

## Does the Fresh Water Supply from the Amur River Flowing into the Sea of Okhotsk Affect Sea Ice Formation?

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### Abstract

The impacts of ground hydrology on the high-latitude oceans, such as melting glaciers and discharge from rivers into the oceans, can affect global climate by mediating the flow of low-density, fresh water inflow that strengthens the ocean's stratification. This suppresses the thermohaline circulation, and also promotes sea-ice formation. Our time series analysis based on sea-ice and river-discharge data indicates that the effect of this fresh water on the sea-ice in the Okhotsk Sea, into which the second largest Siberian River, the Amur, discharges, is relatively unimportant. Interannual variations in the ice extent are negatively correlated with the amount of discharge. We find circumstantial evidence that the inflow of warmer river water tends to raise the sea surface temperature, and that it suppresses ice formation in the following winter. This potential explanation for the negative correlation implies that sensible heat transported by large rivers in high latitudes should be reconsidered in studying global climate change.

### 1. Introduction

The Sea of Okhotsk (OK), which is located between Siberia and the North Pacific, is covered by ice from November through June, and is one of the southernmost ice-covered oceans in the Northern Hemisphere. The interannual variability of the sea-ice in the OK is large and sea-ice coverage has abruptly decreased since the end of the 1980's

(Tachibana et al. 1996). Also, the sea-ice influences large scale climate such as the development of the Aleutian low and the formation of the North Pacific intermediate waters (Talley 1991; Honda et al. 1996; Yasuda 1997). In analogy with the Arctic Ocean, sea-ice in the OK has been believed to be influenced by the ground hydrological processes (Akagawa 1977). Previous studies suggest the existence of a highly stratified, low-salinity surface layer in the OK, which suppresses deep convection and promotes freezing (Tsapko 1974; Manak and Mysak 1989; Rostov et al. 1991). It has also been speculated that the low-salinity layer is mainly due

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to the inflow of the fresh water from the Amur River. Although previous studies, such as Akagawa (1977) and Sekine et al. (1996), attempted to find evidence of the river-water influence on the sea-ice using data analyses, the lack of reliable interannual data for sea-ice and river-discharge precluded direct comparison between the ice-data and the discharge-data. Because the period of reliable satellite-based ice-data has been long enough to analyze the interannual variability, we are now able to directly compare the two. The purpose of our study is to quantify the effects of the Amur discharge on the sea-ice on interannual and longer time scales. Since the drainage in the north of the OK is much smaller than that of the Amur, only the Amur discharge is considered in this particular study.

## 2. Data

The data we utilized are as follows: 1) Discharge data at Komsomolsk na-Amure (KOM), issued by the Global Run-off Data Center, D-56002 Koblenz, Germany, from 1964 through 1984. 2) Discharge data at Bogorodskoye (BOG), from 1971 through 1993, except for missing data in the year 1979, which are annually reported by the data books, e.g. Leningrad Hydrometeorology (1986). The method of the runoff observation is as follows. On the vertical cross section of the river at the observatory, they measure the water speeds making an array that has ten horizontal and five vertical grids. Integrating the velocity distribution on the vertical cross section, they calculate the amount of the discharge at least twice a month. They also measure water level every day. Because there is very good relationship between the water level and the discharge, they calculate the daily discharge by the regression equation. 3) Satellite-measured ice extent data in the OK, issued by the Japan Meteorological Agency (JMA) from 1971 through 1996. Information about the JMA data is mentioned in Yamazaki (2000) in detail. According to Yamazaki (2000), the JMA data is subjectively composed by using the GMS and the NOAA satellite images. In addition, since the SSM/I data was available, the SSM/I data has been added to the composition. 4) Monthly precipitation station data around the Amur basin from 1971 through 1992. 5) Sea surface temperature (SST) data in the OK issued by JMA from 1964 through 1995. BOG is located near the estuary and KOM is at about 500 km upstream from BOG, and there are no large confluences of other rivers between the two stations

(Fig. 1). Because the correlation coefficient of the annual discharge measured between them is 0.96, missing values at BOG in 1979 and missing data at KOM after 1984 are filled by substituting data for the other station by linear regression. We also used the precipitation data within the Amur basin as a supplement to confirm confidence in our results.

Before showing the comparison between the sea-ice and the river discharge, we briefly describe climatology of the discharge and the precipitation over the Amur. Since the season in which the Amur is frozen extends from November through April, the discharge in the winter (half year), is only about 10% as large as the summer discharge (See Fig. 2), and the interannual fluctuation of the winter discharge is only about 1% as large as that of summer. (Not shown in figures) There are discharge peaks in the months of June and September. The former is mainly due to melting snow and frozen soil at low altitudes. The latter, on the other hand, is due to monsoon precipitation around this month as well as the melting of high altitude glaciers and snowfall, which accumulated in current and previous years. Because the main season for precipitation in the basin is also within the summer months, the annual mean discharge in a specific year is largely a reflection of the summertime weather of the same year, as well as that of previous years. In addition, the contribution from the melting of glaciers and snow to the discharge appears to be smaller than that of summer precipitation because the annual mean precipitation within the river basin is well correlated with the annual discharge.

## 3. Negative correlation between run-off and ice

Figure 3 shows the interannual variations of the maximum sea-ice extent, the annual mean discharges at BOG and KOM, annual mean precipitation at six stations within the Amur basin, and annual mean SST in the Northwestern OK. Since the main period of the discharge is from May through October, we can assess the influence of the discharge season upon the ice-formation season. The horizontal axis of the ice time series is therefore shifted a year earlier in this figure, e.g., the year labeled 1980 and on the ice axis actually corresponds to 1981. All time series are filtered by three-year moving averages to remove high-frequency variability associated with individual heavy rain events. Because the influences of the river's fresh water on the ocean structures can remain for years (Akagawa

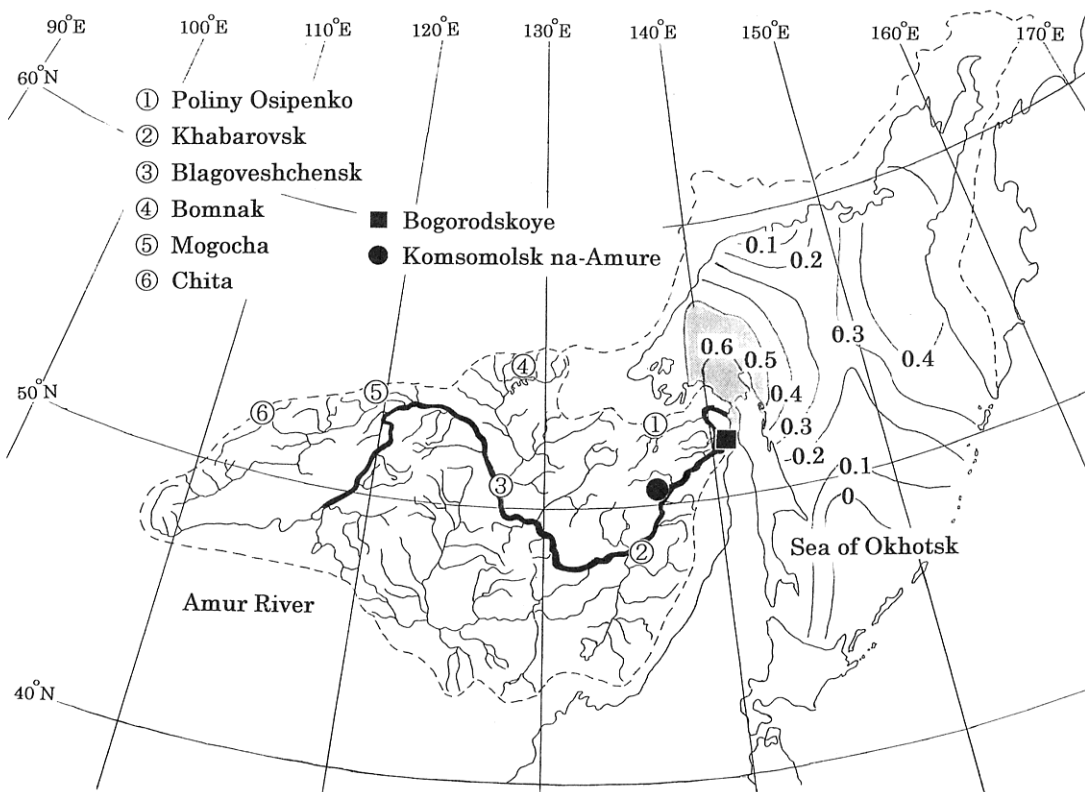


Fig. 1. Area map around the Sea of Okhotsk (OK). The watershed of the Amur River, precipitation stations and the stations of the river discharge are indicated. The distribution of correlation coefficient between the summer-time mean SST (June through October), and the annual mean Amur discharge at KOM, is shown on the OK. These two time sequences are filtered through the use of a three-year moving average. Contours are drawn every 0.1. The shaded areas indicate that the coefficients are higher than 90% statistical significant level, assuming the degrees of freedom is 1/3 of the number of years common to both data sets.

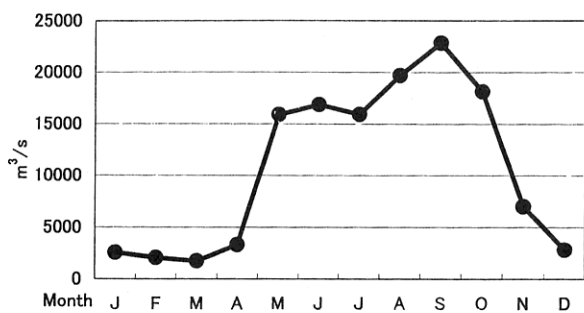


Fig. 2. Normal annual variation of the Amur discharge averaged from 1971 through 1993 at BOG.

1977), the analysis based on filtered data should be meaningful.

This figure obviously shows that two sets of the discharge are strongly negatively correlated with the ice extent ( $r = -0.84$  for BOG and  $r = -0.82$  for KOM as shown in Table 1). This means, that in winters following summers in which the amount of the discharge was below normal, the ice in the OK covers abnormally large areas and vice versa. The annual mean precipitation in the Amur basin also shows the same tendency as the discharge, although the averaged precipitation cannot be regarded as an exact proxy for the river discharge. The correlation coefficient between the precipitation and the ice is not as high as the 90% significant level, but the sign is consistent with both the discharge and the ice. The agreement of the result

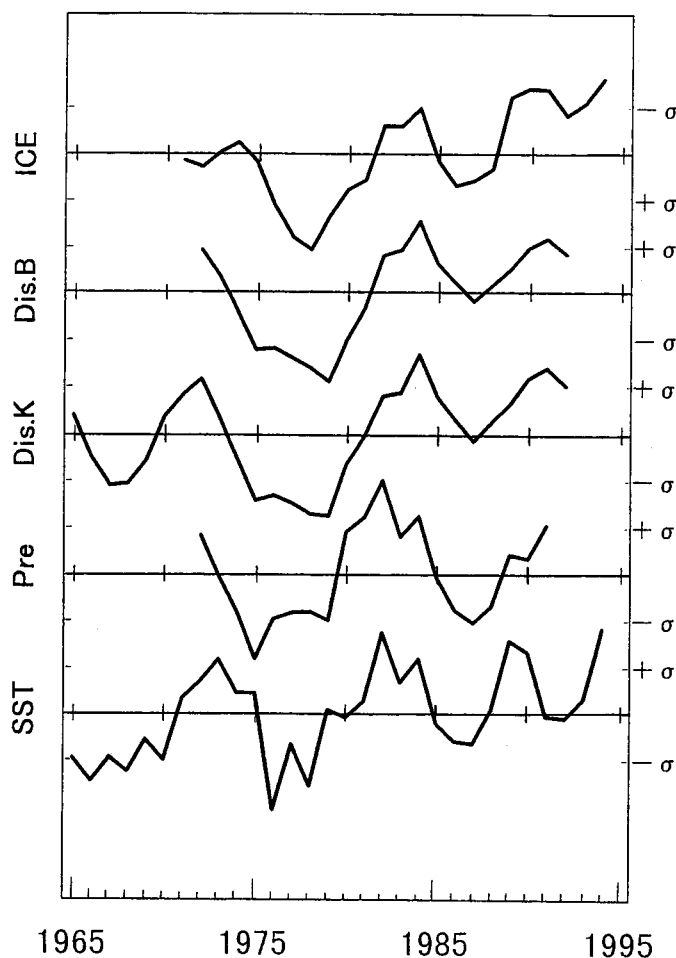


Fig. 3. Standardized time series (top to bottom); interannual variations of the maximum sea-ice area over the OK, discharge at BOG, discharge at KOM, annual mean precipitation over the Amur basin, and summer-average SST in the northwestern part of the OK (140E–144E, 52N–56N). The time series are filtered with a three-year moving average. The horizontal axis extends from 1965 through 1995. The small scales along each vertical axis indicate the standard deviation of each variable. The standard deviation in each variable is (top to bottom);  $1.1 \cdot 10^5 \text{ km}^2$ ,  $56 \text{ km}^3/\text{yr}$ ,  $40 \text{ km}^3/\text{yr}$ ,  $34 \text{ mm}$ ,  $0.28 \text{ }^\circ\text{C}$ . To facilitate comparison, the vertical axis of the sea-ice is reversed, i.e., the positive values indicate less ice.

from two independent datasets enables us to assert that the relationship is completely opposite of what was previously believed to be correct. The analysis based on the unfiltered annual mean discharge data and ice extent also indicates negative correlations, which are still higher than the 99% significant level ( $r = -0.55$  for BOG and  $r = -0.53$  for KOM). Each correlation coefficient and each statistical significant level are shown in Table 2.

#### 4. Possible causes of the negative correlation

A possible cause of this opposite relation is the

influence of the sensible heat advection from the river (Kenneson et al. 1989; Searcy et al. 1996). If the summer temperature of the river is higher than that of the OK, the discharge brings about the advection of warm water into the surface layer of the OK. Because the low-density warm fresh water can easily spread on the surface layer of the sea in the summer (Tsapko 1974; Rostov and Zhabin 1991), the warm SST due to the discharge can reduce the potential for freezing in the following winter. This interpretation is consistent with the facts that (1) the interannual variation of the discharge is positively correlated with summer-time SST in

Table 1. Correlation matrix (upper right), of each pair show in Figure (2), and statistical significance (lower left). Values at the lower left indicates the coefficient in each pair exceed each statistical significance level, and \* indicates that the level is lower than 90%, assuming the number of degrees of freedom is 1/3 of the number of years common to both data sets. The number on the main diagonal cell is the annual mean value in each variable.

|          | Sea ice                             | Dis(Bog)               | Dis(Kom)               | Pre   | SST   |
|----------|-------------------------------------|------------------------|------------------------|-------|-------|
| Sea ice  | 1.2*10 <sup>6</sup> Km <sup>2</sup> | -0.84                  | -0.82                  | -0.55 | -0.73 |
| Dis(Bog) | 99                                  | 333km <sup>3</sup> /yr | 0.98                   | 0.67  | 0.59  |
| Dis(Kom) | 99                                  | 99.9                   | 291km <sup>3</sup> /yr | 0.71  | 0.58  |
| Pre      | *                                   | 95                     | 95                     | 533mm | 0.57  |
| SST      | 95                                  | 90                     | 90                     | *     | 9.2°C |

Table 2. As in Table 1 but for the unfiltered annual mean variables. Statistical significance is estimated assuming that the number of degrees of freedom is the number of years common to both data sets minus two.

|          | Sea ice                             | Dis(Bog)               | Dis(Kom)               | Pre   | SST   |
|----------|-------------------------------------|------------------------|------------------------|-------|-------|
| Sea ice  | 1.2*10 <sup>6</sup> Km <sup>2</sup> | -0.55                  | -0.53                  | -0.39 | -0.64 |
| Dis(Bog) | 99                                  | 333km <sup>3</sup> /yr | 0.97                   | 0.69  | 0.25  |
| Dis(Kom) | 99                                  | 99.9                   | 291km <sup>3</sup> /yr | 0.73  | 0.18  |
| Pre      | 90                                  | 99.9                   | 99.9                   | 533mm | 0.22  |
| SST      | 99.9                                | *                      | *                      | *     | 9.2°C |

the northwestern OK (Table 1), and (2) the SST is negatively correlated with the ice extent. Because the northwestern part is known to be the main ice-production area (Martin et al. 1998), from which the ice moves and spreads towards the south, the SST in this area is able to influence the ice extent throughout the OK. The distribution of the correlation coefficient between summertime SST in the OK and the discharge at KOM exhibits a gradual eastward weakening (Fig. 1), reflecting the eastward penetration and dilution of the warmer river water. According to an atlas of the Amur issued by Far Eastern Aero-geodesy Corporation, 1995, the topography of the Amur is shallow, slow-moving and meandering. It is, therefore, accepted that the water parcels of the Amur have plenty of time to equilibrate to the surrounding summer mean temperature, which is obviously higher than the SST in the OK, since the heat capacity of the continent is, in general, smaller than that of surrounding oceans.

We further calculated the correlations of the mean SSTs in the northwestern OK in three sub-periods (May–June, July–August and September–October)

with the maximum sea-ice area. The correlation coefficients increases with time (–0.16 for May–June, –0.37 for July–August and –0.70 for September–October). This indicates importance of the autumn SST for the formation of the sea ice, and suggests the importance of the sensible heat from the river in autumn, because the annual maximum discharge occurs in September and because the river temperature is highest in the beginning of autumn.

We roughly estimate the annual water budget in the OK as follows. Assuming that the runoff water spreads out uniformly within the hatched northwestern area where there are high correlations between the discharge and the SST (Fig. 1), and that it accumulates on the surface of the ocean without vertical mixing with the underlying saline water, the annual accumulation depth of runoff water will range from 2.6 to 5.0 m year<sup>-1</sup>. On the other hand, Fig. 4.7 of the paper by Lobanova (1989) illustrates that the autumn temperature of the Amur is about 20 °C. Because summer time SST in the northwestern part of the OK is lower than 10 °C, we can

assume the difference of the annual mean temperature between the river and the ocean is about 10 °C. If the difference is 10 °C, fluxes ranging from 42 to 81 W m<sup>-2</sup> are needed in order to release all the excess heat into the atmosphere over a period of a month. Therefore, the heat difference between a large discharge year and a small discharge year is 39 W m<sup>-2</sup>. This value is comparable to the latent and sensible heat released into the atmosphere in the beginning of the winter. According to the ECMWF (European Centre for Medium-Range Weather Forecasts) analysis data for the heat flux, the average surface heat flux in the northwestern OK in November 1991 through 1998 is about 205 W m<sup>-2</sup>, and the standard deviation is about 41 W m<sup>-2</sup>. Because this value is mainly influenced by the interannual variation of atmospheric conditions, the effect of the heat from the river can be comparable to atmospheric variability in the beginning of winter. However, detailed analyses of the heat budgets using numerical methods, such as a box ocean model, should be done in the future study in order to quantify the river effect.

Another possible cause of the negative correlation between the river discharge and the sea-ice could be a mutual relationship to some other variable. Both the runoff and the sea-ice exhibit decadal time-scale variations with a slightly increasing linear trend of the river discharge, accompanied by a declining trend in the sea-ice. If, for example, the summertime atmospheric circulation patterns that directly determine the precipitation over western Siberia are related to the wintertime atmospheric circulations that influence the ice extent, such as the Aleutian low, then we can expect the underlying summer-to-winter connection in the atmospheric patterns also have variability on the decadal time scale. There are some reports that pointed out the existence of a decadal signal over the western Pacific (Nitta and Yamada 1989; Trenberth and Hurrell 1994; Yasunari et al. 1998; Xie et al. 1999), and Siberia (Xie et al. 1999; Chen et al. 1992; Yatagai and Yasunari 1994), involving winter (but not summer) weather. It therefore seems difficult to fully explain the good regional linkage purely on the basis of the global atmospheric circulation. However, these good correlations suggest that there might be undiscovered inter-seasonal connections, and we should make sure of the existence of the inter-seasonal linkage in a future study. Both the indirect large scale influence and the direct sensible heat can contribute to the strength of the relation-

ship between the discharge and the ice.

We have shown that river runoff could affect the high-latitude oceans not only by the injection of fresh water (Hanzlick and Aagaard 1980; Stigebrandt 1981; Holt et al. 1984; Aagaard and Carmack 1989; Bjork 1989; Manak and Mysak 1989) but also by the input of sensible heat, and that these two processes have opposing impacts on sea-ice formation. Which effect is dominant in any particular ocean should be dependent on the scale of the ocean, the time scale of interest, the atmospheric variability, the amount of the discharge, and the river temperature. Because both the scale of the OK and the amount of discharge into the OK are about 10% of the Arctic Ocean, the effect of the sensible heat from the rivers flowing into the Arctic Ocean might be also significant. In order to quantify this effect, one would need to further plan observational studies as well as indirect remote sensing studies and modeling studies. One would also need to systematically gather temperature data for the rivers in the high latitudes through international cooperation.

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