Relationship Between Stratosphere Circulation and Regional Climate

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Abstract- The study aimed to investigate how to influence the intensity, its edge of the polar vortex to the stratospheric warming on the troposphere in relation to global warming. The edge of polar vortex was defined by averaging wind component at 450K potential temperature surface along 60°–65°N during the winter using reanalyze ERA5 data. The results revealed that, recent years, decreasing linear trend of polar vortex 2m/s per decade ($p < 0.1$) was found during the study period (1979 – 2019). In addition, we found that the edge of polar vortex has more impact than the inter-annual polar vortex changes on the winter climate of Mongolia.

We defined strong or weak years of the polar vortex weak, then, we classified it into four combinations depending on the polar vortex intensity (strong (/weak) and air temperature anomaly (above (/below) from the climatology (1981–2010)) over Mongolia. This analysis was extended to characterize the atmospheric pattern of each period in terms of the edge of polar vortex. According to the result, we calculated the regional Ti indexes in every period relating to the edge of the polar vortex during the winter. The study result showed the high correlation between Ti indexes and Winter temperature in Mongolia. These findings suggest that Ti index could be used as seasonal predictor in forecasting winter temperature over Mongolia.

Index Terms- climate, polar vortex, stratosphere, temperature

I. INTRODUCTION

In latest decades, extreme cold-air outbreaks have frequently occurred across over the northern hemisphere, especially northeastern part of US and Eurasia despite global climate warming [1,2,3]. Dzud is an unfavourable weather condition (winter disaster: harsh and extreme cold weather phenomena) that makes it impossible for livestock to graze for long periods during the cold season and leads to mass deaths[4]. The winter disaster causes significant damage in socioeconomic of Mongolia, especially in herders livelihood. Particularly in the 2009/2010, it caused economic losses of 345 million US$14 and livestock mortalities reached 23.4% of the total livestock [5,6].

In the atmospheric science, the polar vortex (PV) is the strong circumpolar westerlies in the stratosphere as extending from the just above the tropopause into the mesosphere during the winter [7]. Climatologically, PV is mainly observed near northern side of Canada and Eurasia from the January to February. determined that center of PV has observed 40% around north America and 25% around Siberia on the 100 hPa pressure levels using ERA-Interim data from 1979 to 2018 [8].

Many scientist have studied the relationship of atmospheric circulation between troposphere and stratosphere [9,10,11]. Particularly, concluded that PV significantly influences the tropospheric circulation and thereby it is possible to be used as an predictor for cold seasons weather forecast[12]. Moreover, a weak PV can lead to an intense cold-air outbreak in midlatitudes, especially into Eurasia[8]. The 500hPa geopotential height anomalies over Mongolia depend on the position of PV core at the stratosphere in the northern hemisphere[9]. Mijiddorj (1983) analysed the timing of spring replacement period of stratospheric circulation with drought. It concluded that the spring and summer drought is rarely observed when the spring replacement period is late. Furthermore, It is possible to forecast summer drought possibility over Mongolia, using wind direction changes over the equator during January to February [10].

Within the context of the above, this study had two objectives. The first is toidentify interannual changes of the polar vortex during the winter months. The second is to investigate the relationship between PV and regional climate. This linkage can improve the seasonal climate forecasting methodology of cold period of year in the mid-latitudes, especially in Mongolia.

The Uralian ridge (UR), trough of east Asia (TEA) and its frontal system (FS) are key indicators of climate predictability during the winter season over central Asia, including Mongolia [13,14]. Scientists concluded that in winter, when Uralian ridge is intense, the lower-level anticyclone shifts to the southeast under the Uralian ridge and feeds Siberian high pressure and strengthens settling cold air mass over the Mongolia [15,16].

When the UR is intense, the high pressure over Siberia (SH) is intensified, Jet stream locates over the low latitude region of the transition zone of Eurasia continent and Pacific Ocean, followed by enhancing cyclogenesis over the western Pacific and sea of the far east and strengthening the East Asian Winter monsoon [17].

II. USED DATA

Reanalysis data: In this study we used daily and monthly parameters (air temperature, wind components, and pressure) of the surface and 37 pressure levels (range: 1000 – 5 hPa) from ERA5[18] reanalysis climate dataset during 1979 – 2019 at 30 km spatial resolution, provided by the European Centre for Medium-Range Weather Forecasts.

Meteorological observation data: Used observational data from 137 meteorological stations located widely throughout Mongolia. The meteorological data used in this study comprised the monthly mean air temperature and the total precipitation during 1971 –2020. Moreover, we used the air temperature at 2m converted at 30 km by using interpolation method [19].

Predicted atmospheric data: we determined future tendency of polar vortex using the horizontal wind component in winter season for each of four pathways (RCP:2.6; 4.5; 6.0; 8.5) data during 2021 – 2100, provided by the 5th Version of the Community Atmosphere Model (CAM) [20], National center for atmospheric research (NCAR).

III. METHODOLOGY

This study used Waugh (2017) methodology. Equation (1) gives the formula for calculating polar vortex as

$$PVI = \frac{1}{\lambda_{60}+\lambda_{65}} \int_{\lambda_{60}}^{\lambda_{65}} \overline{u_{10}} \partial\alpha \qquad \text{(Equation (1))}$$

were u_{10} − average horizontal wind component at 10 hPa, λ − latitude. Moreover, we defined edge of polar vortex that anomalies between average value and long-range value of wind component along the 60-65 degrees at the surface 450K.

$$PV = \frac{\xi_{\alpha} * \nabla\theta}{\rho} \qquad \text{(Equation (2))}$$

Here, PV – potential vortex (10^{-6} $m^2 s^{-1} K\ kg^{-1}$;[21]) ρ – density ($kg\ m^{-3}$), ξ_a – absolute vortex (s^{-1}), θ – potential temperature (K), $\xi_{\alpha} = \xi + f$, ξ нь $\xi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$, f - Coriolis parameter $f = 2\Omega \sin\varphi$.

$$\emptyset = T\left(\frac{P_0}{P}\right)^{R/C_p} \qquad \text{(Equation (3))}$$

Here, T – air temperature (K), P –pressure (hPa), $P_0 = 1000\ hPa$, R – constant of gas, Cp – specific heat capacity, R/cp = 0.286.

We selected years as a winter period that an anomalous air temperature was above and below a specified threshold corresponding to σ (σ: standard deviation) from the climatology (1981–2010) when condition of strong and weak the polar vortex. The statistical test of the trend coefficient was employed based on the Mann–Kendall nonparametric method[22].

IV. RESULT AND DISCUSSION

A. The interannual variation of polar vortex and it`s future tendency

The interannual variation of the averaged of the PV during 1979-2019 in winter season (DJF) using by Mann-Kendall statistical method is shown in Figure 1. A linear decreasing trend of PV 2 m s-1 per decade winter ($p < 0.1$) was found during the study period (1979-2019). These results are directly comparable with Kretschmer (2018) who also calculated PV and reported same trend. This decreasing tendency is might be linked with the rapid warming of Arctic associated with changing atmospheric circulations Iijima and Hori [23].

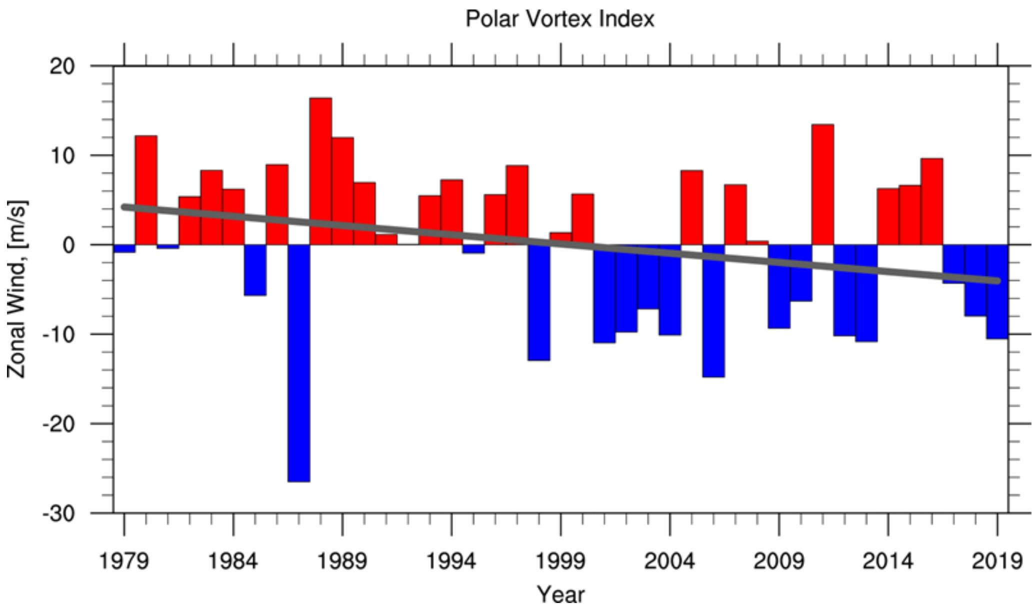

Figure 1: The interannual variation of the averaged of the PV during 1979-2019 in winter season (DJF), [m s^{-1}]. Blue (red) line indicate negative (positive) anomaly of PV, black line indicates linear trends.

Future projection of polar vortex shown in Figure 2. It can be seen that CAM5 models predict PV values that will not change in each of RCP scenarios (except RCP; 8.5) by 2100.

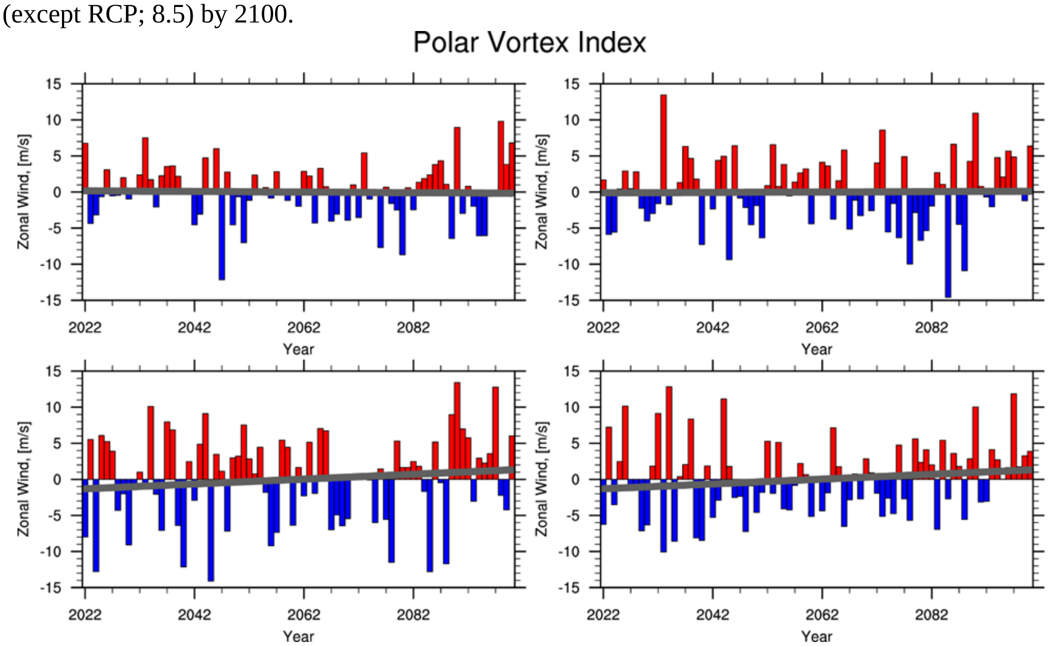

Figure 2: The projected interannual variation of the averaged of the PV during 2021-2100 in winter season (DJF), [m s^{-1}]. Blue (red) line indicate negative (positive) anomaly of PV, black line indicates linear trends.

B. Composite analysis

We employed the statistical analysis method to analyze relationships regional climate condition with polar vortex state (strong / weak). Therefore, we classified it into four combinations depending on the polar vortex intensity (strong/weak) and air temperature anomaly (above/below) from the climatology (1981–2010)) over Mongolia (Table 1). We found 10 cases with below normal the air temperature anomaly and the strong polar vortex and 10 cases with above the normal air temperature anomaly and a weak polar vortex during winter (DJF) for 1979 – 2019 across the country. Therefore, it is important to consider its edge of PV while investigating the regional climate.

Table 1: Number of years for four conditions with above (below) normal air temperature anomaly over Mongolia and a strong (weak) polar vortex during 1979-2019.

	PV			
	+		−	
	Temperature			
Winter season	+	−	+	−
	5	10	10	6

Based on previous analysis, we calculated anomalies of potential polar vortex corresponding surface of 450K potential temperature and defined the edge of stratospheric polar vortex over the Northern Hemisphere in every month (Fig 3). According to the international system of units ($1PVU=10^{-6}\,m^2\,K\,s^{-1}\,kg^{-1}$), we multiplied the unit of potential temperature by 10^{-6}, converted into an integer. The edge of stratospheric polar vortex is defined by the averaged potential vortex along the 60-65ºN of latitude corresponding surface of 450K potential temperature.

From figure 3a, b, the edge of stratospheric polar vortex is observed north side compared to the climatological position when the PV is strong whereas opposite pattern (south side) is observed when the PV is weak.

In terms of anomalies of the potential vortex, when a polar vortex is strong and an air temperature over Mongolia is above normal (PV^+/AT^+) , the positive anomaly is observed over the north polar (80-90ºN, 0-360ºE) whereas, negative anomaly is observed over the northern Europe (50-60ºN, 0-30ºE) and the eastern Siberia (52-63ºN, 100-130ºE). Furthermore, when it is PV^+/AT^- , the positive anomaly is observed over the north polar region (80-90ºN, 0-360ºE), the northern Europe and the eastern Siberia (Fig 3b) Whereas, the negative anomaly is observed over the polar region and the positive anomaly is observed over the eastern Europe and the sea of Agnur (Fig 3c, d) when it is PV^-/AT^+ and PV^-/AT^-.

Therefore, we selected the six regions to predict climate condition over Mongolia during winter season based on above analysis (shown table 2).

Table 2: Selected six regions information.

PV^+	PV^-
A (80-90ºN, 0-360ºE)	A (80-90ºN, 0-360ºE)
B (50-60ºN, 0-30ºE)	D (50-60ºN, 0-30ºE)
C (52-63ºN, 100-130ºE)	F (45-60ºN, 110-150ºE)

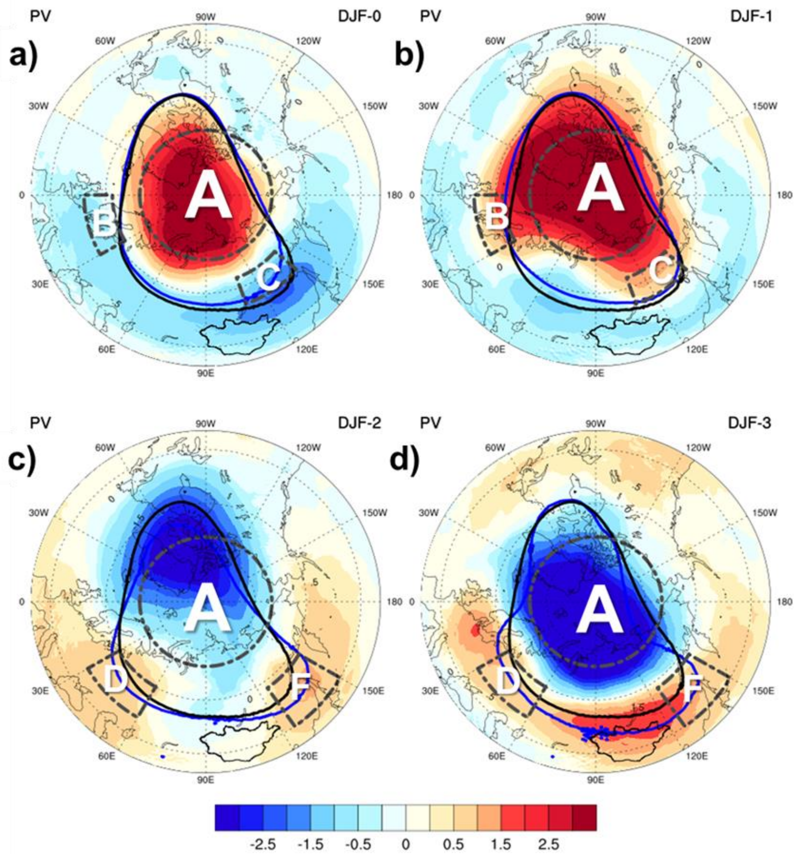

Figure 3: The anomaly of the potential vortex at 450K potential temperature surface in winter and edge of PV in the stratosphere + (-) sign indicates strong (weak) vortex, blue (red) shade indicates negative (positive) air temperature anomaly. Black (cray) line indicates edge of PV (climatological location). Box indicated selected regions [PVU].

As shown table 3, we defined new index (Ti) caused by PV`s condition for investigation synoptic pattern during the winter over selected regions.

Table 3. Definition of the new index (Ti).

№	Selected region	A	B	C	D	F	Index
1.	PV^{+}	+	+	+			T_i=A+B+C
2.	PV^{-}	+			+	+	T_i=A+D+F

C. Relationship atmospheric circulation between the troposphere and the stratosphere

This section highlights the relationships between stationary pressure centers at sea level and the Ti index at the 500 hPa level using the correlation analysis across the Northern hemisphere during winter (Fig 4). As shown in Figure 4, we concluded that the Ti index at the 500 hPa level may be possible to be used as a key indicator to predict pressure center over Mongolia, because Ti index significantly correlated with UR and SH (0.6-0.8, p<0.1).

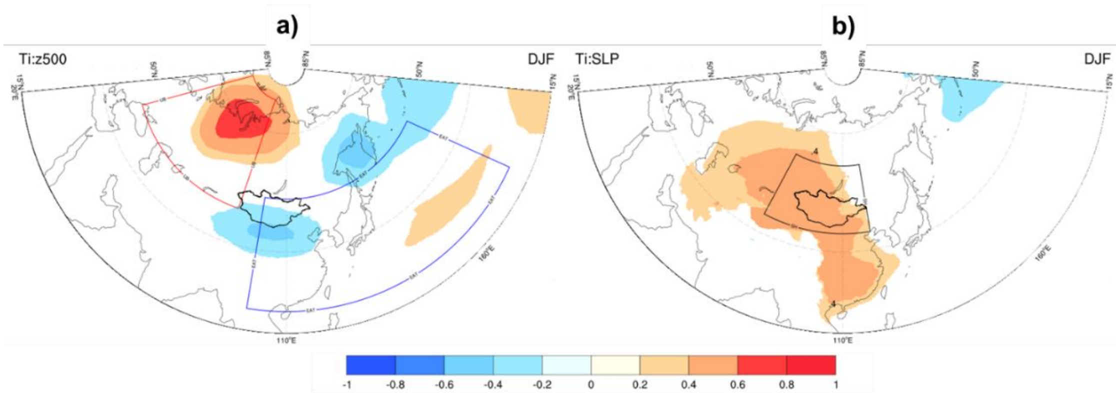

Figure 4. Correlation between Ti at the 500 hPa level and stationary pressure centers at sea level. Red (blue and black) box indicates Uralian ridge (Trough of east Asia and Siberian High), respectively [dm].

D. Relationship between the atmospheric circulation of stratosphere and regional climate

This section discusses atmospheric circulation and regional climate in Mongolia. The circulation of the atmosphere is a key component of regional climate because it responds to the distribution of temperature gradients and also helps to determine them by transporting cold and warm air mass. Therefore, we carried out regression analysis on relation between air temperature in Mongolia and Ti index at every grid point during winter months (Fig 5).

The regression coefficient distribution was different in region by region and month by month shown as in Figure 5a-c. In December, the coefficients have statistically significant over the southeast Mongolia, whereas it was statistically significant over almost entire Mongolia in January to February. This shows that Ti index is able to indicate regional climate condition during the winter in Mongolia (Fig 5). Additionally, figure 6 shows the variation coefficients of modelled air temperature using regression analysis. The variation coefficients were 10 –30% ($p<0.1$) in almost all over Mongolia in January and February.

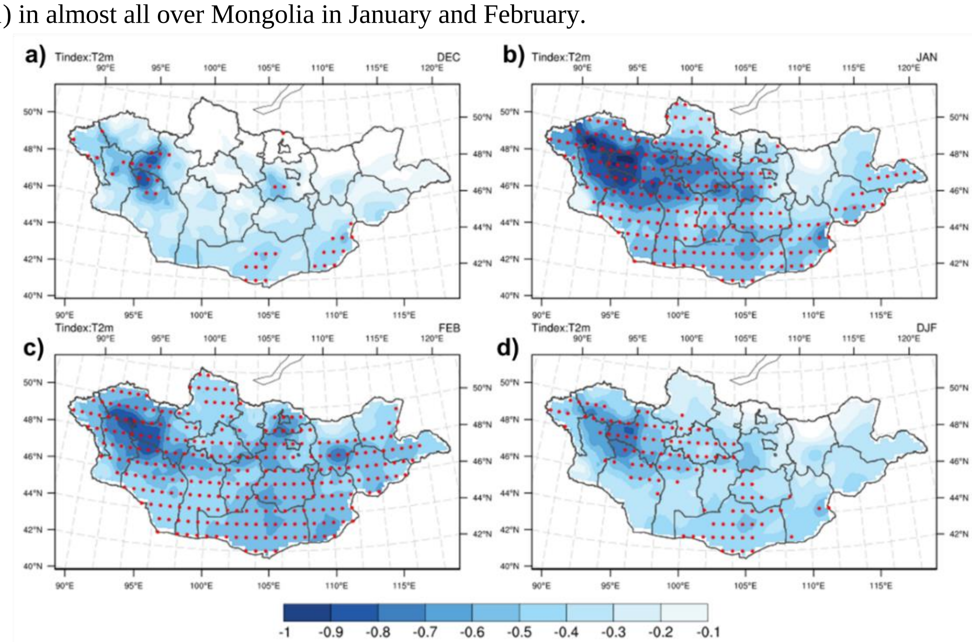

Figure 5: The linear regression coefficients distribution obtained from time series of the air temperature and Ti index during the winter months (1979–2019). The shaded color indicates coefficients and red dots indicate the significant level ($p<0.1$).

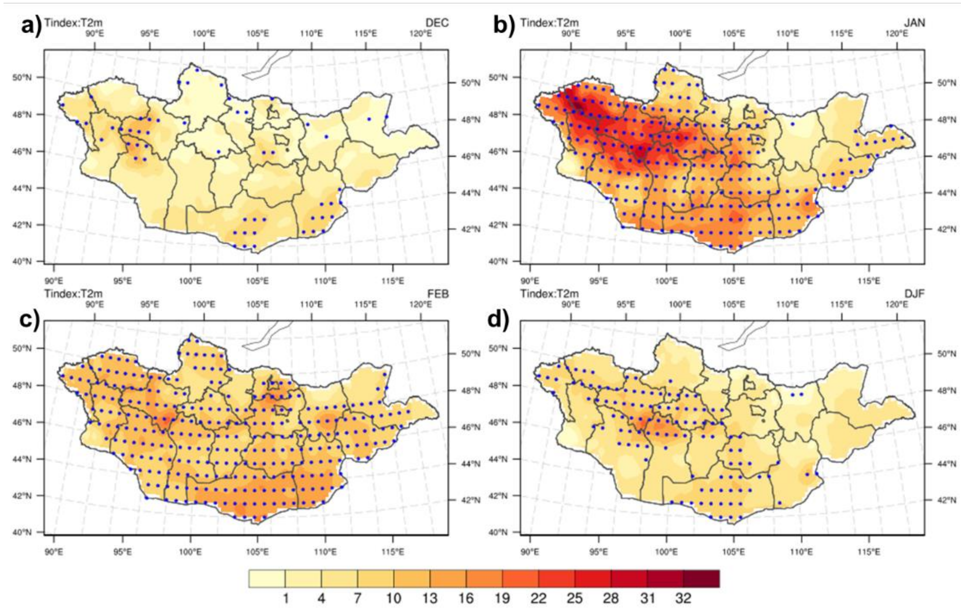

Figure 6. The variation coefficients distribution (1979–2019). Black dots indicate significant level ($p<0.05$)

V. DISCUSSION

The present study examined the interannual variability of polar vortex during winter using ground-based observational data and reanalyze data by classifying the polar vortex as strong and weak. Result showed that latest 41 years, the polar vortex decreased of 2 m s-1 per decade in winter during the study period (1979–2019). We concerned that changes may lead to natural force of Global warming, especially over polar region and will be effected the decreased change in air temperature gradient. In other words, the vertical distribution of horizontal wind components is directly related to the temperature gradient in latitude ($\frac{\partial u}{\partial z} \sim \frac{\partial T}{\partial y}$)[24].

VI. CONCLUSION

According to analysis, obtained 10 years when the polar vortex intensity is intense while the air temperature below climatology and also obtained 5 years when the polar vortex intensity is strengthless while the air temperature above the normal during winter (DJF) for 1979–2019 across the country. Moreover, the potential vortex at the surface of 450K potential temperature is strong when polar vortex is strong.

Therefore, it is important to consider its edge of PV when investigating the regional climate and the edge of PV is caused by the condition of how to extend to the Eurasian continent and coarse country of the Pacific and the Atlantic Ocean. Result showed that Ti index is significantly correlated (r: 0.4–0.8, $p<0.1$) with the Uralian ridge and the Siberian High. Moreover, the regression coefficients (obtained from the air temperature time series into the time series of Ti index) is significantly correlated over entire country except the northeast region during the winter months for (1979-2019) in Mongolia. The results of this study proves that Ti index could be very useful predictor in monthly air temperature forecast during winter in Mongolia.

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REFERENCES

[1] Cohen, J., Screen, J., Furtado, J., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, and J., Justin Jones, 2014: Recent Arctic amplification and extreme mid-latitude weather, *Nature Geosci*, 7, 627–637, https://doi.org/10.1038/ngeo2234.

[2] McCusker, K. E., J. C. Fyfe., and M. Sigmond, 2016: Twenty-five winters of unexpected Eurasian cooling unlikely due to Arctic sea-ice loss, *Nat. Geosci*, 9, 838–842, https://doi.org/10.1038/ngeo2820.

[3] Munkhjargal, E., Shinoda, M., Iijima, Y., and B. Nandintseteseg, 2020: Recently increased cold air outbreaks over Mongolia and their specific synoptic pattern, *Int J Climatol*, 40, 5502– 5514, https://doi.org/10.1002/joc.6531.

[4] Chogsom, D., 1964: Some aspects of Dzud studies, geographical aspects in Mongolia, Ulaanbaatar: Department of Hydrology and Meteorology Service of Mongolia.

[5] Batjargal, Z., Oyun, R., Togtokh, N., and S. Sangidansranjav, 2002: Lessons learned from the dzud 1999–2000 fundamental issues affecting the sustainability of the Mongolian steppe, Ministry of Environment and Green Development, IISCN, Ulaanbaatar, Mongolia. 73–98.

[6] Nandintsetseg, B., Shinoda, M., and B. Erdenetsetseg, 2017: Contributions of multiple climate hazards and overgrazing to the 2009/2010 winter disaster in Mongolia, *Natural Hazards*, 92, 109-126, https://doi.org/10.1007/s11069-017-2954-8.

[7] Waugh, D. W., Sobel, A. H., and L. M. Polvani, 2017: What is the polar vortex and how does it influence weather?, *Bulletin of the American Meteorological Society*, 1, 37–44, https://doi.org/10.1175/BAMS-D-15-00212.1.

[8] Kretschmer, M., Cohen, J., Matthias, V., Runge, J., and D. Coumou, 2018: The different stratospheric influence on cold-extremes in Eurasia and North America, npj *Clim Atmos Sci*, 1, 44, https://doi.org/10.1038/s41612-018-0054-4.

[9] Jadambaa Sh., 1971: On the relationship between the location and shape of the Arctic cyclone in the stratosphere and the processes of the biosphere in Asia, Ulaanbaatar: Department of Hydrology and Meteorology Service of Mongolia.

[10] Namkhai A., 1980: Correlation of Mongolia's average monthly temperature anomaly with the location and transition direction of the stratospheric vortex center, Ulaanbaatar: Department of Hydrology and Meteorology Service of Mongolia.

[11] Thompson, D. W. J., Baldwin, M. P., and J. M. Wallace, 2002: Stratospheric connection to Northern Hemisphere wintertime weather: implications for prediction, *J Clim*, 15, 1421–1428, https://doi.org/10.1175/1520-0442(2002)015%3C1421:SCTNHW%3E2.0.CO;2.

[12] Scaife, A. A., Karpechko, Yu., Baldwin, M. P., Brookshaw, A., Butler, A. H., Eade, R., Gordon, M., MacLachlan, C., Martin, N., Dunstone, N., and D.Smith, 2016: Seasonal winter forecasts and the stratosphere, *Atmos. Sci.* Lett, 17, 51–56, https://doi.org/10.1002/asl.598.

[13] Diao, Y., J. Li., and D. Luo 2006: A new blocking index and its application: Blocking action in the Northern Hemisphere, *J. Climate*, 19, 4819–4839, https://doi.org/10.1175/JCLI3886.1.

[14] Wang, L., Chen, W., Zhou, W., and R. Huang, 2009: Interannual Variations of East Asian Trough Axis at 500 hPa and its Association with the East Asian Winter Monsoon Pathway, *Journal of Climate*, 3, 600–614, https://doi.org/10.1175/2008JCLI2295.1.

[15] Panagiotopoulos, F., Shagedanova, M., Hannachi, A., and D. Stephenson, 2005: Observed trends and teleconnections of the Siberian high: a recently declining center of action, *Journal of Climate*, 9, 1411–1422, https://doi.org/10.1175/JCLI3352.1.

[16] Bayasgalan G., and J-B. Ahn, 2018: Seasonal prediction of high-resolution temperature at2-m height over Mongolia during boreal winter usingboth coupled general circulation model and artificialneural network, *Int J Climatol*, 38, 5418–5429, https://doi.org/10.1002/joc.5848.

[17] Natsagdorj L, and P. Gomboluudev, 2004: Seasonal features of general atmospheric circulation in Central Asia, Papers in Meteorology and Hydrology.

[18] Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., and D. Schepers, 2020: The ERA5 global reanalysis, Q. J. R. *Meteorol. Soc*, 146, 1999–2049, https://doi.org/10.1002/qj.3803.

[19] Gerelchuluun, B. and J.B. Ahn, 2014: Air temperature distribution over Mongolia using dynamical downscaling and statistical correction, *International Journal of Climatology*, 34, 2464– 2476, https://doi.org/10.1002/joc.3853.

[20] Neale, R. B., Richter, J. H., Conley, A. J., Park, S., Lauritzen, P, H., Gettelman, A., and D. L. Williamson, 2010: Description of the NCAR Community Atmosphere Model (CAM 5.0), *NCAR Tech. Note Sci. and Tech. Rep*, NCAR/TN-486+STR, NCAR Publ. Off., Boulder, Colo.

[21] Holton, J.R., Haynes, P.H., McIntyre, M.E., Douglass, A.R., Rood, R.B., and L. Pfister, 1995: Stratosphere-troposphere exchange, *Rev. Geophys*, 33, 403, https://doi.org/10.1029/95RG02097.

[22] Kendall, M.G., 1975: Rank Correlation Methods, 4th edition, Charles Griffin, London.

[23] Iijima, Y., and M.E. Hori, 2018: Cold air formation and advection over Eurasia during “dzud” cold disaster winters in Mongolia, *Nat Hazards*, 92, 45–56, https://doi.org/10.1007/s11069-016-2683-4.

[24] John Marshall., and R. Alan Plumb, 2008: Atmosphere, ocean, and climate dynamics: an introductory text. Amsterdam: Elsevier Academic Press.

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