with, the east Antarctica, the largest part, has the greatest influence in the melting of the glaciers. The figure 1 is shown in the below.

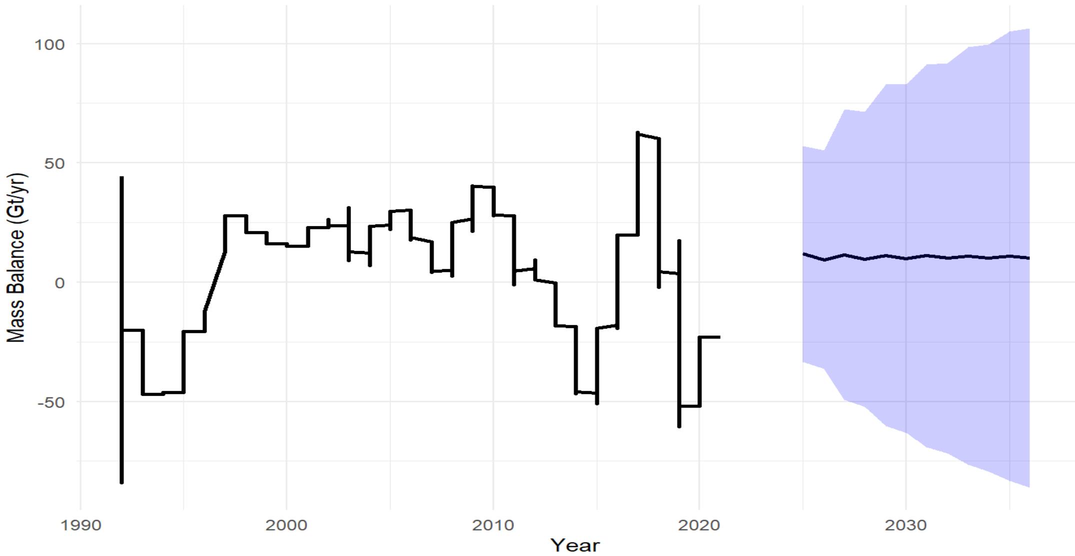

Figure 1. The forecast results of the Mass Balance in East Antarctica by ARIMA

ARIMA's East Antarctic mass balance projection is illustrated in this figure. The black line illustrates substantial mass balance fluctuations from 1990 to 2020. Occasionally, there are substantial positive and negative deviations from the zero-oscillating trajectory. Mass equilibrium is typically maintained within a restricted range; however, oscillations may occur. The uncertainty range, which is typically a 95% confidence interval, is depicted in the blue shaded region, while the predicted mean values are represented by the black line, which commences around 2025. Mass balance is anticipated to remain relatively stable over the next decade. A high degree of uncertainty suggests that the actual values may vary significantly, despite the apparent consistency of the projected mean trend.

3.2. West Antarctica

The figure 2 is shown below, which is the forecast results for the West Antarctica.:

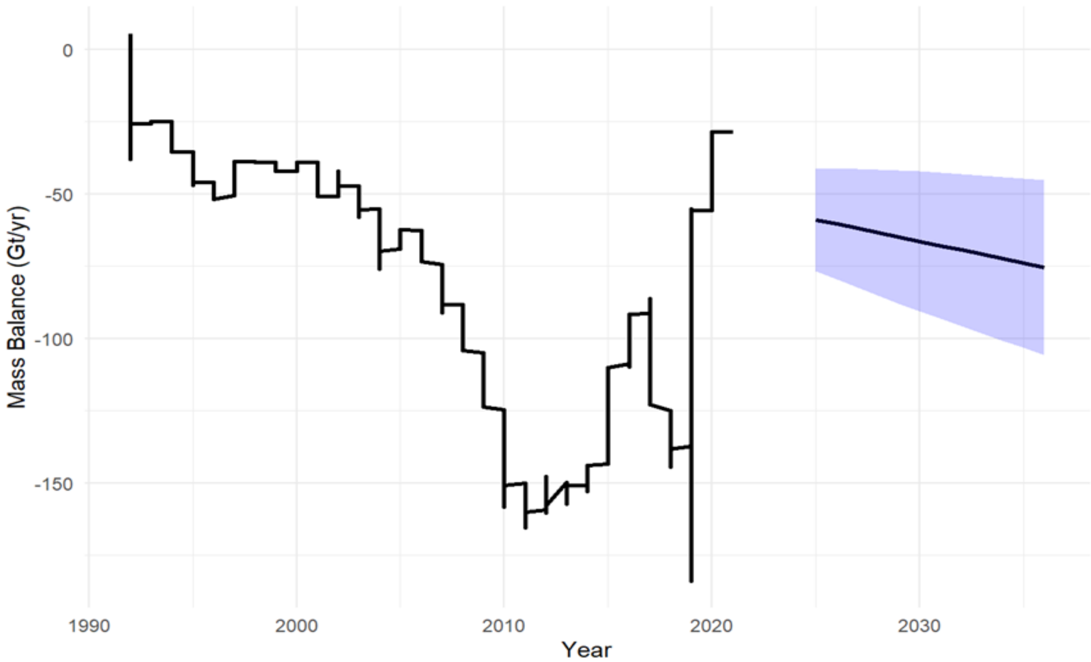

Figure 2. The forecast results of the Mass Balance in West Antarctica by ARIMA

From 1990 to 2020, the mass balance has experienced a substantial decline, as illustrated in the figure 2. The mass balance (in Gt/yr.) has steadily decreased, suggesting that West Antarctica is losing ice mass. Mass balance values below -150 Gt/yr were observed in numerous periods, particularly in the late 1990s and early 2000s, which indicates a significant loss of ice. The prediction anticipates further ice mass loss by assuming a slight continuation of the declining trend. The projected line's flatter slope than the preceding dip implies that ice loss may decrease over time. The confidence interval broadens as the forecast progresses, indicating an increase in uncertainty. The uncertainty indicates that the mean prediction predicts a consistent decline; however, subsequent values may stabilize or decline more rapidly.

To conclude, the necessity of exercise is underscored by the increasing confidence interval, as future environmental changes or unforeseen events may significantly impact mass balance. The necessity of caution is emphasized by the expansion of confidence intervals, as future environmental changes or unforeseen events could have a significant impact on mass balance.

3.3. Model evaluation

ARIMA (1,1,0) is applied for this model as a fundamental method. Three diagnostic plots for East Antarctica residuals from an ARIMA (1,1,0) model are depicted in the Figure 3 below.

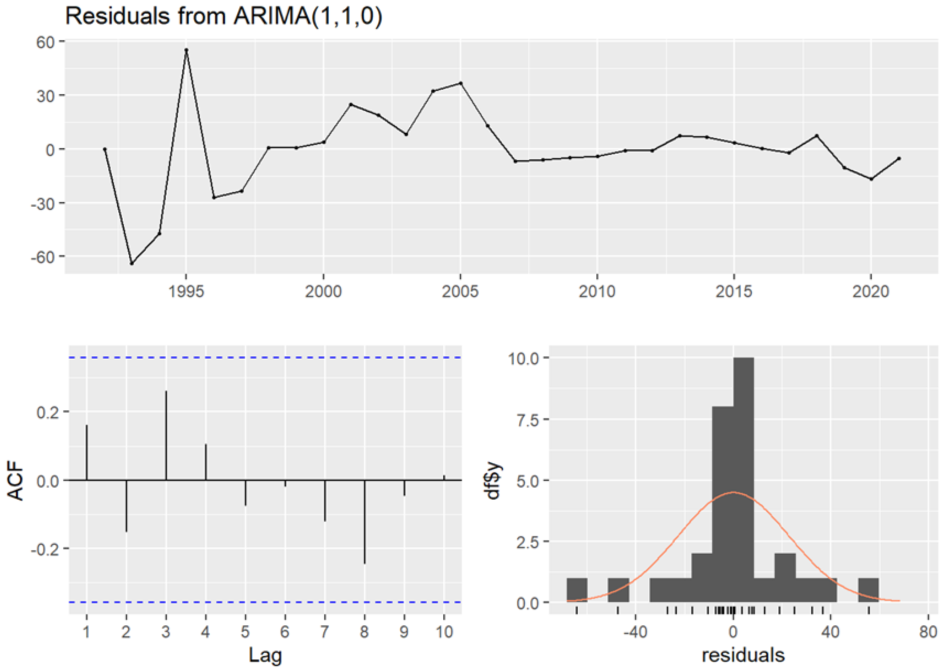

Figure 3. The Residuals Plots for the East Antarctica by the ARIMA(1,1,0)

The top plot displays the residuals, which are the discrepancy between the actual and expected mass balances, from 1992 to 2021. The residual distribution that is ideal is random with respect to zero and lacks any discernible pattern. Simultaneous to conventional residuals. The primary issue with this concept is that it is never a normal distribution, as demonstrated. The residuals fluctuate around zero, but there are instances in which they remain consistently above or below zero, indicating potential model issues. This is particularly evident from 1992 to 1996 and around 20005. A comparable pattern is illustrated in additional figures. The residuals' autocorrelation function (ACF) graphic at the bottom left illustrates their relationship with lagged versions of themselves. Major limits are indicated by blue dashed lines. The majority of spikes should be contained within this range when residuals resemble white noise. It is possible that the model did not detect all data autocorrelations, as evidenced by the significant spikes outside the bounds, which indicate that the residuals are not random. The ARIMA(1,1,0) model was unable to capture the full residual autocorrelation, as evidenced by the spike at lag 2. Lastly, the residual histogram located in the lower left corner illustrates the residual distribution. The shaded region in the histogram should be constrained to a conventional normal distribution centered at zero, similar to the residuals plot. The red line denotes the fitted normal distribution. Even though the histogram is broadly centered around zero, it is not a perfect normal distribution due to outliers, particularly on the negative side.

These facts indicate that the ARIMA (1, 1, 0) model may be a suitable starting point; however, it may require additional modifications to accurately represent the data and make predictions. Parameters or external factors may be employed in experiments to capture data trends, thereby improving predictive power and accuracy. A distinct outcome is depicted in the Figure 4, which is the residual graphs of West Antarctica.

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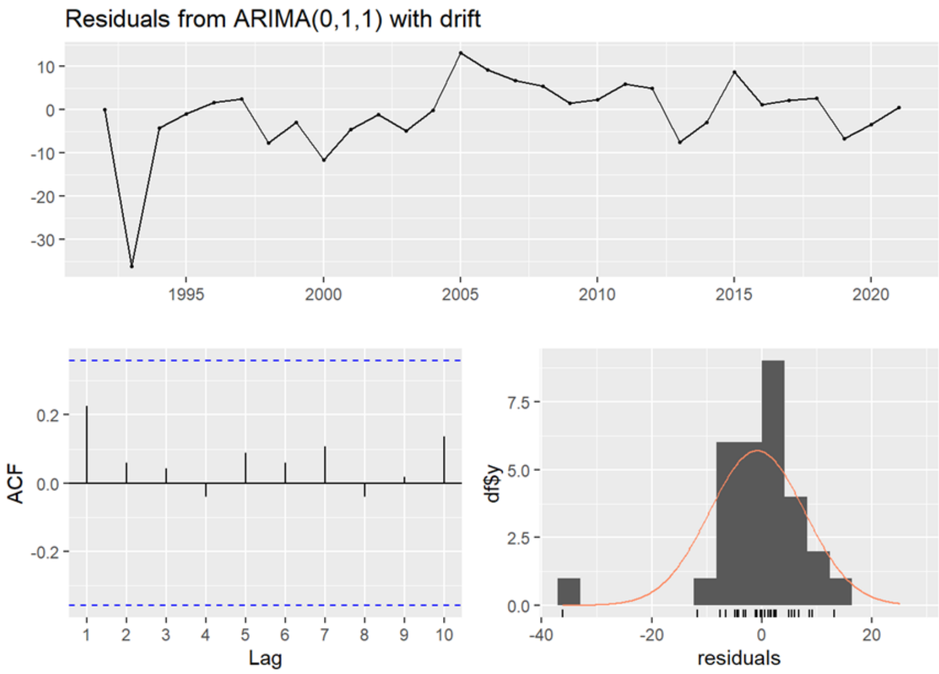

Figure 4. The Residuals Plots for the West Antarctica by the ARIMA (1,1,0)

The absence of any discernible pattern in the residuals plot over time suggests that the model is accurately representing the time-series structure (Figure 4). Nevertheless, residuals are consistently positive or negative for certain periods, which implies that the model is either underfit or lacks a temporal structure. The ACF figure demonstrates that the residuals are primarily uncorrelated, as the confidence intervals encompass the majority of the autocorrelations. In contrast to the East Antarctica plot, this plot contains fewer significant hits, with the majority falling within ±0.2 intervals. In the image, the histogram is broadly bell-shaped; however, there are significant deviations from normality, such as a higher residual frequency near zero and multiple outliers on both tails. The residuals may not be normally distributed, which could indicate heteroscedasticity (a change in residual variance over time) or non-linearity in the data that the model has not yet captured.

Overall, the ARIMA (0,1,1) model has effectively eliminated the majority of autocorrelation and captured a significant portion of the temporal structure, as demonstrated by the ACF graphic. The residual plot over time, however, indicates periods of non-randomness, which may indicate underfitting or missing variables. This is a significant limitation of the model. Furthermore, the residual histogram suggests that the model may benefit from a more complex structure or additional treatments, as it exhibits only minor deviations from normality.

3.4. Discussion

The forecast accuracy of ice sheet mass balance models is considerably influenced by variables that transcend the mere application of Year and Mass balance (Gt/yr). The importance of including wider environmental factors is highlighted by the constraints outlined in the Data Processing section. The model's explanatory capacity is constrained by the omission of essential climatic variables, such as temperature, precipitation, and atmospheric dynamics, which significantly influence variations in mass balance. Disregarding these elements may lead to oversimplified models that perform well on historical data but fail to forecast future trends owing to their insensitivity to external changes.

Research using ARIMA to forecast short-term temperature and precipitation outcomes shown that its accuracy was constrained by its reliance on past data [17]. These models sometimes provide too optimistic forecasts when they neglect fundamental changes or uncertainty in future situations. Enhanced accuracy in predicting ice mass fluctuations was attained via downscaling and incorporating

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comprehensive environmental data into models, as shown by research on the Greenland Ice Sheet [18]. Nonetheless, ARIMA's forecasting skills are fundamentally limited when it just utilizes mass balance and annual data, consequently excluding essential influencing variables. This constraint was also noted in precipitation simulation research, whereby ARIMA failed to capture long-term interannual fluctuations induced by climatic conditions [19].

The model's ability to accurately represent mass balance dynamics is significantly diminished by the omission of essential environmental factors, including temperature, precipitation, and atmospheric conditions. Rising temperatures, for example, are a critical element in the expedited melting of ice in areas like Greenland. Precipitation is a crucial determinant of mass balance, since the glacier's overall stability is directly affected by the volume of snow accumulation. Increased temperatures may result in precipitation falling as rain rather than snow, hence reducing the potential for substantial accumulation [20]. The limitations of ARIMA models are underscored by these seasonal and climatic variations, which they cannot effectively address.

The forecast of mass balance relies on the interaction between glacier movements and Surface Mass Balance (SMB). Surface meltwater in Antarctica may either refreeze or create ponds, leading to increased ice flow into the ocean and the destabilization of ice shelves. This tendency significantly contributes to rising sea levels, especially when the melting of ice shelves from underneath is intensified by ocean warming. The disintegration of ice shelves, particularly in regions such as West Antarctica, is mostly ascribed to increased ocean temperatures that destabilize the migration of inland ice and accelerate ice loss. This phenomenon is particularly pronounced in the Amundsen and Bellingshausen Sea regions, where substantial ice mass loss is due to atmospheric and oceanic conditions [21, 22].

In conclusion, ARIMA models are fundamentally limited when essential climatic variables, such as temperature, precipitation, surface mass balance, and ocean dynamics, are omitted, notwithstanding their potential effectiveness for short-term forecasts. These features must be included into the models to provide more accurate and reliable calculations of ice sheet mass balance.

4. Conclusion

ARIMA models are capable of estimating the mass balance of the Antarctic Ice Sheet, particularly for East and West Antarctica, which can provide insight into future trends. The program analyzes historical data to predict mass balance changes over the next 12 years and identify key patterns. This approach emphasizes the importance of comprehending historical patterns in order to anticipate future trends. The ARIMA model appears to be capable of identifying patterns and producing precise forecasts within its constraints. The study could be enhanced by the inclusion of additional data sources in future research.

The results demonstrate the effectiveness of ARIMA models in time series forecasting, particularly for climatic data with long-term trends. This technique has the potential to be employed to investigate and forecast fluctuations in the mass balance of the Antarctic Ice Sheet, as demonstrated by the model. The model could be further developed to include additional variables in order to enhance the accuracy of forecasts and the comprehension of ice sheet dynamics in future research. This endeavor is essential for the maintenance of global environmental stability, as it enables the monitoring and response to changes in the polar regions.

References

[1] Jansen E, Overpeck J, et al. 2007 Palaeo climate, in: Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[2] Rignot E 2011 Is Antarctica melting. Wiley Interdisciplinary Reviews: Climate Change, 2(3), 324-331.
[3] Lemke P, Ren J, et al. 2007 Observations: changes in snow, ice and frozen ground. Cambridge: Cambridge University Press.

[4] Wingham D J, Ridout A J, Scharroo R, Arthern R and Shum C K 1998 Antarctic elevation change from 1992-1996. Science, 282, 456-458.
[5] Rignot E 1998 Fast recession of a West Antarctic Glacier. Science, 281, 549-551.
[6] Velicogna I and Wahr J 2006 Measurements of time-variable gravity show mass loss in Antarctica. Science, 311, 1754-1756.
[7] Ramillien G, et al. 2006 Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE. GlobPlanet Change, 53, 198-208.
[8] Rignot E, et al. 2008 Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. Nat Geo, 1, 106-110.
[9] Velicogna I 2009 Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. Geophys Res Lett, 36, 19503.
[10] Pritchard H D, Arthern R J, Vaughan D G and Edwards L A 2009 Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. Nature, 461, 971-974.
[11] Surendra J, et al. (2021) Forecast and trend analysis of gold prices in India using auto regressive integrated moving average model. J. Math. Comput. Sci., 11(2), 1166-1175.
[12] Riley T (2022) Geochemical and geochronological data from the LeMay Group, Antarctic Peninsula. NERC EDS UK Polar Data Centre.
[13] Hewamalage H, Bergmeir C and Bandara K (2021) Recurrent neural networks for time series forecasting: Current status and future directions. International Journal of Forecasting, 37(1), 388-427.
[14] ArunKumar K E, et al. (2021) Forecasting the dynamics of cumulative COVID-19 cases (confirmed, recovered and deaths) for top-16 countries using statistical machine learning models: Auto-Regressive Integrated Moving Average (ARIMA) and Seasonal Auto-Regressive Integrated Moving Average (SARIMA). Applied soft computing, 103, 107161.
[15] Khan F M and Gupta R (2020) ARIMA and NAR based prediction model for time series analysis of COVID-19 cases in India. Journal of Safety Science and Resilience, 1(1), 12-18.
[16] Ramadhani F, Sukiyono K and Suryanty M (2020) Forecasting of Paddy Grain and Rice's Price: An ARIMA (Autoregressive Integrated Moving Average) Model Application. SOCA: Jurnal Sosial, Ekonomi Pertanian, 14(2), 224.
[17] Lai Y and Dzombak D A (2020) Use of the autoregressive integrated moving average (ARIMA) model to forecast near-term regional temperature and precipitation. Weather and forecasting, 35(3), 959-976.
[18] Madsen M S, et al. (2022) The role of an interactive Greenland ice sheet in the coupled climate-ice sheet model EC-Earth-PISM. Climate Dynamics, 59(3), 1189-1211.
[19] Kang J, et al. (2020) Prediction of precipitation based on recurrent neural networks in Jingdezhen, Jiangxi Province, China. Atmosphere, 11(3), 246.
[20] Kittel C, et al. (2021). Diverging future surface mass balance between the Antarctic ice shelves and grounded ice sheet. The Cryosphere, 15(3), 1215-1236.
[21] van den Broeke M R, et al. (2023) Contrasting current and future surface melt rates on the ice sheets of Greenland and Antarctica: Lessons from in situ observations and climate models. PLoS Climate, 2(5).
[22] Dunmire D, Lenaerts J T, Datta R T and Gorte T (2022) Antarctic surface climate and surface mass balance in the Community Earth System Model version 2 during the satellite era and into the future (1979–2100). The Cryosphere, 16(10), 4163-4184.