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Key Points:
- Changes in wind direction due to the shift of the center of the Amundsen Sea Low resulted in low temperatures in winter
- ERA-Interim and ERA5 reanalyses showed good agreement with measured monthly data but with a large negative bias in wind speed
- Seasonal correlation coefficients of temperature between the study site and inland sites reached up to 0.72 in spring

Supporting Information:
- Supporting Information S1
- Table S1

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Characteristics of Surface Meteorology at Lindsey Islands, Amundsen Sea, West Antarctica

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Abstract Investigating warming in West Antarctica is important to understand and predict mass balance changes of the ice sheet. However, clear understanding of the extent and rate of warming across West Antarctica has been limited by the lack of ground-based meteorological measurements. An automatic weather station was set up at Lindsey Islands, the Amundsen Sea of West Antarctica, in 2008, and operated for about 7 years. The measured variables showed high interannual variability, particularly in winter seasons. The longitudinal shift of the center of the Amundsen Sea Low contributed to the large variability and resulted in much lower temperatures at the site, especially in winter seasons, through cold advection from the south. The measured data showed good agreement with ERA-Interim and ERA5 reanalysis data, though there was a large negative bias in wind speed. The ERA-Interim reanalysis data showed no significant trends in seasonal averaged temperature from 1980 to 2014, but significant trends were shown in pressure and wind speed in autumn ($p < 0.05$), even though the interpretation of the trend requires caution. The seasonal correlation coefficients of monthly averaged temperature (T) and pressure (P) between the study site and three neighboring automatic weather station sites in the coastal area were >0.8 for T and >0.92 for P and up to 0.76 for P and 0.72 for T at an inland site.

1. Introduction

Air temperature over West Antarctica has increased moderately over past decades (e.g., Bromwich et al., 2013; Ding et al., 2011; Schneider et al., 2011; Steig et al., 2009). Nicolas and Bromwich (2014) reconstructed temperature using the Byrd temperature record (Bromwich et al., 2013) and the National Centers for Environmental Prediction Climate Forecast System Reanalysis data (Saha et al., 2010), and they obtained significant annual warming over West Antarctica by 0.22 ± 0.12 °C per decade for 1958–2012 that is similar to those from Steig et al. (2009) and Monaghan et al. (2008). However, the identification of the dominant and direct cause for the West Antarctic warming appears to be rather complicated because of seasonal temperature variations. For example, Ding et al. (2011) showed that the increasing sea surface temperature in the central tropical Pacific might be responsible for the winter warming in West Antarctica by changing atmospheric circulation at high southern latitudes. According to Schneider et al. (2011), austral spring warming has been largest and most significant in West Antarctica since the late 1970s, due to a change in atmospheric circulation related to the Pacific-South American (PSA) mode PSA-1 associated with sea surface temperatures in the southwestern tropical and subtropical Pacific. Hosking et al. (2013) showed that the Amundsen Sea Low (ASL, modified from the Amundsen-Bellingshausen Seas Low in their paper) influenced the climate of West Antarctica mainly by its longitudinal location rather than its strength, especially during autumn and winter. Bromwich et al. (2013), in contrast to previous studies, showed statistically significant warming in central West Antarctica during austral summer, particularly in December–January over 1958 to 2010. In addition, Nicolas et al. (2017) reported on an episode of extensive and prolonged surface melting observed in the Ross Sea sector of the West Antarctic Ice Sheet in January 2016 via strong and sustained advection of warm maritime air to the area, likely due to the concurrent strong El Niño.

Quantifying the rate of temperature change and understanding the cause for the West Antarctic warming are critical in estimating changes in ice sheet mass balance, which is directly connected to global sea level (e.g., Rignot et al., 2008; The IMBIE Team, 2018). However, studies on surface meteorological characteristics have been limited by lack of measurements on West Antarctica, compared to numerous studies on coastal

East Antarctica (e.g., Argentini et al., 1995; König-Langlo et al., 1998; Lazzara et al., 2012; van den Broeke, 1998a, 1998b), the Antarctica Peninsula (e.g., King, 1994; Morris & Vaughan, 2003), and inland plateau (e.g., Argentini et al., 2014; Lazzara et al., 2012). Moreover, scarce automatic weather station (AWS) data have been used only for specific purposes, such as comparison with numerical model simulations (e.g., Bromwich et al., 1994; van Lipzig et al., 2004), but not for measurement-based data analysis. Some AWSs in West Antarctica have been operated for a long time, but they are located inland (e.g., Bromwich et al., 2013; Reusch & Alley, 2004), which may record different characteristics from those at coastal areas in terms of the temperature trend. Using archived numerical weather forecasts from the Antarctic Mesoscale Prediction System, Nicolas and Nicolas and Bromwich (2011) indicated that the area over West Antarctica was largely influenced by marine air mass intrusion by low-pressure systems due to lower elevation than East Antarctica. That is, the degree of the influence is dependent on the geographic characteristics such as elevation or the distance from the coast.

Recently, more meteorological data for the coastal area of West Antarctica have become available. In 2008, one AWS was set up in Pine Island Glacier (PIG, http://amrc.ssec.wisc.edu/) and three AWSs were installed at Evans Knoll, Thurston Island, and Bear Peninsula in 2011. However, only limited data from PIG were available after 2009. In addition, even though the PIG AWS was located in a coastal area, the near-surface wind regime was different from those in neighboring locations in the coastal area (Djouman & Holland, 2015). Therefore, more meteorological data are needed to better understand atmospheric processes, which play an important role in determining the trend of climate change in West Antarctica. An AWS was installed at Lindsey Islands, Pine Island Bay, in the Amundsen Sea in February in 2008 and has been operated for about 7 years. The significance of this AWS is its location at a coastal area of West Antarctica and its installation time since 2008, which was 3 years earlier than the aforementioned three AWSs. In addition, the AWS data at the study site were not assimilated into any reanalysis data, providing an opportunity to compare the data with reanalysis data. The objectives of this study are (1) to determine the meteorological characteristics in the coastal area of West Antarctica, (2) to investigate the mechanism influencing the characteristics, (3) to find the spatial relationship between the study site and sites near the coastal area, and far inland sites, and (4) to identify the trends over the last 35 years with the aid of reanalysis data.

2. Materials and Methods

2.1. Study Site

Lindsey Islands consist of several individual islands, of which an island of 1.4-km length and 1.0-km width was selected as the study site (73.602°S, 103.021°W). This island is at the southernmost end of the Lindsay Islands chain, about 500 m from the Canisteo peninsula of West Antarctica (Figures 1a and 1b). Figure 1a shows the geographical location of the study site together with three coastal and two inland AWS sites for comparison. On 13 February 2008, 14 Korean researchers on board *Akademik Fedorov*, a Russian icebreaker, visited the island to survey the area as a candidate site for the second Korean Antarctic station (the first being King Sejong Station on King George Island in the Antarctic Peninsula region). To investigate meteorological conditions at the site, an AWS was installed at the highest spot (~37 m m.s.l) of the island without obstacles in any direction (Figure 1c). The surface of the AWS site was covered with relatively large rocks, which was exposed to the atmosphere without snow and ice, probably due to strong wind from the Canisteo Peninsula and/or Cosgrove Ice Shelf. In contrast, more than half of the island was covered with snow and ice.

2.2. Measurements

To measure meteorological variables, single or double sensors were mounted on a 5.5-m mast. Two wind anemometers (model #05103MA, RM Young, USA) were placed at heights of 2.2 and 5.2 m. True north for wind direction was determined based on coordinates using a portable GPS. Temperature/humidity probes (model #HMT335, Vaisala, Finland) were also installed at two levels of 2.0 and 4.9 m. Two pyranometers (model #LI200 Type SL, Licor, USA) were mounted at a height of 5.0 m with one looking up and the other looking down to measure downward and upward shortwave radiation. A pelican box at the surface was used to contain a data logger (model #CR1000, Campbell Scientific Inc., USA) and a barometer (model #PTB100, Vaisala, Finland). Batteries (660 amp-hours) charged by two solar panels (20 and 18 W) provided 12 VDC power to the AWS. All data were sampled once a minute. All hourly mean and standard deviation data (changed to half hourly since 27 February 2012) were only stored, but 2-hourly averaged data with wind

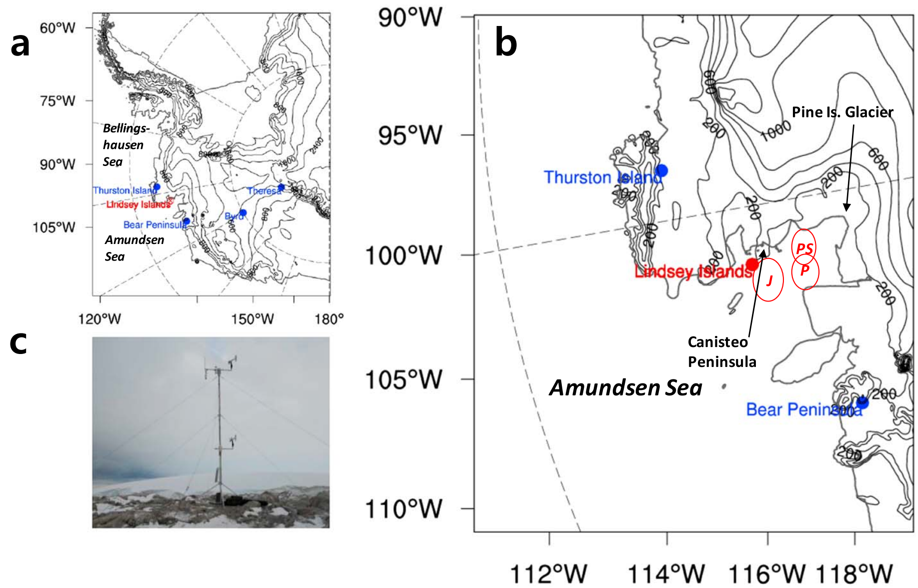

Figure 1. Site map showing (a) the location of the study sites with topography (contours, m). (b) Enlarged view of the site map where the Lindsey Islands are located, and (c) AWS at the study site. The contour intervals of elevation in (a) and (b) are 400 and 200 m, respectively. Red circles in (b) are approximate locations of Research vessels, RRS *James Clark Ross* (*J*), *Polarstern* (*PS*), and *Nathaniel B. Palmer* (*P*) whose data were used in section 3.1.

gust were stored in the data logger and transmitted through an Argos Satellite transmitter to monitor the meteorological conditions around the island and diagnose the state of the AWS for the next visit. Universal Time Coordinated time zone was used for data recording.

On 27 February 2012, four Korean researchers from Korea Polar Research Institute visited the site for the maintenance of the AWS. They were able to access the site via the *Araon*, the Korean ice-breaking research vessel during oceanographic survey on the Amundsen Sea. The two wind anemometers were replaced with the same models as they were broken. Based on retrieved data at the site, one broke in 2010 and the other in 2011. Although the two temperature/humidity probes were functioning well, they were also replaced with

Table 1
Summary of Sensors for the Automatic Weather Station (AWS) at Lindsey Islands

Variables	Sensors/accuracy	Model (period)	Model (period)	Manufacturer	Heights (from the surface)
Wind speed (WS)/wind direction (WD)	Wind monitor WS: ±0.3 m/s; WD: ±3°	05103MA (Feb. 2008 to Feb. 2012)	05103 (Feb. 2012~)	R.M. Young	5.2/2.2 m
Temperature (T)/relative humidity (RH)	Temp./humid. probe HMT335·T: ±0.2 °C·RH: ±(1.5 + 0.015 × reading)%RH HMP155·T: ±(0.226–0.0028xT) °C·RH: ±(1.2 + 0.012 × reading) %RH	HMT335 (Feb. 2008 to Feb. 2012)	HMP155 (Feb. 2012~)	Vaisala	4.9/2.0 m
Downward/reflected shortwave radiation	Pyranometer·<5%	LI-210 Type SL (Feb. 2008~)		LI-COR	5.1/4.9 m
Snow accumulation height	Sonic ranging sensor·±1 cm or 0.4% of distance to target	SR50M-45 (Feb. 2008~)		Campbell Sci.	4.7 m
Air pressure	Analogue barometer·PTB100B: ±0.3 hPa·PTB110: ±0.3 hPa	PTB100B (Feb. 2008 to Feb. 2012)	PTB110 (2012.2~)	Vaisala	0.1 m
Data process/storage	Logger	CR1000 (Feb. 2008 to Feb. 2012)	CR1000 with latest OS version (Feb. 2012~)	Campbell Sci.	0.1 m
Data transmit	Argos antenna	ST-20 (Feb. 2008~)		Campbell Sci.	5.0 m

Table 2
Geographical Information on AWS Sites in a Close Order From Lindsey Islands and the Period of Data Availability

Sites	Latitude, longitude	Distance from Lindsey (km)	Elevation (m)	Period	Time installed
Lindsey Islands	73.601°S, 103.021°W		37	Feb. 2008–Dec. 2014	Feb. 2008
Thurston Island	72.532°S, 97.545°W	~190	225	Jan. 2011–Dec. 2014	Jan. 2011
Bear Peninsula	74.548°S, 111.868°W	~290	416	Jan. 2011–Dec. 2014	Jan. 2011
Byrd	80.007°S, 119.438°W	~820	1,539	Feb. 2008–Dec. 2014	Feb. 1980
Theresa	84.602°S, 115.841°W	~1,260	1,455	Feb. 2008–Dec. 2014	Nov. 1994

Note. The most recent elevations were updated for Thurston Island and Bear Peninsula in 2019 using by the U.S. UNAVCO Trimble GPS unit.

brand new ones (model #HMP155, Vaisala, Finland), according to the policy of the use of the same models at study sites by Korea Polar Research Institute. The data logger also was replaced by the same model, but with the latest operating system version to configure the new temperature/humidity probes (HMP155). Table 1 shows the list of instruments installed in 2008 and 2012, respectively.

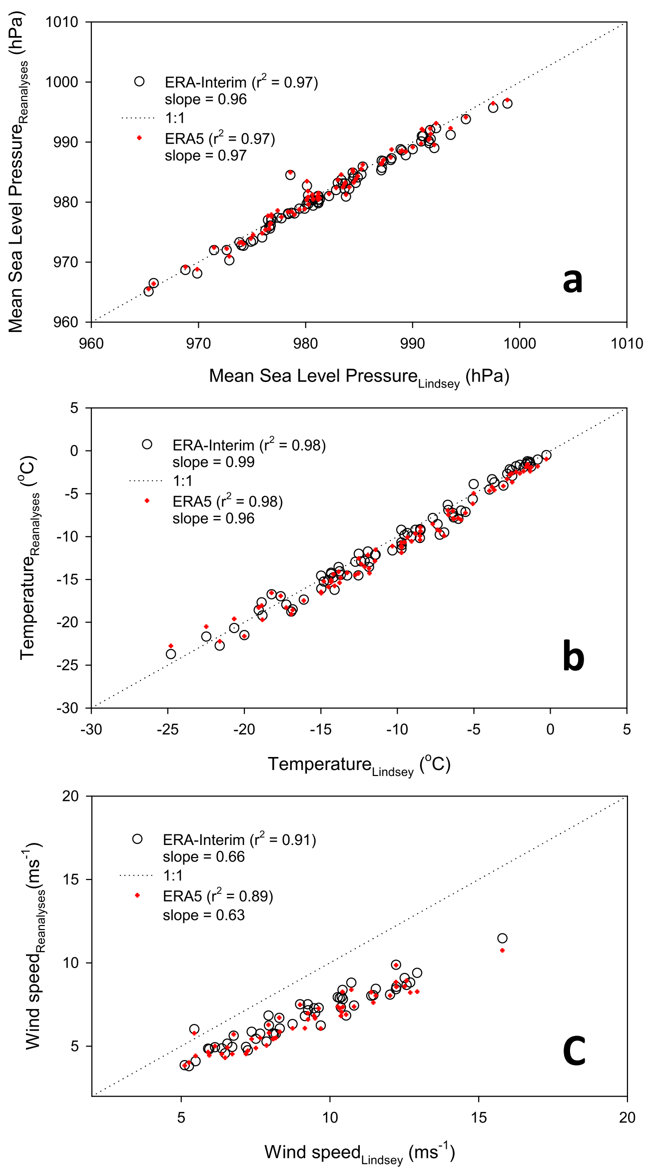

Figure 2. Scatter plots of monthly averaged (a) mean mean sea level pressure, (b) temperature, and (c) wind speed between measured data, and ERA-Interim and ERA5 reanalysis data from 2008 to 2014.

3. Data

3.1. Quality Check for Measured Data

As mentioned earlier, the two temperature/humidity probes and one barometer were replaced in February 2012. Before the replacement, the existing and new sensors were compared at the surface (barometers) and at 2.0 m (temperature/humidity probes) for about 8 hr at the site. Unexpectedly, the magnitude of the new sensor for pressure was about 9.7 hPa lower than that of the existing one, despite their good agreement in temporal variability (r^2 = 0.91). Air temperature from HMP335 showed a bias of −0.36 °C, which was acceptable considering the uncertainty for each sensor (±0.2 °C for HMP335 and ±0.25 °C for HMP155 over the measured mean temperature of −7.7 °C; Table 1).

From 2008 to 2014 three research vessels (RVs) explored the Amundsen Sea: *Nathaniel B. Palmer* in 2009 (Jacobs, 2014), *Polarstern* in 2010 (König-Langlo, 2010), and RRS *James Clark Ross* (*JCR*) in 2014. To ensure quality of the measured data at the site additionally, our data were compared with those obtained from the three RVs when they were within ±5° in latitude and longitude from the study site (Figure 1b). Among them, the *JCR* was closest to Lindsey Islands and stayed longer. All pressure data were converted into mean sea level pressure using each measurement height and temperature considering exponential decrease with altitude. In case of temperature and wind speed, however, no adjustments were made because *JCR* was >25 km and the others were >78 km away from the study site with small difference in measurement heights (19–37 m for RVs and 39–42.5 m for the AWS at Lindsey Islands). Table S1 in the supporting information summarizes biases between the meteorological data of three research vessel cruises and those at the Lindsey Islands. Due to a small bias (0.47 hPa) from *JCR* in 2014, pressure from the new barometer at the study site was determined for reference data and 9.7 hPa was subtracted from the existing data for this study. Biases for temperature ranged from −1.46 to 0.36 °C, likely resulting from the difference in locations. For wind speed, unfortunately, no data were available at the study site in February 2014. Wind speed data from *Palmer* and *Polarstern* showed relatively small biases despite the distance, indicating similar magnitudes of wind speed at the coastal area regardless of the locations during the comparison period. Although these results do not necessarily

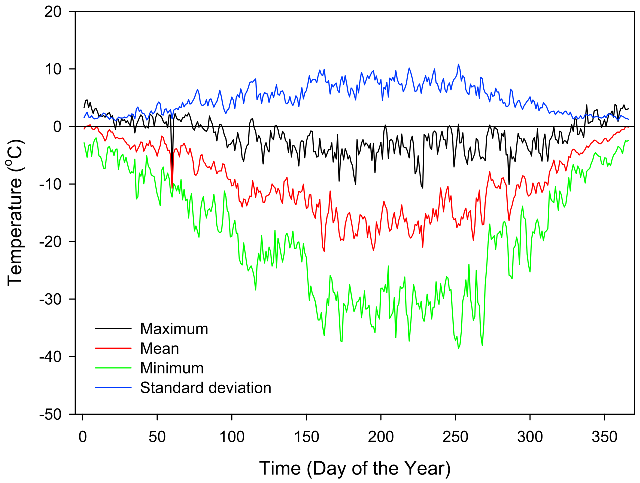

Figure 3. Daily maximum (black), mean (red), minimum (green) air temperature, and its standard deviation (blue; °C) from February 2008 to December 2014.

guarantee the quality of the compared data at the study site directly for all the operated period, the sensors operated normally during the comparison period. For the whole period, quality control was ensured through comparison with each mean and standard deviation for temperature and wind. Pressure data at the surface were examined based on the general behaviors on a monthly basis along with its standard deviation. Temperature at 2.0 m and wind at 5.2 m were otherwise used for the analysis. Two-hourly averaged data were used for the analysis and averaged for daily, monthly, seasonal, and annual values from 2008 to 2014. While temperature and pressure were available continuously, wind data at 5.2-m height were available only from mid-February in 2008 to late August in 2011 and from late February in 2012 to late March in 2013.

3.2. Additional Data for Analysis

To investigate spatial variations in surface meteorological variables, the measured data at Lindsey Islands were compared with those from five Wisconsin AWSs located from the coast to inland West Antarctica. Geographical information and data availability of the AWSs are summarized in Table 2. Two sites (Thurston Island and Bear Peninsula) are located near Lindsey Islands within 300 km at the coastal area with relatively low elevations of ~<300 m, while the other two sites (Byrd and Theresa) are far inland, more than 1,400 km away at high altitudes of >~1,450 m. We did not include AWS data at Evans Knoll, because she was found to be surrounded by crevasses.

3.3. Reanalysis Data and ASL Indices

Reanalysis data are important for understanding atmospheric processes in Antarctica because measured data are limited compared to the vast size of the continent (e.g., Turner et al., 2016). Among various reanalysis products, European Center for Medium Range Weather Forecasting (ECMWF) Interim Reanalysis (ERA-Interim; Dee et al., 2011) is known to better represent weather systems in the Amundsen-Bellingshausen Seas (Bracegirdle, 2012). Recently, ECMWF released ERA5 reanalysis data with a high resolution of 30-km horizontal grid and 137 vertical levels from the surface up to a height of 80 km (ECMWF, 2017). We employed the reanalysis data of monthly averaged mean sea level pressure, air temperature at 2 m, and wind speed at 10 m height from ERA-Interim (0.75 square grid) and ERA5 (30 km grid) to compare them with measured data over 2008–2014. We used 6-hourly output from the grid point with a surface elevation of 54.7 m (ERA-Interim), as well as hourly output from the grid point with a surface elevation of 21.4 m (ERA5) nearest to the study site.

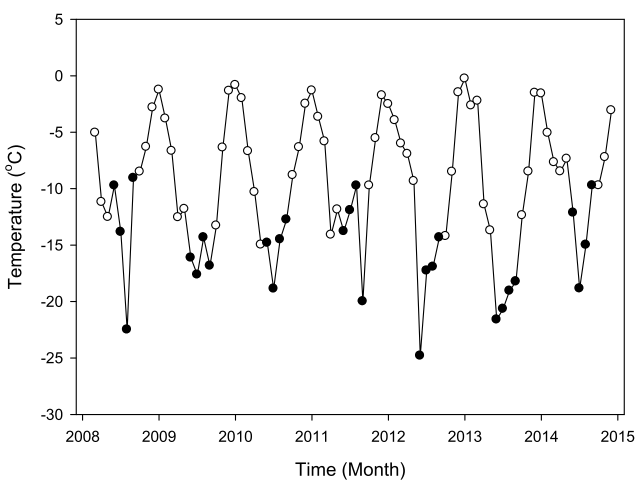

Figure 4. Variation in monthly averaged air temperature (°C) from March 2008 to December 2014. Black dots indicate June, July, August, and September each year.

Figures 2a–2c show scatter plots of monthly averaged mean sea level pressure, temperature, and wind speed between measured and ERA-Interim/ERA5 reanalysis data from 2008 to 2014. These comparisons are meaningful because our data were not assimilated into the reanalysis data. Pressure from ERA-Interim and ERA5 reanalyses matched remarkably well with measured pressure with r^2s of 0.97 and 0.97, respectively. Temperatures from ERA-Interim and ERA5 reanalyses also show excellent agreements with measured data with r^2 of 0.98. This is unexpected considering their difference in the spatial scale. High r^2s of 0.91 and 0.89 are obtained between each reanalysis and measured wind speed data. However, wind speed from reanalysis data is much weaker than the measured with slopes of 0.66 and 0.63 regardless of the levels of the reanalysis (64.7 and 31.4 m, respectively) and measured height (~42 m). It is worthwhile to note that wind speed from ERA-Interim at higher elevation shows similar magnitude compared to that from ERA-5 at lower elevation. Compared to RV data, in addition, the measured wind speed at the site was in a reasonable range. The lower winds speed from the reanalyses could be attributed to poor representation in models related to insufficient

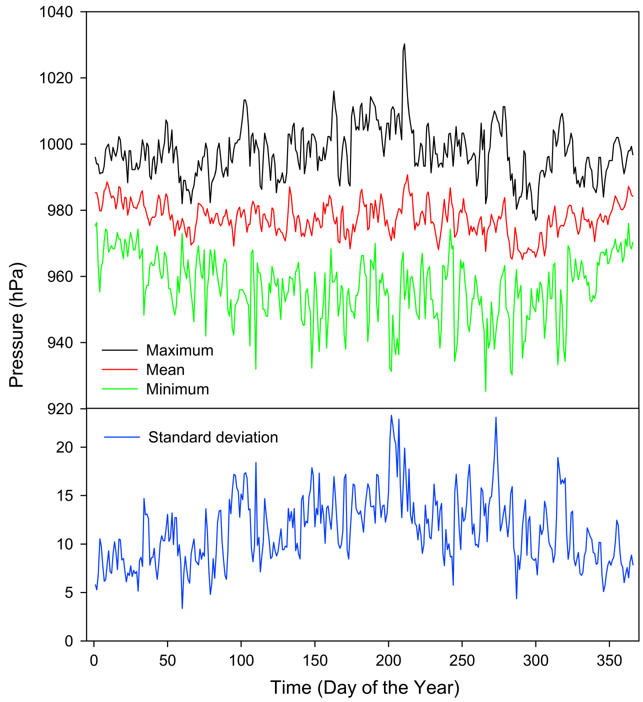

Figure 5. Same as in Figure 3 except for atmospheric pressure.

resolution. Jones et al. (2016) showed that the ERA-Interim reanalysis wind underestimated severely measured wind speed when the observed wind speed was high (>15 m/s) due to flow distortion at a coastal area with mountainous terrain. Their and our results imply that wind speed from ERA-Interim reanalysis underestimates measured wind speed at coastal areas over West Antarctica, where steep and complicated topography plays an important role in producing strong wind (e.g., Turner et al., 2009).

The study site is strongly influenced by the ASL. As the climatological area of low pressure located over the South Pacific sector of the Southern Ocean between the Antarctic Peninsula and the Ross Sea, ASL plays an important role in determining the climate over West Antarctica (e.g., Hosking et al., 2013; Turner et al., 2013). Hosking et al. (2013) found that the longitude of the ASL center plays the most important role in the climate of West Antarctica. At this study, we examined the role of ASL on the variability of the measured data by employing ASL Indices Ver2 (https://legacy.bas.ac.uk/data/absl/) over the same period as ERA-Interim reanalysis data.

4. Results

4.1. Meteorological Characteristics

Figure 3 shows the daily mean, minimum, and maximum air temperature with its standard deviation at 2 m over the time period 2008–2014. The daily mean air temperature ranged from −22 °C in winter to about 0 °C in summer. Its standard deviation shows larger value in winter, indicating greater temperature variability, but decreases toward summer. The minimum temperature reached −38.6 °C at 1200 on 8 September 2013, and it was up to −5.0 °C in summer. The maximum temperature reached 4.6 °C (2400 on 12 January 2013) and around 0 °C even in winter, showing smaller annual variation than the mean and minimum temperatures.

Figure 4 shows the variation in monthly averaged air temperature from March 2008 to December 2014. It ranged from −24.8 °C (June 2012) to −0.3 °C (January 2013). On average, July was the coldest month, but the month with annual minimum temperature varied from year to year (June–September). The monthly mean air temperature below −20 °C was observed in August 2008, September 2011, and June 2012, during which the temperature was lower by more than 5 °C than the preceding or succeeding months. A consecutive appearance of low temperature around −20 °C was observed over four months from June to September in 2013, when the annual mean temperature was the lowest among the seven years. The cause for the low temperatures is discussed in section 5.1.

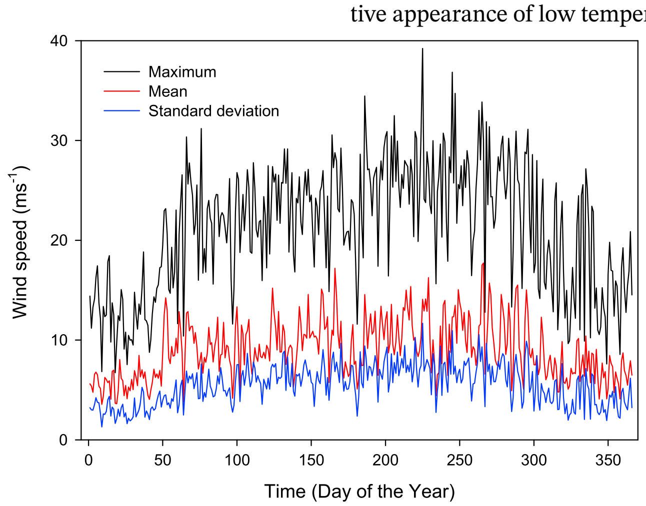

Figure 6. Same as in Figure 3 except for wind speed without daily minimum wind speed.

Figure 5 shows the daily mean, minimum, and maximum atmospheric pressure with its standard deviation. The mean pressure ranged from 965.1 to 990.7 hPa. Overall, the standard deviation was smaller in summer than in nonsummer seasons, particularly with small standard deviation in early March and October, showing relatively low mean pressure possibly due to semiannual oscillation (SAO; e.g., van Loon, 1967). The minimum pressure was 925.3 hPa (0800 on 22 September 2008), while the maximum pressure was 1,030.3 hPa (0000–0800 on July 29, 2011). From 2009 to 2011, pressure exhibited larger annual variabilities (with standard deviation of more than 22 hPa) than in other years on annual basis (not shown). Pressure was higher in 2009 (980.1 hPa) and 2011 (981.4 hPa), but lower in 2010 (973.1 hPa). For reference, the standard deviation using annual average was 2.89 hPa from 2009 to 2014, which is in the range reported by Connolley (1997).

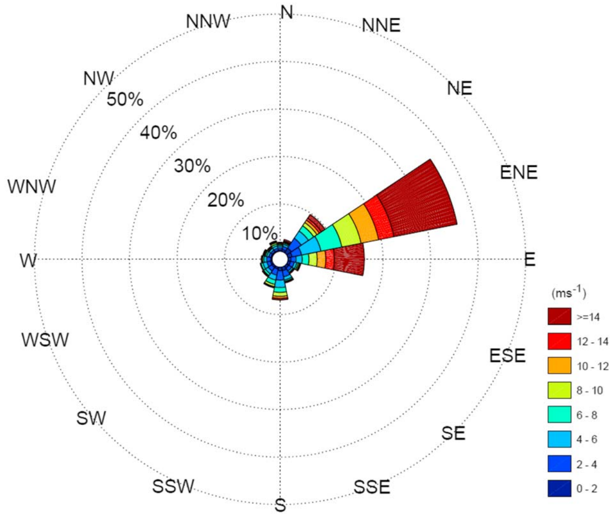

Figure 7. Wind rose over the entire period at the study site.

Figure 6 shows the daily mean and maximum wind speed with its standard deviation at the height of 5.2 m from the surface. Daily mean wind speed ranged from 3.5 to 17.7 m/s, and it was weaker in summer than in non-summer seasons. In addition, wind speed variability was more pronounced in nonsummer seasons than in summer. The maximum recorded gust was 44.9 m/s (0600 on 12 August 2010).

The wind blew mainly from the east with the maximum frequency of east-northeast (Figure 7) regardless of seasons. Approximately 5% of the total wind was from the south. Monthly directional constancy (DC) fluctuated from 0.2 to 0.93 (Figure 8), where DC from the Bear Peninsular is included. For reference, the correlation between wind speeds at both sites was high with a range from 0.68 (spring) to 0.83 (autumn). While DC from the Bear Peninsular remained high by more than 0.6, there was large variability in DC from Lindsey Islands. Months with DC of >0.8 accounted for 28%, whereas those with DC of <0.6 accounted for 19%. High DC was observed in summer, such as 0.88 in February 2010 and 0.9 in December 2010, indicating that the site was basically under influence of the advection of cold air from inland. However, some instances of low DC even in winter indicate that the island was also influenced by low-pressure centers frequently passing by the site. Months with small DC, for example, 0.37 in August 2008 show that the frequency of wind from the south is comparable to that of the prevailing wind (i.e., northeast) at Lindsey Islands (Figure 9).

4.2. Comparison With Other AWSs

Table 3 summarizes seasonal mean meteorological values at five sites from autumn in 2011 to spring in 2014. The missing data at Byrd in October 2012 were filled with mean values in October over 2008–2014. The highest mean temperature was observed at Lindsey Islands with −9.9 °C, whereas the lowest (−26.7 °C) was observed at Byrd. The mean differences in temperature at Lindsey Islands were 1.2 °C (Thurston Island) and 3.8 °C (Bear Peninsula) at the coastal area. The difference was much greater for inland sites ranging from 12 °C (Theresa) to 16.8 °C (Byrd). The difference was largest in autumn for all sites. For pressure, the difference at the study site ranged from 24.8 hPa (Thurston Island) to 173 hPa (Byrd), which was largest in winter for all sites.

We calculated seasonal correlation coefficients (R) of temperature and pressure between the study site and four other AWS sites, spanning ~11° of latitude and ~16° of longitude with a range of 1,500 m of elevation. Table S2 shows the seasonal R values calculated using monthly averaged temperature and pressure at Lindsey Islands with the corresponding values at four AWS sites over 2011–2014. The seasonal R values ranged from 0.46 (Theresa in winter) to 0.92 (Thurston Island in autumn and spring) for temperature and from 0.58 (Theresa in spring) to 0.99 (Thurston Island in summer) for pressure (Table S2). The R values of temperature and pressure were greater than 0.8 between Lindsey Islands and the coastal sites. The correlations were relatively low between Lindsey Islands and the two inland sites. However, it is noteworthy that seasonal R values between the study site and Byrd were 0.72 in spring (>0.56 in other seasons) for temperature and 0.76 in winter (>0.66 in other seasons) for pressure in spite of the distance and difference in elevation.

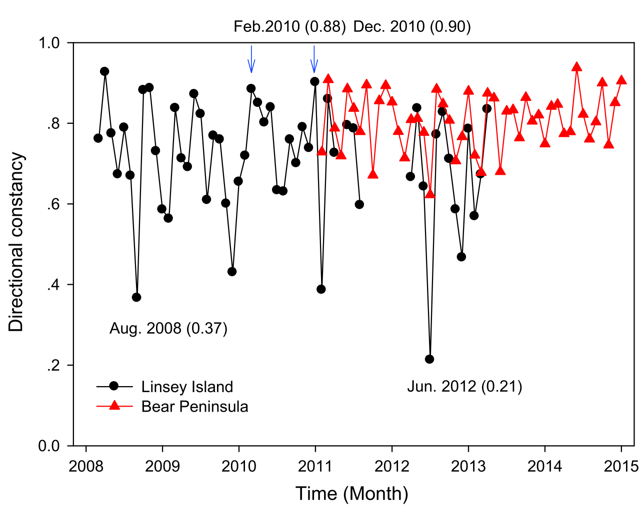

Figure 8. Time series of monthly directional constancy at Lindsey Islands (black) and Bear Peninsula (red), with some high DC in summer and some low DC in winter at Lindsey Islands as an example. DC = directional constancy.

5. Discussions

5.1. Influence of the ASL

As shown earlier, significantly low monthly mean temperature below −20 °C occurred in winter (Figure 4), which can be attributed to the change in wind direction. Figure 9 shows the air temperature with 16 wind direction bins during August in 2008 and 2009. The wind was more southerly in 2008 than in 2009, resulting in lower temperature

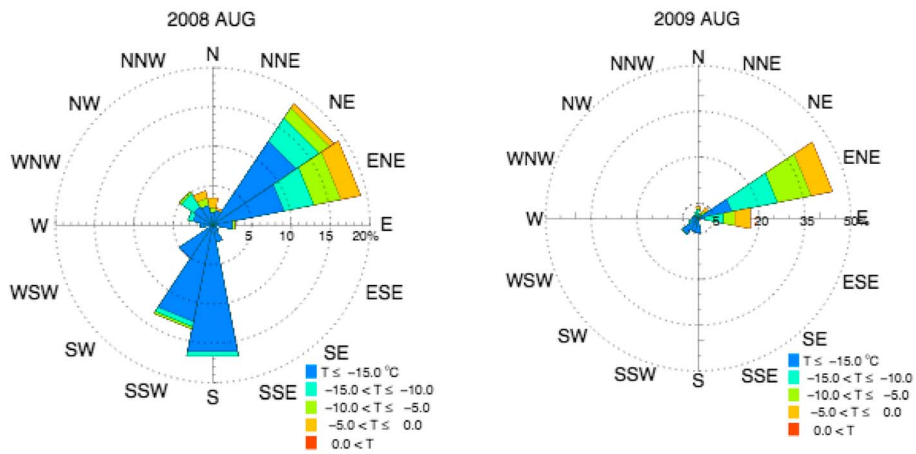

Figure 9. Air temperature distribution with 16 wind direction bins on August in 2008 (left) and 2009 (right).

in August 2008 (−22.5 °C) than in August 2009 (−14.3 °C). In addition, the DC was about 0.4 and 0.8 in 2008 and 2009, respectively (Figure 8). The study site is mainly influenced by the advection of cold air from inland through the eastern Canisteo Peninsula, as in most coastal areas of Antarctica. However, when the wind regime changes due to large-scale atmospheric processes such as ASL, colder air from the south can influence the temperature at the site.

Figure 10a shows variations in the frequency of east and south winds with the longitude of the ASL center. We used eight wind direction bins to examine overall changes in wind direction at the site with the location of the ASL center. The frequency of the east and south winds largely depends on the longitude of the ASL center. When the ASL center is located around 240°E (120°W), the east wind to the study site is much more dominant than the south wind. As the ASL center moves toward east (or west) from around 240°E, the frequency of the east wind tends to decrease, while that of the south wind tends to increase.

The change in the wind regime influences temperature at the site directly or indirectly, particularly in winter. Figure 10b shows the relationships between the longitude of the ASL center and monthly averaged temperature from measurement and reanalysis data in winter. We used measured temperature from 2008 to 2014 and reanalysis temperature from 1980 to 2014. In winter, the longitude of the ASL center and temperature showed a relatively good agreement with $p < 0.05$ in spite of small r^2 values of 0.24 for reanalysis and 0.16 for measurement (Table 4). Overall, as the ASL center moved eastward, temperatures tended to drop. Considering the longitude of >220°E, the relationship was stronger, particularly for measured data with an r^2 of 0.72 (Table 4). For the longitude of <220°E, the relationship between the longitude of the ASL center and temperature was weak, especially for the reanalysis data.

As in temperature, for the longitude of >220°E, the wind speed also decreased as the longitude of the ASL center shifted eastward (not shown). Wind speed was in good agreement with the location of the ASL center with r^2 values of 0.95 for the measurement and 0.35 for the reanalysis data ($p < 0.05$). During the analysis period, the strongest wind speed was observed in September 2008 when the longitude of the ASL center

Table 3
Summary of Seasonal Mean Temperature (T) and Pressure (P) at Five Sites From Autumn, 2011, to Spring, 2014

Site season	Lindsey T (°C) (P, hPa)	Thurston Island T (°C) (P, hPa)	Bear Peninsula T (°C) (P, hPa)	Byrd T (°C) (P, hPa)	Theresa T (°C) (P, hPa)
Autumn	−8.8 (976.1)	−10.3 (952.2)	−14.0 (928.4)	−28.8 (804.7)	−24.1 (816.1)
Winter	−16.8 (979.4)	−16.6 (953.9)	−19.0 (928.6)	−33.1 (803.3)	−27.5 (815.3)
Spring	−11.5 (977.8)	−12.8 (952.8)	−15.1 (928.2)	−27.4 (804.9)	−22.5 (816.4)
Summer	−2.4 (981.3)	−4.7 (957.4)	−6.6 (933.8)	−16.4 (811.1)	−13.6 (820.9)
Mean	−9.9 (978.9)	−11.1 (954.1)	−13.7 (929.8)	−26.7 (806.0)	−21.9 (817.2)

Note. Missing data of temperature on October 2012 at Byrd were filled with mean values on October over 2008 to 2014. The data from the other automatic weather stations were obtained from the Antarctic Meteorological Research Center (http://amrc.ssec.wisc.edu/).

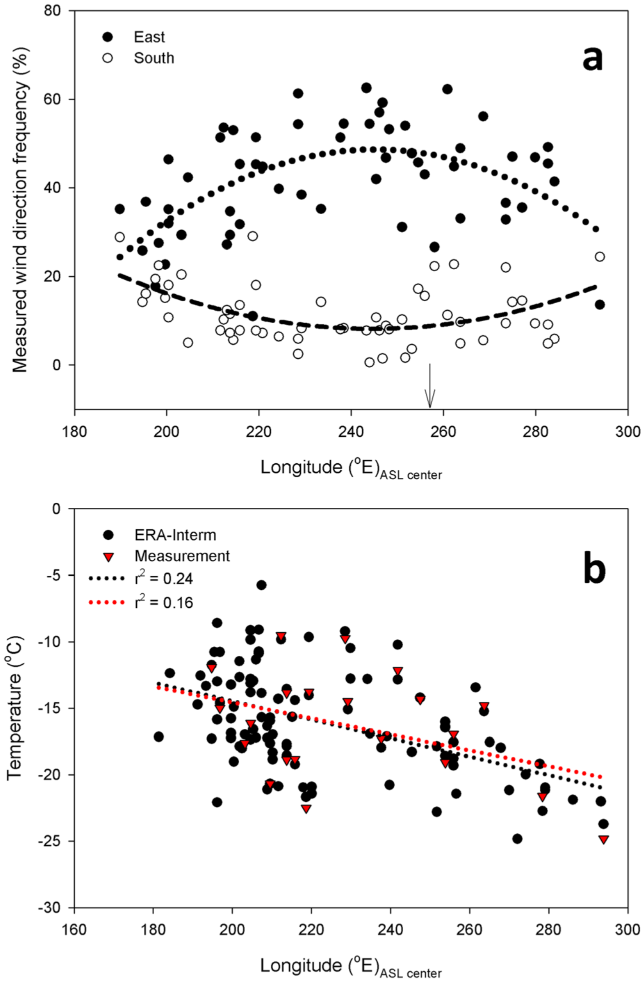

Figure 10. (a) Relationship between the longitude of the ASL center and monthly frequency of east and south winds at the site from 2008 to 2013 for all seasons. Dotted and dashed lines are fitted to measured data using quadratic equations. (↓) indicates the longitude of the study site. (b) Relationship between the longitude of ASL the center and monthly average temperature in winter from 1980 (2008) to 2014 (2014) for ERA-Interim (measurement). ASL = Amundsen Sea Low.

was approximately ~244°E and the central pressure was about 958 hPa, the deepest during the measurement period.

The climate of West Antarctica is largely influenced by the tropics (e.g., Ding et al., 2011). Djouman and Holland (2015) showed that at PIG, ~180 km away from the study site, the surface wind direction changed from the northwest during El Niño to north during La Niña in 2012 on an annual basis. During the same period, wind direction remained unchanged at Thurston Island and Bear Peninsula. Similar to the latter sites, the study site also showed a similar dominant northeast wind direction on an annual basis during La Niña in 2012 as in the other years. This indicates that ASL plays an important role in the wind regime of the site under the influence of winds from the continent, particularly in winter, leading to temperature decrease.

5.2. Trends

Surface temperature trend is a major issue in West Antarctica and the Antarctic Peninsula in terms of ice sheet mass loss. In particular, the trend is important in the coastal areas of West Antarctica because temperature is above the freezing point in summer, as shown in Figure 3. We examined the trends of temperature, pressure, and wind speed using the measured data at Lindsey Islands over the past 7 years. Wind speed data were unavailable for the period when the anemometers were broken, and they were filled with data obtained on the basis of the good relationship between Lindsey Islands and Bear Peninsula as mentioned in section 4.1 . Based on the analysis, there were no significant trends for all variables in all seasons due to large interannual variability over relatively short seven years (not shown). Trends of seasonal averaged temperature, pressure, and wind speed over 1980–2014 were also analyzed using ERA-Interim reanalysis data. Among them, pressure and wind speed show significant trends ($p < 0.05$) only in autumn (Figure 11). Pressure in autumn decreases at the rate of −0.18 hPa/year that drives the increase in wind speed at a rate of 0.02 $m \cdot s^{-1} \cdot year^{-1}$. Over the past 35 years, pressure over the ASL sector has deepened with a rate of −0.12 hPa/year ($p < 0.05$) from the ASL indices, which is associated with the pressure decrease at an area near the study site in autumn. However, pressure at the center of ASL does not show significant decrease (not shown).

Despite significant variations in pressure and wind speed in autumn, no change was observed in temperature in the same season. However, it is notable that the trends for temperature and pressure, (and wind speed related to pressure) should be interpreted with caution, although the measured and ERA-Interim reanalysis datasets agree well for the analysis period. Good relationships over seven years do not necessary mean that reanalysis data guarantee long-term trends. Nicolas and Bromwich (2014) showed the spurious behavior of reanalysis

Table 4
Relationship Between the Location of ASL Center, Temperature (T), and Wind Speed (WS)

Longitude (°)		All r^2	All *p value*	>220 r^2	>220 *p value*	<220 r^2	<220 *p value*
Measurement	*T*	0.16	<0.05	0.72	<0.05	0.1	<0.05
	WS	0.15	<0.05	0.95	<0.05	0.01	>0.05
Reanalysis	*T*	0.24	<0.05	0.32	<0.05	0.04	>0.05
	WS	0.02	>0.05	0.35	<0.05	0.08	<0.05

Note. ASL = Amundsen Sea Low.

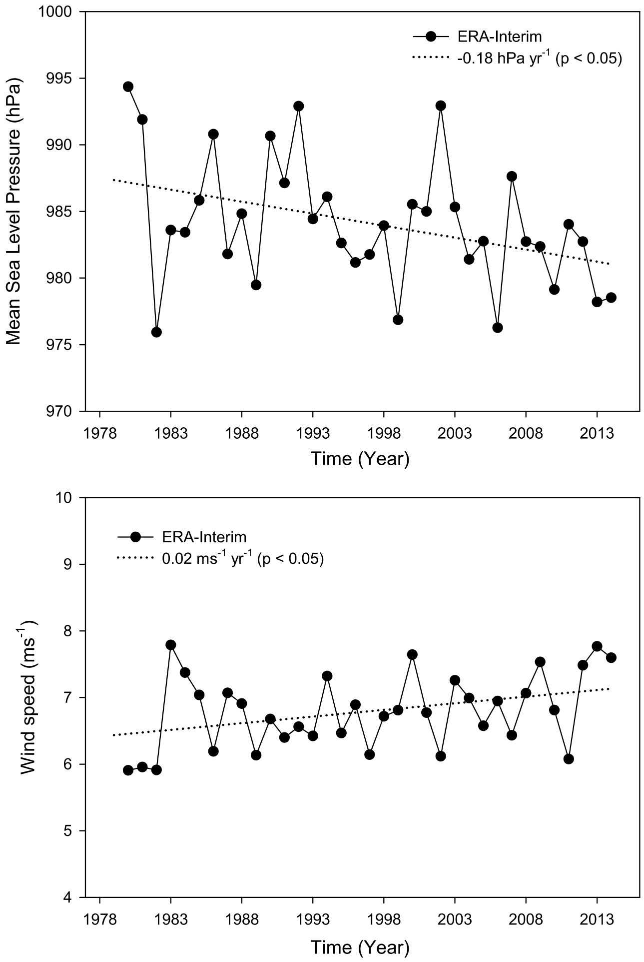

Figure 11. Trends of seasonal averaged mean sea level pressure (top) and wind speed (bottom) in autumn from 1980 to 2014.

temperature in the 1979–2009 time series that reduced the reliability of their trends compared to their reconstruction. Fogt et al. (2018) showed that their reconstruction was consistent with observed pressure and produced weaker pressure trends than the reanalysis products, such as ERA-Interim. Nevertheless, they showed that the skill of the reconstruction was weaker in the South Pacific, limiting the understanding of long-term pressure variability and trends in this region, where circulation changes have been key drivers of climate variability. Therefore, further studies are required to identify the trends in the coastal areas of West Antarctica.

5.3. Spatial Relationship of Temperature and Pressure With Other Sites

Reusch and Alley (2004) showed that the average intersite seasonal R of temperature was higher during autumn and winter (mean R ~0.7) than in summer ($R = 0.44$) among six AWS sites in West Antarctica spanning ~90° of longitude (~900 to ~1,400 km) during 1979–1993. They also showed that R between Byrd and other sites was very small in summer ($R < 0.27$, mean $R = 0.09$). We showed that seasonal R values of temperature between the study site and inland sites were not low, with 0.56 for Byrd (~820 km away from Lindsey Islands) and 0.58 for Theresa (~1,260 km) in summer, and 0.72 for Byrd and 0.69 for Theresa in spring. This is contrasted with high correlations in autumn and winter from Reusch and Alley (2004), indicating that spatial variation in temperature may be more strongly connected with latitude from coastal to inland area than with longitude at inland area in West Antarctica, particularly in spring and summer.

Harmonic analysis was conducted for mean annual cycles of pressure and temperature to compare their variability characteristics from coastal to inland areas. The second harmonic for pressure, semiannual oscillation (SAO) represents climatological characteristics, and it is an important component of the Southern Hemisphere climate (Meehl, 1991; van Loon, 1967). van den Broeke (1998a, 1998b, 2000) examined the influence of SAO on near-surface temperature, wind speed, and cloudiness using observations of 27 stations over 1957–79 and showed the different effects of SAO on temperature over the inland plateau, coasts of East Antarctica, the Antarctic Peninsula, and inland West Antarctica, except for coasts of West Antarctica, where data were not available. Therefore, conducting harmonic analysis at both the coastal and inland areas of West Antarctica is crucial to understand the effect of SAO on temperature and how both areas are connected in West Antarctica. Before comparing the influence of SAO at the five sites, we first examined the influence of SAO on temperature at Lindsey Islands using monthly mean pressure and temperature for 7 years.

Figure 12 shows the measured annual cycles of monthly mean pressure and temperature with the first harmonic H_1, the second H_2 from pressure and temperature and the third H_3 from pressure in Lindsey Islands from 2008 to 2014. The total variance of the annual cycle in monthly mean pressure explained by the first two harmonics, $H_1(P)$ and $H_2(P)$, was 84.2%. Among which the second harmonic explains the largest part of the total variance (67.3%) and the amplitude of $H_2(P)$ was 3.19 hPa, which are in the range of those from the coastal stations in East Antarctica (van den Broeke, 1998a). This indicates that a distinct SAO feature is seen in Lindsey Islands. It is worthwhile to note, however, that the third harmonic, $H_3(P)$, explains 15.7% of the total variance of the annual cycle, which is comparable to the first harmonic, $H_1(P)$, explaining ~17%. This is different from the results of van den Broeke (1998a), where $H_3(P)$ was negligible. At the study site, the longitudinal shift of the ASL center between summer and winter seems to play a role as $H_3(P)$ to the annual cycle of pressure (Figure 10a; e.g., Hosking et al., 2013). In the meanwhile, the total variance of the annual cycle in monthly mean temperature is almost entirely explained by the first harmonic, $H_1(T)$

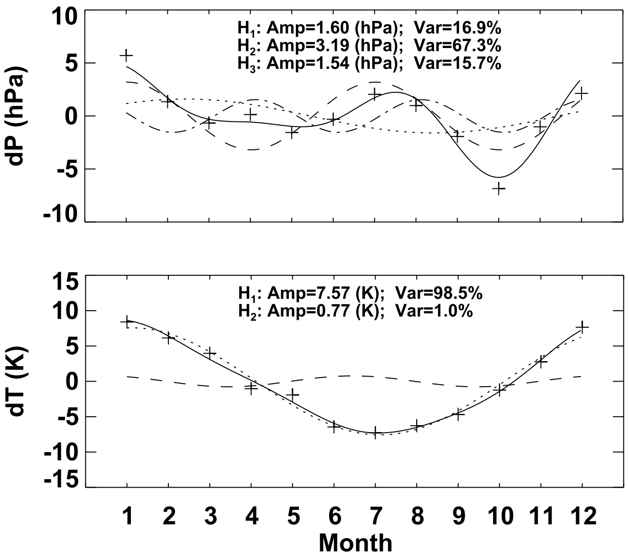

Figure 12. Measurements (pluses), the first harmonic H_1 (dotted line), the second harmonic H_2 (dashed line), H_3 (dash-dotted line), and $H_1 + H_2$ (+ H_3) (solid line) of mean annual cycles of pressure P (top) and temperature T (bottom) for 2008–2014.

(98.1%) and the second is negligible, meaning that temperature is not influenced by SAO at the site. The amplitude (0.7 °C) and variance (1.0%) explained by $H_2(T)$ agree well with those from the Antarctic Peninsula (van den Broeke, 1998a).

To identify the significance of SAO in coastal and inland sites, and to compare the influence of SAO on temperature, harmonic analysis was performed using monthly mean data from 2011 to 2014. Table S3 summarizes the amplitude and percentage of the total variance explained by the first and second harmonics of monthly mean pressure and temperature cycles ($H_1(P)$, $H_2(P)$ and $H_1(T)$, and $H_2(T)$) with sums of the variances, H_1+ H_2 at the five sites. The amplitude and the explained variances showed large differences between the coastal and inland sites. While the amplitude and the percentage of the total variance explained by the first harmonic $H_1(P)$ are larger than those by the second harmonic $H_2(P)$ for inland sites, the latter is greater than the former for the coastal sites, except for Bear Peninsula, where the amplitude and explained variance by $H_1(P)$ and $H_2(P)$ are similar in magnitude. This result indicates that SAO is more influential at the coastal sites. The significant contribution of the third harmonic, $H_3(P)$ to annual cycle is also a characteristic of the coastal sites.

Regardless of the location, the total variances of the annual cycles in monthly mean temperature could be explained mostly by the first two harmonics (>96%), among which the first harmonics explain the largest part of the total variances of the annual cycles. The percentage of the total variance explained by the second harmonics of the annual temperature cycle at the coastal area is only 0.6–4.8%. However, the second harmonics, $H_2(T)$, are significant inland, explaining 6.5% and 11.1% of the total variance at Byrd and Theresa, respectively. According to the harmonic analysis, variations in pressure and temperature are similar to each other at coastal sites, likely resulting in relatively high correlation. In the meanwhile, relative low correlations between Lindsey Islands and inland sites is partly attributed to large difference in the roles of SAO and the third harmonic.

6. Summary and Conclusions

An AWS was installed at Lindsey Islands, the Amundsen Sea, close to the coastal area of West Antarctica in 2008 and was operated for 7 years. High interannual variability is shown in temperature, pressure, and wind speed, with particularly higher values in winter. The daily mean air temperature ranged from −22 °C in winter to about 0 °C in summer, with the daily minimum (maximum) temperature of −38.6 (4.6) °C. On average, July was the coldest month and months with annual minimum temperature of <−20 °C varied from year to year between June and September. The change in wind direction due to the longitudinal shift of the center of ASL resulted in the low air temperature in winter through colder air advection from the south. The magnitude of the daily mean pressure ranged from 965.1 to 990.7 hPa. Relatively low pressure with a small standard deviation occurred in early March and October, associated with SAO. Daily mean wind speed ranged from 3.5 to 17.7 m/s with the maximum gust of 44.9 m/s. The wind was mainly from the east, with a maximum frequency in east-northeast regardless of season. DC fluctuated from 0.2 to 0.93 on a monthly basis with some high values in summer. This is because the study site is basically under influence of the advection of cold air from the inland ice sheet. Some low DCs in winter are due to the influence of ASL. The frequency of the east (south) wind was the maximum (minimum) when the longitude of the ASL center was around 240°E. In the longitude of >220°E, both temperature and wind speed tended to decrease as the ASL center moved eastward ($p < 0.05$).

The measured temperature, pressure, and wind speed at the study site showed good relationship with ERA-Interim and ERA5 reanalysis data despite large negative biases in both wind speed. We found that there were no significant trends in seasonal averaged temperature over 1980 to 2014 based on the reanalysis data. However, in autumn, significant trends were found in pressure and wind speed ($p < 0.05$).

The R values of temperature and pressure were larger than 0.8 between Lindsey Islands and the coastal sites (Thurston Island and Bear Peninsular), but they were relatively low for the two sites inland (Theresa and Byrd). However, the *R* of temperature was high with ~0.7 in spring and >0.56 in summer at the sites inland. While the amplitude and the percentage of the total variance explained by the first harmonic for pressure were larger than those by the second harmonic inland, the opposite was observed for the coastal sites, indicating that SAO was more pronounced at the coastal sites. The contribution of the third harmonic, $H_3(P)$ to the annual cycle was also significant at the coastal sites. The shift of the ASL center with season, related to $H_3(P)$ seems to play an important role in the annual cycle of pressure in the region. The influence of SAO on temperature was negligible in the coastal area, but it was significant inland. In conclusion, we added important and invaluable meteorological records obtained in the Lindsey Islands to the coastal area of West Antarctica. Our analysis indicates that meteorological characteristics in the Lindsey Islands are largely governed by the location of ASL and associated passages of depressions. Except for autumn, we found no significant trends in the study sites that could be in part because the study site sits near the center of ASL, though uncertainty in trend may be high. Finally, spatial variation in temperature is more strongly connected from coastal to inland area in West Antarctica, particularly in spring.

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