ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 37, MAY 2020, 532–544

• Original Paper •

Specific Relationship between the Surface Air Temperature and the Area of the Terra Nova Bay Polynya, Antarctica

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(Received 17 July 2019; revised 15 December 2019; accepted 19 January 2020)

ABSTRACT

Antarctic polynyas play an important role in regional atmosphere–ice–ocean interactions and are considered to help generate the global deep ocean conveyer belt. Polynyas therefore have a potential impact on the Earth's climate in terms of the production of sea ice and high-salinity shelf water. In this study, we investigated the relationship between the area of the Terra Nova Bay polynya and the air temperature as well as the eastward and northward wind based on the ERA5 and ERA-Interim reanalysis datasets and observations from automatic weather stations during the polar night. We examined the correlation between each factor and the polynya area under different temperature conditions. Previous studies have focused more on the effect of winds on the polynya, but the relationship between air temperature and the polynya area has not been fully investigated. Our study shows, eliminating the influence of winds, lower air temperature has a stronger positive correlation with the polynya area. The results show that the relationship between the polynya area and air temperature is more likely to be interactively influenced. As temperature drops, the relationship of the polynya area with air temperature becomes closer with increasing correlation coefficients. In the low temperature conditions, the correlation coefficients of the polynya area with air temperature are above 0.5, larger than that with the wind speed.

Key words: air temperature, wind speed, polynya area, specific relationship, Terra Nova Bay

Citation: Ding, Y. F., X. Cheng, X. C. Li, M. Shokr, J. W. Yuan, Q. H. Yang, and F. M. Hui, 2020: Specific relationship between the surface air temperature and the area of the Terra Nova Bay polynya, Antarctica. *Adv. Atmos. Sci.*, **37**(5), 532–544, https://doi.org/10.1007/s00376-020-9146-2.

Article Highlights:

- Reanalysis and observational data reveal interactive effects between air temperature and the area of the Terra Nova Bay polynya.
- As air temperature declines, the polynya area shows increasing correlation coefficients with air temperature versus wind speed.
- The relationship of the polynya area with lower air temperature is significantly closer than that with wind speed.

1. Introduction

A polynya is a recurrent phenomenon in the polar region where sea ice is quickly removed either by melting or advection and then the ocean surface is exposed to the

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cold air, which will further intensify the ice formation. Therefore, polynyas are always covered by a mix of open water and thin ice and consequently impart a significant control over the energy balance of ice-covered ocean surfaces. Polynyas are broadly categorized into sensible heat polynya driven by ocean upwelling, and latent heat polynya driven by strong winds (Massom et al., 1998). In the Antarctic, polynyas are also regarded as major sources of sea ice production (Massom et al., 1998; Barber and Massom, 2007). Although polynyas only cover a small fraction of the ocean surface, high-salinity shelf water formed in polynyas owing to the large brine rejection from sea ice growth, plays an important role in the formation of the Antarctic Bottom Water (Marsland et al., 2004; Tamura et al., 2008; Fusco et al., 2009; Ohshima and Coauthors, 2013). The open water in polynyas also promotes the transfer of heat and water vapor between the atmosphere and the ocean (Andreas and Murphy, 1986; Massom et al., 1998; Marcq and Weiss, 2012; Haid and Timmermann, 2013) and provides space for mammals to feed and breed during the Antarctic winter (Stirling, 1997; Gilchrist and Robertson, 2000). The dynamics of polynyas are therefore of great importance in our understanding of the polar environment.

The Terra Nova Bay (TNB) polynya (TNBP) (Fig. 1), located in the Antarctic Ross Sea, is a typical latent heat polynya (Bromwich and Kurtz, 1984). High-salinity shelf water produced in the TNBP accounts for almost 10% of the Antarctic Bottom Water in the Ross Sea (Rusciano et al., 2013) and this cold water is an important factor in the thermohaline properties controlling floating glaciers (Budillon and Spezie, 2000). Previous studies have shown that the formation of the TNBP mainly depends on the sea ice driven by strong and persistent katabatic winds and the blocking of sea ice by the Drygalski ice tongue (Fig. 1) (Bromwich and Kurtz, 1984; Bromwich, 1989; Bromwich et al., 1993). In addition, ocean currents, tides, synoptic winds and cyclones affect the polynya area (Kurtz and Bromwich, 1985; Massom et al., 2003; Knuth and Cassano, 2011; Rusciano et al., 2013). Cold air flows away from the summit of the Antarctic ice sheet and converges in confluence zones, such as glaciers, which provide smooth, narrow channels leading to an enhanced supply of negatively buoyant air to the downwind coastal slopes, allowing katabatic winds to be both intense and persistent (Bromwich et al., 1993). The katabatic winds funneled by the Reeves glacier are the major force driving most of the TNBP sea ice as a result of the flat and wide outflow window provided by the Nansen ice shelf, whereas winds from the Priestley and David glaciers are secondary forces affecting the northern and southern sea ice flow of the polynya (Bromwich and Kurtz, 1984; Bromwich et al.,

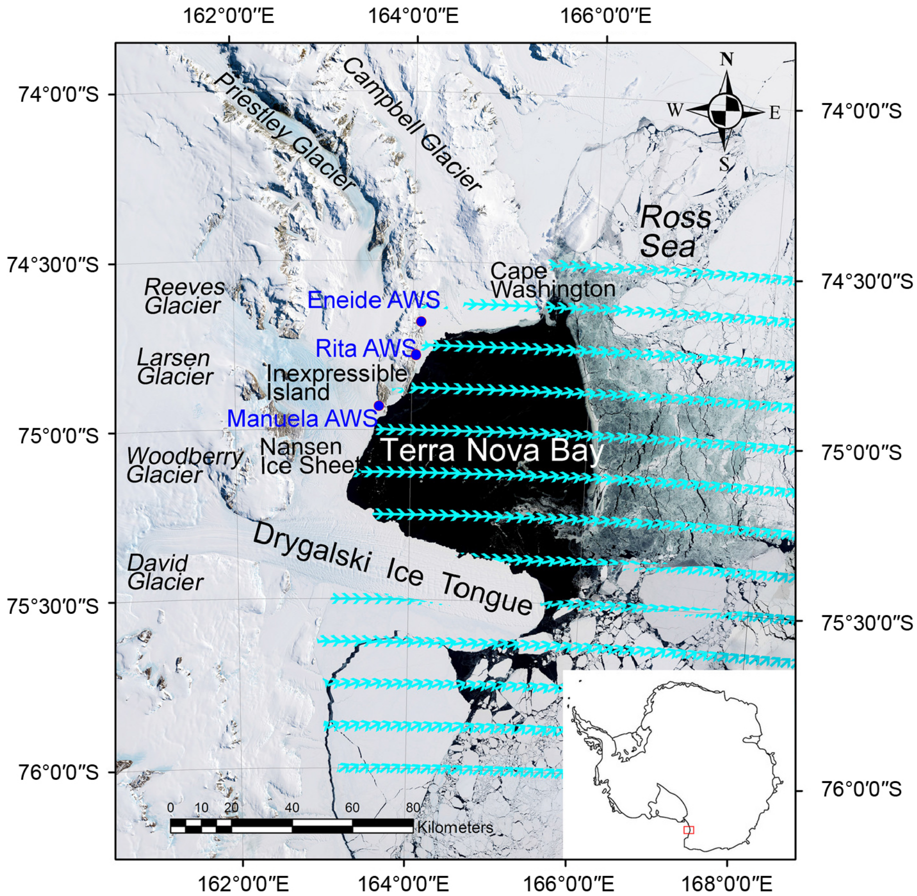

Fig. 1. Study area of Terra Nova Bay. The blue arrows stand for the local wind direction. The base map is from the Landsat-8 satellite images on 17, 23, 24 and 28 November 2017.

1993; Gallée and Schayes, 1994; Van Woert et al., 2001). Hollands and Dierking (2016) used a sequence of images to show a detailed ice drift and deformation process related to the strong winds in the TNB. As a result of these strong winds, the TNBP is regarded as a significant source of ice production and the growth rate of ice per unit area in the TNBP is 1.6 times that of the Ross ice shelf polynya (Petrelli et al., 2008). The size and production of ice in small polynyas, such as the TNBP, are more influenced by katabatic winds (Sansiviero et al., 2017) than large polynyas, which depend more on synoptic winds (Coggins et al., 2014; Nihashi and Ohshima, 2015).

Apart from the direct forcing of the winds on the polynya, the polynya also shows a close relationship with the air temperature in two potential aspects. One aspect is the forcing of the air temperature on the polynya. This forcing might be due to the effect on the ice formation, growth rate and reproduction. The severity and duration of cold air temperature is a critical factor in the thermodynamics of sea ice growth (Shokr and Sinha, 2015). The growth rate of thin ice is more rapid at lower temperatures than higher (Nakawo and Sinha, 1981; Heil et al., 1996; Lei et al., 2010). Meanwhile, the air temperature also affects the outflow of wind and therefore may act indirectly on the polynya area (Pease, 1987; Bromwich, 1989). Another aspect is the air temperature may be affected by the ocean–atmosphere heat flux as a result of the strong exchange of energy between the atmosphere and open water in the polynya (Andreas and Murphy, 1986; Kottmeier and Engelbart, 1992; Van Woert, 1999; Cassano et al., 2010; Marcq and Weiss, 2012; Haid and Timmermann, 2013). Nevertheless, previous research has shown that this heat flux is a minor source of the heat affecting changes in air temperature (Overland and Guest, 1991).

As mentioned above, the relationship between the air temperature and the polynya is complicated, which has not been fully investigated in previous studies of latent heat polynya (Maqueda et al., 2004). The two factors are more likely to be affecting each other simultaneously. It is not convincing to extract the unilateral influence of one on the other or determine which factor more dominantly affects another based on the data used in the study. We therefore primarily focus on the changes in the relationship between the polynya area and the air temperature, rather than the causality.

In this study, we examine in detail the relationship of the polynya area with winds and air temperature in specific intervals of air temperature using the polynya area, the local air temperature, eastward and northward wind speed and the surface sensible and latent heat fluxes. The air temperature and wind speed are obtained from the ERA5, ERA-Interim reanalysis datasets and observations by automatic weather stations (AWSs). The heat flux data are also from ERA5 and ERA-Interim.

2. Data and methods

The study area for the TNBP is bounded by the eastern coast of Victoria Land, the western waters of the Ross Sea, the northern part of the Drygalski ice tongue, and the southern part of Cape Washington (Fig. 1). The polynya area during 2005–2015 was mainly estimated from the sea ice concentration (SIC) obtained from the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) and the Advanced Microwave Scanning Radiometer 2 (AMSR-2). The data gap between 5 October 2011 and 2 July 2012 was filled by the Special Sensor Microwave-Imager/Sounder (SSMIS). All the processed SIC data were provided by the University of Bremen with a resolution of 6.25 km × 6.25 km (Spreen et al., 2008). According to previous research (Markus and Burns, 1995; Massom et al., 1998; Van Woert et al., 2001; Parmiggiani, 2006), we set the threshold for SIC as < 70% to define the ice-free and thin ice-covered region. Moreover, we selected 45 images from SSMIS (uniformly distributed from September to November 2010 and March to August 2013), 15 images from AMSR-E (uniformly distributed from September to November 2010), and 30 images from AMSR-2 (uniformly distributed from March to August 2013) to investigate the differences of the polynya area under the above two SIC sources. Previous research has shown the polynya area estimated by the MODIS ice surface temperature (IST) is more accurate (Ciappa et al., 2012; Aulicino et al., 2018). However, considering the effect of the cloud on MODIS IST data, we chose to use the SIC extracted from the passive microwave products to estimate the polynya area. The uncertainties of the polynya area and comparisons with the area from MODIS IST are discussed in section 4.

Since the winds and air temperature may affect each other simultaneously, we used partial correlation to control two of the three factors (air temperature, eastward and northward wind speed), and then examined the relationship of the polynya area with the rest. The air temperature, eastward and northward wind speed are from the ERA5 and ERA-Interim reanalysis datasets provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and from observations by the Eneide, Rita and Manuela AWSs in the period 2005–15. The surface sensible and latent heat flux (SSHF and SLHF) are from the ERA5 and ERA-Interim reanalysis datasets in the period 2005–15 (note: the heat flux in this paper is positive upwards). The air temperature from the reanalysis data was estimated at 2 m above the surface. The eastward and northward wind speed is the horizontal speed of air moving towards the east and north, at a height of 10 m above the surface. The Eneide and Rita AWSs, located in the northwest of the bay (Fig. 1), are maintained by the Italian Antarctic scientific station (note: the data and information were obtained from "Meteo-Climatological Observatory at MZS and Victoria Land " of PNRA—http://www.climantartide.it). The Manuela AWS, located on Inexpressible Island (Fig. 1), is maintained by the University of Wisconsin–Madison (Lazzara et al., 2012). Wind speed at 7 m (10 m before 2008) and air temperature at 2 m above ground level were obtained every hour from the Eneide and Rita AWSs. Wind speed and air temperature at 2 m above ground level were obtained every three hours from the Manuela AWS. The wind recorded by the Manuela AWS was missing from 2006 to 2011 due to problems with the anemometer.

To remove the seasonal signal in the analyses, the multi-year mean of the same day during 2005–15 was subtracted from all data (hereafter referred to as deseasonalized). To minimize the effect of solar radiation on the air temperature, all analyses were performed for the period of April to August.

3. Results

3.1. *Validation of the ERA-Interim reanalysis data*

In order to validate the data from the reanalysis, spatial correlations between air temperature from ERA5 and each one of the AWSs are presented in Fig. 2. The correlation at each grid point was obtained between daily air temperature (2005–15) from ERA5 and the observation from each AWS, which was assumed to be the same at all grid points (i.e., the single temperature from the AWS was applied to all grid points). The deseasonalized air temperature from ERA5 shows good agreement with the observations from the three AWSs, with correlation coefficients generally above 0.5, and even above 0.8, with the observations from the Eneide and Manuela AWSs. Figure 3 shows the time series of the averaged air temperature from five grids in ERA5 and ERA-Interim and the observations by the three AWSs during 2005–15. The air temperature in the five grids from the two reanalysis datasets all show similar trends to the observations. Generally, the air temperature from ERA5 is higher than that from ERA-Interim and is closer to the observations of Eneide and Rita AWS. The observation from Manuela is lower than the other two observations and the reanalysis. The agreement between the air temperature from the reanalysis and AWS observations was also discussed in Fusco et al. (2002). One should note, however, that the three AWSs are in different geographical locations and therefore may cause different correlations with the reanalysis shown in Fig. 2. The Manuela AWS is located on the Nansen ice shelf and is directly affected by the cold air from the ice sheet, resulting in the records of lower air temperature. According to the observatory at MZS (http://www.climantartide.it), the records from the Eneide and Rita AWSs are corresponding to the TNB and Enigma Lake respectively, which might be the reason why the correlation between the reanalysis and the observation by Eneide is stronger than by Rita. Though the two AWSs are close, the different environmental conditions will cause the difference in air temperature observations (i.e., the AWS located in the valleys at MZS may record higher air temperature than the AWS located on the ice shelf due to the effect of winds).

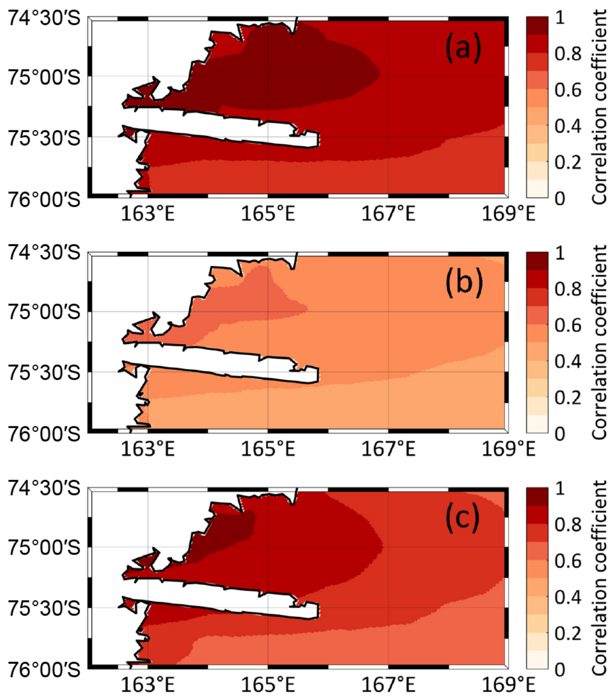

Fig. 2. Correlations between the deseasonalized air temperature from the ERA5 reanalysis and observations from the (a) Eneide, (b) Rita and (c) Manuela AWSs.

The daily averaged SSHF and SLHF in the polynya from the two reanalysis datasets are both higher than other areas, especially for the data from ERA5 (Fig. 4). The heat flux from ERA5 is larger than that from ERA-Interim and shows a more evident polynya pattern. According to Fusco et al. (2009), the annual mean of the surface heat budget in TNB during 1990–2006 was around 120 W m^{-2}, which is equal to a daily averaged heat flux of ~104×10^5 J m^{-2}. We considered this to be consistent with the total heat flux in Fig. 4 (note: the daily averaged SSHF and SLHF in TNB is about 70×10^5 J m^{-2} and 30×10^5 J m^{-2} from ERA5). Therefore, considering the agreement of the air temperature between the reanalysis and observations as well as the heat flux in the polynya area shown in the reanalysis, we assumed that the reanalysis data, especially for ERA5, in TNB is of good enough quality and therefore could be applied in this study (note: ERA5 is the primary reanalysis dataset used in the following analyses, with ERA-Interim only used for support).

3.2. *Time series of polynya area and air temperature*

Figure 5 shows the average air temperature from the three observations (Eneide, Rita and Manuela AWSs) and the ERA5 reanalysis, corresponding to the polynya area in the period of March to November. The air temperature decreases rapidly in March and gradually increases after September. During the polar night (April to August), the air temperature is generally stable and shows downward trends for both observations and reanalysis. This is the period when the outer edge of the polynya becomes stable and marks the edge of the fully consolidated pack ice (the period is indicated by the white band in Fig. 5). The average temperature in this period from the Eneide, Rita and Manuela AWSs is −20.29°C ± 5.36°C, −21.59°C ± 5.40°C and −25.24°C ± 5.02°C, respectively, and the average temper-

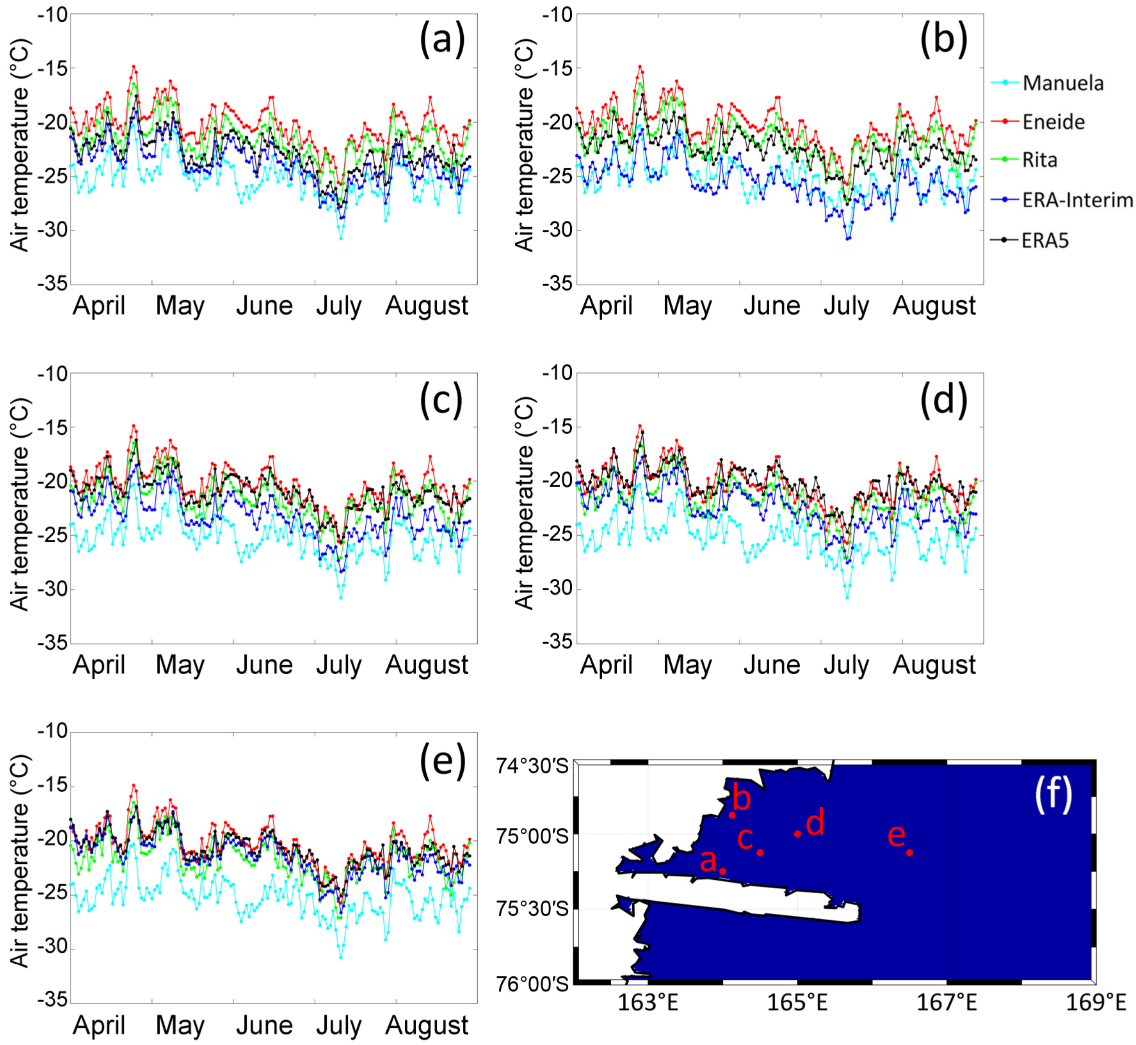

Fig. 3. Time series of the average air temperature from the grids in ERA5 and ERA-Interim reanalysis and observations by Eneide, Rita and Manuela AWS in the period 2005−15. Panels (a–e) are the time series of each reanalysis grid shown in (f).

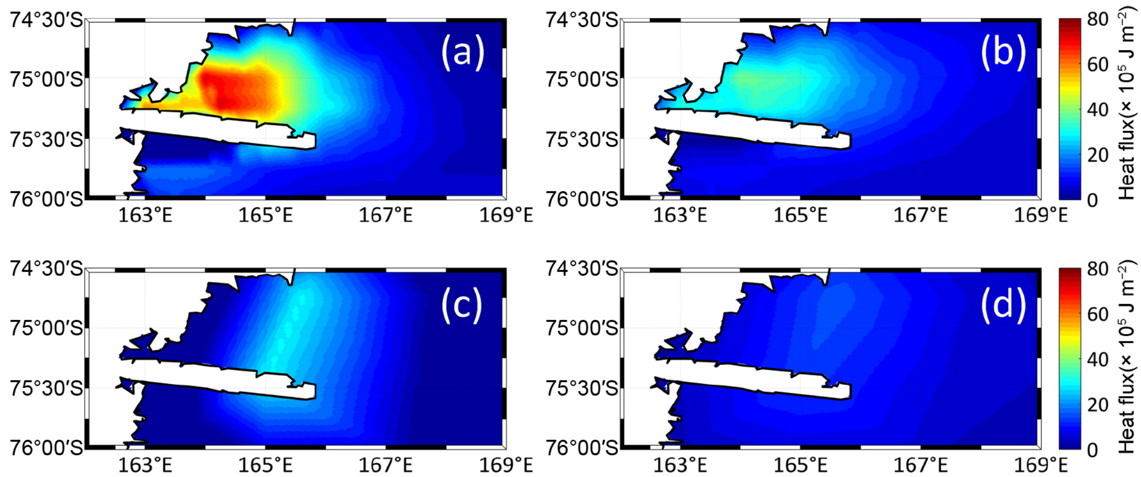

Fig. 4. Average of daily sensible and latent heat flux in the period of April to August during 2005−15: (a, b) sensible and latent heat flux from ERA5 reanalysis; (c, d) sensible and latent heat flux from ERA-Interim reanalysis.

ature from ERA5 is −21.20°C ± 4.16°C.

As the temperature decreases in March, TNB is quickly covered by sea ice and the open water area shows a clear downward trend during the polar night (April to August).

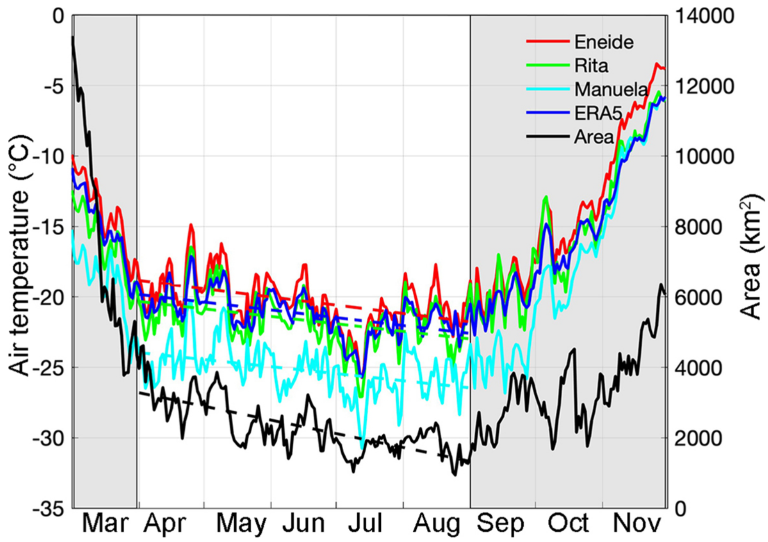

Fig. 5. Time series of the average air temperature (left-hand *y*-axis) from observations and ERA5 reanalysis and the corresponding averaged polynya area (right-hand *y*-axis) in the period of March to November during 2005−15.

The temporally averaged area is 2310.83 ± 758.32 km^2 during the polar night [note: the daily and monthly polynya area in the whole period of 2005−15 are shown in Fig. S1 and S2 in the electronic supplementary materials (ESM)]. The monthly averaged area decreases from 3250.95 km^2 in April to 1802.49 km^2 in August, which is consistent with the decreasing trend of air temperature at polar night. A significant increase in the open water area in TNB occurs after October, later than the recovery of the air temperature. The difference for the polynya area calculated from AMSR-E and SSMIS during their overlapping period is 488 km^2, and from AMSR-2 and SSMIS during their overlapping period it is 353 km^2; both are lower than the standard deviation of 758.32 km^2. Therefore, we considered that the area difference caused by the different SIC sources was acceptable.

3.3. *Relationships of the polynya with winds and air temperature*

Figure 6 shows the partial correlation coefficients between the polynya area and the air temperature from the three observations and the reanalysis data of ERA5 and ERA-Interim in the period of April to August during 2005−15. The partial correlation was performed by controlling two (i.e., eastward and northward wind speed) of the three factors and calculating the correlation coefficient between the area and the remaining factor (i.e., air temperature). The results show that the deseasonalized data (Fig. 6a) have similar correlations with the raw data (Fig. 6b). All 1639 observations and reanalysis data were used to calculate the correlation between the polynya area and each atmospheric variable (eastward, northward wind and air temperature), except for the observations from Manuela AWS. There were 1363 observations of air temperature and 724 observations of wind speed from Manuela AWS (note: the specific amounts of reanalysis data and observations are shown in Table S1 in the ESM; the information of the observed wind speed against the air temperature are shown in Fig. S3 in the ESM). The correlation coefficients between the deseasonalized polynya area and air temperature are 0.44 and 0.47 based on ERA5 and ERA-Interim; and 0.39, 0.29 and 0.32 based on the observations of the Eneide, Rita and Manuela AWSs. The statistically significant correlation coefficients for the raw data are higher but have the same signs as those of the deseasonalized data. The correlations of polynya area with air temperature from reanalysis and observations are all higher than those with the eastward and northward wind speed. The polynya area is negatively correlated with the northward wind as a result of the inshore wind, which helps push the sea ice into the polynya.

Spatial maps of the temporal correlation coefficients between the polynya area on the one hand and air temperature, eastward and northward wind from ERA5 on the other hand are shown in Fig. 7. The correlation coefficient at each pixel in the map results from having correlated the time series of ERA5 (2005−15) with the time series of the polynya area, which was fixed for all pixels. Air temperature is weakly correlated with the polynya area near the shore, but the correlation gradually increases offshore (Fig. 7a). The greater correlation offshore may result from a longer period for it to have been influenced by the open water in the polynya, while the air temperature near the coast is easily disturbed by the strong winds. An opposite trend is demonstrated by the eastward wind (Fig. 7b). The winds near the coast are more correlated with the polynya area than the winds far from the coast. This could be explained by the decreasing effect of the offshore wind on the removal of the sea ice in TNB as the downwind distance increases. The northward wind usually acts as an inshore wind and impedes the outflow of the polynya ice, therefore showing a negative correlation with the polynya area in TNB (Fig. 7c). This negative correlation is weaker than the positive correlation of the polynya area with air temperature and eastward wind speed.

The correlation between the eastward/northward wind speed and the polynya area is due to the winds forcing on the polynya. Even though the positive correlation between air temperature and polynya area has been established, the causality is still unknown. This raises the question of which one (air temperature or polynya area) is the stimulus and which is the response, or if the two factors interactively affect each other. It is worth noting that if the air temperature is the response, then the correlation coefficient between

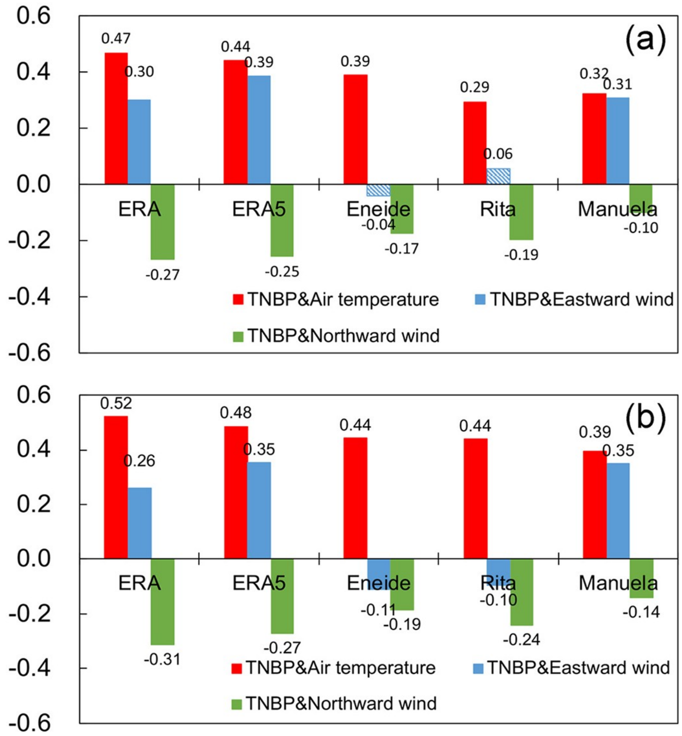

Fig. 6. Correlations of the polynya area with air temperature, eastward and northward wind speeds from the observations and reanalysis of ERA5 and ERA-Interim: (a) deseasonalized data; (b) raw data. The unshaded columns indicate statistically significant correlations (95% confidence level).

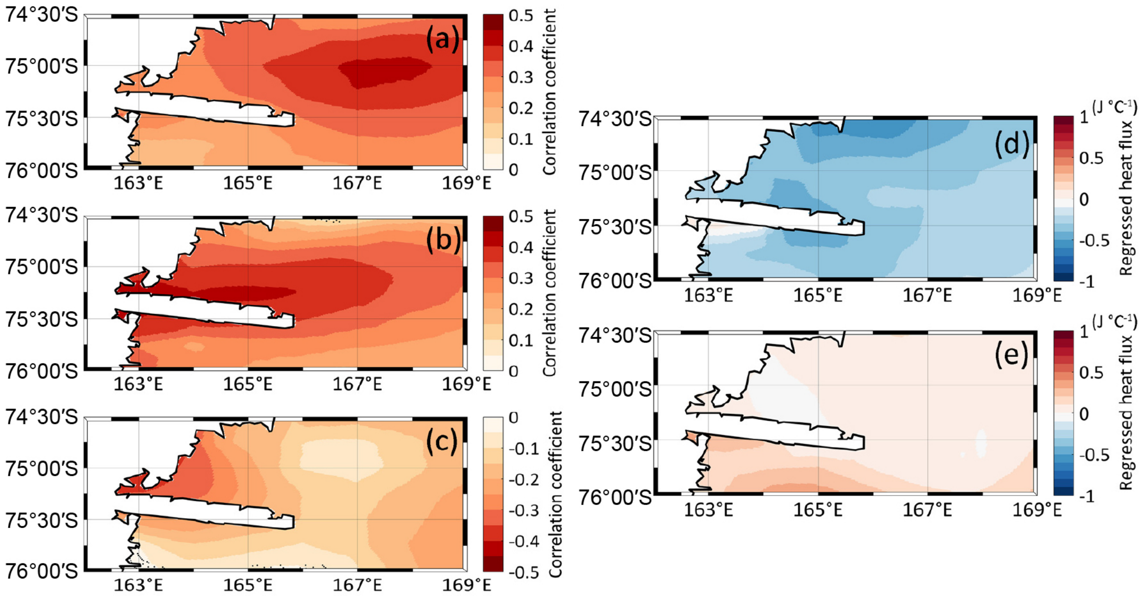

Fig. 7. Spatial correlation between the deseasonalized polynya area and (a) air temperature, (b) eastward wind speed and (c) northward wind speed from the ERA5 reanalysis and regressed (d) sensible and (e) latent heat flux against air temperature. The undotted areas indicate statistically significant correlations (95% confidence level).

the heat flux and air temperature should be positive. However, the negative correlations between the SSHF and the air temperature (Fig. 7d) and the near-zero regression coefficient between the SLHF and air temperature (Fig. 7e) suggest that the heating effect of the heat transport on the air temperature is very weak, or at least the air temperature is not the major response to the polynya area. Nevertheless, it does not mean that the air temperature is the stimulus either. The negative correlation (Fig. 7d) between the SSHF and the air temperature is primarily from the temperature gradient. In austral winter, the sea surface temperature varies less than the air temperature and therefore the temperature gradient between the air and sea surface is mainly determined by the air temperature (note: the sea surface temperature is higher than the air temperature in the winter of TNB). The increase in air temperature will weaken the temperature gradient and then reduces the flux transport (Fig. 7d). Though the latent heat is released as water freezes and also as water evaporates into the air above the open water, neither of them is the major source to warm the air temperature, which is consistent with the near-zero regression coefficient between the SLHF and the air temperature (Fig. 7e). The process is called "latent" because it is not associated with a change in temperature, but rather with a change of state (https://nsidc.org/cryosphere/seaice/characteristics/polynyas.html). The above explanation suggests that even though the heat flux from the open water in the polynya could warm the air from the physical mechanism perspective, the air temperature is at least not the major response to the polynya area. The increase of the air temperature is more likely due to external factors (i.e., the relatively warmer air blowing from the ice sheet) rather than the response to the polynya.

To further examine the potential causality between the polynya area and air temperature, we calculated the lead and lag correlations between the two factors in the following conditions: (i) the air temperature is one to ten days before the polynya area (Fig. 8a); (ii) the polynya area is one to ten days before the air temperature (Fig. 8b). The results show that the correlation is significantly positive when considering either one of the two factors (air temperature and the polynya area) is one to two days before the other. The positive correlation gradually weakens as the lead/lag days increase. The correlation is higher when the air temperature leads the polynya area (Fig. 8a), which suggests that the

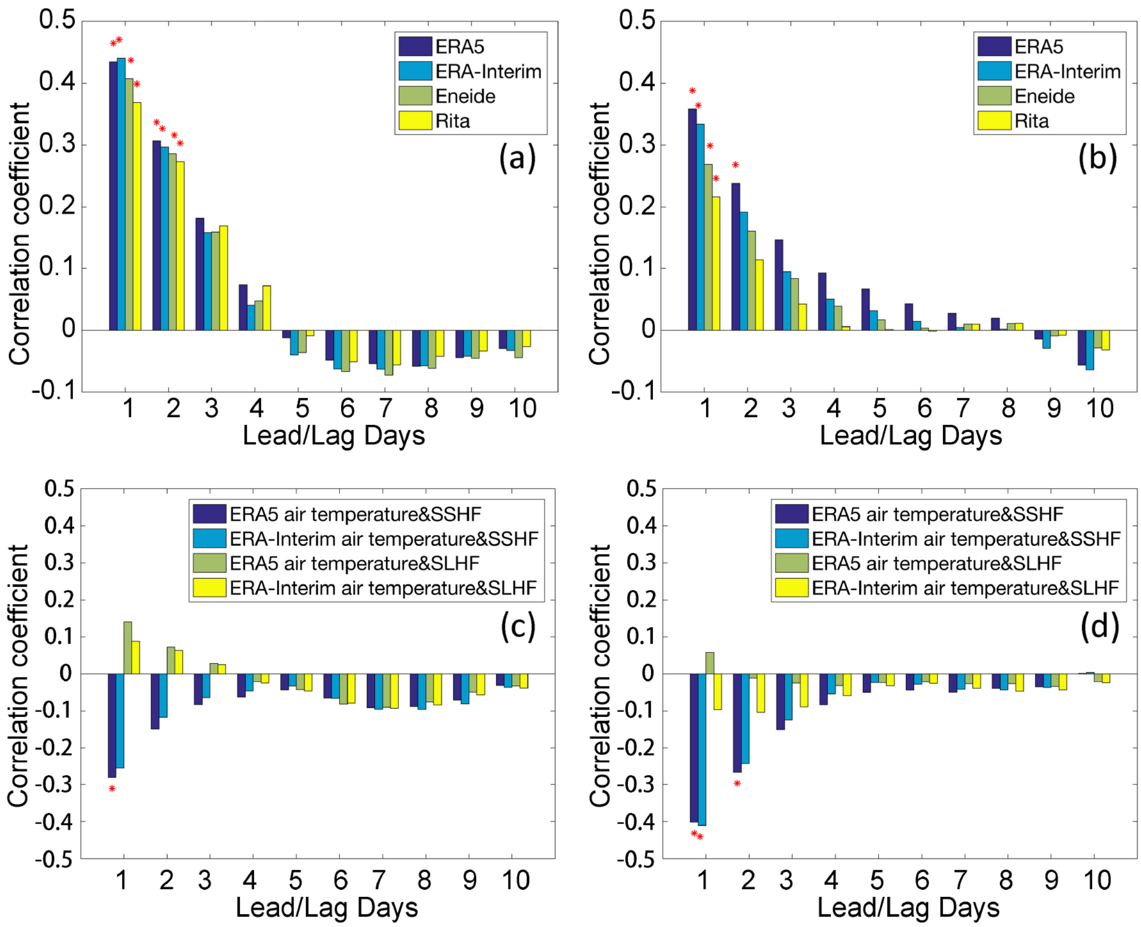

Fig. 8. The lead and lag correlations between the deseasonalized air temperature and the polynya area and between the air temperature and heat flux: (a) the air temperature is before the polynya area; (b) the polynya area is before the air temperature; (c) the air temperature is before the sensible and latent heat flux; (d) the sensible and latent heat flux are before the air temperature. The columns marked with red stars indicate statistically significant correlations (90% confidence level).

effect of air temperature on the polynya area might be stronger than the other way around. The negative correlations between the air temperature and the heat flux (Fig. 8c and Fig. 8d) also suggest that the heating of the polynya on the air temperature is very weak, no matter which factor (air temperature or the heat flux) leads the other. We therefore hypothesize that the forcing of air temperature to the polynya area (due to ice formation) may be higher than the heating effect of the polynya on the air temperature (due to heat flux transport). However, the above analyses cannot give a certain conclusion. Considering the complicated interaction between the polynya area and the air temperature, we mainly focus on the relationship between the two factors not the causality in the following analyses.

3.4. *Relationship at specific temperatures*

To estimate the specific relationship, we divided the air temperature into 10°C intervals. Figure 9 shows that the correlation between the deseasonalized air temperature and the polynya area could be divided into three categories. First, air temperature higher than approximately −14°C around the coast shows a significant positive correlation with the polynya area, with a coefficient near the shore above 0.8 when the air temperature is within approximately −10°C to 0°C (Fig. 9a). The area of significant correlations gradually retreats as the air temperature decreases in this category (Fig. 9b and 9c). The significant correlations appearing near the coast are partly due to the large variabilities of sea ice formation in TNB in the early decreasing and recovery stage of air temperature, during which the temperature is relatively higher (note: the boundary of the polynya is uncertain in this period). The strong correlation between the air temperature and the eastward wind speed in Fig. 10b (approximately −10°C to 0°C) suggests that the positive relationships might be due to the relation of air temperature with the eastward wind in the intervals. Second, the polynya area shows weak and negative correlations with the air temperature as the temperature decreases to −20°C (Figs. 9d, e and f). The negative correlations distribute widely over the polynya with the small coefficients around −0.2. According to Fig. 10b, the correlations between the air temperature and the northward wind speed strengthen in this category, which may cause the corresponding negative correlations between the air temperature and the polynya area (note: the northward winds impede the sea ice moving out of the polynya and therefore contribute negatively to the polynya area). Third, even lower air temperatures (i.e., below about −20°C) have a broader positive correlation with the polynya area. The significant correlations distribute widely over the polynya with the coefficients greater than 0.4 (Figs. 9g, h and i). The widely distributed stronger correlations in the third category indicate that the lower air temperature has a closer relationship with the polynya area.

Figure 10a shows the partial correlation of the deseasonalized polynya area with air temperature, eastward and northward wind speed in each interval. The partial correlation was performed by controlling two of the three atmospheric variables (air temperature, eastward and northward wind speed) and calculating the correlation coefficient between the remaining one and the polynya area. The results show that the correlation coefficients of the polynya area with eastward and northward wind speed gradually decline as air temperature drops, while the correlation between the air temperature and the polynya area increases. The eastward and northward wind speed show significant positive and negative correlation with the polynya area in almost all intervals. Nevertheless, the higher correlation coefficients above 0.6 for eastward wind and below −0.4 for northward wind with the polynya area, usually appear in higher air temperature intervals. Significant correlations between the air temperature and the polynya area only occur in lower temperature intervals and gradually increase from 0.16 to 0.52 as temperat-

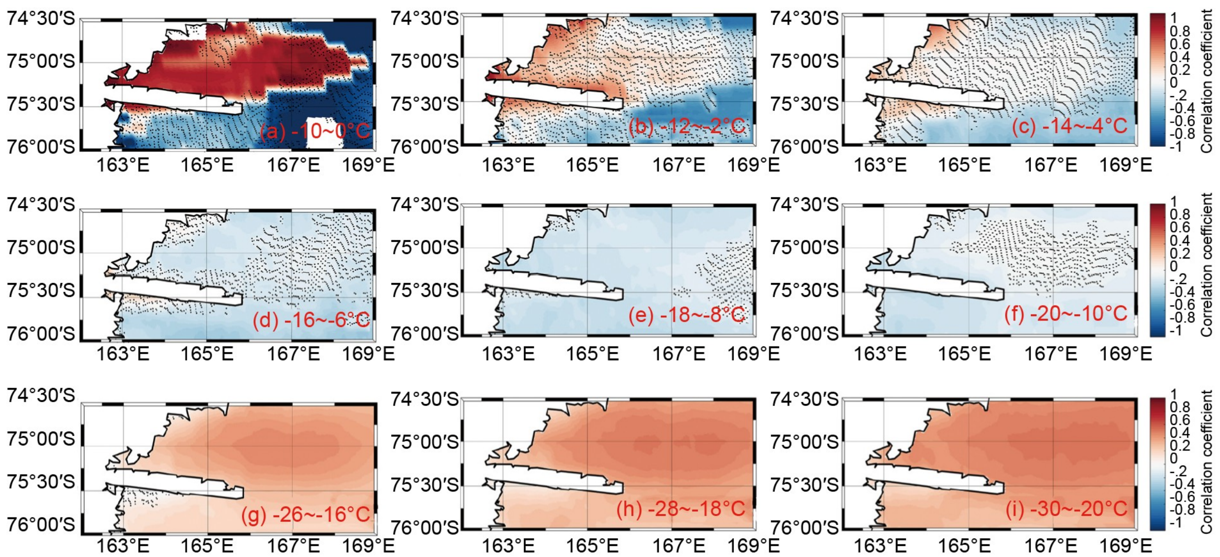

Fig. 9. Correlations between the deseasonalized polynya area and the air temperature from the ERA5 reanalysis in the different temperature intervals. The undotted areas indicate statistically significant correlations (95% confidence level).

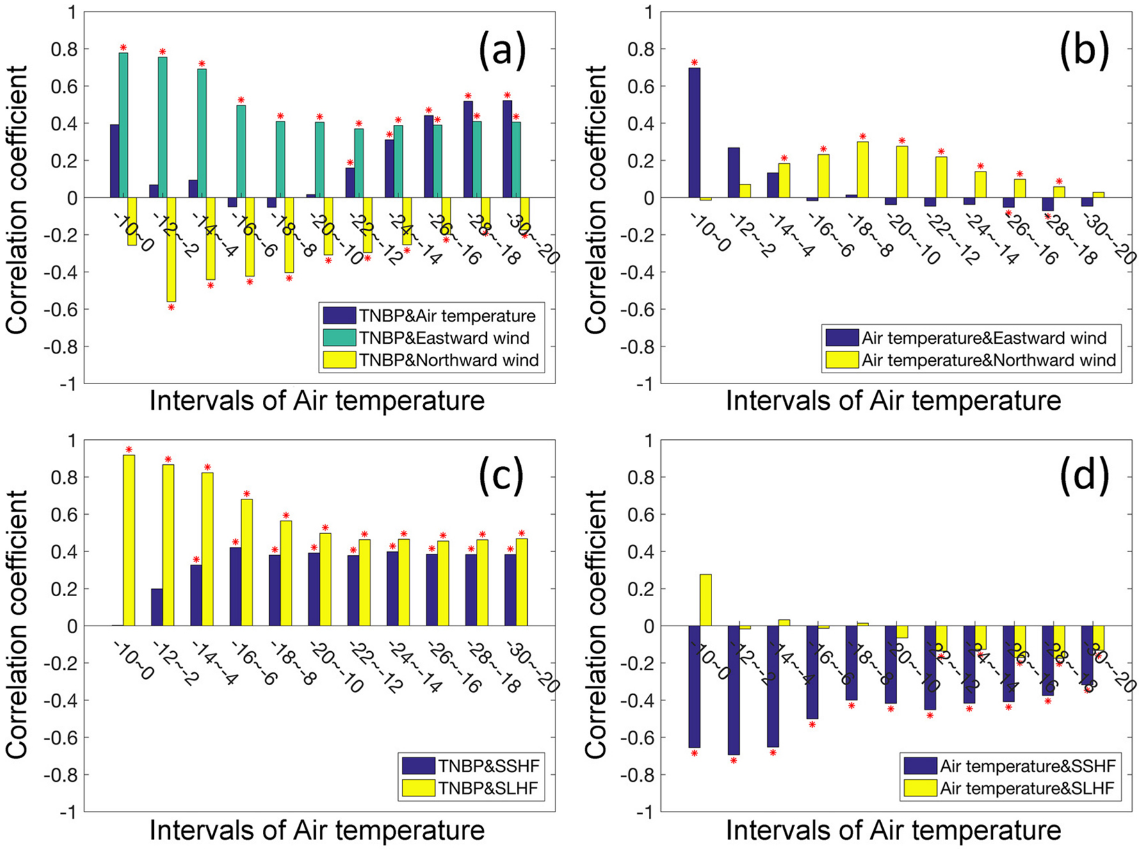

Fig. 10. Correlations of the deseasonalized polynya area with (a) the air temperature and eastward and northward wind speed and (c) the sensible and latent heat flux. Correlations of the deseasonalized air temperature with (b) the eastward and northward wind speed and (d) the sensible and latent heat flux. The air temperature, wind speed and heat flux are from the ERA5 reanalysis. The columns marked with red stars indicate statistically significant correlations (95% confidence level).

ure decreases, which is consistent with the spatial correlation shown in the third category in Fig. 9. According to the weak and non-significant correlation between air temperature and eastward wind speed (Fig. 10b), the positive relationship between low air temperature and the polynya area is not from the synergistic relation with the eastward wind speed. The SSHF and SLHF will increase as the polynya area increases and this phenomenon is shown in all temperature intervals (Fig. 10c). However, the negative and weak correlations of the air temperature with the SSHF and SLHF (Fig. 10d) suggest that heating of the air by the polynya is unimportant for all temperature intervals, which agrees well with the previous analyses.

According to the above analyses, the positive correlation between the polynya area and the air temperature is unlikely due to the heating effect of the polynya through the heat transport. Here, we hypothesize that the low air temperature may have a forcing on the polynya area through new ice formation, which may result in the positive correlation with the polynya area. Based on this hypothesis, the low air temperature may contribute more to the variations in polynya area than the winds, i.e., in the interval of −30°C to −20°C, the air temperature accounts for about 25% of the variations in polynya area, larger than the contribution from the eastward (~16%) and northward (~3%) wind speed.

4. Discussion

We have presented a combined analysis of the relationship of air temperature and wind speed with the area of the TNBP at specific temperatures at polar night during 2005−15. The results from both the reanalysis and observations indicate that air temperature gradually shows an increasing positive correlation with the polynya area as temperature declines, while the correlation of the eastward and northward wind speed with the polynya area decreases. The negative or very weak correlations between the heat flux and the air temperature suggest that the heating of the air by the polynya is not an important factor, which means the positive correlation between the air temperature and the polynya area is unlikely to be from the response of the temperature to the polynya. From the aspect of rapid ice formation in lower air temperature, the positive correlation is possibly due to the response of the polynya to air temperature (note: here, we only propose a potential hypothesis; model simulations are needed for further conclusions). The relationship between the air temperature and the polynya area can be divided into three categories as temperature declines. First, the positive correlations between air temperature and the polynya area appears near the coast and the significant areas gradually retreat as temperature declines. Second, air temperature shows weak and negative correlation with the polynya area, which might be owing to the stronger correlation of the air temperature with the northward wind speed in this category. Third, the positive correlations of the even lower air temperature with the polynya area distribute widely over TNB, which is the major result in this study, i.e., that the polynya area has a significantly closer relationship with the low air temperature.

The pressure gradient between the ice sheet and the ocean surface is also affected by air turbulence, which influences the output of katabatic winds. Strong pressure gradients are more likely to disrupt the production of cold air in winter as a result of mixing between warm maritime air and cold continental air (Bromwich, 1989). However, considering the very weak correlation between wind speed and lower air temperature (Fig. 10b), we suggest that the polynya area is more directly related to the low air temperature and not the synergistic relation with winds. The surface conductive heat flux of thin ice at −20°C ± 1°C is about twice that at −10°C ± 1°C (Lei et al., 2010). It has been observed that open water rapidly freezes when the air temperature is very low. The Canadian Ice Service observed that thin ice quickly thickens to 100 mm within 24 hours at a steady air temperature of −25°C (Shokr and Sinha, 2015). Though the effect of lower air temperature on the polynya area from the aspect of the rapid ice formation is a hypothesis in this study, it needs to be seriously considered in further studies of the polynya, i.e., the TNBP. It is essential to examine the relationship between the specific temperatures and the polynya, for the objective of obtaining detailed polynya variations. Though the TNBP is a smaller polynya in the Antarctic, the high rate of sea ice production and high-salinity shelf water in the polynya will directly affect the Antarctic bottom water in the Ross Sea and, in turn, the circumpolar deep water currents. Our study shows a changing relationship between the air temperature and the polynya area at specific temperature intervals. Further studies will apply a regional model to Antarctic coastal polynyas to examine the underlying mechanisms.

The polynya area estimated in the study was based on the microwave products of SIC. Previous studies have proposed another method to retrieve the polynya area by using the MODIS IST data (Ciappa et al., 2012; Aulicino et al., 2018). The MODIS IST data derived from the thermal infrared MODIS bands provide new polynya observations of high horizontal resolution (1 km) and seem to have higher accuracy in area estimation than the microwave data. Table 1 shows the TNBP area estimated in different research. The area of ~0.9 × 10^3 km^2 estimated from the MODIS IST data is smaller (Ciappa et al., 2012), which might be due to the smaller size of the subregion of TNB and the finer resolution of the MODIS data. The polynya area estimated in Kern (2009) and Martin et al. (2007) are both from the microwave data but based on different methods. Kern used the difference of the brightness temperature, while Martin et al. used ice thickness to determine the polynya area. The average area estimated in this study is about 1.5 × 10^3 km^2 larger than that from the MODIS IST. However, the results show that the polynya areas estimated from the microwave data based on the different methods [4.2 × 10^3 km^2 in Kern (2009) and 3.0 × 10^3 km^2 in Martin et al. (2007)] are both greater than that from the MODIS IST. The difference is highly likely due to the different datasets. In general, the area estimated in this study is smaller than that from Kern (2009) and Martin et al. (2007), which also used the microwave data for area estimation, but our results range in the middle of the three given studies. The difference is highly likely due to the different study periods and the methods used for the area estimation [note: the area in Kern (2009) and Martin et al. (2007) was estimated during 1992–2002].

Table 1. Averaged polynya area estimated from this study and previous research.

Year	TNBP area (×10^3 km^2) estimated from			
	This study	Ciappa et al. (2012)	Kern. (2009)	Martin. et al. (2007)
2005	2.4	~0.97		
2006	1.8	~0.60		
2007	3.1	~0.98		
2008	3.0	~0.90		
2009	2.7	~0.93		
2010	3.1	~0.85		
2011	1.8			
2012	2.3			
2013	2.4			
2014	2.3			
2015	1.6			
Average	2.4 ± 0.5 (2005–15)	~0.87 ± 0.14 (2005–10)	4.2 ± 0.8 (1992–2002)	3.0 ± 0.8 (1992–2002)

Note: The polynya area from this study, Ciappa et al. (2012) and Martin et al. (2007) was estimated in the period of April to October. The polynya area from Kern (2009) was estimated in the period of June to September.

5. Conclusions

In this study, we used ERA5 reanalysis data (with ERA-Interim reanalysis as support) and AWS observations at polar night to examine the relationship between the area of the TNBP and air temperature as well as the eastward and northward wind speed. The 2-m air temperature from ERA5 was found to correlate well with the AWS measurements. Moreover, the correlation coefficients of the polynya area with air temperature are above 0.4 based on the reanalysis and above 0.3 based on the observations, which are greater than the correlations with the eastward and northward wind speed. The polynya area shows a downward trend during the polar night (April–August), from an average of 3250.95 km^2 in April to 1802.49 km^2 in August, consistent with the decreasing trend of air temperature. The average area is 2310.83 ± 758.32 km^2 in the period of April to August during 2005–15.

The main conclusion from this study is that the relationship of the polynya area with low air temperature is closer than that with eastward and northward wind speed in the same temperature intervals. The positive correlation between the air temperature is unlikely due to the effect of heat flux from the polynya on the air. Nevertheless, it is also arbitrary to conclude that the lower air temperature has a direct forcing on the polynya area. The results suggest that the two factors are more likely affecting each other, though the response of the polynya area to the air temperature seems to be stronger from the lead and lag correlation. It is clear that the relationship of the polynya area with the air temperature becomes closer as air temperature drops, while the relationship with the wind speed weakens. The analyses based on partial correlation suggest that the close relationship between the low air temperature and the polynya area is not from the synergistic relation with wind speed. In the intervals of low air temperature (i.e., air temperature < −26 °C), the positive correlation of the polynya area with air temperature is outstanding.

Acknowledgements. This work was funded by the National Natural Science Foundation of China (Grant No. 41830536, Grant No. 41676190, and Grant No. 41941009) and the Fundamental Research Funds for the Central Universities (Grant No. 12500-312231103).The authors thank the University of Bremen for providing the AMSR-E, AMSR-2 and SSMIS SIC data, as well as the University of Wisconsin–Madison Automatic Weather Station Program (NSF Grant No. ANT-1543305) and PNRA, the Italian National Program for Antarctic Research project Meteo-climatological Observations, for providing the observational data. The authors also thank David BROMWICH from The Ohio State University for his helpful comments.

Electronic supplementary material: Supplementary material is available in the online version of this article at https://doi.org/10.1007/s00376-020-9146-2.

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