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Assessment of surface pressure between Zhongshan and Dome A in East Antarctica from different meteorological reanalyses

Aihong Xie§*
Ian Allison†
Cunde Xiao‡§*
*Shimeng Wang**
Jiawen Ren and*
*Dahe Qin**

*State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, No. 320, Donggang Western Road, Lanzhou, Gansu 730000, China
†Antarctic Climate and Ecosystems, Cooperative Research Centre, Private Bag 80, Hobart, Tasmania 7001, Australia
‡Chinese Academy of Meteorological Sciences, No. 46, Zhongguancun South Street, Haidian District, Beijing 100081, China
§Corresponding authors:
Xie (xieaih@lzb.ac.cn) and
Xiao (cdxiao@lzb.ac.cn)

Abstract

The accuracy of daily mean surface pressure from five meteorological reanalyses is assessed against in situ observations from automatic weather stations in East Antarctica for 2005 to 2008. The in situ observations are from Zhongshan, LGB69, EAGLE, and Dome A. The five reanalyses all explain more than 87% of the average variance and have annual root mean square errors between 15 hPa and 45 hPa. The ERA Interim reanalysis performs best against both criteria. The NCEP-1, NCEP-2, and 20CRv2 reanalyses have negative biases of 29.7 hPa, 25.9 hPa, and 11.1 hPa, respectively, while ERA Interim and JCDAS have positive biases of 4.9 hPa and 14.9 hPa. The reanalyses do not show obvious seasonal differences. The errors generally tend to decrease from the coast to the interior of the East Antarctic ice sheet, although there are regional differences between the performance of the different reanalyses. ERA Interim is superior to other reanalyses, probably because of its 4D assimilation scheme, which is strongly guided by satellite observations. The three NCEP reanalyses perform worst; their assimilation scheme is more constrained by limited observations and 20CRv2 has less input data, assimilating only surface pressure observations. Despite deficiencies and limitations, the reanalyses are still powerful tools for climate studies in the Antarctic region. However, more in situ observations are required, especially from the vast interior of Antarctica.

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Introduction

The Antarctic continent perhaps represents the largest spatial meteorological data void on the globe. For many areas of Antarctica, especially East Antarctica, it is difficult to place current weather and climate trends in a long-term climatological perspective as the meteorological records are spatially poor and of short duration compared with other regions (Bromwich et al., 2007). The lack of spatial density in Antarctic meteorological data makes it a challenge to separate local changes from those of regional or continental scale, especially in the Antarctic interior where data density is lowest (Li et al., 2012). Apart from a small number of mostly coastal stations with human observers, automatic weather stations (AWSs) are the dominant source of direct measurements for near-surface climate parameters on the Antarctic Ice Sheet (e.g., Allison et al.,1993; Allison, 1998; Reusch and Alley, 2004; Lazzara et al., 2012; van den Broeke and van Lipzig, 2004). To improve discontinuous and spatially incomplete meteorological records in the region, the Chinese National Antarctic Research Expedition (CHINARE) undertook eight traverses between 2005 and 2014 from the coast of East Antarctic at Zhongshan Station to Dome Argus (Dome A) at the summit of the ice sheet. Three AWSs were deployed along this route at LGB69, EAGLE, and Dome A, and these are operated in collaboration with the Australian Antarctic Division (AAD). Dome A, which earlier aerial surveys show has a relatively thin ice cover (Ren et al., 2009), received little attention prior to 2005 (Jones, 2007) due to its inaccessibility (because of high elevation, extremely low temperature, and distance from the coast). But subsequent to the initial Chinese traverse to Dome A in 2005, it has become a new focus area for polar study, and a new inland summer station, Kunlun, has been established there (Jones, 2007; Anonymous, 2005, 2006; Ren et al., 2009; Sun et al., 2009; Stone, 2007).

However, considering Antarctica covers an area of 14×10^6 km^2, the in situ data are quite limited, especially in the interior of the inland ice sheet. It is thus necessary to expand the limited observational data to a larger scale in Antarctica using other techniques. This research contributes to that by comparing the accuracy of surface pressure determined by different meteorological reanalyses compared to observations for the East Antarctic region between Zhongshan and Dome A.

The reanalyses investigated here are the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis (hereafter referred to as NCEP-1), the updated reanalysis of the NCEP/Department of Energy Atmospheric Model Intercomparison Project (NCEP/DOE AMIP-II) (NCEP-2), the second Twentieth Century Reanalysis (20CRv2) released by the National Oceanic and Atmospheric Administration's (NOAA's) Earth System Research Laboratory (ESRL) Physical Sciences Division and the University of Colorado CIRES Climate Diagnostics Center, the updated European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis from 1989 onward (ERA Interim), and the real-time operation of the Japan Meteorological Agency's (JMA's) Climate Data Assimilation System (JCDAS). In most cases, the products are freely available and have widespread application in many branches of meteorological and climatological research (Bromwich and Fogt, 2004; Bromwich et al., 2007; Jones and Lister, 2007; Yu et al., 2012).

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Previous research on the reliability of global reanalyses in the polar regions has paid more attention to temperature, wind, cloud, radiation, and so on (Bromwich and Fogt, 2004; Bromwich et al., 2007; Boccara et al., 2008; Kennedy et al., 2011; Bracegirdle and Marshall, 2012). These studies indicate that, overall, accuracy is much higher in the Arctic than the Antarctic, and that ERA-40 more closely fits the observations than NCEP-1.

However, there has been less research done on atmospheric pressure in East Antarctica. Based on the surface and radiosonde data from staffed Antarctic observation stations, Bracegirdle and Marshall (2012) compared the observed mean sea level pressure (MSLP) with the output from five reanalyses and demonstrated that ERA Interim showed a significantly smaller standard deviation, and the most stable decadal mean bias at long-term stations (those that have good temporal data coverage over the three decades from 1979). Yu et al. (2010) validated the ERA-40 and NCEP-1 reanalysis data in Antarctica, showing that atmospheric pressure at different height levels in the ERA-40 data are in better agreement with observed pressure than that in the NCEP-1 at the interannual timescale, and that both ERA-40 and NCEP-1 capture the observed intraseasonal variability in pressure and temperature during the austral winter. Jones and Lister (2007) compared four different monthly sea level pressure data sets for the southern hemisphere (south of 15°S) for the 1961–2000 period and concluded that, away from observing station locations, it is impossible to say which provides the best decadal average monthly sea level pressure values, because of assumptions made in the data set derivation.

The present study compares the accuracy and reliability of the global reanalysis surface pressure from NCEP-1, NCEP-2, 20CRv2, ERA Interim, and JCDAS against daily observations made by AWS between Zhongshan Station and Dome A (Kunlun Station), East Antarctica. In the second section, we present the pressure from observations and reanalyses, and describe the methodology of error analysis. The third section provides an assessment of the reanalyses and discusses the reasons for regional differences between them. Major conclusions are summarized in the final section.

Data and Methodology

OBSERVATIONAL METEOROLOGICAL DATA

CHINARE has deployed a series of AWSs in East Antarctica, and we use three of these (LGB69, EAGLE, Dome A) plus observations from Zhongshan Station for comparison with the reanalysis data sets. Zhongshan Station is on the East Antarctic coast, LGB69 is on the near-coastal escarpment of the ice sheet, EAGLE is in the interior region, and Dome A is the summit of the East Antarctic Ice Sheet. These stations are in a line approximately along 77°E longitude (Fig. 1). The pressure sensors used are the VAISALA CS106 at Zhongshan Station, and the Paroscientific Digiquartz 6015A in the three AWSs (Xiao et al., 2008; Xie et al., 2010; Ma et al., 2010). Table 1 provides details of the AWSs used in this study.

Data from Zhongshan Station and from some of the AWSs are made available through the Global Telecommunications System (GTS). The GTS data include three-hourly temperature, wind, and station level pressure for Dome A (WMO89577) and EAGLE (WMO89578). Data from LGB69 are not sent to the GTS. The GTS data are presumably assimilated into the reanalyses and thus the reanalysis and observed data populations are not completely independent.

REANALYSIS DATA SETS

The NCEP-1 reanalysis data (1948 to present) was created from a complex system of programs, libraries, scripts, and data sets (Kalnay et al., 1996; Kistler et al., 2001). The NCEP-2 reanalysis (1979 to present) is an improved reanalysis system that corrects human errors and updates parameterizations of physical processes (Kanamitsu et al., 2002). 20CRv2 (1871 to present) utilizes Ensemble Kalman Filter data assimilation to generate first-guess fields, and it prescribes monthly sea-ice concentration and sea-surface temperature fields (Compo et al., 2011; Parker, 2011). The ERA Interim reanalysis (1989 to present) was introduced to incorporate improvements to ERA-40, such as a refined data assimilation scheme and a refined numerical weather prediction model, a T255 spherical-harmonic representation for the basic dynamical fields, and assimilation of Global Positioning System radio occultation measurements of atmospheric temperatures (Dee and Uppala, 2009; Dee et al., 2011; Poli et al., 2010; Uppala et al., 2005). The JCDAS reanalysis continues the Japanese 25-year Reanalysis (JRA-25) for the period 1979 to 2004, with the data assimilation cycle extended from January 2005 to the present day (Onogi et al., 2007).

The reanalyses NCEP-1, NCEP-2, and 20CRv2 are provided by NOAA/NCEP (http://www.esrl.noaa.gov/psd/data/gridded), and the daily mean pressure for these are available on the T62 Gaussian grid (192 × 94) at 1.875° × 1.875° spatial resolution for NCEP-1 and NCEP-2 (Kalnay et al., 1996; Kistler et al., 2001), and at 2° × 2° spatial resolution for 20CRv2 (Compo et al., 2011). The pressure from ERA Interim reanalysis is on a T255 reduced Gaussian grid with a spatial resolution of 1.5° × 1.5° available on the ECMWF Data Server (http://data-portal.ecmwf.int/data/d/interim_daily/), including several products unavailable in the ERA-40 (Poli et al., 2010; Dee and Uppala, 2009; Berrisford et al., 2009). The JCDAS reanalysis provides pressure on a T106 Gaussian grid (320 × 160) at approximately 1.125° × 1.125° spatial resolution and is available from the website http://jra.kishou.go.jp/JRA-25/index_en.html. All the pressure data used in this study are surface pressure data (not mean sea level pressure) and arithmetically averaged into monthly, seasonal, and annual values. The daily values for ERA Interim are from the original 6-hourly outputs, while the daily values are downloaded directly from the other four reanalysis websites.

METHODOLOGY

Corrections for the difference in elevation between the in situ measurement point and the grid cell reanalysis average might make the comparison at different horizontal resolutions more compatible. However, in this study the observational data are directly compared with those from the reanalysis grid cell covering each observation site without interpolation for the following reasons.

- Compared with other areas covered by glaciers or ice caps, such as middle-latitude mountains, Antarctica has very low topographic relief, especially in the Dome A area, which has a surface slope of less than 0.009% (Zhang et al., 2007).
- Different interpolation methods may introduce new errors because of the assumptions in the correction (Wang and Zeng, 2012).
- Some new errors may also be introduced due to height differences between the different reanalysis grids.
- The four in situ stations lie in different grid cells for each reanalysis (Fig. 2).

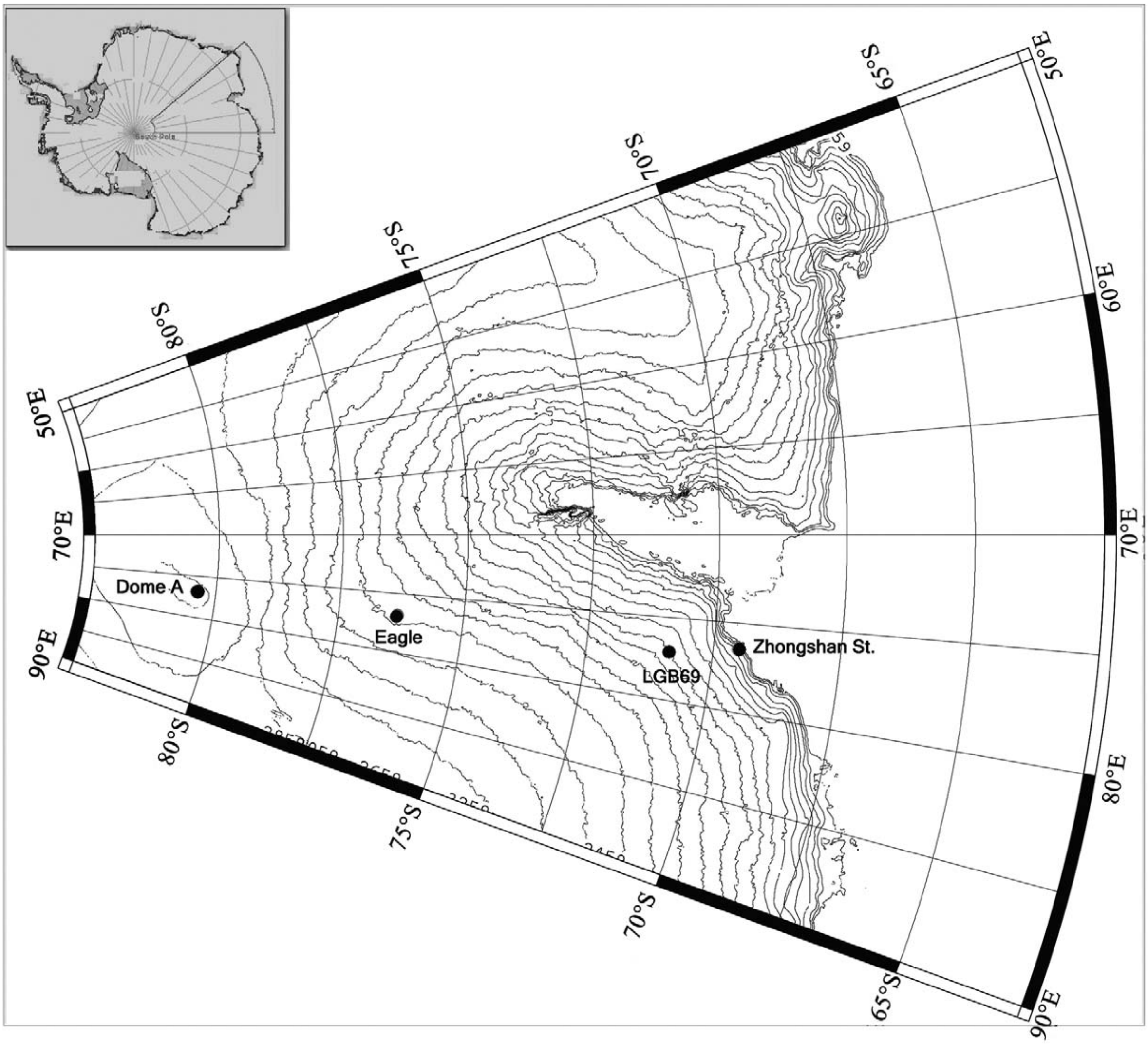

FIGURE 1. Location of AWSs along the traverse route from Zhongshan Station to Dome A.

TABLE 1

Site description and pressure sensor specification for the four automatic weather stations (AWS).

	Zhongshan	LGB69	EAGLE	Dome A
Period	1 Jan 2005–31 Dec 2008	1 Jan 2005–12 Apr 2007 25 Oct 2007–20 Aug 2008	27 Jan 2005–10 Nov 2007 1 Jan 2008–31 Dec 2008	18 Jan 2005–10 Nov 2007 1 Jan 2008–31 Dec 2008
Long./Lat.	69.37°S, 76.37°E	70.83°S, 77.07°E	76.57°S, 77.03°′E	80.37°S, 77.35°E
Elev. a.s.l.	15 m	1854 m	2852 m	4093 m
Distance from coast	<20 km	160 km	806 km	1228 km
Range	500-1400 hPa	691 to 791 hPa	635 to 735 hPa	530 to 610 hPa
Accuracy	0.3 hPa	0.2 hPa	0.2 hPa	0.2 hPa
Resolution	0.1 hPa	0.1 hPa	0.1 hPa	0.1 hPa
Type	VAISALA CS106	Paroscientific Digiquartz 6015A	Paroscientific Digiquartz 6015A	Paroscientific Digiquartz 6015A

Note: For the AWS at Dome A, EAGLE, and LGB69, accuracy does not include wind effects.

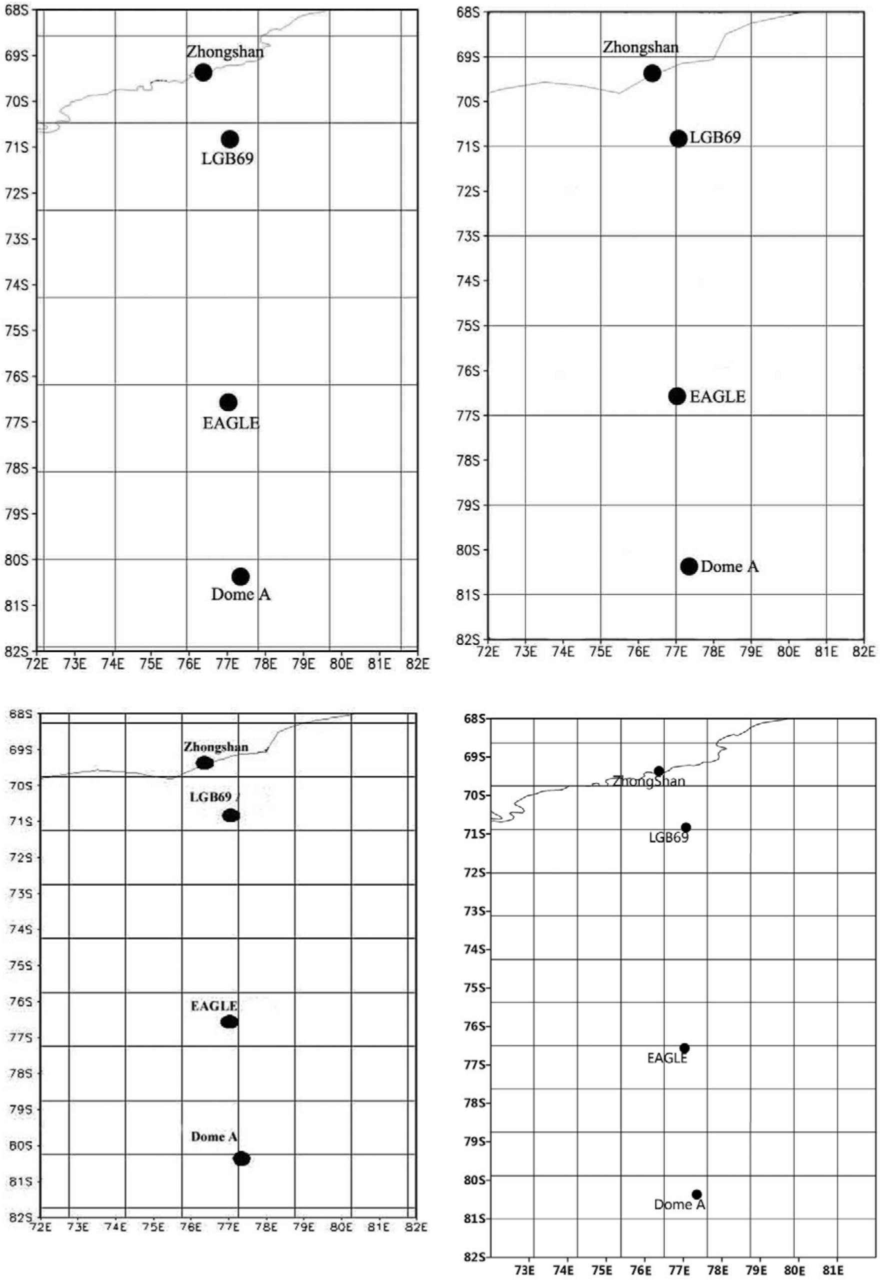

FIGURE 2. Locations of the AWSs within the reanalysis grids for NCEP-1 and NCEP-2. (a) T62 Gaussian grid, 1.875° × 1.875° spatial resolution, 20CRv2. (b) Similar to T62 Gaussian grid, 2° × 2°), ERA Interim. (c) T255 Gaussian grid, 1.5° × 1.5°. (d) Japan Climate Data Assimilation System (JCDAS) T106 Gaussian grid, 1.125° × 1.125°).

- As discussed later, interpolation is not an important factor that controls the pressure comparison.

Hence we consider neither elevation corrections nor interpolation of reanalyses, and the observational data are directly compared with those from the reanalysis grid cell covering each observation site. Figure 2 shows the location of the four in situ sites relative to the different reanalysis grids.

In each case, we calculate the root-mean-square error (RMSE), correlation coefficient (R), square of the correlation coefficient (R^2), and bias for each AWS site and reanalysis, and then assess the five reanalyses from a daily and annual perspective. Taylor diagrams are used to provide a concise and quick statistical summary of how well each reanalysis matches observation in terms of their correlation, the errors in the pattern of variations, and the ratio of their variances on a two-dimensional plot (Taylor, 2001). The shorter the distance to the observation point (OBS) on this diagram, the better agreement between the reanalysis and field observation. For more details, see http://www.ncl.ucar.edu/.

Results and Discussions

We calculate the monthly, seasonal, and annual mean values of pressure observations (Table 2) for the period 2005 to 2008. The annual mean pressure is 984.3 hPa, 774.6 hPa, 682.5 hPa, and 573.3 hPa at Zhongshan, LGB69, EAGLE, and Dome A, respectively. These show the expected decrease with altitude. The monthly and seasonal average pressure also decreases with altitude. The seasons are defined as the austral spring (SON), summer (DJF), autumn (MAM), and winter (JJA).

TABLE 2

Annual, seasonal, and monthly observational surface pressure (hPa) for Zhongshan, LGB69, EAGLE, and Dome A.

	Annual	Spring (SON)	Summer (DJF)	Autumn (MAM)	Winter (JJA)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Zhongshan	984.3	980.9	984.8	985.5	986.0	985.9	982.7	984.8	985.6	986.0	987.8	986.0	984.3	982.3	979.3	981.3	985.8
LGB69	774.6	771.6	778.7	774.1	771.6	780.5	776.3	775.7	774.2	772.4	773.5	769.9	771.4	769.8	768.9	776.2	779.3
EAGLE	682.5	678.9	688.7	682.9	681.0	689.7	684.1	683.4	683.1	682.1	684.0	680.8	678.3	676.7	675.9	684.0	692.4
Dome A	573.3	569.9	580.6	573.3	570.7	582.2	575.2	574.2	572.9	572.8	574.0	570.3	567.8	567.5	566.7	575.5	584.6

ASSESSMENT OF THE DAILY PERFORMANCE OF REANALYSES PRESSURE

Figure 3 shows the daily pressure biases between the reanalyses NCEP-1, NCEP-2, 20CRv2, ERA Interim, and JCDAS and the observations at the four stations.

NCEP-1 Reanalysis

NCEP-1 consistently overestimates pressure at Dome A with a positive bias of 16.5 hPa, and it considerably underestimates pressure at Zhongshan Station and EAGLE with negative biases of 99.6 hPa and 36.8 hPa, respectively (Fig. 3, part a, and Table 3). The mean bias across all stations is up to 29.7 hPa. NCEP-1 performs best at LGB69, where it has a bias of only 1.0 hPa and an RMSE of 1.9 hPa (Table 4) and explains 96.1% of the variance (Table 5). NCEP-1 performs worst at Zhongshan Station with only 76.6% of the variance explained. All four in situ stations are located north of the NCEP-1 grid center points (Fig. 2) and hence at lower elevation. However, the NCEP-1 reanalysis pressure does not consistently underestimate the observation values at different stations (Table 3), demonstrating that difference of latitude and elevation between the observation sites and reanalysis grid center points is not the only factor influencing the bias.

The NCEP-1 analysis system efficiently assimilates upper-air observations, but it is only marginally influenced by surface observations because the model orography differs from reality, and because surface observations do not significantly affect the upper-air potential vorticity (Kalnay et al., 1996; Kistler et al., 2001). Furthermore, the surface pressure is influenced by temperature, which is strongly influenced by the model parameterization of energy fluxes at the surface (Kalnay et al., 1996; Kistler et al., 2001), especially for Antarctica where there is a low density of meteorological observation stations. On the other hand, the large bias may come from human assimilation errors that were discovered too late to repeat the affected period of reanalysis (Kanamitsu et al., 2002). PAOBs (sea level pressure values derived from manual analysis) significantly affected global analyses poleward of 40°S (Kalnay et al., 1996; Kistler et al., 2001). PAOBs are used in the current NCEP operational analyses, with the observation errors for PAOBs assumed to be 2 hPa compared to 1 hPa for stations, but they are not used at all by ECMWF (Kistler et al., 2001).

NCEP-2 Reanalysis

Similar to NCEP-1, NCEP-2 consistently underestimates the surface pressure at Zhongshan Station and EAGLE with biases of –108.8 hPa and –32.5 hPa, respectively, and overestimates pressure at Dome A with a bias of 25.6 hPa (Table 3 and Fig. 3, part b). However, unlike NCEP-1, NCEP-2 also overestimates at LGB69. NCEP-2 performs worst at Zhongshan Station, where it can only explain 74.7% of the variance (Table 5). NCEP-2 performs best at LGB69, with the smallest bias of 12.3 hPa, and explains 95.8% of variance. NCEP-2 explains 92.3% and 90.0% of the variance at EAGLE and Dome A, respectively. NCEP-2 is simply a rerun of NCEP-1 with the same input data and vertical and horizontal resolution, but it focuses on the period since 1979 and improves the physical processes and known errors in NCEP-1 (Kanamitsu et al., 2002; Roads, 2003). For example, existing issues with wintertime precipitation, surface pressure, and surface fluxes in high latitudes are improved by correcting a ‘‘spectral snow’’ problem (Kanamitsu et al., 2002). Despite these improvements, NCEP-2 should only be regarded as an updated and improved version of NCEP-1, but not a next generation reanalysis. As a result, the regional difference in NCEP-2 performance is rather similar to that of NCEP-1.

20CRv2 Reanalysis

Similar to NCEP-1 and NCEP-2, the 20CRv2 reanalysis consistently underestimates surface pressure at Zhongshan station (Fig. 3, part c). It has a large bias of –105.4 hPa, and explains 86.0% of the variance there. Also, 20CRv2 shows substantial overestimation at LGB69, where it explains 92.3% of the variance and has a mean bias of 61.1 hPa, which is much larger than that for NCEP-1 (1.0 hPa) and NCEP-2 (12.3 hPa). However, unlike NCEP-1 and NCEP-2, 20CRv2 performs rather well at Dome A and EAGLE. It has the smallest biases of –4.4 hPa and +4.5 hPa, and explains 93.8% and 79.0% of the variance at EAGLE and Dome A, respectively. This is mainly because 20CRv2 assimilates only surface pressure reports and uses observed monthly sea-surface temperature and sea-ice distributions as boundary conditions, while the four other reanalyses make use of many types of observational data (Compo et al., 2011). The similarity of regional differences between 20CRv2 and NCEP-1 and NCEP-2 performances is probably mainly due to the coupled NCEP atmosphere-land model utilized in 20CRv2. Although 20CRv2 is the newest reanalysis and has produced a long series of reanalysis data spanning 1871 to the present, it performs no better than NCEP-1 or NCEP-2, and much worse than ERA Interim and JCDAS. Certainly, a large source of error in 20CRv2 is the low density of mean sea level pressure observations over Antarctica.

ERA Interim Reanalysis

ERA Interim has superior performance (Fig. 3, part d) and captures more than 93% of variance at each station (Table 5). It shows the largest bias of +29.0 hPa at LGB69 and has smaller

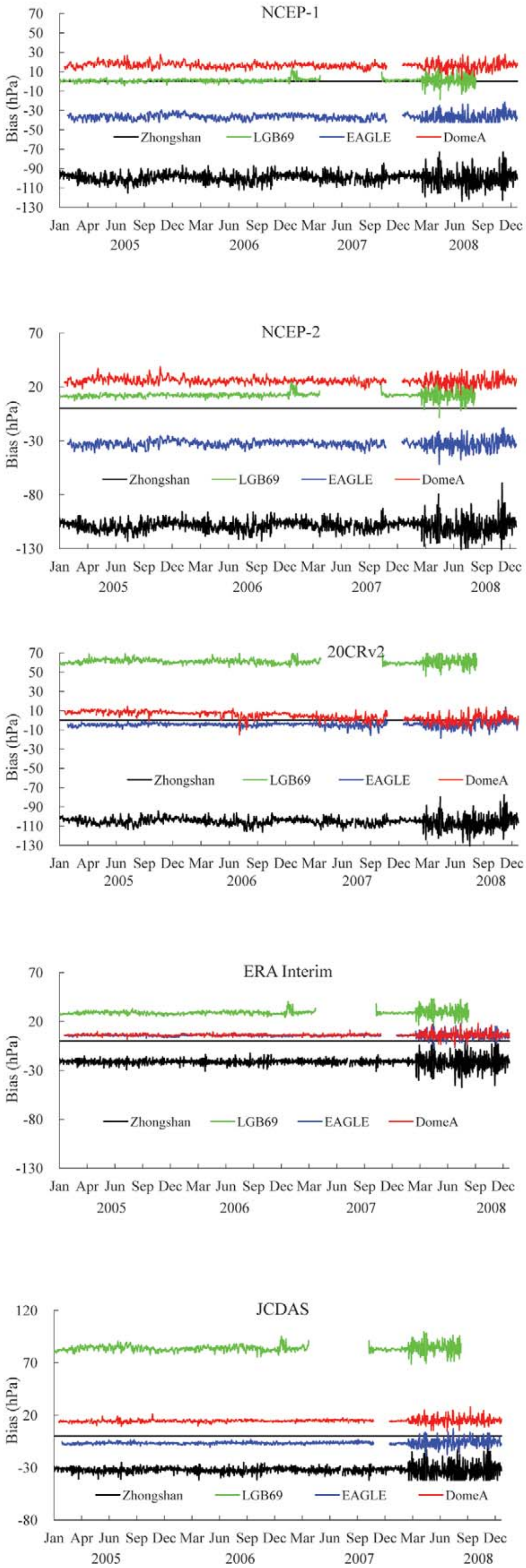

FIGURE 3. Daily pressure bias (hPa) between the reanalysis and the observation for four years (2005–2008) at Zhongshan (black), LGB69 (emerald green), EAGLE (blue), and Dome A (red) for (a) NCEP-1, (b) NCEP-2, (c) 20CRv2, (d) ERA Interim, and (e) JCDAS.

biases of –21.2 hPa, +5.7 hPa, and +6.2 hPa at Zhongshan, EAGLE, and Dome A, respectively. ERA Interim performs much better over East Antarctica than the NCEP reanalyses for the following reasons (Dee et al., 2011; Uppala et al., 2005).

- The core component of the ERA-Interim data assimilation system is the 12-hourly 4D-Var of the upper-air atmospheric state. The version of 4D-Var used for ERA Interim also updates a set of parameter estimates that define bias corrections needed for the majority of satellite-based radiance observations. Newly introduced in ERA-Interim is the use of wavelet-like weighting functions.
- Many scientific and technical improvements in the surface analysis have been implemented in recent years. These components of the data assimilation system use relatively simple data interpolation schemes.
- ERA-Interim uses sets of observations and boundary forcing fields acquired for ERA-40 through 2001, and from ECMWF operations. The number of observations assimilated in ERA-Interim has increased from approximately 10^6 per day on average in 1989, to nearly 10^7 per day in 2010. The overwhelming majority of data, and most of the increase over time, originate from satellites.

JCDAS Reanalysis

JCDAS has similar regional differences to ERA Interim and performs best at EAGLE with a mean bias of –6.5 hPa, and it captures 98.8% of the variance. It performs worst at LGB69 with a mean bias of 83.7 hPa. The performance of JCDAS is quite good at Zhongshan and Dome A with biases of –32.4 hPa and 14.7 hPa, respectively. JCDAS explains more than 92% of variance at these stations (Table 5). The major data source in JCDAS is observational data supplied by ECMWF as used in the ERA-40 reanalysis, which contains conventional data, wind data retrieved from geostationary satellites, and level 1c TOVS and ATOVS radiance temperature data. The ERA-40 observational data set contains not only the original merged data set from ECMWF and NCEP-1 archives, but also conventional data supplied additionally from NCAR and NCEP. It has the largest amount of historical observational data available at present. The original NCEP-1 archives were also supplied but not used in JCDAS, because most of the data in these archives were included in the ECMWF observational data (Onogi et al., 2007). These data sources result in principally the same correspondence with the observation and the same regional difference in JCDAS and ERA Interim performances.

Comparison between Different Reanalyses

The Taylor diagram (Fig. 4) summarizes the overall performance of the five reanalyses compared with the corresponding observations (Taylor, 2001). On this diagram, the correlation coefficient and the RMSE between reanalysis and observation, along with the ratio of the standard deviations of the two patterns, are all indicated by a single point. The radial co-ordinate gives the magnitude of total standard deviation normalized by the observed value, and the angular co-ordinate gives the correlation with observations. It follows that the distance between the observed point and any reanalysis point is proportional to the RMSE. The points shown in Figure 4 are concentrated along the line whose standard deviation equals one

TABLE 3

Bias (hPa) between the reanalyses and observations at the four stations.

	Zhongshan	LGB69	EAGLE	Dome A	Average
NCEP-1	–99.6	1.0	–36.8	16.5	–29.7
NCEP-2	–108.8	12.3	–32.5	25.6	–25.9
20CRv2	–105.4	61.1	–4.4	4.5	–11.1
ERA Interim	–21.2	29.0	5.7	6.2	4.9
JCDAS	–32.4	83.7	–6.5	14.7	14.9
Average	–73.5	37.4	–14.9	13.5	–9.4

(OBS line) and lie relatively near the OBS point, corroborating that the five reanalyses have good performance compared with in situ observations.

In general, ERA Interim (4 in Fig. 4) and JCDAS (5 in Fig. 4) demonstrate the best correspondence with the observations, while the three NCEP reanalyses (1, 2, and 3) have the worst performance. That is similar to previous comparisons of ERA-40, NCEP-1, NCEP-2, and JRA-25 (Bromwich et al., 2007; Boccara et al., 2008). On average, 88.8%, 88.2%, 87.7%, 96.3%, and 95.0% of the variance is explained by NCEP-1, NCEP-2, 20CRv2, ERA Interim, and JCDAS reanalyses, respectively, and the corresponding RMSE values are 38.7 hPa, 45.0 hPa, 44.5 hPa, 15.7 hPa, and 34.4 hPa (Table 4). The better performance of ERA Interim is mainly due to its 4D-Var data assimilation system. The data assimilation of ERA Interim also benefits from quality control that draws on experience from ERA-40 and JRA-25, variational bias correction of satellite radiance data, and more extensive use of radiances with an improved fast radiative transfer model (Dee et al., 2011; Uppala et al., 2005). Another reason for better performance may be the different spatial resolutions of the five reanalyses. The large inconsistency between NCEP pressure values and observations may not be due only to insufficient observations, but also to the quality of the incorporated observations and their seasonal variability, since few observations are available during the polar night (Hines et al., 2000).

ASSESSMENT OF THE ANNUAL PERFORMANCE OF REANALYSES

The multiyear variation of daily mean pressure from reanalyses and from observations for the 2005–2008 period is shown in Figure 5. This shows that the reanalyses have similar patterns of variation to the observations. On average, all the reanalyses can explain more than 70% of variance for each station (Table 5), however, the mean RMSE has large regional differences between the reanalyses (Table 4).

Zhongshan Station Observations

Compared with the observed pressure at Zhongshan (Fig. 5, part a), all reanalyses demonstrate a negative bias, although the annual mean bias is different between reanalyses, with the largest bias of –108.8 hPa in NCEP-2 and the smallest bias of –21.2 hPa in ERA Interim (Table 3). All the pressure values from the three NCEP reanalyses are much lower than the observations with a bias of more than –99 hPa (Table 4). NCEP-1, NCEP-2, and 20CRv2 respectively explain 76.6%, 74.7%, and 86.0% of the variance at Zhongshan (Table 5). Although ERA Interim performs best and can explain 93.9% of variance, it also has a bias of –21.2 hPa. The better performance is mainly attributable to the data assimilation (Dee et al., 2011). JCDAS is the second best performing reanalysis at Zhongshan, with a bias of –32.4 hPa, and explaining 93.3% of variance. The assimilation scheme in NCEP appears more constrained by the observations (Bromwich and Fogt, 2004), compared to the assimilation scheme in ERA-Interim, which is strongly guided by satellite observations. East Antarctic observations are very scarce, which may explain the poorer performance of the three NCEP reanalyses compared with ERA Interim. Another reason for the large negative bias may be because, in the three NCEP reanalysis grids, Zhongshan is located north of and lower in elevation than the center point (Fig. 2, parts a and b) in a region of relatively steep topography (Xie et al., 2014; Ding et al., 2010). However, in the ERA Interim and JCDAS grids, Zhongshan is located south of the center point, which is at sea level (Fig. 2, parts c and d), but these reanalyses also show underestimation. In this study, the reanalysis pressure is directly

TABLE 4

Root mean square error (RMSE) (hPa) between the reanalyses and observations at the four stations.

	Zhongshan	LGB69	EAGLE	Dome A	Average
NCEP-1	99.7	1.9	36.6	16.7	38.7
NCEP-2	108.9	12.5	32.7	25.8	45.0
20CRv2	105.5	61.1	5.0	6.4	44.5
ERA Interim	21.4	29.0	5.8	6.5	15.7
JCDAS	32.5	83.7	6.5	14.8	34.4
Average	73.6	37.6	17.3	14.0	35.6

TABLE 5

Pressure variance (%) explained by the reanalyses at the four stations.

	Zhongshan	LGB69	EAGLE	Dome A	Average
NCEP-1	76.6	96.1	92.7	89.8	88.8
NCEP-2	74.7	95.8	92.3	90.0	88.2
20CRv2	86.0	92.3	93.8	79.0	87.7
ERA Interim	93.9	96.2	99.4	95.7	96.3
JCDAS	93.3	92.6	98.8	95.1	95.0
Average	84.9	94.6	95.4	89.9	91.2

compared with the observations without interpolation, and while location in the reanalysis grids may affect the bias, it is not the only factor.

LGB69 AWS Observations

Compared with the observations at LGB69, all reanalyses show a positive bias (Fig. 5, part b), opposite to that at Zhongshan Station. The observed and the NCEP-1 values almost overlie each other: this high level of skill is unique to NCEP-1 and is indicated by the highest correlation coefficient of 0.98 ($n \geq 860$, $p < 0.0001$). The mean annual bias is largest in JCDAS (83.7 hPa) and least in NCEP-1 (1.0 hPa). However, all five reanalysis data sets can explain more than 92% of the variance. LGB69 is located south of and higher in elevation than the center point in the 20CRv2, ERA Interim, and JCDAS grids (Fig. 2, parts b, c, and d), which may partially explain the positive bias in these reanalyses. However, LGB69 is located north of and lower in elevation than the NCEP-1 grid center point (Fig. 2, part a). This again suggests that while noninterpolation may influence the reanalysis pressure comparison, the influence is not vital.

EAGLE AWS Observations

Figure 5, part c, shows that all the reanalysis data sets generally show greatest correlation with observations at EAGLE compared with the other AWS sites. Similarly to at LGB69, all five reanalysis data sets can explain more than 92% of the variance.

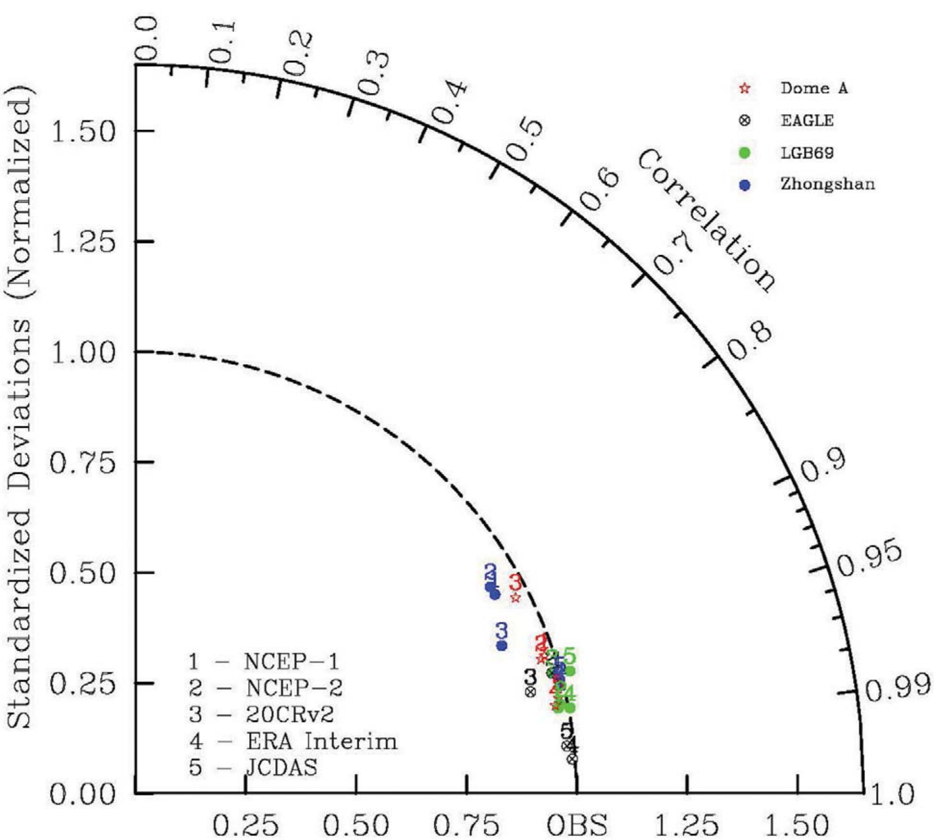

FIGURE 4. Taylor diagram for second-order statistics of annual pressure extracted from five reanalyses. The radial coordinate gives the magnitude of total standard deviation, normalized by the observed value, and the angular coordinate gives the correlation with observations. It follows that the distance between the observed point (OBS) and any reanalysis point is proportional to the root mean square error (RMSE). Numbers 1, 2, 3, 4, and 5 indicate reanalysis of NCEP-1, NCEP-2, 20CRv2, ERA Interim, and JCDAS compared with the corresponding observation at Zhongshan (closed blue circle), LGB69 (closed green circle), EAGLE (black circle with cross), and Dome A (red star).

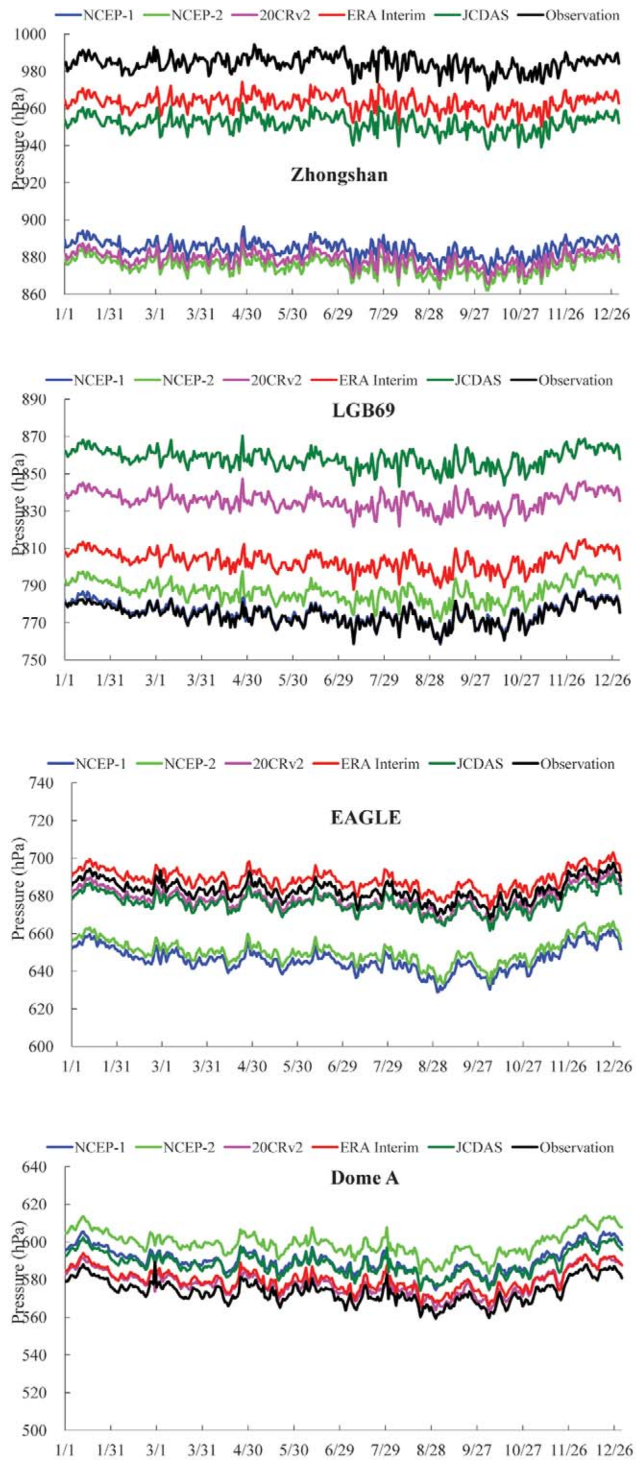

FIGURE 5. Annual cycle of daily mean pressure (hPa) compared with the in situ value at stations (a) Zhongshan, (b) LGB69, (c) EAGLE, and (d) Dome A during 2005–2008.

ERA Interim, JCDAS, and 20CRv2 explain the most variance at 99.4%, 98.8%, and 93.8%, respectively, with small biases of 5.7 hPa, –6.5 hPa, and –4.4 hPa, respectively. NCEP-1 and NCEP-2 are the worst performing, with large biases of –36.8 hPa and –32.5 hPa. 20CRv2 obviously performs better than NCEP-1 and NCEP-2, perhaps because of the different assimilation system in 20CRv2 with a different Gaussian grid resolution, as shown in Figure 2, parts a and b.

Dome A AWS Reanalysis Performance

Figure 5, part d, shows the performance of the reanalysis at Dome A. The ERA Interim pressure closely follows the observations throughout the year; this high level of skill (annual bias 6.2 hPa; 95.7% of variance explained) is unique to ERA Interim. ERA Interim is strongly guided by satellite observations and relies on a better model climatology that produces overall lower biases. 20CRv2 also has a low bias (4.5 hPa), but it explains no more than 79% of variance. JCDAS and NCEP-1 have positive biases of 14.7 hPa and 16.5 hPa and explain 95.1% and 89.8% of variance, respectively. NCEP-2 has the largest bias of 25.6 hPa and explains 90% of variance. All the reanalyses show a positive bias, which indicates once again that, since Dome A is located north of the NCEP-1, NCEP-2, ERA Interim, and JCDAS grid-center points (Fig. 2, parts a, c, and d), and south of the 20CRv2 center point (Fig. 2, part b), that the effect of noninterpolation is not crucial. On average, the reanalyses perform better at Dome A than at the other three stations. The low bias at Dome A perhaps results because the grid cells are smaller at higher latitude, and because the surface over the Dome A area is very flat and smooth, with a slope of less than 0.08% (Sun et al., 2009; Xiao et al., 2008; Zhang et al., 2007). This uniform surface around Dome A better benefits the model modifying than the complicated one in other regions.

Comparison between Different Regions

The reanalyses generally have the worst performance at Zhongshan, and second worst at LGB69. As a whole, both the bias and RMSE decrease from the edge to the interior (Tables 3 and 4), which perhaps results from the smaller grid cells at higher latitude.

In comparison with the in situ observations (Figs. 3 and 5), the average RMSE values are 73.6 hPa, 37.6 hPa, 17.3 hPa, and 14.0 hPa at Zhongshan, LGB69, EAGLE, and Dome A, respectively (Table 4). All the reanalysis data sets exhibit inevitable errors, although they use state-of-the-art global data assimilation systems, and the observation databases contain data collected from land surface, ship, rawinsonde, pibal, aircraft, and satellite (Kalnay et al., 1996; Kistler et al., 2001; Kanamitsu et al., 2002; Compo et al., 2011; Onogi et al., 2007). The errors may be influenced by a number of factors. All observational data refer to pressure measured at specific points, while the reanalyses present the average value over a grid cell: this scale mismatch is one reason for the differences between reanalyses and observations. There are also significant differences in the temporal data coverage. Daily mean pressure is obtained as an average of hourly values for observations, while it is an average of 6-hourly values for ERA Interim and daily values for NCEP-1, NCEP-2, 20CRv2, and JCDAS.

In Figure 4, all the correlation coefficients exceed 0.86 ($n \geq 860$, $p < 0.001$), indicating that all the reanalyses reproduce the annual pressure variability. However, the points on the Taylor diagram are scattered because the reanalyses provide different consistency with observations at different stations. This multistatistic representation shows that in general the reanalyses (and especially ERA Interim) perform best at EAGLE. They perform worst overall at Zhongshan, especially NCEP-1, NCEP-2, and 20CRv2. In contrast to the uniform surface of the interior, the coastal regions of Antarctica have varied topography, with more complicated and variable thermal properties. This may be a factor in the greater difference between observations and reanalysis data at Zhongshan than at some of the inland sites.

The error of the NCEP reanalyses tends to be large at Dome A, and regional differences might also be due to the data assimilated in the reanalyses. In situ meteorological observations are very sparse in the Antarctic interior, and the surface data available for assimilation decreases with southward latitude and altitude. However, compared with an assessment of reanalysis temperature in this region (Xie et al., 2014), the reanalyses perform better on pressure. Pressure features vary slowly on a large spatial scale, whereas temperature is much more affected by local factors.

ASSESSMENT OF THE SEASONAL PERFORMANCE OF REANALYSES

The annual range of pressure, from the observations, is 8.5 hPa, 11.6 hPa, 16.5 hPa, and 17.8 hPa, respectively, at Zhongshan Station, LGB69, EAGLE, and Dome A (Table 2). The annual range increases from the coast to the interior of the East Antarctica Ice Sheet, with increasing altitude and latitude. The observed minimum value of monthly averaged pressure occurs in October at all sites, while the observed maximum occurs in June at Zhongshan, in January at LGB69, and in December at EAGLE and Dome A. This is consistent with the result of Allison (1998), who found a pronounced semiannual oscillation in monthly mean pressure at AWS in the interior of the Lambert Glacier basin, with maxima in July and December.

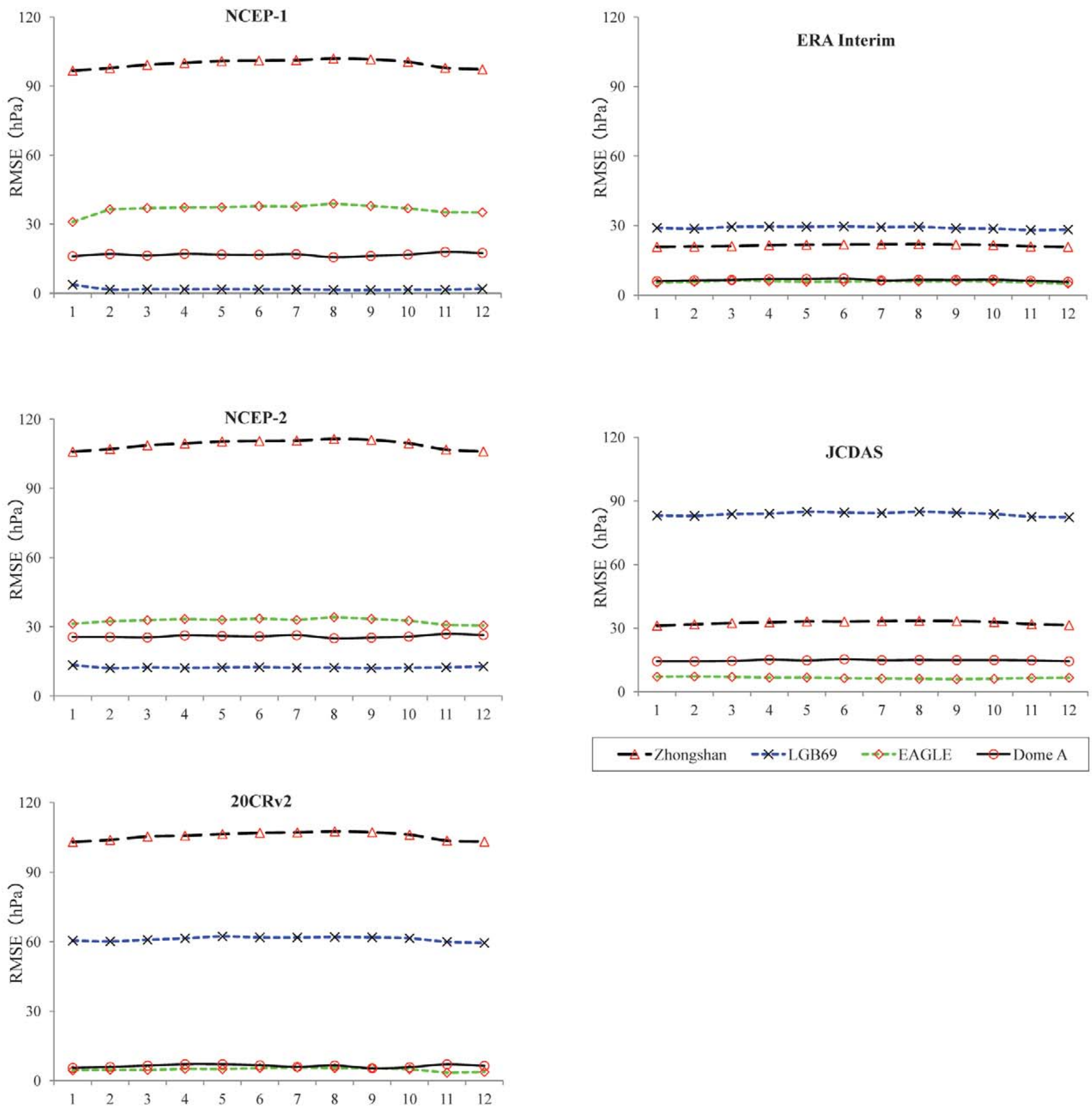

FIGURE 6. Monthly RMSE (hPa) for the reanalyses at the four in situ stations of Zhongshan (black dashed line with red triangle), LGB69 (blue dashed line with cross), EAGLE (green dashed line with red rhombus), and Dome A (black line with red circle).

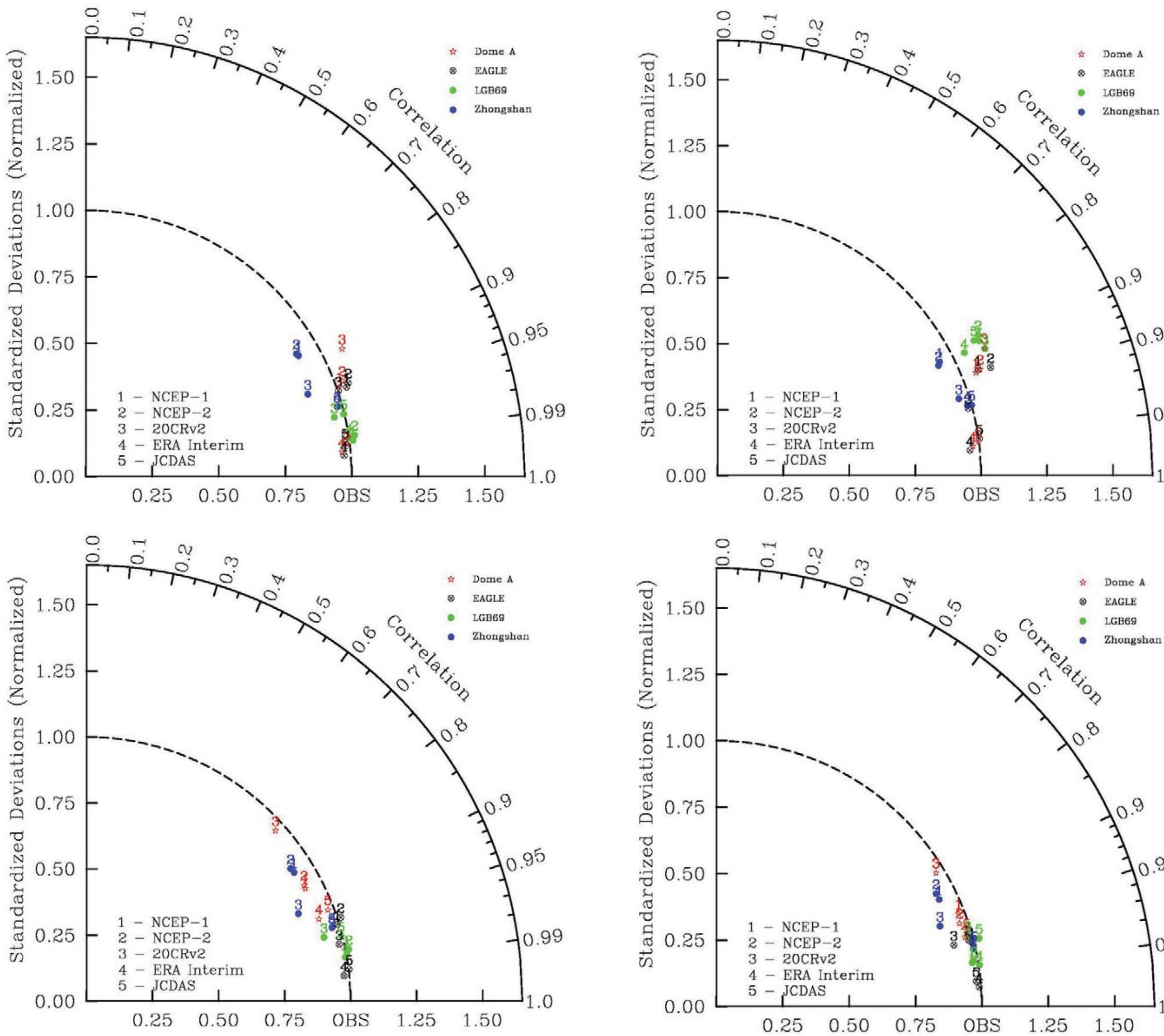

FIGURE 7. Taylor diagram (see Fig. 3 for details) for the Austral seasons of (a) spring (SON), (b) summer (DJF), (c) autumn (MAM), and (d) winter (JJA).

Neither daily mean pressure values (Fig. 5) nor monthly RMSE values (Fig. 6) show any obvious seasonality, which is different from the polar region results of Bromwich et al. (2007) and Bromwich and Fogt (2004). Taylor diagrams (Fig. 7) are also very similar for the four seasons, which is different from the situation with reanalysis temperature in this region (Xie et al., 2014).

Conclusions

From comparison of reanalysis products from NCEP-1, NCEP-2, 20CRv2, ERA Interim, and JCDAS with in situ observations of surface pressure during 2005 to 2008 at Zhongshan, LGB69, EAGLE, and Dome A, East Antarctica, we demonstrate the following:

- The reanalyses capture temporal pressure variations with high annual correlation with observations ($R \geq 0.86$, $n \geq 860$, $p < 0.001$). They respectively explain 88.8%, 88.2%, 87.7%, 96.3%, and 95.0% of variance for NCEP-1, NCEP-2, 20CRv2, ERA Interim, and JCDAS reanalyses.
- In general, ERA Interim pressure values best correspond to the observations in this region, followed by JCDAS, while the three NCEP reanalyses perform worst. Although it is an updated version of NCEP-1, NCEP-2 doesn't always exhibit better performance. The relatively poor performance of 20CRv2 may be because it assimilates only surface pressure reports and uses observed monthly sea-surface temperature and sea-ice distributions as boundary conditions.
- NCEP-1, NCEP-2, and 20CRv2 show negative average biases of 29.7 hPa, 25.9 hPa, and 11.1 hPa, respectively, while ERA Interim and JCDAS show positive average biases of 4.9 hPa and 14.9 hPa.
- The pressure values from the reanalyses show regional differences, with both RMSE and bias tending to decrease from the coast to the interior of the East Antarctica Ice Sheet.

- The reanalyses do not show an obvious seasonal difference in performance for surface pressure. This is different from the situation for 2 m air temperature.
- Performance of the reanalyses varies regionally, and there is no one reanalysis product that is always superior to others.

However, despite the limitations and deficiencies of pressure reanalysis in Antarctica, the reanalyses are still powerful tools for climate studies in the region. To acquire better knowledge of weather and climate, more in situ observations are required, especially for the vast inland regions of Antarctica.

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