Interannual variations of sea ice types and relationships with air temperature in the Sea of Okhotsk during 1988-1997

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Abstract. A new algorithm for microwave radiometer was developed to discriminate ice types in the Sea of Okhotsk. Although a trend of decreasing sea ice area in the Sea of Okhotsk has been observed and it was 29.4 % per decade since 1989, analysis of ice types showed that the fraction of thin ice area to the total sea ice area had increased 15.1% per decade. This indicates thinning of ice during 1988-1997. The fraction of thin ice area was large when the winter temperature was high. The new ice analysis was applied also to the daily changes of ice types in the ice tongue which was observed in the northern part of Okhotsk Sea. As the ice tongue was isolated from other ice distribution, in situ growth and decay of sea ice can be analyzed.

1. Introduction

Sea ice extent in the Sea of Okhotsk has been decreasing rapidly since 1989 [*Tachibana et al.*, 1996]. However, not only sea ice extent and concentration should be analyzed but also ice thickness.

Observation of sea ice in the Sea of Okhotsk by the satellite microwave radiometer involves some technical problems. The problems originate from false sea ice signals that come from atmospheric effects which turn up at low latitudes, and a coastal/land effect that contaminates the data due to the high ratio of land surrounding the sea [*Cho et al.*, 1996]. By using 85 GHz channel of SSM/I, this study researches the near surface condition and also decrease the marginal effects. In this study, a new algorithm for the Special Sensor Microwave Imager (SSM/I) on board the satellite DMSP was used to calculate ice concentration and to classify ice types simultaneously. This method is useful to investigate variations of sea ice extent with thickness in response to climate change.

2. Discrimination of ice types

Sea ice classification experiments that have been done by airborne sensors and in laboratories have also used the higher frequency channels [*Troy et al.*, 1981, *Eppler et al.*, 1992]. These experiments showed that distinction of ice types was possible by combining higher frequency channels with the other channels. A parameter $R_{37V/85V}$ was established by the ratio between the vertically polarized 37 GHz (37V) and the vertically polarized 85 GHz (85V) of SSM/I, to obtain higher resolution ability than before and to discriminate ice types according to thickness. Then an algorithm was developed to distinguish among coastal fast ice, floes, young ice, and newly formed ice. The threshold values were revised for SSM/I on the basis of results from experiments made with an Airborne Microwave Radiometer (AMR), that has the 89 GHz channels, and an airborne infrared radiometer, in February 1996 in the Sea of Okhotsk and Lake Saroma.

This new algorithm used a weather filter as suggested by *Comiso et al.* (1992), and also used a high resolution channel, so that the resolution ability increased 4 times. This gave a decrease in coast noise and marginal ice zone noise by checking the pixel including the margins of land/ice and water/ice so that false sea ice signals decreased considerably. In total this gave less false sea ice signals even though the algorithm used 85V, which is easily influenced by water vapor.

The 14th International Symposium on Okhotsk Sea & Sea Ice, Feb. 1999

The parameter of high spatial resolution channels 85GHz in SSM/I has been used in areas with more than 80% ice concentration calculated by the NASA Team algorithm. The 85 GHz channels of SSM/I have a resolution of 12.5 km, twice the resolution of the other channels.

3. Recent trend of sea ice coverage in the Sea of Okhotsk

Figure 1 shows sea ice classifications and the ice concentrations on the days with maximum sea ice extent in 1988 and 1996, calculated by the new algorithm. In 1988, most of the sea was covered by floe ice, signals of fast ice type appeared in the center of the area and along the eastern coast of Sakhalin. This was apparently due to thick floes covered with snow. In 1996, most of the sea ice was thin, but floes still existed in the center of the sea and along off of eastern Sakhalin.

Figure 2 shows a time series of mean air temperature during December and March and sea ice extent, with data taken from one day showed maximum extent, from 1988 to 1996, in the Sea of Okhotsk, calculated by using the NASA Team algorithm. The ice classification was shown in Fig. 2. Trends of gradually increasing air temperature and significantly decreasing sea ice extent are shown in Figure 2, where it can be seen that the slope for sea ice extent is -0.048×10^{6} km^{2} yr^{-1} (29.4% per decade). In 1988 a maximum in the extent of sea ice is found where the sea ice occupied about 80% of the Sea of Okhotsk. This should be compared to a minimum in 1997 where the ice only occupied 50%.

If the sea ice in the Sea of Okhotsk becomes thinner and stays for shorter periods due to influence of global warming in future, it is predicted that climatological and oceanic change will occur in this area. It is obvious from this figure that areas of the thick sea ice such as fast ice and floes have decreased in this period.

Even though the total area of sea ice is decreasing, the fraction of thin ice compared to the total area has increased 15.1% per decade. On the other hand, the fraction of thick ice compared to the total area has decreased 43.4% per decade. The correlation coefficient of the total ice extent with the mean air temperature is low -0.54, but the correlation between the fraction of the thin ice area and the mean air temperature is high 0.81. The relationships between the thin ice fraction and air temperature can be seen in Figure 3.

4. Observation of ice tongue

A ice tongue was observed in the northern part of Sea of Okhotsk (Figure 4). This ice tongue is similar to the ice tongue "Odden" in the Greenland Sea (*Wadhams et al.*, 1996). The ice tongue persisted more than one month. The new algorithm was applied to observe day-by-day changes in the ice types forming the ice tongue. Since the ice tongue was isolated from the other ice distribution, changes in ice type was occurred due to in situ melt or freeze of ice. Then, we may discuss freeze/melt processes eliminating advection effect. The ice tongue was consisted of thin ice in the early stage, the core of ice tongue was formed by the ice floe after the one month. However, it varied due to changes in air temperature (Figure 5). From December 31, 1996 to January 3, 1997, A warm period was observed in the northern part of Okhotsk Sea. The ice condition was varied in this period, the ice tongue was decayed. After the warm period, the ice tongue expanded with the thin ice coverage. The ice type was changed to ice floe in the middle of January as temperature was low for a week. The ice tongue was observed also in the 1995/96 winter. The mean air temperature was high in the both winter, it is not obvious that warm condition affects on the formation of the ice tongue.

5. Conclusions

This study developed the new algorithm by which it is possible to display ice classification and distribution with high resolution by use of the vertically polarized 85GHz channel. This study leads to the following results for sea ice changes in the Sea of Okhotsk.

In the period from 1988 to 1997, the ratio of thin ice increased by 15.1% per decade, while the ratio of thick ice decreased by 43.4 % per decade and the total area of sea ice decreased by 29.4 % per decade. The decrease of the area of total ice and thick ice, and the increase of the fraction of thin ice area is probably due to a temperature rise. When the sea ice area is consisted of thin ice, the ice extent is unstable therefore easy to disappear.

Ice types in the ice tongue in the northern part of Okhotsk Sea was observed using the new algorithm. It varied with temperature fluctuation and it may indicate local ice formation and deformation as the head ice tongue was isolated from the other ice area.

Acknowledgment. We used AMR data provided from the National Space Development Agency of Japan (NASDA), SSM/I data distributed from the National Snow and Ice Data Center (NSIDC) and anomaly temperature data in the Sea of Okhotsk provided from the Global Historical Climatology Network (GHCN).

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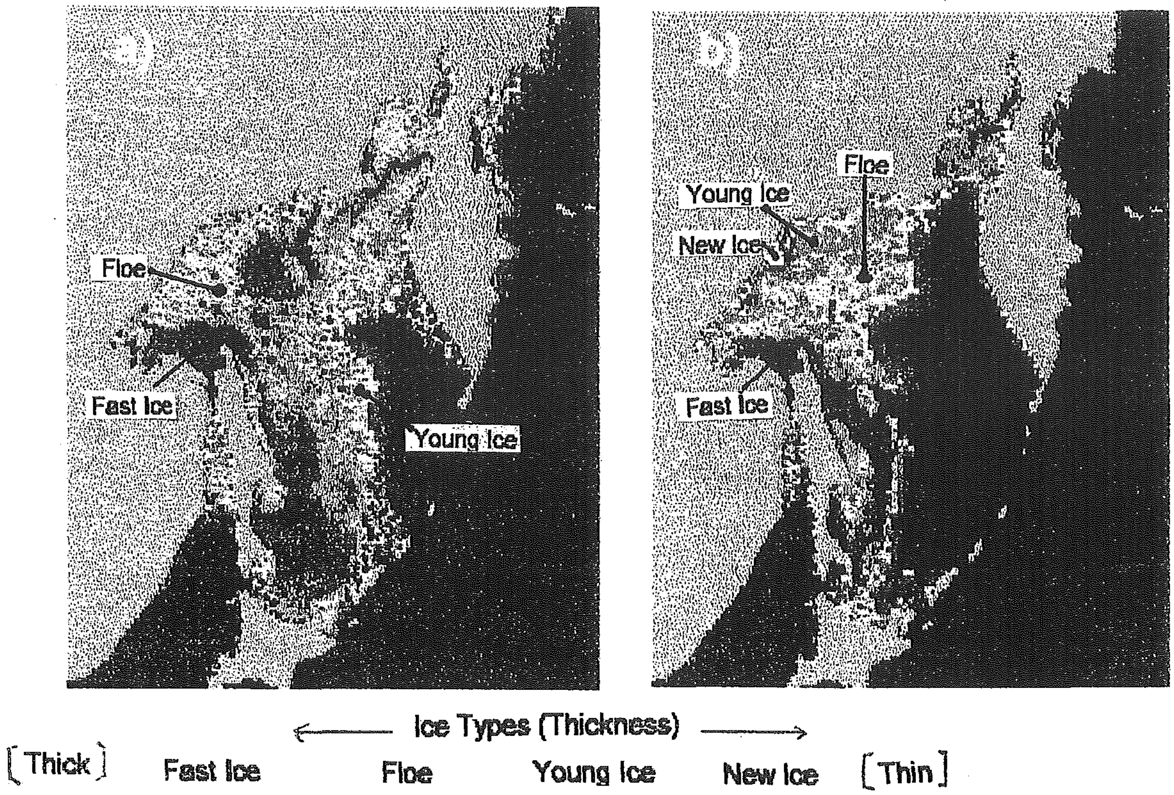

Figure 1. Classified concentration maps for Sea of Okhotsk on (a) March 9, 1988, and (b) March 14, 1996 derived from SSM/I.

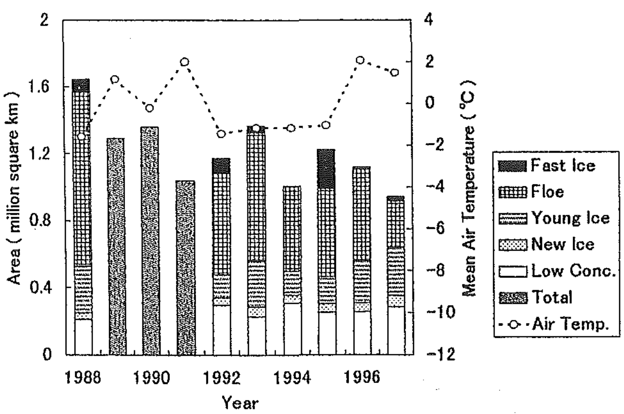

Figure 2. Time series of maximum sea ice extent and ice types during 1988 to 1997 and mean air temperature from December to March in the Sea of Okhotsk. The ice extent was calculated by the NASA Team algorithm, the ice types was calculated by a new algorithm using 85GHz.

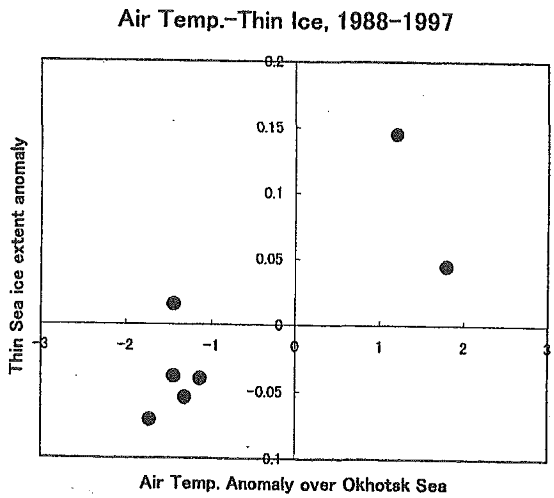

Figure 3. Relationships between air temperature and thin ice extent during 1988-1997. The results of 1989-91 was not included due to data problem.

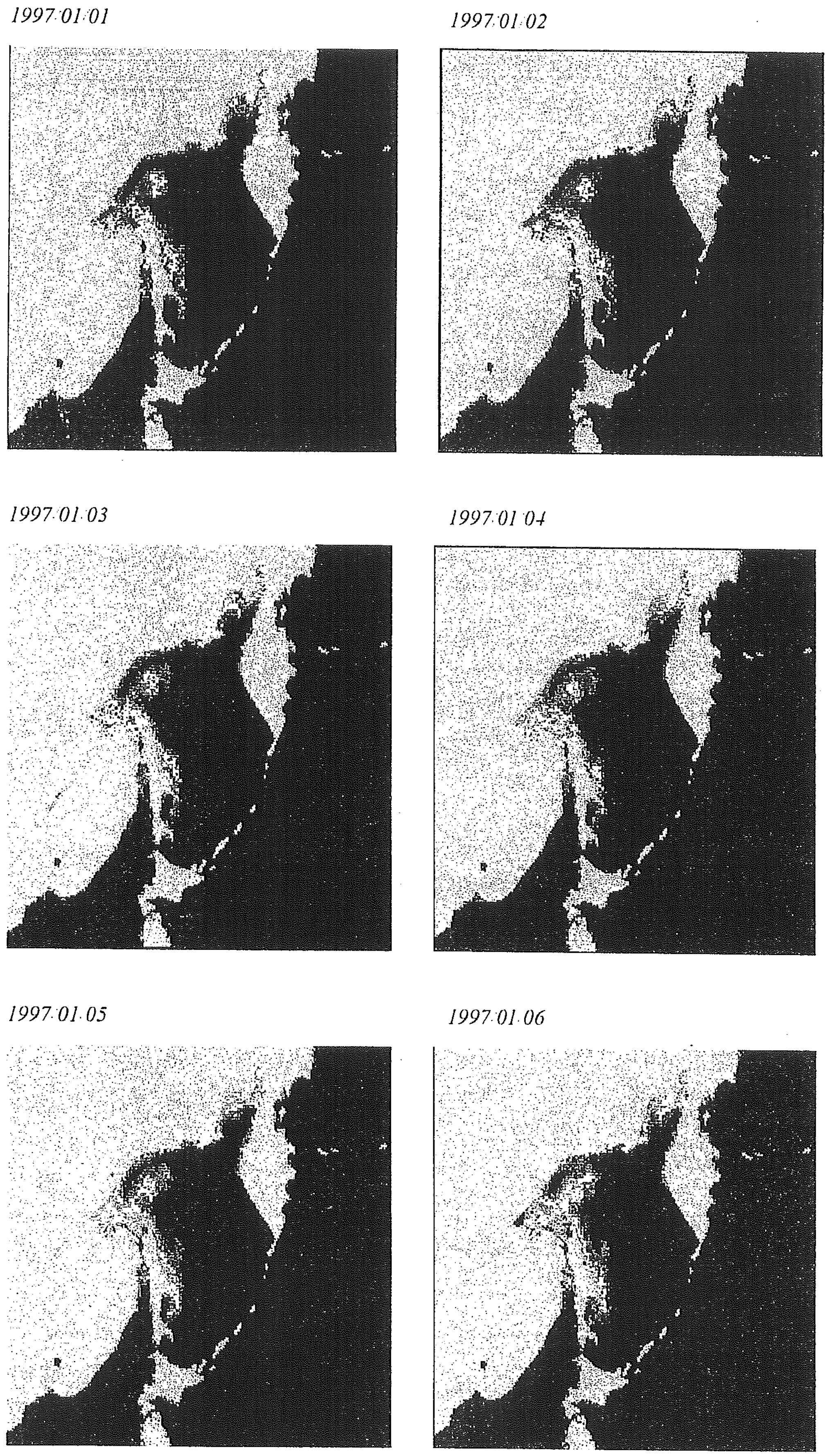

Figure 4. Daily variations of the ice tongue in the northern part of Sea of Okhotsk, Jan. 1997.