Influence of the annual Arctic Oscillation on the negative correlation between Okhotsk Sea ice and Amur River discharge

Masayo Ogi[1] and Yoshihiro Tachibana[2]

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[1] Newly obtained observational discharge data reveal the cause of a significant negative correlation between Amur River discharge and Okhotsk Sea ice at multiyear timescales. The annually integrated Arctic Oscillation (AO) influences both summer discharge and winter ice. Summer discharge is larger and winter ice is reduced during positive AO years. Annual AO also influences the annual horizontal moisture flux convergence in the river basin. When the annual AO is positive, the annual mean air temperatures are warm over Eurasia, particularly over the Amur River basin and the Okhotsk. Consequently, autumn SSTs are warmer in the Okhotsk Sea. The warmer autumn SSTs suppress ice formation during the following winter. Freshwater from the river is not the main control of multiyear ice variability. Consideration of the annual AO provides a new look at climate system persistence at multi-seasonal scales. **Citation:** Ogi, M., and Y. Tachibana (2006), Influence of the annual Arctic Oscillation on the negative correlation between Okhotsk Sea ice and Amur River discharge, *Geophys. Res. Lett.*, *33*, L08709, doi:10.1029/2006GL025838.

1. Introduction

[2] Freshwater discharging from large rivers is an important factor controlling the formation of sea ice because it causes a large stratification that suppresses deep convection and promotes freezing. The Amur River is the forth largest river in north Eurasia and it supplies much of the freshwater to the Okhotsk Sea, one of the southernmost ice-covered oceans in the Northern Hemisphere. Atmospheric circulations are also important in the formation of sea ice in the Okhotsk Sea [e.g., *Fang and Wallace*, 1994; *Tachibana et al.*, 1996]. *Yamazaki* [2000] showed that the Okhotsk Sea ice formation is influenced by the winter North Atlantic Oscillation (NAO). Variations in Okhotsk Sea ice are therefore influenced by both large-scale atmospheric circulations and hydrological processes associated with the river. *Ogi et al.* [2001] used time series analyses from 1971 to 1993 to suggest that interannual variations in Okhotsk Sea ice were negatively correlated with discharge from the Amur River. Years with large river discharge are followed by suppressed sea ice formation in the Okhotsk Sea and vice versa. This negative correlation is counter to the expected influence of freshwater. Discharge data given by *Ogi et al.* [2001] ends in 1993, and this lack of data precludes a determination of whether the negative correlation is causal. In addition, the reason for the negative correlation is unclear.

[3] Recently, we have obtained discharge data from the Far Eastern Regional Hydrometeorological Research Institute, Russia (FERHRI), extending the discharge data record to 2004. These extra data and additional recent data are consistent with a negative correlation. Figure 1 shows the annual mean Amur River discharge and the maximum sea ice coverage in the Okhotsk Sea from 1971 through 2004. Clearly, discharge is negatively correlated with sea ice coverage. A 3-year moving average highlights multiyear timescale changes and shows a clearer negative correlation than at interannual timescales.

[4] This study will identify the cause of the negative correlation between discharge and sea ice with respect to long-term climate variations. The Amur River freezes in winter; discharge is largest in summer [*Ogi et al.*, 2001, Figure 2]. Thus, the summer atmosphere controls the discharge. However, the Okhotsk Sea is ice-covered only in winter. The season-to-season connection suggests persistence in the atmosphere that extends beyond one or two seasons. *Ogi et al.* [2003] showed an example of such seasonal atmospheric persistence by which summertime atmospheric circulations were influenced by the NAO/AO of the previous winter. The summer atmospheric pattern related to the winter NAO/AO was also characterized by a seesaw pattern, which is similar to the winter AO. The leading mode of an empirical orthogonal function (EOF) analysis for individual calendar months appears a seesaw pattern between the Arctic and mid latitudes in both summer and winter [*Ogi et al.*, 2004a]. The winter-to-summer linkage described by *Ogi et al.* [2003] was interpreted as a preferred transition from one polarity of the winter AO to the same polarity of the summer AO. The negative correlation in Figure 1 may therefore be related to persistent atmospheric variations in winter and summer. The first step to solving the season-to-season connection must consider variations in annual mean atmospheric patterns and their connection to both discharge and sea ice. This paper will show that the annually integrated AO influences both summertime discharge and wintertime sea ice.

2. Data

[5] We obtained Amur River discharge data recorded at Bogorodskoye from 1971 through 2004 from FERHRI. Data from 1979 were missing, and the climatological mean in the present analysis was substituted for that year. The annual mean (January–December) discharge data is used as the discharge index. Sea ice data for the Okhotsk Sea were derived from Japan Meteorological Agency (JMA) data from 1971 through 2004. The sea ice coverage index is

[1]Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan.

[2]Institute of Observational Research for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan.

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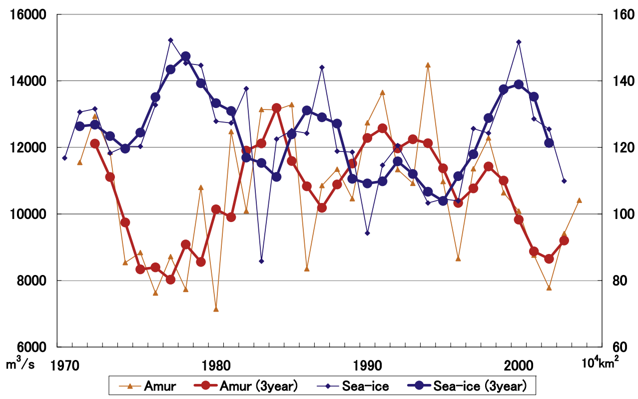

Figure 1. Time series of the annual mean discharge from the Amur River (red lines) and maximum sea ice area over the Okhotsk Sea (blue lines). The thick lines are filtered with a 3-year moving average; the red and blue lines are discharge and sea ice, respectively. Note that the sea ice series is shifted to the left by 1 year.

the maximum sea ice extent in a year. Sea ice extent is normally largest in late February or March. Atmospheric data come from the NCEP/NCAR reanalysis data set covering 1971 to 2004 [*Kistler et al.*, 2001]. The AO [*Thompson and Wallace*, 1998] index from 1971 to 2004 is available from the Climate Prediction Center. The annual mean value (January–December) of the AO index is used as the annual AO index. The monthly mean sea surface temperature (SST) data set includes global sea ice coverage and SST data (HadISST) at a 1° × 1° resolution from 1971 to 2003. Vertically integrated horizontal moisture flux data estimated by *Oshima and Yamazaki* [2004] are also used. The moisture flux from 1979 to 2002 was estimated using four daily (six-hourly) NCEP-DOE reanalysis-2 (NCEP R2) data at 2.5° × 2.5° resolution. Area-averaged values of annual mean moisture flux convergence within the Amur River basin were computed for the present study. The Amur River basin is defined here to be between 45 and 55°N and 110 and 135°E. The values of the moisture flux convergence and the Amur River discharge have comparable quantity with each other.

[6] The main seasons for discharge and sea ice are summer and winter respectively; thus, calendar years for comparing discharge and ice differ. Sea ice time series were therefore shifted 1 year earlier in all correlation analyses that consider the influence of the discharge on sea ice. In addition, a 3-year moving average filter was applied to all data analyzed in this study because the negative correlation in Figure 1 is more pronounced at multiyear timescales than at interannual timescales.

3. Results

[7] Annual mean large-scale atmospheric patterns that influence annual discharge and sea ice are presented. Figure 2a shows an annual mean sea level pressure (SLP) anomaly pattern regressed onto the annual discharge. A seesaw pattern occurs between a negative area over the Arctic Ocean and positive areas over the midlatitudes. SLP patterns related to the sea ice variation (Figure 2b) show a similar seesaw pattern but with the opposite sign. A negative correlation was found between the discharge and the sea ice, as shown in Figure 1; thus, the similar atmospheric large-scale patterns with opposite signs in

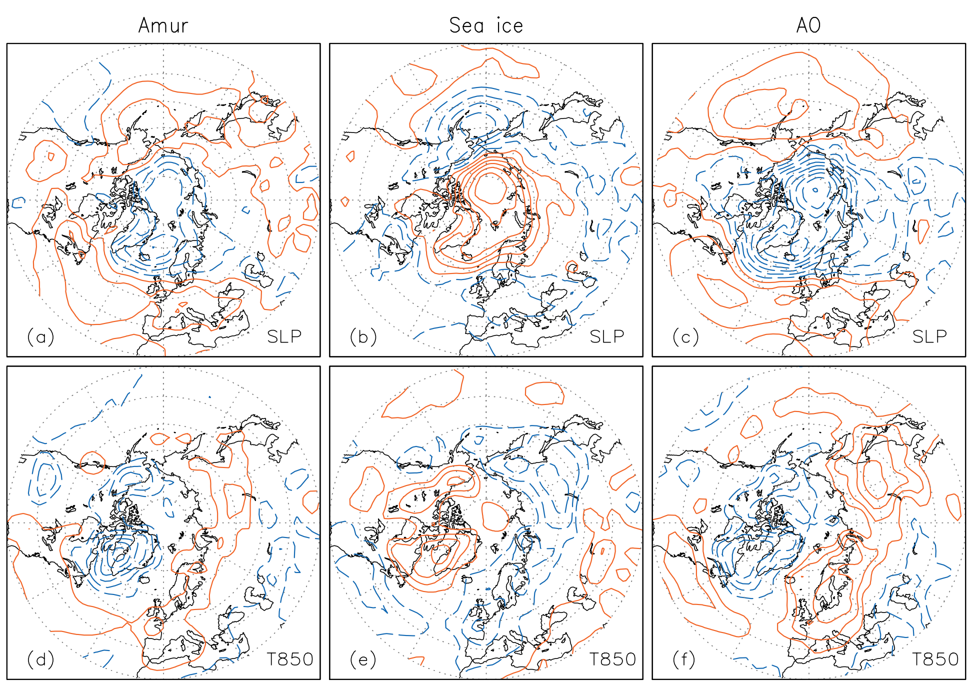

Figure 2. (a–c) Horizontal maps of annual mean sea level pressure (SLP) and (d–f) temperature at 850 hPa regressed onto the annual mean Amur River discharge (Figures 2a and 2d), the maximum sea ice in the Okhotsk Sea (Figures 2b and 2e), and the annual mean AO index (Figures 2c and 2f). Red solid contours denote positive values, and blue dashed contours indicate negative values. Contour intervals are 0.2 m (e.g., −0.1, 0.1, 0.3...) for SLP and 0.1 K for the temperature (e.g., −0.1, 0.1...). All data were filtered with a 3-year moving average.

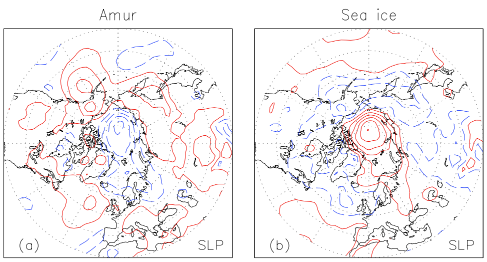

Figure 3. As in Figure 2 except for the regression maps of the SLP for warmer half of year (May–October) onto (a) the annual mean Amur River discharge and (b) the maximum sea ice in the Okhotsk Sea.

Figures 2a and 2b are reasonable. Similarities in the atmospheric patterns indicate that the seesaw pattern between mid- and high latitudes influences both the discharge and the sea ice. The annual mean AO (Figure 2c), also a seesaw pattern between mid- and high latitudes, is similar to the pattern in Figure 2a and is of the opposite sign to that in Figure 2b. Pattern correlation coefficients poleward of 30°N for the discharge (Figure 2a) and the sea ice (Figure 2b) with the AO (Figure 2c) are 0.80 and −0.82, respectively. Negative anomalies near the pole and positive anomalies at midlatitudes are characteristic of a positive AO pattern [*Thompson and Wallace*, 1998]. Thus, present results show that during positive AO years, discharge is greater and sea ice is suppressed in the following winter. When the annual mean atmospheric patterns at upper levels were regressed onto the discharge, the sea ice and the annual mean AO index resembled the surface patterns shown in Figure 2.

[8] The annual mean temperature anomaly at 850 hPa regressed onto the annual discharge shows negative values over the Arctic and positive values over midlatitudes (Figure 2d). The regression of the annual mean temperature at 850 hPa onto the sea ice in the following winter resembles the pattern of the discharge regression, but with the opposite sign (see Figures 2d and 2e). A prominent warm temperature signal at 850 hPa related to the annual AO (Figure 2f) covers wide areas of Eurasia with centers in both northern Europe and the Far East; a cold temperature signature covers the Arctic. Annual mean atmospheric temperature patterns correlated with both discharge and sea ice therefore resemble AO signatures. *Thompson and Wallace* [1998] noted that the wintertime AO is strongly coupled with surface air temperature fluctuations over Eurasia. *Ogi et al.* [2004a] also demonstrated that the summer air temperature over Eurasia is related to the summer AO. The annual mean AO signal in Figure 2f reflects the surface temperature signals over Eurasia throughout the year. Therefore, a positive annual AO causes anomalous warmth over the Amur River basin and the Okhotsk Sea.

[9] We further examine the relationship of atmospheric patterns for warmer and colder halves of the year with the annual discharge and the ice. Figure 3 shows the SLP anomaly pattern in warmer half of the year regressed onto the discharge and the sea ice. The SLP anomaly patterns of warmer half of the year both in Figures 3a and 3b are similar to those of the annual mean SLP (Figures 2a and 2b). These summer patterns are also similar to the summer AO pattern shown in Figure 2 of *Ogi et al.* [2004a]. The atmospheric pattern for winter colder half of the year also showed similar pattern as in Figure 2. Thus, atmospheric patterns for warmer and colder halves of the year that were correlated with the annual discharge and the ice are also similar to those shown in Figure 2. Annual patterns in Figure 2 therefore reflect an AO-like pattern through the year.

[10] Figure 4a shows the regression of the annual mean SLP with the annual mean vertically integrated horizontal moisture flux convergence averaged over the Amur River basin. The SLP is again characterized by an AO-like seesaw pattern between the Arctic regions and midlatitudes. The annual AO therefore dominates the area-averaged moisture flux in the Amur River basin. The area-averaged moisture flux convergence is nearly equal to the precipitation minus the evaporation over the basin, and therefore controls the river discharge anomaly. Thus, the annual AO also influences the discharge. The moisture flux and its variability in summer are, on average, ten times larger than winter values. Thus the AO-like atmospheric spatial structure shown in Figure 4a is mostly influenced by summer patterns and summer moisture flux. Figure 4b shows the multi-year variations of the annual AO, the Amur River discharge and the moisture flux convergence. Obviously, variations of the three are in good correlations.

[11] SSTs before the ice formation season are an important parameter influencing subsequent ice formation. The Okhotsk Sea usually starts to freeze in early December; thus, SST conditions during autumn (September–November) were considered. Figure 5 shows the correlation/regression coefficients of the autumn SST over the Okhotsk Sea with the discharge (a), the sea ice (b), and the annual AO index (c).

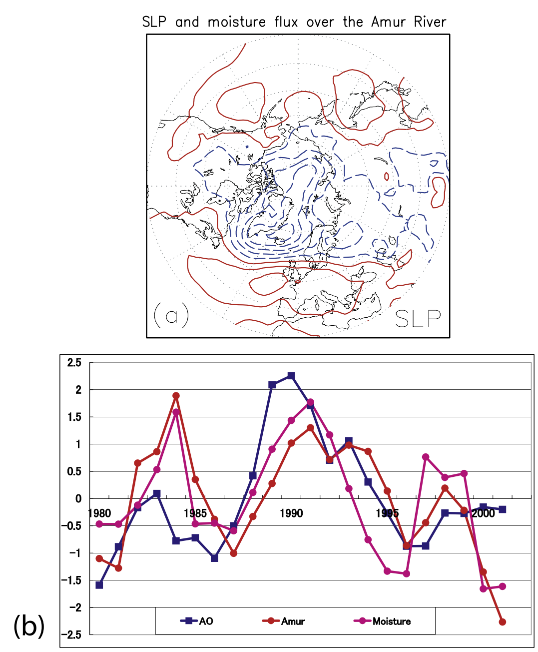

Figure 4. (a) As in Figure 2 except for the regression maps of the SLP and the moisture flux convergence over the Amur River basin (45–55°N, 110–135°E). Red lines are positive and blue lines are negative. The contour interval is 0.2 m. (b) Standardized time series of the annual mean AO index (blue line), the annual mean Amur River discharge (red line) and the annual mean moisture flux convergence over the Amur River basin (pink line). The lines are filtered with a 3-year moving average.

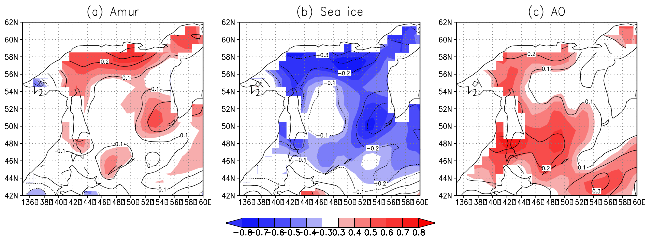

Figure 5. As in Figure 2 except for the correlation/regression maps of sea surface temperature (SST) in autumn (September–November) and (a) the annual mean Amur River discharge, (b) the maximum sea ice in the Okhotsk Sea, and (c) the annual mean AO index. Contours show regression values and shadings indicate the correlation coefficients. The contour interval is 0.1°C; the correlation coefficients below 0.3 are not plotted.

Autumn SST anomalies show positive, negative and positive correlations with discharge, sea ice and annual AO, respectively, over the Okhotsk Sea. Autumn SSTs are warmer when the annual AO phase is positive. Such SST anomalies are consistent with the correlation of the annual AO with the sea ice because the positive annual AO causes anomalously warm air temperatures over the Okhotsk Sea (see Figure 2f). The warmer SSTs inhibit ice formation in the subsequent winter.

4. Conclusions and Discussion

[12] This study investigated the negative correlation between Amur River discharge and Okhotsk Sea ice formation. The results show that the annual AO regulates the annual Amur River discharge. Positive annual AO causes anomalous horizontal moisture flux convergence over the Amur River basin, resulting in increased discharge. It should be noted that atmospheric patterns for warmer half of the year that is correlated with the annual discharge and the ice are also similar to those of the AO. The warmer atmospheric temperatures accompanying the positive annual AO cause anomalously warm autumn SSTs in the Okhotsk Sea. The warm temperatures related to the annual AO are consistent with the warm summer temperatures given by *Ogi et al.* [2004a], which showed that anomalously warm summer temperatures over Eurasia are closely related to the positive phase of the summer AO. The warm autumn SSTs inhibit subsequent sea ice formation. *Yamazaki* [2000] and *Ogi et al.* [2004b] have suggested that the winter NAO/AO influences Okhotsk Sea ice formation because of the warm atmospheric temperatures over Eurasia associated with the positive winter AO. Therefore, AO-related warm temperatures in autumn and winter over Eurasia and the Okhotsk Sea also inhibit sea ice formation. The presence of a strong control, that is, the annual AO, on both summer discharge and winter ice masks the influence of the freshwater supply on the sea ice variation at least at multiyear timescales. If the influence of freshwater discharge dominated, discharge and sea ice would be positively correlated. In practice, the negative correlation between the discharge and the sea ice arises mainly from variations in the annual AO.

[13] This study investigated atmospheric correlations between individual months and annual river discharge and the sea ice. However, significant AO-like signatures as exhibited in Figure 2 were not present in the maps of the individual months. It is the longtime integration of AO-related atmospheric circulations that influence both annual discharge and sea ice. Examinations from the perspective of the annual AO thus yield a new look at persistence in climate systems that extend beyond seasons, in particular for climate subsystems that have a longer memory than the atmosphere.

[14] Better correlations with using the three-year moving average than without the moving average may be due to following reasons. In the winter half of the year, precipitation over the Amur basin is in the form of snow, which does not melt until the following spring. The snowfall thus plays a role in memory beyond the year. Because the AO is related to the air temperature, the ratio between the snowfall and the rainfall over the basin is also related to the AO. Warm summer air temperature brings about a large amount of snowmelt, which also influences the river discharge.

[15] This study demonstrated only the cause of the negative correlation. The next step is a detailed analysis of the large-scale hydrological processes related to the annual AO in the Amur River basin, and quantitative analyses of the relationship between autumn SST preconditioning and the winter sea ice formation. The present results suggest persistence in the AO from the previous summer to winter, which will be examined in future work.

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M. Ogi, Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showamachi, Yokohama 236-0001, Japan. (masayo.ogi@jamstec.go.jp)
Y. Tachibana, Institute of Observational Research for Global Change, Japan Agency for Marine-Earth Science and Technology, 2-15 Natsushima-cho, Yokosuka 237-0061, Japan. (tachi@rh.u-tokai.ac.jp)