A Comparison of South Pacific Antarctic Sea Ice and Atmospheric Circulation Reconstructions Since 1900

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Submitted to *Climate of the Past*

Abstract

The recent changes and record ~~minima~~lows in Antarctic sea ice extent implore the need for longer estimates beyond the short satellite observation period commencing near 1979. However, Antarctic sea ice extent reconstructions since 1900 based on paleo records and those generated based on instrumental observations from the Southern Hemisphere midlatitudes are markedly different, especially prior to 1979. Here, these reconstructions are examined with the goal of understanding the relative strengths and limitations of each reconstruction better so that researchers using the various datasets can interpret them appropriately.

Overall, it is found that the different spatial and temporal resolutions of each dataset play a secondary role to the inherent connections each reconstruction has with its ~~underlying~~implied atmospheric circulation. ~~Several~~Five Southern Hemisphere pressure reconstructions spanning the 20th century are thus examined further. There are different variability and trends poleward of 60°S between ~~paleo~~proxy-based and station-based 20th century pressure reconstructions which are connected to the disagreement between the Antarctic sea ice extent reconstructions examined here. Importantly, ~~sensitivity experiments~~reconstructions based on only coral ~~paleoclimatological~~ records provide the best agreement between the early pressure reconstructions, suggesting a contributing role of tropical variability is present in the station-based pressure (and therefore sea ice) reconstructions~~, while high latitude~~. In contrast, ice core ~~information strongly constrains paleo-based~~ only reconstructions ~~(of both pressure~~ provide a local, high-latitude constraint that creates differences between the proxy-based and ~~sea ice)~~station-based reconstructions near ~~the Antarctic continent~~Antarctica. Our results reveal the greatest consistencies and inconsistencies in available datasets and highlight the need to better

understand the relative roles of the tropics versus high latitudes in historical sea ice variability around Antarctica.

1. Introduction

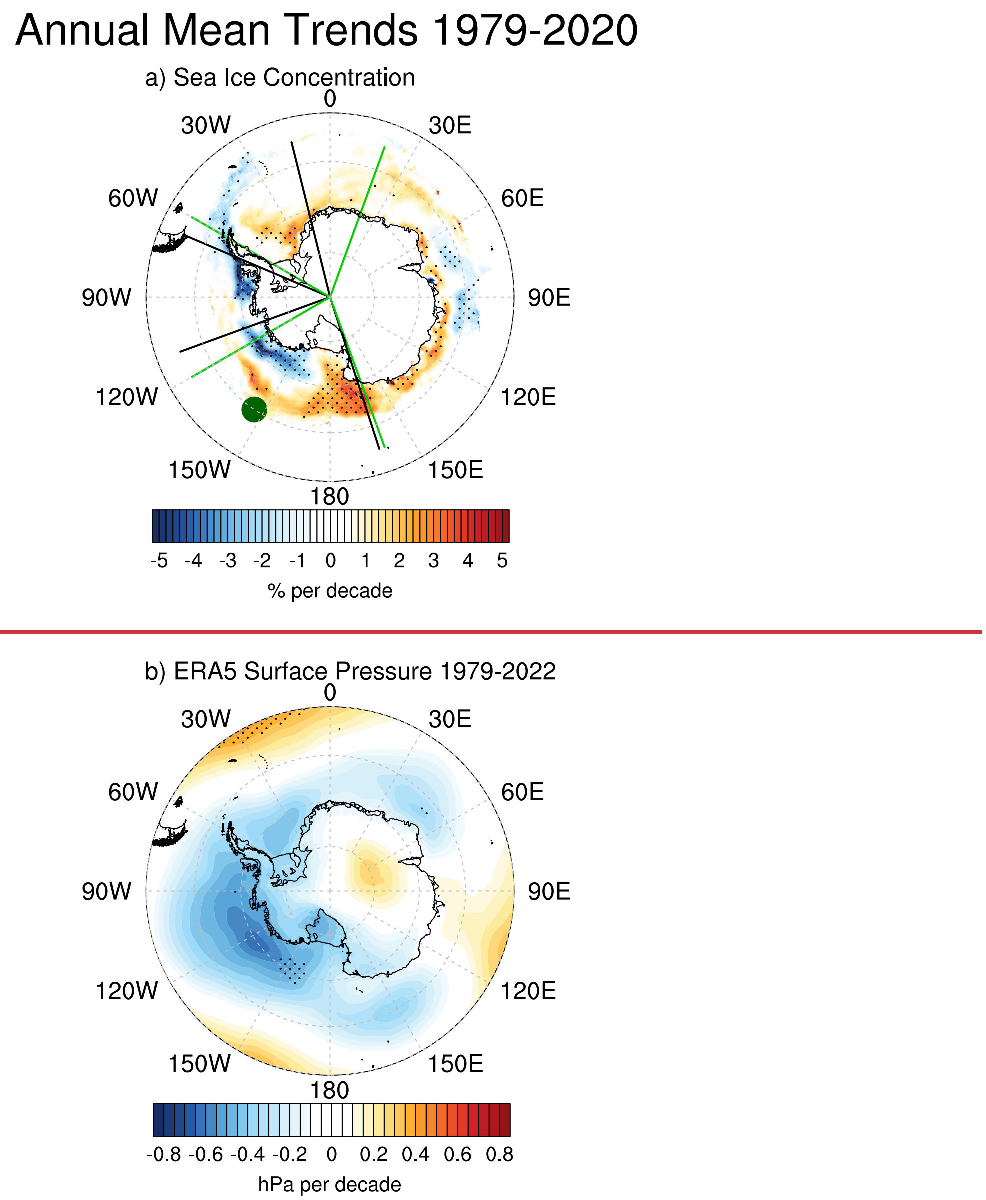
The climate of Antarctica is very complex and highly variable in space and time, influenced by unique processes over the Southern Ocean, the surrounding sea ice, and the continent itself ~~(Jones et al., 2016; Goyal et al., 2021; Raphael et al., 2016; Holland et al., 2022; Blanchard-Wrigglesworth et al., 2021). Although geographically remote from other continents in the Southern Hemisphere, it is also strongly modulated by large-scale patterns of climate variability, including teleconnections from the tropical oceans, in particular in West Antarctica (Li et al., 2021; Lachlan-Cope and Connolley, 2006; Ding et al., 2011). Some of the more pronounced and unique changes in Antarctic climate include a rapid acceleration and thinning of outlet glaciers in the Amundsen Sea embayment (near West Antarctica) (Rignot et al., 2019, 2013; Bamber et al., 2009; Smith et al., 2020), a strengthening of the atmospheric circulation (in particular in austral summer) since 1980 linked to stratospheric ozone depletion (Polvani et al., 2011; Banerjee et al., 2020), and record low total Antarctic sea ice extent set in 2017 (Turner et al., 2017), 2022 (Turner et al., 2022; Wang et al., 2022), and 2023, following multiple decades of a slow equatorward growth in the sea ice edge from 1979-2016 (Parkinson, 2019; Hobbs et al., 2016).~~(Jones et al., 2016; Goyal et al., 2021; Raphael et al., 2016; Holland et al., 2022; Blanchard-Wrigglesworth et al., 2021). Although geographically remote from other continents in the Southern Hemisphere, it is also strongly modulated by large-scale patterns of climate variability, including teleconnections from the tropical oceans, in particular in West Antarctica (Li et al., 2021; Lachlan-Cope and Connolley, 2006; Ding et al., 2011). Some of the more pronounced and unique changes in Antarctic climate include a rapid acceleration and thinning of outlet glaciers in the Amundsen Sea embayment (near West Antarctica) (Rignot et al., 2019, 2013; Bamber et al., 2009; Smith et al., 2020), a strengthening of the atmospheric circulation (in particular in austral summer) since 1980 linked to stratospheric ozone depletion (Polvani et al., 2011; Banerjee et al., 2020), and record low total Antarctic sea ice extent set in 2017 (Turner et al., 2017), 2022 (Turner et al., 2022; Wang et al., 2022), and 2023, following multiple decades of a slow equatorward growth in the sea ice edge from 1979-2016 (Parkinson, 2019; Hobbs et al., 2016).

While the high degree of interannual variability makes it challenging to fully understand these processes and changes, knowledge of them is also compromised by the comparatively temporally short length of instrumental observations (Jones et al., 2016). The majority of Antarctic meteorological measurements of temperature, pressure, and wind extend back until the International Geophysical Year (1957-1958), giving roughly only 60 years of continuous measurements for much of the continent (although most are not located in the interior of the ice sheet) (Turner et al., 2004, 2020). The observational record for Antarctic sea ice is even shorter – beginning near 1978-1979 when modern satellites provided continuous measurements of the sea ice concentration surrounding the continent (Meier et al., 2021; Parkinson, 2019).

Given the large year-to-year variability and the short observational records, other approaches must be employed in order to place the shorter records into a longer term context – a necessary step to better understand the potential uniqueness of ongoing changes across the continent and to provide more aid in deciphering possible mechanisms for these changes. One common approach is to produce reconstructions of past climate prior to direct observational measurements. For Antarctica, these reconstructions generally come in two main approaches. The first approach relies on paleoclimate records such as proxies from ice cores (typically the water isotopic content or snow accumulation) or ocean sediments to provide estimates of climate back centuries to millennia (Thomas et al., 2019; Steig et al., 2013; Thomas et al., 2017; Stenni et al., 2017). These paleoclimate data can be used directly to provide reconstructions of past climate if there is a strong physical relationship between the paleoclimate data and some aspect of observed climate; they can also be assimilated with climate model simulations to provide a more spatially complete reconstruction of climate across Antarctica (Dalaiden et al., 2021a; O'Connor et al., 2021, 2023). The second approach is based on instrumental observations in regions away from Antarctica through statistical models connecting the Antarctic climate with the climate across the Southern Hemisphere (Fogt et al., 2016a, b, 2019, 2022a; Fogt and Connolly, 2021). Assuming these relationships are stationary in time (Clark and Fogt, 2019), this approach creates reconstructions throughout the length of other Southern Hemisphere climate observations based on the relationship during the period of their overlap with Antarctic climate observations.

While the high degree of interannual variability makes it challenging to fully understand these processes and changes, knowledge of them is also compromised by the comparatively temporally short length of instrumental observations (Jones et al., 2016). The majority of Antarctic meteorological measurements of temperature, pressure, and wind extend back until the International Geophysical Year (1957-1958), giving roughly only 60 years of continuous measurements for much of the continent (although most are not located in the interior of the ice sheet) (Turner et al., 2004, 2020). The observational record for Antarctic sea ice is even shorter – beginning in late 1978 when modern satellites provided continuous measurements of the sea ice concentration surrounding the continent (Meier et al., 2021; Parkinson, 2019).

Given the large year-to-year variability and the short observational records in Antarctica, other approaches must be employed to gain a longer term context – a necessary step to better understand the potential uniqueness and possible mechanisms for these changes both now and into the future. One common approach is to produce reconstructions of past climate prior to direct observational measurements. For Antarctica, these reconstructions generally come in two main approaches. The first approach relies on paleoclimate records such as proxies from ice cores (typically the water isotopic content or snow accumulation) or ocean sediments to provide estimates of climate back centuries to millennia (Thomas et al., 2019; Steig et al., 2013; Thomas et al., 2017; Stenni et al., 2017). These paleoclimate data can be used directly to provide reconstructions of past climate if there is a strong physical relationship between the paleoclimate data and some aspect of observed climate; they can also be assimilated with climate model simulations to provide a more spatially complete reconstruction of climate across Antarctica (Dalaiden et al., 2021a; O'Connor et al., 2021, 2023). The second approach is based on instrumental observations in regions away from Antarctica through statistical models connecting the Antarctic climate with the climate across the Southern Hemisphere (Fogt et al., 2016a, b, 2019, 2022a; Fogt and Connolly, 2021). Assuming these relationships are stationary in time (Clark and Fogt, 2019), this approach creates reconstructions throughout the length of other Southern Hemisphere climate observations (most dating back to early 20th century or before) based on the relationship during the period of their overlap with Antarctic climate observations. The proxy-based and instrumental-based approaches have different strengths and weaknesses. Paleo-based reconstructions can provide historical changes on longer timescales and in key regions distant from stations; however, they are often limited to annual resolution and are associated with uncertainties in the precise climate signals recorded. Station-based reconstructions can produce sub-annual resolutions with direct observations of climate but are restricted temporally and spatially by station availability. Additionally, paleo-based reconstructions have the advantage ~~to rely~~of relying on measures of Antarctic climate variability that are located closer to the Southern Ocean, whereas station-based reconstructions largely rely on data from the Southern Hemisphere ~~midlatitude~~mid-latitude land masses. These differences can lead to different estimates of Antarctic climate in the early 20th century ~~(Fogt et al., 2022b).~~(Fogt et al., 2022b). In particular, one key area of differences suggested in earlier work between these various reconstructions was in the south Pacific and Atlantic Oceans stretching from the Ross Sea east to the Weddell Sea – regions of strong trends from observations (or reanalyses) in both sea ice concentration / extent and sea level pressure (Fig. 1). Recently, Fogt et al. (2022b) discussed this area as a key region where further analysis is needed on the similarities and differences between the reconstructions to better understand their utility. This paper will therefore extend the preliminary analysis of Fogt et al. (2022b) to ~~provide further comparison between proxy-based and instrumental-based~~ analyze differences in (primarily West Antarctic annual mean) sea ice reconstructions~~ of 20th century Southern Hemisphere sea ice extent to better understand the origins of their discrepancies~~, with a particular focus on the role of the atmospheric circulation~~ throughout the 20th century as a primary mechanism for these differences~~.


Annual Mean Trends 1979-2020
a) Sea Ice Concentration
0
30W
30E
60W
60E
90W
90E
120W
120E
150W
150E
180
-5 -4 -3 -2 -1 0 1 2 3 4 5
% per decade
b) ERA5 Surface Pressure 1979-2022
0
30W
30E
60W
60E
90W
90E
120W
120E
150W
150E
180
-0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8
hPa per decade

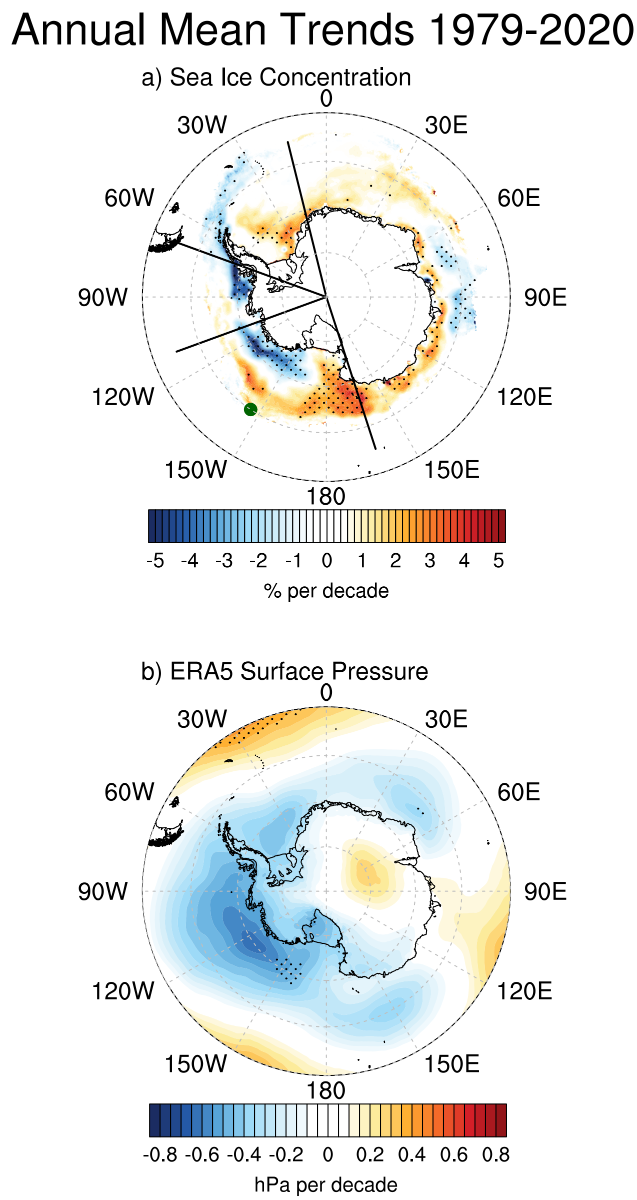


Figure 1. a) Annual mean sea ice concentration trends (% per decade) over 1979–2020. The solid black lines denote the sea ice sector boundaries ~~from Parkinson (2019), while the solid green lines represent the boundaries from~~ Raphael and Hobbs (2014). The dark green dot marks the location of the ice edge approximated by the Thomas and Abram (2016) reconstruction. b) Annual mean ERA5 surface pressure trends (hPa per decade). In both plots, trends statistically different from zero at $p<0.05$ are stippled.

2. Data and Methods

~~Table 1 provides further info on the various reconstructions compared in this paper, while Fig. 2 shows the locations of data used in three separate reconstructions.~~ For station-based reconstructions, we use the Fogt et al. (2022a) seasonal sea ice extent reconstructions and the Fogt and Connolly (2021) merged pressure reconstructions. We also investigate three proxy-based reconstructions for sea ice extent ~~(one of which is spatially complete),~~ and two ~~spatially complete,~~ proxy-based reconstructions for atmospheric pressure. Table 1 provides further information on the reconstructions compared in this paper, while Fig. 2 shows the locations of data used in three separate reconstructions.

2.1) Station and sea ice observations ~~and station-based reconstructions~~

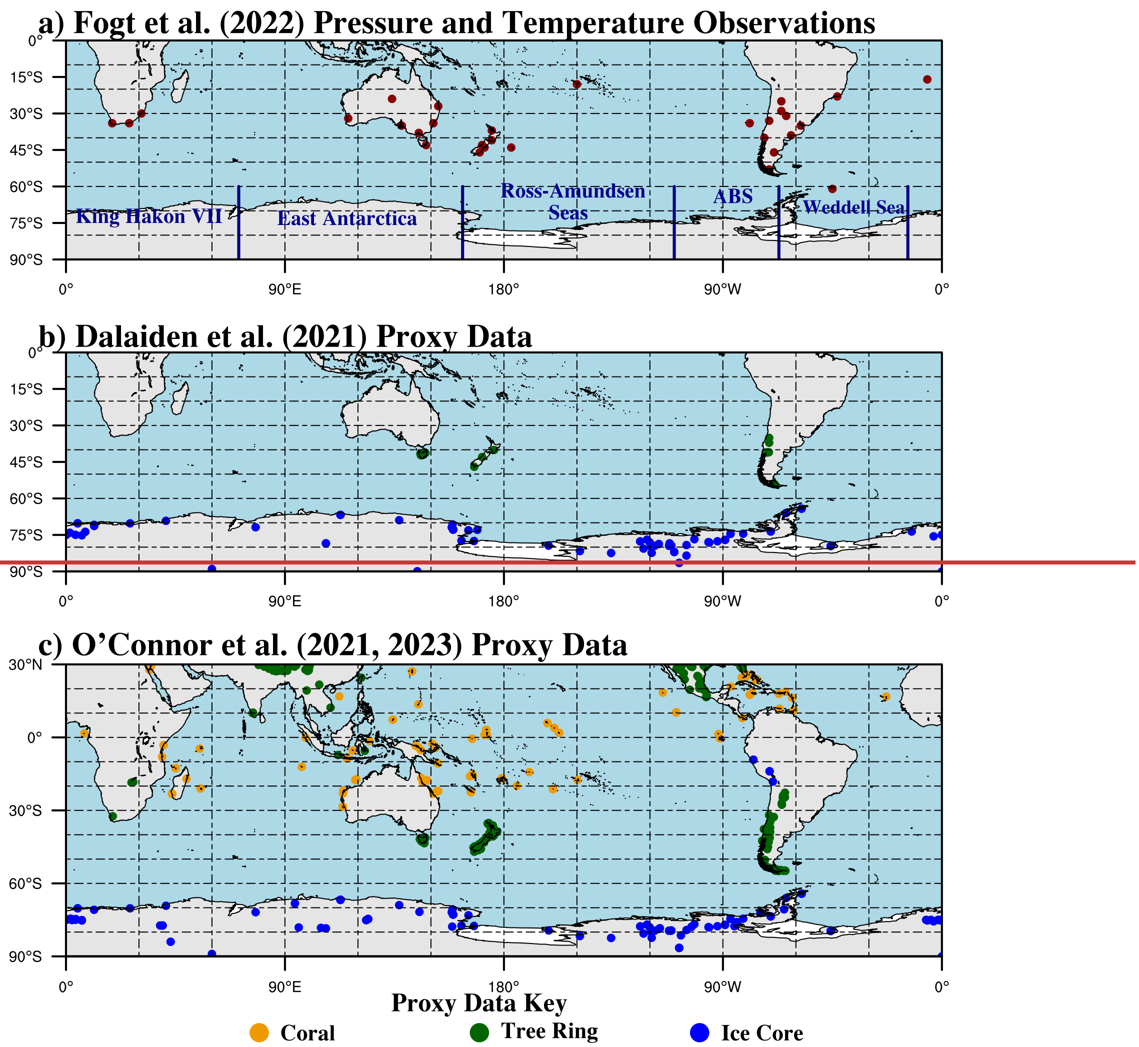
Monthly mean atmospheric pressure and temperature observations across the Southern Hemisphere used in the Fogt et al. (2019) pressure and Fogt et al. (2022a) sea ice reconstruction (Fig. 2a) are primarily obtained from the University Corporation for Atmospheric Research (UCAR) Research Data Archive dataset ds570.0 (https://rda.ucar.edu/datasets/ds570.0~~/#!description).~~/). A few stations from this dataset have been patched and merged with nearby stations to provide the most complete and continuous observational record, following Fogt et al. (2022a). Some other station data have been corrected independently, as discussed in Fogt et al. (2022a).

A few Antarctic pressure observations (Turner et al. 2014) are used to evaluate the pressure variability throughout the 20th century. We combine the Byrd station (year round, 1957- 1970) with the automatic weather station (AWS) data to provide the longest possible estimate in West Antarctica. The combination of the Byrd temperature record has been completed and analyzed in detail in earlier work (Bromwich et al. 2013), but the implications of the merged pressure record have not yet been investigated. Similarly, we use the longest Antarctic Peninsula station (Faraday/ Vernadsky, 1947-present) to represent conditions there. In the southern Weddell Sea sector, we merge the pressure observations from the various locations of Halley station (1957-present), as these are less influenced than temperature measurements at each site that show discontinuities (King et al.). All of these stations are not included as predictor data in the Fogt et al. (2016, 2019) pressure reconstructions. For the longest possible estimate, we also use observations from Orcadas stating in 1903 (Zazulie et al. 2003) - the observations from this station were directly included in the Fogt et al. (2019) spatial pressure reconstruction.

We also make use of the South Orkney fast ice duration time series from Murphy et al. (1995, 2014) as a long-term observationally based estimate of historical sea ice conditions in the Weddell Sea. This dataset was not used in any of the sea ice reconstructions evaluated here, so it serves as an independent dataset to compare historical sea ice variations in the Weddell Sea.

Dataset and shortened name	Type ~~(station or paleo based)~~	Variable(s) used in this study	Data Used in Reconstruction	Time Period	Resolution (Temporal / Spatial)
Fogt et al. (2022a) FOGT22_STAT	Station	Sea ice extent	Station pressure and temperature, indices of climate variability (Fig. 2a)	1905-2020	Seasonal, 5 sectors (Fig. 2a) + total sea ice extent
Fogt and Connolly (2021) FC21_STAT	Station	Near surface pressure	Fogt et al. (2019) reconstruction merged with NOAA 20CRv3 equatorward of 60°S	1905-2016	Seasonal, global, interpolated to 1°x1°
Abram et al. (2010) AB10_PALEO	Paleo	Sea ice extent	~~3~~methanesulphonic acid content from three Antarctic Peninsula ice cores	1900-2004	Winter (August-October), 70°W – 100°W (Bellingshausen Sea, Fig. 1a)
Thomas and Abram (2016) TA16_PALEO	Paleo	Sea ice extent	~~Coastal West Antarctica ice core~~methanesulphonic acid content from an ice core located off the Amundsen Sea coast	1702-2010	Annual, ice edge at 146°W (Fig. 1a)
Dalaiden et al. (2021) DAL21_ASSIM	Paleo data assimilation with climate model prior (fixed over time)	Sea ice extent (derived from sea ice concentration); mean sea level pressure	Ice core δ^{18}O (uncalibrated) and ~~surface~~snow accumulation~~;~~ (uncalibrated); tree ring width data (calibrated against temperature and precipitation; Fig. 2b); used isotope-~~enable~~enabled CESM1 last millennium ensemble as a prior (natural variability)	1800-2000	Sea ice extent: Annual, 5 sectors as in Raphael and Hobbs (2014) and Fogt et al. (2022a) Pressure: annual, global, 1°x1°
O'Connor et al. (2021) OCON21_ASSIM	Paleo data assimilation with climate model prior (fixed over time)	Mean sea level pressure	Global ice core, tree ring, and coral / sclerosponges (~~Fig.~~all calibrated against temperature; tree-rings calibrated against temperature and precipitation; Fig. 2c); used CESM1 Pacific pacemaker ensemble (with external forcings) as a prior	1900-2005	Annual, global, 1°x1°
O'Connor et al. (2023) OCON23_ASSIM	Paleo data assimilation with climate model prior (fixed over time)	Mean sea level pressure from sensitivity experiments	~~1~~one reconstruction using only ice core data (calibrated against temperature) and ~~1~~one reconstruction using only coral data (calibrated against temperature)	1900-2005	Annual, global, ~~interpoated~~interpolated to 1°x1°

Table 1. Details on the various reconstruction datasets used in this study.


a) Fogt et al. (2022) Pressure and Temperature Observations
King Hakon VII
East Antarctica
Ross-Amundsen Seas
ABS
Weddell Sea
b) Dalaiden et al. (2021) Proxy Data
c) O'Connor et al. (2021, 2023) Proxy Data
0°
15°S
30°S
45°S
60°S
75°S
90°S
30°N
90°E
180°
90°W
Proxy Data Key
Coral
Tree Ring
Ice Core

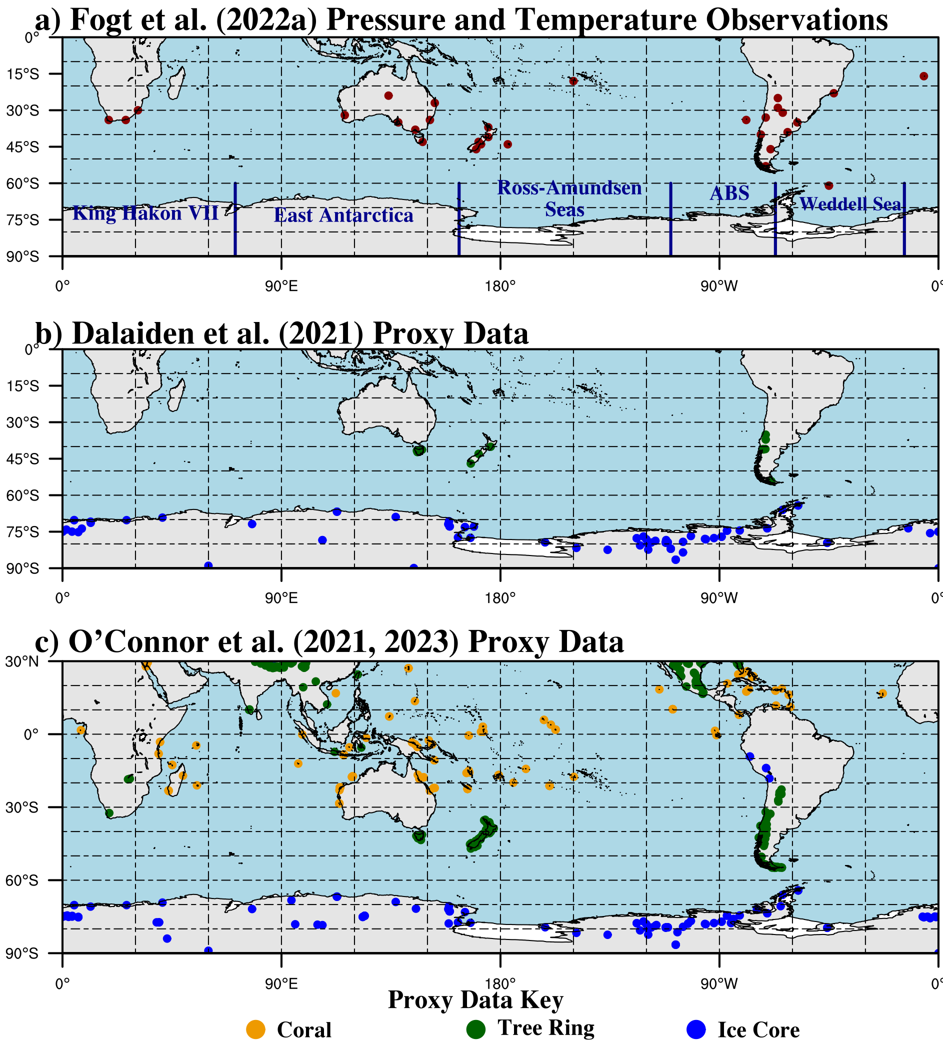


Figure 2. Map of a) temperature and pressure observations used in the Fogt et al. (2022a) seasonal sea ice reconstructions (the same pressure stations were used in the Fogt et al. (2019) and Fogt and Connolly (2021) pressure reconstruction); b) proxy data locations used in the Dalaiden et al. (2021) pressure and sea ice reconstructions; c) proxy data locations used in the O'Connor et al. (2021, 2023) pressure reconstructions. The Fogt et al. (2022a) seasonal sea ice reconstructions used only a subset of the available observations and also indices of atmospheric and oceanic variability in their reconstructions, depending on the sea ice sector being reconstructed (Table 1), depicted in a) (ABS= Amundsen-Bellingshausen Seas). For b), the ice core locations are a combination of the δ^{18}O and the surface accumulation measurements. For c), the coral proxies also include sclerosponges. Although the O'Connor et al. (2021, 2023) assimilated proxy data span the entire globe, only the data south of 30°N are shown as these have the strongest influence on the reconstruction near Antarctica.

Observed sea ice concentration, from which sea ice extent is calculated, is obtained from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager - Special Sensor Microwave Imager/Sounder (SSM/I-SSMIS). ~~The Fogt et al. (2022a) sea ice extent reconstructions~~We specifically use the Climate Data Record (CDR) daily concentration fields from the National Oceanic and Atmospheric Administration / National Snow and Ice Data Center (NOAA/NSIDC) Climate Data Record of Passive Microwave Sea Ice Concentration, Version 4 (https://nsidc.org/data/g02202) ~~(Meier et al., 2021). The CDR algorithm output combines of~~(Meier et al., 2021). The CDR algorithm output combines ice concentration estimates from the National Aeronautics and Space Administration (NASA) Team algorithm and the NASA Bootstrap algorithm, and are available at a 25 km x 25 km polar stereographic grid. Sea ice extent is calculated as the ~~equatorward limit of the~~cumulative area ~~bounded by~~of grid cells with at least 15% sea ice concentration~~ isoline~~; monthly, seasonal, and annual means are calculated from the daily sea ice concentration data. Patching of a short temporal discontinuity of the sea ice observations between December 1987 and January 1988 was done as in Fogt et al. (2022a). Longitude bounds for the sea ice sectors used in this study follow~~ Raphael and Hobbs (2014),~~ Raphael and Hobbs (2014), specifically defined as: Amundsen-Bellingshausen Seas (250°-290°E), Weddell Sea (290°-346°E), and the Ross-Amundsen Sea (162°-250°E); see Figs. 1 and 2a for boundaries.

2.2) Station-based reconstructions

We use the best-fit reconstruction from the Fogt et al. (2022a) seasonal sea ice extent reconstructions, hereafter FOGT22_STAT, conducted separately for the Raphael and Hobbs

(2014) sectors as well as for the total extent as the station-based sea ice extent reconstruction. To get the annual mean, the four seasons were averaged together each year.

The seasonal spatially complete pressure reconstructions of Fogt et al. (2019) span the region poleward of 60°S at 100km resolution, and are a kriging interpolation of individual Antarctic station reconstructions from Fogt et al. (2016a,b). The Fogt et al. (2019) seasonal Antarctic pressure reconstruction has been merged with the National Oceanic and Atmospheric Administration (NOAA) 20th century reanalysis version 3 data ~~(Slivinski et al., 2019)~~(Slivinski et al., 2019) equatorward of 60°S, as discussed in Fogt and Connolly (2021), hereafter FC21_STAT, which we use for comparison in this study. We similarly average the F21_STAT over the four seasons to calculate the annual mean for comparison.

2.~~2~~3) Paleo-based reconstructions

While there are a few ocean sediment~~-~~-derived sea ice extent reconstructions near the Antarctic Peninsula relevant to this study, Thomas et al. (2019) note that the poorer temporal resolution and lack of calibration of most marine sediments create challenges when combining and comparing them to ice core~~-~~-derived sea ice reconstructions. We therefore employ two main ice core based reconstructions of sea ice extent, as in Fogt et al. ~~(2022b): Abram et al. (2010) used a~~(2022b): Abram et al. (2010) , which ends in 2004 (Table 1), used three ice cores from the Antarctic Peninsula to reconstruct the winter sea ice extent from 70°W – 100°W, in the Bellingshausen Sea (outlined in Fig. ~~1a). The Abram et al. (2010) reconstruction ends in 2004. Further west, Thomas and Abram (2016) provide a reconstruction with annual resolution of the sea ice extent in the Ross Sea (marked in Fig. 1a). Both Abram et al. (2010) and Thomas and Abram (2016)~~1a), hereafter AB10_PALEO. Further west, Thomas and Abram (2016) provide a reconstruction, hereafter TA16_PALEO, with annual resolution of the sea ice extent in the Ross

Sea (marked in Fig. 1a). Both AB10_PALEO and TA16_PALEO reconstructed the sea ice extent based on the methanesulphonic acid (MSA) content – an indicator related to the algal blooms occurring during the ice break-up periods - -from different Antarctic ice cores by calibrating them against sea ice extent from satellite observations.

As mentioned earlier, multiple ice core, tree-ring, and coral proxy records can be assimilated with Earth System Model simulations to provide annual mean gridded estimates of not only sea ice extent and concentration, but also atmospheric pressure. We employ two such estimates of previous Antarctic climate in this study- those of Dalaiden et al. (2021) and O'Connor et al. (2021, 2023; no sea ice reconstruction), which both use proxy measurements but different data assimilation filters and different Earth System Model simulations as the data assimilation "prior" (the initial guess that is updated with proxy data) (Table 1). Although no sea ice nor atmospheric pressure observations are directly assimilated, the data assimilation relies on the covariance between assimilated observations and those variables given by the Earth System Model to reconstruct them (Widmann et al., 2010; Goosse et al., 2010; Hakim et al., 2016). The temporal variability thus only comes from proxy records, which are spatially interpolated during data assimilation. Therefore, the final reconstruction is dynamically consistent through all the reconstructed climate variables. For Dalaiden et al. (2021) we use the sea ice concentration, extent, and sea level pressure datasets generated using the isotope-enabled Community Earth System Model version 1 (CESM1) last millennium ensemble as the prior (Brady et al., 2019), and based on Southern Hemisphere ice cores and tree rings (Fig. 2b). We further use the O'Connor et al. (2021) pressure dataset generated using the CESM1 tropical Pacific pacemaker ensemble of simulations (Schneider and Deser, 2018) as the data assimilation prior, as this ensemble best represents historical external forcing and Pacific variability relative to other simulations (for more details see O'Connor et al., 2021). The O'Connor et al. (2021) dataset includes a global proxy database of ice cores, corals, and tree rings, synthesized by the PAGES2k working group (Fig. 2c) (PAGES2k Consortium et al., 2017), with additional snow accumulation records (Thomas et al., 2017). The comparison between the Dalaiden et al. (2021) reconstruction and the O'Connor et al. (2021) reconstruction reveals the roles of different filtering methods, proxy databases, and climate model priors. O'Connor et al. (2023) provide additional single-proxy reconstructions, using the same configuration as O'Connor et al. (2021), but based only on the assimilation of ice core or coral records. The comparison between these sensitivity experiments with O'Connor et al. (2021) allows a better understanding of the possible role of certain proxy data on the resulting reconstruction.

3. Results

3.1) Comparison of Antarctic sea ice extent reconstructions

As alluded to in the introduction and Fogt et al. *2.4) Reconstructions based on paleo data assimilation*

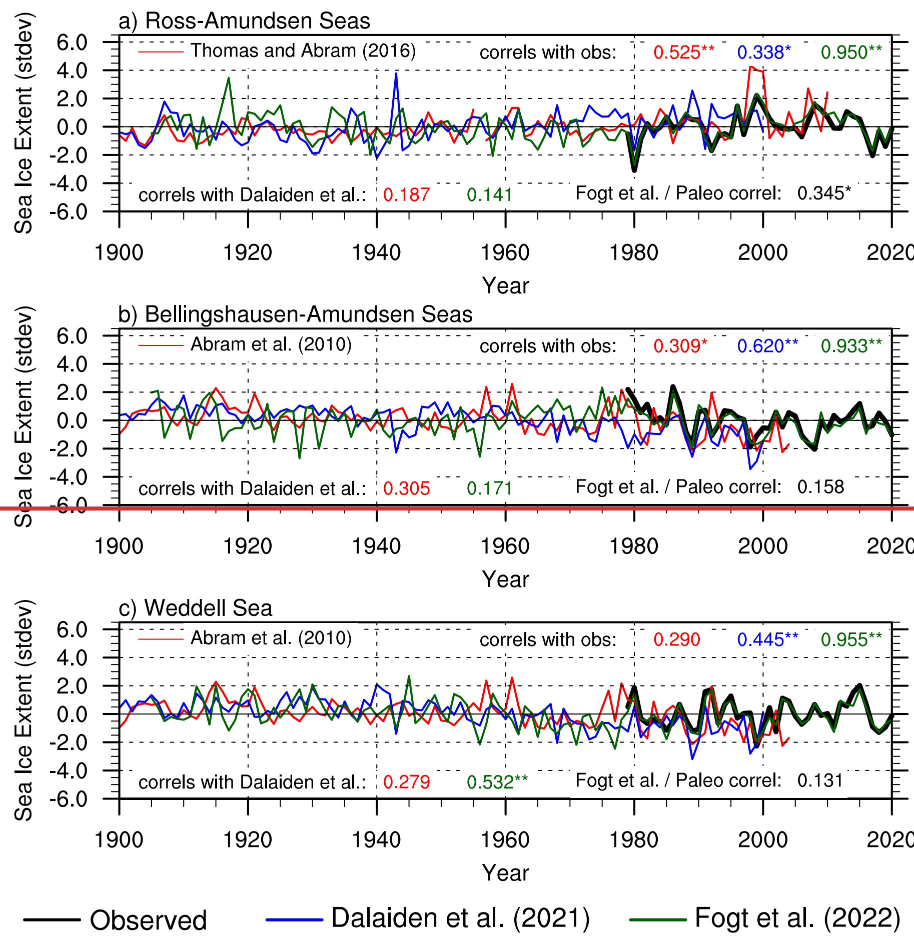
As mentioned earlier, multiple ice core, tree-ring, and coral proxy records can be assimilated within Earth System Model simulations to provide annual mean gridded estimates of not only sea ice extent and concentration, but also atmospheric pressure. We employ two such estimates of previous Antarctic climate in this study- those of Dalaiden et al. (2021) and O'Connor et al. (2021, 2023; no sea ice reconstruction), which both use proxy measurements but different data assimilation filters and different Earth System Model simulations as the data assimilation "prior" (the initial guess that is updated with proxy data) (Table 1). Although no sea ice nor atmospheric pressure observations are directly assimilated, the data assimilation relies on the covariance between the climate in the proxy locations and sea ice concentration or sea-level pressure, based on covariance patterns in the data assimilation prior (Widmann et al., 2010; Goosse et al., 2010; Hakim et al., 2016). The temporal variability thus only comes from proxy records, which are spatially interpolated during data assimilation. Therefore, the final reconstruction is dynamically consistent through all the reconstructed climate variables. For Dalaiden et al. (2021), hereafter DAL21_ASSIM, we use the sea ice concentration, extent, and sea level pressure datasets generated using the isotope-enabled Community Earth System Model version 1 (CESM1) last millennium ensemble as the prior (Brady et al., 2019), and based on Southern Hemisphere ice cores and tree rings (Fig. 2b). The sea ice extent from DAL21_ASSIM was calculated using the Raphael and Hobbs (2014) boundaries to compare with FOGT_STAT. We further use the O'Connor et al. (2021) pressure dataset, hereafter OCON21_ASSIM, generated using the CESM1 tropical Pacific pacemaker ensemble of simulations (Schneider and Deser, 2018) as the data assimilation prior, as this ensemble best represents historical external forcing and Pacific variability relative to other simulations (for more details see O'Connor et al., 2021). The OCON21_ASSIM dataset includes a global proxy database of ice cores, corals, and tree rings, synthesized by the PAGES2k working group (Fig. 2c) (PAGES2k Consortium et al., 2017), with additional snow accumulation records (Thomas et al., 2017; as in Dalaiden et al., 2021). It is worth mentioning that the prior used in the DAL21_ASSIM and OCON21_ASSIM reconstructions is fixed over time (i.e., each reconstructed year is based on the same prior) but while the prior used in the OCON21_ASSIM reconstruction includes the anthropogenic forcing, the reconstruction of DAL21_ASSIM solely relies on the natural climate variability as in Hakim et al. (2016) and Steiger et al. (2018). Therefore, since the prior remains constant over time, the temporal variability of the reconstruction only arises from the proxies. The comparison between the DAL21_ASSIM reconstruction and the OCON21_ASSIM reconstruction reveals the roles of different filtering methods, proxy databases, and atmospheric forcings used to form the climate model priors. O'Connor et al. (2023), hereafter OCON23_ASSIM, provide additional single-proxy reconstructions, using the same configuration as OCON21_ASSIM, but based only on the assimilation of ice core or coral records. The comparison between these sensitivity experiments with OCON21_ASSIM allows a better understanding of the possible role of certain proxy data on the resulting reconstruction.

3. Results

3.1) Comparison of Antarctic sea ice extent reconstructions

As alluded to in the introduction and Fogt et al. (2022a,b), there are substantial sea ice extent differences between ~~the station-based sea ice extent~~ FOGT_STAT reconstructions ~~of Fogt et al. (2022a)~~ and those based on paleo data, including from data assimilation-based reconstructions. To investigate these differences further, the various time series of standardized (to place on same scale) annual-mean sea ice extent anomalies from the Ross-Amundsen Sea sector east to the Weddell Sea (see Fig. 1 for sector boundaries) are plotted in Fig. 3. Not surprisingly, the correlations with observations (color-coded numbers at the ~~Fogt et al. (2022a) reconstructions with the observed data (green number in upper~~top right of each panel in Fig. 3) are the highest for the FOGT_STAT reconstructions ($p<0.01$), as these reconstructions were specifically statistically calibrated to provide the best match to the observations. However, the correlations of the paleo-based reconstructions (including the ~~Dalaiden et al. (2021)~~DAL21_ASSIM reconstruction which is not directly calibrated to sea ice observations) ~~reconstructions~~ are also uniformly positive~~, and the Thomas and Abram (2016) provides the~~

highest correlations of the paleo-based reconstructions in the Ross-Amundsen Seas (Fig. 3a, $r=0.525$, $p<0.01$), while the Dalaiden et al. (2021) estimates from their data assimilation-based reconstruction are the highest correlations nearer to the Antarctic Peninsula in the Bellingshausen-Amundsen (Fig. 3b, $r=0.620$, $p<0.01$) and Weddell Seas (Fig. 3c, $r=0.445$, $p<0.01$)..



a) Ross-Amundsen Seas
Thomas and Abram (2016)
correls with obs: 0.525** 0.338* 0.950**
correls with Dalaiden et al.: 0.187 0.141
Fogt et al. / Paleo correl: 0.345*
b) Bellingshausen-Amundsen Seas
Abram et al. (2010)
correls with obs: 0.309* 0.620** 0.933**
correls with Dalaiden et al.: 0.305 0.171
Fogt et al. / Paleo correl: 0.158
c) Weddell Sea
Abram et al. (2010)
correls with obs: 0.290 0.445** 0.955**
correls with Dalaiden et al.: 0.279 0.532**
Fogt et al. / Paleo correl: 0.131
Sea Ice Extent (stdev)
Year
Observed
Dalaiden et al. (2021)
Fogt et al. (2022)

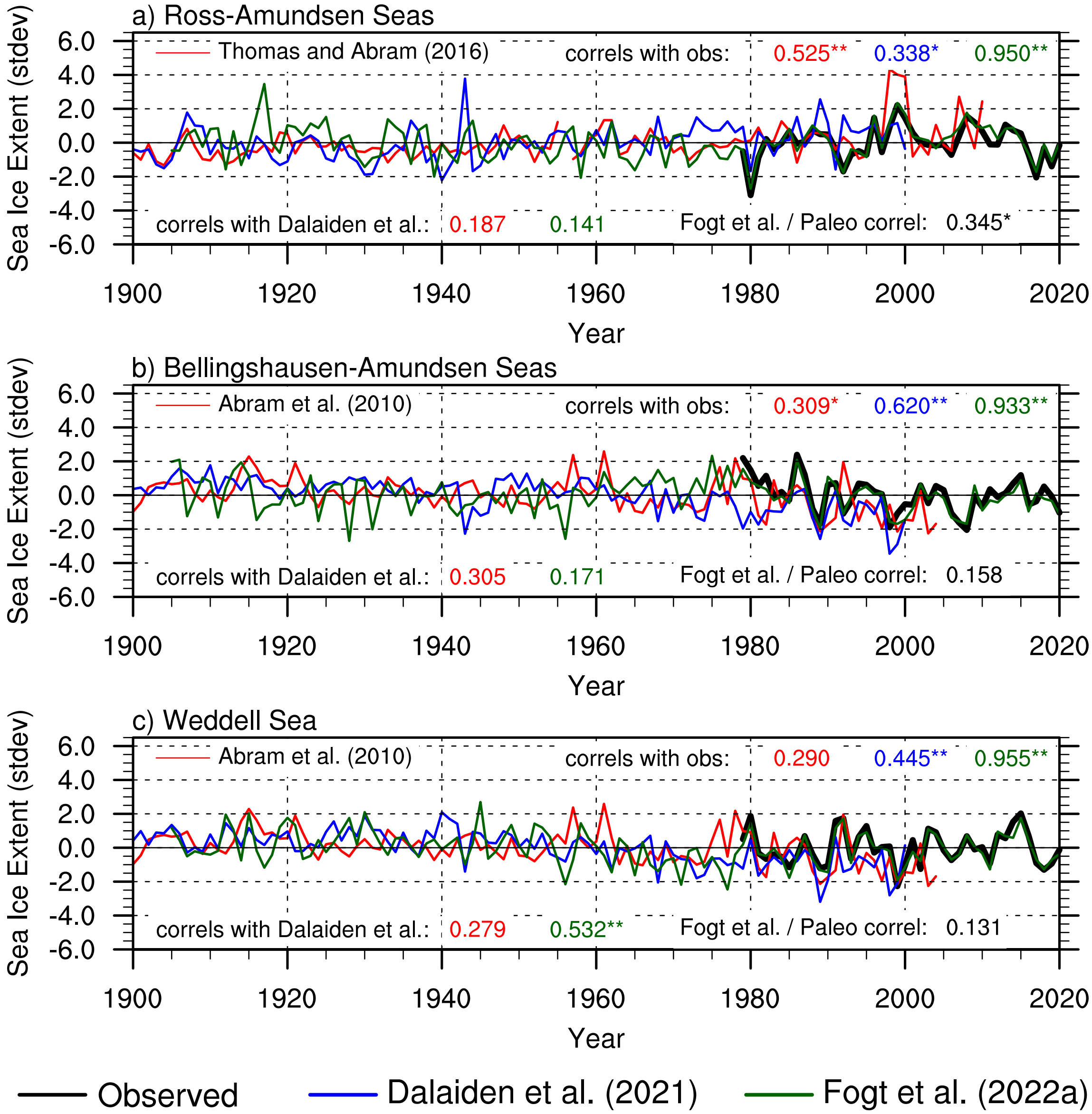


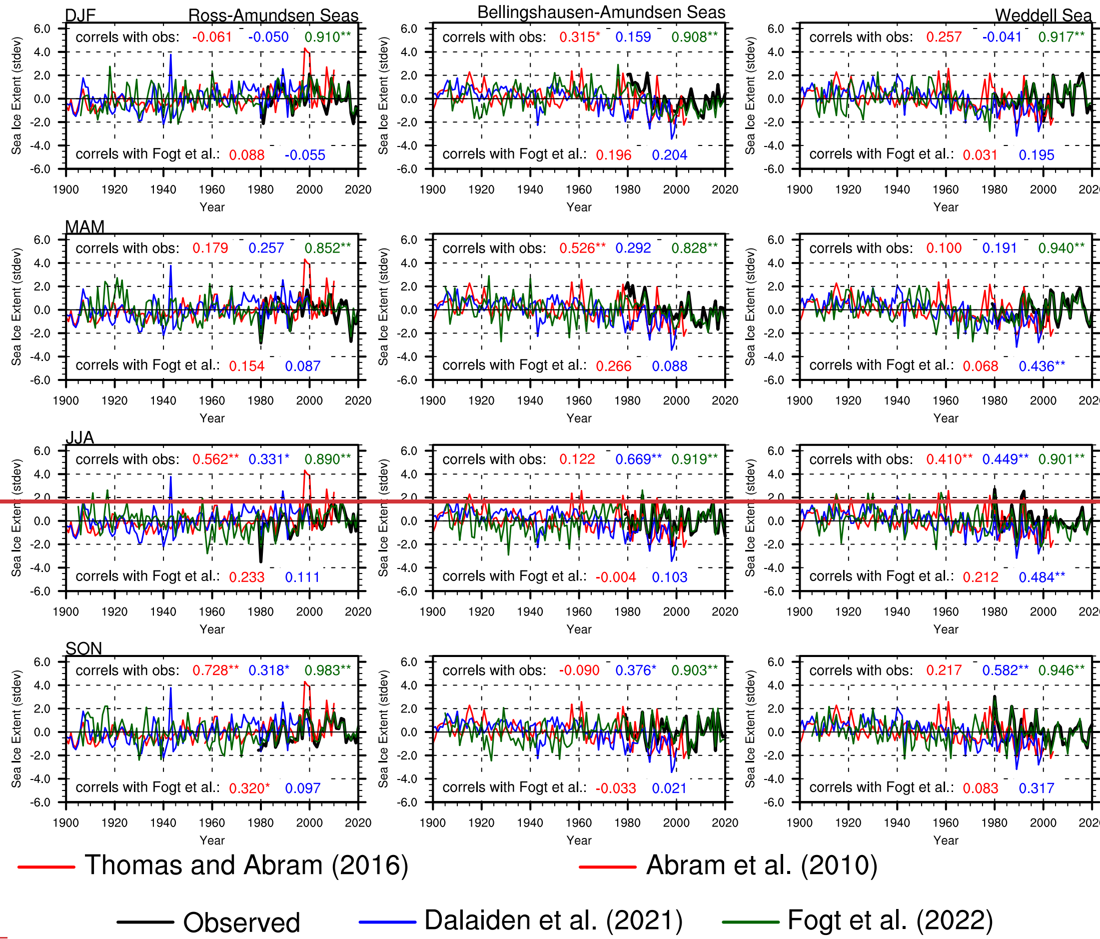
Figure 3. Annual mean sea ice extent timeseries from various reconstructions approximately related to the Raphael and Hobbs (2014) sea ice boundaries in Fig. 1 for the a) Ross-Amundsen Seas; b) Bellingshausen-Amundsen Seas; c) Weddell Sea~~. The Dalaiden et al. (2021) sectors have been adjusted to the Raphael and Hobbs (2014) boundaries.~~; paleo-based reconstructions are given in red and labeled separately for each panel. The correlations with satellite observations (in black) during the period of overlap are given in the top of each panel, with the colors denoting the individual timeseries~~.~~ as given in the legend. At the bottom, correlations with the Dalaiden et al. (2021) and Fogt et al. (2022a) reconstructions are similarly provided. In each case, after adjusting the sample size by the lag1 correlation as needed, correlations significantly different from zero at p<0.05 and p<0.01 are marked with * and **, respectively.

In contrast, ~~however, ~~the cross-correlations between the various sea ice extent reconstructions (text at bottom of each panel in Fig. 3) are much weaker overall (numbers at bottom of each plot), often falling below 0.30 (from 1905-2020, $p<0.05$~~), suggesting that~~). The weak cross-correlations suggest the interannual variability in the ~~Dalaiden et al. (2021)~~DAL21_ASSIM estimates ~~from a climate model that assimilates paleo data ~~and ~~estimates~~those from ice cores directly (both ~~Thomas~~TA16_PALEO and ~~Abram (2016) and Abram et al. (2010))~~AB10_PALEO) differ substantially~~; part~~. Part of this difference could be from a larger number of ice cores included in the ~~Dalaiden et al. (2021)~~DAL21_ASSIM reconstruction~~ (Fig. 2b) than those of Abram et al. (2010) and Thomas and Abram (2016). In~~, smoothing out the ~~Bellingshausen-Amundsen sector~~non-climatic noise (Fig. ~~3b), even though the Dalaiden et al. (2021) estimate shows a correlation of r=0.620 with observations (blue number, top of plot), the correlation of the Fogt et al. (2022a) data with the Dalaiden et al. (2021) estimate~~2b, Table 1). There is ~~only r=0.171 ($p>0.05$) during 1905-2000. Since the Fogt et al. (2022a) data are strongly correlated r=0.933 ($p<0.01$) with observations after 1979, the low correlation~~slightly better agreement between ~~these two estimates during 1905-2020 suggests they do not have similar interannual variability prior to 1979, as demonstrated in Fogt et al. (2022a,b). Of note, though, are a few cross-correlations that are near the same strength of the paleo-based estimates with observations, namely the Abram et al. (2010) correlation with the Dalaiden et al. (2021) estimates in the Bellingshausen-Amundsen Sea (Fig. 3b, r=0.305, $p>0.05$) and the Fogt et al. (2022) and Dalaiden et al. (2021) estimates in the Weddell Sea (Fig. ~~the reconstructions in the Weddell Sea, particularly for the FOGT_STAT and DAL21_ASSIM estimates (Fig. 3c, r=0.532, $p<0.01$). ~~Even though there are some agreements, the overall linear trends in the data look notably different (to be addressed later), and there are sudden anomalies in each dataset that are~~

rarely replicated in others, including for the paleo-based reconstructions in the period of satellite observations.

While it is straightforward to plot the timeseries together as in Fig. 3, understanding the differences between them-, especially prior to 1979, is much more complex, as the various reconstructions were created inwith markedly distinct and incongruent methods (Table 1) and data (Fig. 2). Further, while they are all representing sea ice extent in some fashion, the reconstruction resolutions (Table 1) also indicates they are representing it in many different ways as well (some as the ice edge latitude at a specific point, some as an area, and all with different2). First, the various temporal resolutions). One important challenge is that the Fogt et al. (2022a) of each reconstruction may result in differences: the FOGT_STAT reconstructions were generated based on in Fig. 3 are averages of seasonal statistical relationships, producing reconstructions separately for the four meteorological seasons. These seasonal reconstructions were averaged together to give the annual mean values in Fig. 3 to compare with all the other paleo-based reconstructions that only have annual mean resolution (the exception being the MSA-based reconstruction of Abram et al. (2010) is for August-October, Table 1). Nonetheless,, and even though the paleo-based reconstructions often represent the annual mean, they may be biased slightly to a particular time in the year affected primarily by the accumulation at the ice core site(s) from which the paleo-based reconstructions were generated. To understand if the relationships improve seasonally, Fig. 4 investigates the reconstructions agreement for each sector (by column) and each season (rows).

ComparedIn contrast to the annual mean data in Fig. 3, there are frequent negative correlations between the various datasets and the observations (again except for the Fogt et al. (2022a) reconstructions that were explicitly calibrated to the seasonal observations),numbers at the top of each panel in Fig. 4) as well as between the paleo-based reconstructions and those from ~~Fogt et al. (2022a) given by the~~ FOGT_STAT (numbers at the bottom of each panel in Fig. 4~~.~~). For the Ross-Amundsen sector, ~~the Thomas and Abram (2016)~~TA16_PALEO most closely aligns with the austral winter (JJA) and austral spring (SON) seasons, near the seasonal maximum sea ice extent. ~~The correlations with observations of the Thomas and Abram (2016) data exceed 0.56 (p<0.01) in these seasons, higher than the correlation of the annual mean in Fig. 3 (r=0.525, p<0.02); despite the higher correlations with the observations, the correlations of Thomas and Abram (2016) and the seasonal Fogt et al. (2022a) reconstructions however are slightly lower than for the annual (r=0.345 for annual, max for SON is r=0.320, both p<0.05). As before, this suggests a reduction in the reconstruction cross correlations prior to satellite observations (i.e., before 1979). The seasonal relationships of the Abram et al. (2010)~~The seasonal relationships of the AB10_PALEO reconstruction are a bit more nuanced: it has considerably higher correlations in MAM with observations in the Bellingshausen-Amundsen sector (r=0.526, p<0.01), but the weakest correlations in this season in the Weddell sector (r=0.10, p>0.05).



For the DAL21_ASSIM reconstruction, the relationships with observations are weakest in austral summer (Fig. 4, top row) for all sectors, and generally the highest during the second half of the year (Fig. 4, bottom two rows). Similarly, the correlations between the FOGT_STAT reconstruction and DAL21_ASSIM are typically highest in JJA.

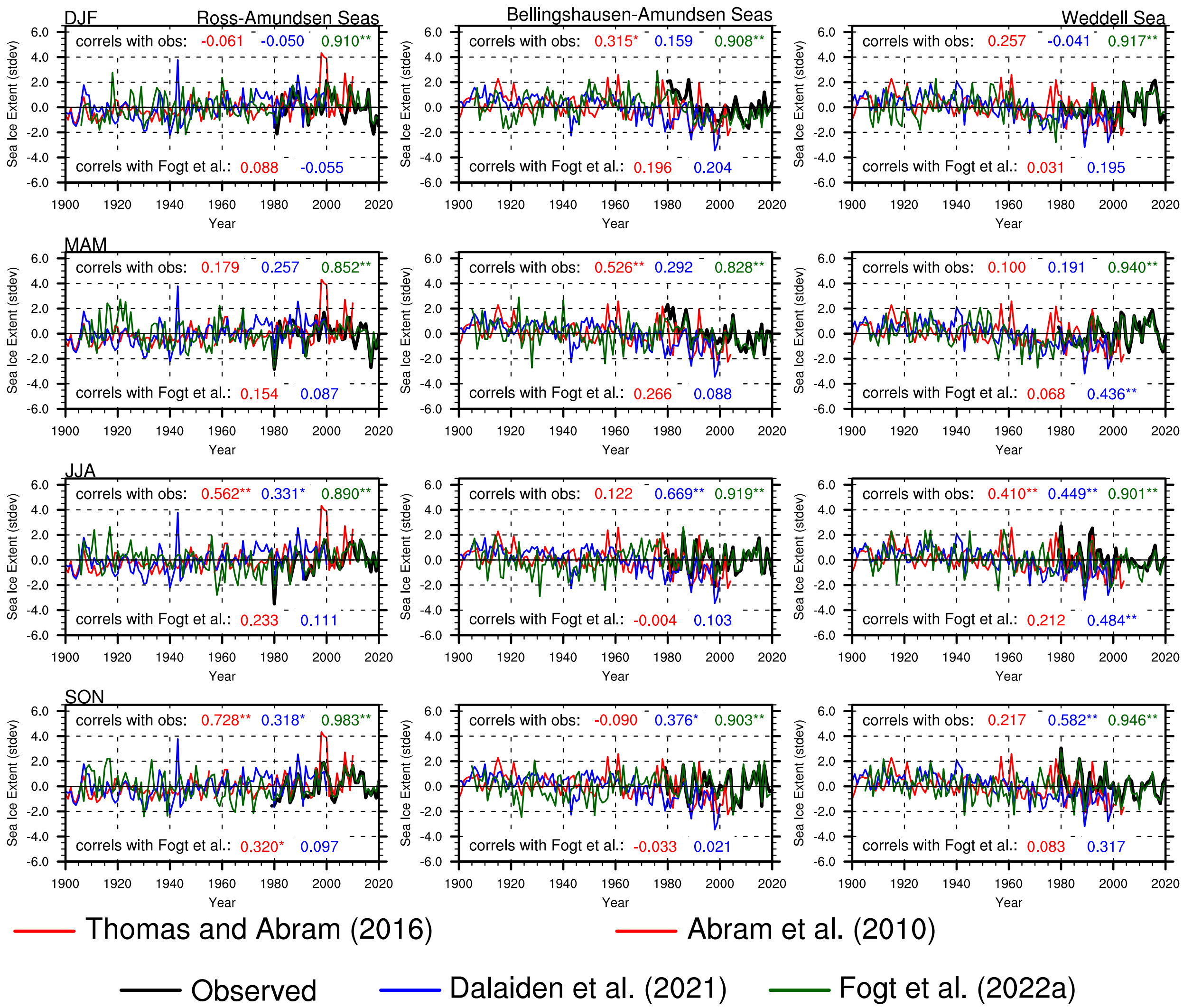
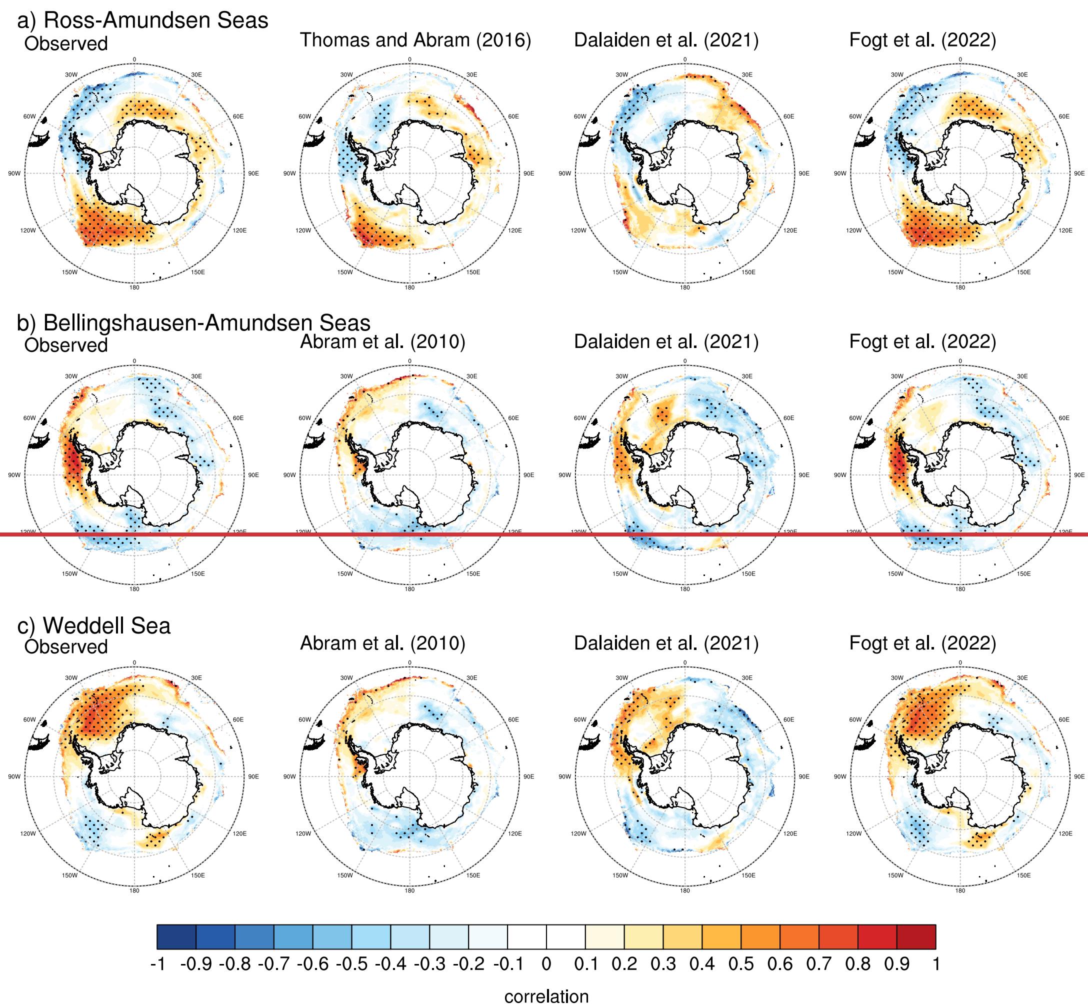


Figure 4. As in Fig. 3, but with the seasonal mean observations and reconstructions of Fogt et al. (~~2022~~2022a) with the annual mean paleo-based reconstructions. The Thomas and Abram (2016) paleo-based reconstruction is used for the Ross-Amundsen sector (left column), while the Abram et al. (2010) reconstruction is used for the other two sectors~~.~~ (middle and right columns). The correlations are color coded following the legend. Correlations with observations are given at the top of each panel, and correlations with seasonally-varying Fogt et al. (2022a) reconstructions are given at the bottom of each panel.

~~For the Dalaiden et al. (2021) estimates of sea ice from the data assimilation-based reconstruction, the relationships with observations are weakest in austral summer (top row) for all sectors, and generally the highest in austral winter and spring (bottom two rows). Interestingly, the correlations between the Fogt et al. (2022a) reconstruction and the estimates~~

~~from Dalaiden et al. (2021) are in typically highest in JJA, and even exceed the correlations of the paleo-based reconstructions with observations in the Weddel sector in this season (r=0.484, $p<0.01$), suggesting that there is some shared interannual variability in these datasets prior to 1979 in the winter season.~~

While the ~~seasonal~~ comparisons in Fig. 4 reveal that ~~better~~the agreement between the various reconstructions is not uniform throughout the year, , the various spatial footprints of the reconstructions can ~~be achieved apart from the annual mean representation, there are other factors that could lead to~~also create differences ~~in the reconstruction that would not be captured by individual portions of the seasonal cycle~~between the reconstructions. In particular, while ice core-based reconstructions can provide information directly over the continent on longer timescales, their connections to Antarctic climate are geographically limited (Table 1), restricted to the prominent pathway of tracers from the ocean/ice boundary near the ice edge to their deposition at the ice core site (Thomas et al. 2019). In contrast, both the ~~Fogt et al. (2022a)~~FOGT_STAT and ~~Dalaiden et al. (2021)~~DAL21_ASSIM reconstructions represent the cumulative sea ice area >15% in specific geographic boundaries (Figs. 1a and 2a). To investigate the role the various spatial configurations may play in the differences between the reconstructions, each annual mean reconstruction was correlated through time with the full spatial field of annual mean sea ice concentration satellite observations (at each grid point separately); these correlations are plotted in Fig. 5, with correlations statistically different from zero at $p<0.05$ stippled. In Fig. 5, the correlation of the observed sea ice extent series for each sector with the satellite sea ice concentration field is provided in the far left column for comparison of the maximum expected correlation pattern and magnitude.


a) Ross-Amundsen Seas
Observed
Thomas and Abram (2016)
Dalaiden et al. (2021)
Fogt et al. (2022)
b) Bellingshausen-Amundsen Seas
Observed
Abram et al. (2010)
Dalaiden et al. (2021)
Fogt et al. (2022)
c) Weddell Sea
Observed
Abram et al. (2010)
Dalaiden et al. (2021)
Fogt et al. (2022)
-1 -0.9 -0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
correlation

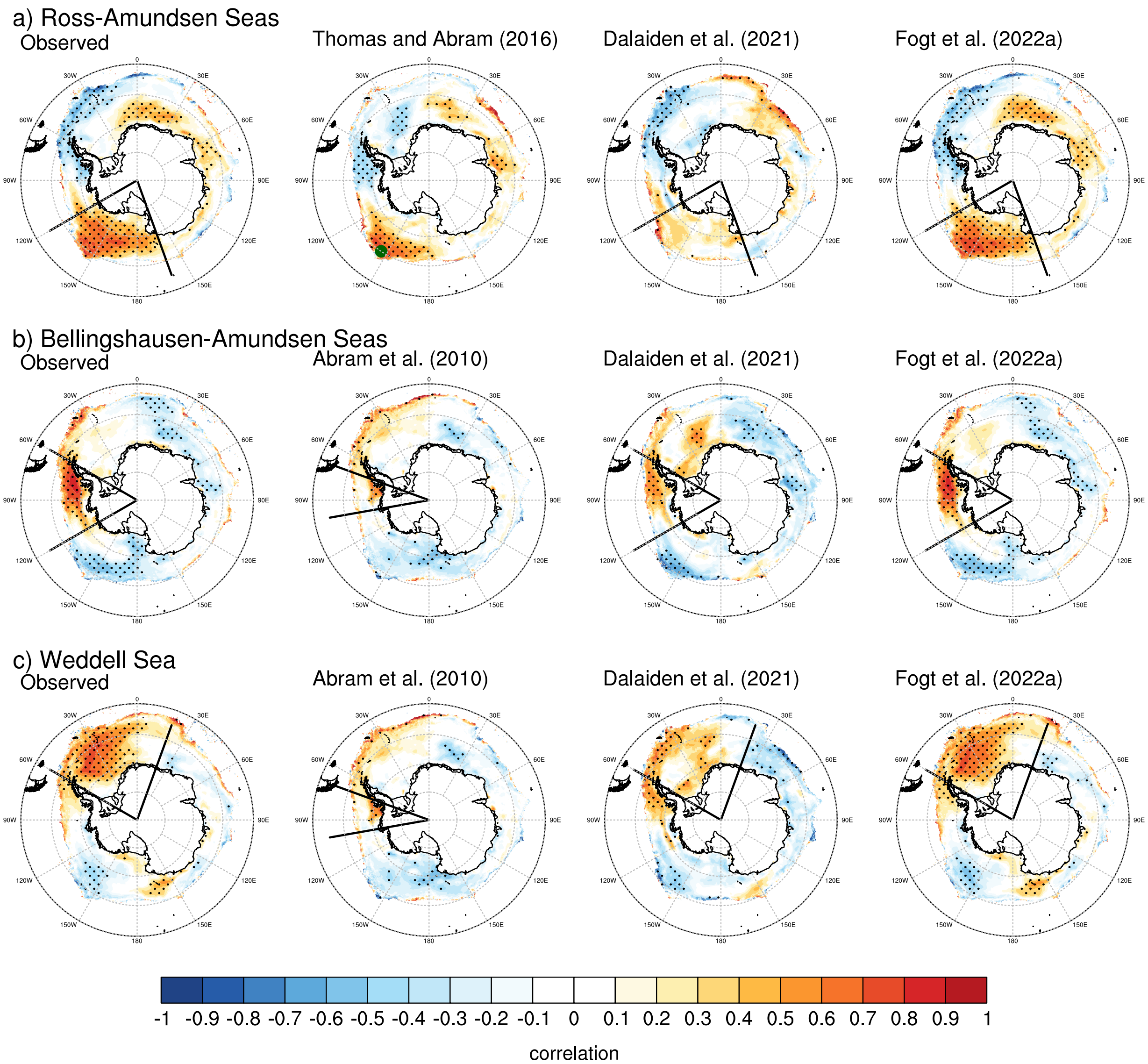


Figure 5. Correlations (1979-end of series) of annual mean sea ice extent timeseries with the observed annual mean sea ice concentration field, separated by the Raphael and Hobbs (2014) sectors, as in Fig. 3. The solid lines (or marker for Thomas and Abram (2016) represent the longitudinal boundaries of the observations or reconstructions for each sector (Table 1). In each row, correlations of the observed sea ice extent time series with the sea ice concentration are given for reference. a) Ross-Amundsen Seas; b) ~~Belingshausen~~Bellingshausen-Amundsen Seas; c) Weddell Sea.

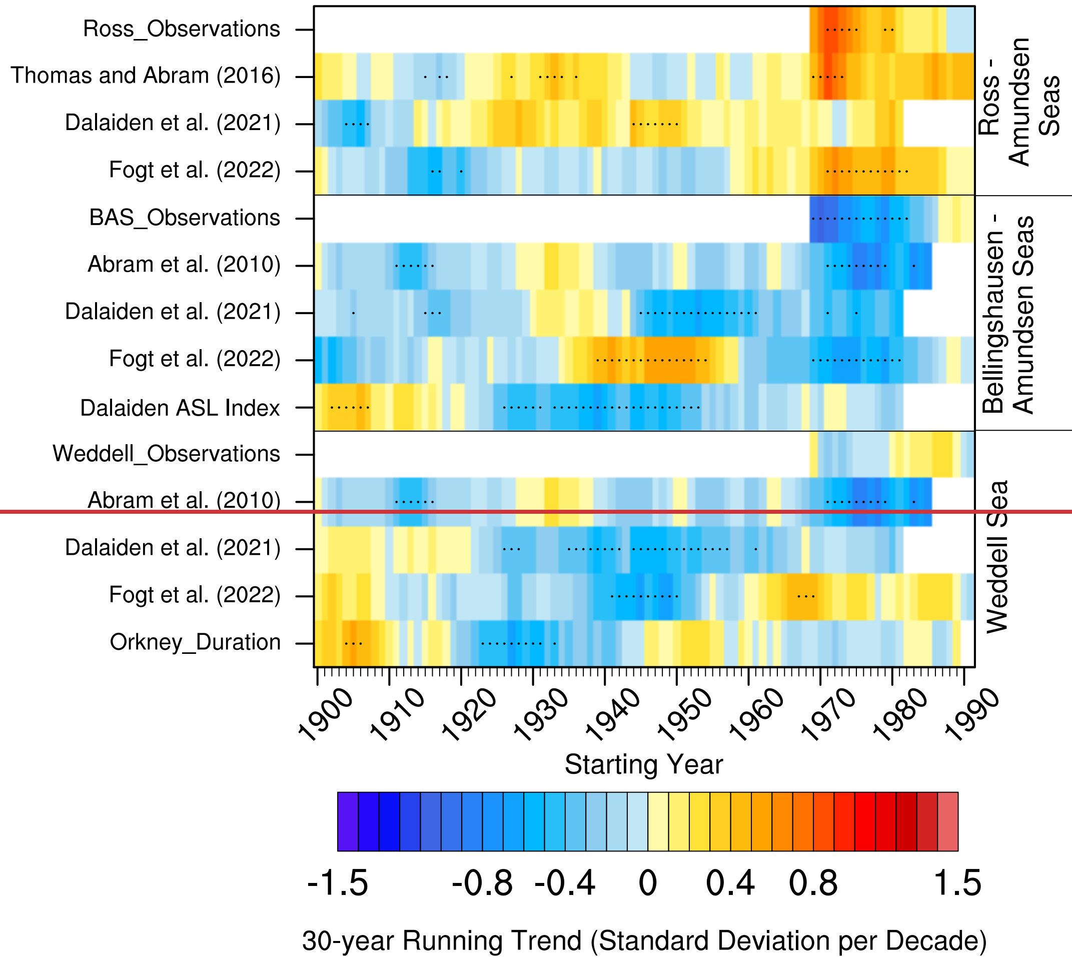
In the Ross-Amundsen sector (Fig. 5, top row), the ~~Thomas~~TA16_PALEO and ~~Abram (2016) and Fogt et al. (2022a)~~FOGT_STAT reconstructions represent the observed pattern well, although as expected the region of positive correlations with the ~~Thomas and Abram~~

~~(2016)~~TA16_PALEO is smaller and confined closer to the ice edge – their reconstruction is an estimate of the ice edge at a point in the Ross Sea (Fig. 1, Table 1). While the ~~Dalaiden et al. (2021)~~DAL21_ASSIM spatial correlation field is notably weaker, it is important to remember that unlike the other sea ice extent estimates examined here, this reconstruction was not calibrated ~~in any way to sea ice, and was only extracted from the climate model simulations constrained by paleo data.~~to sea ice observations. Nonetheless, it still maintains a similar spatial pattern of positive and negative correlations to the other datasets, suggesting that its geographic representation is broadly similar to other datasets.

The ~~Abram et al. (2010)~~AB10_PALEO reconstruction shows a much weaker pattern of correlations than the other estimates in the Bellingshausen-Amundsen and Weddell sectors (middle and bottom rows of Fig. 5), while the ~~Dalaiden et al. (2021)~~DAL21_ASSIM estimates align much better with observations in these sectors. The ~~Abram et al. (2010)~~AB10_PALEO relationships with the sea ice concentrations only modestly improves seasonally (not shown). Together, this suggests that the spatial (and to a lesser extent, seasonal) limitation of the ice conditions represented by the ~~Abram et al. (2010)~~AB10_PALEO reconstruction is an important contributing factor of its differences with the other sea ice extent estimates examined here. From Fig. 5, the ~~Abram et al. (2010)~~AB10_PALEO reconstruction has significant correlations at the far equatorward sea ice edge, stretching from the Bellingshausen Sea eastward across the Antarctic Peninsula to the Weddell Sea, different ~~than~~from the 70°W-100°W region originally suggested. This different spatial relationship in the annual mean (compared to the originally published August – October) also explains why it has correlations with sea ice observations from both the Bellingshausen-Amundsen and Weddell sectors (Figs. 3-4), albeit much weaker than other reconstructions. This spatial relationship is to be expected as it is only based on three

Antarctic Peninsula ice cores (Table 1), compared to the array of ice cores used in DAL21_ASSIM (Fig. 2b)

The timeseries in Figs. 3-4 suggest that while there are notable differences in the interannual variability in the various reconstructions, there are also differences in longer-term changes and especially the trends through time. Figure 6 investigates these discrepancies through the use of 30-year running trends, similar to that done in Fogt et al. (2022b), but including the Weddell sector and other data sources.


Ross_Observations
Thomas and Abram (2016)
Dalaiden et al. (2021)
Fogt et al. (2022)
BAS_Observations
Abram et al. (2010)
Dalaiden et al. (2021)
Fogt et al. (2022)
Dalaiden ASL Index
Weddell_Observations
Abram et al. (2010)
Dalaiden et al. (2021)
Fogt et al. (2022)
Orkney_Duration
Ross - Amundsen Seas
Bellingshausen - Amundsen Seas
Weddell Sea
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
Starting Year
-1.5
-0.8
-0.4
0
0.4
0.8
1.5
30-year Running Trend (Standard Deviation per Decade)

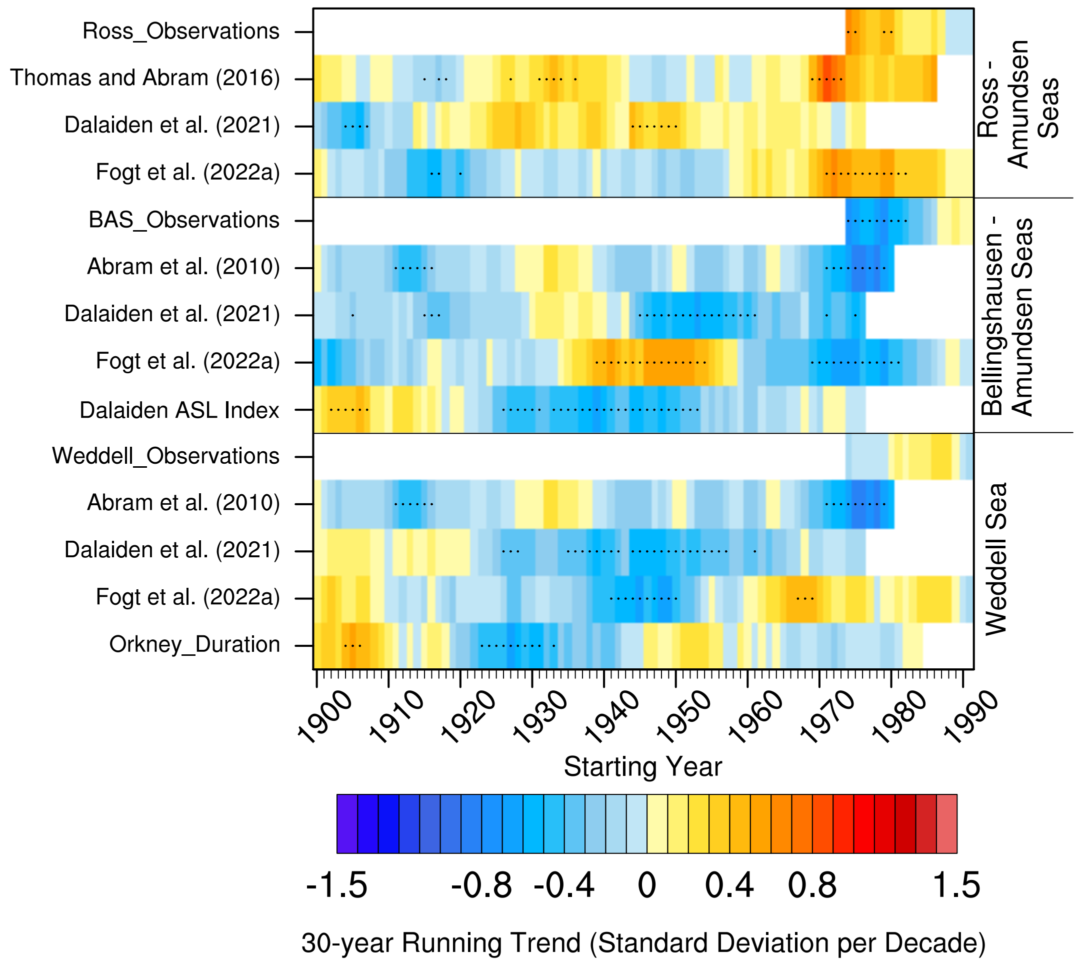


Figure 6. 30-year running trends (standard deviations per decade) of the annual mean sea ice extent timeseries in Fig. 3. Individual 30-year trends that are statistically different from zero at *p*<0.05 are stippled. For the Weddell Sea, the fast ice duration at the Orkney islands from Murphy et al. (1995) is also provided. For the Bellingshausen-Amundsen Sea region, the ASL index from Dalaiden et al. (2021), defined as the annual mean 500 hPa geopotential heihtheight from 60°-75°S, 170°E – 70°W, is also shown. Trends are only calculated if 25 years or more are available in each 30-year window.

One clear pattern in the satellite-observed trends discussed in the introduction and shown in Fig. 1a is the opposing nature of positive sea ice extent trends (equatorward movement of the ice edge) in the Ross Sea and negative sea ice extent trends in the Bellingshausen-Amundsen sector (Fig. 6). As suggested in Fogt et al. (2022a) in their investigation of the total Antarctic sea ice extent trends and evident in Fig. 6, theseThese trends reverse and weaken after the 2016 sudden decline, (Fig. 6; Fogt et al. 2022a), but still demonstrate opposite behavior, strongly tied to the atmospheric circulation around the Amundsen Sea low (Hosking et al., 2013; Raphael et al., 2016; Holland and Kwok, 2012).(Hosking et al., 2013; Raphael et al., 2016; Holland and Kwok, 2012). While the various reconstructions capture the observed trends (including their statistical significance), there are marked differences in the signs of the trends prior to the satellite observations around 1979. In particular, paleo-based sea ice extent estimates generally displayindicate that the observed trends are part of a long-term continuous trend of the same sign throughout much of the 20th century (i.e., that there are increases in the Ross Sea sector and decreases in the Bellingshausen Sea region throughout the 20th century);; this story is also consistent in the Weddell sector, as the paleo-based reconstructions only show statistically significant trends prior to 1979 that are the same sign as the observed trends after 1979. In contrast, the Fogt et al. (2022a)FOGT_STAT reconstructions show a pronounced shift in the trend sign and magnitude through time. The Fogt et al. (2022a)FOGT_STAT sea ice reconstruction trends are characterized with statistically significant positive trends in the middle 20th century in the Bellingshausen-Amundsen sector (opposite the decreases after 1979 there), and statistically significant negative trends in the Ross Sea in the early 20th century, with a prolonged period of weaker negative trends throughout the 20th century, opposite to the strong positive trends in the satellite observations starting in 1979 (Fig. 6). In the Weddell sector, where there is a better agreement between the Fogt et al. (2022a)FOGT_STAT and Dalaiden et al. (2021)DAL21_ASSIM estimates (Figs. 3-5), the trends align better through time. Moreover, these trends and their temporal changes in both significance and sign are broadly aligned with the South Orkney fast ice duration dataset of Murphy et al. (1995),Murphy et al. (1995), with positive trends in the first portion of the 20th century that change to negative trends through much of the middle 20th century, to weak trends during the satellite observation period.

While the seasonal and spatial differences between the various reconstructions evaluated in Figs. 2-~~3~~5 undoubtedly play a role (especially for the ~~Abram et al. (2010)~~AB10_PALEO reconstruction), Fig. ~~5~~6 suggests that changes in the underlying implied atmospheric circulation are also playing a role. In observations (Fig. 1a), the differing sea ice extent trends in the Bellingshausen and Ross Seas are largely tied to the atmospheric circulation around the Amundsen Sea low and implied sea ice drift changes ~~(Holland and Kwok, 2012; Holland, 2014).~~(Holland and Kwok, 2012; Holland, 2014). Although there are no long-term direct observations, the ASL index extracted from the pressure field in ~~the proxy-based~~DAL21_ASSIM reconstructions ~~of Dalaiden et al. (2021) show~~shows changes through time that are nearly opposite the ~~Fogt et al. (2022a)~~FOGT_STAT reconstructions for the Bellingshausen-Amundsen sector~~ in the early and middle 20th centuries~~, potentially confirming that underlying atmospheric circulation changes are a dominant contribution to the different sea ice changes.

While reconstruction uncertainty will always play a role in differences between various historical estimates, the comparisons of the various sea ice reconstructions thus far suggest that: a) the ~~Abram et al. (2010)~~AB10_PALEO is primarily different from other reconstructions because of its different spatial footprint; b) the methodology used to create the reconstructions or their temporal resolution does not play a consistent role, as correlations between the proxy-based reconstructions as well as with the station-based reconstructions vary considerably; c) the atmospheric circulation associated with the sea ice reconstructions appears to be a dominant mechanism for differences between them. To investigate this further, the role of implied changes in the atmospheric circulation underlying the proxy-based and station-based reconstructions is therefore the focus for the remainder of this paper.

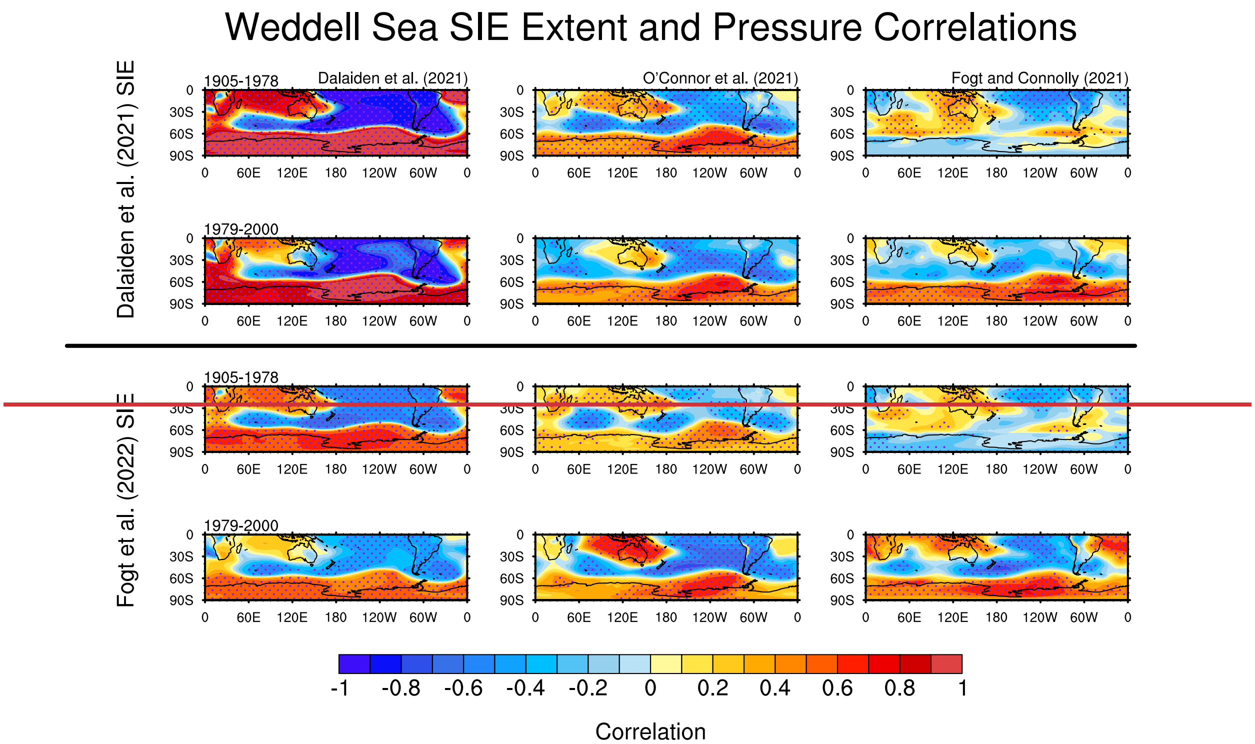
3.2) Connection to the atmospheric circulation changes and comparison of Antarctic sea level pressure reconstructions

Since 20th century atmospheric reanalyses have been shown to have long-term artificial pressure trends throughout the early and middle 20th century (Schneider and Fogt, 2018; Fogt et al., 2020), our analysis of the relationship between sea ice extent and the atmospheric circulation is focused on other estimates of pressure. In particular, for consistency we employ estimates of pressure from reconstructions generated using proxy data assimilation with various climate model priors and proxy datasets, including the Dalaiden et al. (2021) and O'Connor et al. (2021,2023) datasets (Table 1). For a station-based estimate, we also investigate the Fogt and Connolly (2021) dataset, which is a blend interpolated seasonal Antarctic station pressure reconstructions south of 60°S (Fogt et al., 2019, 2017), and the NOAA 20th century reanalysis version 3 equatorward of 60°S (Table 1). Since the Antarctic station pressure reconstructions were generated using a similar statistical technique as the Fogt et al. (2022a) sea ice extent reconstructions, this allows for an evaluation of other estimates that are expected to provide similar temporal variability as the Fogt et al. (2022a) sea ice extent reconstructions.

Since 20th century atmospheric reanalyses have been shown to have long-term artificial pressure trends throughout the early and middle 20th century (Schneider and Fogt, 2018; Fogt et al., 2020), our analysis of the relationship between sea ice extent and the atmospheric circulation is focused on other estimates. In particular, we examine pressure reconstructions generated using proxy data assimilation with various climate model priors and proxy datasets, including the

DAL21_ASSIM and O'Connor et al. (2021, 2023) datasets (Table 1), as well as a station-based estimate, FC21_STAT,

Figure 7 displays the correlations for the Weddell sector sea ice extent from Dalaiden et al. (2021) with the(top rows) DAL21_ASSIM and (bottom rows) FOGT_STAT with three gridded pressure datasets in the top rows, and the Weddell sector sea ice extent reconstructions from Fogt et al. (2022a) with the same gridded datasets in the bottom rows. The gridded pressure datasets are grouped by columns, and further broken into the pre-satellite sea ice observation period of 1905-1978 (top rows of each section) and satellite-era sea ice observation period (1979-2000). Overall the patterns are quite similar in each of the panels, reflecting the broad similarities of the sea ice reconstructions in the Weddell sector (Figs. 3-5). Here, the sea ice extent reconstructions show a strong positive correlation with pressure over the Antarctic continent that changes to negative correlations with pressure in the Pacific Ocean from the midlatitudes and equatorward, including South America. For both the Dalaiden et al. (2021)DAL21_ASSIM and O'Connor et al. (2021)OCON21_ASSIM pressure datasets, regardless of the sea ice extent estimate (top or bottom half of Fig. 7), these relationships exist in a similar fashion throughout time, suggesting



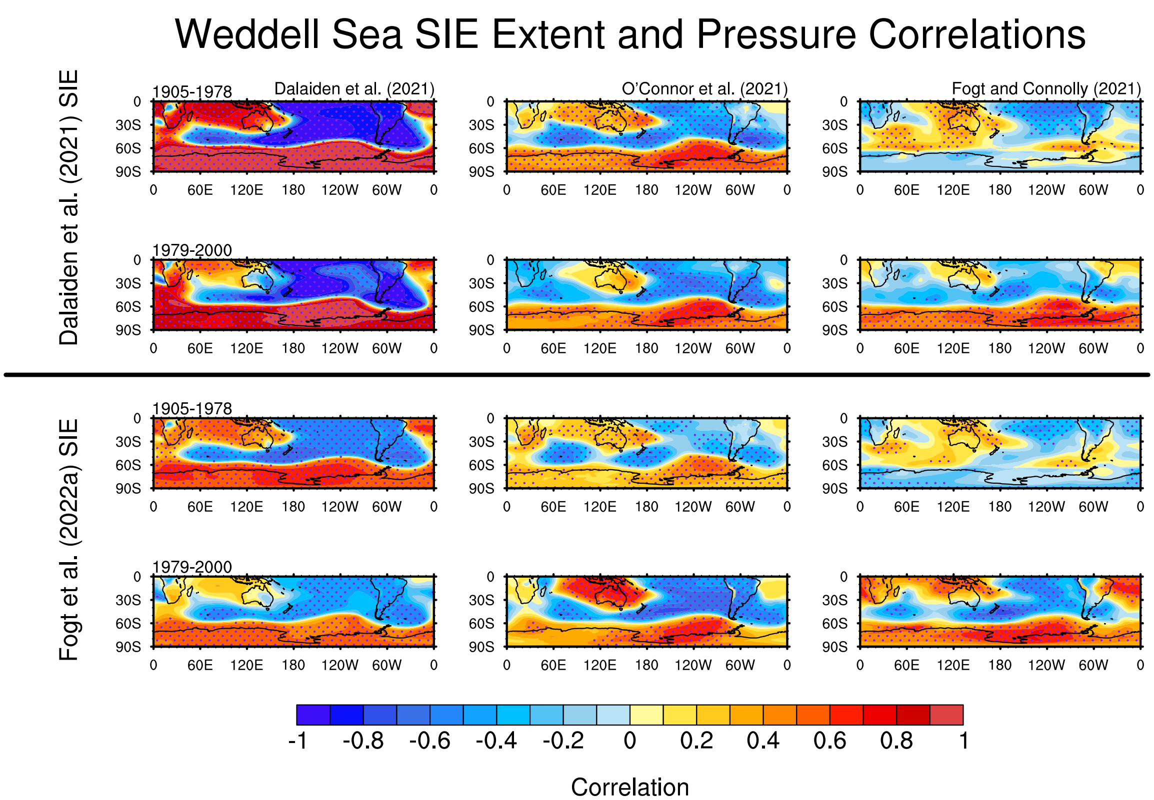


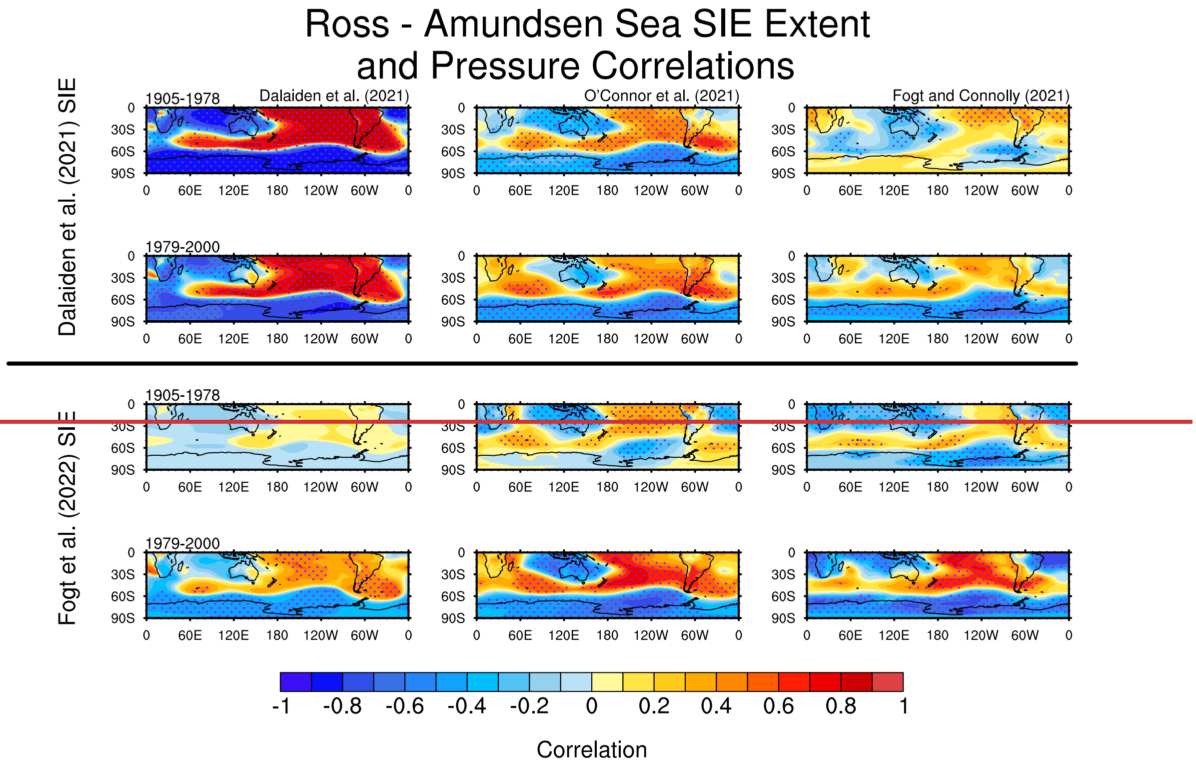
Figure 7. Annual mean correlations of (top half) Dalaiden et al. (2021) and (bottom half) Fogt et al. (2022a) sea ice extent correlations for the Weddell Sea with three 20th century spatially complete pressure reconstructions (columns). In each half, the top row are ~~for~~ correlations in the

pre-satellite period, 1905-1978, and the bottom are for 1979-2000. The pressure reconstructions are (left column) Dalaiden et al. (2021), (middle column) O'Connor et al. (2021), and (right column) Fogt and Connolly (2021). Correlations statistically different from zero at $p<0.05$ are stippled.

the Weddell sea ice maintains a similar relationship with pressure across the entire Southern Hemisphere from data assimilation-based products~~ with a fixed prior.~~. However, ~~when comparing with~~for the ~~Fogt and Connolly (2021)~~FC21_STAT pressure dataset, the relationship ~~between~~with Weddell sea ice extent, regardless of the sea ice extent estimate (~~Dalaiden et al. (2021)~~DAL21_ASSIM or ~~Fogt et al. (2022a))~~FOGT_STAT) shows a change in ~~the relationship over Antarctica, flipping to a weakly negative (generally not statistically significant) correlation~~sign poleward of 60°S in the 1905-1978 (right column in Fig. 7). While the trends in the Weddell sea ice extent change less dramatically through time than in the Ross, Amundsen, and Bellingshausen sectors (Fig. 6), there are still changes in the sea ice extent trends in the Weddell sector in the ~~Fogt et al. (2022a)~~FOGT_STAT reconstruction, with perhaps too strongly positive sea ice extent trends at the end of the 20th century (compared to observations) juxtaposed by negative sea ice extent trends in the middle twentieth century (Fig. 6). If the statistical relationship between the atmospheric circulation and sea ice extent changed in time (Fig. 7, right column), this could be linked (at least statistically, and perhaps incorrectly) to the changes in the sea ice extent trends displayed in the ~~Fogt et al. (2022a) sea ice extent~~FOGT_STAT reconstructions, but not in the paleo-reconstructions (Fig. 6).

Interestingly, when examining the correlation of sea ice extent reconstructions in the Ross-Amundsen sector ~~with~~ (Fig. 8), this sea ice-pressure relationship across the various ~~gridded historical pressure~~ datasets ~~(Fig. 8), this pattern~~ is ~~not fully maintained, and there are more differences in the spatial correlation patterns not~~ only ~~between the two sea ice extent estimates,~~

~~but also dependent on the various~~apparent for the DAL21_ASSIM pressure ~~datasets (columns in Fig. 8).~~dataset. For the ~~Dalaiden et al. (2021)~~DAL21_ASSIM sea ice extent estimate (Fig. 8, left column), the pressure relationships are maintained throughout time, and are even stronger in the 1905-1978 period for the ~~Dalaiden et al. (2021)~~DAL21_ASSIM pressure estimate. As in the Weddell sector, the correlation pattern of the ~~Dalaiden et al. (2021)~~DAL21_ASSIM sea ice extent estimate with the ~~the Fogt and Connolly (2021)~~FC21_STAT pressure dataset in the Ross-Amundsen sector again changes through time poleward of 60°S over the Antarctic continent, from overall weakly positive and insignificant correlations from 1905-1978 to statistically significant (p<0.05) negative correlations after 1979 (Fig. 8, top two rows of rightmost column). A notable exception however is off the coast of West Antarctica, in the vicinity of the Amundsen Sea low, where correlations remain significantly (p<0.05) negative throughout time, highlighting the key role of this feature for regional sea ice variability ~~(Hosking et al., 2013; Raphael et al., 2016).~~



(Hosking et al., 2013; Raphael et al., 2016). However, for the FOGT_STAT**Figure 8.** As in Fig. 7, but for the sea ice extent reconstructions for the Ross-Amundsen Seas sector.

For the Fogt et al. (2022a) sea ice extent reconstructions (bottom two rows in Fig. 8), a different story emerges. The correlations, while of a generally similar sign, are weaker for all pressure datasets (columns in Fig. 8) in the 1905-1978 period compared to the 1979-2000 period. In particular, the statistically significant (p<0.05) negative correlations within the region of the Amundsen Sea low are maintained throughout time, especially in the Fogt and Connolly (2021)FC21_STAT pressure dataset (Fig. 8, right column, bottom two rows); these are reduced however when using the Dalaiden et al. (2021)DAL21_ASSIM pressure dataset with the Fogt et al. (2022a)FOGT_STAT sea ice extent reconstruction (Fig. 8, left column, bottom two rows).

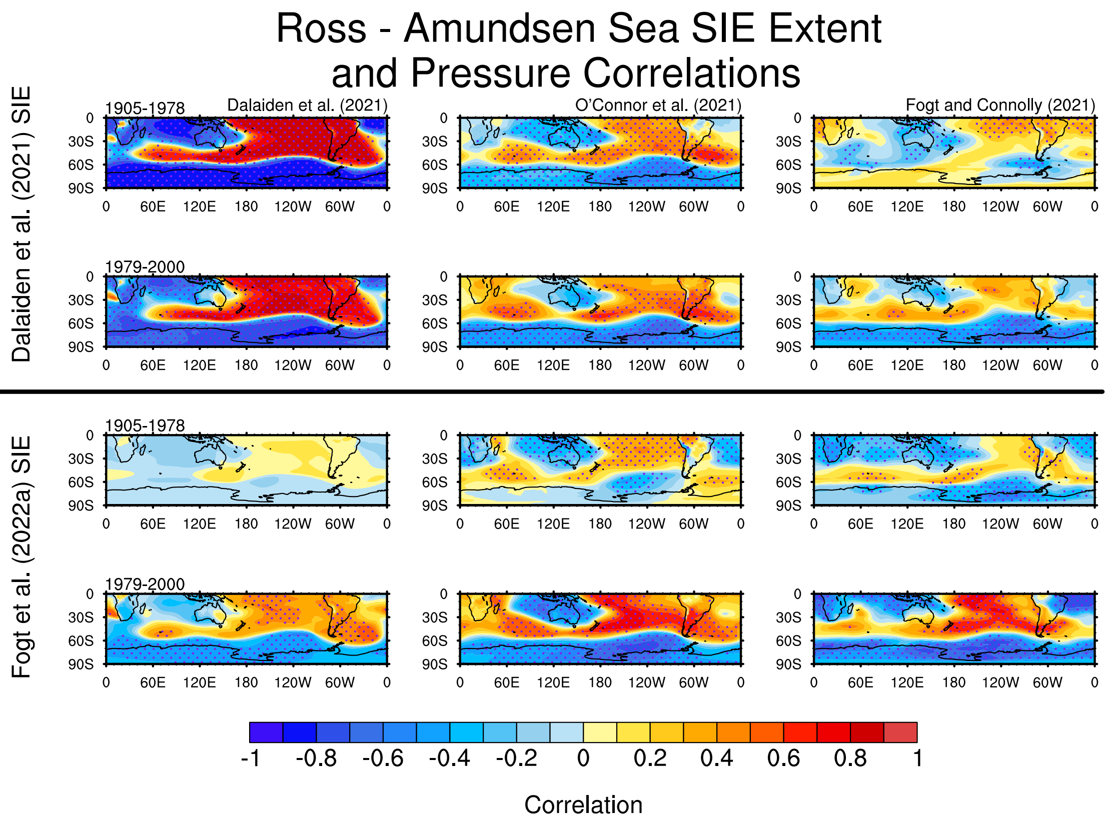
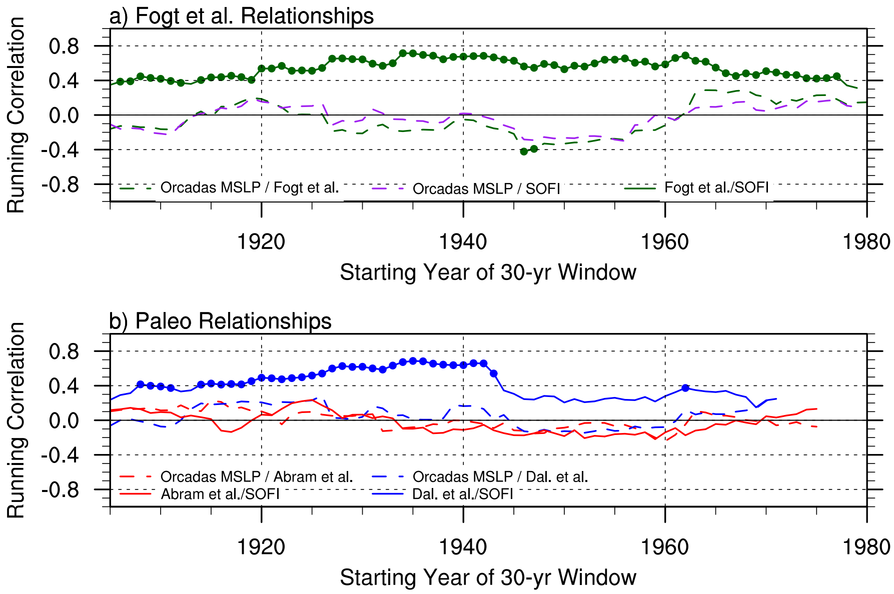


Figure 8. As in Fig. 7, but for the sea ice extent reconstructions for the Ross-Amundsen Seas sector.

Are changes in time of the sea ice – pressure relationship in time in the Weddell sector from Fig. 7 a real feature, or is this an artifact of the reconstructions (sea ice extent, pressure, or both) generated by their limitations? While there are no direct spatially complete observations of sea ice or pressure throughout the full 20th century, the Weddell sector is one of the few places with longer historical observations of both pressure ~~and sea ice conditions, afforded by the observations collected at Orcadas station (60.7°S, 44.7°W) since 1903 (Zazulie et al., 2010), and the fast-ice duration series around this island from Murphy et al.~~, afforded by the observations collected at Orcadas station (60.7°S, 44.7°W) since 1903 (Zazulie et al., 2010), and sea ice conditions, represented by the fast-ice duration series around Orcadas from Murphy et al. (1995). The running correlations of these key observations with sea ice estimates are provided in Fig. 9 as the only observation-based investigation into the possible reality of a time-varying sea ice /

pressure relationship within the Weddell ~~sea~~Sea. In Fig. 9a, the annual mean ~~Fogt et al. (2022a)~~FOGT_STAT Weddell sea ice extent reconstruction maintains a statistically significant (p<0.05) positive relationship throughout time with the South Orkney fast ice (SOFI) record (solid lines, Fig. 9a). ~~Given this, it is not surprising then that both the relationship between the Fogt et al. (2022a) Weddell sea ice extent reconstruction and the~~Although usually not statistically significant, both FOGT_STAT SOFI duration similarly change sign through time with the pressure at Orcadas station (dashed lines in Fig. 9a), ~~potentially confirming~~which is consistent with the ~~spatial~~Weddell SIE-gridded pressure correlation change through time presented in the right column of Fig. 7. While the Weddell sea ice extent estimate from ~~Dalaiden et al. (2021)~~DAL21_ASSIM also is positively correlated through time with the SOFI duration (solid blue line, Fig. 9b, albeit only significant [p<0.05] for 30-year windows ~~starting prior to 1945~~in the early 20th century), the Orcadas observed pressure and Weddell sea ice extent estimate from ~~Dalaiden et al. (2021) are weakly correlated (p>0.05), near zero through time (although still with some deviation in sign, but not~~DAL21_ASSIM have no statistically ~~meaningful).~~significant correlations. There is therefore ~~much~~ stronger support ~~of~~for changes in the relationship of high latitude pressure and Weddell sea ice from the statistically-generated sea ice and pressure reconstructions than there is from the paleo-based reconstructions, consistent with Fig. 7.



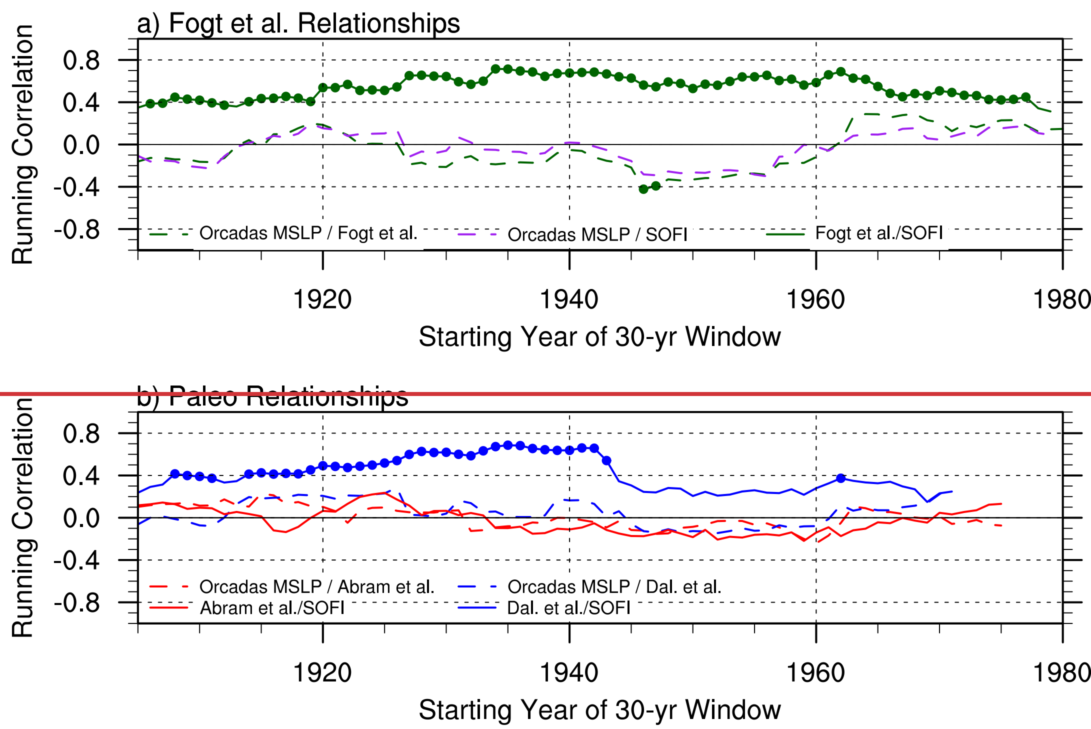
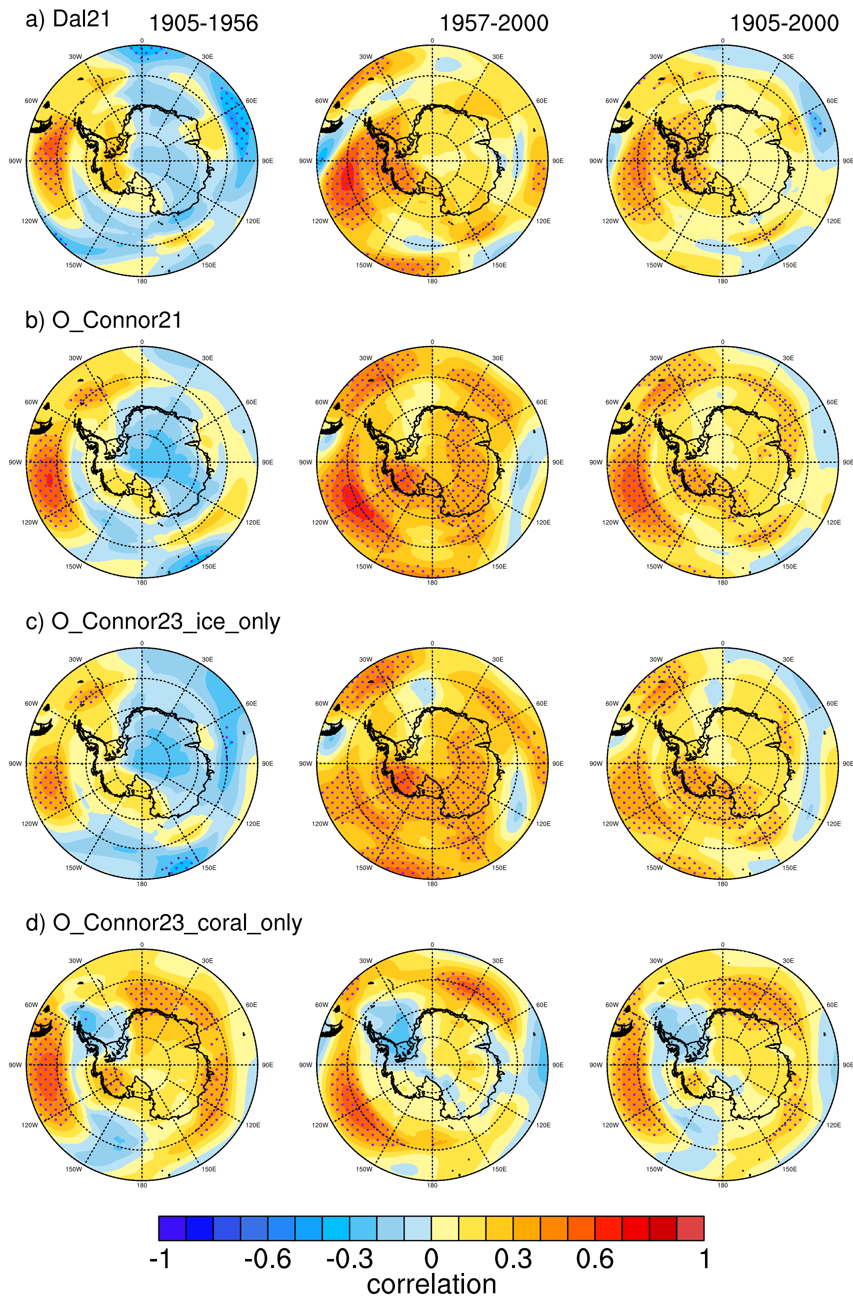


Figure 9. 30-year running correlations between pairs of the South Orkney Fast Ice (SOFI) duration from Murphy et al. (1995, 2014), various sea ice extent estimates, or Orcadas station mean sea level pressure. Correlations significantly different from zero at *p*<0.05 are marked with a circle.

3.3) Differences in atmospheric pressure reconstructions

The connections of the various sea ice reconstructions with the atmospheric circulation in Figs. 7-9 suggest, just like with the sea ice, that there are also differences in the underlying atmospheric circulation from the Fogt and Connolly (2021)FC21_STAT dataset and the Dalaiden et al. (2021) and O'Connor et al. (2021)DAL21_ASSIM and OCON21_ASSIM proxy-data assimilation datasets. While some of these differences were discussed in O'Connor et al. (2021), it is not clear how they may impact sea ice changes through time. To understand these differences better and the role they may play in the differences in the sea ice reconstructions, correlations between the various annual mean gridded pressure datasets are provided in Fig. 10. To help pinpoint the sensitivity of the correlations to the paleo data assimilated into the climate model, the O'Connor et al. (2021) pressure reconstruction was expanded by separately examining reconstructions assimilating ice core and coral data only from O'Connor et al. (2023). We examine these separately to better isolate thein Table 1 are provided in Fig. 10.


a) Dal21
1905-1956
1957-2000
1905-2000
b) O_Connor21
c) O_Connor23_ice_only
d) O_Connor23_coral_only
-1
-0.6
-0.3
0
0.3
0.6
1
correlation

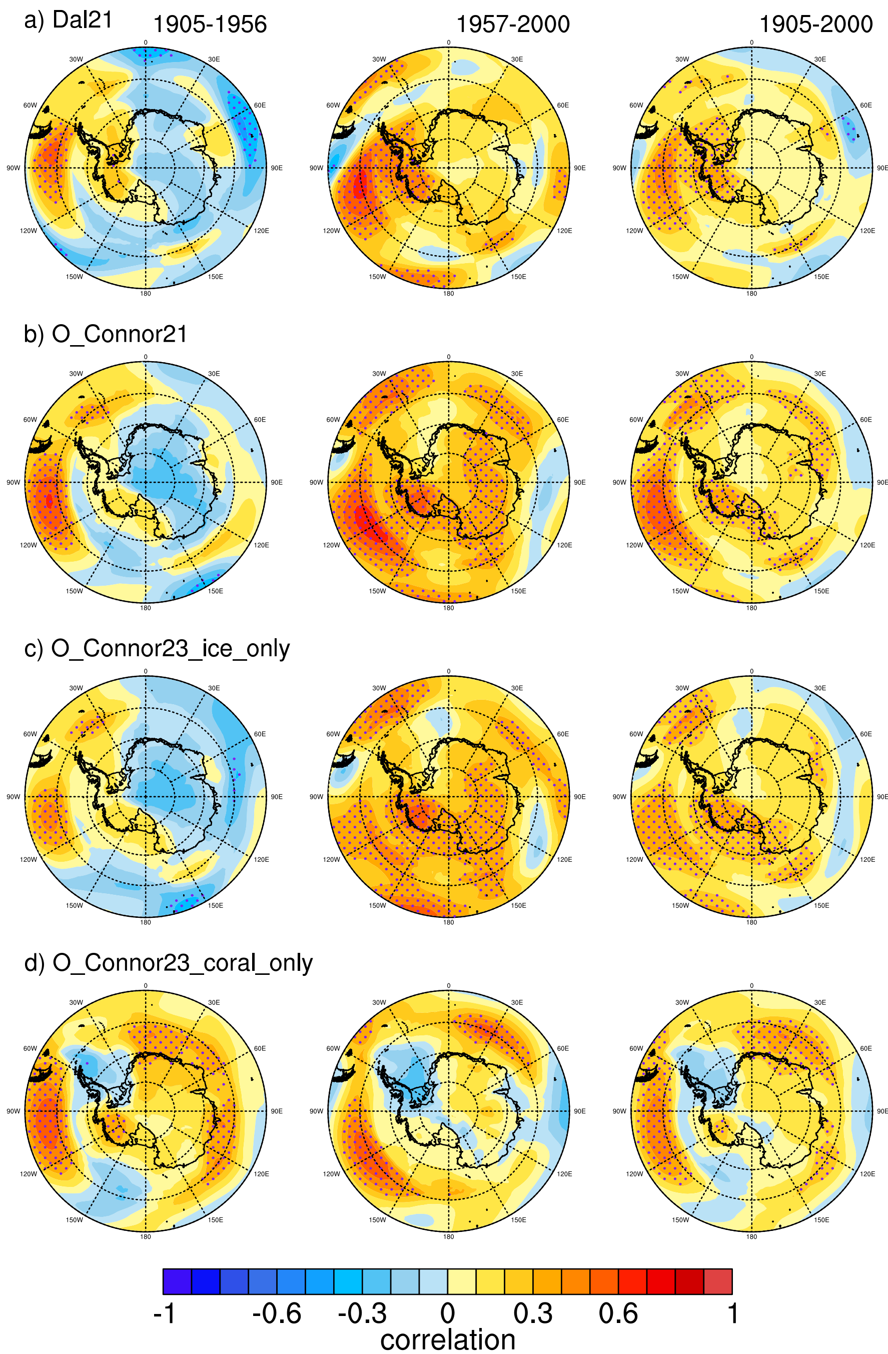


Figure 10. Correlations of annual mean pressure at each grid point between the various paleo-based reconstructions with the Fogt and Connolly (2021) reconstruction. a) Dalaiden et al. (2021); b) O'Connor et al. (2021); c) O'Connor et al. (2023) ice core-based proxies only; d) O'Connor et al. (2023) coral-based proxies only. The columns denote three time periods: 1905-1956 (left column, prior to Antarctic data), 1957-2000 (middle column), and the full period of overlap 1905-2000 (right column). Correlations statistically different from zero at $p<0.05$ are stippled. All datasets were linearly detrended over the specific time period prior to calculating the correlations; further details on each dataset is provided in Table 1 and the proxy locations are given in Fig. 2.

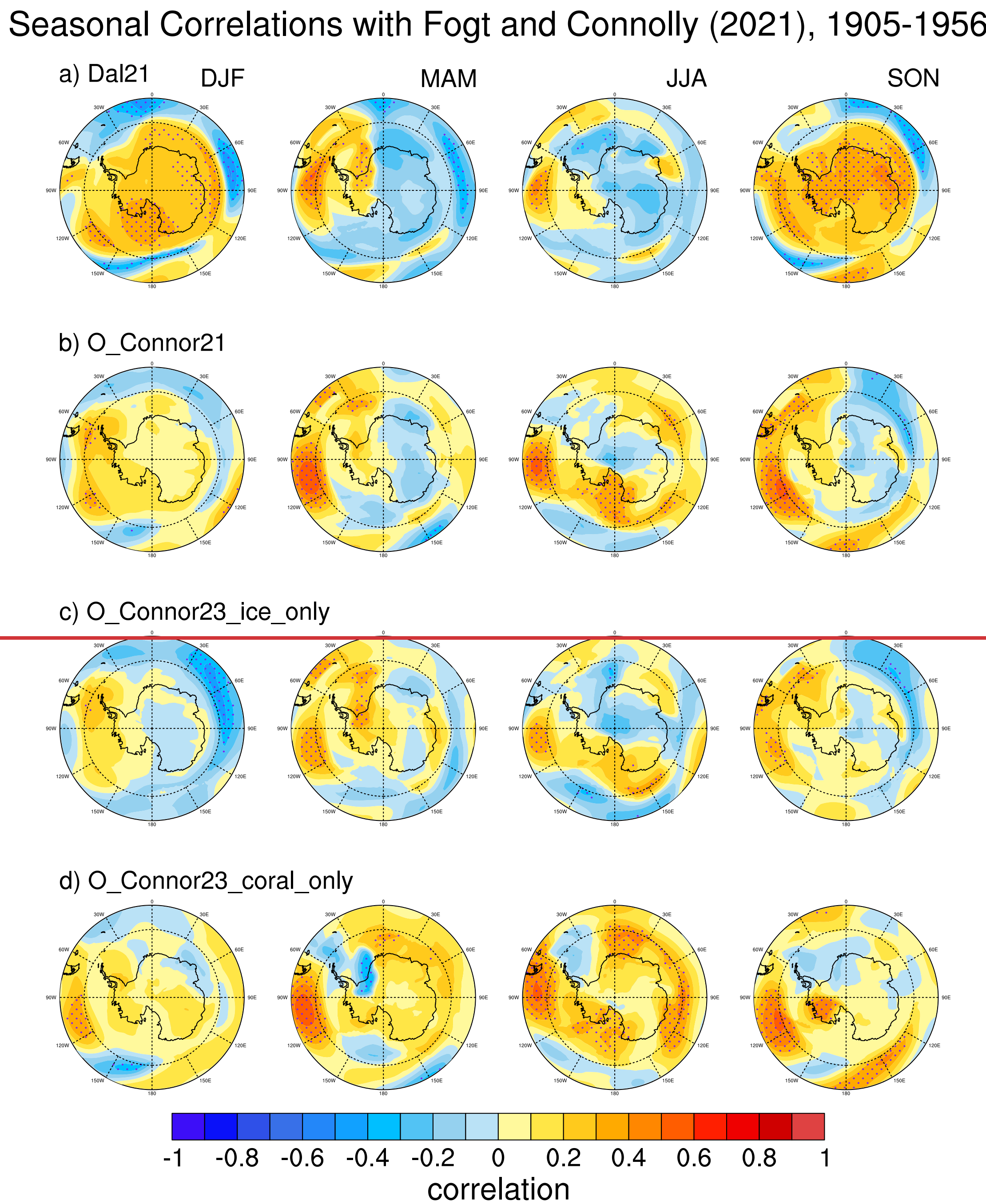
rolePrior to the start of tropical paleo data constraints (from corals) and those primarily from Antarctica (from ice cores, Fig. 2c) on the comparison of thesemost Antarctic pressure reconstructions with the Fogt and Connolly (2021) data. Inobservations, during the 1905-1956 time period (left column, Fig. 10), there are similar correlation patterns between for the DAL21_ASSIM, OCON21_ASSIM, and the Dalaiden et al. (2021), O'Connor et al. (2021), and the O'Connor et al. (2023) OCON23_ASSIM (ice core only) datasets, suggesting that the ice core data provide a strong constraint to the pressure variability in the paleo-basedassimilation reconstructions near Antarctica, and that the inclusion of external forcing in the data assimilation prior (for the O'Connor et al. (2021, 2023) reconstructions) has minimal influence. Meanwhile, there are positive and even statistically significant (p<0.05) correlations between the O'Connor et al. (2023OCON23_ASSIM (coral only) and Fogt and Connolly (2021)FC21_STAT datasets (Fig. 10d, left column) in the early period. This suggests that tropical teleconnections, captured by the coral paleo data, play an important role in the interannual variability in the Fogt and Connolly (2021) dataset. Given that the predictor data for the Fogt and Connolly (2021) dataset is confined to the Southern Hemisphere landmasses large distances away from Antarctica, it is not surprising that there is better agreement with the coral-only dataset of O'Connor et al. (2023) and Fogt and Connolly (2021) pressure dataset over Antarctica. However, given the different pattern with the paleo-based datasets (left column, Fig. 10a-c), it is also clear that the local ice core variability over Antarctica is opposite that of the coral-based tropical variability (especially over East Antarctica, where tropical teleconnections to Antarctica are generally weaker; Li et al., 2021), with the former dominating the overall reconstruction for the paleo-based datasets. Notably, during 1957-2000 the agreement improves from 1905-1956 for the full reconstructions (Fig. 10a-b, middle column, especially for the O'Connor et al. reconstructions) as well as the ice

~~core-only reconstruction from O'Connor et al. (2023, Fig. 10c, middle column), while the agreement weakens for the coral-only reconstruction (Fig. 10d, middle column). This suggests the Fogt and Connolly (2021)~~FC21_STAT dataset. However, it is also clear the local ice core variability over Antarctica, which dominates the reconstructions in Figs. 10a-c, is opposite to that of the coral-based tropical variability (Fig 10d,), especially over East Antarctica, where tropical teleconnections to Antarctica are generally weaker (Li et al., 2021).

During 1957-2000, the agreement improves from 1905-1956 for all but the OCON23_ASSIM coral-only reconstructions (Fig. 10, middle column). This suggests that the FC21_STAT dataset aligns more with tropical variability in the early 20th century, which dominates its response, but more with ice core related variability in the latter half of the 20th century, which dominates the paleo-~~based~~data assimilation reconstructions near Antarctica. Further, given the greater skill in the O'Connor et al. (2021, 2023) reconstructions relative to ~~Dalaiden et al. (2021)~~DAL21_ASSIM in the later period, this also ~~suggest~~suggests that including external forcing in the climate model prior is important.

Since there was some effect of seasonality on the relationship between the paleo-based and statistically based sea ice reconstructions in Fig. 4, we examine the correlations for each season ~~(like with the Fogt et al. (2022a) sea ice reconstructions, the Fogt and Connolly (2021) pressure datasets were constructed seasonally, and annually averaged for Fig. 10, Table 1)~~ in the 1905-1956 period in Fig. 11. ~~However, for~~For the pressure datasets, the change in seasonal skill in Fig. 11 is dampened compared to that for Antarctic sea ice extent in Fig. 4. There are more correlations statistically significant (p<0.05) for the ~~Dalaiden et al. (2021)~~DAL21_ASSIM dataset in DJF and SON, likely tied to when the skill of the ~~Fogt and Connolly (2021)~~FC21_STAT dataset is the highest. For the O'Connor et al. (2021,2023) datasets (Figs.

11b-d), the agreement is slightly better over the Ross Sea and West Antarctica in winter. This improvement is due to contributions from both ice cores and corals, with the corals providing enhanced agreement off the coast and across East Antarctica (Figs. ~~10c~~11c,d). The ice core-only reconstruction provides better agreement over West Antarctica in SON (Fig. ~~10d~~11d, right column). Another interesting feature, worthy of further study, is the opposite ~~agreement~~correlation in the Weddell Sea in MAM between the ice core-only reconstruction (Fig. ~~10c~~11c, significantly [$p<0.05$] positively correlated) and the coral-only reconstruction (Fig. ~~10d~~11d, significantly [$p<0.05$] negatively correlated); the significant positive correlations over the Weddell Sea onto the Antarctic continent in MAM are also seen in the ~~Dalaiden et al. (2021)~~DAL21_ASSIM reconstruction, related to the ice core constraints (since this dataset does not assimilate coral proxies).


Seasonal Correlations with Fogt and Connolly (2021), 1905-1956
a) Dal21
DJF
MAM
JJA
SON
b) O_Connor21
c) O_Connor23_ice_only
d) O_Connor23_coral_only
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
correlation

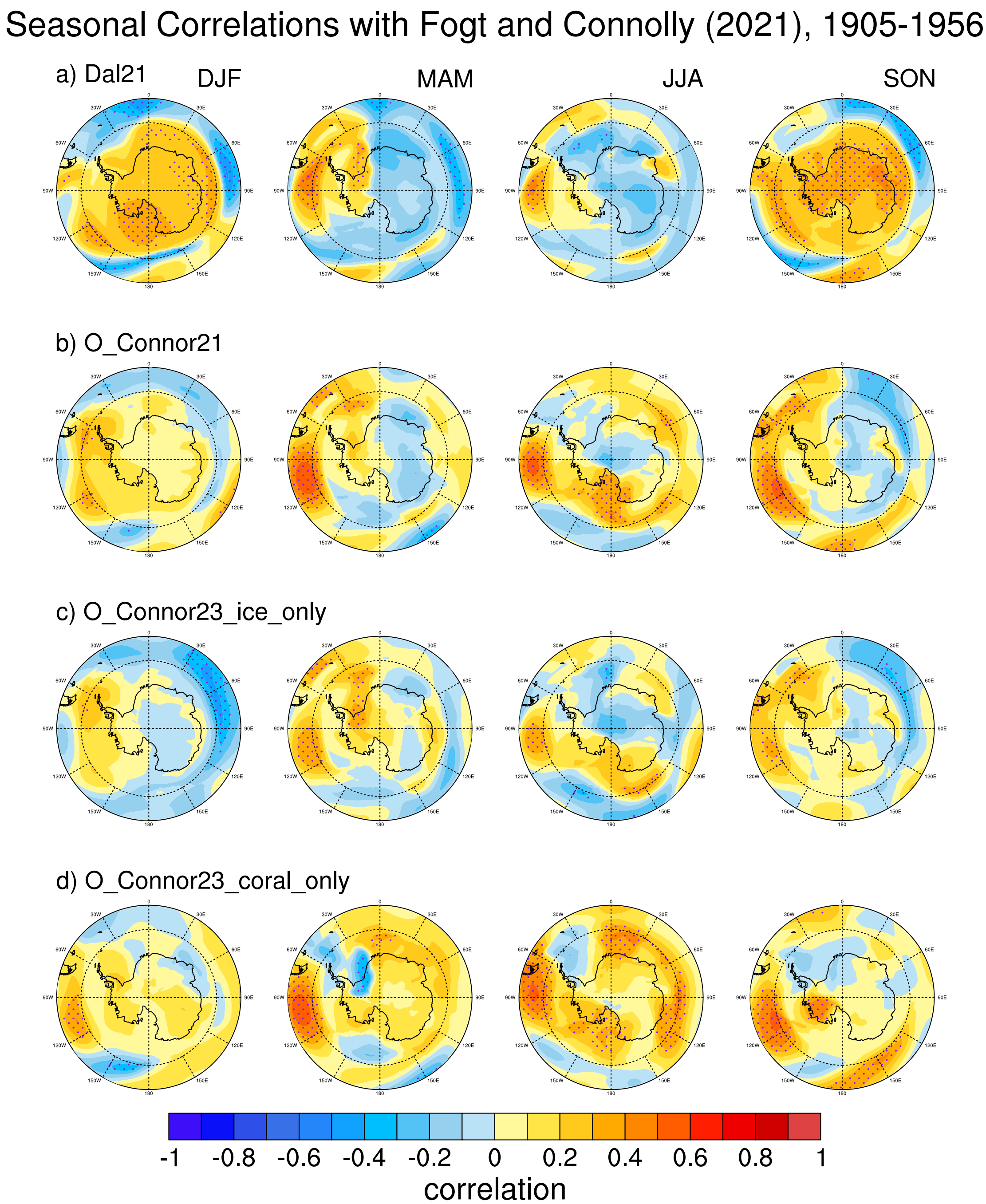
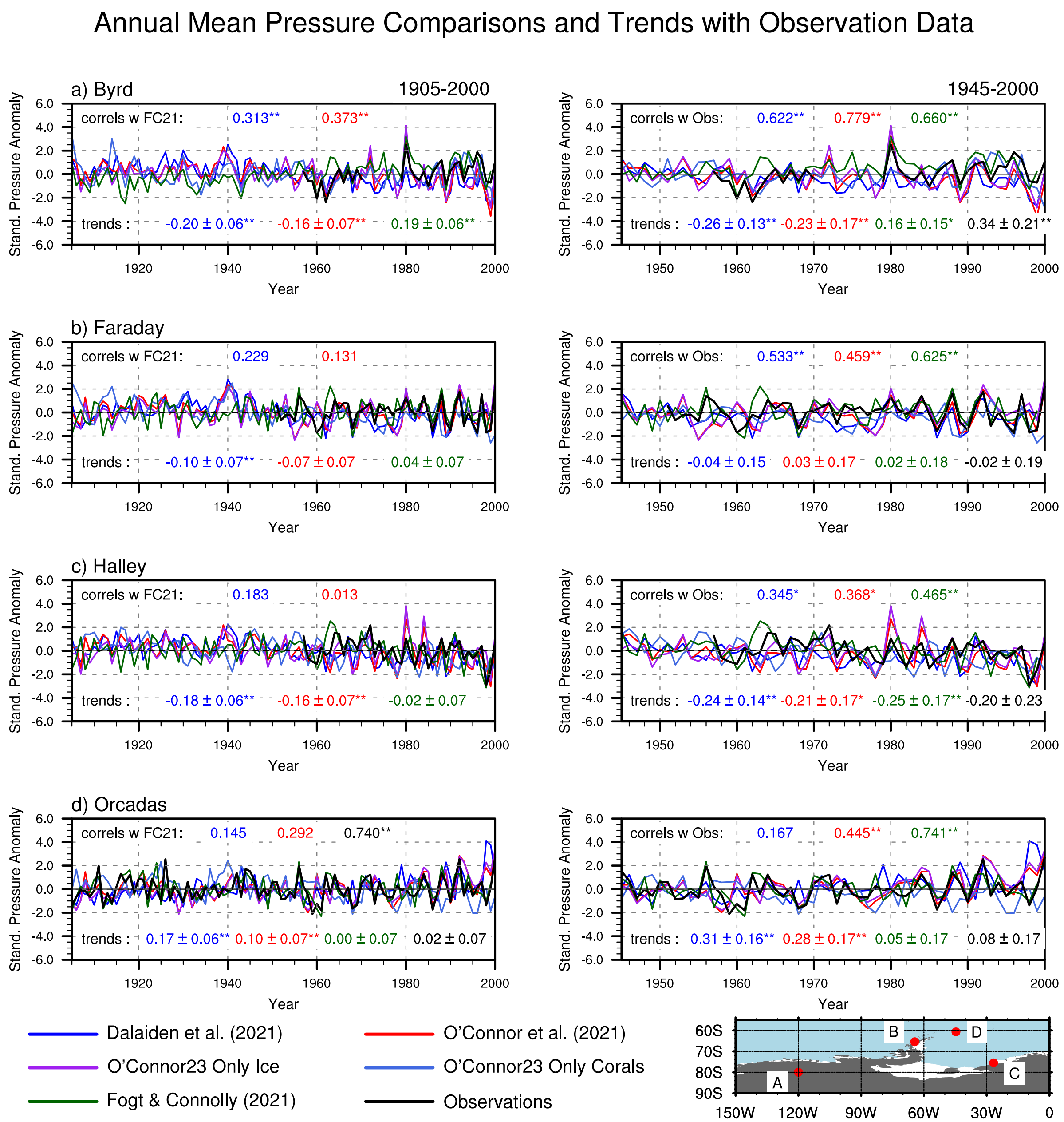


Figure 11. As in Fig. 10, but for correlations of the annual mean pressure reconstructions with the seasonal mean reconstruction of Fogt and Connolly (2021) during 1905-1956. The columns, from left to right, represent DJF, MAM, JJA, and SON, respectively.

To ~~more completely~~further evaluate these datasets, annual mean comparisons with select observations are conducted in Fig. 12 using the ~~gridpoints~~grid points nearest to the station locations (for reference, a map of the stations is provided in the legend of Fig. 12). In the full period 1905-2000 (left column), correlations of the paleo-based datasets with the ~~Fogt and Connolly (2021)~~FC21_STAT dataset are generally near zero, and only significant (here, p<0.01) over the West Antarctic continent at Byrd station~~.~~ (Fig. 12a). The correlations with the observations ~~improve after 1945~~ (right column in Fig. ~~11~~12, near the start of data at Faraday), most now significant at p<0.01, are generally higher than with FC21_STAT, especially for the ~~O'Connor et al. (2021)~~OCON21_ASSIM dataset. The inclusion of more proxy data in the ~~O'Connor et al. (2021)~~OCON21_ASSIM dataset (Fig. 2c) and the inclusion of an anthropogenically forced prior (Table 1) likely lead to overall better agreement with the observations than for the ~~Dalaiden et al. (2021)~~DAL21_ASSIM dataset; however both of these paleo-~~based~~assimilation datasets use a moderately coarse spatial resolution prior that may limit their comparison at a single point. It is also important to note that while the ~~Fogt and Connolly (2021)~~FC21_STAT correlations are overall higher than the ~~paleo-based~~other reconstructions, this dataset is calibrated directly to these observations, and for Orcadas, direct observations (and not a reconstruction) are used~~, hence why the correlations are strong in both time periods at this location, black correlation values at top of the figures in the bottom row of Fig. 12).~~.

~~More striking than the change in correlation in Fig. 12 are the changes in the linear trends through time across the various datasets (given by the values at the bottom of each panel).~~



~~In the full time period (1905-2000, left column of Fig. 12), both the Dalaiden et al. (2021) and O'Connor et al. (2021) datasets show statistically significant (*p*<0.01) pressure decreases at Byrd and Halley stations (Figs. 12a,c), but statistically significant (*p*<0.01) pressure increases at Orcadas (Fig. 12d). The Fogt and Connolly (2021) dataset, in strong contrast, shows significant (*p*<0.05) pressure increases at Byrd in both time periods (consistent with observations after 1957,~~

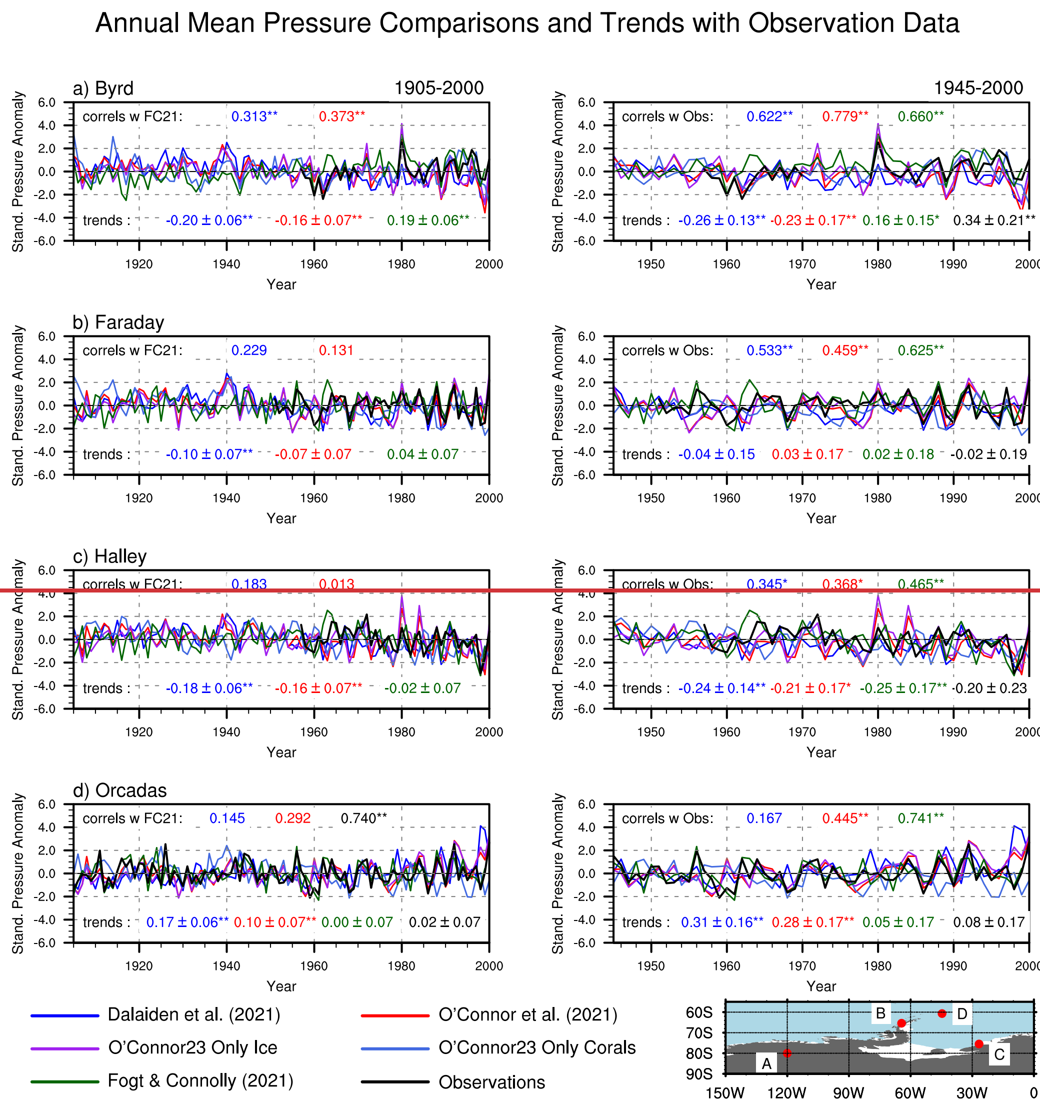


Figure 12. Timeseries of standardized pressure anomalies at various locations given in the map at the bottom right. (i.e., A = panel a). The observations, mostly starting around 1957 (1903 for Orcadas, panel d), are shown in black. For the left column, correlations given at the top of each panel are with the Fogt and Connolly (2021) dataset during 1905-2020, and trends at the bottom are calculated for the 1905-2020 period. For the right column, the correlations are with the observations, and both correlations and trends are calculated during 1945-2020. In all panels, correlations and trends are color-coded based on the timeseries color in the legend, with values significantly different from zero at $p<0.05$ and $p<0.01$ are marked with * and **, respectively.

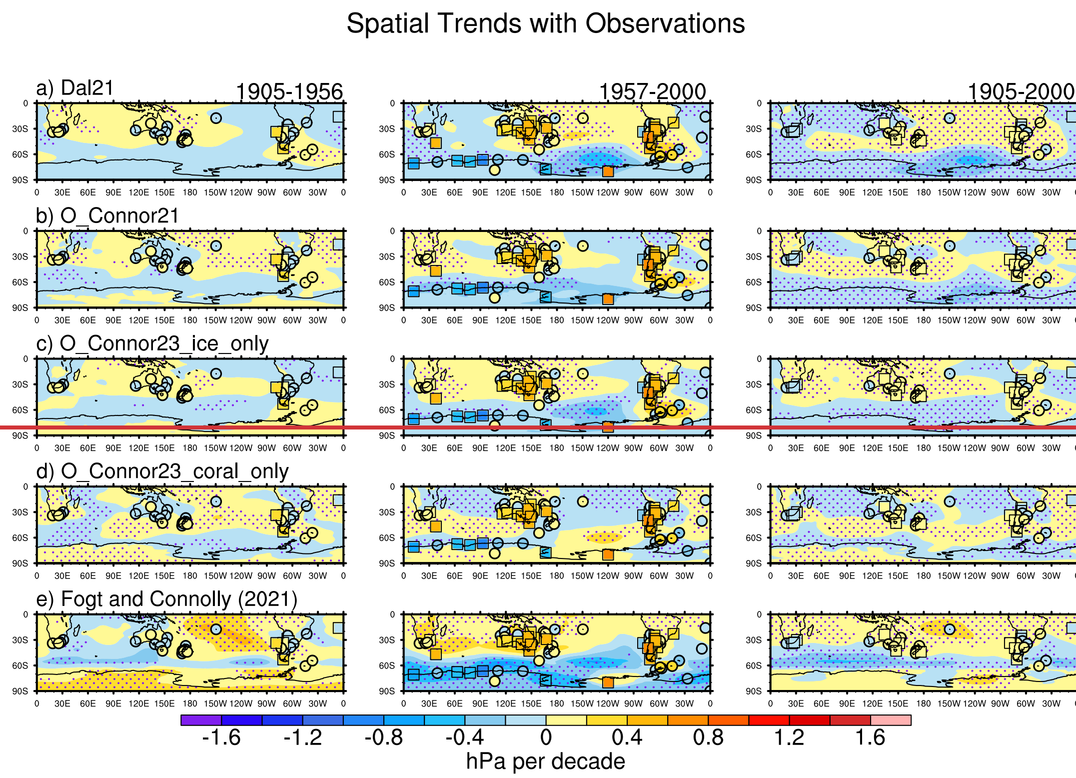
The changes in the linear trends through time across the various datasets (given by the color-coded values at the bottom of each panel) are also noteworthy in Fig. 12. In the full time period (1905-2000, left column of Fig.

~~Fig.~~12), both the DAL21_ASSIM and OCON21_ASSIM datasets show statistically significant (*p*<0.01) pressure decreases at Byrd and Halley stations (Figs. 12a,c), but statistically significant (*p*<0.01) pressure increases at Orcadas (Fig. 12d). The FC21_STAT dataset, in strong contrast, shows significant (*p*<0.05) pressure increases at Byrd in both time periods (consistent with observations after 1957, Fig. 12a), and only significant (*p*<0.01) pressure decreases at Halley station after 1945 (Fig. 12c, right column). The much stronger and sometimes different signed trends in the paleo-~~based~~assimilation pressure reconstructions compared to the ~~Fogt and Connolly (2021)~~FC21_STAT dataset during 1905-2020, and even with most observations after 1945, are undoubtedly a strong contributor to the differences seen in the Antarctic sea ice extent reconstructions~~ between the paleo-based and statistically based reconstructions; there are statistically significant differences in the underlying atmospheric circulation used to generate these reconstructions that connect to their differences in trends seen in Figs. 3 and 6~~.

Both the Dalaiden et al. (2021) and O'Connor et al. (2021) studies focus on marked pressure decreases in the region of the Amundsen Sea low, which as discussed earlier, has a strong role in regional sea ice conditions examined in this study ~~(Hosking et al., 2013; Raphael et al., 2016; Holland and Kwok, 2012).~~(Hosking et al., 2013; Raphael et al., 2016; Holland and Kwok, 2012). It is much more challenging to investigate the reality of these long term changes in this region, as there are no direct observations (the closest stations are represented by those in Fig. 12~~), and~~).

Further the ~~Fogt and Connolly (2021)~~FC21_STAT dataset shows the lowest skill (compared to the ERA-Interim reanalysis) spatially in this region~~,~~ (Fogt et al. 2019), consistent with the fact that even contemporary reanalyses show the greatest disparity (in terms of pressure correlations and trends) in this region as well ~~(Fogt et al., 2018).~~(Fogt et al., 2018). Given the disparities in trends seen from observation locations in Fig. 12, it is not surprising that the datasets also have dramatically different trends in this region, which have similar implications for differences in sea ice extent trends. To visualize this in perspective, a full spatial comparison across the Southern Hemisphere of the pressure trends in the various datasets in three time periods, along with available observations, is provided in Fig. ~~13 as a final comparison of these products~~13.

First, for the period of Antarctic observations (1957-2000, middle column of Fig. 13), observations indicate statistically significant (boxes, $p<0.05$) pressure decreases only over coastal East Antarctica, with insignificant positive annual mean trends over the East Antarctic plateau at Vostok (78.5°S, 106.9°E, the only observation plotted in central East Antarctica in Fig. 13~~,~~), consistent with ERA5 surface pressure trends during 1979-2022 in Fig. 1b~~)~~.. At Byrd station in central West



~~**Figure 13.** Linear near-surface annual mean pressure trends (hPa per decade) for 1905-1956 (left column), 1957-2000 (middle column), and 1905-2000 (right column) for various datasets in each row a) Dalaiden et al. (2021); b) O'Connor et al. (2021) proxy reconstruction c) O'Connor et al. (2023) reconstruction with only ice core proxies; d) O'Connor et al. (2023) reconstruction with only coral proxies; e) Fogt and Connolly (2021) station-based reconstruction. Trends from observation data, where available, are plotted using the same color scale on top of the gridded pressure trends. Stippling indicates gridded pressure trends significantly different from zero at p<0.05, boxes indicate trends in observations significantly different from zero at p<0.05.~~

Antarctica, statistically significant positive trends (annual mean) are observed (also seen in Fig. 12a). The various datasets capture these patterns to differing degrees~~: paleo-based~~. Paleo-data assimilation datasets generally only have statistically significant negative trends along the Antarctic coastline, consistent with the positive annual mean SAM trend ~~(Fogt and Marshall, 2020),~~(Fogt and Marshall, 2020), but only capture positive trends in the Antarctic interior in coral-only reconstruction (middle column Figs. 13a-d). Indeed, the coral-only reconstruction has positive pressure trends everywhere over Antarctica except along the Antarctic Peninsula and

Weddell Sea (Fig. 13d, middle column), and therefore is the only dataset to miss the observed significant negative pressure trends along the East Antarctic coastline. Meanwhile, the ~~Fogt and Connolly (2021)~~FC21_STAT dataset ~~incorrectly has~~is the only one to have significant (p<0.05) negative, instead of the observed positive, pressure trends over the East Antarctic plateau, but it does capture a regional pressure increase in West Antarctica (Figs. 13e middle column, Fig. 12). The ~~Dalaiden et al. (2021)~~DAL21_ASSIM dataset has a marked significant deepening of the Amundsen Sea low during 1957-2000 (Fig. 13a, middle column), which is largely driven by ice core paleo data (Fig. 2b), and thus reduced in the ~~O'Connor et al. (2021)~~OCON21_ASSIM dataset by the inclusion of coral data (Figs. 13b-d; Fig. 2c). This suggests that if the significant pressure increases over West Antarctica are correct, there ~~is likely~~might be a tropical signal, either internal or forced, to these positive trends (to be discussed in more detail later). In the midlatitudes during 1957-2000, the coral-only reconstruction (Fig. 13d) captures the pattern seen in observations the best (the ~~Fogt and Connolly (2021)~~FC21_STAT dataset is not independent of observations in these locations since it is merely the 20th century reanalysis north of 60°S, Table 1). It should be noted that there are large inconsistencies ~~with~~between observations at Tahiti in the central tropical Pacific and the 20CRv3, as discussed in ~~Fogt and Connolly (2021).~~FC21_STAT.

~~For the early 20th century during~~

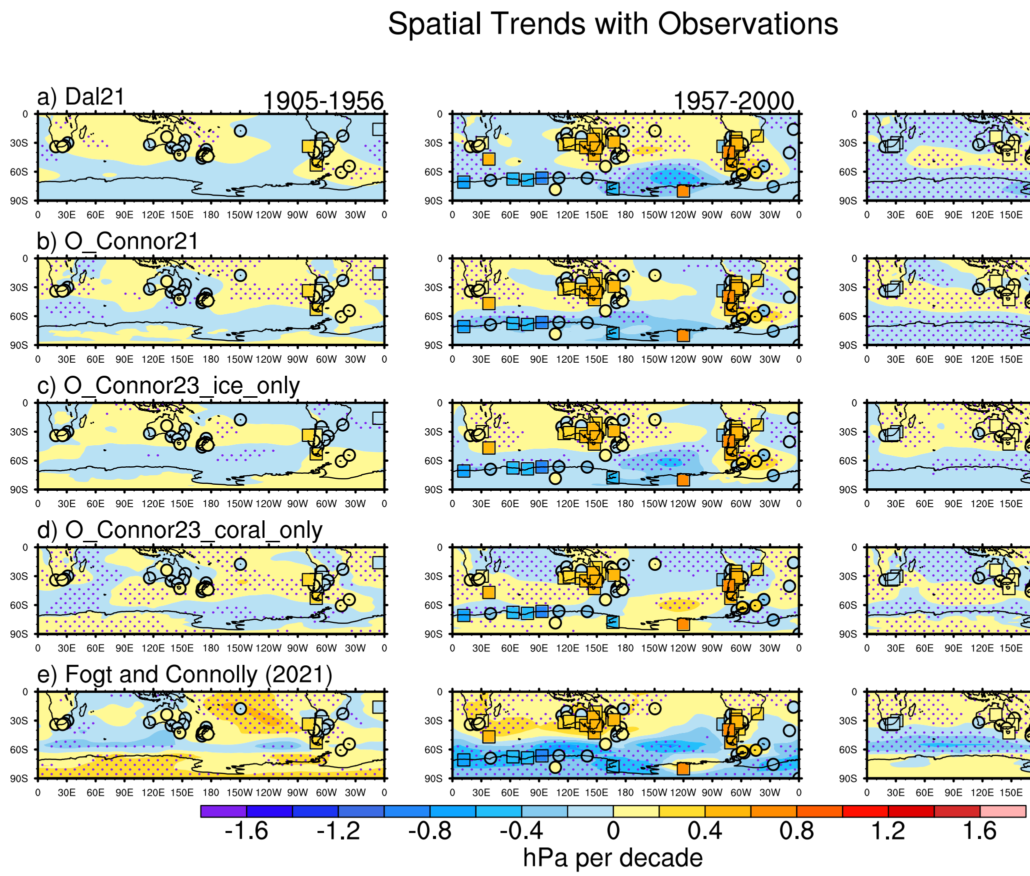


Figure 13. Linear near-surface annual mean pressure trends (hPa per decade) for 1905-1956~~,~~ (left column), 1957-2000 (middle column), and 1905-2000 (right column) for various datasets in each row a) Dalaiden et al. (2021); b) O'Connor et al. (2021) proxy reconstruction c) O'Connor et al. (2023) reconstruction with only ice core proxies; d) O'Connor et al. (2023) reconstruction with only coral proxies; e) Fogt and Connolly (2021) station-based reconstruction. Trends from observation data, where available, are plotted using the same color scale on top of the ~~clear~~ gridded pressure trends. Stippling indicates gridded pressure trends significantly different from zero at p<0.05, boxes indicate trends in observations significantly different from zero at p<0.05

Figure 13 clearly demonstrates the difference in trends in 1905-1956 between the ~~Fogt and Connolly (2021)~~ FC21_STAT dataset and those of ~~Dalaiden et al. (2021) and O'Connor et al (2021) is distinct.~~DAL21_ASSIM and OCON21_ASSIM. Pressure trends over the Antarctic continent reverse in the ~~Fogt and Connolly (2021) dataset,~~FC21_STAT dataset (significantly positive in early 20th century, Fig. 13e left column, significantly negative in late 20th century, Fig. 13e right column) while they remain insignificant in most paleo-~~based~~assimilation datasets. It is interesting however that the coral-only reconstruction from ~~O'Connor et al. (2023)~~ OCON23_ASSIM (Fig. 13d) also produces statistically significant positive trends over Antarctica in all time periods, consistent with the ~~Fogt and Connolly (2021)~~FC21_STAT dataset during 1905-1956, and aligning with the period when these two datasets agree the most (Figs. 11-12). Notably, this coral-only dataset agrees the best with observations in the ~~midlatitudes~~mid-latitudes during 1905-1956 (Fig. 13d, left column), and is quite similar to the pattern in the early 20th century from the full OCON21_ASSIM dataset in the midlatitudes (Fig. 13b, left column), suggesting a primary role of the coral records in constraining the solution in the midlatitudes.

The larger sample size afforded by the full time period from 1905-2000 yields more statistically significant trends across the Southern Hemisphere in the paleo-~~based~~data assimilation datasets (Figs. 13a-d, right column) that are overall similar in structure to the trends in the paleo-based datasets during 1957-2000 Figs. 13a-d, middle column). The coral-only dataset slightly produces better agreement with the midlatitude observations, capturing the significant negative trends over South Africa that are also hinted at by insignificant negative pressure trends at Perth in southwestern Australia. In comparing the paleo-based with the station-based ~~Fogt and Connolly (2021)~~FC21_STAT datasets, the biggest differences are the trends poleward of 60°S, which are insignificant except for pressure increases ($p<0.05$) over West

Antarctica in the ~~Fogt and Connolly (2021)~~FC21_STAT dataset due to the cancellation of different trends in the early and late 20^{th} century in this dataset (Fig. 13e). Compared to the other sources of differences in the Antarctic sea ice reconstructions examined earlier, this connection to the implied changes (or lack thereof) in the atmospheric circulation in the 20^{th} century are a dominant contributing factor to the differences in the linear trends among the Antarctic sea ice estimates seen in Fig. 2; this similar conclusion was reached in Fogt et al. (2022b) using a much more limited analysis.

4. Discussion

While this study largely focuses on causes for the differences between various sea ice and pressure reconstructions, it is important to note that there are broad similarities as well, especially in the Weddell sector where cross-correlations are strongest, even stronger in some seasons than in the annual mean. Further, each of these datasets has their own limitations due to their methodology and assumptions made in their reconstruction procedure, and that every reconstruction is only an estimate and is not without error. Nonetheless, the differences in the sea ice extent reconstruction trends (and to a lesser degree, the interannual variability) largely appear to hinge on whether or not there was a change in the atmospheric circulation in the high southern latitudes (poleward of 60°S) in the 20^{th} century. Paleo-~~based~~assimilation reconstructions, constrained by ice core records over Antarctica, have similar pressure trends through time, which influence the proxy-based sea ice extent reconstructions. In contrast, station-based reconstructions of both pressure and Antarctic sea ice extent show trends that change through time, which reduces their similarities with proxy-based reconstructions (for both sea ice extent and pressure) in the early 20^{th} century. Given that coral-only reconstructions from

~~O'Connor et al. (2023)~~OCON23_ASSIM agree better with the ~~Fogt and Connolly (2021)~~FC21_STAT dataset in the early 20th century, there ~~it~~ is possible that if there was indeed a reversal of atmospheric circulation trends, ~~that these had~~there was a tropical association to them. Nonetheless, the analysis here shows an important influence of the implied atmospheric circulation on Antarctic sea ice variations in both proxy-based and station-based sea ice extent reconstructions, consistent with findings from observations and models ~~(Sun and Eisenman, 2021; Blanchard-Wrigglesworth et al., 2021).~~(Sun and Eisenman, 2021; Blanchard-Wrigglesworth et al., 2021).

In looking more closely at the analysis presented here, the limited observational data always present a challenge. In particular, in the vicinity of the Amundsen Sea low, Byrd station in West Antarctica (see map in Fig. ~~11~~12) is the only observational record spanning over 30 years in the 150°-90°W sector poleward of 60°S (not including the South Pole). ~~While weather observations started at this station in 1957, it shut down for a period in the 1970s, and was replaced by an automatic weather station nearby. While there has been considerable work done to patch the temperature record at this station (Bromwich et al., 2012), there could be measurement-specific errors that lead to the~~Importantly, this merged observation record shows statistically significant (*p*<0.05) annual mean pressure increases from 1957-2000, while the positive pressure trends at Vostok station in East Antarctica are not significant. While there has been considerable work done to patch the temperature record at this station (Bromwich et al., 2012), there could be measurement-specific errors that lead to the statistically significant positive trend at this station in the observational dataset that may at least partially explain the regional differences in pressure (across West Antarctica and extending northward into the Amundsen and Bellingshausen Seas) between the paleo-~~based~~data assimilation pressure datasets and those of ~~Fogt and Connolly~~

~~(2021).~~FC21_STAT. However, the AWS in the later portion of the record is at a slightly higher elevation than the station observations in the earlier part of the data, which would generate negative pressure trends based on unadjusted instrument elevation changes, opposite the positive annual mean trends seen here. There is also a strong seasonal pattern to the positive pressure trends over West Antarctica, as shown in Fogt et al. (2018). Further work is needed to investigate the Byrd pressure data source, as well to employ historical data from ship logbooks and early expeditions ~~(Edinburgh and Day, 2016; De La Mare, 2009; Fogt et al., 2020; Lorrey et al., 2022)~~(Edinburgh and Day, 2016; de La Mare, 2009; Fogt et al., 2020; Lorrey et al., 2022) to better understand possible atmospheric circulation shifts in the high southern latitudes prior to 1957. Additionally, each kind of observations (e.g., paleo or instrumental observations) has its own advantages and weaknesses. Combining these two sources of information could provide a more accurate reconstruction of historical surface climate changes.

5. Conclusions

The analysis presented in this paper has evaluated various sea ice extent reconstructions spanning the Ross Sea eastward to the Weddell sea, and pressure reconstructions across the entire Southern Hemisphere to explain the differences between the sea ice extent reconstructions. Overall, better agreement in the sea ice extent reconstructions was found in the Weddell sea, despite possible changes in the relationship sea ice shares with the atmospheric pressure in this region throughout the 20th century. In the Ross and Bellingshausen seas, the agreement is weaker, and appears to be more strongly tied to the atmospheric circulation. For ice core based reconstructions studied here, the ~~Thomas and Abram (2016)~~TA16_PALEO reconstruction is fairly consistent with other reconstructions in the Ross sea, while the differing spatial and temporal representation of the ~~Abram et al. (2010)~~AB10_PALEO reconstruction make it challenging to effectively compare to other datasets. Overall, paleo-~~based~~data assimilation and station-based pressure reconstructions give notably different trends from the Ross Sea east to the Weddell Sea throughout the 20th century, especially in the vicinity of the Amundsen Sea low, a semi-permanent pressure cell known to strongly modulate Antarctic sea ice in the Ross, Amundsen, and Bellingshausen Seas ~~(Hosking et al., 2013; Raphael et al., 2016).~~(Hosking et al., 2013; Raphael et al., 2016). There is often better agreement in OCON21_ASSIM reconstructions based solely on coral proxy data with the FC21_STAT reconstruction, especially in the early 20th century. This likely suggests that signals from the tropics, which may or may not include external forcing, tropical variability governs the relationships within the FC21_STAT, while reconstructions based on ice-cores provide a more local constraint to reconstructions near the Antarctic continent. In the latter half of the 20th century, the warming trend in the tropical Pacific can explain the pressure increases found in the coral-only reconstructions in the South Pacific; however, it is unclear how to reconcile that with the Amundsen Sea Low deepening found in the ice core-only reconstructions and all-proxy reconstructions. The relative contributions of the tropics, local internal variability, and external forcing to historical trends remains highly uncertain and deserves further investigation, in agreement with previous studies (e.g., Holland et al., 2022).

While this study has determined that many of the differences in~~ the paleo-based and statistically generated~~ Antarctic sea ice extent reconstructions are tied primarily to their connection to the underlying atmospheric circulation, it is not able to determine the validity of changes in the atmospheric circulation in the early to mid 20th century. Further data extraction from ship logbooks ~~(Lorrey et al., 2022),~~(Lorrey et al., 2022), new climate model simulations assimilating both paleo data and observations, and isolated forcing simulations in coupled climate model simulations may help to understand this potential atmospheric circulation change. Nonetheless, this study has helped to better understand the differences and relative strengths and limitations of not only the Antarctic sea ice reconstructions examined here, but also several pressure reconstructions. It is thus hoped that future users of these valuable datasets will exercise the necessary caution when analyzing them given the knowledge of the processes they represent well, and other mechanisms that they may not reproduce as reliably.

~~Code and~~ Data Availability

~~The Fogt et al. (2022a) sea ice reconstructions can be obtained from the National Snow and Ice Data Ceter dataset G10039 (https://nsidc.org/data/g10039/versions/1) (Fogt et al., 2023). The Fogt et al.~~ The FOGT_STAT sea ice reconstructions can be obtained from the National Snow and Ice Data Center dataset G10039 (https://nsidc.org/data/g10039/versions/1) (Fogt et al., 2023). The Fogt et al. (2019) and Fogt and Connolly (2021) pressure reconstructions can be downloaded from figshare (~~https://doi.org/10.6084/m9.figshare.c.6765447.v1). Data for the Dalaiden et al. (2021)~~https://doi.org/10.6084/m9.figshare.c.6765447.v1). Data for the DAL21_ASSIM sea ice extent and pressure reconstructions are available on Zenodo (~~https://zenodo.org/record/4770179). The O'Connor et al. (2021)~~https://zenodo.org/record/4770179). The OCON21_ASSIM pressure reconstructions are available on Zenodo (~~https://zenodo.org/record/5507607#.Y6OOl-yIb0o~~https://zenodo.org/record/5507607#.Y6OOl-yIb0o) and the ~~sesnsitivity~~sensitivity reconstructions from ~~O'Connor et al. (2023)~~OCON23_ASSIM can also be downloaded from Zenodo (~~https://zenodo.org/record/8007655~~https://zenodo.org/record/8007655).

Author Contributions

RLF and QD designed the study. All authors contributed to writing and editing the manuscript, and RLF produced the figures.

Competing Interests

The authors declare no competing interests.

Acknowledgments

RLF acknowledges support from the U.S. National Science Foundation Office of Polar Programs award #1744998. QD is a Research Fellow within the F.R.S.-FNRS (Belgium).

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