Changes in Sea Ice Extent Within the Arctic and Antarctic

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Introduction

Sea ice, both Arctic and Antarctic, is a key component of the earth system. Its properties and effects are determined by its crystal lattice structure of tightly packed hexagonal layers (Petrich and Eicken, 2010). Additionally, environmental conditions can influence the presence of brine gas and solid salts within the ice structure (Timco and Weeks, 2010). Furthermore, the role of sea ice extends to its impact on climate and surrounding ecosystems.

As an example of this role, sea ice contributes to the earths albedo effect and reflects solar radiation back into space. This effect is also considered seasonal where the albedo effect is strongest during "winter" periods and reduced during "summer" periods (Perovich and Polashenski, 2012). Which in turn helps with maintaining a cooler climate.

Additionally, sea ice influences the surrounding ecosystem by providing habitat for sea ice algae where they provide a source of fixed carbon for other organisms in icy waters (Arrigo and Thomas, 2004). Particularly Antarctic krill which are considered a keystone species which in turn feed the macro-organisms of the Southern Oceans food web (Kohlbach et al, 2017).

Furthermore, baseline sea ice extent also differs between the Arctic and Antarctic. With sea ice extent range in the Arctic being limited due to surrounding land masses resulting in restricted growth compared to Antarctic Sea ice, resulting in double the seasonal cycle of growth and decline compared to the Arctic (Maksym, 2019). Whereas maximum sea ice extent range in the Antarctic is limited by the Antarctic circumpolar current (Martinson, 2012). Furthermore, sea ice tends to be thicker in the Arctic compared to the Antarctic (Maksym, 2019). This is because in the Arctic, surface waters are protected from warmer Atlantic waters by the cold halocline layer (Steele and Boyd, 1998) whereas, the Southern Ocean is exposed to many sources of warmer water limiting thickness (Maksym, 2019).

Additionally, the polar regions are susceptible to climate change where the Arctic and Antarctic have experienced significant warming with the Arctic being impacted more so by increased extreme heat events (Robinson, 2022) which would also impact future biodiversity of Antarctic ecosystems (Post et al, 2019) with potentially similar effects on Arctic regions. This has also resulted in atmospheric circulation changes in the southern hemisphere and a strengthened Southern Stratospheric Polar Vortex with these changes being attributed to human greenhouse gas emissions (Screen et al, 2018). Furthermore, the decrease in surface albedo in the Arctic increases solar radiation absorption resulting in a positive feedback loop however, subsurface ocean heat storage has delayed the effects of the positive feedback (Dai, 2021).

Thereby, the objective of this report is to examine current literature which have produced research on sea ice extent in both the Arctic and Antarctic and to discuss their findings. Along with analysing sea ice extent data to investigate changes in extent since 1980 to evaluate its current state. Uncertainties and limitations along with their reasons and possible methods to overcome them will also be discussed.

Literature Review

The purpose of this section will be to analyse the methods and results of various recent papers based on sea ice extent to understand current aspects of monitoring and investigation.

To begin, a paper produced by Parkinson and DiGirolamo 2021 added additional years to a dataset on a previous study for years 1979-2015 thus, bringing the time scale to 2020. The purpose of this study was to visualise record highs and lows for sea ice extent within the Arctic, Antarctic and globally.

For this study data was acquired using NASA's Scanning Multichannel Microwave Radiometer (SMMR) and the US's DOD's Special Sensor Microwave Imager (SSMI) (Parkinson and DiGirolamo, 2016). Which in turn would calculate sea ice concentrations within grid cell areas with a resolution of 25kmx25km (Parkinson and DiGirolamo, 2021). With datasets sourced from the National Snow and Ice Data Centre (NSIDC) (Cavalieri et al, 1996). Then, using this information to calculate sea ice extents defined as the total area of all grid cells that have concentrations of at minimum 15% (Parkinson and DiGirolamo, 2021).

Furthermore, to obtain monthly data, daily extents were calculated then averaged into their respective months and then respective years for yearly averages (Parkinson and DiGirolamo, 2021). The 42 Januarys for the 1979-2020 period were ranked between 1-42 where 1 represents the lowest extent and 42 the highest with this ranking then done for all other months (Parkinson and DiGirolamo, 2021). These rankings were then used to determine each new monthly and yearly record high and low (Parkinson and DiGirolamo, 2021).

Continuing to the results, Arctic sea-ice was observed to follow the trend of yearly decline in extent with each of the months between 2016-2020 having extents in the lower 33% quantile (Parkinson and DiGirolamo, 2021). Of the 42-year time-period there were zero recorded new monthly highs with only August and September months not experiencing new record lows since 2016 (Parkinson and DiGirolamo, 2021). Where the last record yearly high was observed in 1982 (Parkinson and DiGirolamo, 2021).

Comparatively, the trend for Antarctic sea-ice no longer implies a positive increase (suggested from 1979-2015) in extent but a decrease in extent from 2016 with especially low observations between 2016-2019 with a small rebound in 2020 (Parkinson and DiGirolamo, 2021). With the additional 5 years having zero recorded monthly record highs but 8 monthly record lows being observed (Parkinson and DiGirolamo, 2021). Where 8 calendar months observed record lows between 2016-2020 and yearly average extents had the highest value in 2014 but the lowest in 2017 (Parkinson and DiGirolamo, 2021).

Furthermore, the global results suggested that the additional 5 years is predominantly comprised of low values (Parkinson and DiGirolamo, 2021). Where each of the 60 months of the additional 5 years global extents rank in the lower 29% of the 1979-2020 period where all months except April 2016 ranking in the lower 25% (Parkinson and DiGirolamo, 2021). With each calendar month having at least one record low between 2016-2020 with the maximum being three new record lows with zero new monthly highs since March 2008 (Parkinson and DiGirolamo, 2021).

Thereby to summarise, global ice extent has had three monthly highs and sixty-three monthly lows since 1986 with the last yearly record high being 1982 (Parkinson and DiGirolamo, 2021).

A different paper by Shu et al 2020, evaluated sea ice extents from 44 coupled models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) by comparing them to the results of CMIP5.

For this study monthly sea ice extents from CMIP6 and CMIP5 historical runs was used (Shu et al, 2020). With data from forty-six CMIP6 models where five were used to obtain sea ice extent and the other forty-one provided sea ice concentration data (Shu et al, 2020). Shu et al calculated sea ice extent as the total area of all grid cells where sea ice concentration exceeded 15% (Shu et al, 2020) this calculation was also shared by the previous study mentioned done by Parkinson and DiGirolamo 2021. They excluded the MIROC6 and MIROC-ES2L models due to large sea ice extent biases for Antarctic data due to them suggesting unrealistically low sea ice extent values caused by sea surface temperature values caused by underestimation of cloud cover altering shortwave radiation values (Tatebe et al, 2019; Shu et al, 2020). 307 outputs from the other forty-four CMIP6 models were thus used (Shu et al, 2020).

Additionally, to assess model ability from CMIP5 to CMIP6, CMIP6 results were compared to outputs from forty-nine CMIP5 models where the timescale was 1979-2005(CMIP5) and 1979-2014(CMIP6) for the simulations (Shu et al, 2020). The two data sets for used were acquired from the University of Bremen (Spreen et al, 2008) and the National Snow and Ice Data Centre (NSIDC) (Fetterer et al, 2017). With CMIP5 data being sourced from the NSIDC, Global Ice-Ocean Modelling and Assimilation System (GIOMAS) and Pan-Arctic Ice-Ocean Modelling and Assimilation System (PIOMAS) (Shu et al, 2015).

Continuing to the results, sea ice extent simulations from CMIP6 models between 1979-2005 compared to CMIP5 models were found to be similar when modelling sea ice extent seasonal cycles (Shu et al, 2020). Furthermore, both models successfully capture the negative trend for Arctic extent but not the observed positive trend for Antarctic sea-ice during this timescale and incorrectly assigned a negative trend (Shu et al, 2020). It was found mean bias for extent was slightly bigger for CMIP6 overall (Shu et al, 2020).

However, although the CMIP6 average suggests a negative Antarctic trend 11% of the simulations correctly produced a positive trend (Shu et al, 2020) compared to 16% for CMIP5 (Shu et al, 2015). Additionally, simulations from CMIP5 and CMIP6 cannot reproduce spatial observations for sea ice concentration trends (Shu et al, 2020). Furthermore, intermodal spreads were reduced for CMIP6 models regarding Antarctic sea-ice extent and long-term extent trends for both the Arctic and Antarctic whereas, spread was similar between both models for Arctic extent (Shu et al, 2020).

Furthermore, CMIP6 models didn't capture the increased rate of extent decline between 2000-2014 for the Arctic or, the Antarctic summer extent annual variability (Shu et al, 2020). Thereby suggesting, the models appear to have similar outputs with CMIP6 not necessarily being a significant improvement over CMIP5.

Current State of Sea Ice Extent

The data for the raster plots was acquired from the NSIDC Data Map Services API (National Snow and Ice Data Center, 2024) Larger Plots of extent can be found in the appendices.

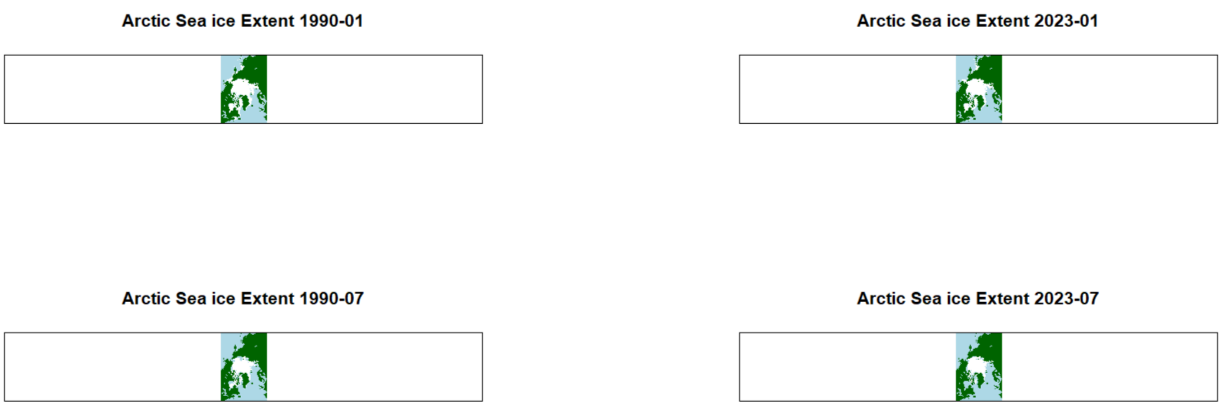

Figure 1: Raster Plots of Sea Ice Extent in the Arctic January/July 1990 and 2023

Based on the raster plots of sea ice extent in the Arctic (Fig 1) it is suggested that current extent is lower than past extent in this case since 1990 where, the difference in extent appears to be greater in the summer period. The sea ice extent also varies seasonally with extent in the Arctic with the minimum extent in September and maximum extent in March (Parkinson et al, 1999) (Northern Hemisphere) although in this case January and July extents were compared but the 6-month gap between comparisons was kept. Furthermore, the decrease in extent does not appear to be uniform across the Arctic instead the decrease in extent seems slightly skewed towards the North Atlantic exposed sea ice. A possible reason for this could be caused by the Bering Strait, an 85km wide 50m deep gap, which influences throughflow from the North Pacific into the Arctic (Hu and Meehl, 2005; Danielson et al, 2014). Which perhaps could limit the amount of warm water influx from the North Pacific whereas, the North Atlantic side is exposed and thus more susceptible to heat influx. Additionally, decreased winter extent is being attributed to warm air influxes from the south alongside the overall warming of the Arctic with main cause of this warming being attributed to anthropogenic CO2 emissions (Stroeve and Notz, 2018).

Comparatively, the Antarctic raster plots (Fig 2) also suggest a decrease in current extent compared to 1990 again including seasonal variation between summer and winter periods where minimum extent is observed in February and maximum extent in September (Serreze and Meier, 2019) again the plot extents instead

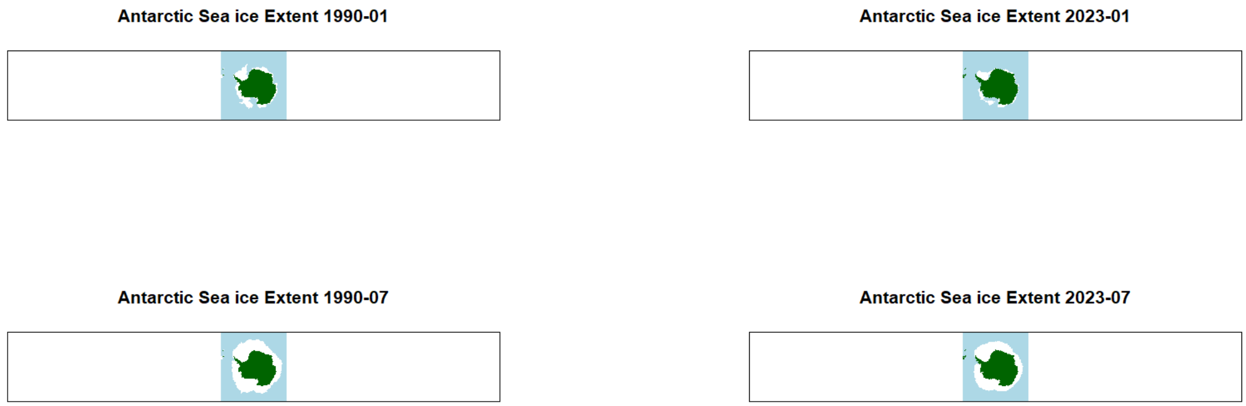

Figure 2: Raster Plots of Sea Ice Extent in the Antarctic JanuaryJuly 1990 and 2023

compare January and July in this case. Additionally, seasonal variation in the Antarctic appears to be more substantial which is attributed to different physical oceanic processes between the regions particularly regarding both dynamic and thermodynamic forcing which influence ice movement, growth and melt (Serreze and Meier, 2019). Furthermore, the difference in extent between 1990 and 2023 also appears to be more uniform rather than attributed to a single area in contrast to the Arctic which may also be caused by the aforementioned processes along with the Southern Ocean being more exposed in all directions.

While visualising ice extent is useful and insights can be drawn from these plots, its also important to quantify changes in sea ice extent to assess the current status for sea ice extent. The data used to produce figures 3 and 4 was acquired from the Met Office Climate Dashboard Cloud available under open government license (Met Office, n.d.) with the specific datasets used originating from NSIDC v3 and NSIDC v3 Antarctic (Fetterer et al, 2017).

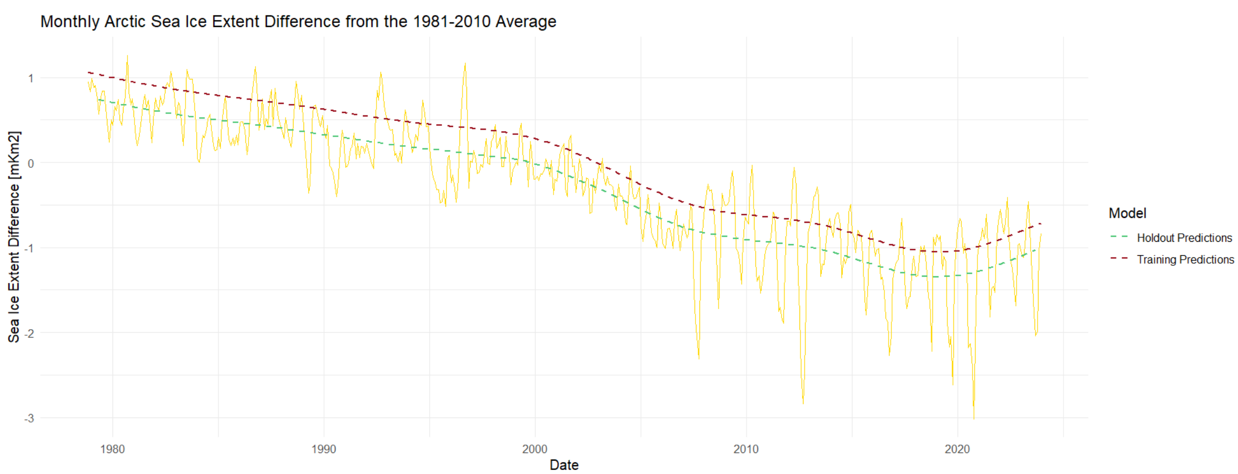

Figure 3: Time series of Sea Ice Extent Difference compared to the 1981-2010 average in the Arctic 1979-2024

To begin figure 3 modelled using both a holdout approach for my GAM model suggests a decrease in extent compared to the 1981-2010 average for the current year with the predicted post 2020 range being between 0mKm2 and -1.5mKm2 (million kilometres squared). Where both trends are suggested to be irregular therefore capturing the complexity of the data. Notably post 2020 the GAM model trends both indicated a potential increase in sea ice extent. The training trend produced an R-Squared of 0.76 and the holdout 0.77 which suggests both capture the variability well with the holdout predictions suggesting my model generalises unseen data well as evidenced by a slight increase in R-Squared. With the R-Squared values suggesting variables strongly correlated with time seem to exert the greatest influence on sea ice extent for the Arctic. This is evidenced as time was used as the only predictor variable for the model where around 75% variability could be considered quite high for a single predictor.

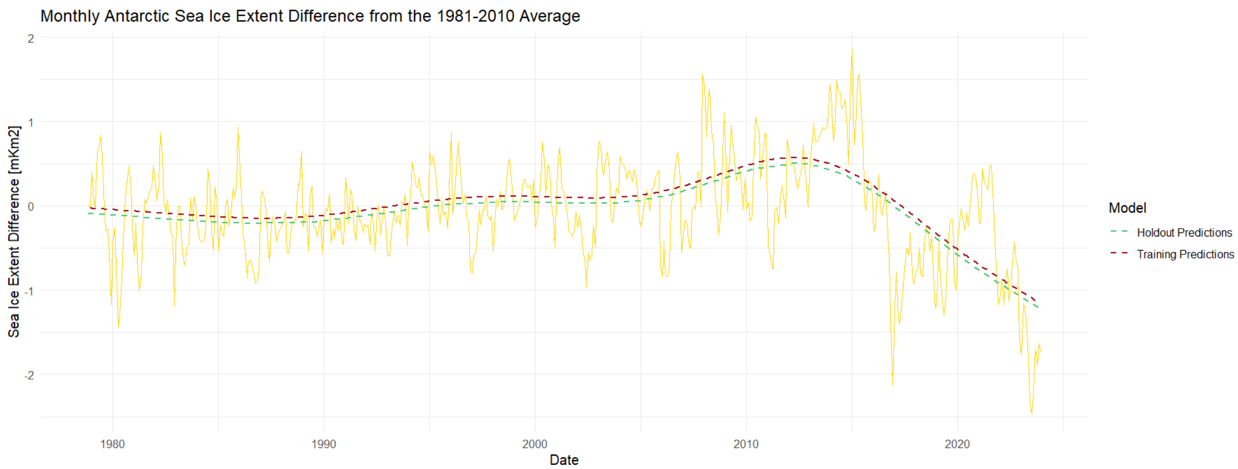

Figure 4: Time series of Sea Ice Extent Difference compared to the 1981-2010 average in the Antarctic 1979-2024

Continuing with figure 4, the differences in extent compared to the 1981-2010 average were suggested to be highly non-linear in comparison to the Arctic. This is suggested by the initial positive increase between 1979-2015 and sharp decreases in 2016 and 2021/22. Based on this, current sea ice extent seems to be significantly worse than historical extents evidenced by the much higher positive differences in extent of 1.8mKm2 in 2015 for the Antarctic compared to 1.2mKm2 in 1996 for the Arctic. Although, it should still be noted maximum extent decreases were still observed to be higher in the Artic than the Antarctic where in 2021 there was 3mKm2 less ice extent compared to the 1981-2010 average in the Arctic compared to 2.4mKm2 for the Antarctic in 2023. As a result of the complexity in the Antarctic data the GAM model produced an R-squared of 0.31 which means only 31% of variability was explained by the training set whereas the holdout set produced an R-Squared of 0.49 which is a substantial improvement. Since only one predictor was used we suggest the increase in R-Squared is unlikely to be a result of over fitting. However, it can be suggested that variables strongly correlated to time have less influence on sea ice extent for the Antarctic suggesting physical ocean and climatic processes could be more influential in explaining sea ice extent for the Antarctic evidenced by the reduction in R-Squared compared to the Arctic. Additionally, both trends agree on predicting further decreases in extent as opposed to the suggested increase in the Arctic.

Uncertainties and Limitations

There are various factors discussed in the literature which influence uncertainty or result in limitations for sea ice data. For example, greater uncertainty can arise depending on the proximity of open water which influences atmospheric factors and thus increases model uncertainties (Ivanova et al, 2014). Furthermore, missing data also plays a part in uncertainties for ice area calculations where estimations are used to fill in missing data (Parkinson and DiGirolamo, 2021). Where missing data points are attributed to satellite malfunctions to which missing daily observations can result in missing data for entire months depending on when satellite operation is restored to which this is a particular issue for historical observations (Andersson et al, 2021). Furthermore, datasets with missing data cannot be used to train machine learning models as it would affect model performance however, missing data is less of an issue in outputs as interpolation can be used to make estimates although this would still add a factor of uncertainty for data interpretation (Andersson et al, 2021). Additionally, models struggle more when interpreting Antarctic data where predicted trends can be inconsistent with observed values (Shu et al, 2020) perhaps due to the greater complexity of the Antarctic trend as suggested in fig 4.

Additionally, false-positives, where non sea ice is mistakenly recorded as being sea ice, from microwave satellite observations can also create uncertainty where in coasts land-sea spillover has a similar signature to sea ice (Maa and Kaleschke, 2010). Model skill is also a limitation discussed where models such as CMIP6 which lack predictive skill i.e. how well the prediction matches observed data and the associated uncertainties from said prediction for sea ice extent (Watts et al, 2021). Where this can occur due to models underestimating various factors an example of which is downward shortwave radiation which has been associated to simulated cloud cover resulting in lower predictive sea surface temperatures (Yang et al, 2020). To which this can result in model bias for sea ice in models such as CMIP6 therefore, increasing uncertainty in model predictions (Roach et al, 2020).

Thus, to summarise most uncertainty in sea ice data stems from missing data from satellite observations, particularly for historical observations, resulting from satellite malfunctions which can impact the training data used for models. With the prediction skill of machine learning based techniques resulting in bias and incorrect trend predictions due to low quality and lack of training data. Additionally, model ability in incorporating variables such as the discussed underestimating of sea surface temperatures resulting from cloud cover simulations.

Proposed Data Science Approaches

To begin, addressing the issues of historical missing data interpolation and imputation could be used to fill in data points. As used for figures 3 and 4, baseline averages could then be applied to determine changes from the baseline this would reduce the weighting of missing/imputed values allowing for a better understanding of current trends. As establishing a historical baseline is important due to the short-term data collection period with first observations being acquired in 1979 meaning less than 50 years of data is available meaning we don't have any information on long terms changes in sea ice extent.

Furthermore, the focus should also be on improving future trend predictions such as applying bias correction to current models to reduce uncertainty. As an example, ensembles can be used to overcome bias. Where multiple forecasts with different starting values can produce a value range over a single trend which would incorporate the uncertainty into the prediction range where mean forecasts can be bias corrected by subtracting mean error fields (Andersson et al, 2021). Model bias prediction is also a factor that can be used to improve current models where convolutional neural networks can be used to predict sea ice model errors using data assimilation from the model variables (Gregory et al, 2023). This would allow us to understand how reliable current models are and whether improvements can be made. Furthermore, computer vision approaches can be used to improve the classification of sea ice. Where using deep learning methods again using convolutional neural networks which have been previously applied to earths observation data but a lesser extent to sea ice (Khaleghian et al, 2021). Where this can reduce the number of false-positive classifications of non-sea ice as sea ice by improving satellite recognition of true sea ice to improve the quality of data acquired.

Additionally, development on regional based climate models may be more appropriate than using a model that tries to explain both Arctic and Antarctic sea ice extents such as CMIP5 and CMIP6. This is evidenced by figures 3 and 4 where using the same model structure resulted in different amounts of variability explained. Based on the R-squared values regional models for the Arctic would require a bigger focus on variables which are strongly correlated with time whereas, a regional Antarctic model would require a bigger focus on variables which are not strongly correlated with time and instead focus on physical and climatic processes. This could potentially reduce the bias induced and therefore reduce the uncertainty of future predictions calculated by the models. Where the reason for regional models would be due the differing geographically structures of the regions previously discussed in this report. Furthermore, using regional models would allow further fine tuning of hyperparameters to which the starting values can impact model performance thereby tuning them further could result in a decrease in uncertainty (Anderson et al, 2021).

Thus, to summarise to tackle missing historical data interpolation and imputation could be used to form a baseline average to reduce the weighting of missing values. With bias correction and ensemble methods being used to reduce uncertainty in future forecasts along with potentially regionally designed models to be more specific in variables and hyperparameters used when explaining sea ice extent for different regions.

Conclusion

To conclude the Arctic and Antarctic are important regions which influence global physical and climatic processes alongside being important ecological zones for various organisms. However, recent trends in sea ice decline threaten the stability of these environments to which the main cause of decline has been associated with climate change resulting from anthropogenic greenhouse gas emissions. Thereby much literature and research has been undertaken to further understand the rates of sea ice decline along with other factors including ice thickness and effects on local ecology.

With some data analysis implying Arctic trends in decline appear to be more easily explained with most of this variability seemingly attributed to variables strongly correlated with time. Comparatively, the Antarctic trend is more complex as both trends struggle to explain as much variability although it can be inferred the variability appears to be more attributed to physical environmental processes as opposed to factors strongly correlated to time.

Therefore, to quantify these impacts various models have been produced such as CMIP6 however, these models contain various biases and uncertainties regarding future predictions resulting in uncertainty into how the rate of decline will change in the future. To overcome these biases and uncertainties various methods such as using ensembles, regional modelling and bias correction can be used to at least minimise the impacts of bias therefore, reducing model uncertainty for current and future predictions.

To close off, it can be inferred that the current health status of the polar regions regarding sea ice extent is decreasing where although the rate of decline may be uncertain it is generally suggested both systems are experiencing sea ice loss. Where it is important to note that an interdisciplinary approach is required to increase the quality of observational data and both physics and machine learning derived models to fully assess sea ice health going forward.

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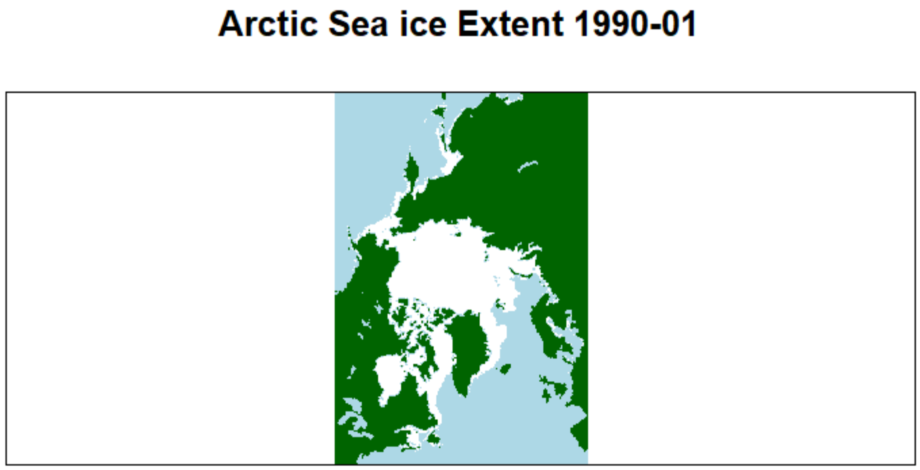
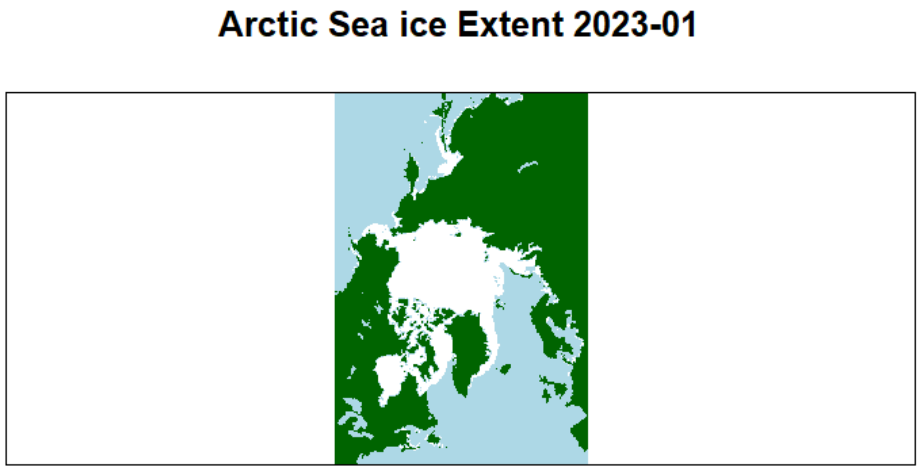

Arctic Sea ice Extent 1990-01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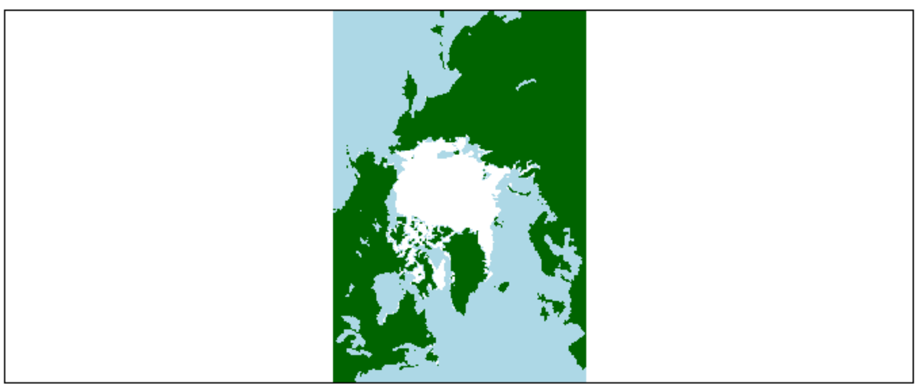

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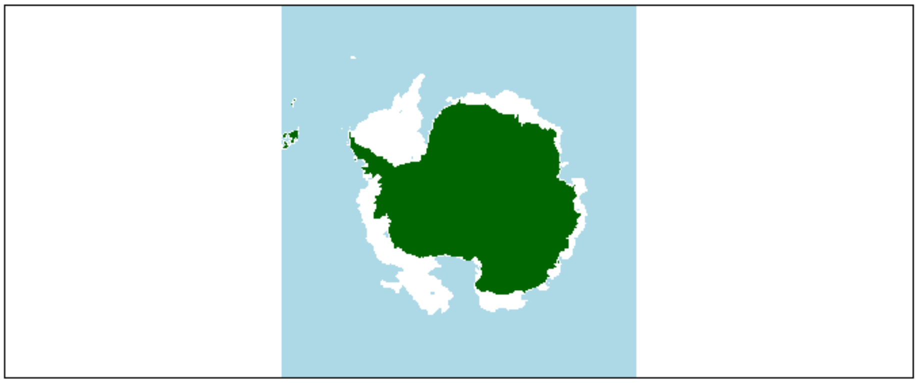

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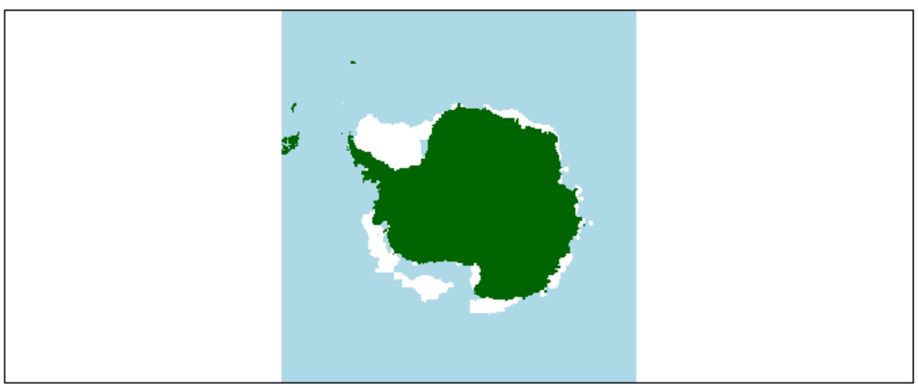
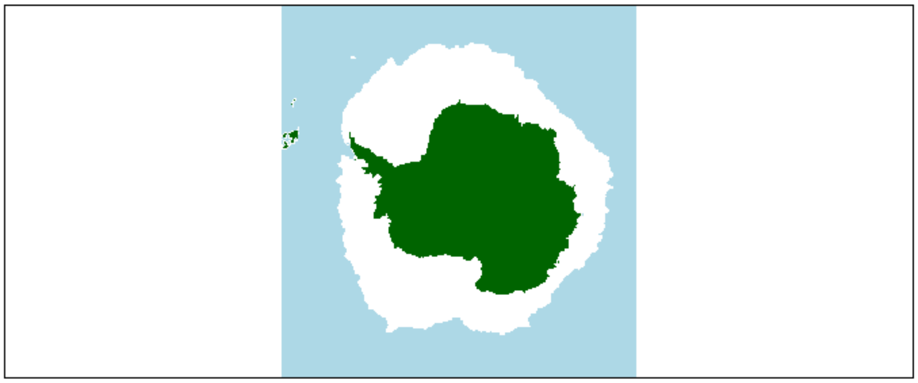


Antarctic Sea ice Extent 1990-07



Antarctic Sea ice Extent 2023-07