ECMWF Re-Analysis Project (ERA)

Technical Report No. 76

Global Sea Ice Concentration Data Set for use with the ECMWF Re-Analysis System

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ABSTRACT

The global sea ice concentration data set used in the ECMWF Re-Analysis system is described. This data set consists of weekly global sea ice concentration data with 1.0 degree latitude/longitude resolution from November 1978 to December 1991. The original data used in the calculations were created from satellite multichannel microwave radiometer data - Scanning Multichannel Microwave Radiometer(SMMR) and Special Sensor Microwave Imager (SSM/I). Discontinuities between SMMR derived data and SSM/I derived data could not be detected. Because many erroneous data were included in the original sea ice concentration data, a quality control process was carried out using reliable SST analyses to remove them. To fix the sea ice limit to be used as a sea ice mask in the numerical prediction model, the sea ice data were compared with manual analyses over the Baltic Sea and the Sea of Okhotsk, and a sea ice concentration of 55% was found for the best criterion. To evaluate the availability of the derived data they were compared with sea ice masks of the AMIP SST, the NMC OI SST and the GISST. The features of the satellite derived sea ice data were more stable and realistic than those of sea ice masks represented within these SST analyses. The satellite sea ice data also showed some interesting features: the seasonal change characteristic of sea ice coverage is different between the Arctic and the Antarctic. The annual mean sea ice extent was almost constant for the Antarctic but it showed a slight decrease for the Arctic. In spite of small inter-annual variations of total sea ice extent, large variations were observed in local sea ice coverage.

1. INTRODUCTION

The introduction of accurate sea ice coverage is essential for the good performance of atmospheric data assimilation models over polar regions. Low level boundary conditions such as heat fluxes, surface stresses, albedo etc. are crucially dependent on whether or not the sea is covered by ice. Some experiments using regional models show that an accurate sea ice coverage significantly improves forecasts in the winter season (*Andersson* and *Gustafsson*, 1994., *Okubo* and *Mannoji*, 1994). Despite its importance, it has been very difficult to determine accurately the sea ice coverage because surface based sea ice observations are limited.

Improvements in space technology have changed this situation. Remote sensing by satellites has played an important role in monitoring sea ice. The sensors used are visible/infrared and microwave radiometers. The usefulness of visible/infrared sensors is limited by persistent cloud cover over the polar oceans and by the polar night. On the other hand, microwave soundings are not hampered by these problems. The principle of microwave sounding is based on the fact that the polarization of microwave radiances differs between sea ice and sea water. The polarization technique greatly reduces the uncertainties in the derived ice concentration resulting from temporal and spatial variations in surface temperature.

The first radiometer to provide complete sea ice conditions over the polar regions was the Electrically Scanning Microwave Radiometer (ESMR) on Nimbus-5. The ESMR has been used to describe seasonal and regional variations in sea ice extent and concentration over both polar regions (*Gloersen* and *Campbell*, 1988). From October 1978, the Scanning Multichannel Microwave Radiometer (SMMR) on Nimbus-7 continued to provide data until August 1987. *Gloersen* and *Campbell* (1988, 1991) investigated the variations in Arctic and Antarctic sea ice cover and revealed that there were significant decreases in ice extent and open-water areas within the ice cover in the Arctic, whereas in the Antarctic there were no significant trend. A report on SMMR sea ice data has been published by *Gloersen et al.*(1992). The Special Sensor Microwave Imagers (SSM/I) on board the DMSP satellites provided data from July 1987 and have been continued to the present day.

From the point of view of global climate change it is very important to assess the climatological situation over the polar regions. *Simmonds* and *Budd* (1991) and *Simmonds* and *Wu* (1993) showed that sea ice conditions in the Antarctic region strongly affect the climate created by Global Circulation Models. Therefore it is essential to use accurate sea ice cover in the ECMWF Re-Analysis (ERA) system. To do this, it was decided to use SMMR and SSM/I sea ice concentration data. The reasons for using satellite data are:

(1) the accuracy of the data is sufficiently good for NWP models (see section 4.1);

(2) the availability and quality of the data is homogeneous during the re-analysis period, from January 1979 to December 1993 (see sections 4.2, 4.3).

Using SMMR and SSM/I sea ice concentration data, a weekly global sea ice concentration data set was created with 1.0 degree latitude/longitude resolution. In this paper, the procedures followed to create the data set, the validation of the data, and some sea ice features during the re-analysis period are described.

2. SMMR AND SSM/I SEA ICE CONCENTRATION DATA

The original data sources used are SMMR Arctic and Antarctic Sea Ice Concentrations on CD-ROM from NASA and DMSP SSM/I Sea Ice Concentration Grids for the Polar regions on CD-ROM from the National Snow and Ice Data Center (NSIDC). The former were derived from the Nimbus-7 SMMR and the latter from DMSP SSM/I. The SSM/I sensor operates every day; however the SMMR sensor operated only every second day, to conserve power. Both data sets were calculated from dual-polarized multispectral radiances. The algorithm used for the conversion from the radiances to sea ice concentration is the NASA team algorithm (*Cavalieri et al.*, 1984; *Steffen* and *Schweiger*, 1991; NSIDC, 1992). The data period for SMMR is from October 25th 1978 to August 20th 1987 and that for SSM/I is from July 9th 1987 to December 31st 1991. Their horizontal resolution is about 25km which corresponds to one scene of the radiance survey.

The accuracy of SMMR and SSM/I sea ice concentrations has been investigated by several researchers. *Cavalieri et al.* (1984) estimated that the relative accuracy of SMMR sea ice concentration data is 5-9% based on the time variation of ice concentration for the central Arctic region and on an analysis of histograms of the parameter used in the conversion algorithm. *Steffen* and *Maslanik* (1988) used Landsat imagery to verify sea ice concentration estimated by SMMR over the northern Baffin Bay during May to June in 1981. They concluded that sea ice concentration can be retrieved from SMMR data to within 3.5% during the pre-melt and onset of melt and 10% during melt periods. Comiso and *Sullivan* (1986) compared SMMR sea ice data and in situ observations (ship and helicopter) over the Weddell Sea during the 1983 Antarctic Marine Ecosystem Research at the Ice Edge Zone Experiment. They obtained a standard error of 13% in SMMR ice concentration. They also reported that this relatively low accuracy reflects not only the uncertainties in the retrieval of satellite data in spring but also the difficulty in obtaining accurate sea ice concentrations from a helicopter and/or ship platform.

Steffen and *Schweiger* (1991) used cloud-free Landsat scenes to validate the NASA team algorithm to determine sea ice concentrations from SSM/I. They concluded that the Landsat and SSM/I ice concentration have a correlation of 0.968 with a standard deviation of 6.6% in spring and fall, and that the standard deviation is increased to 11.7% in the summer season. They identify surface melt during summer as one of reasons for the large summer differences.

Considering these results, the standard error of SMMR and SSM/I sea ice data can be estimated to be 5-7% in the winter season and 10-15% in the summer season. The main cause of the increase of standard error during summer is attributed to surface melt. However the decrease of the accuracy during summer season is not particularly significant for the re-analysis, because in terms of surface conditions for numerical weather prediction (NWP) models, the "pond" created by surface melt should be analyzed preferably as water rather than as ice.

3. CREATION OF WEEKLY SATELLITE SEA ICE CONCENTRATION DATA

Using the SMMR and SSM/I sea ice concentration data, weekly mean sea ice concentration data were created over both polar regions.

3.1 **Quality Control**

The original sea ice concentration data often included false indications of sea ice over the open oceans. These resulted mainly from optically thick cloud, rain and sea surface roughening by surface winds. Although a weather filter (*Gloersen* and *Cavalieri*, 1986) reduced this effect, a substantial number of highly suspect data remained in the original sea ice data. Fig. 1 shows spurious weekly sea ice concentration values calculated using SMMR data without any quality control processes around the British Isles for the second week of March 1987.

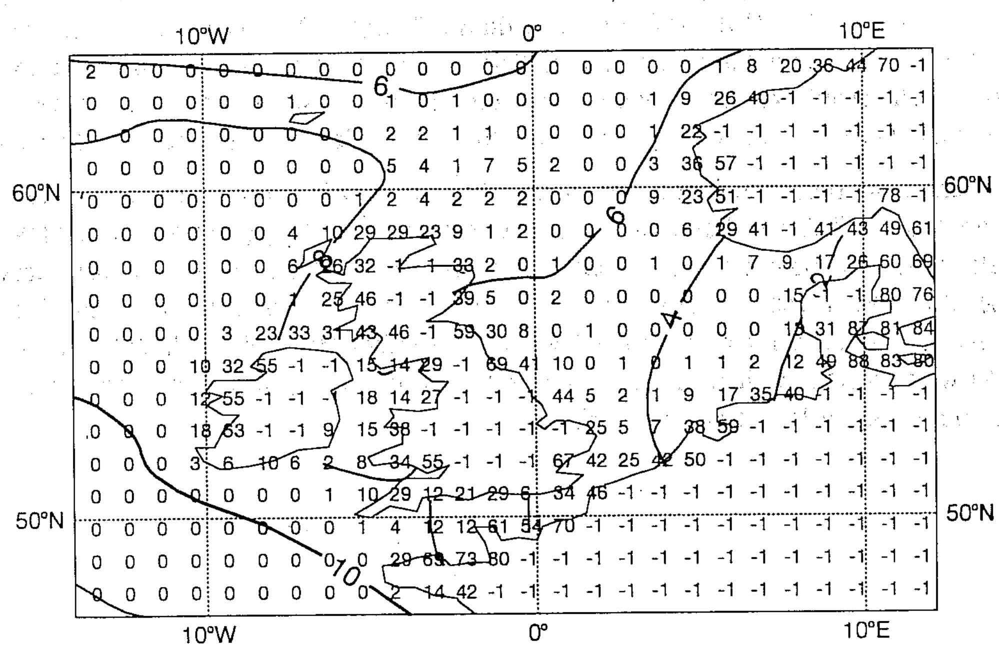


Fig. 1 Grid point values of weekly sea ice concentration around the British Islands on the second weeks of March (March 8) 1987. '-1' shows no data at the grid point. The contours represent Sea Surface Temperature (deg. C). Contour interval is 2.0 degrees.

Each numerical value represents mean sea ice concentration (%) at the 1.0 x 1.0 degree latitude/longitude grid box. '-1' means that no sea ice data were available for that grid box during the week; this would normally be due either to the point being over land, or to no observation having been obtained. Contours on Fig. 1 show the SST field at the same time. Comparing the sea ice data with SST and considering climatological situations, false data are seen especially along the coasts. Sea ice concentration values around the British Isles and the French coast must be erroneous. Suspicious data can also be seen over the North Sea.

To remove these erroneous or suspicious data, quality control (QC) was carried out for the original satellite data before calculating weekly mean sea ice concentrations; if the SST at a datum was greater than +1.0 deg. C, the concentration for that point was set to 0.0%. The SST data used in the QC were GISST created by UK Met. Office (*Parker et.al.*,1992) until October 1981 and NMC OI SST (*Reynolds* and *Smith*, 1994) from November 1981. A 1/4-1/2-1/4 time filter was applied to NMC OI SSTs to eliminate noise coming from the analysis scheme. There are two reasons why +1.0 deg.C was used as the criterion instead of 0.0 or -1.7 deg. C. Firstly, because NMC SSTs were passed through a time filter, the analyzed minimum SSTs are often rounded. Secondly, verifications of the resulting sea ice data gave better results when this value was used. The QC procedure is very simple; however it played a important rôle in creating the data set.

3.2. **Data mapping**

The original SMMR sea ice data are mapped to the same polar grid system as that of SSM/I. Their horizontal resolution is about 25km. As mentioned in section 2 the data were mapped every other day for SMMR and every day for SSM/I. To cover the polar regions completely by SMMR data, it was necessary to accumulate them at least for 6 days. This is the reason why sea ice concentrations are calculated weekly in this study. The conversion from the polar grid into 1.0 x 1.0 latitude/longitude grid was carried out using a program included in the CD-ROMs. The 1.0 x 1.0 latitude/longitude grid mesh contained several SMMR or SSM/I data during 7 days. Weekly mean sea ice concentration values were fixed by simply averaging them. There were no data from the north pole to 86 deg. N due to orbital characteristics of the satellite platforms. 100% was set over this area. Checking the sea ice conditions over the Arctic during the period, this assumption was confirmed to be reasonable.

Data gaps and other problems for the original satellite data which affect the calculation of weekly sea ice data are listed in Table 1. For almost all cases listed in Table 1, missing points could be estimated using data at the same point on 1 or 2 weeks before and 1 week after. However a large data gap from December 3rd 1987 to January 12th 1988 was more serious, and could not be handled in this way. Weekly sea ice concentration data for the 5 weeks (December 6th, 13th, 20th 27th 1987 and January 3rd 1988) were created by linear interpolation in time using data just before (November 11th 1987) and just after (January 10th 1988) the period.

Table 1: Main data gaps or other problems for original satellite data

Date	Period (weeks)	Sensor	Situation
12 - 19 Mar. 1983	2	SMMR	data missing
30 Mar. - 13 Apr. 1986	3	SMMR	many missing points
3 - 15 Apr. 1986	2	SMMR	data missing
6 Dec. 1987 - 13 Jan. 1988	5	SSM/I	data missing
25 Dec. 1991 -	1	SSM/I	many missing points

Fig. 2 and Fig. 3 show sea ice coverage maps created by the data on 21st July 1985 and 22nd December 1985. The thick line represents the sea ice limit fixed by sea ice concentration of 55% and the thin line represents 15%. The 15% ice limit shows the floating ice limit and the 55% shows the closed pack or consolidated ice zone (this will be discussed in the next section). The floating ice zone along the east Greenland coast can be seen in figure 2 and large polynya (large open water areas surrounded by sea ice) can also be seen in the Ross Sea and the Weddell Sea in figure 3.

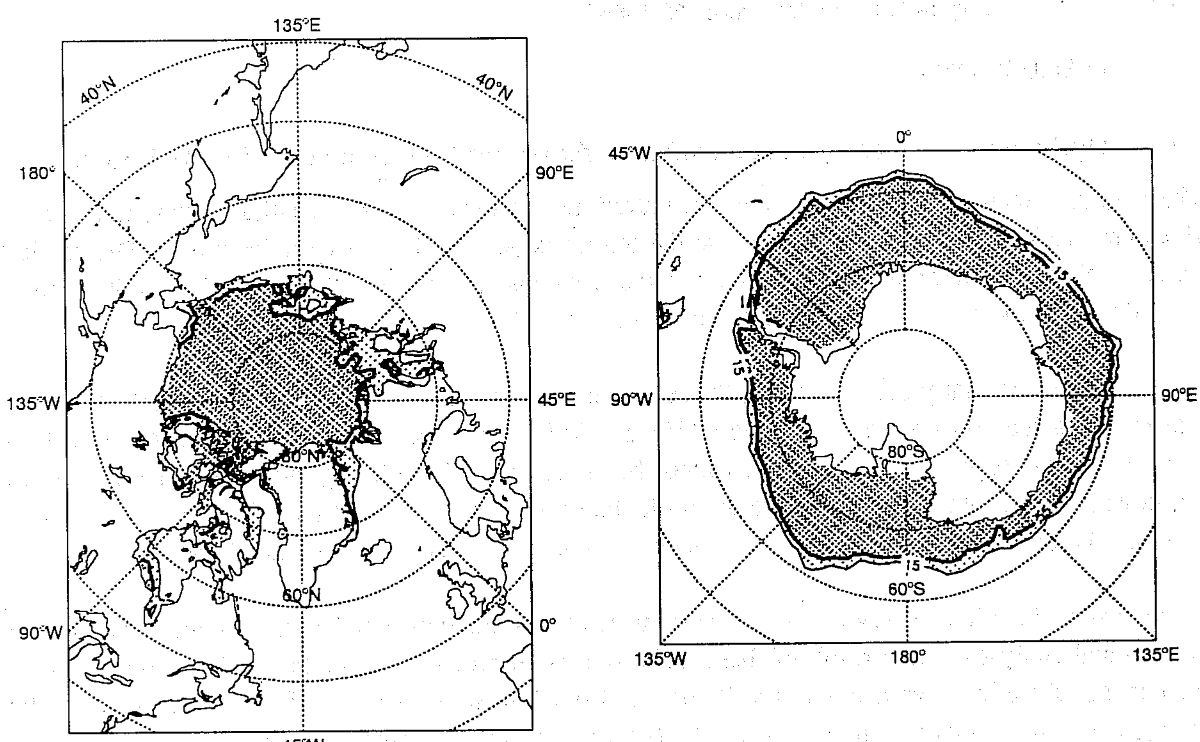


Fig. 2 Weekly mean sea ice coverage maps over the Arctic (left) and the Antarctic (right) on July 21 1985. Thick lines shows 55% sea ice concentration, which represent limits of closed pack ice or consolidated ice. Thin lines show 15% sea ice concentration, which represent limits of floating ice.

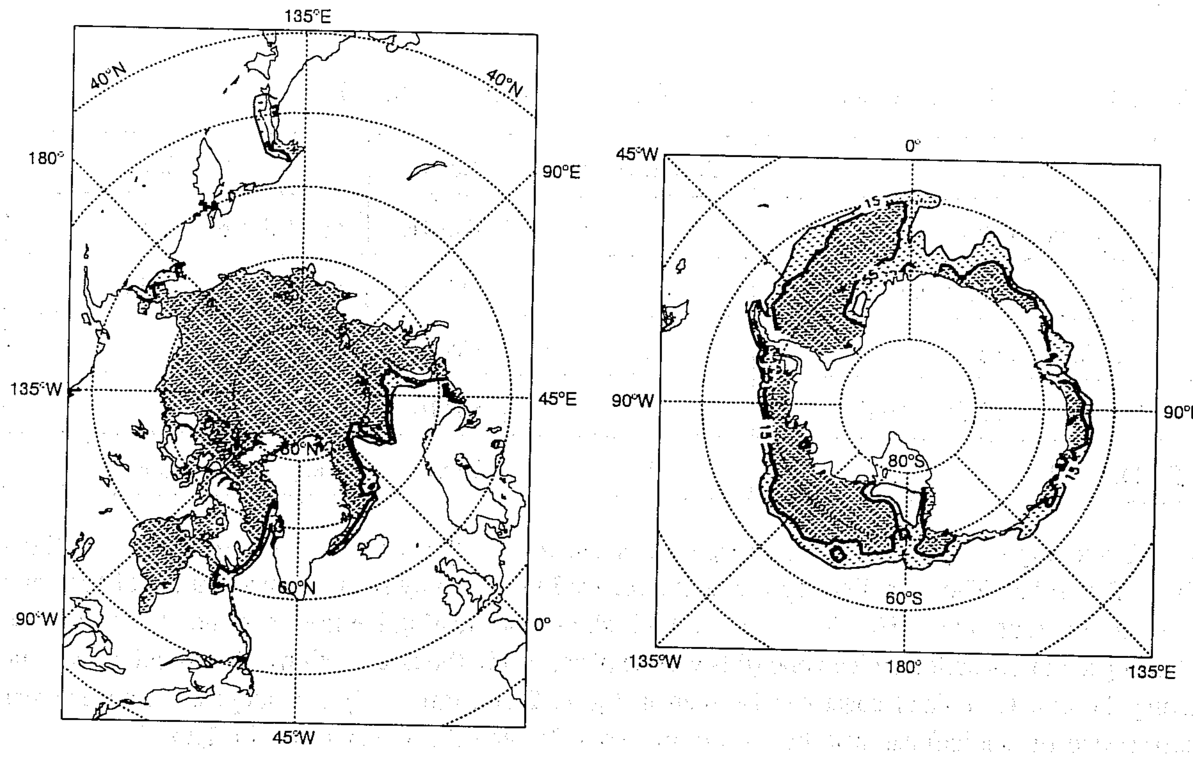


Fig. 3 As figure 2. but on December 22 1985.

4. DISCUSSIONS

4.1. Optimum sea ice concentration value to fix sea ice limit to be used in NWP models

The data set created represents sea ice concentrations for every 1.0 x 1.0 latitude/ longitude grids. However, the ECMWF model does not use the sea ice concentration but a sea ice mask. The sea ice mask specifies whether a point is covered by ice or remains open water. To use the data in the model, an optimum value that fixes sea ice limit must be determined.

Sea ice studies normally use 15% to set the sea ice limit (for example *Gloersen* and *Campbell*, 1991). However sea ice concentrations between 15% and 70% represent open pack ice where interaction between the atmosphere and sea water cannot be neglected. Considering the effect on fluxes from ocean water to the atmosphere, the sea ice limit should be defined so that there is little or no contact between the atmosphere and ocean water, namely closed pack ice or consolidated ice.

To determine the criterion, several comparisons were carried out between the sea ice concentration data and manual analyses. As a result of these, 55% was determined to be the best value. Fig. 4 shows the change of sea ice coverage over the Baltic Sea from January to March 1987 as represented by the sea ice data and by manual analyses from the Institute of Marine Research in Finland. In this figure, 55% of sea ice concentration was used to fix the sea ice limit for SMMR data and closed pack ice and consolidated ice were shown in the manual analyses. The consistency between them is excellent, the only exception being that there was a large area of open water over the Gulf of B2othnia in the manual analysis on 9th February but not in SMMR data dated on 8th February.

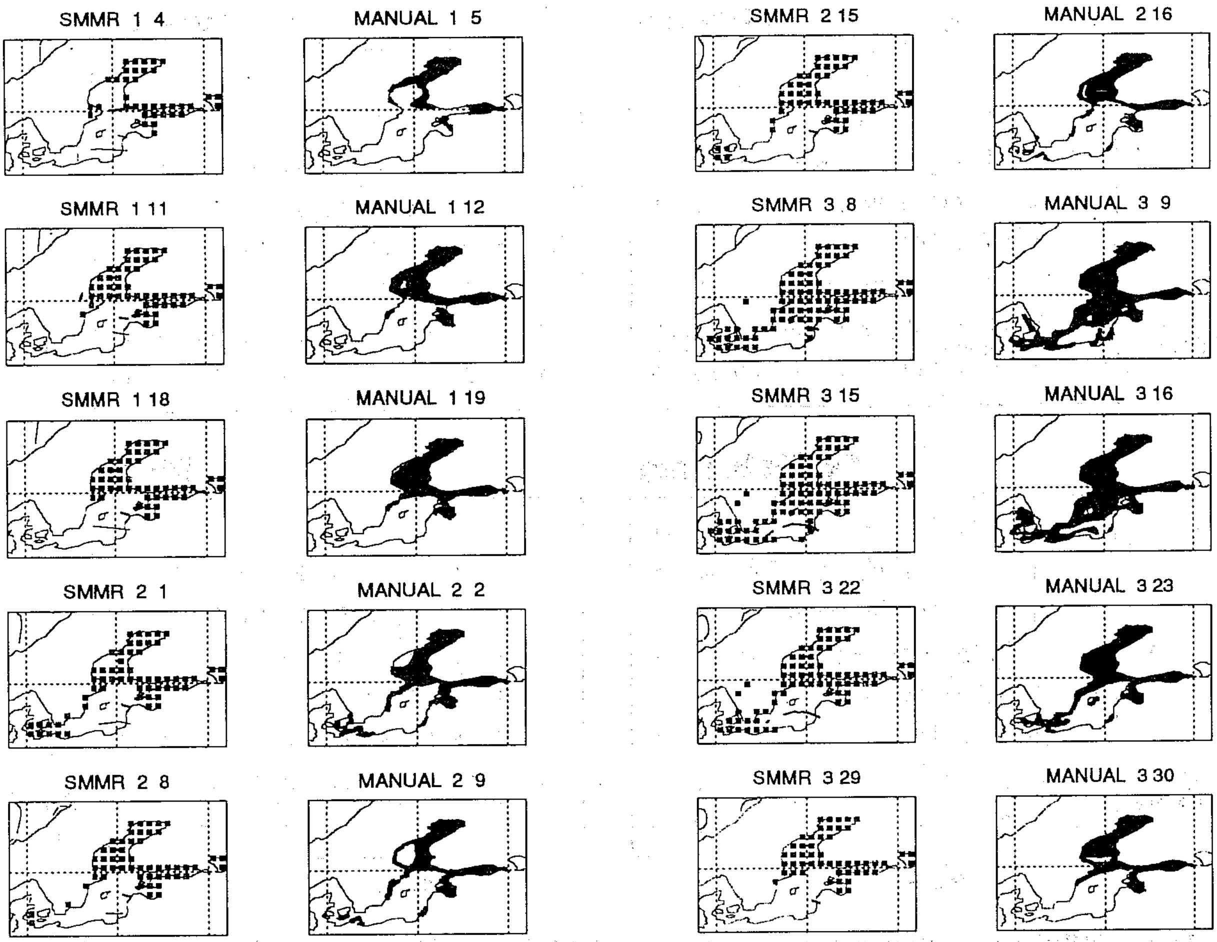


Fig. 4 Sea ice coverage over the Baltic Sea from January 4 to March 29 1987. Maps of left row show sea ice defined by SMMR sea ice concentration data (over 55%). Those on right row show sea ice coverage defined by closed pack ice and consolidated ice estimated from manual analyses by Institute of Marine Research in Finland - The date (month/day) is indicated above each frame.

To investigate the reason of this discrepancy, the original satellite data were checked. There were three SMMR surveys for the week, on 7th, 8th and 10th February. Sea ice concentrations for 1.0 x 1.0 latitude/longitude grids calculated from each survey data are shown in figure 5.1 (7th), 5.2 (8th) and 5.3 (10th). Fig. 5.1 shows that SMMR also detected open water on the 7th since sea ice concentrations in the area were relatively small - the smallest value was 13%. Sea ice concentration at these points became higher than the threshold value and continue to be covered by sea ice on 10th. These figures show that open water existed until 7th February but that the area was closed by sea ice on 8th. Weekly mean sea ice data shown in figure 5-4 could not represent such a rapid change because they were created by averaging data observed during the week.

The question remains why the manual analysis shows open water in the 9th February analysis. The next analysis on 12th February did not show the open water. (Figure is not shown here; it was almost the same as that on 16th February in figure 4.) Manual analysis used satellite imagery as a main data source. On checking weather conditions during the period, the weather was clear in this area on the 7th, but became cloudy on the 8th and continued thus for several days. It is possible that the manual analysis on 9th February was carried out using data observed on the 7th or earlier and could not recognize that the open water was closed on the 8th.

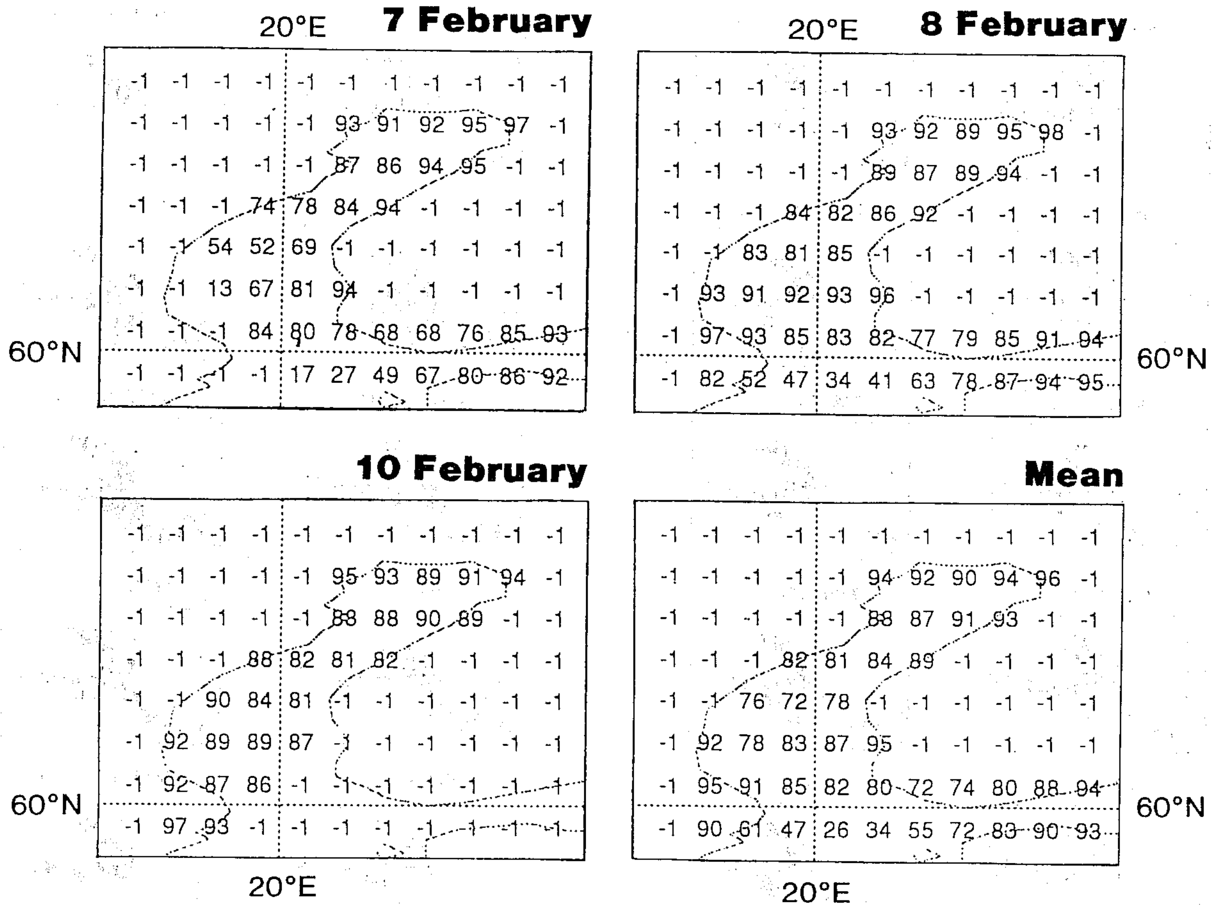


Fig. 5 SMMR sea ice concentration values at every 1.0x1.0 degree grid meshes over the Baltic Sea. Top map (figure 5.1) shows those calculated using data of a survey on 7th February. Second map (figure 5.2) shows the same as top map but on 8th February. Third map (figure 5.3) shows the same as top map but 10th February. Bottom map (figure 5.4) shows those calculated using all data of the week.

Almost the same results were obtained not only for other periods but also other areas. Fig. 6 shows manual analyses of sea ice coverage (closed pack ice and consolidated ice) over the Sea of Okhotsk during winter season in 1986-1987(JMA 1987). Fig. 7 shows sea ice coverage by SMMR data where 55% of sea ice concentration was also used to fix the sea ice limit. There is good consistency between the two data sets except for the melting season. As mentioned in section 2, the difference during the melting season is derived from surface melt of sea ice and this should be treated as open water in the weather model.

The difference between 70% and 55% seems to be due to the bias in the original SMMR data (*Gloersen et al.*, 1992). However the difference seems to be too large for this to be the only the reason. Despite this uncertainty, a value of 55% has been used to fix the sea ice limit.

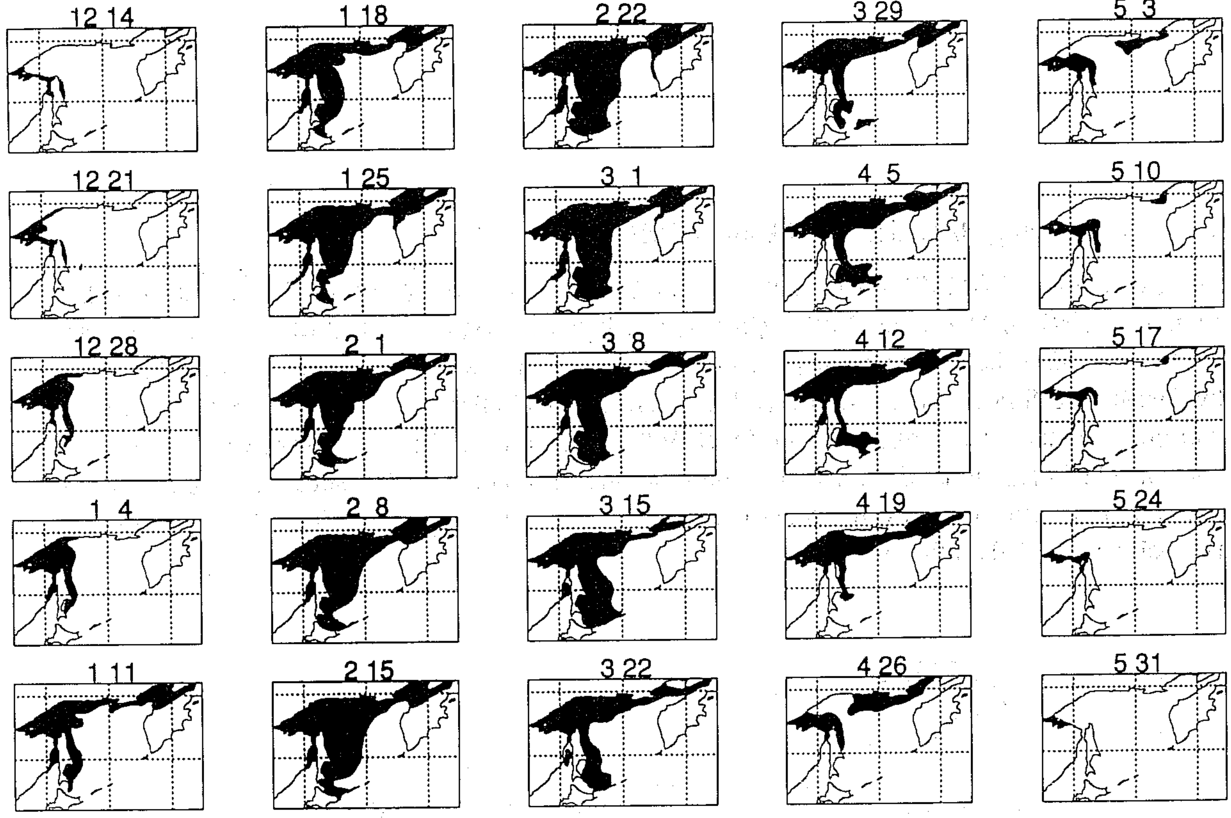


Fig. 6 Sea ice coverage estimated from manual analyses by Japan Meteorological Agency over the Sea if Okhotsk from December 14 1986 to May 31 1987. Sea ice areas are defined by closed pack ice or consolidated ice: namely the areas where sea ice concentration is 7/10 - 10/10. Sea ice over the Bering Sea was not analyzed here.

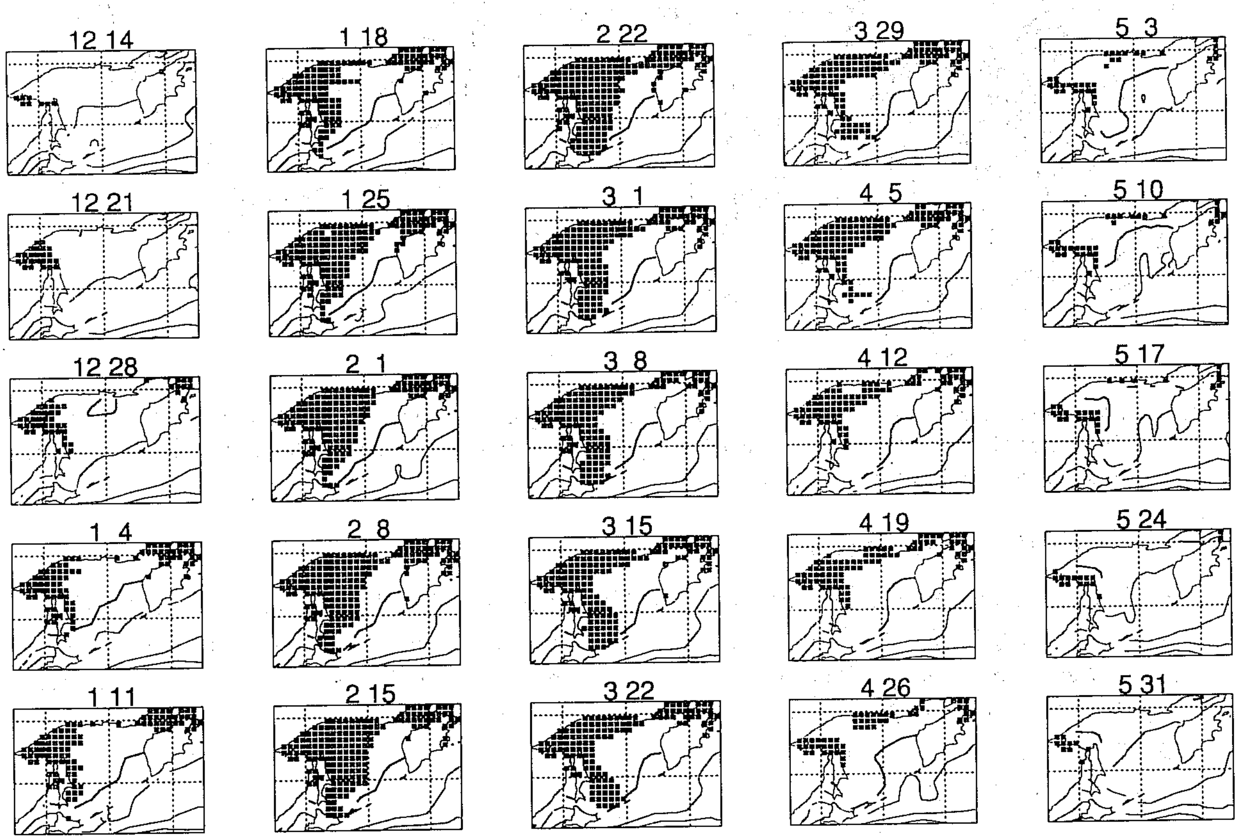


Fig. 7 Sea ice coverage over the Sea of Okhotsk estimated by SMMR data. The sea ice limit was fixed by 55% of sea ice concentration. The date of each map corresponds to that of figure 6.

4.2 Consistency between SMMR and SSM/I sea ice data.

The data period of SMMR sea ice data is from October 1978 to August 1987 and that of SSM/I is from July 1987 to December 1991. Comparison between SMMR and SSM/I sea ice data can be carried out using the data from July 1st to August 22nd in 1987. Fig. 8 shows sea ice limits given by SMMR and SSM/I data on 12th July 1987. Thick lines indicate sea ice concentration of 55% and thin lines indicate 15%. Solid lines are for SSM/I data and dotted lines for SMMR data. Considering unavoidable fluctuations of sea ice concentration and different sounding situations such as different sounding time and frequency, the consistency between the two data is excellent. Similar results have been obtained for the other weeks.

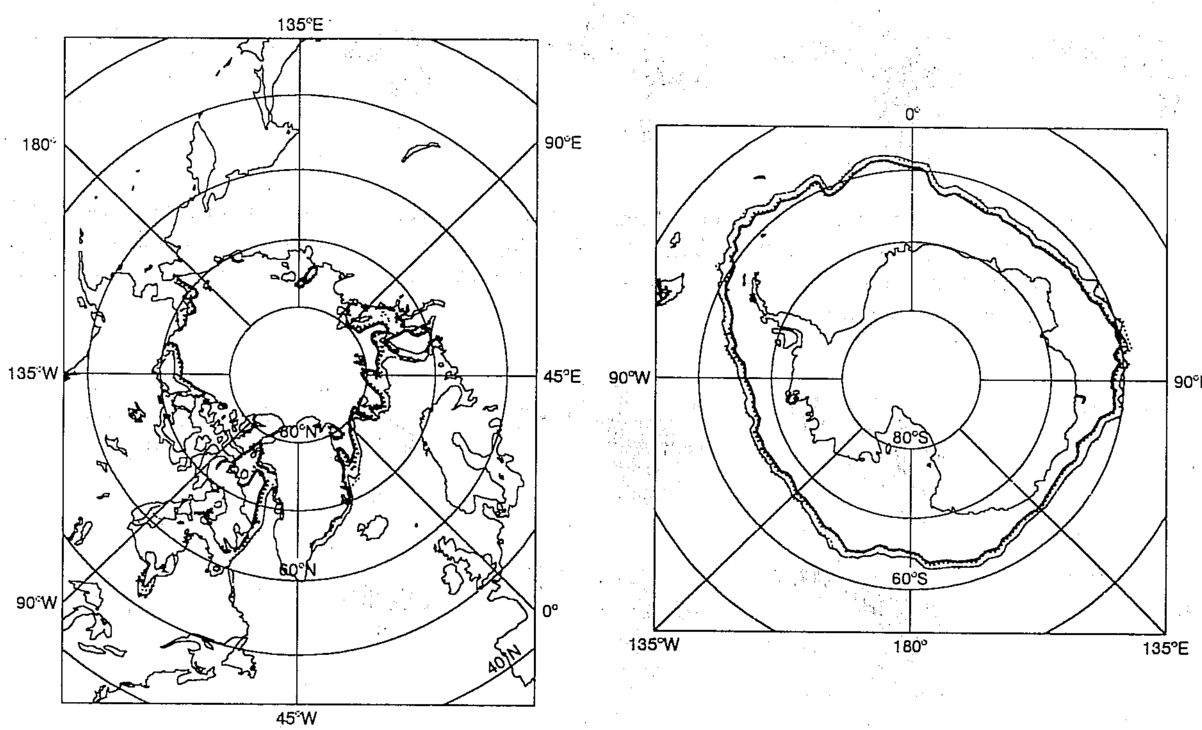
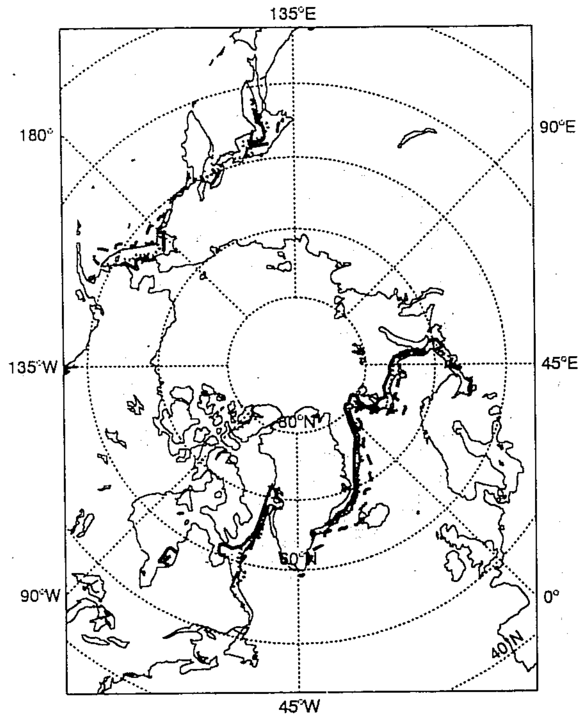


Fig. 8 Sea ice limits over the Arctic (left) and the Antarctic (right) by SMMR and SSM/I data on July 12 1987. Solid lines show that by SSM/I and dot lines by SMMR. Thick lines indicate 55% of sea ice concentration and thin lines indicate 15%.

4.3 Comparison with other sea ice data

We have three sets of sea ice data, contained within the NMC OI SST (*Reynolds* and *Smith*, 1994), AMIP SST (*Gates*, 1992) and GISST (*Parker et al.*, 1992) as ice masks. Sea ice data for the NMC OI SST were created using global sea ice analyses by U.S. Navy/NOAA Joint Ice Center (JIC) (*Reynolds*,1988). The AMIP's analyses were created by combination of COADS/ICE SST climatology and JIC's sea ice analyses. GISST's data were created using NOAA analyses which were largely based on satellite AVHRR and IR images.

Fig. 9 shows monthly mean sea ice limits in December 1979 by SMMR, AMIP data and GISST sea ice data over the Arctic (left) and the Antarctic (right). Sea ice data from NMC OI SST were not available in this period.



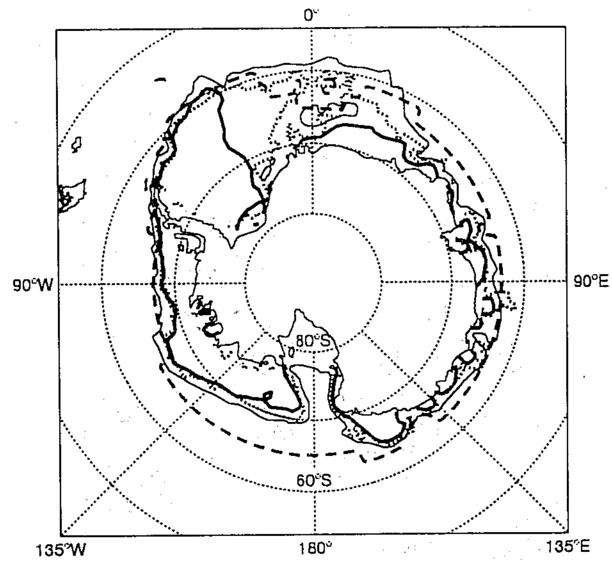


Fig. 9 Monthly mean sea ice limits over both polar regions on December 1979 by SMMR (solid lines), AMIP SST(dash line) and GISST(dot line). Left maps shows the Arctic and right one shows the Antarctic. Thick solid lines indicate sea ice limit fixed by 55% of sea ice concentration and thin solid lines indicate those fixed by 15%.

The AMIP sea ice cover is much more extensive than that of the other data in both regions. It also shows artificial features especially over the Antarctic.GISST is very similar to the SMMR's 55% sea ice concentration line. However, it is close to SMMR's 15% sea ice concentration line along Atlantic side of the Arctic and it is between 15% and 55 % over the Weddell Sea in the Antarctic. Fig. 10 shows the limits in December 1985 for SMMR, AMIP, GISST and NMC OI SST. For the Arctic, the features are almost the same as in December 1979 except over Hudson Bay. GISST's data shows a large area of open water, the others do not. For the Antarctic, sea ice limits by AMIP and GISST completely overlap each other. It seems that the two fields were based on the same data source over the Antarctic region from 1985 to 1988. The sea ice limit in the NMC OI SST is similar to the 15% sea ice concentration line of SMMR data, however it did not show any polynyas in the Ross Sea and the Weddell Sea where the other data showed them.

NMC OI SST used JIC's sea ice data for information of sea ice coverage. The data were used not as a sea ice mask but as SST data of -2.0 deg.C. After the SST analyses, the areas with analyzed SSTs lower than -1.8 deg.C were determined to be covered by sea ice (*Reynolds* and *Smith*, 1994). Sea ice limits fixed by this method will be strongly affected by SST data near the ice edge. For example, if there are no SST observations near the sea ice edge and the gradient of the SST field is small, the area where analyzed SST is lower than -1.8 deg.C may be wider than reality. This is thought to be the reason why sea ice covered areas in the NMC OI SST were much wider than those from the other data, especially for the Antarctic.

The NMC analysis scheme might lead to inaccurate sea ice analysis in areas where few observations could be obtained. For example NMC OI SST sea ice data failed to analyze polynyas over the Ross Sea and the Weddell Sea as shown in figure 10.

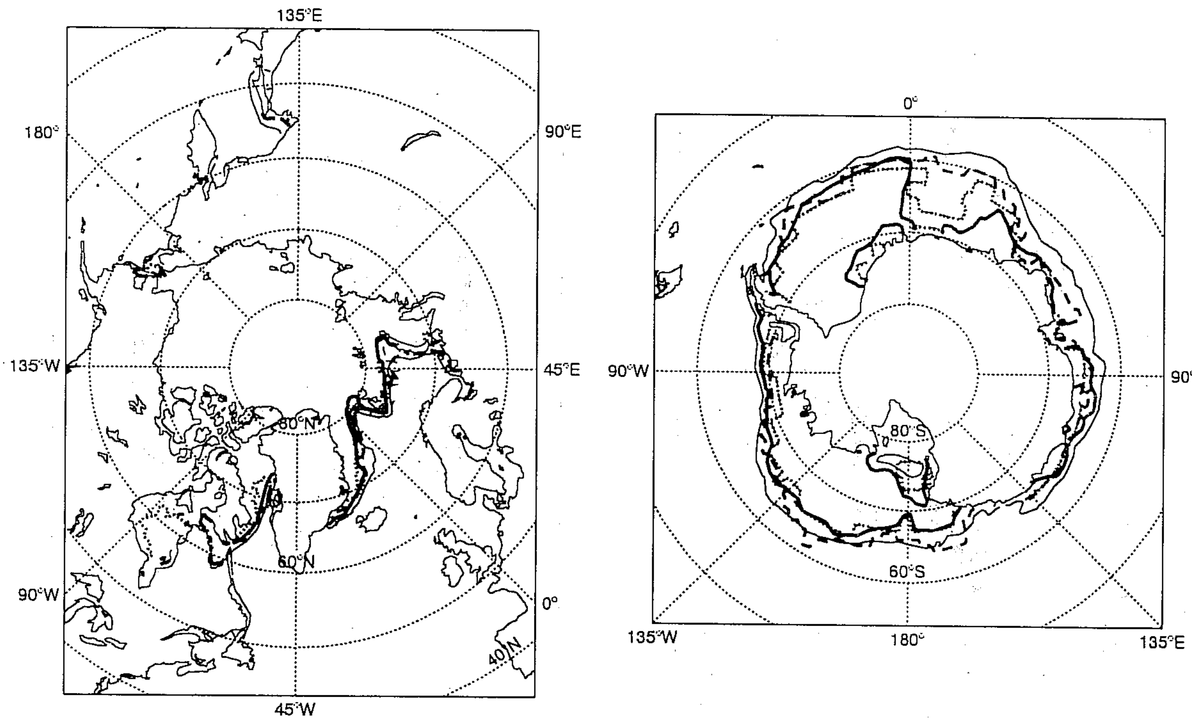


Fig. 10 As figure 8 but on December 1985 by SMMR (solid lines), NMC OI SST (thick dash line), AMIP SST (thin dash line) and GISST (dot line). The sea ice limits of AMIP SST and GISST are on the same line over the Antarctic.

They also showed unrealistic changes of sea ice coverage over closed areas like Hudson Bay especially during the melting season. Fig. 11 shows sea ice coverage over Hudson Bay estimated by SMMR data and NMC OI SST sea ice data during the melting season in 1986. According to the SMMR data, open water appeared in the north west side of the bay and the western part of the Hudson Strait in early June and developed from there at an almost a constant rate. From mid June other open areas also appeared over the western and southern parts of the bay, and the sea ice had almost disappeared in early July except in the south western part. It should be emphasized that the change of the coverage in the SMMR data is smooth and steady. On the contrary, the change in NMC OI SST sea ice data did not evolve smoothly. Large open areas appeared suddenly in the north west of the bay on the 3rd week (15th) of June. It shrank during the next week (22nd) and widened again during the following week (29th). The Hudson Strait remained covered by sea ice during the month, however the sea ice suddenly disappeared completely in the next week (6th July). In July the sea ice over the Hudson Bay remained in the center and did not change markedly during the first 3 weeks. Then, the sea ice seemed to melt rapidly on the last week (27th). These unrealistic changes might be due to the analysis scheme as mentioned above.

4.4 Fluctuation of annual mean sea ice extent in both polar regions

The fluctuation of annual mean sea ice extent from 1979 to 1991 was investigated using the satellite data. The results are shown in figure 12 for the Arctic and in figure 13 for the Antarctic. The corresponding values from NMC OI SST, AMIP and GISST were also plotted in the figures. According to the satellite data, the annual mean sea ice extent in the Antarctic was almost constant during the period. The large increase from 1986 to 1988 in the Antarctic sea ice shown in NMC OI SST, AMIP and GISST was not confirmed by satellite data. As mentioned in section 1, *Gloersen* and *Campbell* (1988,1991) detected a significant decreasing trend in ice extent over the Arctic.

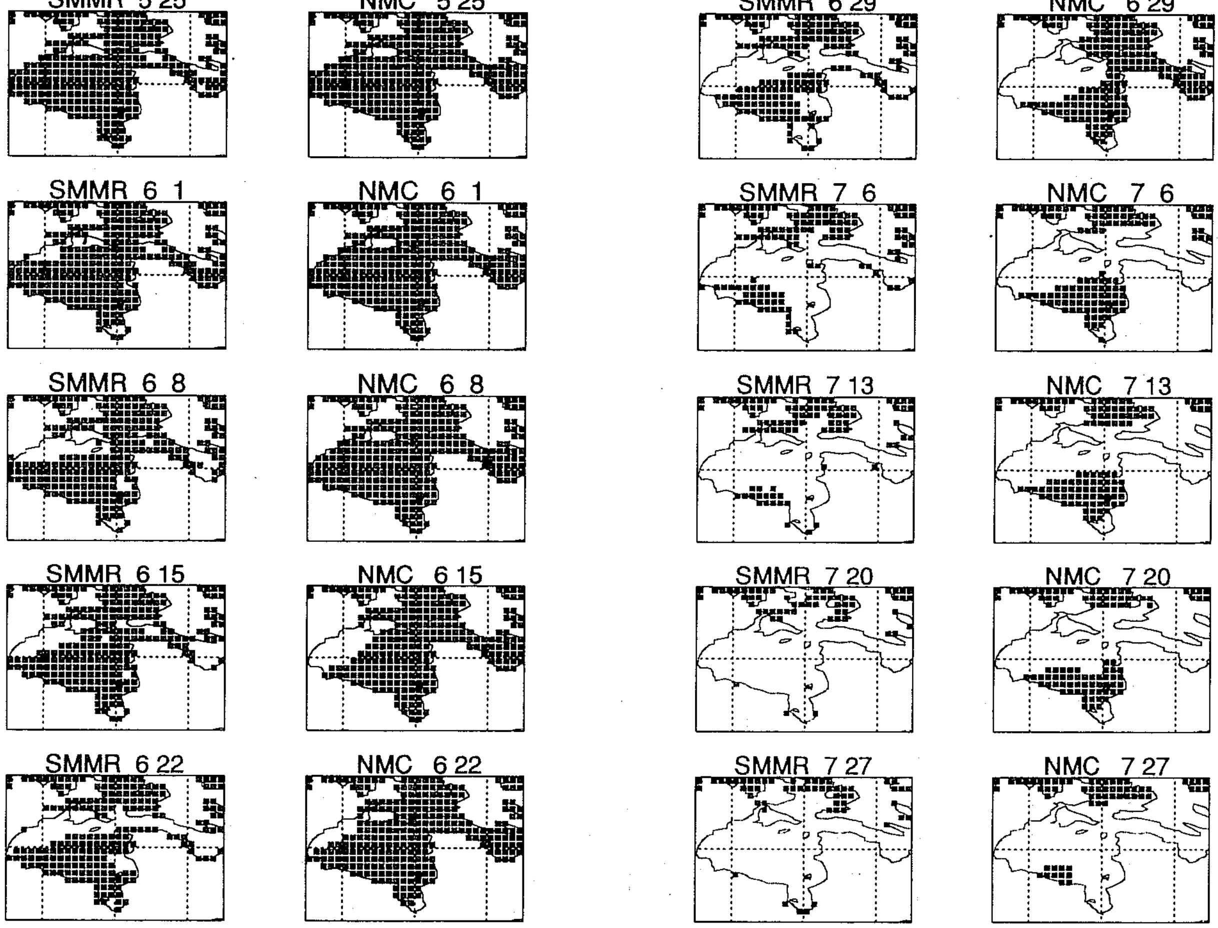


Fig. 11 Sea ice coverage over the Hudson Bay from May 25 to July 27 1986. Maps on left row show sea ice coverage estimated by SMMR data whose sea ice concentration is greater than 55%. Maps on right row show the correspond sea ice coverage by NMS OI SST sea ice data.

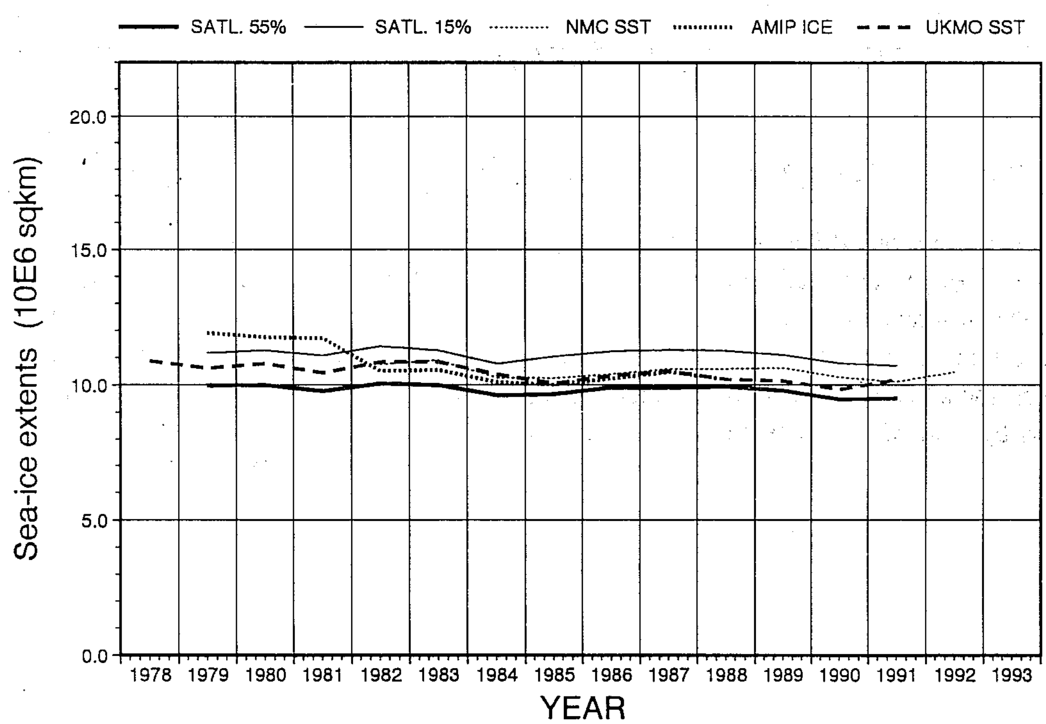


Fig. 12 Annual mean sea ice extents over the Arctic region from 1978 to 1992. Thick solid line represents sea ice extent defined by 55% sea ice concentration limit of satellite data (SMMR and SSM/I data). Thin solid line represents that by 15% sea ice concentration limit of satellite data. Thin dot line, Thick dot line and thick dash line represents that defined by NMC OI SST sea ice data, AMIP SST sea ice data and GISST sea ice data respectively.

This study can also confirm a slight decreasing trend in the ice extent determined by both (15% and 55%) ice extent determined by both (15% and 55%) ice limits in Fig. 12. Note that because each dataset has its own land mask, a comprehensive land mask was used to perform accurate comparison between them. Therefore, relative fluctuations through the period and relative differences between different data sources can be assessed; however the absolute fluctuations in sea ice extent might be smaller.

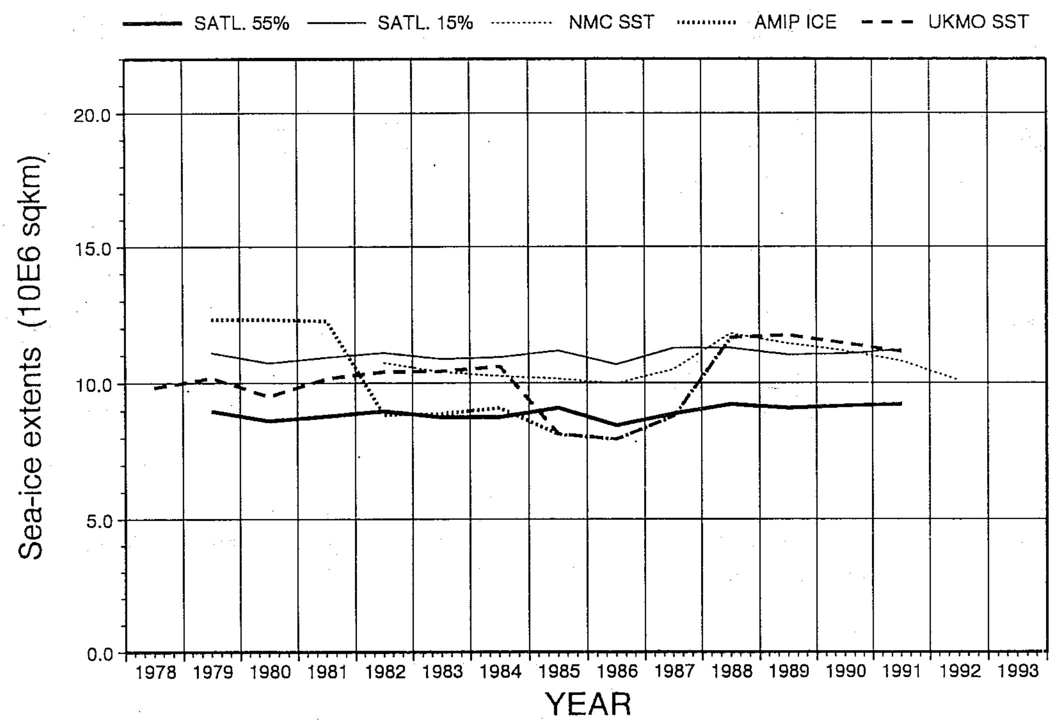


Fig. 13 The same as figure 12 but over the Antarctic.

4.5 Seasonal variations in sea ice coverage over the Arctic and Antarctic regions

The features of seasonal variations of sea ice are different between the Arctic and Antarctic. This is due to the difference of geographical circumstances of sea ice between the two regions. For the Antarctic region, most sea ice is bounded in the south by land and opens in the north to the ocean. However, the situation is very complicated for the Arctic region; several areas are almost completely bounded by land while others are open to the major oceans.

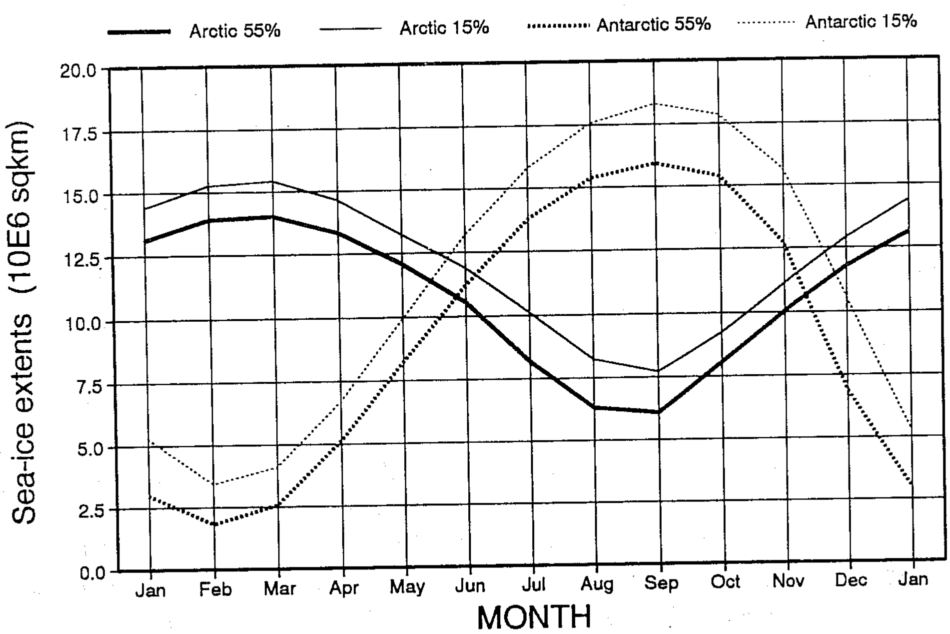


Fig. 14 Mean seasonal variations in sea ice extent over the Arctic (solid lines) and the Antarctic (dot lines). These lines were calculated by satellite data from November 1978 to December 1991. Thick lines show those defined by 55% sea ice concentration and thine lines shows those by 15%.

Fig. 14 shows mean seasonal variations in sea ice extent over both polar regions. Since inter-annual fluctuations of sea ice extent are very small, as mentioned in section 4.4, we simply averaged for every month using data of the whole period. This clearly shows that features of seasonal variation in sea ice extent between the Arctic and Antarctic regions were different. The seasonal variation in the Antarctic region is much bigger and sharper than that in the Arctic region. The growth rate in the Antarctic sea ice from April to July is about 2.5-3.0 x $10^6 km^2$/month and the melting rate from November to December is 5.5 x $10^6 km^2$ /month. The melting rate is about twice the growth rate. This implies that the sea ice situation in spring changes more rapidly than in autumn over the Antarctic. On the contrary the growth rate in the Arctic sea ice from September to January is about 2.0-2.5 x $10^6 km^2$/month and melting rate from April to August is 1.5-2.0 x $10^6 km^2$/month. Both rates were smaller than those in the Antarctic. The fact that the melting rate is smaller than the growth rate is a remarkable difference to the Antarctic.

Figures 15.1 - 15.12 show mean sea ice coverage for all months included in the data set, giving mean monthly sea ice coverage for the period 1979 to 1991. The ice edge shown in these maps are for 15% sea ice concentration (thin line) and 55% (thick line). The former line indicates floating ice zone and the latter indicate consolidated ice limit.

For the Arctic region, sea ice coverage reaches its maximum in February and March. The precise date for which the maximum value is reached will depend on the area. For example, its maximum occurs in February on the Gulf of St. Lawrence and in March on the Baltic Sea. During April to May, sea ice rapidly decays over the Bering Sea, the Sea of Okhotsk, around the Island of Newfoundland and the Baltic Sea. In June, sea ice almost disappears from the northern part of Baffin Bay and the Hudson Bay. These open waters are growing and many open waters appear in the Arctic Ocean along the coast of Siberia and Alaska in July. In August, sea ice has completely disappeared from Baffin

Bay and Hudson Bay. Consolidated sea ice has also disappeared from the east coast of Greenland but there remains floating ice zone. Sea ice coverage reaches its minimum in September. Consolidated sea ice is detached from the continental coast but there remains floating ice zones along the consolidated ice edge and east coast of Greenland. Sea ice starts to grow from the multi year ice around the north pole in October. Sea ice coverage on the east coast of Greenland already becomes almost the same size as that of the maximum in October. In November the Arctic Ocean and the Baffin Bay are almost covered by consolidated ice. However sea ice has not yet appeared over the Sea of Okhotsk nor the Bering Sea. In December, Hudson Bay is completely covered by sea ice. Sea ice starts to grow from the north side over the Sea of Okhotsk and the Bering Sea from December and continues until their maxima in February or March.

For the Antarctic Ocean, maximum growth of sea ice coverage occurred in August to October. The situation of ice melt over the Antarctic is not the same as that of the Arctic. Several polynyas appear on the Antarctic coast in November, while the ice edge facing the ocean does not change largely. Remarkable polynyas are seen on the Ross Sea and the Weddell Sea. The change in the sea ice from November to January is drastic. Polynyas appearing in November or December grow rapidly and the sea ice edge facing the ocean also withdraws inward. This suggests an ice decay proceeding simultaneously over the whole Antarctic region. It becomes almost the same size as its minimum state in January. The minimum state continues for about three months, from January to March. The ice edge starts to grow outward from the coast in April. Contrary to the drastic change during the melting stage, the ice growth is moderate. It grows with almost the same rate until its maximum state in August.

4.6 Inter-annual variations in sea ice cover: local features

The sea ice situation described in the previous section is the mean status during the period. It changed drastically not only year by year but also place by place. For the SMMR period (November 1978 to July 1987), precise discussion has been undertaken by *Gloersen et al.* (1992). In this report, some special features that might affect the ERA results will be presented.

The inter-annual variations of sea ice cover is very large over the Sea of Okhotsk. Fig. 16 shows the monthly sea ice coverage over the Sea of Okhotsk on February in 1979 and 1984. Almost the whole area is covered by ice in 1979 but only a small area along the west coast is covered in 1984. The effect of the difference should be large for the climate of surrounding area.

Sea ice observations by Electrically Scanning Microwave Radiometer (ESMR) carried on the Nimbus 5 satellite revealed existence of large polynyas in the Weddell Sea during winter season in 1973, 1974 and 1976 (*Carsey*, 1980). These should exert a large influence on the atmosphere over the area. However such a polynya could not be detected during the period; from 1979 to 1991.

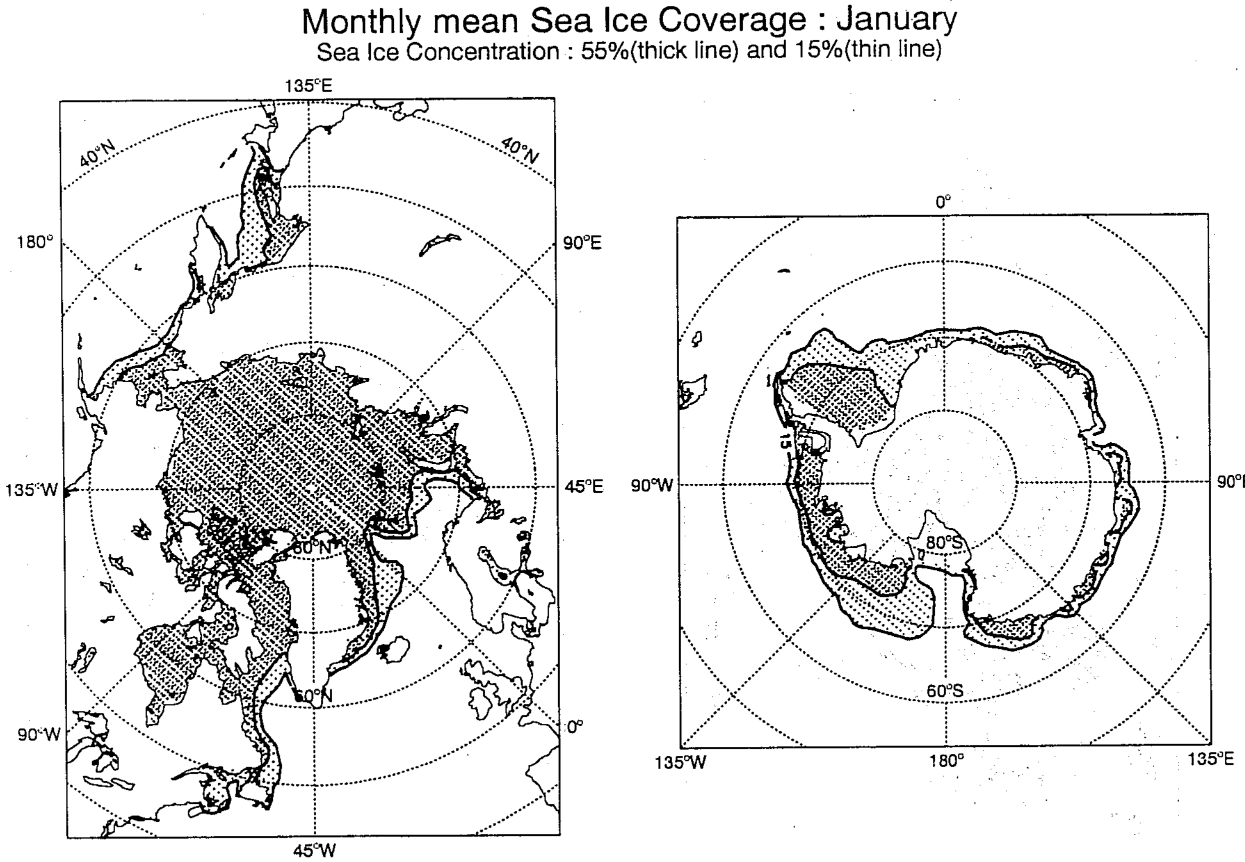


Fig. 15.1 Mean monthly sea ice coverage maps for both polar regions by satellite data (January). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

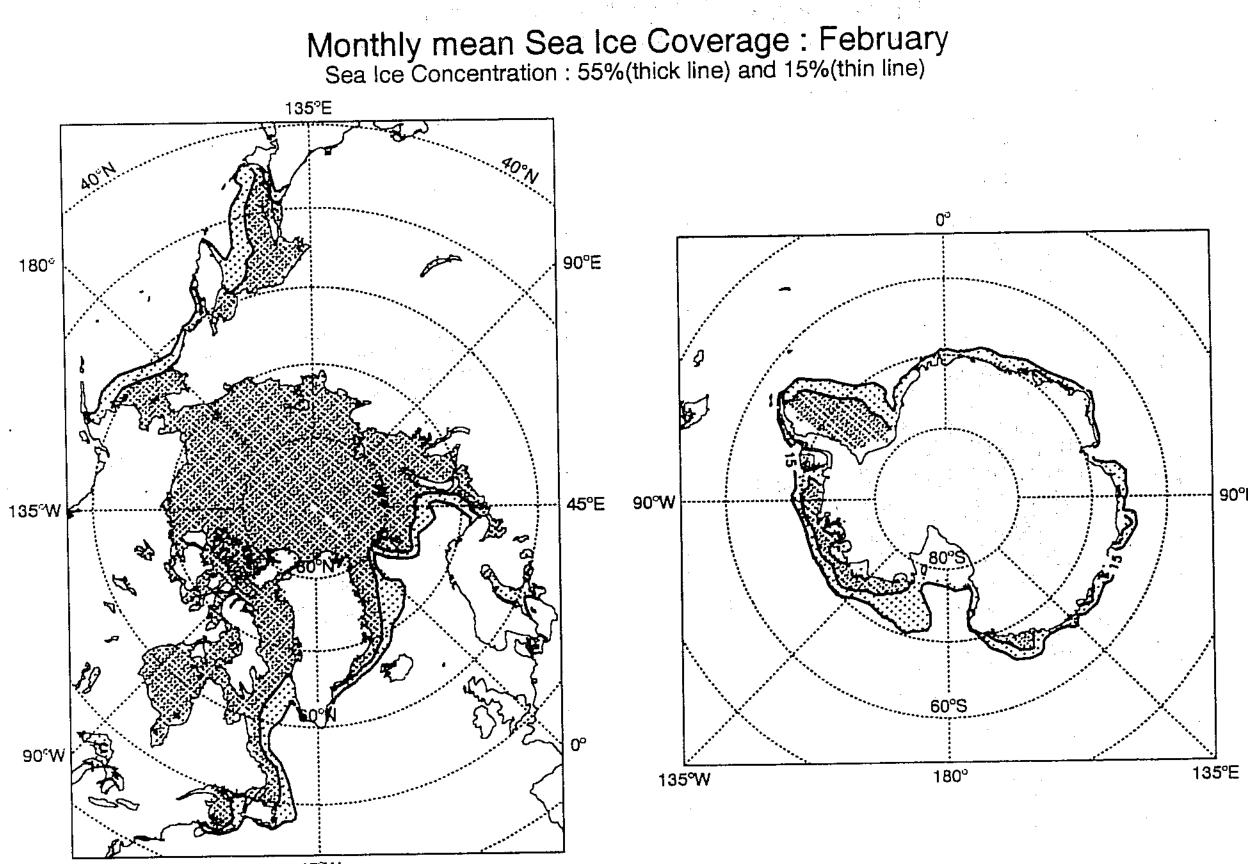


Fig. 15.2 Mean monthly sea ice coverage maps for both polar regions by satellite data (February). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

Monthly mean Sea Ice Coverage : March
Sea Ice Concentration : 55%(thick line) and 15%(thin line)

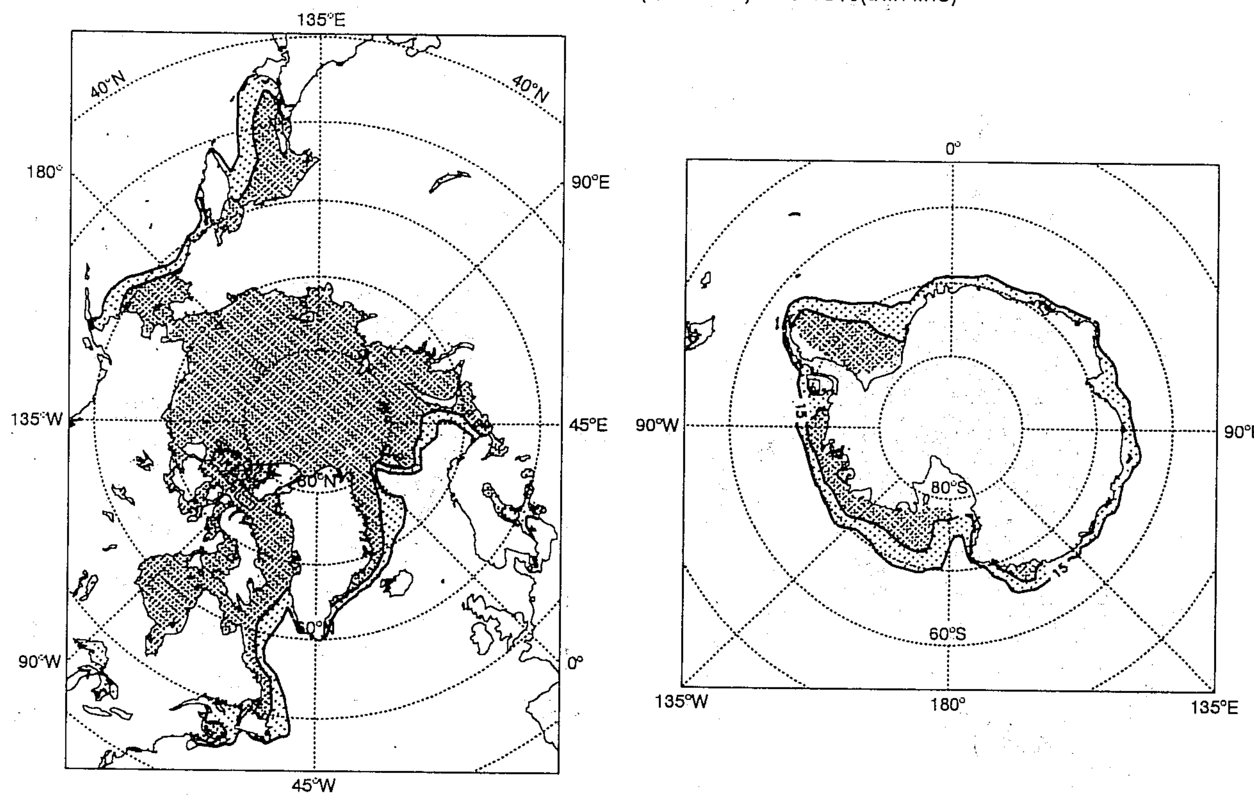


Fig. 15.3 Mean monthly sea ice coverage maps for both polar regions by satellite data (March). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

Monthly mean Sea Ice Coverage : April
Sea Ice Concentration : 55%(thick line) and 15%(thin line)

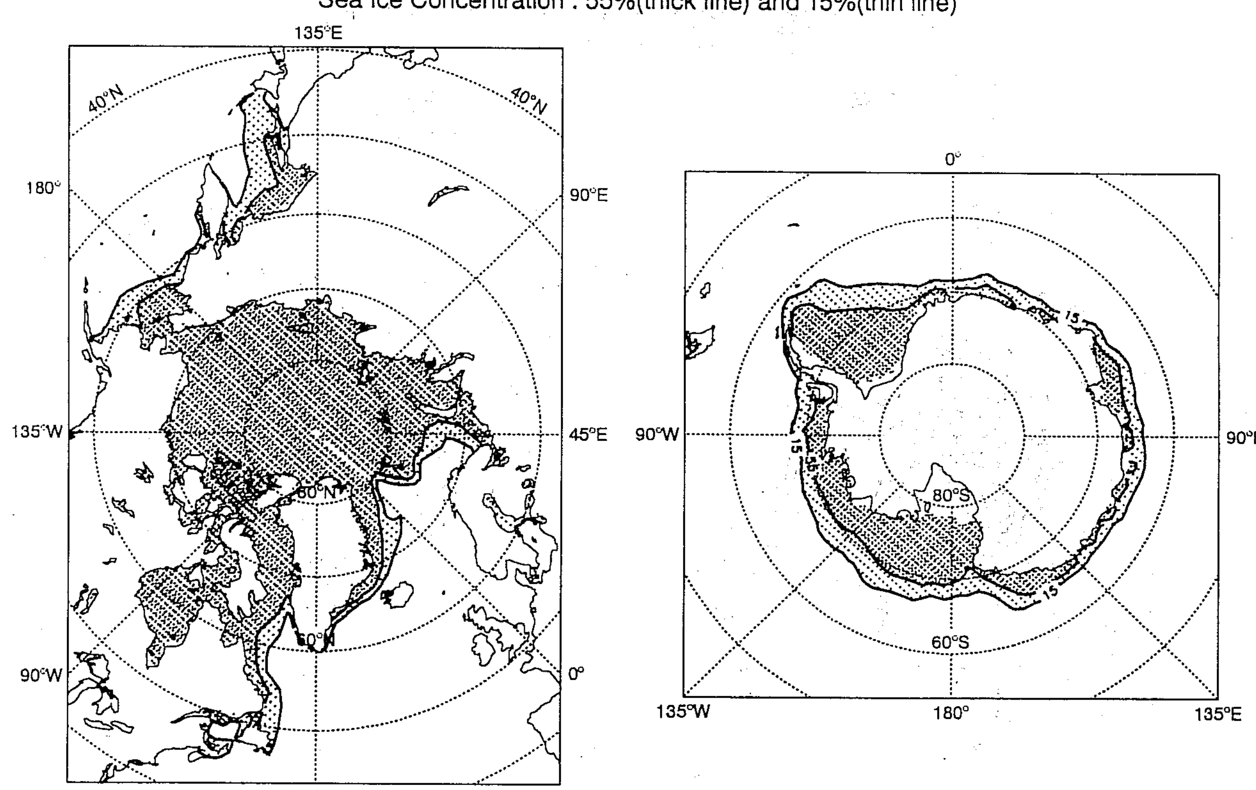


Fig. 15.4 Mean monthly sea ice coverage maps for both polar regions by satellite data (April). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

Monthly mean Sea Ice Coverage : May

Sea Ice Concentration : 55%(thick line) and 15%(thin line)

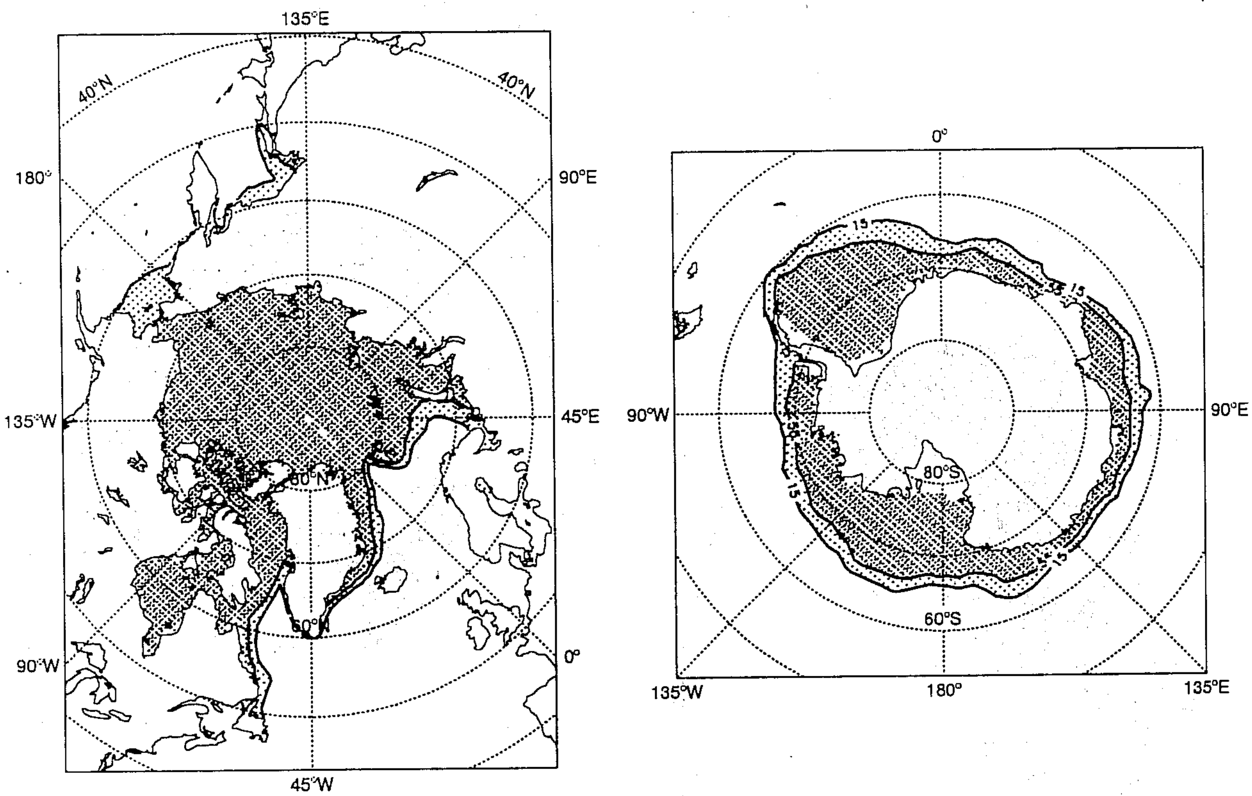


Fig. 15.5 Mean monthly sea ice coverage maps for both polar regions by satellite data (May). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

Monthly mean Sea Ice Coverage : June

Sea Ice Concentration : 55%(thick line) and 15%(thin line)

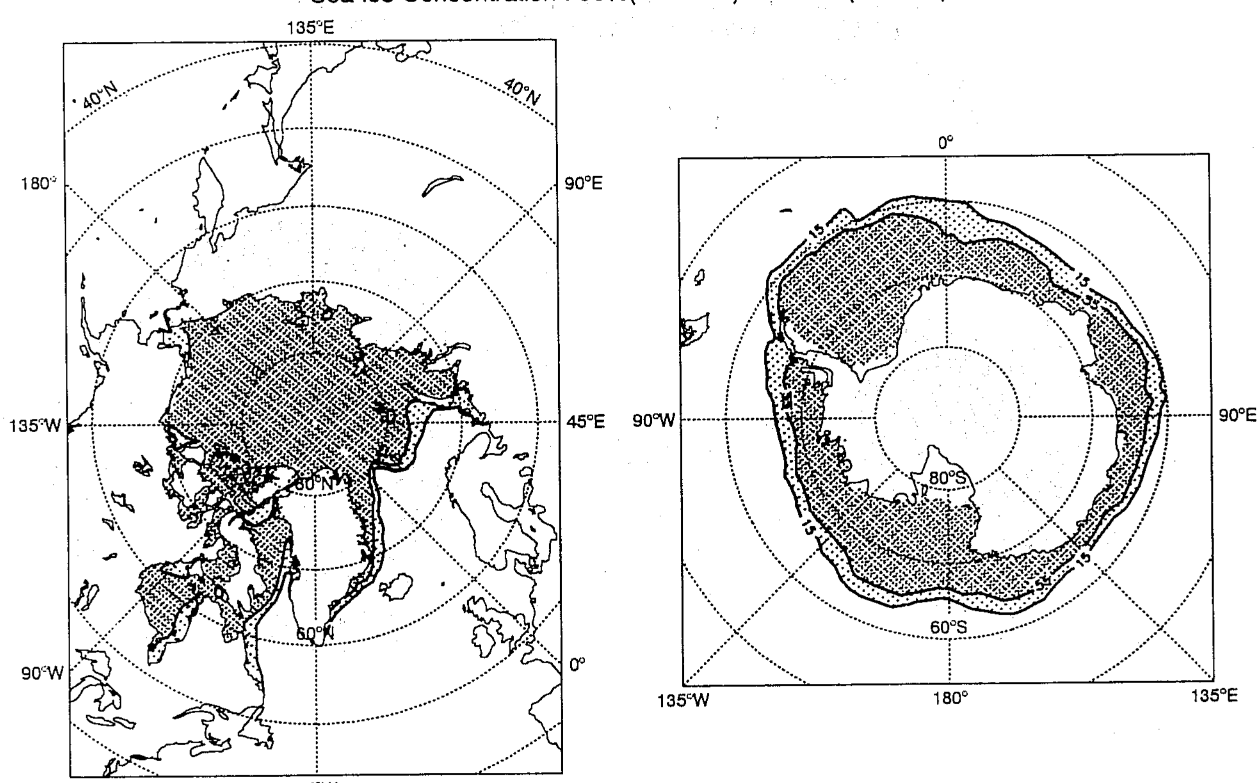


Fig. 15.6 Mean monthly sea ice coverage maps for both polar regions by satellite data (June). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

Monthly mean Sea Ice Coverage : July

Sea Ice Concentration : 55%(thick line) and 15%(thin line)

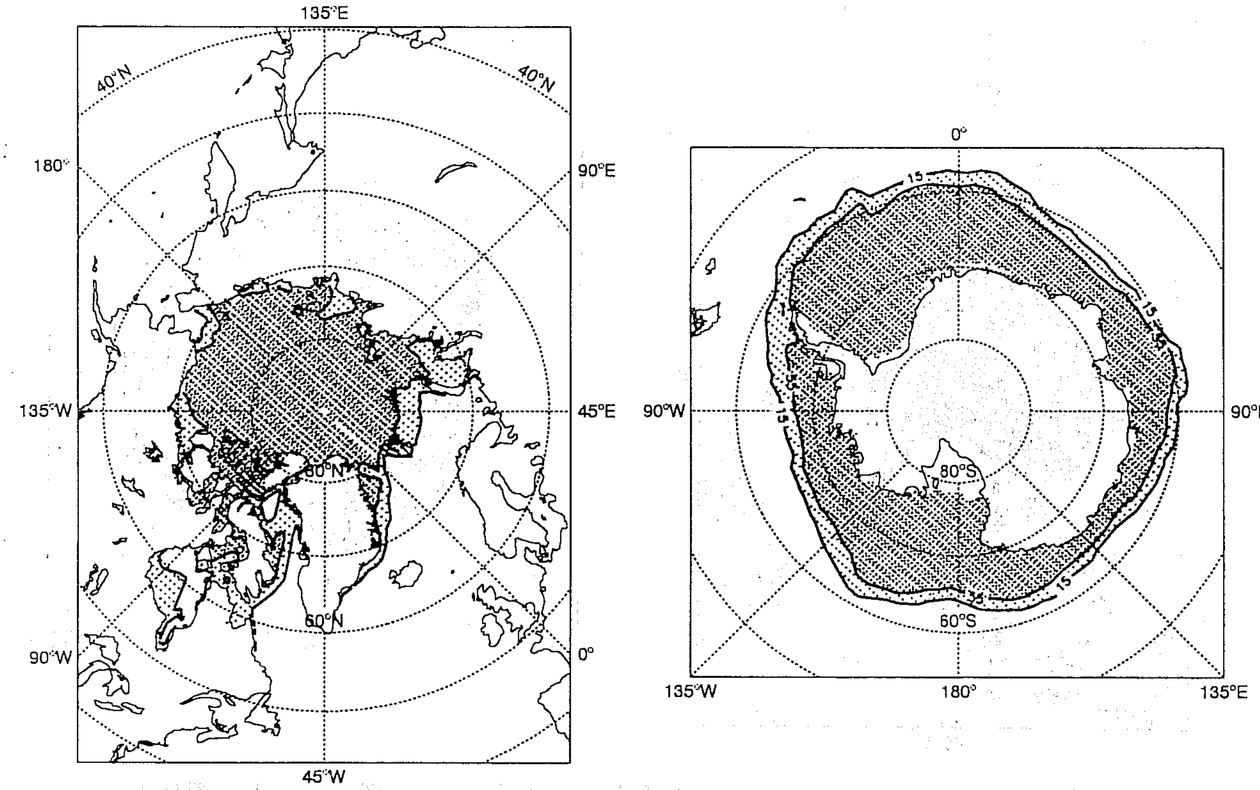


Fig. 15.7 Mean monthly sea ice coverage maps for both polar regions by satellite data (July). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

Monthly mean Sea Ice Coverage : August

Sea Ice Concentration : 55%(thick line) and 15%(thin line)

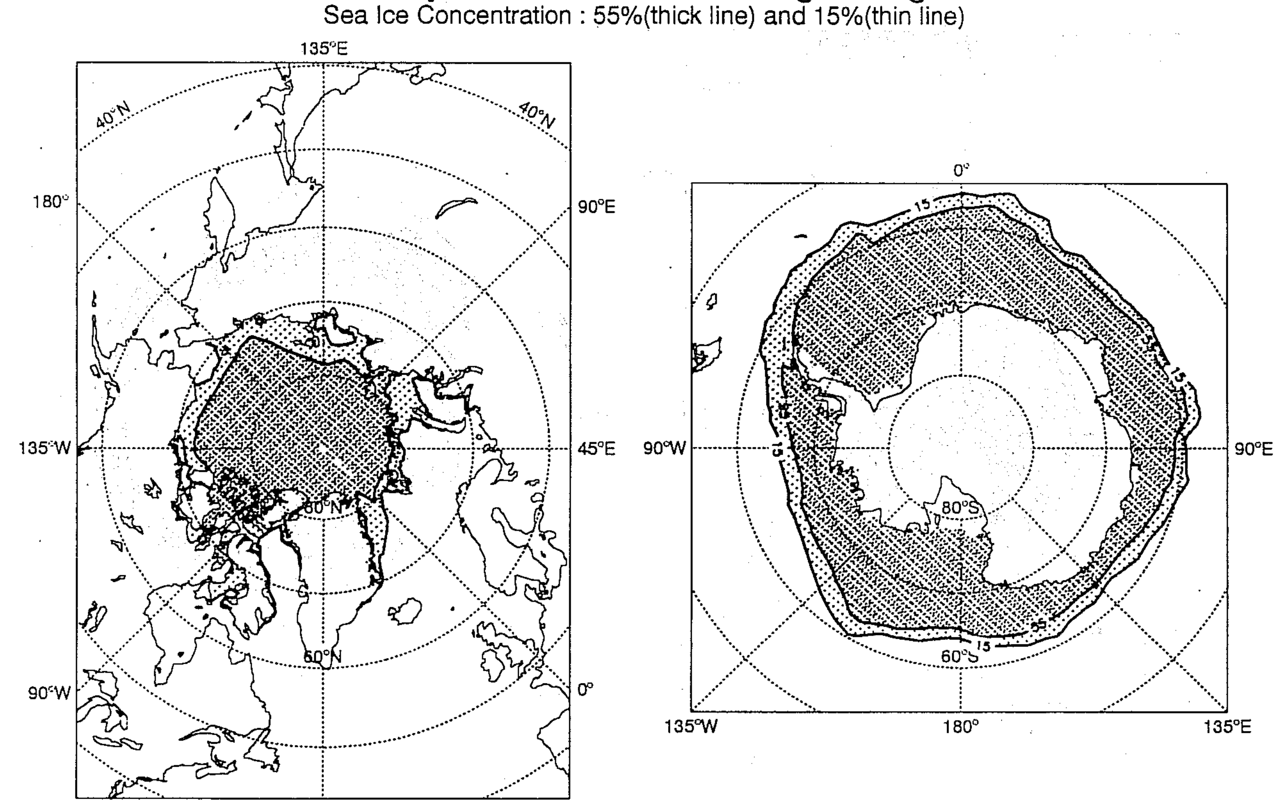


Fig. 15.8 Mean monthly sea ice coverage maps for both polar regions by satellite data (August). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

Monthly mean Sea Ice Coverage : September

Sea Ice Concentration : 55%(thick line) and 15%(thin line)

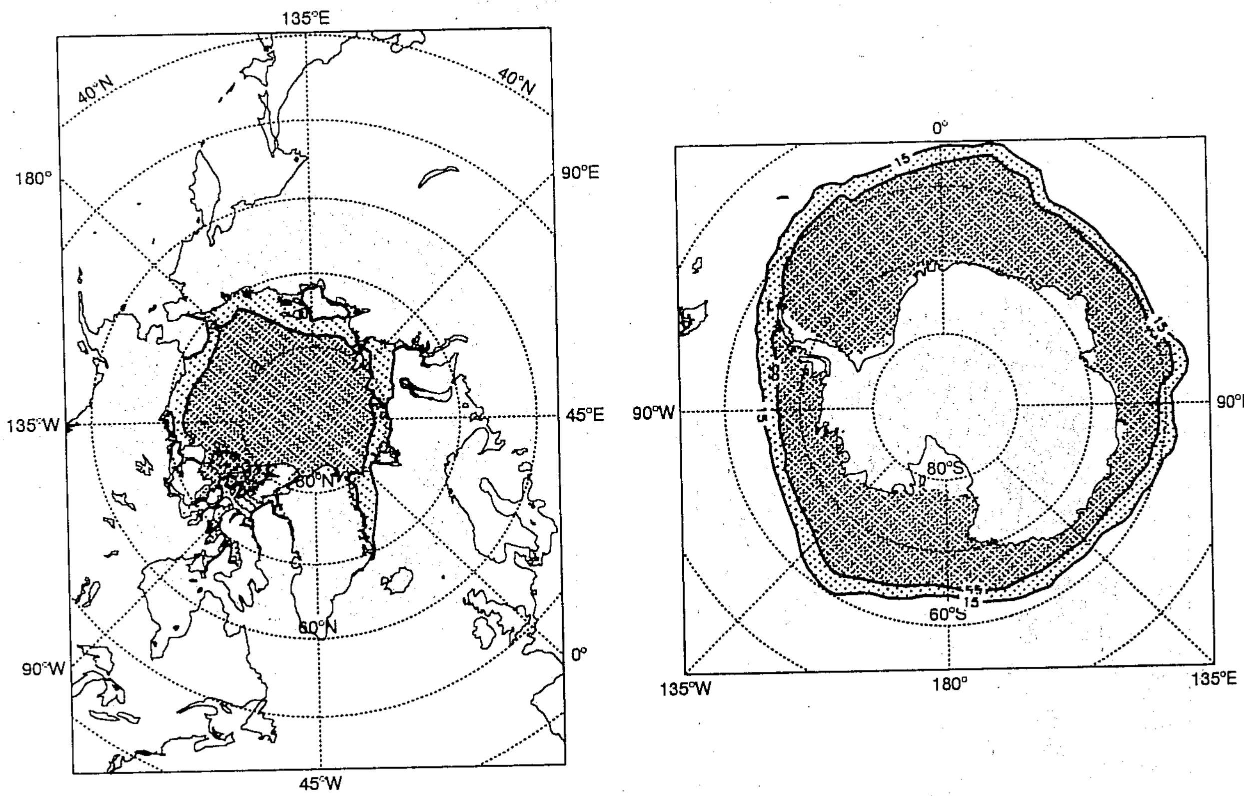


Fig. 15.9 Mean monthly sea ice coverage maps for both polar regions by satellite data (September). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

Monthly mean Sea Ice Coverage : October

Sea Ice Concentration : 55%(thick line) and 15%(thin line)

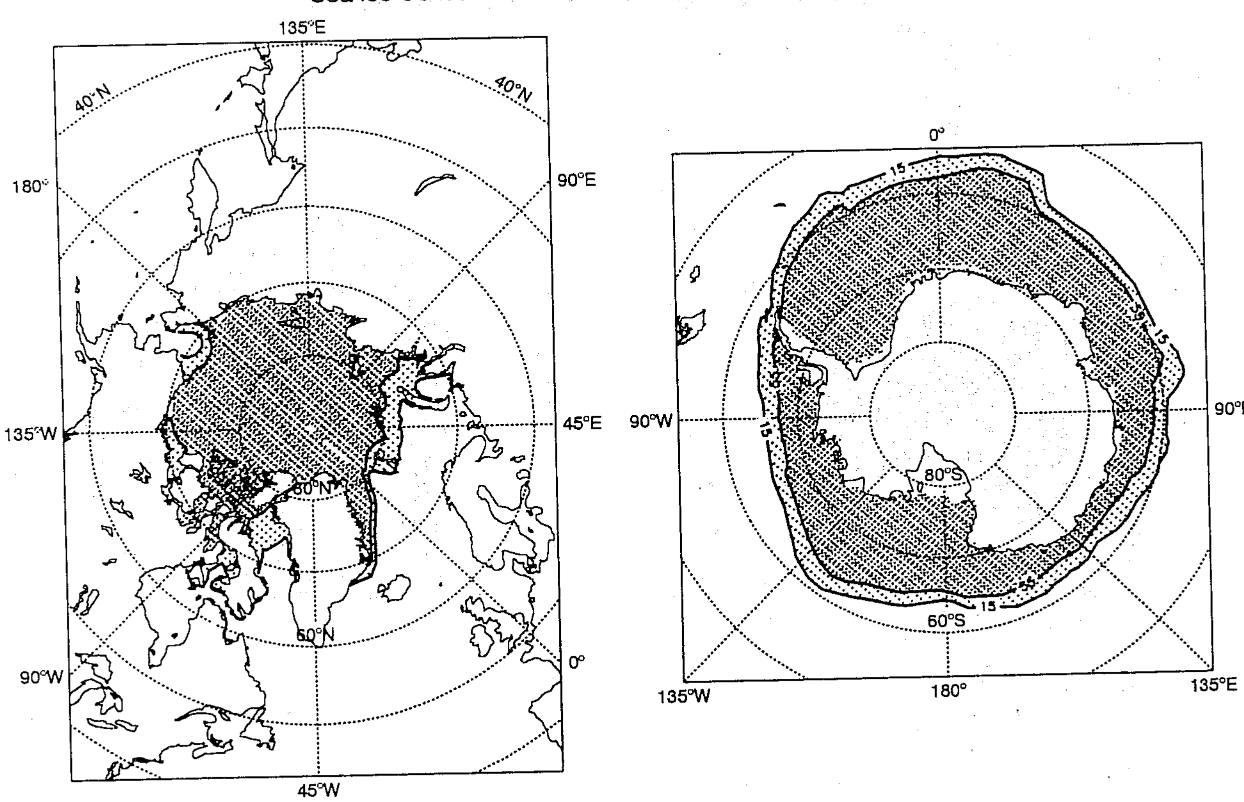


Fig. 15.10 Mean monthly sea ice coverage maps for both polar regions by satellite data (October). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

Monthly mean Sea Ice Coverage : November

Sea Ice Concentration : 55%(thick line) and 15%(thin line)

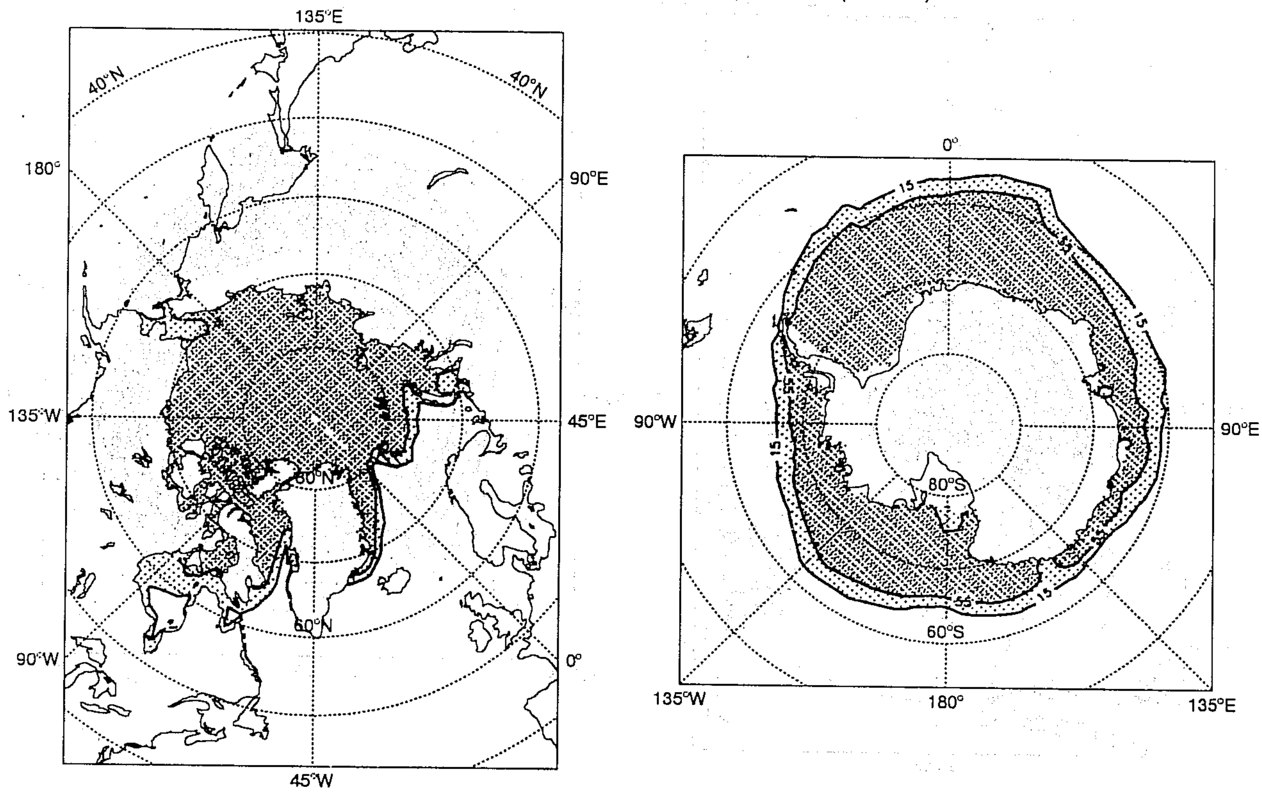


Fig. 15.11 Mean monthly sea ice coverage maps for both polar regions by satellite data (November). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

Monthly mean Sea Ice Coverage : December

Sea Ice Concentration : 55%(thick line) and 15%(thin line)

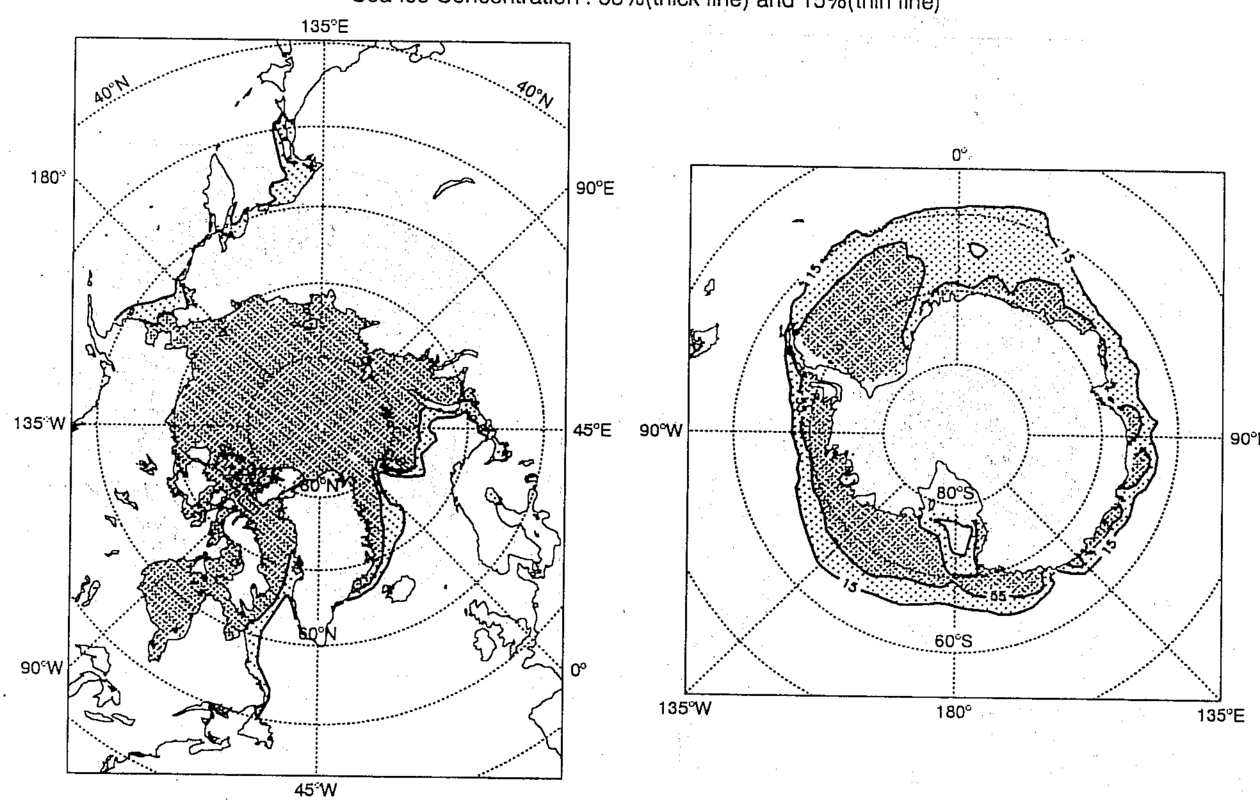


Fig. 15.12 Mean monthly sea ice coverage maps for both polar regions by satellite data (December). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

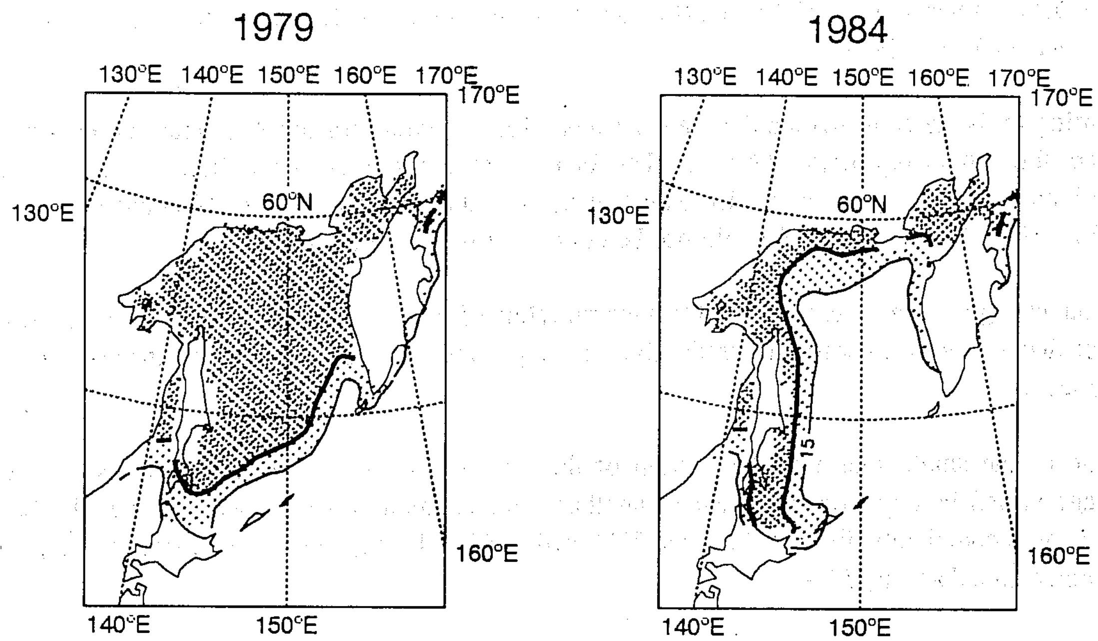


Fig. 16 Monthly mean sea ice coverage over the Sea of Okhotsk on February 1979 (left) and February 1984 (right). Thick line shows sea ice limit defined by 55% sea ice concentration and thine line shows that by 15%.

5. SUMMARY

ECMWF's Re-Analysis (ERA) system uses weekly mean sea ice concentration data which were created on a global scale with a 1.0 degree latitude/longitude resolution. The data period is from November 1978 to December 1991 so far. The original data used were SMMR and SSM/I sea ice concentrations. Although that SMMR and SSM/I are different sounders, very good consistency between them has been observed. The SMMR data were used from November 1978 to July 1987 and SSM/I data were used from August 1987.

Quality control processing on the original data is very important because these data often include false data especially along the coast. Such false data could be removed by comparison with reliable SST analyses at the time. GISSTs by UK Met.Office were used until October 1981 and NMC OI SSTs were used from November 1981 for the QC process.

To fix the sea ice limit used to define the sea ice mask, 55% of sea ice concentrations was found to be the best criterion. Comparing the sea ice data with manual analyses over the Baltic Sea and the Sea of Okhotsk, 55% shows the best consistency for closed pack ice or consolidated ice.

The sea ice data were compared with the sea ice masks represented within the NMC OI SST, AMIP SST and GISST. Generally speaking, satellite sea ice data showed much more stable features through the period compared to other data. Sea ice extent over the Arctic depicted by satellite data was slightly smaller than for the other data and smaller over the Antarctic. Sea ice data represented by AMIP SST before 1981 showed poor quality.

Sea ice data as represented by NMC OI SST often showed unrealistic features which might come from the sea ice analysis scheme.

According to the satellite sea ice data, annual mean sea ice extent for the Antarctic region is almost constant throughout the period, however that for the Arctic region shows a slight decreasing trend. Large increase of annual mean sea ice extent over the Antarctic from 1986 to 1988 shown by NMC OI SST, AMIP SST and GISST could not be confirmed by the satellite data.

Seasonal change of sea ice extent over the Antarctic showed larger amplitude than that over the Arctic. The ice decay process over the Antarctic gives the appearance of proceeding simultaneously over the whole area.

In spite of the small inter-annual variation of the total sea ice extent, local situations of sea ice coverage varied largely from one year to another. For example sea ice coverage over the Sea of Okhotsk was completely different between 1979 and 1984. This variation should significantly affect the climate calculated by ERA.

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