Atmospheric hydrological cycles in the Arctic and Antarctic during the past four decades

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Abstract

Atmospheric hydrological cycles over the Arctic and Antarctic have been investigated in the previous studies and there are some similarity and dissimilarity in the two polar regions. The Arctic and Antarctic are areas of moisture flux convergence through the year. So the precipitation (*P*) exceeds the evaporation (*E*) and the net precipitation (*P-E*) is positive. Therefore, the atmospheric moisture transport is a primary input of water into the polar regions. Meanwhile the climatological seasonal cycles of *P-E* over these regions are dominated by transient moisture flux associated with cyclone activities, the interannual variations are governed by the stationary flux associated with the Arctic Oscillation and the Antarctic Oscillation (AAO). In addition, recent climate changes influence the polar hydrological cycles. Our analyses using an atmospheric reanalysis up to recent years indicated that there were no significant long-term changes in the poleward moisture transport into both the Arctic and Antarctic during 1979-2016. On the other hand, the water vapor (precipitable water) were clearly increasing over the Arctic and gradually decreasing over the Antarctic during the same period. As expected, the increasing trend of water vapor was due to the large warming over the Arctic. There were two reasons for the gradually decreasing trend of water vapor over the Antarctic. The first one was the positive trend of AAO in summer and the second was deepening trend of the Amundsen low in autumn. The trends in water vapor and temperature during the past 38 years further suggest that both polar regions were getting dryer in several seasons. The trend, however, needs to be confirmed by follow-up climatological analyses.

Key words: Arctic, Antarctic, polar region, atmospheric moisture flux, water vapor, precipitable water

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List of abbreviations: *P* – Precipitation, *E* – Evaporation, *P-E* – Net precipitation, *PW* – Precipitable Water, *SAT* – Surface Air Temperature at 2m, *Z850* – Geopotential height at 850 hPa, q_s – Saturated water vapor content, AO – Arctic Oscillation, AAO – Antarctic Oscillation, IPCC – Intergovernmental Panel on the Climate Change, ECMWF – European Centre for Medium-Range Weather Forecasts, JFM – January, February, March, AMJ – April, May, June, JAS - July, August, September, OND – October, November, December

Introduction

Over the Arctic and Antarctic, moisture flux is convergent throughout the year (*see* Fig. 1). The moisture convergence corresponds to the positive difference between precipitation and evaporation (*P-E*), which is so-called net precipitation, and this means that *P* exceeds *E* over the polar regions. The *P-E* over the Arctic is an input of freshwater from the atmosphere into the Ocean and plays an important role in the hydrological cycle and climate system in this region (Aagaard et Carmack 1989, 1994). On the other hand, the *P-E* over the Antarctic is an accumulation and directly affects growth and decay of the ice sheet (Bromwich 1990, Bromwich et al. 1995, Yamazaki 1992). Therefore, the net precipitation and associated moisture transport are key components of the polar hydrological cycle.

In the recent decades, several drastic changes have been observed in the Arctic; the sea ice has been declining accompanied with the Arctic amplification of the global warming (Comiso 2006, Comiso et al. 2008, Screen et Simmonds 2010, Strove et al. 2012), cyclone activity and extreme events have been changed compared to the past (Francis et Vavrus 2012, Screen et Simmonds 2013), while the latter is still under debate. In the Antarctic, the mass of the ice sheet has been decreasing ([1]), westerly jet over the Southern Ocean has been enhanced due to the ozone depletion and global warming (Arblaster et Meehl 2006, Turner et al. 2007) and the Amundsen low has been deepening (Raphael et al. 2016) during the past decade. Moreover, sea ice extent in both polar regions reached record lows in November and December 2016, when during the months the sea ices are increasing in the Arctic and decreasing in the Antarctic. It is expected that these recent changes may further affect the hydrological cycle in polar regions. In this study, at first we review some characteristics of the atmospheric hydrological cycles in the Arctic and Antarctic. After that, we examine the long-term changes in water vapor and its transport over the both regions during the period from 1979 to 2016.

Material and Methods

We used monthly mean precipitable water (*PW*, total amount of water vapor in a column of the atmosphere), vertically integrated moisture flux (eastward component and northward component), surface air temperature at 2m (*SAT*) and geopotential height at 850 hPa (*Z850*) based on the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis (Dee et al. 2011) from 1979 to 2016 (38 years). The data were obtained from the ECMWF website ([WP1]). The horizontal resolution is 0.75° in latitude and longitude. We calculated linear trends at each grid point for each of the variables using the least squares linear regression over the period and applied the Mann-Kendall test for the significant test of trends. We analyzed those variables in 4 seasons and of course the seasons reverse in the Arctic and Antarctic; January, February, March (JFM) mean corresponds to boreal winter and austral summer; April, May, June (AMJ) mean is boreal spring and austral autumn; July, August, September (JAS) mean is boreal summer and austral winter; October, November, December (OND) mean is boreal autumn and austral spring.

Results and Discussion

Climatological characteristics of the atmospheric hydrological cycle

First, we briefly looked back on the climatological characteristics of the atmospheric hydrological cycle based on the previous studies (*e.g.* Bromwich et al. 1995, Yamazaki 1992, Serreze et al. 1995, Serreze and Barry 2000, Oshima et Yamazaki 2004, 2006). There are several similarity and dissimilarity in terms of the hydrological cycles in the Arctic and Antarctic. As mentioned above, water vapor over polar regions is supplied from the surrounding lower latitudes (Fig. 1) and the moisture fluxes are convergent, resulting in the positive *P-E* both over the Arctic (Serreze et al. 1995, Serreze et Barry 2000, Oshima et Yamazaki 2004) and Antarctic (Yamazaki 1992, Bromwich et al. 1995, Oshima et Yamazaki 2004).

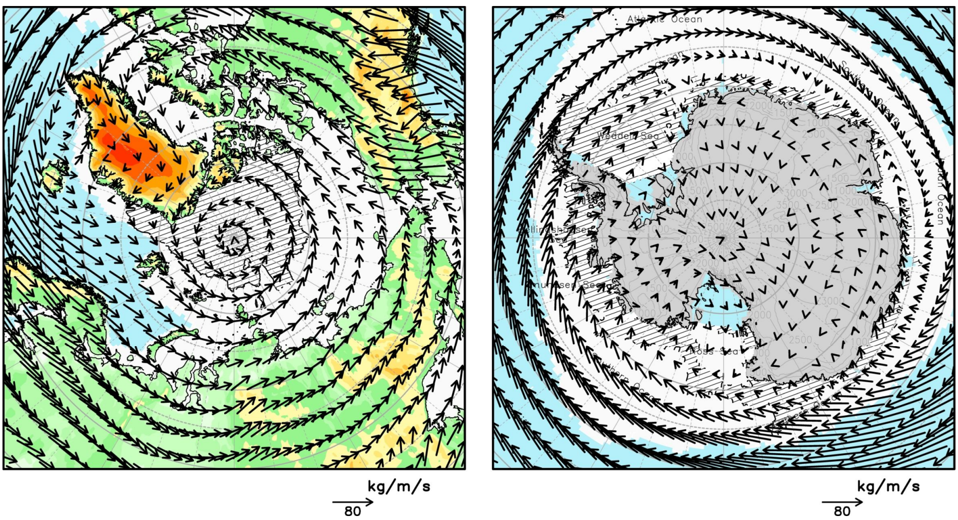

Fig. 1. Vertically integrated moisture flux over (left) the Arctic in boreal summer (July, August, September mean), and (right) the Antarctic in austral winter (July, August, September mean). Colored, white and hatched areas denote topography, maximum and minimum sea ice extent in winter and summer of 2012, respectively.

Those convergences over the polar regions correspond to zonal mean poleward moisture flux at the latitude circle of each region and these are almost equivalent to the *P-E* on long-term average. In addition, the poleward moisture transports into the Arctic and Antarctic are dominated by transient component of moisture flux, which is associated with cyclone activity and the transient flux mainly affects convergence over both polar regions (*e.g.* Oshima et Yamazaki 2004).

Interestingly, the *P-E* indicates the reverse seasonal cycle between the Arctic and Antarctic. The *P-E* shows a boreal summer peak in the Arctic (*e.g.* Serreze et al. 1995, Serreze et Barry 2000), but austral winter in the Antarctic (*e.g.* Yamazaki 1992, Bromwich et al. 1995). The former is reasonable because the *PW* during the warm season is much larger than the cold season. However, the latter is inconsistent with the above logic of the seasonal change in *PW*, while the role of winter cyclone activity on the large *P-E* over the Antarctic had been discussed in the previous studies (Yamazaki 1992, Bromwich et al. 1995). Oshima et Yamazaki (2006) quantitatively explained the reverse seasonal cycles. The large north-south contrast in water vapor during the summer season enhances poleward moisture flux in the Arctic and results in the boreal summer peak of *P-E* over the Arctic. On the other hand, the active cyclone during the winter season strongly promote poleward moisture flux in the Antarctic and results in the austral winter peak of *P-E* over the Antarctic. We further discussed that the root cause must be the differences in geographical environment (land/sea location) between the Arctic and Antarctic.

Interannual variation and long-term changes in the polar regions

According to the previous studies (Roger et al. 2001, Boer et al. 2001, Oshima et Yamazaki 2004), the Arctic Oscillation (AO) and Antarctic Oscillations (AAO) affect the interannual variations of moisture transport over the Arctic and Antarctic, respectively. The AO and AAO are dominant modes of atmospheric internal variability over the Northern and Southern Hemispheres (Thompson et Wallace 1998, Gong et Wang 1999). When the AO (AAO) is positive, the eastward moisture flux enhances accompanied with westerly wind anomaly and poleward moisture flux also intensifies around 60°N (60°S). In contrast, when the AO/AAO is negative, the flux anomalies show in the opposite directions.

We further examined the long-term changes in moisture flux and water vapor over the polar regions up to recent years. Fig. 2 shows the time-series of annual and zonal mean poleward moisture flux surrounding the Arctic and Antarctic, annual mean *PW* and *SAT* averaged over each region during 1979-2016. As mentioned in the Introduction, the poleward moisture flux corresponds to moisture flux convergence and *P-E* over the Arctic and Antarctic. There is no clear long-term trend of the poleward fluxes over the 38 years both in the Arctic (Fig. 2a) and Antarctic (Fig. 2b). This result for the Arctic is consistent with recent study (Dufour et al. 2016). The poleward moisture flux trends are 0.09 (kg/m/s)/38year for the Arctic, and -0.03 (kg/m/s)/38year for the Antarctic, but neither are statistically significant (Table 1). On the other hand, the *PWs* show significant trends in both polar regions. The *PW* is increasing over the Arctic (Fig. 2a) and gradually decreasing over the Antarctic (Fig. 2b). The *PW* trends are 0.73 mm/38year for the Arctic and -0.16 mm/38year for the Antarctic. Both of these are statistically significant (Table 1). As expected, the *PW* over the both regions were positively correlated with the *SAT*. The correlation coefficients are 0.91 for the Arctic and 0.67 for the

Antarctic both above the 99% significant level. Thus, over the Arctic, the large warming of *SAT* (3.17°C/38year) affects the increasing trend of *PW* over the Arctic. However, the *SAT* over the Antarctic does not show a long-term trend (0.03°C/38year) and the cause of the decreasing trend of *PW* over the Antarctica is unclear.

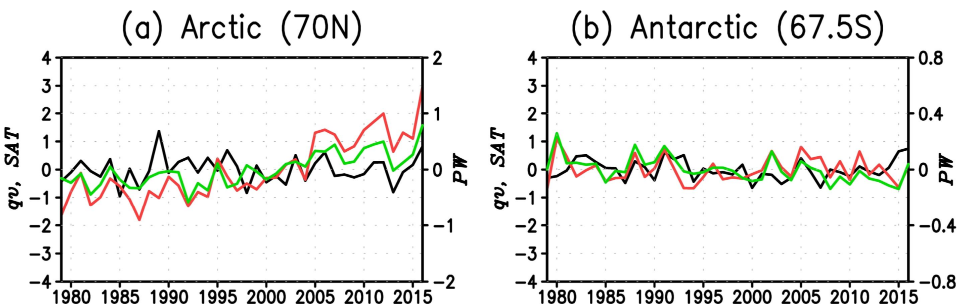

Fig. 2. Time series of annual mean poleward moisture flux (black line), *PW* (green line) and *SAT* (red line) from 1979 to 2016. (a) The poleward moisture flux is zonal mean at 70°N, *PW* and *SAT* are averaged north of 70°N over the Arctic. (b) The poleward moisture flux is zonal mean at 67.5°S, *PW* and *SAT* are averaged south of 67.5°S over the Antarctic. These time series are anomalies from the average over the 38 years. Note that axes of *SAT* (*PW*) show on the left (right) hand side of each panel. Units of poleward moisture flux, *PW* and *SAT* are kg/m/s, mm and °C.

Long-term changes over the Arctic

As in Fig. 2, the time-series of poleward moisture flux, *PW* and *SAT* for 4 seasons are shown in Fig. 3. Similar to the annual mean, in the Arctic, there are no significant trends of poleward moisture flux in 4 seasons (Fig. 3a-d). The *PW* and *SAT* over the Arctic are positively correlated and the both show significant increasing trends in every season (Figs. 3a-d). The correlations between the *PW* and *SAT* range from 0.88 to 0.91 and the trends of *PW* range from 0.33 to 1.14 mm/38year (Table 1). The horizontal distributions in each season showed increasing trends of *PW* over most of the Arctic and also warming trends over almost the same regions (Figs. 4a-d). The large warming trend and associated *PW* increase in boreal winter (JFM, Fig. 4a) and autumn (OND, Fig. 4d), especially over the Barents Sea, corresponded to sea ice reductions. In addition, decreasing trends in *PW* accompanied with cooling trends of *SAT* are seen over the northern part of the Bering Sea and eastern part of Siberia in boreal winter (JFM, Fig. 4a), and broad areas of Siberia in boreal summer (JAS, Fig. 4c) and autumn (OND, Fig. 4d). The *Z850* trends showed negative phase of AO/NAO-like pattern in boreal winter (JFM), dipole anomaly pattern over the Arctic Ocean in summer (JAS), which is known as an influence on the sea ice reduction (Wang et al. 2009), and positive anomaly over the Europe-Siberia regions indicating intensification of the Siberian High in autumn (OND). These changes in atmospheric large-scale circulation affect the above local changes in the *PW* and *SAT* over the Arctic.

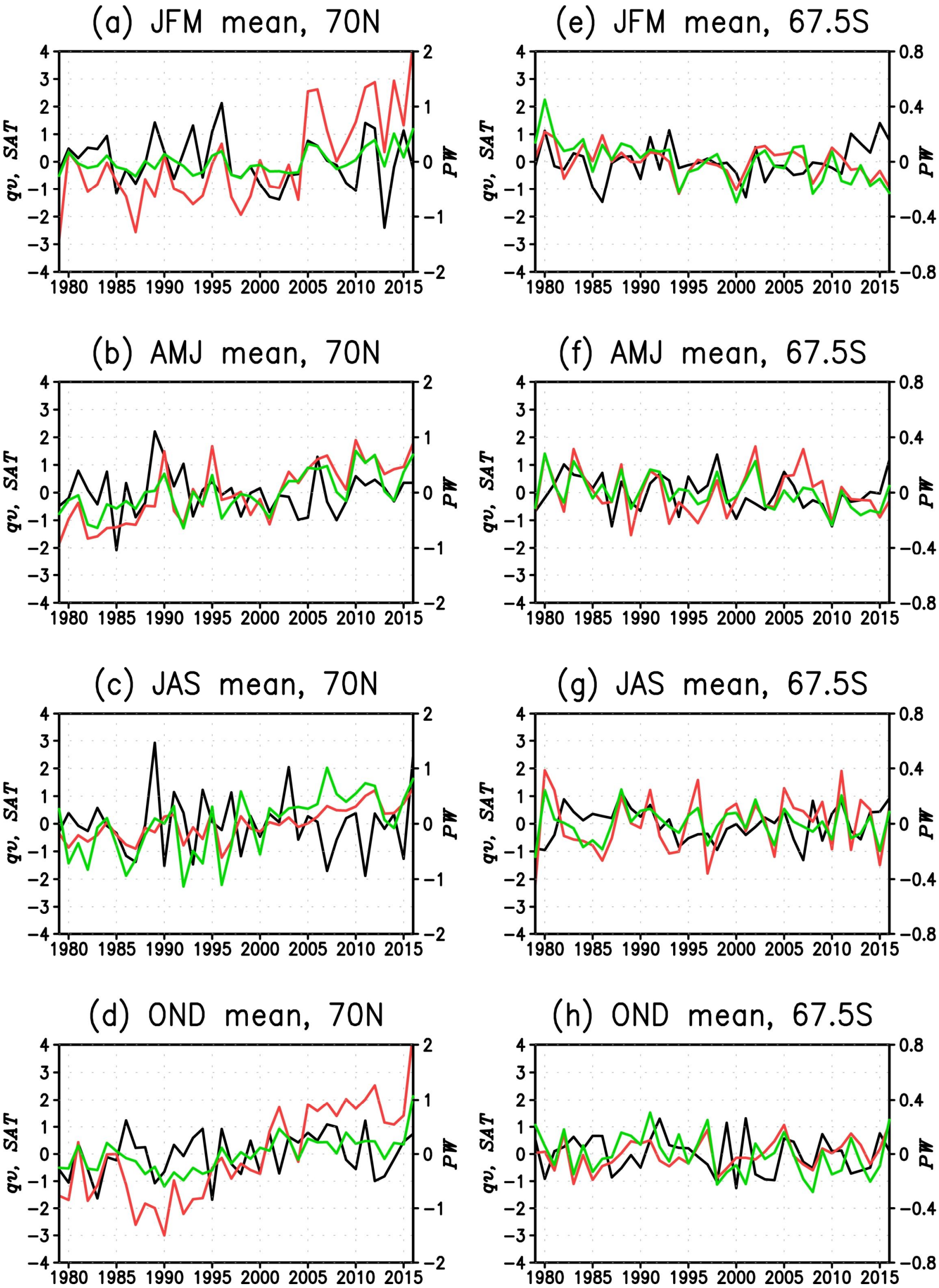

Fig. 3. Same as in Figure 2, but for the seasonal means. (a) boreal winter; JFM mean, (b) boreal spring; AMJ mean, (d) boreal summer; JAS mean, (d) boreal autumn; OND mean in the Arctic. (e) austral summer; JFM mean, (f) austral autumn; AMJ mean, (g) austral winter; JAS mean, (h) austral spring; OND mean in the Antarctic. Black, green and red lines denote poleward moisture flux, *PW* and *SAT*. These time series are anomalies from the average over the 38 years. Note that axes of *SAT* (*PW*) show on the left (right) hand side of each panel.

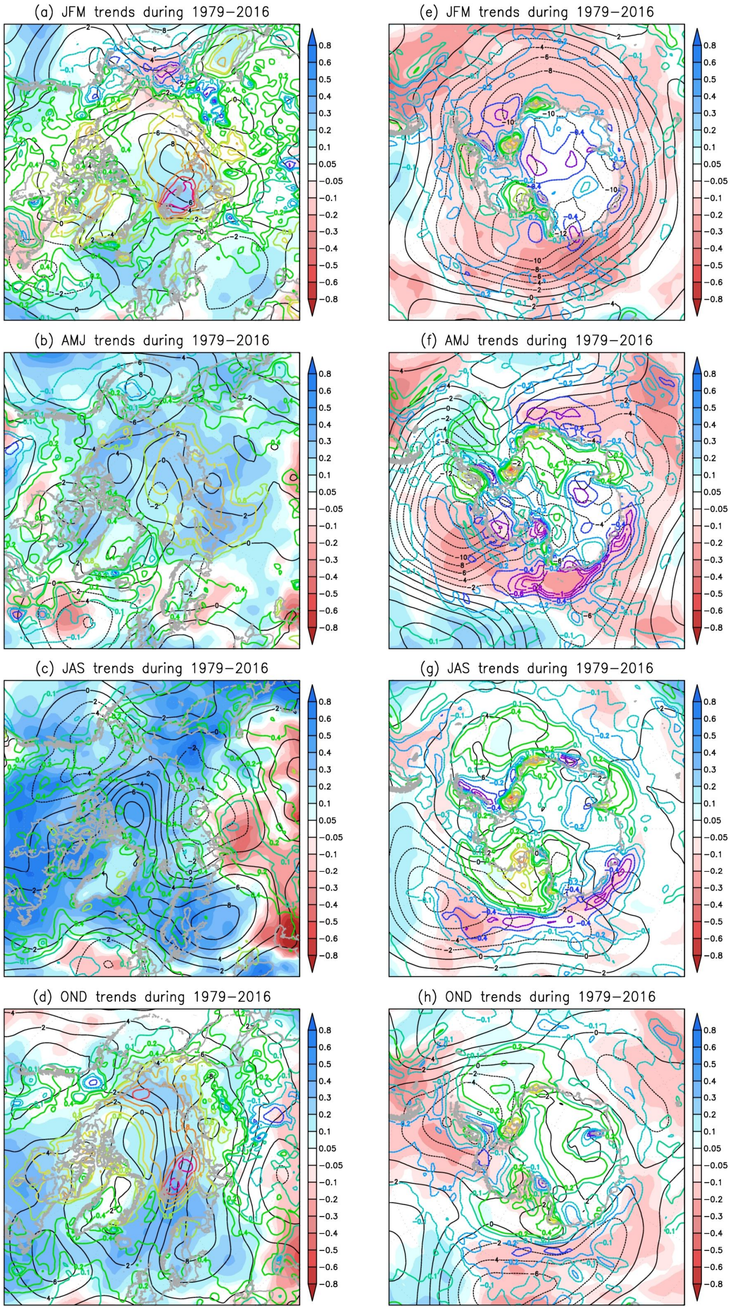

Fig. 4. Spatial distribution of trends of *PW*, *SAT* and *Z850* during the period 1979-2016 over (a-d) the Arctic and (e-h) the Antarctic for 4 seasons. (a) boreal winter; JFM mean, (b) boreal spring; AMJ mean, (d) boreal summer; JAS mean, (d) boreal autumn; OND mean over the Arctic. (e) austral summer; JFM mean, (f) austral autumn; AMJ mean, (g) austral winter; JAS mean, (h) austral spring; OND mean over the Antarctic. Shade, colored contour and black contour denote the trends of *PW* (0.1 mm/38year), *SAT* (0.1 °C/38year), and *Z850* (0.1 m/38year).

Long-term changes over the Antarctic

Same as in the Arctic, the interannual variation of *PW* over the Antarctic was positively correlated with that of *SAT* in each season (Figs. 3e-h). The correlation coefficients ranged from 0.72 to 0.85 in 4 seasons. The *SAT* over the Antarctic showed statistically significant cooling trend only in the austral summer (JFM) of -0.70°C/38year, and in association with this, the *PW* showed a significant decreasing trend of -0.32 mm/38year in this season (Fig. 3e, Table 1). In austral autumn (AMJ, Fig. 3f), the *PW* also showed a significant decreasing trend of -0.17 mm/38year, though the decreasing *SAT* trend of -0.29°C/38year was not statistically significant (Table 1). Thus, those decreasing trends of *PW* in austral summer and autumn contributed to the decreasing trend of annual mean *PW* (Fig. 2b). The spatial distribution of *Z850* trend in austral summer (JFM, Fig. 4e) indicated the positive phase of AAO, as in Arblaster et Meehl (2006) and Turner et al. (2007). This AAO-like pattern leads to cooling trend of *SAT* over the Antarctica and decreasing trend of *PW* over the western Antarctica. The *Z850* trend in austral autumn (AMJ, Fig. 4f) shows that the Amundsen low was deepening during the past 38 years as in Raphael et al. (2016). This affects decreasing trends of *PW* over the Ross Sea and surrounding regions where southerly wind blows in the western part of the low, while some increasing trends are seen over the Antarctic Peninsula and the Weddell Sea. Therefore, the decreasing trends of *PW* associated with the positive trend of AAO in austral summer (Fig. 4e) and with the deepening trend of the Amundsen low in austral autumn (Fig. 4f) reflect the gradually decreasing trend of annual mean *PW* over the Antarctic.

		Annual	JFM	AMJ	JAS	OND
Arctic	*SAT*	3.17***	3.84***	2.82***	1.50***	4.54***
	PW	0.73***	0.33*	0.80***	1.14***	0.66***
	Poleward flux	0.09	-0.39	0.00	0.07	0.69
Antarctic	*SAT*	0.03	-0.70*	-0.29	0.56	0.53
	PW	-0.16***	-0.32***	-0.17**	0.00	-0.13
	Poleward flux	-0.03	0.40	-0.32	0.11	-0.30

Table 1. Linear trends of poleward moisture flux, *SAT* and *PW* during the period 1979-2016. Those corresponding time-series are shown in Figure 2 for the annual mean and in Figure 3 for the 4 seasons. The Mann Kendall test were applied to the trends. ***, ** and * denote statistically significant level at 99, 98 and 95%, respectively.

Additionally, there were several local cooling/warming trends of *SAT* and corresponding increasing/decreasing trends of *PW* over the surrounding areas of the Antarctica. Those trends must be affected by long-term changes in sea ice and large-scale circulation. The decreasing height anomalies of *Z850* emerge over the Ross Sea in austral autumn and winter (AMJ and JAS, Figs. 4f, 4g) and over the Antarctic Peninsula and Ross Sea in austral spring (OND, Fig. 4h). Those affect the increasing (decreasing) trends of *PW* associated with northerly (southerly) wind anomalies in the east (west) of the low. Over narrow areas off Wilkes Land, the *PW* decreases and *SAT* decreases along the coastal line associated with the sea ice increase in austral autumn, winter and spring (Figs. 4f-h). As mentioned before, local circulation changes associated with *SAT* and *PW* are also seen in the Arctic (Figs. 4a-d). These local changes may be partly due to the influence of natural internal variability, including the variation on decadal timescales.

Effect of long-term changes in SAT on PW

We further examined how the *SAT* trend explains the *PW* trend in each season. It is expected that the saturated water vapor content (q_s) increases exponentially with *SAT* which is about 7 %/°C. If the relative humidity is constant in time, 3°C of *SAT* warming induces 21% of *PW* increase. Table 2 shows change rates in q_s estimated from the *SAT* trend during 1979-2016 (Table 1) with the Tetens's equation. Over the Arctic, the increasing rate in *PW* in boreal summer (JAS) was nearly equal to the estimated increase rate of q_s. However, in the other seasons, while the q_s increases, the *PW* do not increase so much compared to the increasing rates in q_s estimated from the *SAT* warming trend. This may be because that there are few sources of water vapor supply, *i.e.* moisture flux inflow from the surrounding region and evaporation from the ocean, in the cold seasons. These indicate a decrease in the relative humidity and suggest that the Arctic was getting dryer in boreal winter, spring and autumn.

	%	Annual	JFM	AMJ	JAS	OND
Arctic	*PW* trend	12.6	13.3	12.8	10.4	19.0
	change in q_s	29.3	41.4	24.6	11.6	46.9
Antarctic	*PW* trend	-6.3	-9.0	-8.3	0.0	-4.9
	change in q_s	0.2	-5.8	-2.8	5.7	4.7

Table 2. Change rates in *PW* trend and in saturated water vapor content (q_s) estimated from the *SAT* trend during 1979-2016. The corresponding *PW* and *SAT* trends are shown in Table 1. The q_s was estimated with the Tetens's equation.

On the other hand, over the Antarctic, the *PW* and q_s in austral summer (JFM) and autumn (AMJ) are decreasing. While signs of those change rates are the same, the decreasing rates of *PW* are much larger than the change in q_s. This is because that the changes in atmospheric large-scale circulation and associated moisture transport in austral summer and autumn, which show the intensification of the AAO and deepening of the Amundsen low, strongly affect the *PW* decreases as shown in Figs. 4e and 4f. The results suggest that the Antarctic was getting dryer in austral summer and autumn as well. In contrast, the change rates in austral winter and spring are inconsistent over the Antarctic, but those trends are small and not significant. In addition, it is needed to examine vertical profiles of changes in *SAT* and humidity, and also to prove the results by using other datasets.

Concluding remarks

Arctic and Antarctic regions are areas of moisture flux convergence throughout the year, and the transient component of moisture flux associated with cyclone activity dominates the poleward moisture transport into the regions (*e.g.* Oshima et Yamazaki 2004). Those interannual variations are affected by the AO and AAO over each polar region (*e.g.* Boer et al. 2001). While both regions have the above-mentioned similar characteristics, the seasonal cycles of *P-E* are reverse over the Arctic and Antarctic. Due to the large amount of water vapor in summer, the *P-E* over the Arctic shows a maximum in boreal summer. In contrast, over the Antarctic, the seasonal change in water vapor is relatively small and active cyclone activity in winter governs the poleward moisture flux in this region, resulting in the austral winter peak of *P-E* over the Antarctic (Oshima et Yamazaki 2006).

The results about the interannual variations and long-term changes during 1979-2016 are as follows.

The interannual variation of *PW* is positively correlated with that of *SAT* over both the Arctic and Antarctic (Figs 2, 3). The *PW* over the Arctic shows an increasing trend during the past 38 years in all seasons (Figs. 2a, 3a-d, Table 1). This is caused by the warming trend over the Arctic and consistent with the previous study (Serreze et al. 2012). On the other hand, the *PW* over the Antarctic is gradually decreasing during the past 38 years (Figs. 2b, 3e, 3f), particularly over the west side of the continent and in austral summer and autumn (Figs. 4e, 4f). We found that the AAO-like trends of *Z850* in austral summer (Fig. 4e) and the deepening of the Amundsen low (Fig. 4f) affect the gradually decreasing trend of the *PW* over the Antarctic. In addition, there are several local changes in the *PW* over both polar regions (Figs. 4a-h) and these reflect changes in atmospheric circulation and sea ice which may be caused by natural internal variability including the variation on decadal timescales.

In the comparison between the *PW* trend and change in q_s estimated from the *SAT* trend during 1979-2016 (Tables 1, 2), the results indicated that the relative humidity decrease during the past 38 years over the Arctic in the seasons except for boreal summer and also over Antarctic in austral summer and autumn (Table 2). This suggests that both polar regions were getting dryer in boreal winter, spring and autumn over the Arctic. Similarly, the trend towards dryer climate was suggested for austral winter and spring over the Antarctic. However this result needs to be further examined vertical structures of the trends and using other datasets.

Regarding the poleward moisture flux, there are no significant long-term trends of the total poleward moisture transport into both the Arctic and Antarctic during the period 1979-2016. This for the Arctic is consistent with Dufour et al. (2016). However, the changes in local area, transport process and seasonality may have been occurring recently and we intend to examine them in forthcoming studies.

References

AAGAARD, K., CARMACK, E.C. (1994): The Arctic Ocean and Climate: A Perspective. *In*: O.M. Johannessen, R.D. Muench and J.E. Overland (eds.): The Polar Oceans and Their Role in Shaping the Global Environment. American Geophysical Union, Washington, D. C., pp. 5-20, doi:10.1029/GM085p0005.

AAGAARD, K., CARMACK, E. C. (1989): The role of sea ice and other fresh water in the Arctic circulation. *Journal of Geophysical Research: Oceans*, 94: 14485-14498, doi:10.1029/JC094iC10p14485.

Arblaster, J. M., Meehl, G.A. (2006): Contributions of External Forcings to Southern Annular Mode Trends. *Journal of Climate*, 19: 2896-2905, doi: 10.1175/JCLI3774.1.

Boer, G.J., Fourest, S. and Yu, B. (2001): The Signature of the Annular Modes in the Moisture Budget. *Journal of Climate*, 14: 3655-3665, doi:10.1175/1520-0442(2001)014<3655:TSOTAM>2.0.CO;2.

Bromwich, D. H. (1990): Estimates of Antarctic precipitation. *Nature*, 343: 627-629.

Bromwich, D. H., Robasky, F. M., Cullather, R. I. and Van Woert, M. L. (1995): The Atmospheric Hydrologic Cycle over the Southern Ocean and Antarctica from Operational Numerical Analyses. *Monthly Weather Review*, 123: 3518-3538, doi:10.1175/1520-0493(1995)123<3518:TAHCOT>2.0.CO;2.

Comiso, J. C. (2006): Abrupt decline in the Arctic winter sea ice cover, *Geophysical Research Letters*, 33: L18504, doi:10.1029/2006GL027341.

Comiso, J. C., Parkinson, C. L., Gersten, R. and Stock, L. (2008): Accelerated decline in the Arctic sea ice cover. *Geophysical Research Letters*, 35: L01703, doi:10.1029/2007GL031972.

Dee, D. P., and 35 co-authors (2011): The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137: 553-597, doi: 10.1002/qj.828.

Dufour, A., Zolina, O. and Gulev, S. K. (2016): Atmospheric Moisture Transport to the Arctic: Assessment of Reanalyses and Analysis of Transport Components. *Journal of Climate*, 29: 5061-5081, doi:10.1175/JCLI-D-15-0559.1.

Francis, J. A., Vavrus, S. J. (2012): Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, 39: L06801, doi:10.1029/2012GL051000.

Gong, D., Wang, S. (1999): Definition of Antarctic Oscillation index. *Geophysical Research Letters*, 26: 459-462, doi:10.1029/1999GL900003.

Oshima, K., Yamazaki, K. (2004): Seasonal variation of moisture transport in polar regions and the relation with annular modes. *Polar meteorology and glaciology*, 18: 30-53.

Oshima, K., Yamazaki, K. (2006): Difference in seasonal variation of net precipitation between the Arctic and Antarctic regions. *Geophysical Research Letters*, 33: L18501, doi:10.1029/2006GL027389.

Raphael, M. N., Marshall, G. J., Turner, J., Fogt, R. L., Schneider, D., Dixon, D. A., Hosking, J. S., Jones, J. M. and Hobbs, W. R. (2016): The Amundsen Sea Low: Variability, Change, and Impact on Antarctic Climate. *Bulletin of the American Meteorological Society*, 97: 111-121, doi: 10.1175/BAMS-D-14-00018.1.

Rogers, A. N., Bromwich, D. H., Sinclair, E. N. and Cullather, R. I. (2001): The Atmospheric Hydrologic Cycle over the Arctic Basin from Reanalyses. Part II: Interannual Variability. *Journal of Climate*, 14: 2414-2429, doi:10.1175/1520-0442(2001)014<2414:TAHCOT>2.0.CO;2.

Screen, J. A., Simmonds, I. (2010): The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, 464: 1334-1337, doi:10.1038/nature09051.

Screen, J. A., Simmonds, I. (2013): Exploring links between Arctic amplification and mid-latitude weather. *Geophysical Research Letters*, 40: 959-964, doi:10.1002/grl.50174.

Serreze, M.C., Barrett, A.P. and Stroeve, J. (2012): Recent changes in tropospheric water vapor over the Arctic as assessed from radiosondes and atmospheric reanalyses. *Journal of Geophysical Research*, 117: D10104, doi:10.1029/2011JD017421.

Serreze, M. C., Barry, R.G. (2000): Atmospheric Components of the Arctic Ocean Hydrologic Budget Assessed from Rawinsonde Data. *In*: E.L. Lewis, E.P. Jones, P. Lemke, T.D. Prowse, and P. Wadhams (eds.): The Freshwater Budget of the Arctic Ocean. Springer Netherlands, Dordrecht.

Serreze, M. C., Barry, R. G. and Walsh, J. E. (1995): Atmospheric Water Vapor Characteristics at 70°N. *Journal of Climate*, 8: 719-731, doi:10.1175/1520-0442(1995)008<0719:AWVCA>2.0.CO;2.

Stroeve, J. C., Serreze, M. C., Holland, M. M., Kay, J. E., Malanik, J. and Barrett, A. P. (2012): The Arctic's rapidly shrinking sea ice cover: a research synthesis. *Climatic Change*, 110: 1005-1027, doi:10.1007/s10584-011-0101-1.

THOMPSON, D. W. J., WALLACE, J. M. (1998): The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters*, 25: 1297-1300, doi:10.1029/98GL00950.

TURNER, J., OVERLAND, J.E. and WALSH, J.E. (2007): An Arctic and antarctic perspective on recent climate change. *International Journal of Climatology*, 27: 277-293, doi:10.1002/joc.1406.

WANG, J., ZHANG, J., WATANABE, E., IKEDA, M., MIZOBATA, K., WALSH, J. E., BAI, X. and WU, B. (2009): Is the Dipole Anomaly a major driver to record lows in Arctic summer sea ice extent?. *Geophysical Research Letters*, 36, L05706, doi:10.1029/2008GL036706.

YAMAZAKI, K. (1992): Moisture Budget in the Antarctic Atmosphere. *Proceedings of the NIPR Symposium on Polar Meteorology and Glaciology*, 6: 36-45.

Web sources

[WP1] ECMWF website (http://apps.ecmwf.int/datasets/).

Other sources

[1] IPCC, Climate Change (2013): The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.), Cambridge University Press, 1535 p.