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An Assessment of Early 20th Century Antarctic Pressure Reconstructions using Historical Observations

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26

27 Abstract

28 While gridded seasonal pressure reconstructions poleward of 60°S extending back to
29 1905 have been recently completed, their skill has not been assessed prior to 1958. To provide a
30 more thorough evaluation of the skill and performance in the early 20th century, these
31 reconstructions are compared to other gridded datasets, historical data from early Antarctic
32 expeditions, ship records, and temporary bases.

33 Overall, the comparison confirms that the reconstruction uncertainty of 2-4 hPa
34 (evaluated after 1979) over the Southern Ocean is a valid estimate of the reconstruction error in
35 the early 20th century. Over the interior and near the coast of Antarctica, direct comparisons with
36 historical data are challenged by elevation-based reductions to sea level pressure. In a few cases,
37 a simple linear adjustment of the reconstruction to sea level matches the historical data well, but
38 in other cases, the differences remain greater than 10 hPa. Despite these large errors,
39 comparisons with continuous multi-season observations demonstrate that aspects of the
40 interannual variability are often still captured, suggesting that the reconstructions have skill
41 representing variations on this timescale, even if it is difficult to determine how well they capture
42 the mean pressure at these higher elevations. Additional comparisons with various 20th century
43 reanalysis products demonstrate the value of assimilating the historical observations in these
44 datasets, which acts to substantially reduce the reanalysis ensemble spread, and bring the
45 reanalysis ensemble mean within the reconstruction and observational uncertainty.

46

47 **1. Introduction**

48 Despite recent dramatic climate-related changes in Antarctica, including warming of
49 West Antarctica (Steig *et al.*, 2009; Bromwich *et al.*, 2012; Jones *et al.*, 2019; Turner *et al.*,
50 2019), retreat of several marine-based glaciers in the Amundsen Sea embayment (Rignot *et al.*,
51 2013, 2019; Edwards *et al.*, 2019), and rapid sea ice loss beginning in austral spring 2016
52 (Stuecker *et al.*, 2017; Turner *et al.*, 2017; Purich and England, 2019), there are significant
53 challenges to understanding how unique these events are in a historical context or how likely
54 they are to change in the future. This is in part due to the high degree of natural climate
55 variability across Antarctica and the fully coupled nature of many of these changes occurring at
56 the atmosphere-ice-ocean interface. When combined with the short observational climate
57 records primarily beginning around the international Geophysical Year (IGY) activities of
58 1957/1958, interpreting these changes in the Antarctic climate has proven to be very difficult
59 (Jones *et al.*, 2016).

60 Data from ice cores across Antarctica help to place ongoing change in a longer context
61 (Bracegirdle *et al.*, 2019), especially through coordinated efforts like the International Trans-
62 Antarctic Scientific Expedition (ITASE; Mayewski *et al.*, 2005). Ice core evidence has helped to
63 compare recent Antarctic warming with variability over the past 2000 years (Stenni *et al.*, 2017)
64 as well as changes in West Antarctica snowfall (Thomas *et al.*, 2008), and when combined with a
65 climate model, longer estimates of Antarctic surface mass balance (Agosta *et al.*, 2019), as
66 examples. Nonetheless, dating of specific events and the suppressed sub-annual temporal
67 resolution in many cores pose challenges for these longer-term estimates of Antarctic climate
68 variability.

69 Other tools to examine historical Antarctic climate variability during the last century
70 include gridded datasets that span the 20th century, such as existing historical reanalyses that only
71 assimilate surface pressure, like the National Oceanic and Atmospheric
72 Administration/Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES)
73 Twentieth Century Reanalysis version 2c (hereafter 20CRv2c, Compo *et al.*, 2011) and the new
74 NOAA-CIRES-DOE version 3 (20CRv3, Slivinski *et al.*, 2019). Similar “sparse-input”
75 reanalyses have been completed by the European Centre for Medium Range Weather Forecasts
76 (ECMWF), including their 20th-century reanalysis (ERA-20C, Poli *et al.*, 2016) and a coupled
77 ocean-atmosphere reanalysis of the 20th century (CERA-20C, Laloyaux *et al.*, 2018), each of
78 which assimilates marine wind observations and surface pressure. As a coupled reanalysis,
79 CERA-20C also assimilates subsurface ocean temperature and salinity observations (Laloyaux *et al.*,
80 *al.*, 2018). While these are spatially and temporally complete throughout the 20th century,
81 unsurprisingly they are sensitive to the number of assimilated surface pressure observations, and
82 therefore the skill changes considerably over the high southern latitudes throughout the 20th
83 century (Schneider and Fogt, 2018; Fogt *et al.*, 2019; Slivinski *et al.*, 2019).

84 An alternative approach to address these challenges is to generate seasonal pressure
85 reconstructions, both at individual Antarctic stations (Fogt *et al.*, 2016a, 2016b), as well as
86 spatially complete poleward of 60°S (Fogt *et al.*, 2017a, 2019). When compared to gridded
87 climate datasets, these reconstructions showed far less sensitivity to changes in the number of
88 observations across Antarctica (Schneider and Fogt, 2018), which is perhaps not surprising given
89 that the reconstructions were based on statistical relationships with a spatially and temporally
90 fixed network of stations in the mid and high latitudes of the Southern Hemisphere (Fogt *et al.*,
91 2016a). However, the skill of the reconstructions was only thoroughly evaluated after the IGY,

92 (1957-1958), when most Antarctic observations began; spatially complete comparisons in
93 reconstruction skill were even more limited and only possible after 1979 through evaluating
94 against the ECMWF Interim reanalysis, ERA-Interim (ERA-Int; Dee *et al.*, 2011). Therefore,
95 the skill of these reconstructions in the early 20th century before the IGY remains unknown,
96 although the underlying relationships governing them are likely stationary (Clark and Fogt,
97 2019). This work aims to provide a more complete evaluation of these reconstructions poleward
98 of 60°S by using available pressure observations that are independent from the reconstructions in
99 the early 20th century.

100

101 **2. Data and Methods**

102 We make use of the best performing seasonal spatially-complete Antarctic pressure
103 reconstructions, which are available from 1905-2013 and based on surface pressure anomalies
104 from the 1981-2010 climatology from ERA-Int (Fogt *et al.*, 2019). The reconstructions are
105 based on a kriging interpolation of 18 Antarctic station reconstructions and observations at
106 Orcadas (locations plotted in bottom right panel of Fig. 1) to an 80km x 80 km Cartesian grid
107 centered over the South Pole. For comparison here, this grid has been converted to a 0.75°x0.75°
108 latitude-longitude grid. Importantly, comparisons with ERA-Int after 1979 (Fogt *et al.*, 2017a,
109 2019) demonstrated that the reconstruction skill varies seasonally, with the highest skill (defined
110 as the best agreement with ERA-Int) in austral summer (December – February, DJF), and the
111 lowest skill in the austral autumn and spring (March-May, MAM, and September-November,
112 SON, respectively). In general, higher reconstruction skill is found over the Antarctic continent
113 (especially near the Antarctic Peninsula), and lower skill at the northern edge of the domain near
114 60°S, especially in the South Pacific (Fogt *et al.*, 2019).

115 Historical pressure data prior to 1957 poleward of 60°S were extracted from three
116 primary datasets to further evaluate the reconstruction skill in the early 20th century. The largest
117 source of pressure data comes from the International Surface Pressure Databank version 3.2.9
118 (ISPD; Cram *et al.*, 2015), which contains subdaily measurements of mean sea level and/or
119 surface pressure from both ships and temporary Antarctic bases (during field expeditions) and
120 early Antarctic stations that began prior to the IGY. Additional sea level and/or surface pressure
121 data were obtained from the International Comprehensive Ocean-Atmosphere Data Set release 3
122 (ICOADS; Freeman *et al.*, 2017); we only make use of ship records in ICOADS that were not
123 available in ISPD. As many new historical observations from both ships and early Antarctic
124 expeditions are still being recovered and digitized, we also make use of a few newly digitized
125 additional pressure observations stemming from the Atmospheric Circulation Reconstructions
126 over the Earth (ACRE) initiative (Allan *et al.*, 2011), obtained directly from Rob Allan, the lead
127 of the ACRE project. Only those ACRE pressure observations that were not part of the current
128 releases of ISPD and ICOADS are utilized here, particularly from Antarctic expeditions in the
129 first few decades of the 20th century. Most historical observations reported both SLP and surface
130 pressure; however, a few observations only reported SLP, and therefore the reconstruction is
131 compared to historical SLP observations throughout. We directly use the historical observations
132 as reported in ISPD, ICOADS, or in the ACRE data for SLP and surface pressure, and do not
133 reduce any surface pressure observations to SLP.

134 In making comparisons, it is important to consider that historical observations can have
135 their own error or bias for many reasons, potentially including incorrect reported location
136 (latitude, longitude, or elevation); problems with the barometer; errors associated with
137 adjustments to sea level pressure; or misspecified corrections to pressure measurements from

138 temperature or gravity. Because measurement errors likely vary in time and space, it is difficult
139 to fully quantify how much these errors contribute to the reported pressure observations (Kent
140 and Berry, 2005). Reanalyses generally define instantaneous, random observation errors that
141 depend on platform and/or time (Compo *et al.*, 2011; Poli *et al.*, 2016; Laloyaux *et al.*, 2018;
142 Slivinski *et al.*, 2019), and analyses comparing these expected errors with background statistics
143 suggest estimates of about 1.5-2 hPa in the early 20th century are reasonable (Slivinski *et al.*,
144 2019). However, Slivinski *et al.* (2019) and more recent comparisons (not shown) also suggest
145 that there is a relatively large systematic error in observations in the Southern Hemisphere in the
146 early 20th century. We therefore assume a conservative estimate of 2 hPa total error in the
147 seasonally-average observation estimates (or an observation error variance of 4 hPa²).

148 In order to compare the historical observations to the reconstructions, additional analysis
149 was required. First, all historical pressure data were converted to hPa, the same units as the
150 pressure reconstructions. Monthly means for all the historical observations were calculated if at
151 least 75% of the days within a given month had at least one observation available, to ensure a
152 reliable monthly pressure estimate. Seasonal means (following the traditional seasonal divisions,
153 DJF, MAM, JJA (June – August), and SON) were calculated to compare to the seasonal pressure
154 reconstructions if at least two monthly means existed using our 75% daily data threshold; data
155 for the third month was added to calculate the seasonal mean if 2 months had met the 75% daily
156 data threshold, and the third month had more than 50% of its daily data. This approach allows
157 for comparison with the maximum amount of data possible. Comparisons of a single monthly
158 mean historical observation (for cases when historical data only had one month meeting our
159 threshold) with the seasonal mean pressure reconstruction produced larger differences (not
160 shown), and so this paper only focuses on comparisons of at least two months of historical data

161 to define a seasonal mean. Altogether, these constraints yielded 271 seasonal means from
162 historical pressure observations prior to 1957. The majority (>75%) of these historical
163 observations occur only in DJF (austral summer), although it is noted that there are several
164 observations after 1940 complete for the entire year. For reference, the year of austral summer
165 refers to the year of December throughout this study.

166 Two more steps were taken prior to making comparisons. First, seasonal mean locations
167 for the historical records were calculated using the coordinates provided in the data archives.
168 These locations varied little for the early Antarctic stations; for observations collected on moving
169 ships, we calculated a seasonal mean location by year for comparison since the reconstruction
170 data are only available seasonally, which limits comparisons at higher temporal and spatial
171 frequency. Of the 130 seasonal means from the ship records, more than 75% of the subdaily
172 pressure observations showed less than a 2 degree standard deviation in the latitude, and half of
173 the ships' standard deviations were less than 15 degrees longitude. In terms of pressure, there
174 was no significant difference between ships that had a standard deviation of more and less than
175 20 degrees longitude in the standard deviations of sub-daily pressure observations. We therefore
176 suggest the error associated with the mean location is more strongly related to the number of
177 strong storms a ship encountered, which are more unique to a specific location rather than the
178 mean location of the ship. As a rough estimate of this error, the mean standard deviation of
179 pressure from the subdaily ship observations, 3.45 hPa, can be used, although more than half of
180 the ships have a pressure standard deviation below 3.0 hPa. This standard deviation of subdaily
181 pressure within one season is much smaller than the interannual standard deviation of monthly
182 pressure across the South Pacific, which ranges from 3-7 hPa based on ERA5 data (contours in
183 Fig. 1, bottom right panel).

184 Lastly, to compare the pressure reconstructions to the historical pressure observations,
185 elevation adjustments were needed. The pressure reconstructions, originally constructed as
186 surface pressure anomalies based on the underlying topography of ERA-Int at $0.75^\circ \times 0.75^\circ$
187 latitude / longitude resolution, were adjusted to sea level pressure using a rough linear estimate
188 of 12 hPa pressure decrease per 100 m elevation gain. The 12 hPa approximation is larger than
189 the 10 hPa per 100m assumed in the middle latitudes in the lower troposphere given the colder
190 and drier (and therefore denser) air commonly observed poleward of 60°S . Without simultaneous
191 measurements of temperature and humidity, it is challenging to provide a more accurate
192 adjustment to sea level pressure. Furthermore, reduction to sea level pressure is known to be
193 problematic in nearly all gridded climate datasets (and observations themselves) over Antarctica,
194 including 20CRv3 (Slivinski *et al.*, 2019). This adjustment to sea level was necessary even for
195 historical observations that had both surface and sea level pressure data, as due to the smoothing
196 of the topography of ERA-Int at even the 0.75° resolution, model elevations and observed
197 elevations (where known – this value is not always given in the historical data) are often quite
198 different; these elevation differences similarly make it challenging to adequately compare
199 surface pressure observations with the surface pressure (anomaly) reconstructions. Importantly,
200 elevation differences can also arise due to the smoothing of the steep Antarctic coastline in ERA-
201 Int, and therefore influence comparisons from ships close to the Antarctic continent. This
202 adjustment to sea level introduces the greatest error and uncertainty in our comparison, as will be
203 discussed in detail throughout. Nonetheless, the simple linear adjustment allows us to evaluate
204 interannual (or intra-annual) variability and provide further information on reconstruction
205 performance than otherwise would be possible.

206 In the comparisons, the reconstruction data are extracted from the gridpoint closest to the
207 seasonal mean location in the reconstruction field. To provide further comparison for select
208 observations that span more than one season, from the reanalyses we also extract both surface
209 and sea level pressure data from the closest gridpoint using the ensemble mean in all but ERA-
210 20C (which has only one estimate). This approach also introduces some error, called the ‘error
211 of representativeness’, reflecting how well a reanalysis gridpoint represents the point location
212 from the observation; this error is assumed to be one of the largest components of observation
213 errors in the reanalyses, at least in 20CRv3 (Slivinski *et al.*, 2019), and is similar to the
214 elevation-based errors for the reconstruction evaluations described previously. Importantly,
215 these reanalyses are not independent of the observations used for comparison here: ERA-20C
216 and CERA-20C assimilate surface pressure and marine surface wind observations from ISPD
217 version 3.2.6 and ICOADS version 2.5.1 (Poli *et al.*, 2016; Laloyaux *et al.*, 2018); 20CRv2c
218 assimilates pressure from ISPD version 3.2.9 and ICOADS version 2.5.P; and 20CRv3
219 assimilates pressure from ISPD version 4.7 and ICOADS version 3+v2 (Slivinski *et al.*, 2019).
220 Since the comparisons are made with ISPD v3.2.9 and ICOADS v3, the observations were at
221 least available to be assimilated in both version of 20CR, and likely for ERA-20C and CERA-
222 20C. However, the assimilation combines the instantaneous observations with a background
223 guess from the forecast model, so fields from different reanalyses are expected to differ from
224 each other (as they each use different forecast models and assimilation algorithms), as well as
225 from the seasonally-averaged observation estimates analyzed here. In addition, each reanalysis
226 system has its own quality control algorithm that will blacklist observations deemed unfit for
227 assimilation; thus, even if a given set of observations are available to the assimilation algorithm,
228 they may not all have been assimilated. Finally, the reanalyses each employ their own

229 observation bias correction scheme, which removes significant, consistent differences between
230 the observations and the background fields. For simplicity, we only consider the uncorrected
231 observations here, but note that systematic differences between the reanalyses and observations
232 in our comparison may have been ameliorated by taking into account the observation bias
233 corrections calculated within each reanalysis.

234 Reconstruction performance compared to the historical observations is evaluated using
235 three primary statistics: overall bias, defined as the mean difference between the seasonal
236 historical observation estimates and reconstructions at sea level (reconstruction minus
237 observations); the mean absolute error (MAE), defined as the mean absolute difference to
238 remove offsetting effects of positive and negative difference; and the root mean square
239 difference (RMSD), which due to the squaring of the differences prior to calculating the mean,
240 gives slightly higher weighting to larger absolute differences than the MAE. For observations
241 that span only one season or have the bias of the same sign across all seasons, the absolute value
242 of the bias and MAE will yield identical results. In all cases, these three statistics were
243 calculated over the full length of each observational record. Further averaging both spatially and
244 temporally is conducted to assess the overall reconstruction performance. Since the
245 reconstruction error determined by Fogt et al. (2019) over 1979-2013 is assumed to be constant
246 in time, it is assumed that there are no (temporally) correlated errors in the reconstruction; the
247 evaluations in this paper help to determine the persistence of reconstruction errors through the
248 early 20th century.

249

250 **3. Results**

251 *3.1. Historical data availability*

252 Prior to estimating the seasonal pressure reconstruction skill in the early 20th century, it is
253 important to recognize the large changes in the number of observations poleward of 60°S,
254 especially before 1957. Figure 1 displays the location and data type for all of the 271 seasonal
255 means that were compared to the reconstruction; open circles represent seasonal mean positions
256 of ship data while filled circles denote base or station records that were stationary or only had
257 minor movements over time. As expected, there are very few observations prior to 1930,
258 although there is a relative increase in the 1910-1919 during the height of the ‘Age of Heroes’
259 which includes expeditions to the South Pole, the Australian Antarctic Expeditions, and the
260 British Imperial Trans-Antarctic Expedition led by Ernest Shackleton. The decrease in the
261 number of observations in the 1940s is not only a challenge in the high southern latitudes but
262 also worldwide, associated with the Second World War. Nearly half of the historical
263 observations used for comparison here come from the years just prior to the IGY (1950-1957),
264 with several early Antarctic stations established over the continent (especially along the
265 Antarctic Peninsula), and frequent ships along the East Antarctic coastline. A notable gap in
266 observational coverage is within the Weddell Sea (east of the Antarctic Peninsula) and
267 throughout much of the South Atlantic. In addition to persistent sea ice in the Weddell Sea
268 (Cavalieri and Parkinson, 2008), the South Atlantic area is far from commercial sailing or
269 whaling routes and is likely one of the greatest spatial data voids globally (for example, see Fig.
270 1 of Allan and Ansell, 2006).

271

272

273 *3.2. Overall reconstruction performance*

274 With this temporal evolution of historical data in mind, the reconstruction performance is
275 displayed as a bar chart in Fig. 2; the overall statistics (averaged over all available observations)
276 are given at the bottom: mean bias = -0.79 hPa; mean MAE = 4.05 hPa; mean RMSD = 4.26 hPa.
277 Recalling that the overall comparison is primarily during austral summer, these values are
278 considerably higher than the skill assessed in earlier work in comparison to ERA-Int (Fogt *et al.*,
279 2017a, 2019), which estimated an MAE over the Antarctic continent generally less than 1.5 hPa
280 and over the Southern Ocean around 2-3 hPa. Indeed, the values seem even higher than the
281 MAE in Fogt *et al.* (2019) in the non-summer months in the South Pacific, the region of highest
282 MAE compared to ERA-Int which ranged from 2-4 hPa.

283 This quick comparison initially suggests that the seasonal pressure construction
284 performance is of much lower quality prior to 1957 than it is after 1957. However, when
285 considering that the observation estimates have their own errors (assumed to be approximately
286 ~2 hPa in the early 20th century), the higher MAE prior to 1957 is not far from the assumed
287 observational error. Further, when looking at the average skill as a function of latitude (Fig. 2),
288 the bias is near zero in both of the latitude bands that primarily lie over the Southern Ocean (60°-
289 65°S and 60°-70°S), potentially suggesting that the historical observation estimates tend to
290 fluctuate near the reconstruction seasonal mean overall (both above and below, cancelling to near
291 zero). The MAE in these latitude bands, near 3 hPa, better reflects the overall performance as it
292 removes the cancellation between positive and negative differences. The MAE of 3 hPa is
293 consistent with the skill reflected in Fogt *et al.* (2019), and is also close to the assumed
294 observation error of 2 hPa. In contrast, where Fogt *et al.* (2019) demonstrate lower MAE over
295 the Antarctic continent (due to more station observations constraining the reconstruction skill),
296 comparisons with the historical observation estimates clearly show an increase in MAE poleward

297 of 65°S, which is primarily from stations over the Antarctic continent (poleward of 70°S). As
298 noted earlier, this increase in MAE is an artifact of the elevation sensitivity when comparing the
299 historical observations at (often unknown) elevations different from the seasonal pressure
300 reconstruction based on the underlying topography of the ERA-Int 0.75°x0.75° grid. The simple
301 linear offset of 12 hPa per 100 m creates sea level pressures that are consistently too low
302 (evidenced by the negative bias), which gives rise to large MAE and RMSD over the Antarctic
303 continent.

304 The sensitivity to elevation is also apparent in the comparisons as a function of longitude.
305 There is a strong negative bias in the 330°-30°E range, along the mountainous Antarctic
306 Peninsula. In ERA-Int, this terrain was greatly smoothed but still elevated, while the
307 observations are often along the coast near sea level. In other longitude zones, the mean bias is
308 typically in the range of ± 1 hPa, with MAE around 3-4 hPa. Given that Fig. 1 indicates that
309 outside of 330°-30°E, the seasonal mean observation estimates primarily are over the ocean and
310 less influenced by elevation corrections, the comparison by longitude again reflects a similar
311 skill of the reconstruction (over the Southern Ocean at least) as observed in Fogt *et al.* (2019)
312 during 1979-2013. Comparisons by decade typically have MAE also in the 3-4 hPa range,
313 consistent with the previous evaluation. One outlier is the 1910s, which from Fig. 1 has a
314 relatively high percentage of historical observations on or near the Antarctic continent,
315 suggesting that elevation corrections are again giving a misleading impression of relatively low
316 reconstruction skill.

317 To further visualize the spatial and elevation dependence of reconstruction performance,
318 Fig. 3 displays the decadal mean RMSD for each station by decade. Several key points emerge
319 from Fig. 3. First, there is an indication from ships in the South Pacific north of the Amundsen

320 and Bellingshausen Seas (roughly 60°-70°S, 150°-90°W) that the reconstruction skill is
321 considerably lower, with RMSD values often above 6 hPa. Since these are seasonal pressure
322 estimates from ships (Fig. 1), elevation correction is not an issue. Rather, the larger errors are
323 consistent with the much lower reconstruction performance in this region of high interannual
324 variability (which often exceed observational errors based on interannual monthly pressure
325 standard deviations as large as 7 hPa in Fig. 1), as discussed in previous evaluations (Fogt *et al.*,
326 2017a, 2019). The larger interannual pressure variability here may also suggest that using the
327 mean ship location could be introducing more error in this sector compared to other regions
328 around Antarctica (Fig. 1). Second, for comparisons in the Southern Ocean for nearly all other
329 regions, the RMSD is generally below 4 hPa, and the majority of the comparisons with the
330 seasonal mean ship observation estimates show RMSD in the 3-4 hPa range. These values are
331 consistent with the slightly lower performance of the reconstruction over the Southern Ocean.
332 However, these values of RMSD still fall within expected error when considering errors in both
333 observation estimates and the reconstruction (taken as the square root of the sum of the
334 observational and reconstruction error variances). Lastly, it is clear that many of the higher
335 errors (exceeding 6 hPa) are found along the coast, the Antarctic Peninsula, or in the interior of
336 the continent. Even on the Ross Ice Shelf, RMSD values are typically larger than 4 hPa. As will
337 be more clearly demonstrated later, these larger differences are due to elevation corrections to
338 the historical observations in or near areas of high or vastly varying terrain. We will show that
339 the reconstruction skill is likely much higher in these areas than suggested by the RMSD values
340 in Fig. 3. Remarkably, in every decade since the 1930s, there are multiple locations where the
341 RMSD values (over the ocean) are less than 1hPa, which is an excellent agreement with the
342 historical observations. Given that we make comparisons with the seasonal mean ship position,

343 that the historical observation estimates are rarely complete for the full season, and that they
344 themselves have errors, this high agreement is noteworthy. It suggests that the reconstruction
345 can be used as a reliable approximation of Antarctic pressure in most regions on and around the
346 continent back to at least the 1930s.

347

348 *3.3 Reconstruction performance evaluated with selected historical observations*

349 The reconstruction performance is perhaps best evaluated by comparing to individual
350 historical observations, which is the focus for the remainder of the study. To facilitate these
351 assessments, a subset of representative stations and ship seasonal locations has been selected;
352 their average location, name, and mean RMSD values over the entire record length are plotted in
353 Fig. 4. We have purposely selected historical pressure estimates with longer records than a
354 single season, and as many complete records from earlier portions of the 20th century as possible,
355 although the sample size is quite limited (Fig. 1). In general, the reconstruction performance
356 indicated by the mean RMSD in Fig. 4 at these locations is comparable to the overall decadal
357 mean performance in Fig. 3, although we do not closely examine any stations with RMSD less
358 than 2 hPa, and only one station where inadequate elevation corrections challenge the assessment
359 of reconstruction skill (Cape Denison). Recall, all of these data were available for assimilation
360 into 20CRv2c and 20CRv3 (and likely available for CERA-20C and ERA-20C), so the
361 comparisons with the reanalyses are not necessarily always independent as discussed in section
362 2.

363 Figure 5 displays three seasonally-averaged historical observation estimates where the
364 mean RMSD values are 2-3 hPa, consistent with the reconstruction skill and uncertainty assessed
365 in Fogt *et al.* (2019), and within the assumed observational error variance of 4 hPa². Plotted with

366 the historical observations (in red) are the mean sea level pressure (solid) and surface pressure
367 (dashed, when available) from the nearest gridpoint of 20CRv2c (green), 20CRv3 (orange),
368 ERA-20C (purple), and CERA-20C (blue). To compare with the skill evaluation in Fogt *et al.*
369 (2019), the correlations (if more than 10 values are available) and MAE (in hPa) for each gridded
370 dataset are given at the bottom of each panel: the first number is based on the MSLP, and the
371 second number (where available) is based on surface pressure.

372 Station 889340 (from the ISPD archive) is situated along the Antarctic Peninsula (Fig. 4)
373 and has a continuous pressure record beginning in 1948 for all seasons. As such, it is one of
374 many such stations that provide a useful evaluation of reconstruction skill, and the overall MAE
375 from the reconstruction is less than 2 hPa. Moreover, the temporal variability is well captured (r
376 > 0.80 in all datasets). The various reanalysis products have similar MAE (generally from 1-2
377 hPa), well within the likely observational uncertainty, with CERA-20C having the lowest for
378 MSLP, and 20CRv2c having the lowest for surface pressure. Despite the low MAE / RMSD at
379 this station, adjustment of the reconstruction to sea level pressure may play a small role in its
380 performance, as there are differences in both the historical MSLP and surface pressure, as well as
381 the MSLP and surface pressure in the reanalyses. Nonetheless, this station shows the viability of
382 the reconstruction shortly before the IGY along the Antarctic Peninsula, a region of relatively
383 higher reconstruction skill compared to ERA-Int after 1979 (Fogt *et al.*, 2017a, 2019).

384 Deck 215 (Fig. 5b) from ICOADS has adequate observational coverage only during
385 austral summer. The reconstruction skill is comparable to the skill seen in the southern Indian
386 Ocean during much of the 1930s (Fig. 3). The reconstruction MAE is 2.5 hPa, slightly higher
387 than all reanalyses but ERA-20C, which was found to be one of the lower performing reanalyses
388 in the early 20th century near Antarctica (Schneider and Fogt, 2018). Despite the higher MAE

389 for the reconstruction (which, unlike the reanalysis products, is entirely independent from these
390 historical observations), the historical observation values nearly all fall within the reconstruction
391 uncertainty (95% confidence interval, gray shading), and the reconstruction uncertainty would
392 clearly overlap with the observational uncertainty throughout time. Together, the comparison
393 with Deck 215 data suggests the original assessment of the reconstruction skill provides a good
394 approximation of its performance in the early 20th century. Although the interannual variability
395 is not as strongly captured as in Fig. 5a (correlation is not provided since only six years of data
396 exist), it should be noted that the reanalysis datasets also do not reproduce the interannual
397 variability well (perhaps due to observational errors or the spatial averaging). We also observe
398 that the surface pressure in 20CRv2c is notably different than the surface pressure from the other
399 reanalyses, probably due to the spectral effects in the 20CRv2c elevation field noted by Slivinski
400 et al. (2019).

401 For a longer observational record over the Southern Ocean, Deck 899 (Fig. 4, from
402 ICOADS) also has pressure observations only for austral summer but over multiple decades (Fig.
403 5c). The location varied during these many voyages, but overall the observational estimate of
404 the seasonal mean falls within or very near the reconstruction uncertainty. Indeed, the
405 reconstruction agrees better with the seasonally-averaged ship-based values than the reanalyses
406 (MAE of 2.23 hPa compared to 2.3 – 3.7 hPa from reanalyses, although almost all datasets
407 would fall within the observational uncertainty at this location). The correlations are much lower
408 for these ship data across all datasets, due to differing fluctuations between a few years (i.e.,
409 1933-1934, 1936-1937, 1945-1946), however the interannual variability is better captured after
410 1946. In general, the reconstruction also aligns well with the MSLP from the reanalyses, except
411 for DJF 1934 when the ship traversed a large span of the southern Indian Ocean (from 88°E in

412 December 1934 to 47°E in February 1935). Therefore, the use of the seasonal mean location
413 could be artificially suggesting a lower reconstruction skill for this observational estimate.
414 Nonetheless, as in Figs. 5a and 5b, this comparison further suggests that the uncertainty of the
415 reconstruction is a good estimate of the reconstruction error in the early 20th century. Overall, the
416 reconstruction agrees well with many historical seasonal-mean observation values that were
417 withheld during the reconstruction's development. As in Fig. 5b, we note that there are larger
418 differences in the surface pressure from 20CRv2c which clearly fall outside the uncertainty from
419 using a seasonal mean ship location.

420 Figure 5 presents several comparisons where elevation corrections did not have a
421 noticeable influence on the evaluation of the reconstruction and are perhaps more representative
422 of the overall reconstruction quality. In many other locations, elevation adjustments appear to
423 play a more important role (especially on or near the Antarctic continent) in comparing the
424 reconstruction and observational estimates. At a few of these locations, a simple linear
425 adjustment of 12 hPa per 100m from the ERA-Int elevation at the reconstruction's gridpoint
426 proved sufficient to readily compare it to the historical values. A subset of these stations is
427 presented in Fig. 6.

428 Perhaps the most famous early American expeditions to Antarctica were those led by
429 Admiral Richard E. Byrd, who set up a station called Little America in several different field
430 campaigns spanning three decades (Byrd, 2003). Although the mean location of Little America
431 was on the Ross Ice Shelf (it varied negligibly during each campaign in comparison to the
432 resolution of the gridded datasets used in this study; Fig. 4), there were notable differences in
433 observed MSLP and surface pressure at the location (Fig. 6a). When adjusting the reconstruction
434 to sea level, a good match is observed both in overall mean pressure (MAE = 3.63 hPa) and

435 interannual variability. Surprisingly, the reconstruction performs much better than the MSLP
436 from 20CRv2c or 20CRv3, most notably due to the much higher MSLP in these two datasets
437 from the 1940s onward compared to the reconstruction and observed values. However, the
438 20CRv2c surface pressure nearly perfectly matches the observed surface pressure (an MAE of
439 only 2.39 hPa), while 20CRv3 has very similar values for surface and sea level pressure
440 observations. We note that although there are significant offsets from the observed values for
441 most of the datasets ($MAE > 6$ hPa for both), the interannual variability is well-captured, with
442 the reconstruction correlation of 0.85, and surface pressure correlations from the reanalyses all
443 above 0.85. The consistent difference between the observations and 20CRv3 could be due to
444 elevation issues or to a detected bias in the observations; this will be examined in more detail
445 later. CERA-20C, as seen earlier, performs with the highest skill for MSLP ($r=0.9$). Also note
446 that the offset from the surface pressure to MSLP is not constant, as this difference, through the
447 hypsometric equation, is influenced by both temperature and humidity. Therefore, some of the
448 larger errors in the reconstruction and the reanalyses, particularly in the 1950s, could be due to
449 too strong of an increase in the surface pressure as it was reduced to sea level, since the gap
450 between surface pressure and sea level pressure is much lower in the historical observations
451 during the 1950s. Observational uncertainties, including the various bias corrections employed
452 by the reanalyses as discussed previously, can also create some of these differences between
453 products when compared to the observations.

454 Much earlier in Antarctic history, under the leadership of Jean-Baptiste Charcot, the
455 French conducted their second expedition that wintered over on Peterman Island in 1908-1910.
456 The ship associated with this expedition was Porquoi Pas, with a mean location near the
457 Antarctic Peninsula (Fig. 4). Due to the close proximity of the high terrain of the Antarctic

458 Peninsula, elevation adjustments to the reconstruction were necessary but may not have been
459 sufficient at this location. From historical observations, the difference between surface pressure
460 and sea level pressure ranged from nearly 20 hPa to as little as 5 hPa in DJF 1909 (Fig. 6b).
461 Despite the challenges in correcting for the elevation differences, as seen in Fig. 6b, the
462 adjustment brings the observed MSLP to the far upper-limits of the reconstruction uncertainty,
463 and clearly within the observational uncertainty. Further, the reconstruction agrees well with the
464 observational estimates: the MAE of 3.15 hPa is nearly consistent with time, and the seasonal
465 cycle of the pressure during this portion of the early 20th century is well captured by the
466 reconstruction. It is also encouraging to see high skill in both 20CR datasets, and again in
467 CERA-20C at this location, all within the observational uncertainty; the lower performance of
468 ERA-20C could be related to a cold bias or perhaps resolution issue, as there is a much larger
469 difference between surface pressure (dashed line) and MSLP (solid line) in ERA-20C compared
470 to the observations or CERA-20C. The differences in surface pressure between 20CRv3 and the
471 observations are also noteworthy, with an MAE of 38.60, reflecting differences in model and
472 observed orography.

473 Similarly situated near the Antarctic Peninsula (Fig. 4), Argentine Island provides a long
474 continuous record much like in Fig. 5a, but with a noticeable influence of elevation-based
475 pressure corrections (Fig. 6c). As with Porquoi Pas, the linear SLP adjustment brings the
476 reconstruction close to the historical estimates, but they fall at the upper-bound of the
477 reconstruction uncertainty, and are much closer to the reanalyses overall. All comparisons are
478 within the expected observational uncertainty. The interannual variability is well-captured by
479 the reconstruction ($r=0.82$), although it may be slightly dampened in the early 1950s.
480 Interestingly, ERA-20C surface pressure aligns closely with the historical observations (with an

481 MAE of 1.63 hPa), but this reanalysis again demonstrates the highest MAE compared to MSLP
482 (4.88 hPa). In contrast, CERA-20C shows the lowest MAE based on MSLP (0.66 hPa), but
483 considerably lower surface pressure than observed (an MAE of 18.29 hPa), though not as low as
484 surface pressure in 20CRv3 (an MAE of 33.42). All reanalyses show very high correlations with
485 observations for both MSLP and surface pressure ($r > 0.85$).

486 The long, albeit discontinuous record at the Little America station location (Fig. 4)
487 provides an opportunity to further evaluate the reconstruction in comparison to the historical
488 reanalyses, and importantly, to assess the reconstruction skill in light of the reanalyses' internally
489 estimated uncertainties. For the reanalyses studied here, all but ERA-20 are ensemble
490 reanalyses, and therefore the ensemble spread from the seasonal mean ensemble members can be
491 further employed to assess the quality of these products through time and provide a more
492 complete comparison of their skill relative to that of the reconstruction. The MSLP from the
493 closest gridpoint of 20CRv2c, 20CRv3, and CERA-20C are plotted in Fig. 7, along with 95%
494 confidence intervals calculated as 1.96 times the ensemble standard deviation of seasonally
495 averaged MSLP from the 56, 80, and 10 ensemble members of 20CRv2c, 20CRv3, and CERA-
496 20C, respectively. The performance varies slightly at neighboring gridpoints for MSLP, but
497 varies considerably if using surface pressure, suggesting elevation gradients from the nearby
498 Roosevelt Island or the edge of the Ross Ice Shelf can influence the reanalysis estimate at this
499 location.

500 Similar to but slightly larger than the reconstruction, Fig. 7 shows that CERA-20C has a
501 pronounced annual cycle of MSLP at Little America, while both 20CRv2C and 20CRv3 have a
502 dampened annual cycle. Nonetheless, Fig. 7 also demonstrates that there is a marked decrease in
503 the reanalyses' uncertainties at the times when the Little America data were assimilated, which

504 effectively constrained the reanalysis estimates. There are also other reductions in the reanalysis
505 uncertainties prior to the establishment of Little America, including the data assimilated from the
506 South Pole race of 1911-1912 (the Norwegian base Framheim was very close to Little America
507 (Fogt *et al.*, 2017b)) and the data from the first British Antarctic Expedition (1908-1909, which
508 established a base near present day McMurdo station west of Little America, at Cape Royds).
509 At these times, the reanalyses and reconstruction show considerable agreement, and the
510 reanalysis uncertainty (colored shading in Fig. 7) overlaps the reconstruction uncertainty (gray
511 shading in Fig. 7). Exceptions are in 1929 for all reanalyses and in 1911 for 20CRv2c and
512 20CRv3 when the reconstruction and reanalysis uncertainties do not overlap, with the
513 reconstruction seasonal mean MSLP lower than the reanalyses. Nonetheless, the overall
514 agreement at all other times suggests that although there may still be larger MAE in the
515 reanalyses MSLP when compared only during the times of direct observations (as in Figs. 5-6),
516 the observations and reconstruction both fall within the reanalyses uncertainty (estimated by the
517 ensemble spread), and the reanalyses have benefited greatly from assimilating this historical data
518 (moving much closer to, if not within, the observational uncertainty). Clearly, at other periods
519 when data are not available, the reanalysis spread is considerably larger, but the reconstruction
520 nearly always falls within the reanalyses' uncertainties (the high positive pressure values in
521 CERA-20C in 1944 are one exception). We note that the reanalysis uncertainty estimates
522 themselves require further improvement, particularly in the Southern Hemisphere: Slivinski *et al*
523 (2019) show artificial signals in the uncertainty of 20CRv2c, and demonstrate that the
524 uncertainty in this region still remains too large in 20CRv3. Conversely, Laloyaux *et al.* (2018)
525 acknowledge that the small ensemble of CERA-20C can result in overly-confident estimates of
526 uncertainty. Consistent with the comparison to observations (Fig. 6a), the CERA-20C MSLP and

527 reconstruction (Fig. 7c) show the most similarity throughout the early 20th century at the Little
528 America location (RMSD = 4.32 hPa), and for this location 20CRv3 performs better than
529 20CRv2c (RMSD of 5.95 hPa compared to 8.22 hPa).

530 Evaluation of the reconstruction skill in Figs. 2 and 3 often indicates substantial
531 differences, suggesting that the seasonal mean values from the historical observations do not
532 always fall within the reconstruction uncertainty when elevation corrections are applied,
533 particularly near high terrain (even when their uncertainty is accounted for; not shown). To
534 examine this issue further, Figure 8 depicts two cases – a set of Antarctic expedition ship records
535 (Deck 246, Fig. 8a) and a temporary base (Cape Denison, Fig. 8b), where elevation corrections
536 have mixed results; MAE values in Fig. 8 are only calculated for MSLP. Ships included in Deck
537 246 (from ICOADS) operated discontinuously near present day Dumont d’Urville station in the
538 Ross Sea sector of Antarctica (Fig. 4); the data from ICOADS have two disparate locations in
539 January – February 1912 (the mean of these would be over the continent), so instead of
540 averaging data from both locations, each were treated as separate data points in Fig. 8a and the
541 comparison statistics. The two different values for MAE in Fig. 8a are therefore based on the
542 MSLP at these two different locations, with the data closer to the Ross Ice Shelf (second value)
543 agreeing better with all gridded datasets than the data closer to the East Antarctic plateau, near
544 the location plotted in Fig. 4. Even with this potentially conflicting information, the
545 reconstruction performs very well after adjustment to sea level pressure, with an MAE of 2.32 /
546 1.85. A closer look shows that the majority of this error is from DJF 1910, when the
547 reconstruction was about 6 hPa lower than the observational estimate, otherwise it is generally
548 within 1.5 hPa. This performance exceeds the reanalyses’ performance for Deck 246, as the
549 reanalyses typically have much higher MSLP values.

550 In contrast, the famous base for the Australian Antarctic Expedition, Cape Denison
551 (Mawson, 1998), situated along the East Antarctic coast south of Australia (Fig. 4) is marked
552 with much lower performance across all datasets (Figure 8b). Elevation corrections and the
553 models' orography have a strong effect here, clearly demonstrated by the large differences in
554 surface and sea level pressure in observations and reanalyses (note, surface pressure is plotted on
555 the right axis, but because of the large differences in surface pressure the MAE is not given).
556 Whereas the seasonal means of the historical observations demonstrate surface pressures around
557 920 hPa on average, sea level pressure estimates from the station are around 70 hPa higher, at
558 around 990 hPa. Such high differences in the two over the cold ice sheet plateau compromise the
559 quality of the reduced sea level pressure (not only in observations, but across all datasets). The
560 MAE for the reconstruction (13.50 hPa) is one of the highest of all locations examined.
561 Although the reanalyses' errors are nearly half of this (around 5-7 hPa, likely improved by
562 making further use of temperature and humidity calculated within the reanalyses to reduce
563 surface pressure to sea level), the errors are still large, and the reanalyses and reconstructions all
564 likely fall outside the observational uncertainty. Furthermore, it is difficult to assess how well
565 the interannual variability of the MSLP is reproduced, since there are fewer than ten observations
566 and the reduction to sea level varies considerably by season (affected by temperature and
567 humidity), but the reconstruction was adjusted to sea level uniformly (and linearly) across all
568 seasons. Nonetheless, the limited comparison demonstrates that overall there is still good
569 agreement in the surface pressure interannual variability (despite large differences in magnitude)
570 between the reanalyses and the reconstruction, which potentially suggests that the reconstruction
571 is still capturing aspects of the pressure variability at this location in the early 20th century.
572 Importantly, due to the influence of crude elevation adjustments, it is highly likely that the

573 reconstruction is performing better than indicated by the MAE (Fig. 8b) or RMSD (Fig. 4).
574 Unfortunately, the reconstruction skill is difficult to precisely determine at this or any other
575 location (as suggested in reviewing Fig. 2) where large elevation adjustments make the
576 comparison to historical estimates challenging.

577

578 **4. Discussion and Conclusions**

579 The analysis presented here has compared seasonal Antarctic pressure reconstructions to
580 numerous historical observations and reanalyses throughout the early 20th century. As none of
581 these historical data were included in the reconstruction calibration, they serve as an independent
582 evaluation of the reconstruction skill during a period when relatively little is known about
583 Antarctic climate variability.

584 The results overall confirm that the reconstruction error and uncertainty assessed in
585 earlier work (Fogt *et al.*, 2017b, 2019), a mean absolute error of around 2-4 hPa across the
586 Southern Ocean, is supported when comparing with ship observations. A few ship records
587 suggest even higher reconstruction skill (MAE less than 2 hPa), while others situated north of the
588 Amundsen and Bellingshausen Seas demonstrate lower skill (MAE above 4 hPa), consistent with
589 earlier work. Furthermore, most comparisons with ship observations that span multiple seasons
590 indicate the reconstruction also captures the interannual variability well (correlations often
591 greater than 0.80). Comparison with historical reanalyses provide further evaluation of the
592 reconstruction's performance, as they assimilate most of the historical observations used here but
593 are independent of the reconstruction.

594 While the comparisons with observation estimates taken at sea level are relatively
595 straightforward and further validate the reliability of the early portions of the reconstruction, it is

596 far more challenging to make assessments of the reconstruction skill over areas of higher
597 elevation or near the coastline. In many of these locations, reduction of the reconstruction
598 pressure (which was constructed as surface pressure anomalies relative to the ERA-Int model
599 topography) to sea level pressure using a simple linear adjustment does not satisfactorily agree
600 with the historical data, even after considering the potential observational error. In many of
601 these locations, there are also large differences between 20th century reanalysis MSLP and the
602 historical observational estimates, highlighting the reduced reliability of MSLP from all sources
603 over the cold, high Antarctic continent. While the general comparisons conducted here suggest a
604 larger reconstruction MAE of nearly 6 hPa or more over high elevation, a closer examination at
605 select locations reveals that the reconstruction uncertainty is likely much lower than this and
606 perhaps as low as 1-3 hPa, as indicated in Fogt *et al.* (2019).

607 This work has demonstrated the value of digitizing historical observations from ships and
608 temporary bases for both understanding long term change across the high southern latitudes and
609 evaluating gridded datasets. While their temporary nature may make them difficult to use for
610 assessing long-term variability and change, when coupled with gridded climate datasets like the
611 seasonal Antarctic pressure reconstructions evaluated here, they serve as an independent and
612 valuable tool of documenting historical climate. As one recent example, the use of newly
613 digitized historical observations and pressure reconstructions shed new light on exceptional
614 conditions during the South Pole race of 1911-1912 (Fogt *et al.*, 2017c, 2018; Sienicki, 2018).
615 Future work will hopefully continue to unlock the power of these and other historical
616 observations, so that the ongoing change across the high southern latitudes can be placed in a
617 much-needed longer historical context (Jones *et al.*, 2016).

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620

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629

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777 **Figure Captions**

778 **Figure 1.** Maps of seasonal mean data location grouped by decade. Open circles represent
779 seasonal mean locations from ship records, and filled circles are for temporary bases on the
780 continent. The bottom left plot shows the location of all 271 seasonal mean observations
781 compared, while the bottom right plot shows the locations of the 18 station reconstructions
782 (brown) and observations from Orcadas (grey) used to generate the spatially complete pressure
783 reconstruction. Contours on the bottom right panel are the standard deviations of monthly ERA5
784 surface pressure anomalies for reference, contoured every 0.5 hPa.

785
786 **Figure 2.** Mean reconstruction skill statistics (columns; bias, MAE, and RMSD) compared to
787 historical observations, and averaged over various latitudes (top row), longitudes (middle row),
788 and decades (bottom row). The statistics calculated over all observations are listed at the bottom
789 of the figure.

790
791 **Figure 3.** Decadal mean RMSD plotted by decade.

792
793 **Figure 4.** Map showing observational mean (over full length of record) RMSD for select
794 representative locations examined in more detail.

795
796 **Figure 5.** Time series of historical observations, reconstruction (with 95% confidence interval in
797 grey shading), and gridded reanalysis problems for observations representative of the lowest
798 RMSD (solid lines for MSLP, dashed lines for surface pressure). The name is the record
799 identifier provided in ISPD or ICOADS. In a), the x-axis varies by season, and the labels
800 represent the DJF seasons for each year; in b) and c) only DJF data are plotted and the label
801 represents the DJF season. The white spaces in c) represent discontinuities in the observations.
802 The values at the bottom of each panel are the correlations (if more than 10 data points are
803 available) and MAE values (first numbers based on MSLP, second (where available) based on
804 surface pressure) for each dataset. The data for station 889340 were from ISPD, while Deck 215
805 and Deck 899 were from ICOADS.

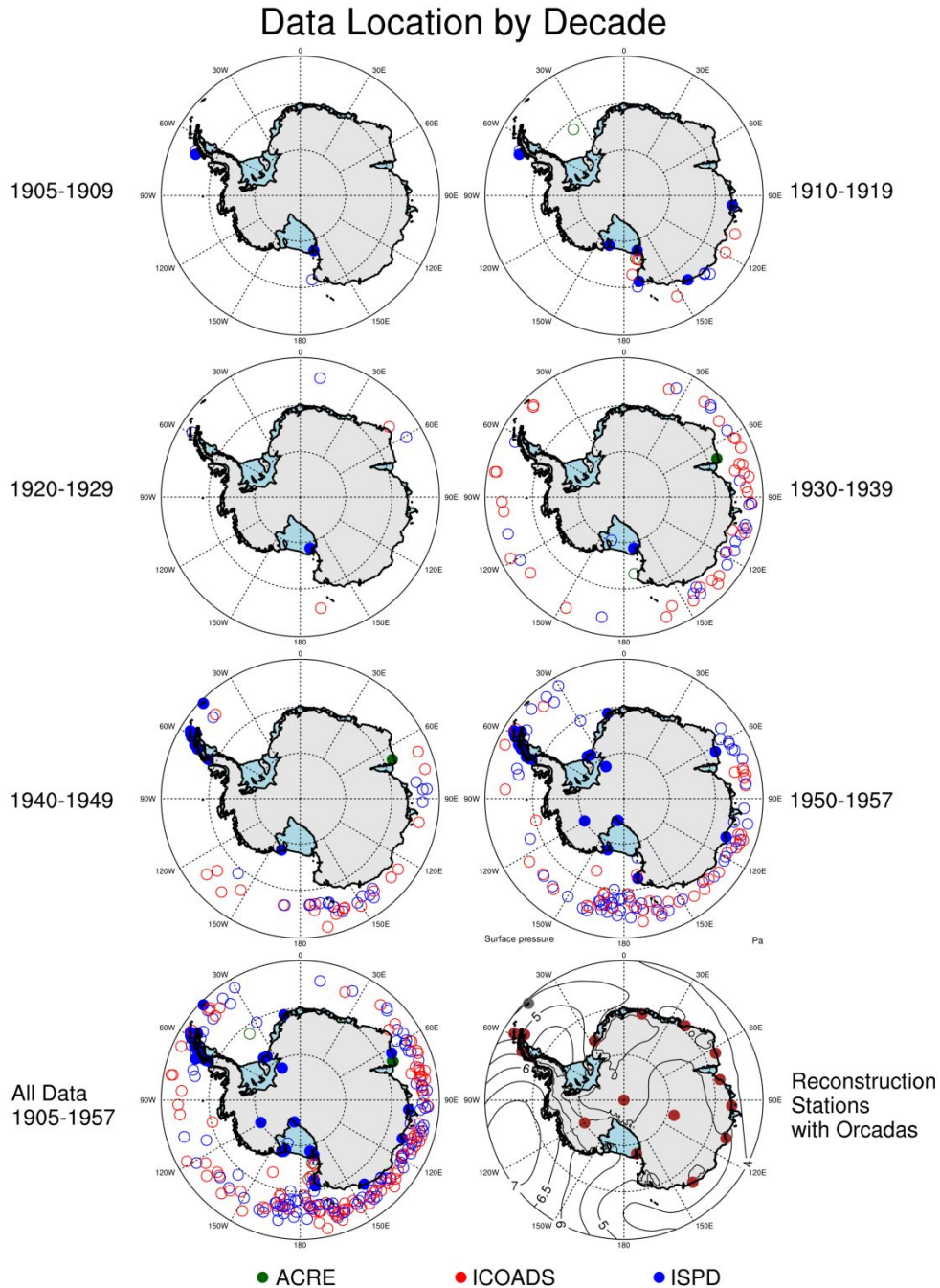
806
807 **Figure 6.** As in Fig. 5, but representative of stations where elevation corrections (reduction to
808 sea level pressure) play an important aspect of the reconstruction performance evaluation. All
809 data in this figure were obtained from ISPD.

810
811 **Figure 7.** Time series of seasonal mean MSLP for all four seasons at Little America (from
812 ISPD) on the northern edge of the Ross Ice Shelf for the reconstruction along with values from a)
813 20CRv2c; b) 20CRv3; c) CERA-20C. The gray shading in each panel represents the 95%
814 confidence interval for the reconstruction, while the colored shading represents 95% confidence
815 intervals for each of the reanalyses (calculated as the 1.96 times the standard deviation across the
816 seasonal mean ensemble members). The overall RMSD compared to the reconstruction is given
817 in the upper right for each dataset.

818
819 **Figure 8.** As in Fig. 5, but for a) Deck 246, which operated near the East Antarctic coast
820 discontinuously between 1910-1930, and b) observations at Cape Denison during the Australian
821 Antarctic Expedition of 1911-1914. Note in b) that surface pressure is plotted on the right axis.

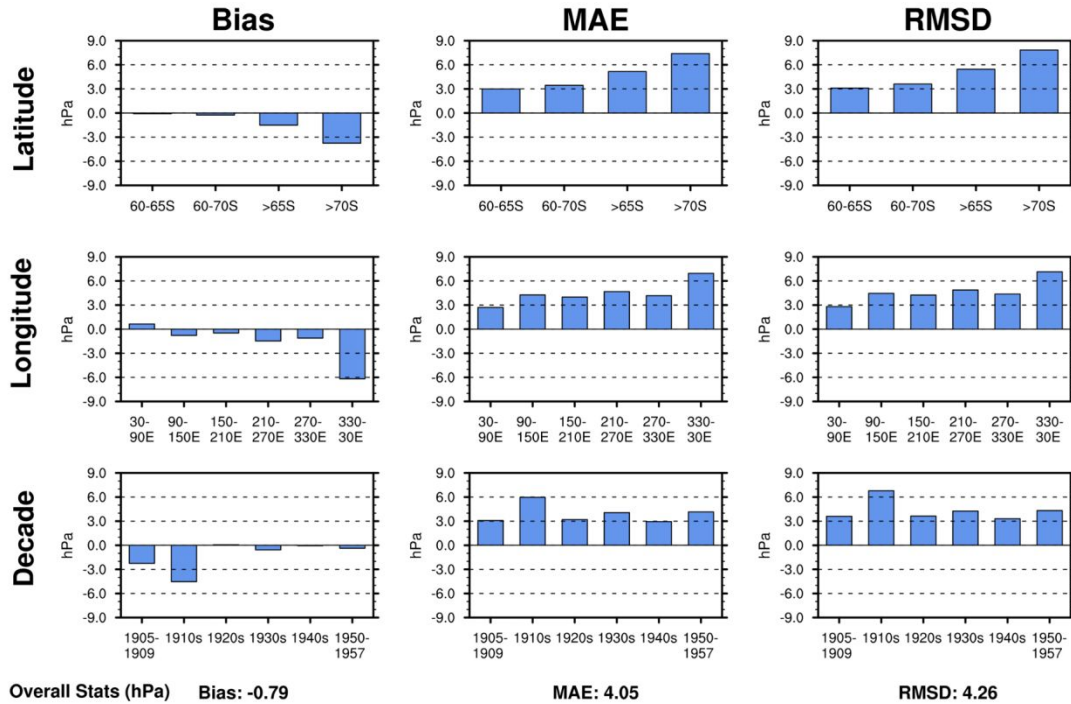
822 MAE values are based only on MSLP since there is a wide range of surface pressure values (>30
823 hPa), all primarily reflecting elevation differences in the underlying models. For a) the MAE
824 values (both based on MSLP) are calculated using the two different locations in DJF 1911. Cape
825 Denison data were obtained from ISPD, while data for Deck 246 were obtained from ICOADS
826 version 3.

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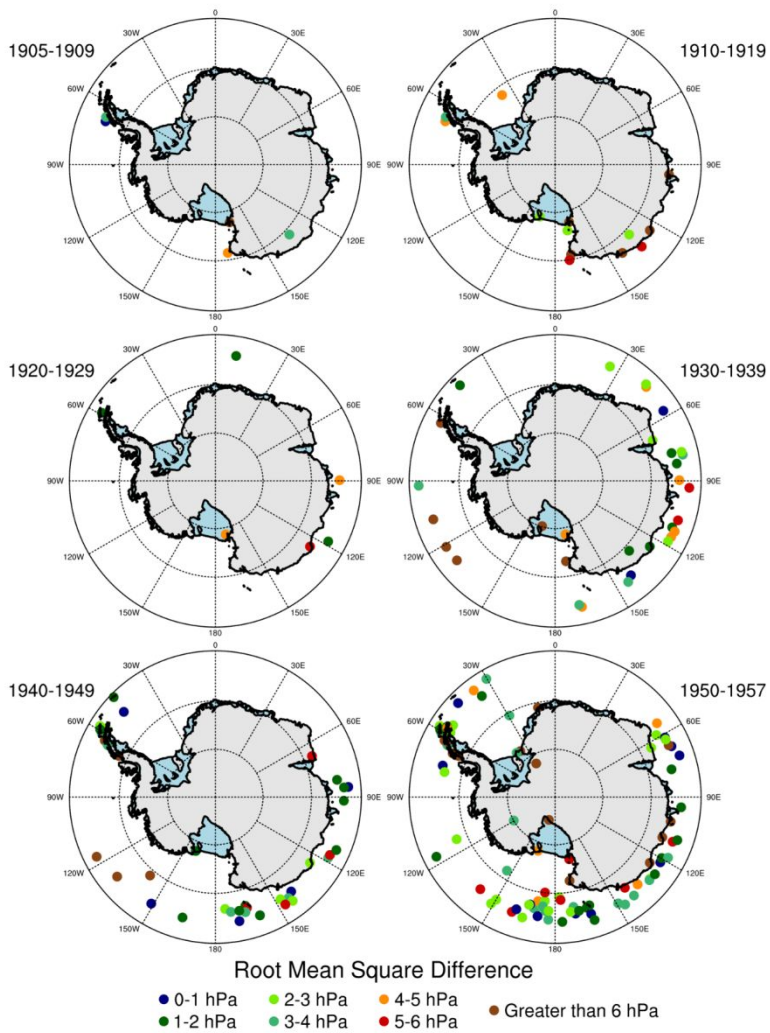
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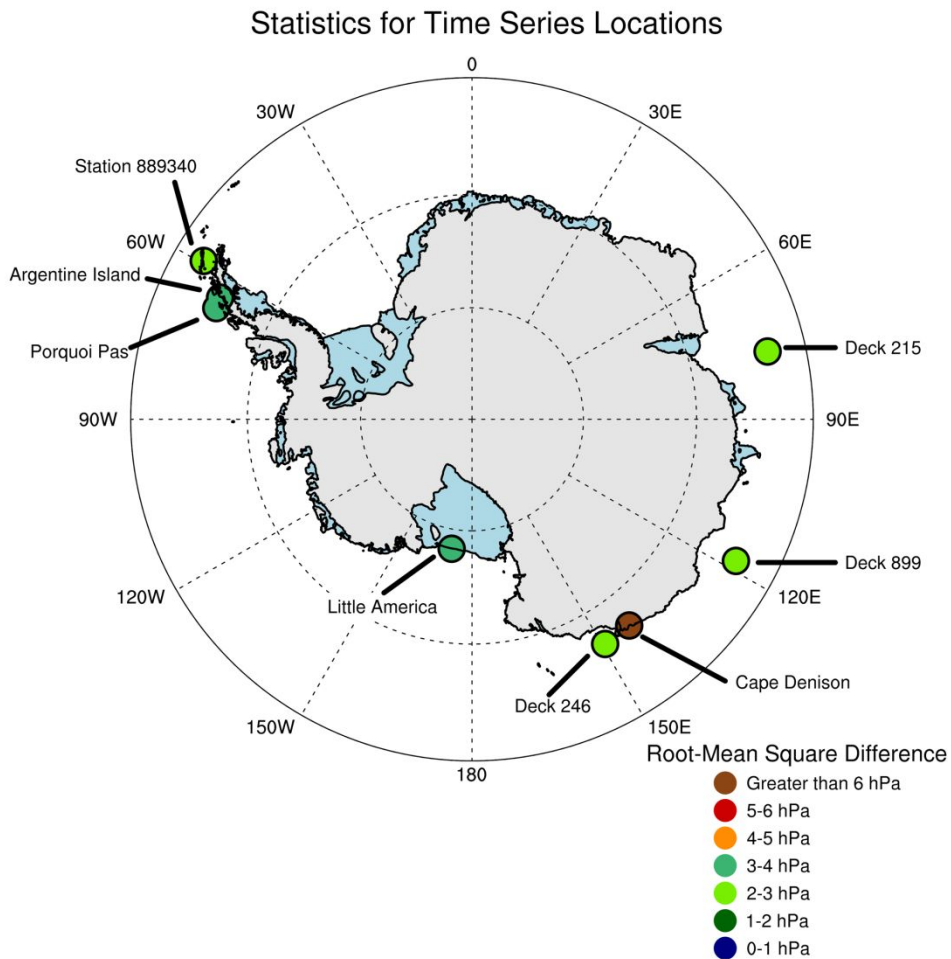
Figure 2. Mean reconstruction skill statistics (columns; bias, MAE, and RMSD) compared to historical observations, and averaged over various latitude bands (top row), longitude bands (middle row), and decades (bottom row). The statistics calculated over all observations are listed at the bottom of the figure.



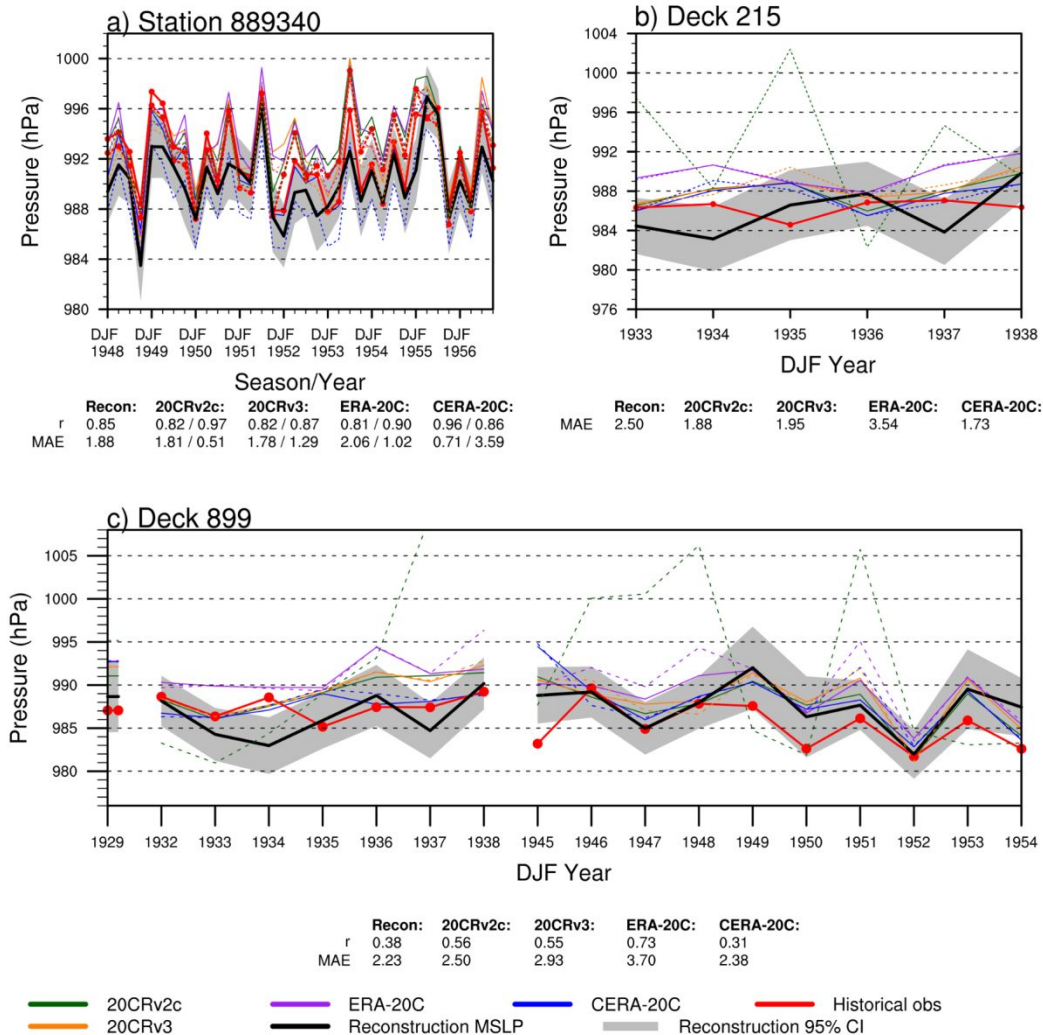
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Figure 3. Decadal mean RMSD plotted by decade.

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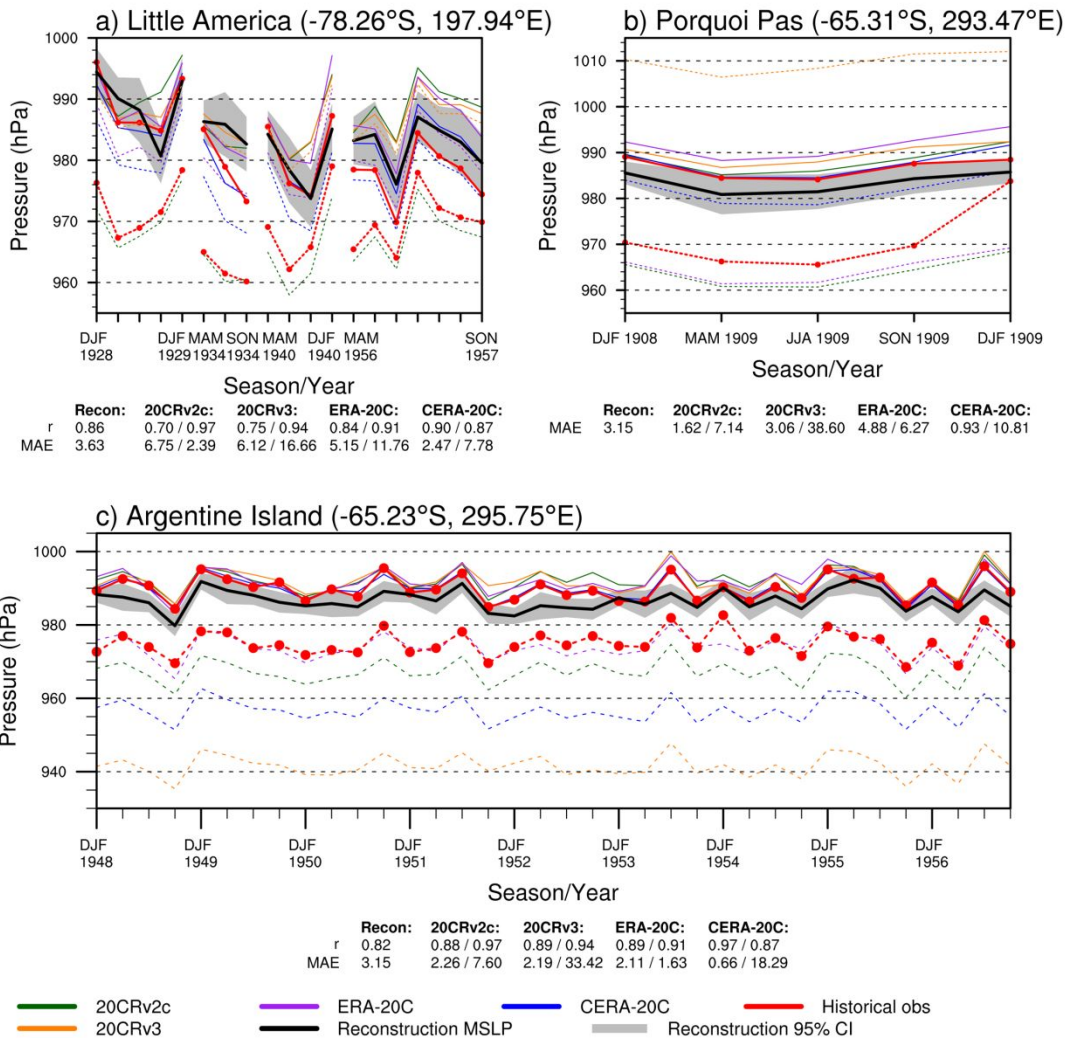


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 847 **Figure 4.** Map showing observational mean (over full length of record) RMSD for select
 848 representative locations examined in more detail.
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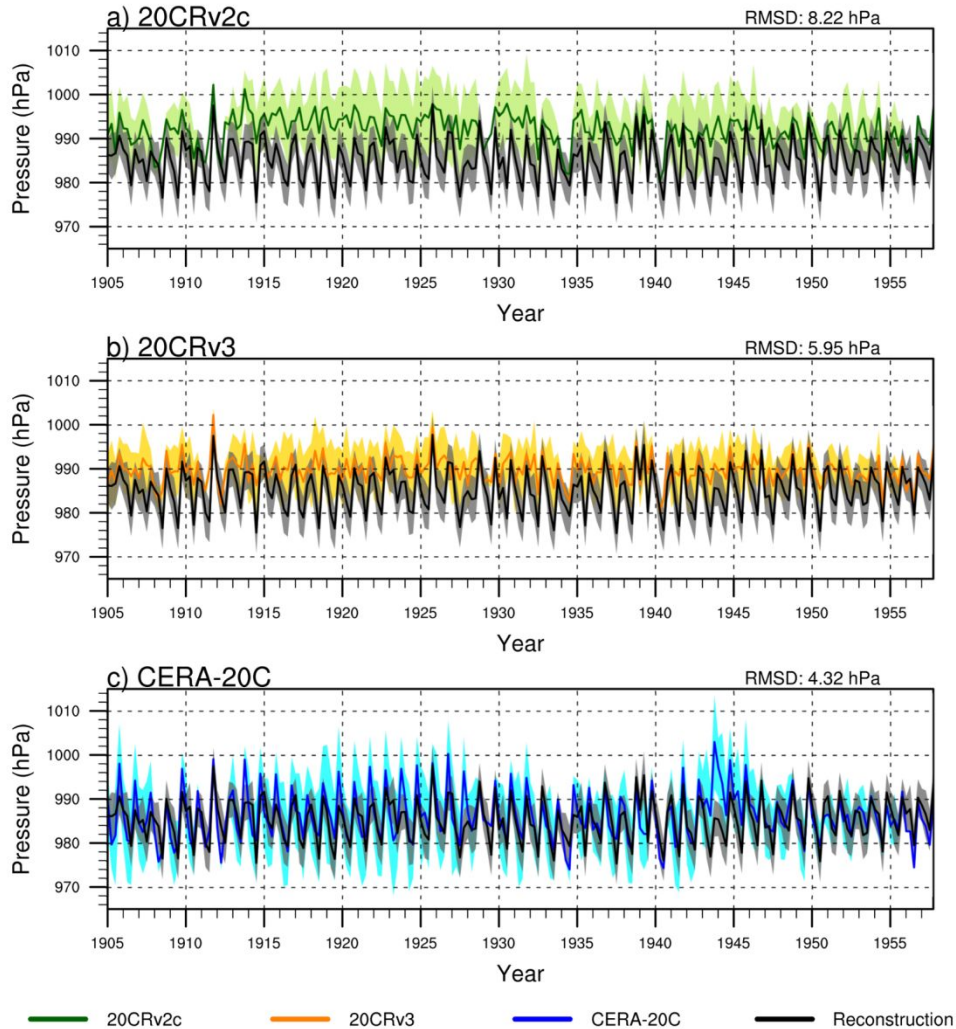


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Figure 5. Time series of historical observations, reconstruction (with 95% confidence interval in grey shading), and gridded reanalysis products for observations representative of the lowest RMSD (solid lines for MSLP, dashed lines for surface pressure). The name is the record identifier provided in ISPD or ICOADS. In a), the x-axis varies by season, and the labels represent the DJF seasons for each year; in b) and c) only DJF data are plotted and the label represents the DJF season. The white spaces in c) represent discontinuities in the observations. The values at the bottom of each panel are the correlations (if more than 10 data points are available) and MAE values (first numbers based on MSLP, second (where available) based on surface pressure) for each dataset. The data for station 889340 are from ISPD, while Deck 215 and Deck 899 are from ICOADS.

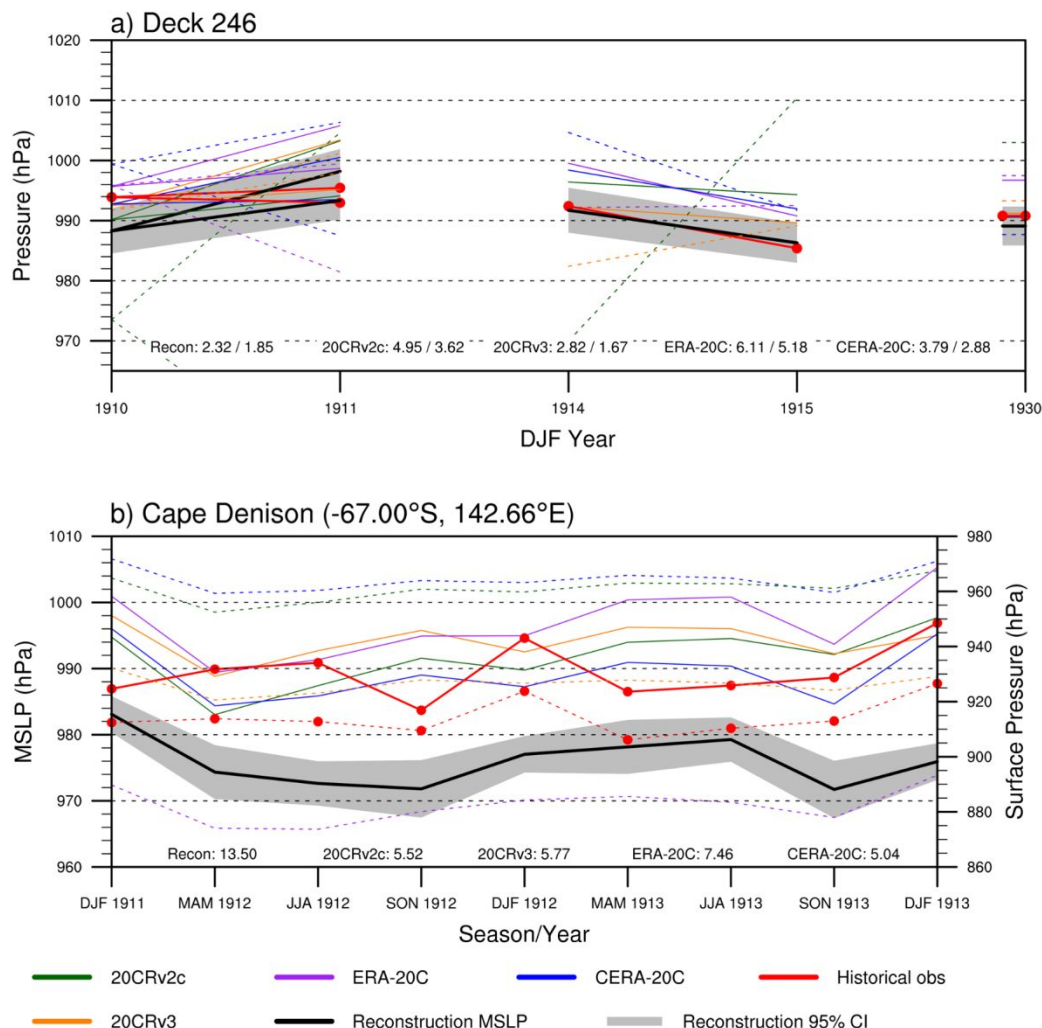


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 863 **Figure 6.** As in Fig. 5, but representative of stations where elevation corrections (reduction to
 864 sea level pressure) play an important aspect of the reconstruction performance evaluation. In all
 865 panels, the x-axis varies by season. All data in this figure were obtained from ISPD version 3.
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Figure 7. Time series of seasonal mean MSLP for all four seasons at Little America (from ISPD) on the northern edge of the Ross Ice Shelf for the reconstruction along with values from a) 20CRv2c; b) 20CRv3; c) CERA-20C. The gray shading in each panel represents the 95% confidence interval for the reconstruction, while the colored shading represents 95% confidence intervals for each of the reanalyses (calculated as the 1.96 times the standard deviation across the seasonal mean ensemble members). The overall RMSD compared to the reconstruction is given in the upper right for each dataset.



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1 An Assessment of Early 20th Century Antarctic Pressure
2 Reconstructions using Historical Observations

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4 Short title: An assessment of early 20th century Antarctic pressure reconstructions

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6

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26 **Keywords:** Antarctica, climate, pressure, data recovery

27

28 Abstract

29 While gridded seasonal pressure reconstructions poleward of 60°S extending back to
30 1905 have been recently completed, their skill has not been assessed prior to 1958. To provide a
31 more thorough evaluation of the skill and performance in the early 20th century, these
32 reconstructions are compared to other gridded datasets, historical data from early Antarctic
33 expeditions, ship records, and temporary bases ~~to further evaluate their performance.~~

34 Overall, the comparison confirms that the reconstruction uncertainty of 2-4 hPa
35 (evaluated after 1979) over the Southern Ocean is a valid estimate of the reconstruction error in
36 the early 20th century. Over the interior and near the coast of Antarctica, direct comparisons with
37 historical data are challenged by elevation-based reductions to sea level pressure. In a few cases,
38 a simple linear adjustment of the reconstruction to sea level matches the historical data well, but
39 in other cases, the differences remain greater than 10 hPa. Despite these large errors,
40 comparisons with continuous multi-season observations demonstrate that aspects of the
41 interannual variability are often still captured, suggesting that the reconstructions have skill
42 representing variations on this timescale, even if it is difficult to determine how well they capture
43 the mean pressure at these higher elevations. Additional comparisons with various 20th century
44 reanalysis products demonstrate the value of assimilating the historical observations in these
45 datasets, which acts to substantially reduce the reanalysis ensemble spread, and bring the
46 reanalysis ensemble mean within the reconstruction and observational uncertainty.

47

48 1. Introduction

49 Despite recent dramatic climate-related changes in Antarctica, including warming of
50 West Antarctica (Steig *et al.*, 2009; Bromwich *et al.*, 2012; Jones *et al.*, 2019; Turner *et al.*,
51 2019), retreat of several marine-based glaciers in the Amundsen Sea embayment (Rignot *et al.*,
52 2013, 2019; Edwards *et al.*, 2019), and rapid sea ice loss beginning in austral spring 2016
53 (Stuecker *et al.*, 2017; Turner *et al.*, 2017; Purich and England, 2019), there are significant
54 challenges to understanding how unique these events are in a historical context or how likely
55 they are to change in the future. This is in part due to the high degree of natural climate
56 variability across Antarctica and the fully coupled nature of many of these changes occurring at
57 the atmosphere-ice-ocean interface. When combined with the short observational climate
58 records primarily beginning around [the international Geophysical Year \(IGY\) activities of](#)
59 1957/1958, interpreting these changes in the Antarctic climate has proven to be very difficult
60 (Jones *et al.*, 2016).

61 Data from ice cores across Antarctica help to place ongoing change in a longer context
62 (Bracegirdle *et al.*, 2019), especially through coordinated efforts like the International Trans-
63 Antarctic Scientific Expedition (ITASE; Mayewski *et al.*, 2005). Ice core evidence has helped to
64 compare recent Antarctic warming with variability over the past 2000 years (Stenni *et al.*, 2017)
65 as well as changes in West Antarctica snowfall (Thomas *et al.*, 2008), and when combined with a
66 climate model, longer estimates of Antarctic surface mass balance (Agosta *et al.*, 2019), as
67 examples. Nonetheless, dating of specific events and the suppressed sub-annual temporal
68 resolution in many cores pose challenges for these longer-term estimates of Antarctic climate
69 variability.

70 Other tools to examine historical Antarctic climate variability during the last century
71 include gridded datasets that span the 20th century, such as existing historical reanalyses that only
72 assimilate surface pressure, like the National Oceanic and Atmospheric
73 Administration/Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES)
74 Twentieth Century Reanalysis version 2c (hereafter 20CRv2c, Compo *et al.*, 2011) and the new
75 NOAA-CIRES-DOE version 3 (20CRv3, Slivinski *et al.*, 2019). Similar “sparse-input”
76 reanalyses have been completed by the European Centre for Medium Range Weather Forecasts
77 (ECMWF), including their 20th-century reanalysis (ERA-20C, Poli *et al.*, 2016) and a coupled
78 ocean-atmosphere reanalysis of the 20th century (CERA-20C, Laloyaux *et al.*, 2018), each of
79 which assimilates marine wind observations and surface pressure. As a coupled reanalysis,
80 CERA-20C also assimilates subsurface ocean temperature and salinity observations (Laloyaux *et al.*
81 *et al.*, 2018). While these are spatially and temporally complete throughout the 20th century,
82 unsurprisingly they are sensitive to the number of assimilated surface pressure observations, and
83 therefore the skill changes considerably over the high southern latitudes throughout the 20th
84 century (Schneider and Fogt, 2018; Fogt *et al.*, 2019; Slivinski *et al.*, 2019).

85 An alternative approach to address these challenges is to generate seasonal pressure
86 reconstructions [poleward of 60°S, both at individual Antarctic stations \(Fogt *et al.*, 2016a,](#)
87 [2016b\)\(Fogt *et al.*, 2016a, 2016b, 2017a, 2019\), as well as spatially complete poleward of 60°S](#)
88 [\(Fogt *et al.*, 2017a, 2019\)](#). When compared to gridded climate datasets, these reconstructions
89 showed far less sensitivity to changes in the number of observations across Antarctica (Schneider
90 and Fogt, 2018), which is perhaps not surprising given that the reconstructions were based on
91 statistical relationships with a spatially and temporally fixed network of stations in the mid and
92 high latitudes of the Southern Hemisphere (Fogt *et al.*, 2016a). However, the skill of the

93 reconstructions was only thoroughly evaluated after the ~~International Geophysical Year (IGY,~~
94 ~~(1957-1958)~~, when most Antarctic observations began; spatially complete comparisons in
95 reconstruction skill were even more limited and only possible after 1979 through evaluating
96 against the ECMWF Interim reanalysis, ERA-Interim (ERA-Int; Dee *et al.*, 2011). Therefore,
97 the skill of these reconstructions in the early 20th century before the IGY remains unknown,
98 [although the underlying relationships governing them are likely stationary \(Clark and Fogt,](#)
99 [2019\)](#). This work aims to provide a more complete evaluation of these reconstructions poleward
100 of 60°S by using available pressure observations that are independent from the reconstructions in
101 the early 20th century.

102

103 2. Data and Methods

104 We make use of the best performing seasonal spatially-complete Antarctic pressure
105 reconstructions, which are available from 1905-2013 and based on surface pressure anomalies
106 from the 1981-2010 climatology from ERA-Int (Fogt *et al.*, 2019). The reconstructions ~~are~~
107 [based on a kriging interpolation of 18 Antarctic station reconstructions and observations at](#)
108 [Orcadas \(locations plotted in bottom right panel of Fig. 1\) to originally created on](#) an 80km x 80
109 km Cartesian grid centered over the South Pole. For comparison here, this grid has been
110 converted to a 0.75°x0.75° latitude-longitude grid. Importantly, comparisons with ERA-Int after
111 1979 (Fogt *et al.*, 2017a, 2019) demonstrated that the reconstruction skill varies seasonally, with
112 the highest skill (defined as the best agreement with ERA-Int) in austral summer (December –
113 February, DJF), and the lowest skill in the austral autumn and spring (March-May, MAM, and
114 September-November, SON, respectively). In general, higher reconstruction skill is found over

115 the Antarctic continent (especially near the Antarctic Peninsula), and lower skill at the northern
116 edge of the domain near 60°S, especially in the South Pacific (Fogt *et al.*, 2019).

117 Historical pressure data prior to 1957 poleward of 60°S were extracted from three
118 primary datasets to further evaluate the reconstruction skill in the early 20th century. The largest
119 source of pressure data comes from the International Surface Pressure Databank version 3.2.9
120 (ISPD; Cram *et al.*, 2015), which contains subdaily measurements of mean sea level and/or
121 surface pressure from both ships and temporary Antarctic bases (during field expeditions) and
122 early Antarctic stations that began prior to the IGY. Additional sea level and/or surface pressure
123 data were obtained from the International Comprehensive Ocean-Atmosphere Data Set release 3
124 (ICOADS; Freeman *et al.*, 2017); we only make use of ship records in ICOADS that were not
125 available in ISPD. As many new historical observations from both ships and early Antarctic
126 expeditions are still being recovered and digitized, we also make use of a few newly digitized
127 additional pressure observations stemming from the Atmospheric Circulation Reconstructions
128 over the Earth (ACRE) initiative (Allan *et al.*, 2011), obtained directly from Rob Allan, the lead
129 of the ACRE project. Only those ACRE pressure observations that were not part of the current
130 releases of ISPD and ICOADS are utilized here, particularly from Antarctic expeditions in the
131 first few decades of the 20th century. Most historical observations reported both SLP and surface
132 pressure; however, a few observations only reported SLP, and therefore the reconstruction is
133 compared to historical SLP observations throughout. We directly use the historical observations
134 as reported in ISPD, ICOADS, or in the ACRE data for SLP and surface pressure, and do not
135 reduce any surface pressure observations to SLP.

136 In making comparisons, it is important to consider that historical observations can have
137 their own error or bias for many reasons, potentially including incorrect reported location

138 (latitude, longitude, or elevation); problems with the barometer; errors associated with
139 adjustments to sea level pressure; or misspecified corrections to pressure measurements from
140 temperature or gravity. Because measurement errors likely vary in time and space, it is difficult
141 to fully quantify how much these errors contribute to the reported pressure observations ([Kent
142 and Berry, 2005](#)). Reanalyses generally define instantaneous, random observation errors that
143 depend on platform and/or time (Compo *et al.*, 2011; Poli *et al.*, 2016; Laloyaux *et al.*, 2018;
144 Slivinski *et al.*, 2019), and analyses comparing these expected errors with background statistics
145 suggest estimates of about 1.5-2 hPa in the early 20th century are reasonable (Slivinski *et al.*,
146 2019). However, Slivinski *et al.* (2019) and more recent comparisons (not shown) also suggest
147 that there is a relatively large systematic error in observations in the Southern Hemisphere in the
148 early 20th century. We therefore assume a conservative estimate of 2 hPa total error in the
149 seasonally-average observation estimates (or an observation error variance of 4 hPa²).

150 In order to compare the historical observations to the reconstructions, additional analysis
151 was required. First, all historical pressure data were converted to hPa, the same units as the
152 pressure reconstructions. Monthly means for all the historical observations were calculated if at
153 least 75% of the days within a given month had at least one observation available, to ensure a
154 reliable monthly pressure estimate. Seasonal means (following the traditional seasonal divisions,
155 DJF, MAM, JJA (June – August), and SON) were calculated to compare to the seasonal pressure
156 reconstructions if at least two monthly means existed using our 75% daily data threshold; data
157 for the third month was added to calculate the seasonal mean if 2 months had met the 75% daily
158 data threshold, and the third month had more than 50% of its daily data. This approach allows
159 for comparison with the maximum amount of data possible. Comparisons of a single monthly
160 mean historical observation (for cases when historical data only had one month meeting our

161 threshold) with the seasonal mean pressure reconstruction produced larger differences (not
162 shown), and so this paper only focuses on comparisons of at least two months of historical data
163 to define a seasonal mean. Altogether, these constraints yielded 271 seasonal means from
164 historical pressure observations prior to 1957. The majority (>75%) of these historical
165 observations occur only in DJF (austral summer), although it is noted that there are several
166 observations after 1940 complete for the entire year. For reference, the year of austral summer
167 refers to the year of December throughout this study.

168 Two more steps were taken prior to making comparisons. First, seasonal mean locations
169 for the historical records were calculated using the coordinates provided in the data archives.
170 These locations varied little for the early Antarctic stations; for observations collected on moving
171 ships, we calculated a seasonal mean location by year for comparison since the reconstruction
172 data are only available seasonally, which limits comparisons at higher temporal and spatial
173 frequency. Of the 130 seasonal means from the ship records, more than 75% of the subdaily
174 pressure observations showed less than a 2 degree standard deviation in the latitude, and half of
175 the ships' standard deviations were less than 15 degrees longitude. In terms of pressure, there
176 was no significant difference between ships that had a standard deviation of more and less than
177 20 degrees longitude in the standard deviations of sub-daily pressure observations. We therefore
178 suggest the error associated with the mean location is more strongly related to the number of
179 strong storms a ship encountered, which are more unique to a specific location rather than the
180 mean location of the ship. As a rough estimate of this error, the mean standard deviation of
181 pressure from the subdaily ship observations, 3.45 hPa, can be used, although more than half of
182 the ships have a pressure standard deviation below 3.0 hPa. [This standard deviation of subdaily](#)
183 [pressure within one season is much smaller than the interannual standard deviation of monthly](#)

184 [pressure across the South Pacific, which ranges from 3-7 hPa based on ERA5 data \(contours in](#)
185 [Fig. 1, bottom right panel\).](#)

186 Lastly, to compare the pressure reconstructions to the historical pressure observations,
187 elevation adjustments were needed. The pressure reconstructions, originally constructed as
188 surface pressure anomalies based on the underlying topography of ERA-Int at $0.75^\circ \times 0.75^\circ$
189 latitude / longitude resolution, were adjusted to sea level pressure using a rough linear estimate
190 of 12 hPa pressure decrease per 100 m elevation gain. The 12 hPa approximation is larger than
191 the 10 hPa per 100m assumed in the middle latitudes in the lower troposphere given the colder
192 and drier (and therefore denser) air commonly observed poleward of 60°S . Without simultaneous
193 measurements of temperature and humidity, it is challenging to provide a more accurate
194 adjustment to sea level pressure. Furthermore, reduction to sea level pressure is known to be
195 problematic in nearly all gridded climate datasets (and observations themselves) over Antarctica,
196 including 20CRv3 (Slivinski *et al.*, 2019). This adjustment to sea level was necessary even for
197 historical observations that had both surface and sea level pressure data, as due to the smoothing
198 of the topography of ERA-Int at even the 0.75° resolution, model elevations and observed
199 elevations (where known – this value is not always given in the historical data) are often quite
200 different; these elevation differences similarly make it challenging to adequately compare
201 surface pressure observations with the surface pressure (anomaly) reconstructions. Importantly,
202 elevation differences can also arise due to the smoothing of the steep Antarctic coastline in ERA-
203 Int, and therefore influence comparisons from ships close to the Antarctic continent. This
204 adjustment to sea level introduces the greatest error and uncertainty in our comparison, as will be
205 discussed in detail throughout. Nonetheless, the simple linear adjustment allows us to evaluate

206 interannual (or intra-annual) variability and provide further information on reconstruction
207 performance than otherwise would be possible.

208 In the comparisons, the reconstruction data are extracted from the gridpoint closest to the
209 seasonal mean location in the reconstruction field. To provide further comparison for select
210 observations that span more than one season, from the reanalyses we also extract both surface
211 and sea level pressure data from the closest gridpoint using the ensemble mean in all but ERA-
212 20C (which has only one estimate). [This approach also introduces some error, called the ‘error
213 of representativeness’, reflecting how well a reanalysis gridpoint represents the point location
214 from the observation; this error is assumed to be one of the largest components of observation
215 errors in the reanalyses, at least in 20CRv3 \(Slivinski *et al.*, 2019\), and is similar to the
216 elevation-based errors for the reconstruction evaluations described previously.](#)
217 [Importantly](#) ~~However~~, these reanalyses are not independent of the observations used for
218 comparison here: ERA-20C and CERA-20C assimilate surface pressure and marine surface wind
219 observations from ISPD version 3.2.6 and ICOADS version 2.5.1 (Poli *et al.*, 2016; Laloyaux *et*
220 *al.*, 2018); 20CRv2c assimilates pressure from ISPD version 3.2.9 and ICOADS version 2.5.P;
221 and 20CRv3 assimilates pressure from ISPD version 4.7 and ICOADS version 3+v2 (Slivinski *et*
222 *al.*, 2019). [Since the comparisons are made with ISPD v3.2.9 and ICOADS v3, the observations
223 were at least available to be assimilated in both version of 20CR, and likely for ERA-20C and
224 CERA-20C. However, t](#)The assimilation combines the instantaneous observations with a
225 background guess from the forecast model, so fields from different reanalyses are expected to
226 differ from each other (as they each use different forecast models and assimilation algorithms),
227 as well as from the seasonally-averaged observation estimates analyzed here. In addition, each
228 reanalysis system has its own quality control algorithm that will blacklist observations deemed

229 unfit for assimilation; thus, even if a given set of observations are available to the assimilation
230 algorithm, they may not all have been assimilated. Finally, the reanalyses each employ their own
231 observation bias correction scheme, which removes significant, consistent differences between
232 the observations and the background fields. For simplicity, we only consider the uncorrected
233 observations here, but note that systematic differences between the reanalyses and observations
234 in our comparison may have been ameliorated by taking into account the observation bias
235 corrections calculated within each reanalysis.

236 Reconstruction performance compared to the historical observations is evaluated using
237 three primary statistics: overall bias, defined as the mean difference between the seasonal
238 historical observation estimates and reconstructions at sea level (reconstruction minus
239 observations); the mean absolute error (MAE), defined as the mean absolute difference to
240 remove offsetting effects of positive and negative difference; and the root mean square
241 difference (RMSD), which due to the squaring of the differences prior to calculating the mean,
242 gives slightly higher weighting to larger absolute differences than the MAE. For observations
243 that span only one season or have the bias of the same sign across all seasons, the absolute value
244 of the bias and MAE will yield identical results. In all cases, these three statistics were
245 calculated over the full length of each observational record. Further averaging both spatially and
246 temporally is conducted to assess the overall reconstruction performance. [Since the
247 reconstruction error determined by Fogt et al. \(2019\) over 1979-2013 is assumed to be constant
248 in time, it is assumed that there are no \(temporally\) correlated errors in the reconstruction; the
249 evaluations in this paper help to determine the persistence of reconstruction errors through the
250 early 20th century.](#)

251

252 3. Results

253 3.1. Historical data availability

254 Prior to estimating the seasonal pressure reconstruction skill in the early 20th century, it is
255 important to recognize the large changes in the number of observations poleward of 60°S,
256 especially before 1957. Figure 1 displays the location and data type for all of the 271 seasonal
257 means that were compared to the reconstruction; open circles represent seasonal mean positions
258 of ship data while filled circles denote base or station records that were stationary or only had
259 minor movements over time. As expected, there are very few observations prior to 1930,
260 although there is a relative increase in the 1910-1919 during the height of the ‘Age of Heroes’
261 which includes expeditions to the South Pole, the Australian Antarctic Expeditions, and the
262 British Imperial Trans-Antarctic Expedition led by Ernest Shackleton. The decrease in the
263 number of observations in the 1940s is not only a challenge in the high southern latitudes but
264 also worldwide, associated with the Second World War. Nearly half of the historical
265 observations used for comparison here come from the years just prior to the IGY (1950-1957),
266 with several early Antarctic stations established over the continent (especially along the
267 Antarctic Peninsula), and frequent ships along the East Antarctic coastline. A notable gap in
268 observational coverage is within the Weddell Sea (east of the Antarctic Peninsula) and
269 throughout much of the South Atlantic. In addition to persistent sea ice in the Weddell Sea
270 (Cavalieri and Parkinson, 2008), the South Atlantic area is far from commercial sailing or
271 whaling routes and is likely one of the greatest spatial data voids globally (for example, see Fig.
272 1 of Allan and Ansell, 2006).

273

274

275 3.2. Overall reconstruction performance

276 With this temporal evolution of historical data in mind, the reconstruction performance is
277 displayed as a bar chart in Fig. 2; the overall statistics (averaged over all available observations)
278 are given at the bottom: mean bias = -0.79 hPa; mean MAE = 4.05 hPa; mean RMSD = 4.26 hPa.
279 Recalling that the overall comparison is primarily during austral summer, these values are
280 considerably higher than the skill assessed in earlier work in comparison to ERA-Int (Fogt *et al.*,
281 2017a, 2019), which estimated an MAE over the Antarctic continent generally less than 1.5 hPa
282 and over the Southern Ocean around 2-3 hPa. Indeed, the values seem even higher than the
283 MAE in Fogt *et al.* (2019) in the non-summer months in the South Pacific, the region of highest
284 MAE compared to ERA-Int which ranged from 2-4 hPa.

285 This quick comparison initially suggests that the seasonal pressure construction
286 performance is of much lower quality prior to 1957 than it is after 1957. However, when
287 considering that the observation estimates have their own errors (assumed to be approximately
288 ~2 hPa in the early 20th century), the higher MAE prior to 1957 is not far from the assumed
289 observational error. Further, when looking at the average skill as a function of latitude (Fig. 2),
290 the bias is near zero in both of the latitude bands that primarily lie over the Southern Ocean (60°-
291 65°S and 60°-70°S), potentially suggesting that the historical observation estimates tend to
292 fluctuate near the reconstruction seasonal mean overall (both above and below, cancelling to near
293 zero). The MAE in these latitude bands, near 3 hPa, better reflects the overall performance as it
294 removes the cancellation between positive and negative differences. The MAE of 3 hPa is
295 consistent with the skill reflected in Fogt *et al.* (2019), and is also close to the assumed
296 observation error of 2 hPa. In contrast, where Fogt *et al.* (2019) demonstrate lower MAE over
297 the Antarctic continent (due to more station observations constraining the reconstruction skill),

298 comparisons with the historical observation estimates clearly show an increase in MAE poleward
299 of 65°S, which is primarily from stations over the Antarctic continent (poleward of 70°S). As
300 noted earlier, this increase in MAE is an artifact of the elevation sensitivity when comparing the
301 historical observations at (often unknown) elevations different from the seasonal pressure
302 reconstruction based on the underlying topography of the ERA-Int 0.75°x0.75° grid. The simple
303 linear offset of 12 hPa per 100 m creates sea level pressures that are consistently too low
304 (evidenced by the negative bias), which gives rise to large MAE and RMSD over the Antarctic
305 continent.

306 The sensitivity to elevation is also apparent in the comparisons as a function of longitude.
307 There is a strong negative bias in the 330°-30°E range, along the mountainous Antarctic
308 Peninsula. In ERA-Int, this terrain was greatly smoothed but still elevated, while the
309 observations are often along the coast near sea level. In other longitude zones, the mean bias is
310 typically in the range of ± 1 hPa, with MAE around 3-4 hPa. Given that Fig. 1 indicates that
311 outside of 330°-30°E, the seasonal mean observation estimates primarily are over the ocean and
312 less influenced by elevation corrections, the comparison by longitude again reflects a similar
313 skill of the reconstruction (over the Southern Ocean at least) as observed in Fogt *et al.* (2019)
314 during 1979-2013. Comparisons by decade typically have MAE also in the 3-4 hPa range,
315 consistent with the previous evaluation. One outlier is the 1910s, which from Fig. 1 has a
316 relatively high percentage of historical observations on or near the Antarctic continent,
317 suggesting that elevation corrections are again giving a misleading impression of relatively low
318 reconstruction skill.

319 To further visualize the spatial and elevation dependence of reconstruction performance,
320 Fig. 3 displays the decadal mean RMSD for each station by decade. Several key points emerge

321 from Fig. 3. First, there is an indication from ships in the South Pacific north of the Amundsen
322 and Bellingshausen Seas (roughly 60°-70°S, 150°-90°W) that the reconstruction skill is
323 considerably lower, with RMSD values often above 6 hPa. Since these are seasonal pressure
324 estimates from ships (Fig. 1), elevation correction is not an issue. Rather, the larger errors are
325 consistent with the much lower reconstruction performance in this region of high interannual
326 variability (which often exceed observational errors based on interannual monthly pressure
327 standard deviations as large as 7 hPa in Fig. 1~~likely exceed observational errors~~), as
328 discussed in previous evaluations (Fogt *et al.*, 2017a, 2019). The larger interannual pressure
329 variability here may also suggest that using the mean ship location could be introducing more
330 error in this sector compared to other regions around Antarctica (Fig. 1). Second, for
331 comparisons in the Southern Ocean for nearly all other regions, the RMSD is generally below 4
332 hPa, and the majority of the comparisons with the seasonal mean ship observation estimates
333 show RMSD in the 3-4 hPa range. These values are consistent with the slightly lower
334 performance of the reconstruction over the Southern Ocean. However, these values of RMSD
335 still fall within expected error when considering errors in both observation estimates and the
336 reconstruction (taken as the square root of the sum of the observational and reconstruction error
337 variances). Lastly, it is clear that many of the higher errors (exceeding 6 hPa) are found along
338 the coast, the Antarctic Peninsula, or in the interior of the continent. Even on the Ross Ice Shelf,
339 RMSD values are typically larger than 4 hPa. As will be more clearly demonstrated later, these
340 larger differences are due to elevation corrections to the historical observations in or near areas
341 of high or vastly varying terrain. We will show that the reconstruction skill is likely much higher
342 in these areas than suggested by the RMSD values in Fig. 3. Remarkably, in every decade since
343 the 1930s, there are multiple locations where the RMSD values (over the ocean) are less than

344 1hPa, which is an excellent agreement with the historical observations. Given that we make
345 comparisons with the seasonal mean ship position, that the historical observation estimates are
346 rarely complete for the full season, and that they themselves have errors, this high agreement is
347 noteworthy. It suggests that the reconstruction can be used as a reliable approximation of
348 Antarctic pressure in most regions on and around the continent back to at least the 1930s.

349

350 *3.3 Reconstruction performance evaluated with selected historical observations*

351 The reconstruction performance is perhaps best evaluated by comparing to individual
352 historical observations, which is the focus for the remainder of the study. To facilitate these
353 assessments, a subset of representative stations and ship seasonal locations has been selected;
354 their average location, name, and mean RMSD values over the entire record length are plotted in
355 Fig. 4. We have purposely selected historical pressure estimates with longer records than a
356 single season, and as many complete records from earlier portions of the 20th century as possible,
357 although the sample size is quite limited (Fig. 1). In general, the reconstruction performance
358 indicated by the mean RMSD in Fig. 4 at these locations is comparable to the overall decadal
359 mean performance in Fig. 3, although we do not closely examine any stations with RMSD less
360 than 2 hPa, and only one station where inadequate elevation corrections challenge the assessment
361 of reconstruction skill (Cape Denison). [Recall, all of these data were available for assimilation
362 into 20CRv2c and 20CRv3 \(and likely available for CERA-20C and ERA-20C\), so the
363 comparisons with the reanalyses are not necessarily always independent as discussed in section
364 2.](#)

365 Figure 5 displays three seasonally-averaged historical observation estimates where the
366 mean RMSD values are 2-3 hPa, consistent with the reconstruction skill and uncertainty assessed

367 in Fogt *et al.* (2019), and within the assumed observational error variance of 4 hPa². Plotted with
368 the historical observations (in red) are the mean sea level pressure (solid) and surface pressure
369 (dashed, when available) from the nearest gridpoint of 20CRv2c (green), 20CRv3 (orange),
370 ERA-20C (purple), and CERA-20C (blue). To compare with the skill evaluation in Fogt *et al.*
371 (2019), the correlations (if more than 10 values are available) and MAE (in hPa) for each gridded
372 dataset are given at the bottom of each panel: the first number is based on the MSLP, and the
373 second number (where available) is based on surface pressure.

374 Station 889340 (from the ISPD archive) is situated along the Antarctic Peninsula (Fig. 4)
375 and has a continuous pressure record beginning in 1948 for all seasons. As such, it is one of
376 many such stations that provide a useful evaluation of reconstruction skill, and the overall MAE
377 from the reconstruction is less than 2 hPa. Moreover, the temporal variability is well captured (r
378 > 0.80 in all datasets). The various reanalysis products have similar MAE (generally from 1-2
379 hPa), well within the likely observational uncertainty, with CERA-20C having the lowest for
380 MSLP, and 20CRv2c having the lowest for surface pressure. Despite the low MAE / RMSD at
381 this station, adjustment of the reconstruction to sea level pressure may play a small role in its
382 performance, as there are differences in both the historical MSLP and surface pressure, as well as
383 the MSLP and surface pressure in the reanalyses. Nonetheless, this station shows the viability of
384 the reconstruction shortly before the IGY along the Antarctic Peninsula, a region of relatively
385 higher reconstruction skill compared to ERA-Int after 1979 (Fogt *et al.*, 2017a, 2019).

386 Deck 215 (Fig. 5b) from ICOADS has adequate observational coverage only during
387 austral summer. The reconstruction skill is comparable to the skill seen in the southern Indian
388 Ocean during much of the 1930s (Fig. 3). The reconstruction MAE is 2.5 hPa, slightly higher
389 than all reanalyses but ERA-20C, which was found to be one of the lower performing reanalyses

390 in the early 20th century near Antarctica (Schneider and Fogt, 2018). Despite the higher MAE
391 for the reconstruction (which, unlike the reanalysis products, is entirely independent from these
392 historical observations), the historical observation values nearly all fall within the reconstruction
393 uncertainty (95% confidence interval, gray shading), and the reconstruction uncertainty would
394 clearly overlap with the observational uncertainty throughout time. Together, the comparison
395 with Deck 215 data suggests the original assessment of the reconstruction skill provides a good
396 approximation of its performance in the early 20th century. Although the interannual variability
397 is not as strongly captured as in Fig. 5a (correlation is not provided since only six -years of data
398 exist), it should be noted that the reanalysis datasets also do not reproduce the interannual
399 variability well (perhaps due to observational errors or the spatial averaging). We also observe
400 that the surface pressure in 20CRv2c is notably different than the surface pressure from the other
401 reanalyses, probably due to the spectral effects in the 20CRv2c elevation field noted by Slivinski
402 et al. (2019).

403 For a longer observational record over the Southern Ocean, Deck 899 (Fig. 4, from
404 ICOADS) also has pressure observations only for austral summer but over multiple decades (Fig.
405 5c). The location varied during these many voyages, but overall the observational estimate of
406 the seasonal mean falls within or very near the reconstruction uncertainty. Indeed, the
407 reconstruction agrees better with the seasonally-averaged ship-based values than the reanalyses
408 (MAE of 2.23 hPa compared to 2.3 – 3.7 hPa from reanalyses, although almost all datasets
409 would fall within the observational uncertainty at this location). The correlations are much lower
410 for ~~this~~-these ship data across all datasets, due to differing fluctuations between a few years (i.e.,
411 1933-1934, 1936-1937, 1945-1946), however the interannual variability is better captured after
412 1946. In general, the reconstruction also aligns well with the MSLP from the reanalyses, except

413 for DJF 1934 when the ship traversed a large span of the southern Indian Ocean (from 88°E in
414 December 1934 to 47°E in February 1935). Therefore, the use of the seasonal mean location
415 could be artificially suggesting a lower reconstruction skill for this observational estimate.
416 Nonetheless, as in Figs. 5a and 5b, this comparison further suggests that the uncertainty of the
417 reconstruction is a good estimate of the reconstruction error in the early 20th century. Overall, the
418 reconstruction agrees well with many historical seasonal-mean observation values that were
419 withheld during the reconstruction's development. As in Fig. 5b, we note that there are larger
420 differences in the surface pressure from 20CRv2c which clearly fall outside the uncertainty from
421 using a seasonal mean ship location.

422 Figure 5 presents several comparisons where elevation corrections did not have a
423 noticeable influence on the evaluation of the reconstruction and are perhaps more representative
424 of the overall reconstruction quality. In many other locations, elevation adjustments appear to
425 play a more important role (especially on or near the Antarctic continent) in comparing the
426 reconstruction and observational estimates. At a few of these locations, a simple linear
427 adjustment of 12 hPa per 100m from the ERA-Int elevation at the reconstruction's gridpoint
428 proved sufficient to readily compare it to the historical values. A subset of these stations is
429 presented in Fig. 6.

430 Perhaps the most famous early American expeditions to Antarctica were those led by
431 Admiral Richard E. Byrd, who set up a station called Little America in several different field
432 campaigns spanning three decades (Byrd, 2003). Although the mean location of Little America
433 was on the Ross Ice Shelf (it varied negligibly during each campaign in comparison to the
434 resolution of the gridded datasets used in this study; Fig. 4), there were notable differences in
435 observed MSLP and surface pressure at the location (Fig. 6a). When adjusting the reconstruction

436 to sea level, a good match is observed both in overall mean pressure (MAE = 3.63 hPa) and
437 interannual variability. Surprisingly, the reconstruction performs much better than the MSLP
438 from 20CRv2c or 20CRv3, most notably due to the much higher MSLP in these two datasets
439 from the 1940s onward compared to the reconstruction and observed values. However, the
440 20CRv2c surface pressure nearly perfectly matches the observed surface pressure (an MAE of
441 only 2.39 hPa), while 20CRv3 has very similar values for surface and sea level pressure
442 observations. We note that although there are significant offsets from the observed values for
443 most of the datasets (MAE > 6 hPa for both), the interannual variability is well-captured, with
444 the reconstruction correlation of 0.85, and surface pressure correlations from the reanalyses all
445 above 0.85. The consistent difference between the observations and 20CRv3 could be due to
446 elevation issues or to a detected bias in the observations; this will be examined in more detail
447 later. CERA-20C, as seen earlier, performs with the highest skill for MSLP ($r=0.9$). Also note
448 that the offset from the surface pressure to MSLP is not constant, as this difference, through the
449 hypsometric equation, is influenced by both temperature and humidity. Therefore, some of the
450 larger errors in the reconstruction and the reanalyses, particularly in the 1950s, could be due to
451 too strong of an increase in the surface pressure as it was reduced to sea level, since the gap
452 between surface pressure and sea level pressure is much lower in the historical observations
453 during the 1950s. Observational uncertainties, including the various bias corrections employed
454 by the reanalyses as discussed previously, can also create some of these differences between
455 products when compared to the observations.

456 Much earlier in Antarctic history, under the leadership of Jean-Baptiste Charcot, the
457 French conducted their second expedition that wintered over on Peterman Island in 1908-1910.
458 The ship associated with this expedition was Porquoy Pas, with a mean location near the

459 Antarctic Peninsula (Fig. 4). Due to the close proximity of the high terrain of the Antarctic
460 Peninsula, elevation adjustments to the reconstruction were necessary but may not have been
461 sufficient at this location. From historical observations, the difference between surface pressure
462 and sea level pressure ranged from nearly 20 hPa to as little as 5 hPa in DJF 1909 (Fig. 6b).
463 Despite the challenges in correcting for the elevation differences, as seen in Fig. 6b, the
464 adjustment brings the observed MSLP to the far upper-limits of the reconstruction uncertainty,
465 and clearly within the observational uncertainty. Further, the reconstruction agrees well with the
466 observational estimates: the MAE of 3.15 hPa is nearly consistent with time, and the seasonal
467 cycle of the pressure during this portion of the early 20th century is well captured by the
468 reconstruction. It is also encouraging to see high skill in both 20CR datasets, and again in
469 CERA-20C at this location, all within the observational uncertainty; the lower performance of
470 ERA-20C could be related to a cold bias or perhaps resolution issue, as there is a much larger
471 difference between surface pressure (dashed line) and MSLP (solid line) in ERA-20C compared
472 to the observations or CERA-20C. The differences in surface pressure between 20CRv3 and the
473 observations are also noteworthy, with an MAE of 38.60, reflecting differences in model and
474 observed orography.

475 Similarly situated near the Antarctic Peninsula (Fig. 4), Argentine Island provides a long
476 continuous record much like in Fig. 5a, but with a noticeable influence of elevation-based
477 pressure corrections (Fig. 6c). As with Porquoi Pas, the linear SLP adjustment brings the
478 reconstruction close to the historical estimates, but they fall at the upper-bound of the
479 reconstruction uncertainty, and are much closer to the reanalyses overall. All comparisons are
480 within the expected observational uncertainty. The interannual variability is well-captured by
481 the reconstruction ($r=0.82$), although it may be slightly dampened in the early 1950s.

482 Interestingly, ERA-20C surface pressure aligns closely with the historical observations (with an
483 MAE of 1.63 hPa), but this reanalysis again demonstrates the highest MAE compared to MSLP
484 (4.88 hPa). In contrast, CERA-20C shows the lowest MAE based on MSLP (0.66 hPa), but
485 considerably lower surface pressure than observed (an MAE of 18.29 hPa), though not as low as
486 surface pressure in 20CRv3 (an MAE of 33.42). All reanalyses show very high correlations with
487 observations for both MSLP and surface pressure ($r > 0.85$).

488 The long, albeit discontinuous record at the Little America station location (Fig. 4)
489 provides an opportunity to further evaluate the reconstruction in comparison to the historical
490 reanalyses, and importantly, to assess the reconstruction skill in light of the reanalyses' internally
491 estimated uncertainties. For the reanalyses studied here, all but ERA-20 are ensemble
492 reanalyses, and therefore the ensemble spread from the seasonal mean ensemble members can be
493 further employed to assess the quality of these products through time and provide a more
494 complete comparison of their skill relative to that of the reconstruction. The MSLP from the
495 closest gridpoint of 20CRv2c, 20CRv3, and CERA-20C are plotted in Fig. 7, along with 95%
496 confidence intervals calculated as 1.96 times the ensemble standard deviation of seasonally
497 averaged MSLP from the 56, 80, and 10 ensemble members of 20CRv2c, 20CRv3, and CERA-
498 20C, respectively. The performance varies slightly at neighboring gridpoints for MSLP, but
499 varies considerably if using surface pressure, suggesting elevation gradients from the nearby
500 Roosevelt Island or the edge of the Ross Ice Shelf can influence the reanalysis ~~solution~~ estimate
501 at this location.

502 Similar to but slightly larger than the reconstruction, Fig. 7 shows that CERA-20C has a
503 pronounced annual cycle of MSLP at Little America, while both 20CRv2C and 20CRv3 have a
504 dampened annual cycle. Nonetheless, Fig. 7 also demonstrates that there is a marked decrease in

505 the reanalyses' uncertainties at the times when the Little America data were assimilated, which
506 effectively constrained the reanalysis solutions estimates. There are also other reductions in the
507 reanalysis uncertainties prior to the establishment of Little America, including the data
508 assimilated from the South Pole race of 1911-1912 (the Norwegian base Framheim was very
509 close to Little America (Fogt *et al.*, 2017b)) and the data from the first British Antarctic
510 Expedition (1908-1909, which established a base near present day McMurdo station west of
511 Little America, at Cape Royds). At these times, the reanalyses and reconstruction show
512 considerable agreement, and the reanalysis uncertainty (colored shading in Fig. 7) overlaps the
513 reconstruction uncertainty (gray shading in Fig. 7). Exceptions are in 1929 for all reanalyses and
514 in 1911 for 20CRv2c and 20CRv3 when the reconstruction and reanalysis uncertainties do not
515 overlap, with the reconstruction seasonal mean MSLP lower than the reanalyses. Nonetheless,
516 the overall agreement at all other times suggests that although there may still be larger MAE in
517 the reanalyses MSLP when compared only during the times of direct observations (as in Figs. 5-
518 6), the observations and reconstruction both fall within the reanalyses uncertainty (estimated by
519 the ensemble spread), and the reanalyses have benefited greatly from assimilating this historical
520 data (moving much closer to, if not within, the observational uncertainty). Clearly, at other
521 periods when data are not available, the reanalysis spread is considerably larger, but the
522 reconstruction nearly always falls within the reanalyses' uncertainties (the high positive pressure
523 values in CERA-20C in 1944 are one exception). We note that the reanalysis uncertainty
524 estimates themselves require further improvement, particularly in the Southern Hemisphere:
525 Slivinski *et al* (2019) show artificial signals in the uncertainty of 20CRv2c, and demonstrate that
526 the uncertainty in this region still remains too large in 20CRv3. Conversely, Laloyaux *et al.*
527 (2018) acknowledge that the small ensemble of CERA-20C can result in overly-confident

528 estimates of uncertainty. Consistent with the comparison to observations (Fig. 6a), the CERA-
529 20C MSLP and reconstruction (Fig. 7c) show the most similarity throughout the early 20th
530 century at the Little America location (RMSD = 4.32 hPa), and for this location 20CRv3
531 performs better than 20CRv2c (RMSD of 5.95 hPa compared to 8.22 hPa).

532 Evaluation of the reconstruction skill in Figs. 2 and 3 often indicates substantial
533 differences, suggesting that the seasonal mean values from the historical observations do not
534 always fall within the reconstruction uncertainty when elevation corrections are applied,
535 particularly near high terrain (even when their uncertainty is accounted for; not shown). To
536 examine this issue further, Figure 8 depicts two cases – a set of Antarctic expedition a ship
537 records (Deck 246, Fig. 8a) and a temporary base (Cape Denison, Fig. 8b), where elevation
538 corrections have mixed results; MAE values in Fig. 8 are only calculated for MSLP. Ships
539 included in Deck 246 (from ICOADS) operated discontinuously near present day Dumont
540 d'Urville station in the Ross Sea sector of Antarctica (Fig. 4); the data from ICOADS have two
541 disparate locations in January – February 1912 (the mean of these would be over the continent),
542 so instead of averaging data from both locations, each were treated as separate data points in Fig.
543 8a and the comparison statistics. The two different values for MAE in Fig. 8a are therefore
544 based on the MSLP at these two different locations, with the data closer to the Ross Ice Shelf
545 (second value) agreeing better with all gridded datasets than the data closer to the East Antarctic
546 plateau, near the location plotted in Fig. 4. Even with this potentially conflicting information,
547 the reconstruction performs very well after adjustment to sea level pressure, with an MAE of
548 2.32 / 1.85. A closer look shows that the majority of this error is from DJF 1910, when the
549 reconstruction was about 6 hPa lower than the observational estimate, otherwise it is generally

550 within 1.5 hPa. This performance exceeds the reanalyses' performance for Deck 246, as the
551 reanalyses typically have much higher MSLP values.

552 In contrast, the famous base for the Australian Antarctic Expedition, Cape Denison
553 (Mawson, 1998), situated along the East Antarctic coast south of Australia (Fig. 4) is marked
554 with much lower performance across all datasets (Figure 8b). Elevation corrections and the
555 models' orography have a strong effect here, clearly demonstrated by the large differences in
556 surface and sea level pressure in observations and reanalyses (note, surface pressure is plotted on
557 the right axis, but because of the large differences in surface pressure the MAE is not given).
558 Whereas the seasonal means of the historical observations demonstrate surface pressures around
559 920 hPa on average, sea level pressure estimates from the station are around 70 hPa higher, at
560 around 990 hPa. Such high differences in the two over the cold ice sheet plateau compromise the
561 quality of the reduced sea level pressure (not only in observations, but across all datasets). The
562 MAE for the reconstruction (13.50 hPa) is one of the highest of all locations examined.
563 Although the reanalyses' errors are nearly half of this (around 5-7 hPa, likely improved by
564 making further use of temperature and humidity calculated within the reanalyses to reduce
565 surface pressure to sea level), the errors are still large, and the reanalyses and reconstructions all
566 likely fall outside the observational uncertainty. Furthermore, it is difficult to assess how well
567 the interannual variability of the MSLP is reproduced, since there are fewer than ten observations
568 and the reduction to sea level varies considerably by season (affected by temperature and
569 humidity), but the reconstruction was adjusted to sea level uniformly (and linearly) across all
570 seasons. Nonetheless, the limited comparison demonstrates that overall there is still good
571 agreement in the surface pressure interannual variability (despite large differences in magnitude)
572 between the reanalyses and the reconstruction, which potentially suggests that the reconstruction

573 is still capturing aspects of the pressure variability at this location in the early 20th century.
574 Importantly, due to the influence of crude elevation adjustments, it is highly likely that the
575 reconstruction is performing better than indicated by the MAE (Fig. 8b) or RMSD (Fig. 4).
576 Unfortunately, the reconstruction skill is difficult to precisely determine at this or any other
577 location (as suggested in reviewing Fig. 2) where large elevation adjustments make the
578 comparison to historical estimates challenging.

579

580 **4. Discussion and Conclusions**

581 The analysis presented here has compared seasonal Antarctic pressure reconstructions to
582 numerous historical observations and reanalyses throughout the early 20th century. As none of
583 these historical data were included in the reconstruction calibration, they serve as an independent
584 evaluation of the reconstruction skill during a period when relatively little is known about
585 Antarctic climate variability.

586 The results overall confirm that the reconstruction error and uncertainty assessed in
587 earlier work (Fogt *et al.*, 2017b, 2019), a mean absolute error of around 2-4 hPa across the
588 Southern Ocean, is supported when comparing with ship observations. A few ship records
589 suggest even higher reconstruction skill (MAE less than 2 hPa), while others situated north of the
590 Amundsen and Bellingshausen Seas demonstrate lower skill (MAE above 4 hPa), consistent with
591 earlier work. Furthermore, most comparisons with ship observations that span multiple seasons
592 indicate the reconstruction also captures the interannual variability well (correlations often
593 greater than 0.80). Comparison with historical reanalyses provide further evaluation of the
594 reconstruction's performance, as they assimilate most of the historical observations used here but
595 are independent of the reconstruction.

596 While the comparisons with observation estimates taken at sea level are relatively
597 straightforward and further validate the reliability of the early portions of the reconstruction, it is
598 far more challenging to make assessments of the reconstruction skill over areas of higher
599 elevation or near the coastline. In many of these locations, reduction of the reconstruction
600 pressure (which was constructed as surface pressure anomalies relative to the ERA-Int model
601 topography) to sea level pressure using a simple linear adjustment does not satisfactorily agree
602 with the historical data, even after considering the potential observational error. In many of
603 these locations, there are also large differences between 20th century reanalysis MSLP and the
604 historical observational estimates, highlighting the reduced reliability of MSLP from all sources
605 over the cold, high Antarctic continent. While the general comparisons conducted here suggest a
606 larger reconstruction MAE of nearly 6 hPa or more over high elevation, a closer examination at
607 select locations reveals that the reconstruction uncertainty is likely much lower than this and
608 perhaps as low as 1-3 hPa, as indicated in Fogt *et al.* (2019).

609 This work has demonstrated the value of digitizing historical observations from ships and
610 temporary bases for both understanding long term change across the high southern latitudes and
611 evaluating gridded datasets. While their temporary nature may make them difficult to use for
612 assessing long-term variability and change, when coupled with gridded climate datasets like the
613 seasonal Antarctic pressure reconstructions evaluated here, they serve as an independent and
614 valuable tool of documenting historical climate. As one recent example, the use of newly
615 digitized historical observations and pressure reconstructions shed new light on exceptional
616 conditions during the South Pole race of 1911-1912 (Fogt *et al.*, 2017c, 2018; Sienicki, 2018).
617 Future work will hopefully continue to unlock the power of these and other historical

618 observations, so that the ongoing change across the high southern latitudes can be placed in a
619 much-needed longer historical context (Jones *et al.*, 2016).

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919 **Figure Captions**

920 **Figure 1.** Maps of seasonal mean data location grouped by decade. Open circles represent
921 seasonal mean locations from ship records, and filled circles are for temporary bases on the
922 continent. The bottom left plot shows the location of all 271 seasonal mean observations
923 compared, while the bottom right plot shows the locations of the 18 station reconstructions
924 (brown) and observations from Orcadas (grey) used to generate the spatially complete pressure
925 reconstruction. Contours on the bottom right panel are the standard deviations of monthly ERA5
926 surface pressure anomalies for reference, contoured every 0.5 hPa. ~~Map of seasonal mean data~~
927 ~~location grouped by decade, with the bottom plot showing the location of all 271 seasonal mean~~
928 ~~observations compared. Open circles represent seasonal mean locations from ship records.~~

929
930 **Figure 2.** Mean reconstruction skill statistics (columns; bias, MAE, and RMSD) compared to
931 historical observations, and averaged over various latitudes (top row), longitudes (middle row),
932 and decades (bottom row). The statistics calculated over all observations are listed at the bottom
933 of the figure.

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935 **Figure 3.** Decadal mean RMSD plotted by decade.

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937 **Figure 4.** Map showing observational mean (over full length of record) RMSD for select
938 representative locations examined in more detail.

939
940 **Figure 5.** Time series of historical observations, reconstruction (with 95% confidence interval in
941 grey shading), and gridded reanalysis problems for observations representative of the lowest
942 RMSD (solid lines for MSLP, dashed lines for surface pressure). The name is the record
943 identifier provided in ISPD or ICOADS. In a), the x-axis varies by season, and the labels
944 represent the DJF seasons for each year; in b) and c) only DJF data are plotted and the label
945 represents the DJF season. The white spaces in c) represent discontinuities in the observations.
946 The values at the bottom of each panel are the correlations (if more than 10 data points are
947 available) and MAE values (first numbers based on MSLP, second (where available) based on
948 surface pressure) for each dataset. The data for station 889340 were from ISPD, while Deck 215
949 and Deck 899 were from ICOADS.

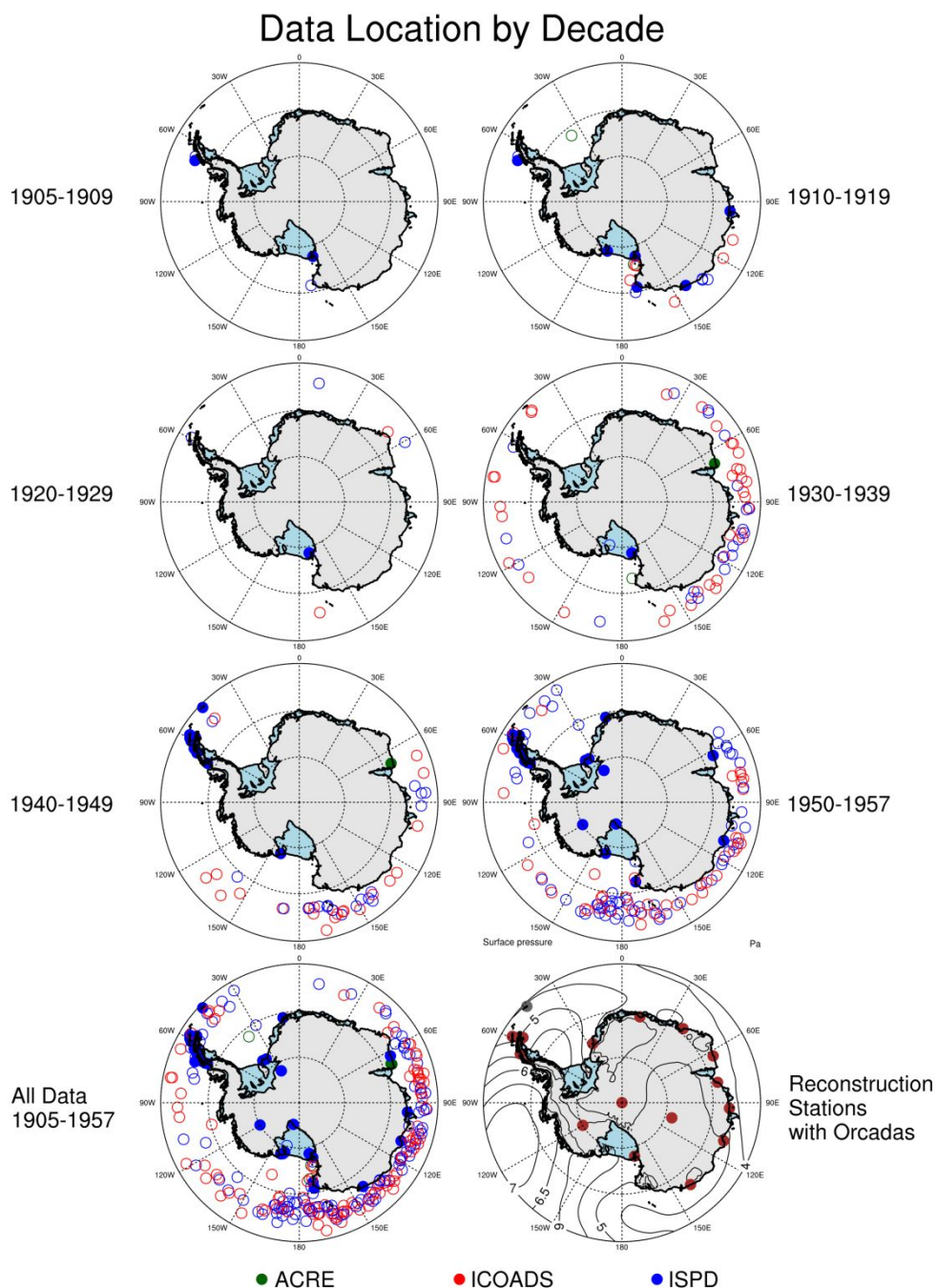
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952 sea level pressure) play an important aspect of the reconstruction performance evaluation. All
953 data in this figure were obtained from ISPD.

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955 **Figure 7.** Time series of seasonal mean MSLP for all four seasons at Little America (from
956 ISPD) on the northern edge of the Ross Ice Shelf for the reconstruction along with values from a)
957 20CRv2c; b) 20CRv3; c) CERA-20C. The gray shading in each panel represents the 95%
958 confidence interval for the reconstruction, while the colored shading represents 95% confidence
959 intervals for each of the reanalyses (calculated as the 1.96 times the standard deviation across the
960 seasonal mean ensemble members). The overall RMSD compared to the reconstruction is given
961 in the upper right for each dataset.

962

963 **Figure 8.** As in Fig. 5, but for a) Deck 246, which operated near the East Antarctic coast
964 discontinuously between 1910-1930, and b) observations at Cape Denison during the Australian
965 Antarctic Expedition of 1911-1914. Note in b) that surface pressure is plotted on the right axis.
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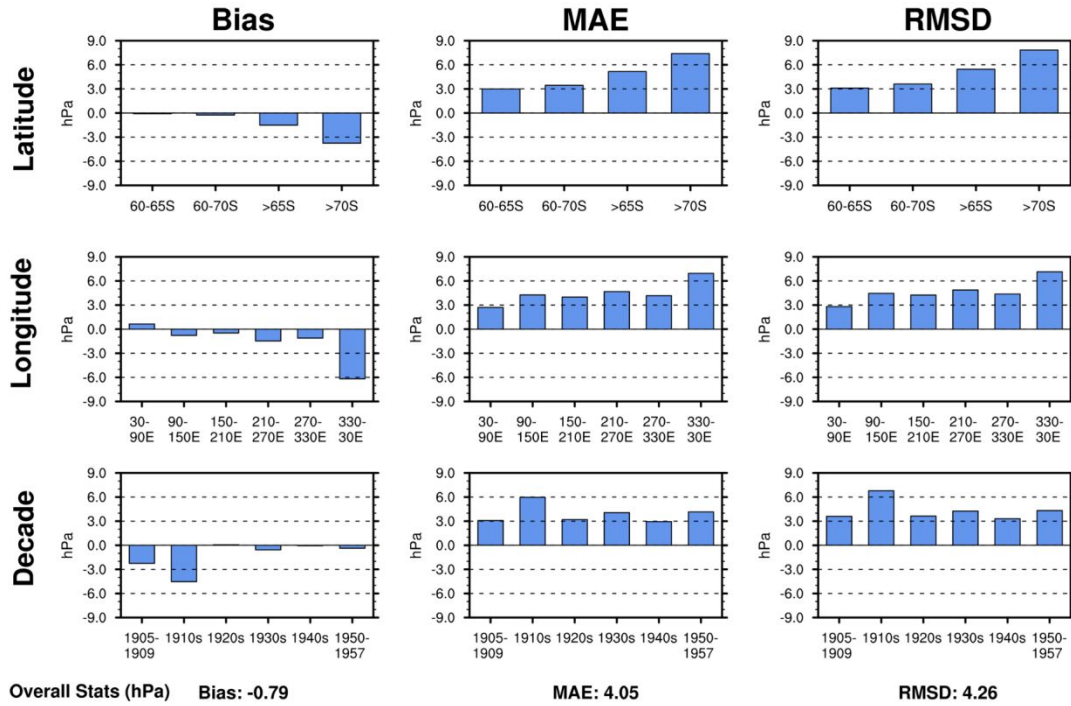
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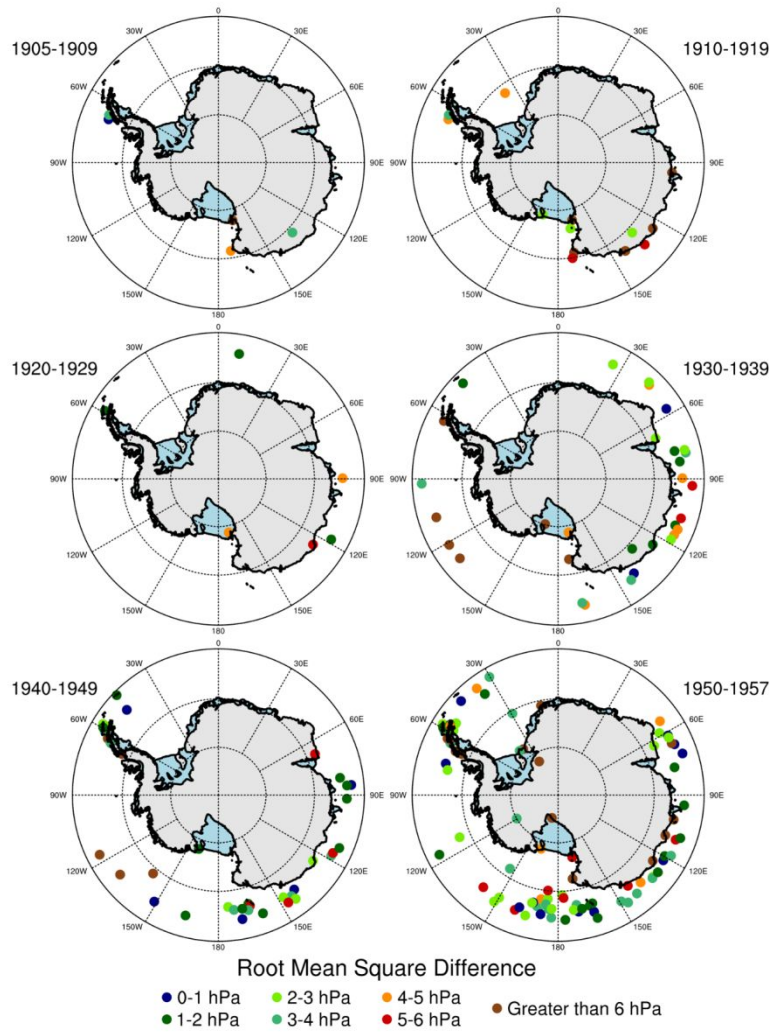
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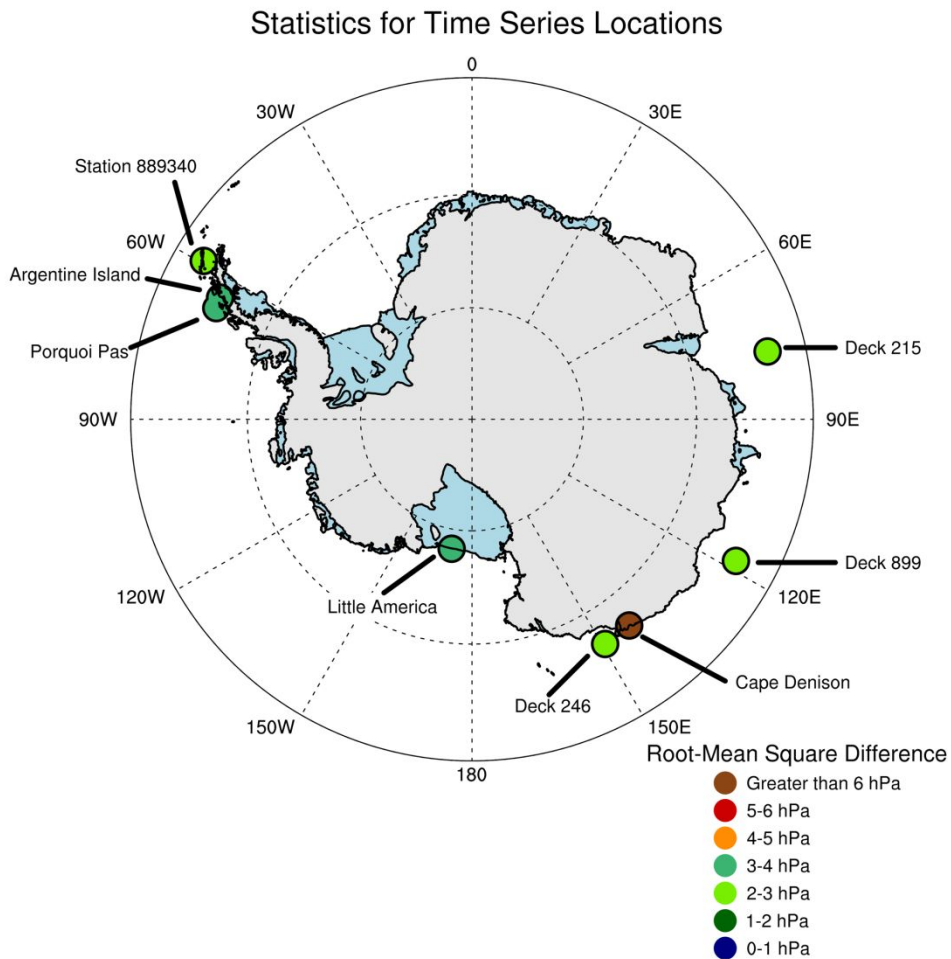
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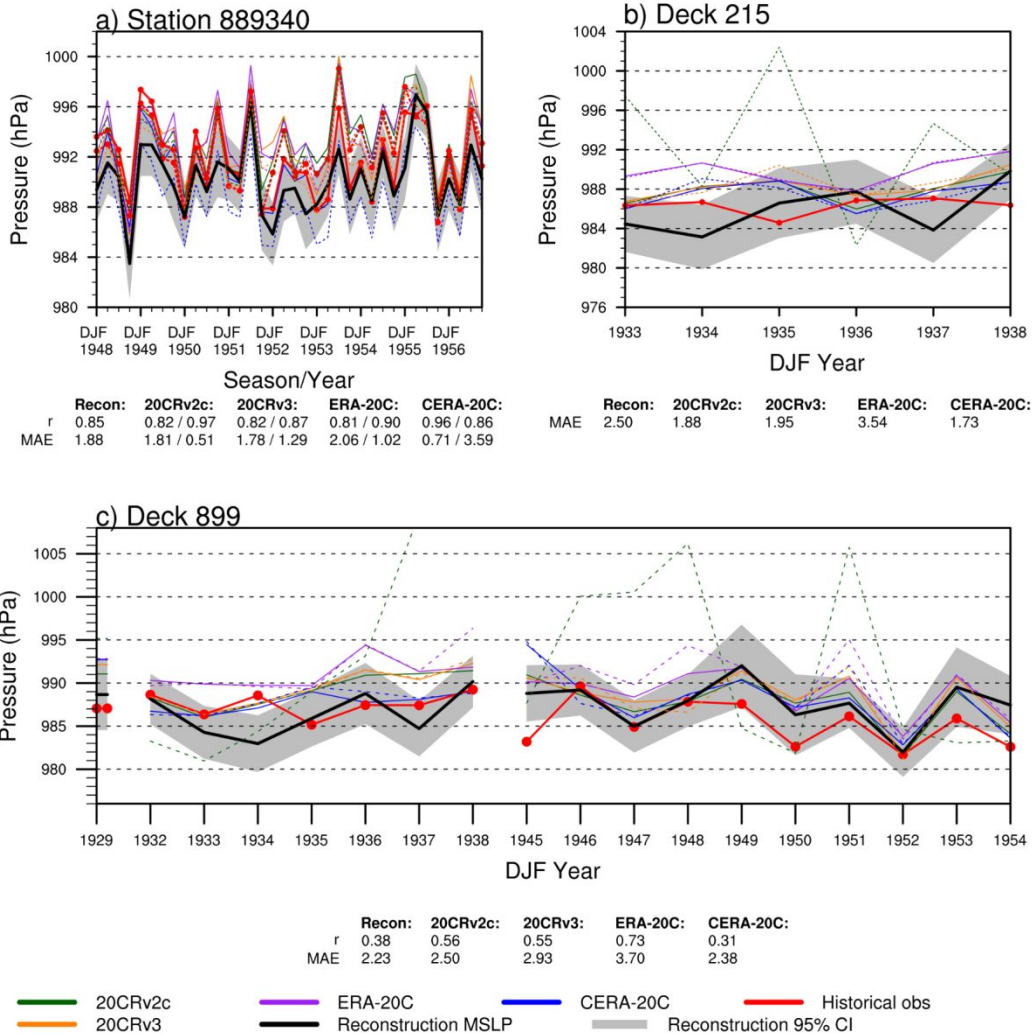
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Figure 3. Decadal mean RMSD plotted by decade.

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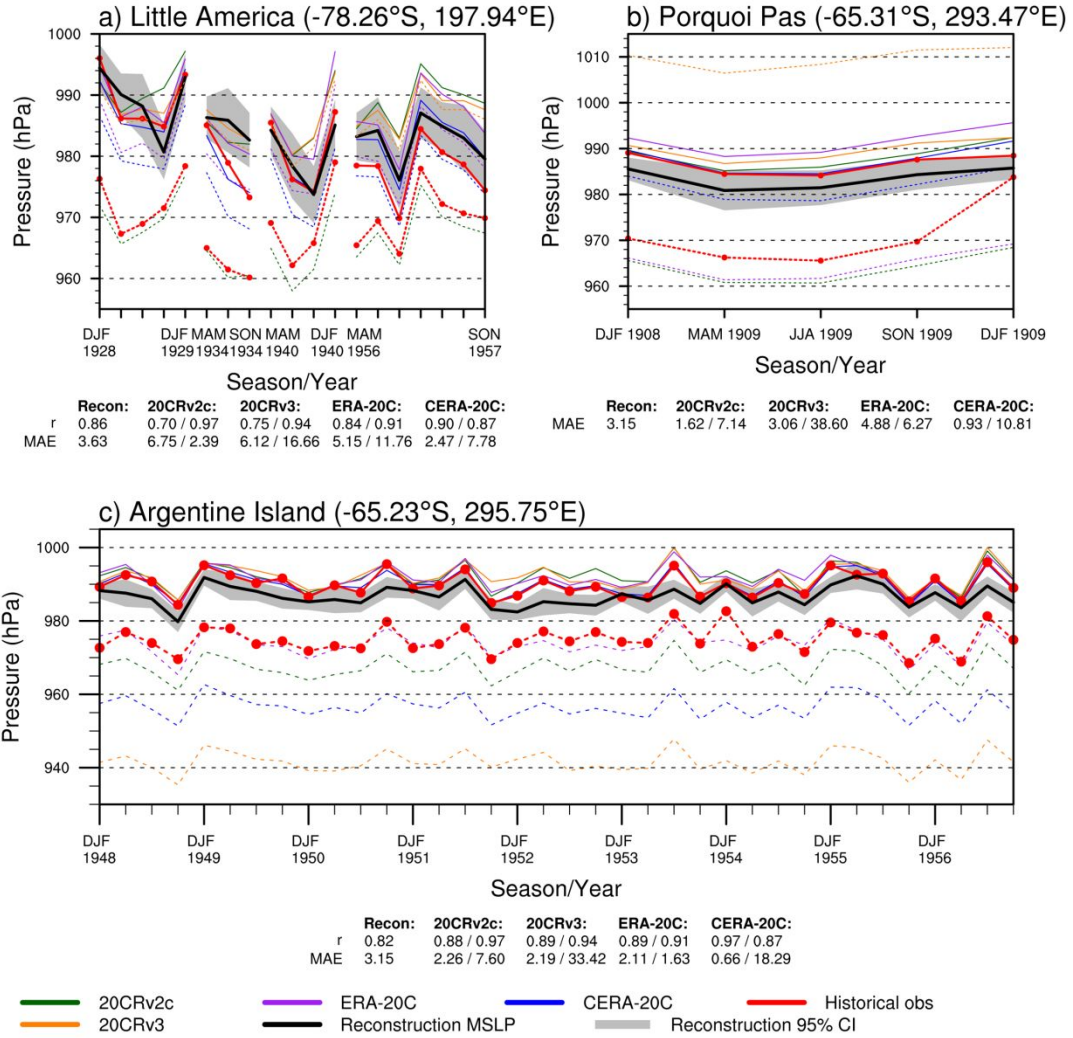


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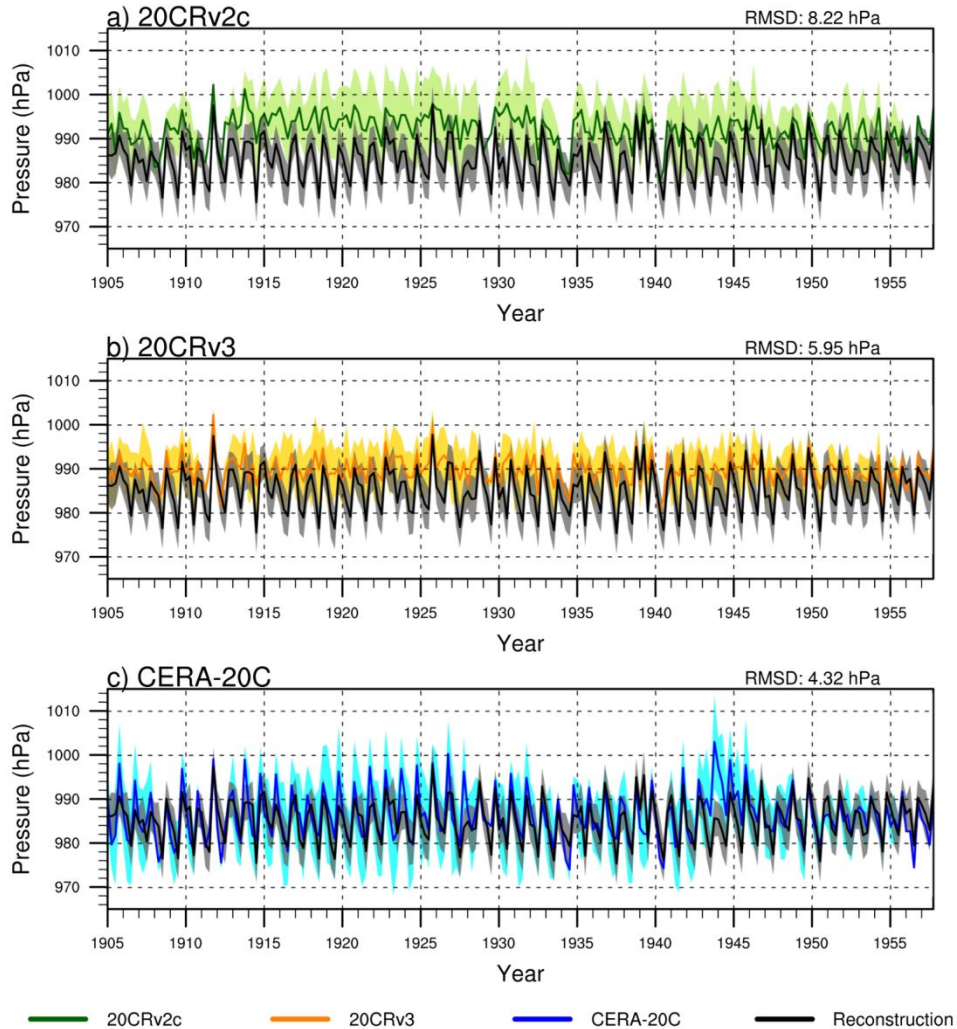
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Figure 5. Time series of historical observations, reconstruction (with 95% confidence interval in grey shading), and gridded reanalysis products for observations representative of the lowest RMSD (solid lines for MSLP, dashed lines for surface pressure). The name is the record identifier provided in ISPD or ICOADS. In a), the x-axis varies by season, and the labels represent the DJF seasons for each year; in b) and c) only DJF data are plotted and the label represents the DJF season. The white spaces in c) represent discontinuities in the observations. The values at the bottom of each panel are the correlations (if more than 10 data points are available) and MAE values (first numbers based on MSLP, second (where available) based on surface pressure) for each dataset. The data for station 889340 are from ISPD, while Deck 215 and Deck 899 are from ICOADS.



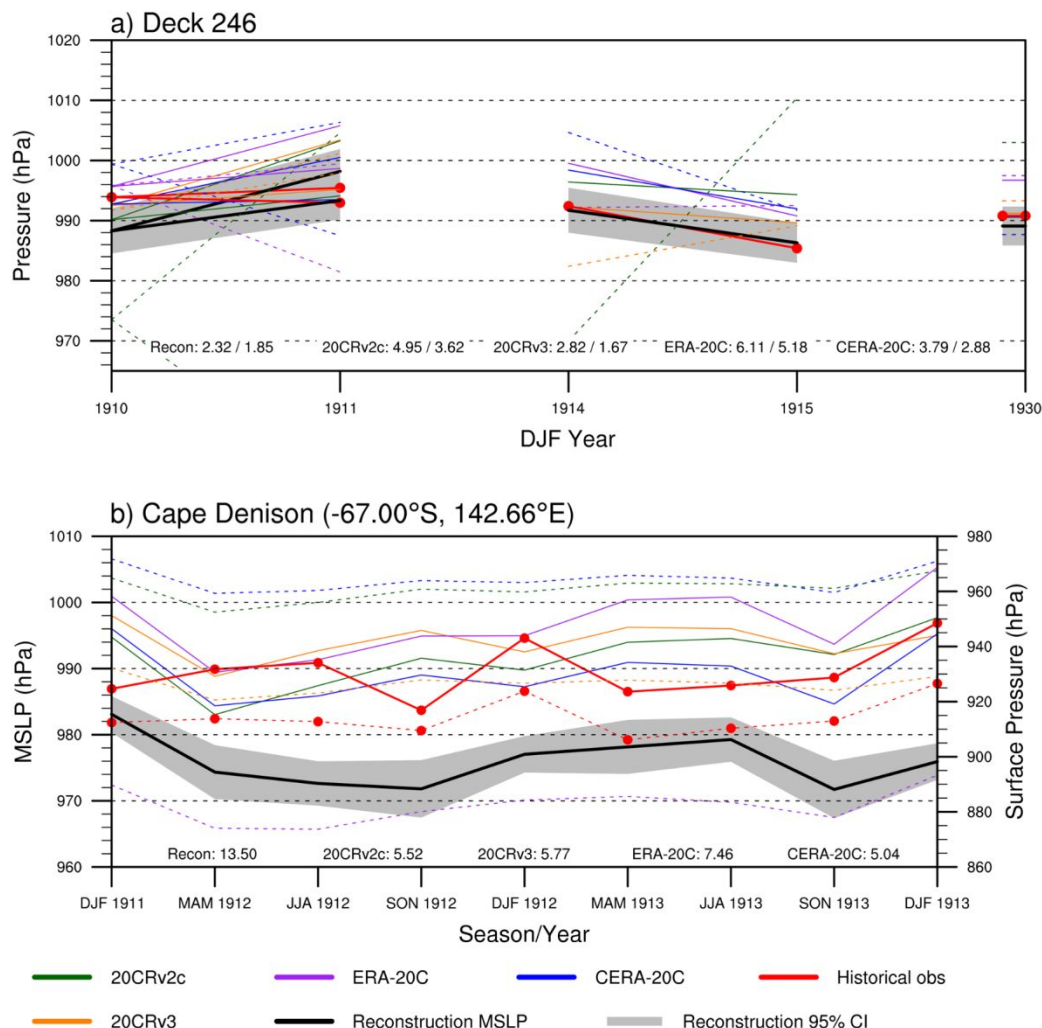
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Figure 6. As in Fig. 5, but representative of stations where elevation corrections (reduction to sea level pressure) play an important aspect of the reconstruction performance evaluation. In all panels, the x-axis varies by season. All data in this figure were obtained from ISPD version 3.



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Figure 7. Time series of seasonal mean MSLP for all four seasons at Little America (from ISPD) on the northern edge of the Ross Ice Shelf for the reconstruction along with values from a) 20CRv2c; b) 20CRv3; c) CERA-20C. The gray shading in each panel represents the 95% confidence interval for the reconstruction, while the colored shading represents 95% confidence intervals for each of the reanalyses (calculated as the 1.96 times the standard deviation across the seasonal mean ensemble members). The overall RMSD compared to the reconstruction is given in the upper right for each dataset.



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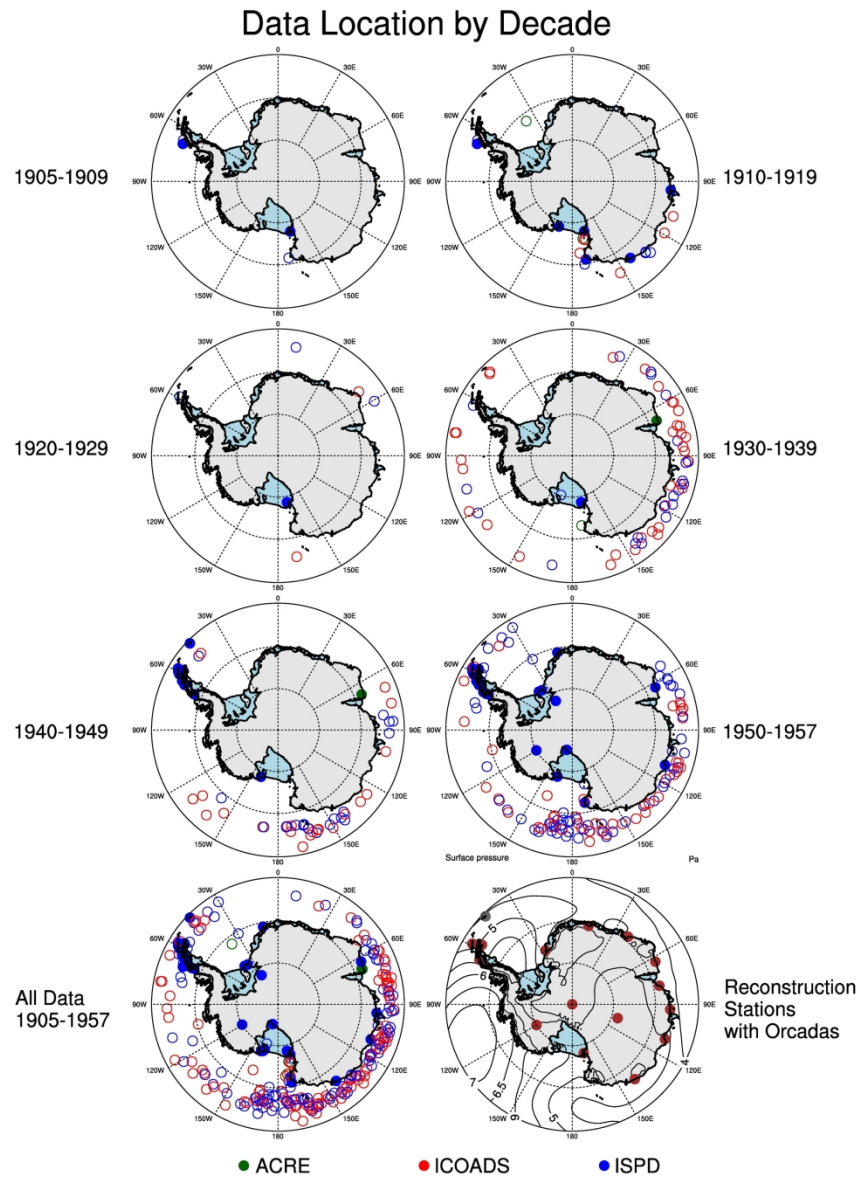


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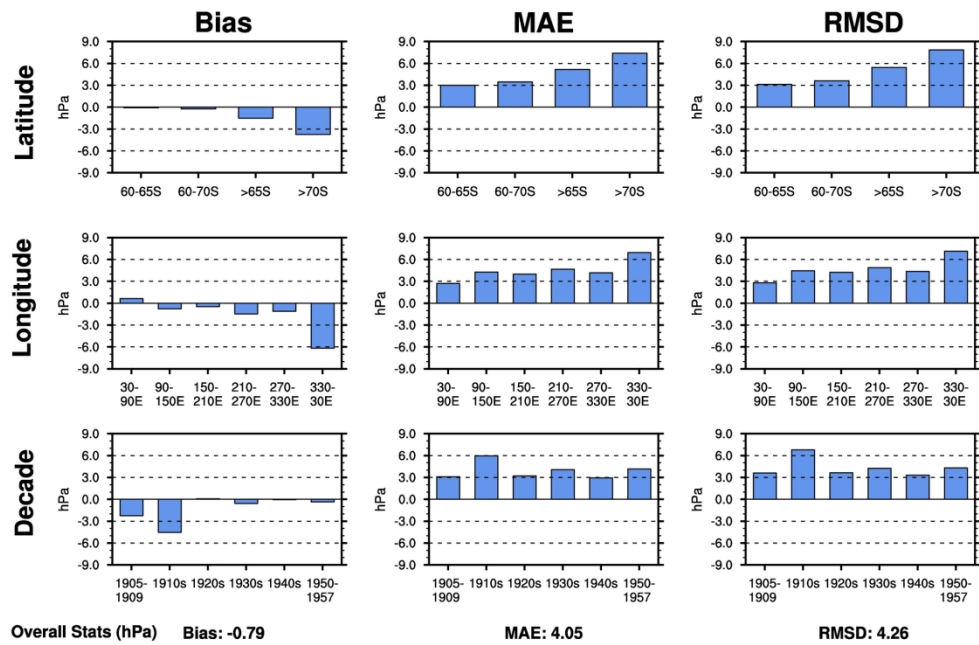


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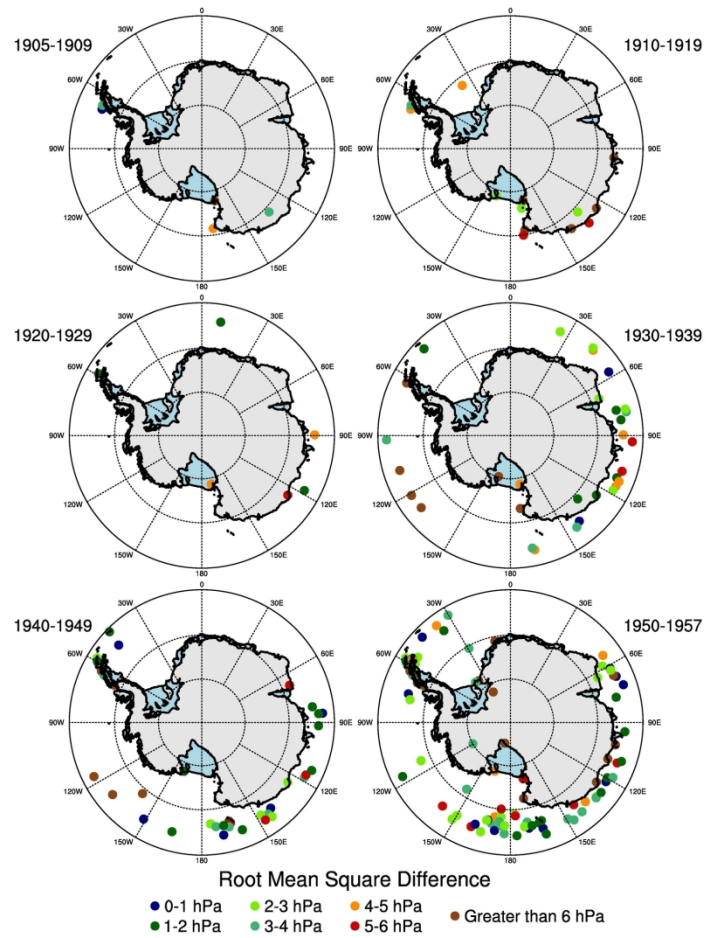


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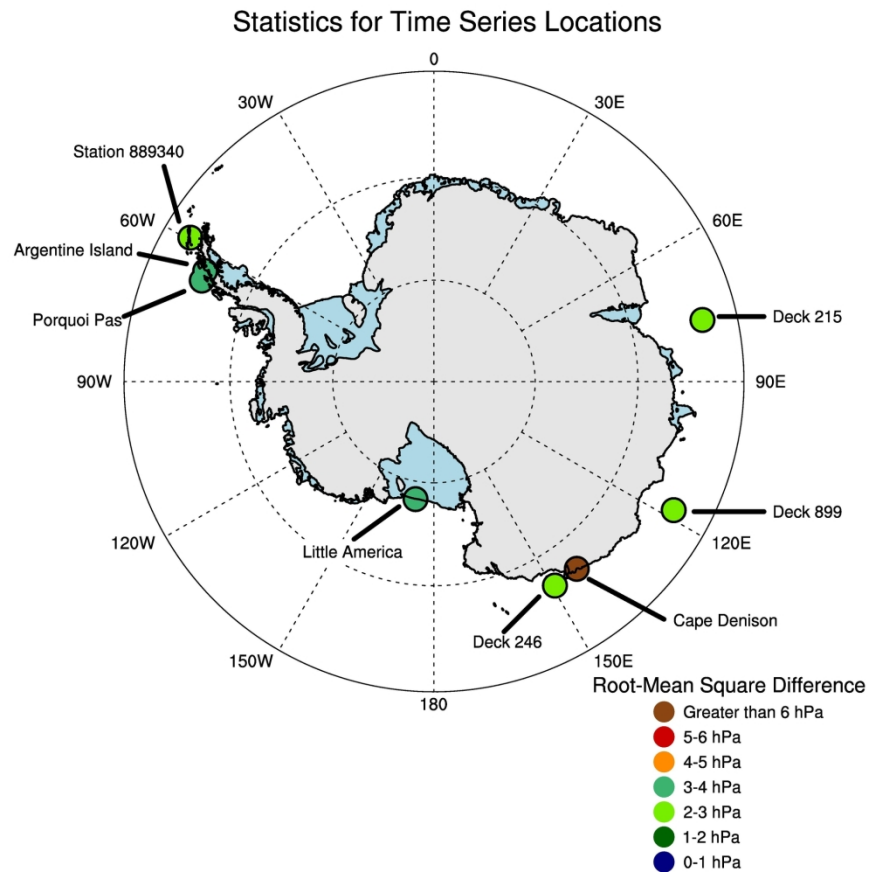


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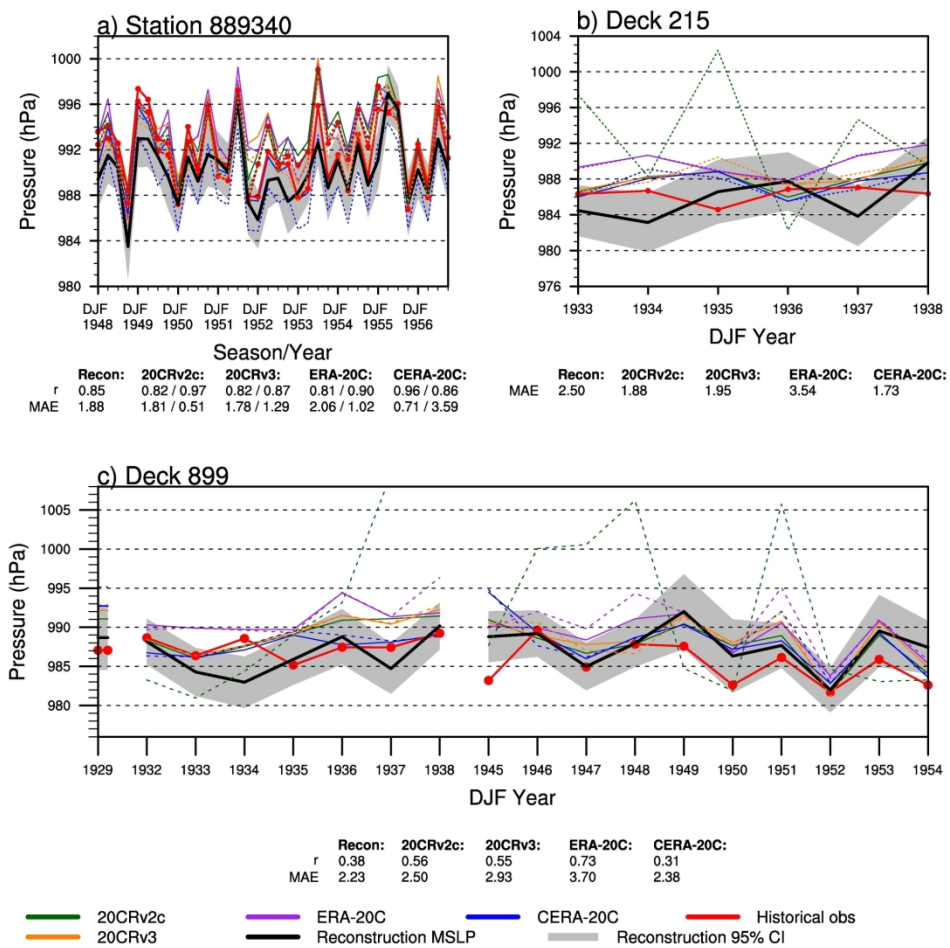


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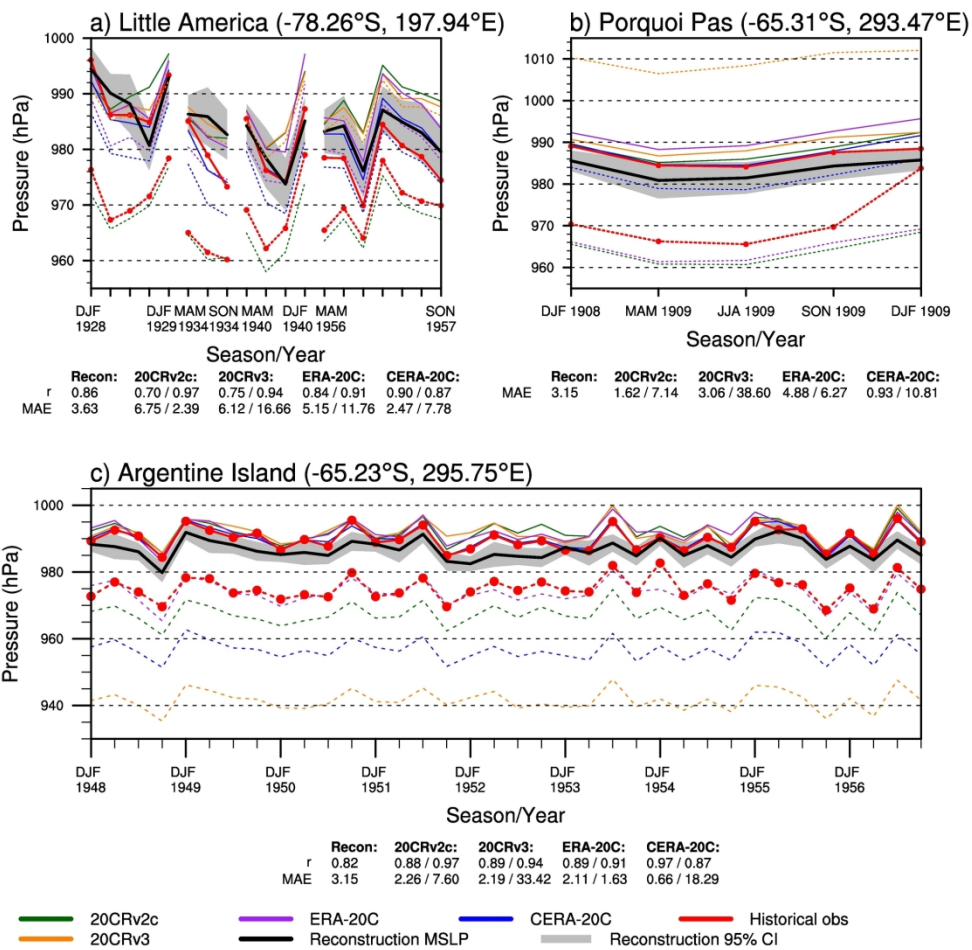


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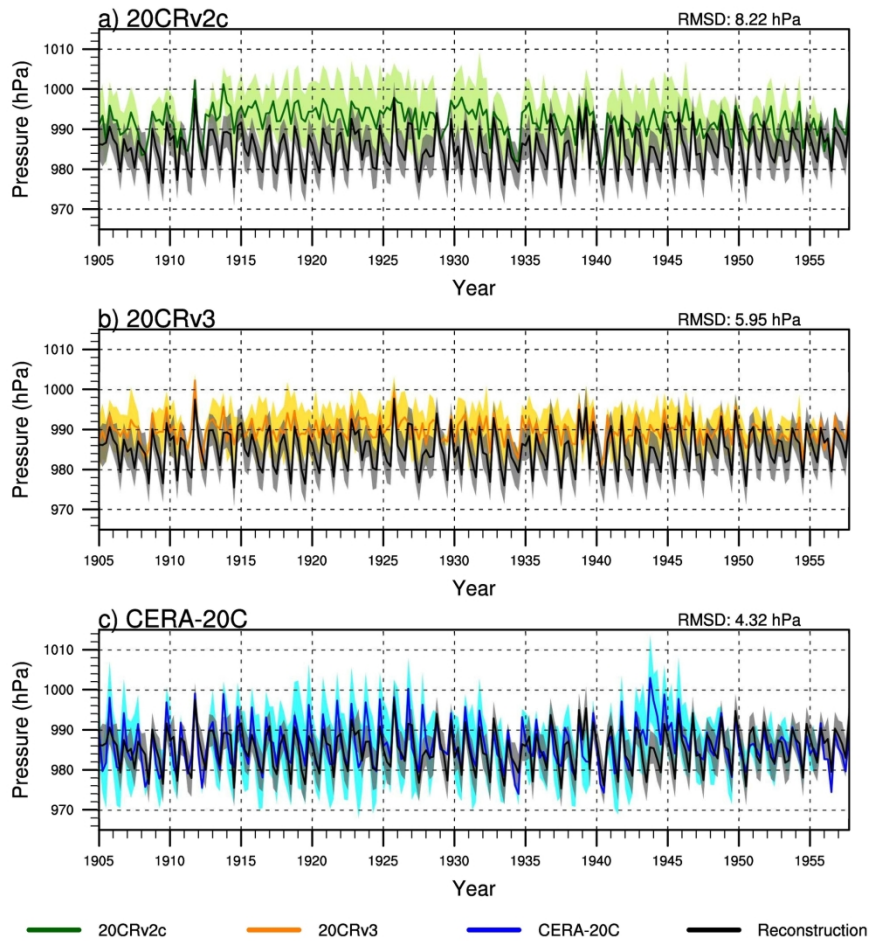


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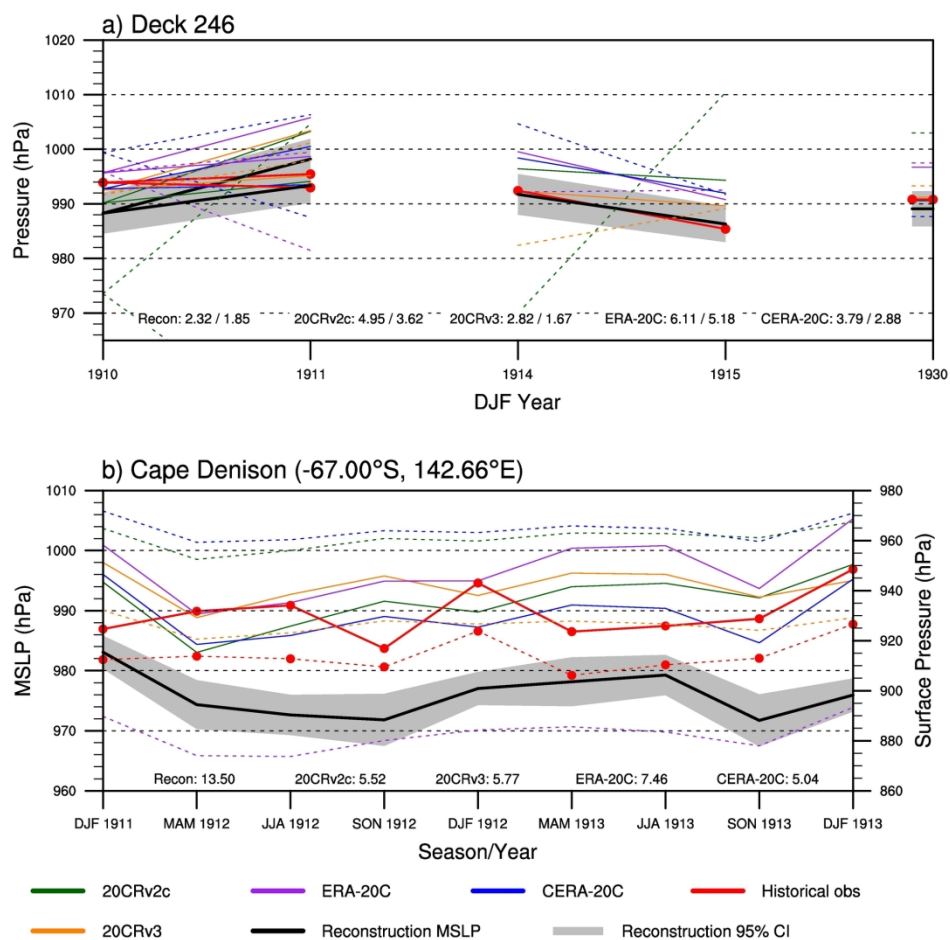


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An Assessment of Early 20th Century Antarctic Pressure Reconstructions using Historical Observations

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Graphical Abstract

While gridded seasonal pressure reconstructions poleward of 60°S extending back to 1905 have been recently completed, their skill has not been assessed prior to 1958. To provide a more thorough evaluation of the skill in the early 20th century, these reconstructions are compared to other gridded datasets, historical data from early Antarctic expeditions, ship records, and temporary bases, such as the Little America base shown in the image, to further evaluate their performance.

