A New Monthly Pressure Dataset Poleward of 60°S since 1957

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ABSTRACT

This study presents a new monthly pressure dataset poleward of 60°S, from 1957 to 2016, based on a kriging interpolation from observed pressure anomalies across the Antarctic continent. Overall, the reconstruction performs well when evaluated against ERA-Interim. In comparison to other reanalyses, the reconstruction has interannual variability after 1970 similar to products that span the entire twentieth century and is a marked improvement on the first-generation reanalysis products. The reconstruction also produces weaker pressure trends than the reanalysis products evaluated here, which are consistent with observations. However, the skill of the reconstruction is weaker in the South Pacific and therefore does not improve the understanding of long-term pressure variability and trends in this region, where circulation changes have been key drivers of climate variability in West Antarctica and the Antarctic Peninsula.

1. Introduction

Along with warming across West Antarctica (Steig et al. 2009; Nicolas and Bromwich 2014) and the Antarctic Peninsula in the late twentieth century (Turner et al. 2005; Clem and Fogg 2013; Turner et al. 2016), there have been notable seasonal high southern latitude atmospheric circulation trends. These are primarily manifested as a positive southern annular mode (SAM) index trend in austral summer and autumn (Marshall 2003; Fogg et al. 2009) and the deepening of the Amundsen Sea low (ASL), especially outside of austral winter (Meehl et al. 2016; Holland and Kwok 2012; England et al. 2016; Fogg and Wovrosh 2015; Fogg and Zbacnik 2014; Raphael et al. 2016). However, the quality of the first generation of gridded atmospheric reanalysis datasets that employ assimilation of satellite data has been shown to be considerably lower in the high southern latitudes prior to the modern satellite era in 1979 (Bromwich and Fogg 2004; Bromwich et al. 2007),

making it challenging to interpret multidecadal atmospheric circulation trends poleward of 60°S. Although other long-term atmospheric reanalyses that span the entire twentieth century have been shown to have fewer notable changes in their performance after 1979, they still show significant disagreement in the early twentieth century (Fogg et al. 2017).

To improve on this, here we present and evaluate a new monthly pressure dataset poleward of 60°S extending back to 1957, produced by interpolating the array of long-term station observations using a kriging procedure. This new reconstruction improves dramatically on the first-generation reanalyses, is comparable in skill to reanalysis products that span the twentieth century, and provides another estimate of historical pressure variability over the Antarctic continent.

2. Data and methods

a. Data employed

The monthly spatial pressure reconstruction was performed using monthly observations from 19 different Antarctic stations spanning the entire continent from 1957 to 2016, displayed in Fig. 1 with details about the stations listed in Table 1. The observations were obtained from the Reference Antarctic Data for Environmental

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Research (READER) dataset (Turner et al. 2004). The monthly data were all converted to anomalies using the 1981–2010 climatology, which allows for the combination of surface pressure (for interior stations) and sea level pressure observations (primarily coastal stations) to be used in the reconstruction. From Table 1, the majority of the stations have only a few missing months of data, although Byrd station has several years during the 1970s when nearly all the data are missing, as by Bromwich et al. (2013). Once the automatic weather station (AWS) data became readily available in 1980 at Byrd, fewer gaps in the data were recorded. The missing AWS data at Byrd station were patched using bilinearly interpolated surface pressure data from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) through monthly linear regression, as done in other seasonal pressure reconstructions (Fogt et al. 2016, 2017).

We employ the ERA-Interim data to generate the reconstruction and evaluate it after 1979. The new monthly reconstruction is compared to other reanalysis datasets during their periods of overlap in 1957–2016, namely, the first-generation reanalysis products from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (NNR; Kalnay et al. 1996) and the 40-yr ECMWF Re-Analysis (E40; Uppala et al. 2005), and three reanalyses available during the full twentieth century: the National Oceanic and Atmospheric Administration (NOAA)–Cooperative Institute for Research in Environmental Sciences (CIRES) Twentieth Century Reanalysis, version 2c (20CR; Compo et al. 2011); ECMWF twentieth century reanalysis (ERA-20C; 1900–2010; Poli et al. 2016); and ECMWF Coupled Ocean–Atmosphere Reanalysis of the Twentieth Century (CERA-20C; 1901–2010; Laloyaux et al. 2017). All three of these century-long reanalyses assimilate surface pressure observations from the International Surface Pressure Databank (ISPD; Cram et al. 2015), while ERA-20C and CERA-20C additionally assimilate marine surface winds from the International Comprehensive Ocean–Atmosphere Data Set (ICOADS; Freeman et al. 2017). As a coupled atmosphere–ocean reanalysis, CERA-20C also assimilates ocean temperature and salinity from the Hadley Centre’s EN4 dataset (Good et al. 2013); the ocean coupling in CERA-20C improves its performance over ERA-20C for the Antarctic region (Laloyaux et al. 2017; Schneider and Fogt 2018). For 20CR and CERA-20C, we use the ensemble mean data.

b. Reconstruction procedure

We employ the kriging method to interpolate between the 19 monthly pressure observations during 1957–2016

(Fig. 1; Table 1) on an $80\text{ km} \times 80\text{ km}$ Cartesian grid centered at the South Pole. This method was used successfully for snowfall (Monaghan et al. 2006) and temperature (Monaghan et al. 2008) interpolation over Antarctica, and later refined for monthly temperature (Nicolas and Bromwich 2014) and seasonal pressure reconstructions (Fogt et al. 2017). The refinements conducted by Nicolas and Bromwich (2014) optimize the weighting coefficients used in the kriging interpolation, which helps to minimize the risk of overfitting the reconstruction by considering the relationships between stations. The kriging method also ensures that the reconstructed values will match the observations perfectly at each of the 19 stations. Here, the kriging weights are based on ERA-Interim data, since earlier work demonstrated it to be the most reliable atmospheric reanalysis dataset for Antarctic pressure (Bracegirdle and Marshall 2012).

To perform the monthly spatial pressure reconstruction, the missing values for station data needed to be filled. This was accomplished by estimating all the missing values from kriging weights, which were generated at each month during 1979–2016 from the varying combinations of complete station records (missing records not included) using the ERA-Interim gridded surface pressure data.

c. Reconstruction evaluation

To evaluate the monthly spatial pressure reconstruction, multiple validation methods were used with the ERA-Interim data after 1979. Along with calculating the reconstruction correlation r^2 with ERA-Interim data, a verification correlation was also calculated. We employ a similar validation procedure as in Nicolas and Bromwich (2014), where the full period is split into two separate, nonoverlapping 18-yr periods (1979–97 and 1998–2016). The kriging weights are determined for each period and subsequently used to predict the withheld years, which are concatenated to produce the verification reconstruction. We also use the reduction of error (RE) and the coefficient of efficiency (CE) to evaluate the reconstruction skill, both of which compare the reconstruction to the climatological mean.

3. Results

The reconstruction evaluation is displayed in Fig. 2. For both the original and verification reconstructions, squared correlations are above 0.80 across the entire continent and exceed 0.90 in many cases (significant at $p < 0.01$). This reflects the constraint that the reconstruction must match the station observations perfectly and that ERA-Interim has high correlations with

FIG. 1. Map of the 19 stations used in the kriging interpolation and reconstruction.

station observations across Antarctica (Bracegirdle and Marshall 2012). The similarities between the original and verification correlations in Figs. 2a and 2b also indicate that the reconstruction is not sensitive to the period used to generate the kriging weights, as both periods yield nearly identical reconstructions. The high skill is partly attributed to the high spatial correlations between the pressure anomalies at each station and the neighboring grid points (Fogt et al. 2016). The squared correlations remain above 0.4 across much of the domain poleward of 60°S, except in the South Pacific in the vicinity of the ASL. The lower skill in this region is a combination of two factors: high monthly and interannual pressure variability, which is the largest in the entire Southern Hemisphere (Connolley 1997), and the fact that the pressure variability here is constrained by comparably distant observations located along the Antarctic Peninsula, in central West Antarctica, and on the Ross Ice Shelf (Fig. 1). Incorporating additional data from the station Russkaya

on the coast of West Antarctica (74.8°S, 136.9°W) in the 1980s improves the reconstruction skill in this region (see Figs. S1 and S2 in the supplemental material), but the observations are available only for a decade and do not constrain the solution prior to 1979, after which many other gridded data products are available. In agreement with the squared correlations, the RE and CE values (Figs. 2b,c) indicate reconstruction skill that is higher than using the climatological mean (i.e., positive values) nearly everywhere poleward of 60°S, with the exception again of the South Pacific. Strong similarities between the RE and CE reflect the reconstruction robustness and the match between the original and verification reconstructions.

The interannual seasonal pressure variability poleward of 60°S in the reconstruction and other gridded products is presented in Fig. 3; given above each panel in Fig. 3 is the root-mean-square difference (RMSD) between the various reanalyses and the reconstruction. In summer [December–February (DJF); Fig. 3a], the

TABLE 1. Listing of the stations used as anchor points for the kriging interpolation, as shown in Fig. 1. Also given is the starting year for observations and the percent of monthly data available during 1957–2016. To provide the most complete and long-term records, data from O'Higgins and Marsh as well as McMurdo and Scott Base were merged using linear regression into a single record. Data for Marambio start in September 1970 but are >99% complete during 1971–2016.

Station name	Latitude (°S)	Longitude (°E)	Starting year	Complete (%; 1957–2016)
Amundsen-Scott	90.0	0.0	1957	100
Bellingshausen	62.2	−58.9	1959	96.5
Byrd	80.0	−119.4	1957	85
Casey	66.3	110.6	1957	99.7
Davis	68.6	78.0	1957	92.5
Dumont d'Urville	66.7	140.0	1956	100
Esperanza	63.4	−57.0	1945	100
Faraday	65.3	−64.3	1947	100
Halley	75.5	−26.7	1957	100
Marambio	64.2	−56.7	1970	77.2
Mawson	67.6	62.9	1954	100
McMurdo	77.9	166.8	1956	100
Mirny	66.6	93.0	1956	100
Novolazarevskaya	70.8	11.8	1961	93.2
O'Higgins–Marsh	63.3	−57.9	1969	87.9
Orcadas	60.7	−44.7	1903	100
Rothera	67.6	−68.1	1946	96.8
Syowa	69.0	39.6	1957	92.1
Vostok	78.5	106.9	1958	95.5

agreement is the highest between all products, reflecting the greater density of observations during the Antarctic field season and the seasonal cycle of the reanalysis skill discussed in earlier work (Bromwich and Fogt 2004). In the other seasons, the reconstruction has large differences with E40 and NNR, with RMSD values near or above 2.0 hPa, especially in winter. Comparison of the reconstruction with the twentieth-century reanalyses demonstrates an overall similarity in RMSD between 20CR and ERA-20C, with CERA-20C agreeing the best with the reconstruction and consistently showing RMSD values below 1.0 hPa. All time series in Fig. 3 are significantly ($p < 0.01$) negatively correlated to the (Marshall 2003) SAM index (Fig. S3 in the supplemental material). Notably, the agreement between the products improves markedly after 1970, although CERA-20C tends to better align with the reconstruction back to 1957. From these limited comparisons, it is clear that the reconstruction is an improvement from E40 and NNR; we therefore further evaluate its skill only in comparison to the century-long reanalysis products.

Spatial plots of the linear trends by season for the reconstruction and the century-long reanalyses are given in Fig. 4 during 1957–2010, the period of overlap between all of these products. While the kriging method ensures that the reconstruction will perfectly match the observations (circles in Fig. 4d), there can be subtle differences in the magnitude and significance of the trends, as the observed trends are

calculated only over all available observations, while the reconstruction method fills in the gaps in the station record and therefore represents the best estimate of the trend without any missing data. Nonetheless, the differences in the reconstruction and observed trends are most marked at Byrd station in Fig. 4 as a result of the higher percentage of missing data in this record. Figure 4 indicates that the reanalyses tend to produce stronger negative trends in all seasons in comparison to the reconstruction and observations. Notably, all products have different trend structures in the ASL region, where the reconstruction skill is weakest and it produces much weaker trends in this region. Unfortunately, it is difficult to estimate the pressure variability and trends in this region (prior to 1979 at least) from any one product alone, despite its likely significance on the regional climate (Hosking et al. 2013). While the reanalyses show the most negative trends in the ASL in autumn [March–May (MAM)], this is in contrast to the positive observation and reconstruction trends at Byrd station and along the Antarctica Peninsula (significant at Orcadas). Indeed, very few observation trends in MAM are statistically significant, with the only significant negative trend near the ASL being at McMurdo–Scott Base. In SON, the differences are most striking, with observations and the reconstruction indicating weakly positive trends (significant at Byrd station and Orcadas), with the reanalyses showing negative trends in most regions, and none showing regions of significant

Station Recon/ERA-Int Pressure Comparison 1979-2016

FIG. 2. Evaluation statistics for monthly reconstruction data compared to ERA-Interim, 1979–2016. (a) Squared correlation, (b) validation reconstruction correlation, (c) RE, and (d) CE.

positive trends on the continent, in agreement with the observations. Overall, CERA-20C appears to have the best agreement with the observations and reconstruction, in both spatial pattern and magnitude.

To further characterize the differences between the products, we examine the seasonal pressure trends for different periods of at least 30 yr of data averaged over 60°–90°S in Fig. 5. In DJF, all the reanalyses

FIG. 3. Seasonal mean time series of pressure anomalies averaged 60°–90°S. (a) DJF, (b) MAM, (c) JJA, and (d) SON. Above each plot are the RMSD values for each reanalysis (by color, given in the legend) compared to the reconstruction during 1957–2016.

produce much stronger trends during 1960–2005 than the reconstruction, as suggested in Fig. 4, and only CERA-20C indicates a period of positive trends in DJF prior to 1992, as indicated in the reconstruction. In MAM, CERA-20C and the reconstruction similarly show a period of positive trends before 1997, after which 20CR and ERA-20C have much more negative (and significant) trends than indicated in the reconstruction. While all products generally agree in polar cap-averaged insignificant trends in JJA, the positive trends in SON that emerge with end dates after 2000 in the reconstruction are only broadly captured in CERA-20C and notably absent in ERA-20C and 20CR. In these two reanalyses, positive trends emerge only after a start date of 1970, but they are notably weaker than in the reconstruction. Overall, and consistent with Fig. 4, all reanalyses products tend to produce stronger negative trends than in the

reconstruction and underestimate or miss periods of positive pressure trends. Further, as suggested by Fig. 3, the differences between the products are largest before 1970, and overall CERA-20C agrees best with the reconstruction.

4. Conclusions

This paper has evaluated a new monthly pressure dataset poleward of 60°S compared to ERA-Interim (after 1979) and other selected reanalysis products after 1957. Overall, the reconstruction is a strong improvement from the E40 and NNR reanalyses, with modest, but notable, improvements compared to the century-long reanalyses (CERA-20C, ERA-20C, and 20CR). In particular, all the reanalyses produce much stronger negative trends than the reconstruction and often underestimate or miss periods and regions of positive

60-90S Seasonal Pressure Trends

FIG. 4. (left)–(right) Spatial seasonal trends during 1957–2010 for (a) 20CR, (b) CERA-20C, (c) ERA-20C, and (d) reconstruction. Stippling indicates trends that are significantly different from zero at $p < 0.05$. Also plotted in (d) are the observed trends (filled circles). Thick circles in (d) indicate observed trends statistically different from zero at $p < 0.05$. Because of the high density of stations and the later start dates, trends for Marambio and O'Higgins–Marsh are not shown in (d).

Seasonal Pressure Trends (60–90S)

FIG. 5. (left)–(right) Seasonal pressure trends averaged 60°–90°S for different starting (indicated by y-axis values) and ending (indicated by x-axis values) years. Trends are shown only if data are at least 30 years long. Trends significantly different from zero at $p < 0.10$ (diagonal hatching) and $p < 0.05$ (stippling) are marked. Trends calculated using the longest period of data are found at the bottom right of each panel, and the diagonal area where shading starts corresponds to trends calculated using exactly 30 yr of data.

pressure trends in observations, especially before 1970. While the reconstruction improves upon these products over the Antarctic continent given that it perfectly matches the 19 stations used in the interpolation, its skill

in the Amundsen Sea region is lower as a result of high interannual variability and weak correlation of this variability to nearby station observations. We therefore urge caution in using the reconstruction, or any gridded

product (such as reanalyses) for that matter, in interpreting historical changes in the ASL prior to 1979, despite its likely significance for the regional climate (Hosking et al. 2013).

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