Proc. NIPR Symp. Polar Meteorol. Glaciol., **4**, 58–73, 1991

FLUCTUATIONS OF SEA ICE EXTENT IN THE ANTARCTIC

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Abstract: The sea ice area in the Antarctic is large in winter, while most of the sea ice melts in summer. This seasonal difference in coverage is very large, approximately the area of the Antarctic continent. In this study, characteristics of the normal seasonal change of sea ice area, such as seasonal asymmetric behavior of ice extent and change of sea ice concentration are investigated using a 12 year-long weekly sea ice data set for the Antarctic. The week to week fluctuations of the open water area in the sea ice area are observed to be large in spring. The open water area in the sea ice area plays an important role in the movement of sea ice. Drastic change of the open water area is observed at the beginning and end of the freezing period. The characteristic scales in time and space for sea ice movements are obtained from spectral analyses. Some conditions of synoptic scale could be important for the movement of sea ice.

1. Introduction

1.1. Sea ice extent

From satellite observations (ZWALLY *et al.*, 1983a), it is evident that in the Antarctic the sea ice area shrinks rapidly in spring and early summer, whereas it expands slowly in autumn and winter. The open water area in the sea ice may play an important role in this seasonal change. The present study describes the annual and inter-annual changes in sea ice extent, and discusses the conditions of the open water area.

On the seasonal changes in sea ice conditions, GLOERSON and CAMPBELL (1988) noted that the most regularly occurring characteristic feature is the time of the minimum in the Antarctic sea ice. This minimum period fell within a few days of February 25 every year from 1978 to 1987. Before discussing anomalous fluctuations of the sea ice area, regular seasonal changes should be understood. The limit of sea ice distribution is controlled by local production (melting and freezing) and the advection of ice mass. COMISO and ZWALLY (1984) revealed that the monthly change of the sea ice edge position shows good correlation with the advance and the retreat of the freezing isotherm line at the sea surface. The present paper investigates the seasonal changes in kinematic behavior and points out the characteristic phenomena of the sea ice kinematics in the Antarctic.

1.2. Polar climate and sea ice

A large area of open water exists within the sea ice pack in the Antarctic, even in mid-winter. To understand the kinematics of the sea ice, investigations of the open water are important. The open water is important also for polar climate. RASCHKE *et al.* (1973) estimated radiation at the top of the atmosphere using Nimbus-3 data and showed that net radiation is minimum (below $-0.25[\mathrm{cal \cdot cm^{-2} \cdot min^{-1}}] = -175[\mathrm{W \cdot m^{-2}}]$) in winter in the 60°–65°S zone, *i.e.*, the zone corresponding to the sea ice in winter. WELLER (1980) estimated the heat flux in various areas of the Antarctic (Table 5 in WELLER, 1980). The latent heat flux in the pack ice zone is as large as that in the open ocean, whereas the sensible heat is from 3 to 5 times larger in the pack ice zone than that in the open ocean. The sensible heat flux in the pack ice zone is an important component in the energy balance. The rate of the ice-free to the ice-cover areas is important for energy balance, as it changes the efficiency of heat exchange (STEELE *et al.*, 1989).

GOODY (1980) reviewed the influences of polar processes on world climate and referred to the importance of lead formation in sea ice. ACKLEY (1981) pointed out that the sea ice edge is not the optimum region for a zone of enhanced cyclogenesis, and that the strongest contrast may be found between continental ice and sea ice (see also CARLETON, 1983). As ACKLEY (1981) concluded, the sea ice-weather relationship is probably one of the least known components of the climatic system. This process is, however, considered to be one of the most important factors affecting high latitude climate. Therefore, the large scale extent of sea ice and the distribution of open water should be monitored.

Investigations on the following themes are carried out in this study:

1. Annual and inter-annual changes in sea ice area: seasonal asymmetric behavior of ice extent and changes of sea ice concentration and open water area using 12 years of data.
2. Seasonal changes in kinematic behavior.
3. Characteristic time and space scales for sea ice movement in the Antarctic.

2. Data

The sea ice data set used in this study is the Navy-NOAA Joint Ice Center (JIC) Digital Sea Ice Data, which is distributed through the National Snow and Ice Data Center, Boulder, Colorado. The data were digitized from weekly sea ice charts produced by Navy-NOAA JIC. The smallest homogeneous area resolved by the mapping system is about from 20 km to 40 km. Boundaries at the edge of the sea ice area are accurate to within 20 km under typical conditions. These weekly analyses were performed based on a variety of sources, including microwave imagery by NASA (ZWALLY *et al.*, 1983b; BARRY, 1986). The data are plotted in spherical polar coordinate system with a grid scale of 0.25° in latitude and 0.5° in longitude. The accuracy of analyzing sea ice concentration varies throughout the year. Although accuracy is good when extensive ice is present, the accuracy is less in fall and early winter when new ice is forming.

In this study, when more than 20% of the area is covered by pack ice, we call it

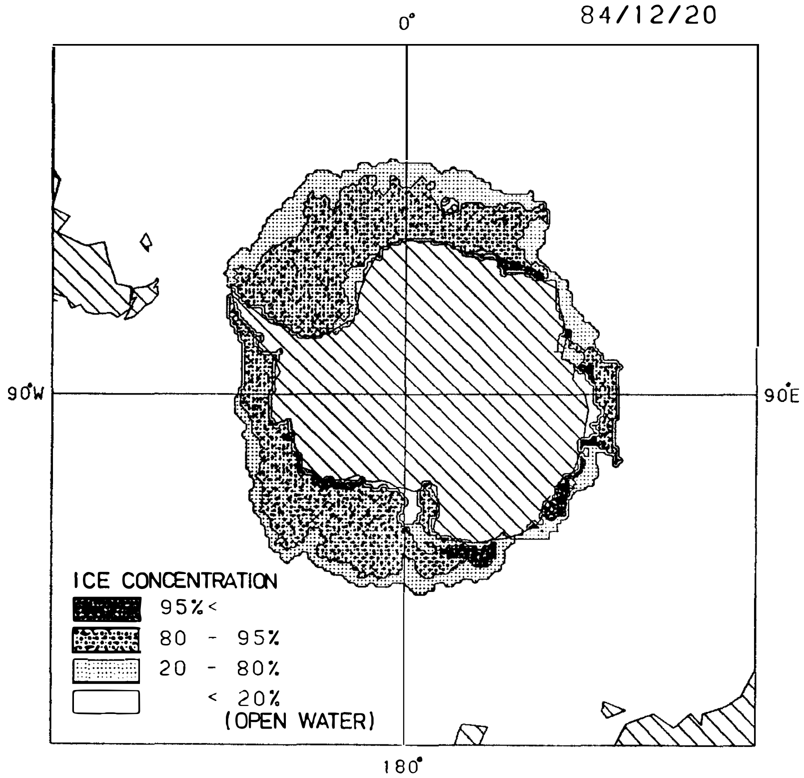


Fig. 1. Sea ice distribution (Dec. 20, 1984) obtained using the Navy-NOAA Joint Ice Center Data. The sea ice edge is defined with concentration of 20% in this data set. Differences in sea ice areal concentration are indicated by dots.

the "*sea ice area*". Although 15% (or less) is often used as the lowest limit of concentration for defining the sea ice area in the other studies (WMO, 1970), the concentration of 20% is used due to the limit of concentration-resolution of the sea ice data used in the present study. The available measurements may not be accurate enough to estimate differences of concentration as large as 5% especially in the marginal sea ice area. As the concentration gradient in the corresponding marginal area is very large, concentration difference of 5% for defining the sea ice edge seems to affect estimations of the sea ice area little. The estimation for the concentration of a packed sea ice area seems to be less accurate. The data between 1973–84 are used in this study. Figure 1 shows an example of sea ice distribution in the Antarctic which is obtained from the Navy-NOAA sea ice data set.

3. Sea Ice Extent

3.1. Annual and inter-annual changes in sea ice extent

The sea ice area is defined as an area where more than 20% of the surface is covered by pack ice. The sea ice area in the Southern Heamisphere fluctuates seasonally between about 20×10^6 km^2 (winter) and 4×10^6 km^2 (summer). The annual fluctuation of about 80% in the Antarctic is larger than that in the Arctic (50%, from 7.8×10^6 km^2 to 14.8×10^6 km^2 (PARKINSON *et al.*, 1987)). This large annual fluctuation of the Antarctic sea ice is comparable to the area of the Antarctic Ice Sheet (14×10^6 km^2,

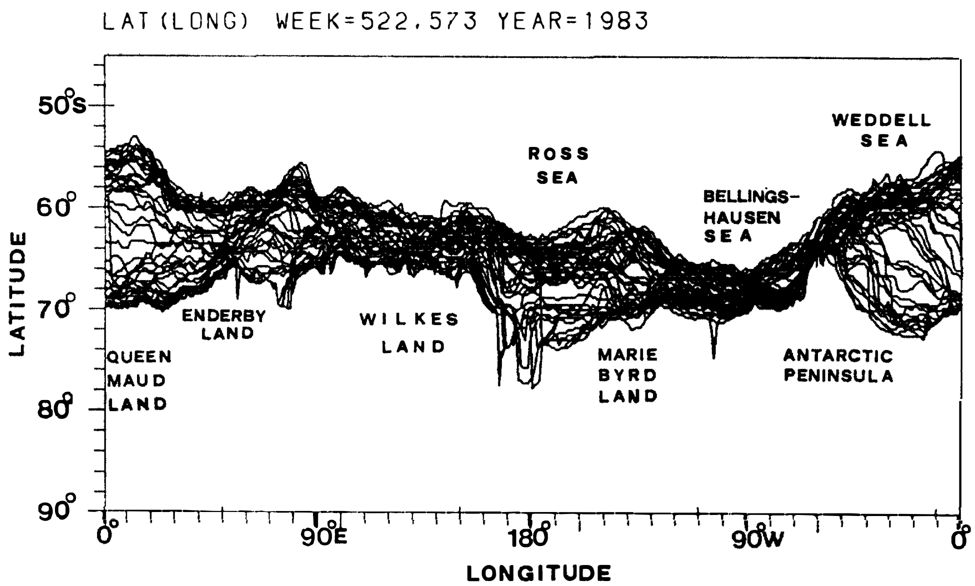


Fig. 2. Annual range of sea ice limit (ENOMOTO and OHMURA, 1990). Composite map of the sea ice edge from 52 weekly data in 1983. The sea ice edges are often either near their maximum positions or along the continent. At these two extreme positions, the sea ice edge seems to be stable.

SUYETOBA, 1966). The sea ice distribution also shows considerable regional difference. Large variation occurs in the Ross and Weddell Sea sectors.

The regional variation of range of sea ice extent is shown in Fig. 2. All weekly sea ice limits in 1983 are contoured in this figure and large seasonal variations are observed in the above-mentioned two areas. The topographic configuration of the Antarctic Peninsula causes a unique gap of sea ice distribution at 60°W longitude. The density of the lines of sea ice limit show the spatial (latitudinal) frequency of presence. The limits tend to stay either near the Antarctic coast or their northernmost positions. The lines near the coast implies that the polar summer is warm enough to melt almost all sea ice. Multi-year sea ice is rare in the Antarctic. The lines near their northern positions implies the existence of some control conditions which limit the extent of sea ice or which affect kinematic instability of sea ice between their extreme positions (ENOMOTO and OHMURA, 1990). In the Weddell Sea sector, there is a trend for the sea ice limit to advance north-eastward and retreats south-westward. The seasonal difference of sea ice extent is characterized by the dominant annual cycle with a seasonally asymmetric changing rate (Fig. 3(a)). The retreat of sea ice limit in spring is much more rapid than its advance in autumn.

The "*sea ice area*" consists of "*ice covered area*" and "*open water area*". The "*ice covered area*" is defined as the area actually covered by ice in the observed area. The ice covered area is calculated as follows:

$$\textit{ice covered area} = \textit{sea ice area} \times \textit{ice concentration}$$

"*Open water area*" in sea ice area is calculated as

$$\textit{open water area} = \textit{sea ice area} - \textit{ice covered area}$$

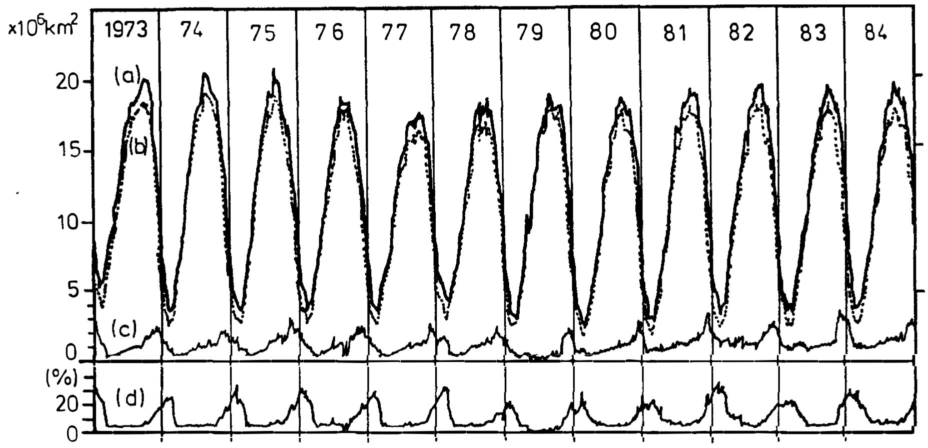


Fig. 3. Year to year fluctuations of (a) sea ice area, (b) ice covered area, (c) open water area and (d) open water/sea ice area ratio.

The ice covered area is calculated and shown in Fig. 3(b) (dashed line). The annual maximum of sea ice area was observed to decrease up to 1977 and increase thereafter (ZWALLY *et al.*, 1983a). The annual maximum and annual minimum of sea ice extent show opposite tendencies. The smallest value in the annual maximum of sea ice area between 1973 and 1980 was observed in winter 1977, whereas the annual minimum of sea ice area in the following summer was relatively large.

Open water area within the ice pack is indicated in Fig. 3(c). The open water area is maximum in spring when the total area begins to decrease. The ratio of open water area to the sea ice area is shown in Fig. 3(d). It is maximum in summer. Due to difficulties in estimating concentration of packed sea ice area during the freezing period, it must be discussed carefully. Available data sets seems to assume often the value of 95% for such case. This results in the pseudo-dominant value around 5% of open water area in the early observations in 1973, 74 and 75 (Fig. 3(d)). There are phase differences between the maximum months of sea ice area, open water area and ratio of open water area to sea ice area. It is worth noting that the open water area and its ratio begin to increase in winter (July) when the sea ice area is still increasing, and then the open water area increases rapidly in spring. The open water area in the sea ice area has a tendency of very rapid decrease in autumn (March), while in the Arctic, from the seasonal change of open water area observed by GLOERSON and CAMPBELL (1988), a rapid increase of open water area in the sea ice area can be found. This fact implies that there may be nearly instantaneous freezing at the beginning of winter season in a large area in the Antarctic, while in the Arctic there may be nearly instantaneous melting in spring in the sea ice area which is bounded by land.

During the period of rapid retreat of sea ice limit, the sea ice area and open water area fluctuate greatly. Figure 4 shows week to week changes of the sea ice area. Decrease of area is indicated by negative values in the figure. The week to week variability of rate of change is large in spring. The sea ice field may be active kinematically in spring, and a large amount of heat exchange is considered to occur. These situations are presumably characterized by a large amount of open water area (*e.g.*, polynya, lead). Figure 5 shows the week to week variability of the rate of change of

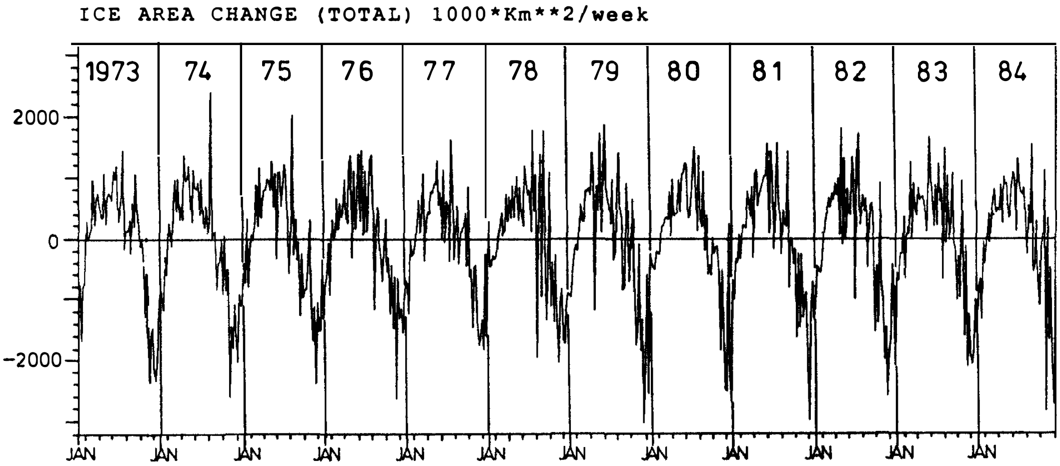


Fig. 4. Week to week change of sea ice area (10^3 km²/week). Positive values indicate increase of sea ice area. Week to week fluctuations are large from late winter to summer.

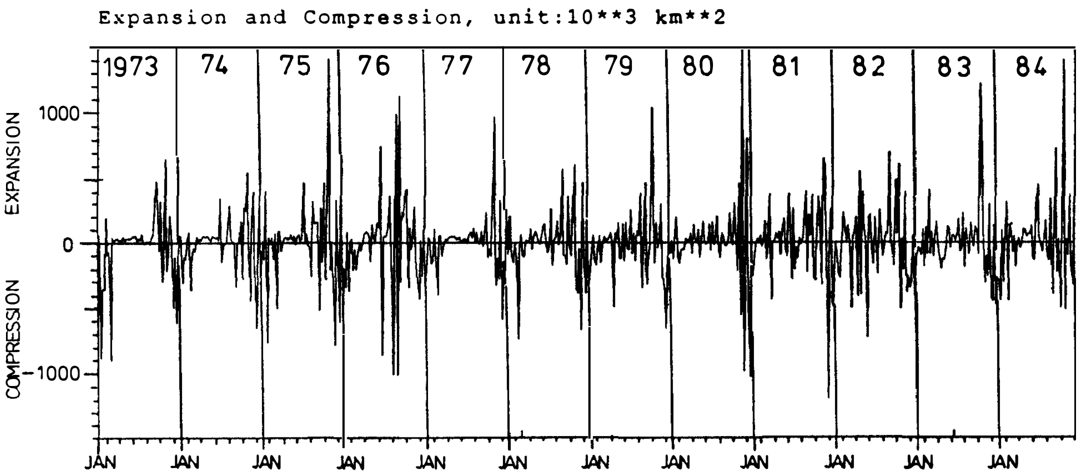


Fig. 5. Week to week change of open water area (unit: 10^3 km²/week).

open water area. The rate is steady in the open water area in autumn (March–May), the period of advance of sea ice area, while it fluctuates considerably in spring. Therefore, the area of leads and polynyas is expected to vary greatly in spring. Thinning and concentrating of the sea ice occur alternately.

3.2. *Spatial and temporal variations*

The fluctuations of the sea ice area and open water area all around Antarctica are discussed in Fig. 3. Regional differences are investigated in this section. Figure 6 shows a longitude-time section of the sea ice area. The period with large extent of sea ice (40×10^3 km² $\sim$ in the longitudinal sector of 10 degree) is hatched. The longitudinal sector between 120°E–150°E seems to fluctuate substantially. There are apparently no clear relationships between the persistence period of large ice extent (length of period of the hatched area in Fig. 6) and the sea ice area.

The longitude-time section of the open water-ice covered area ratio is shown in

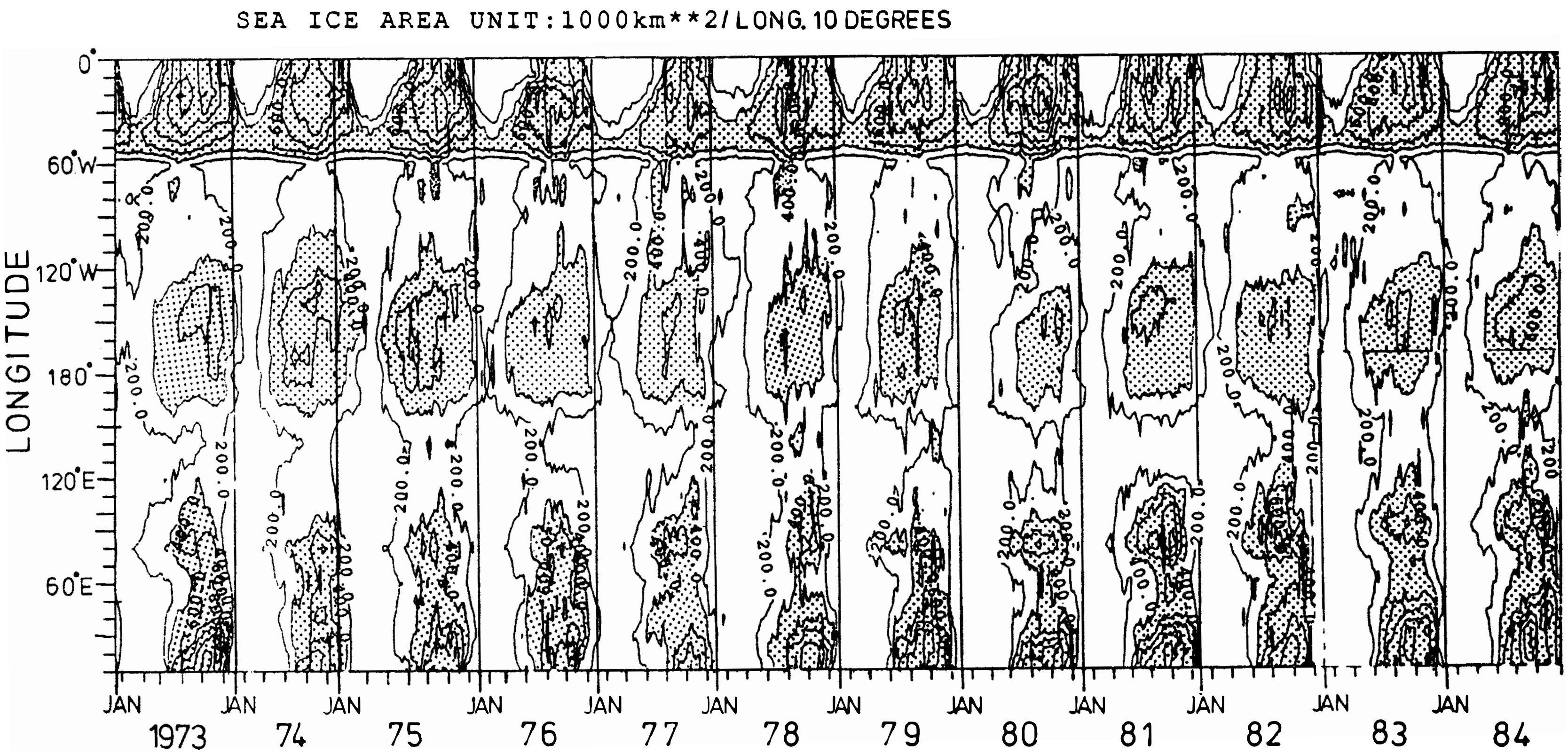


Fig. 6. Longitude-time section of sea ice area.

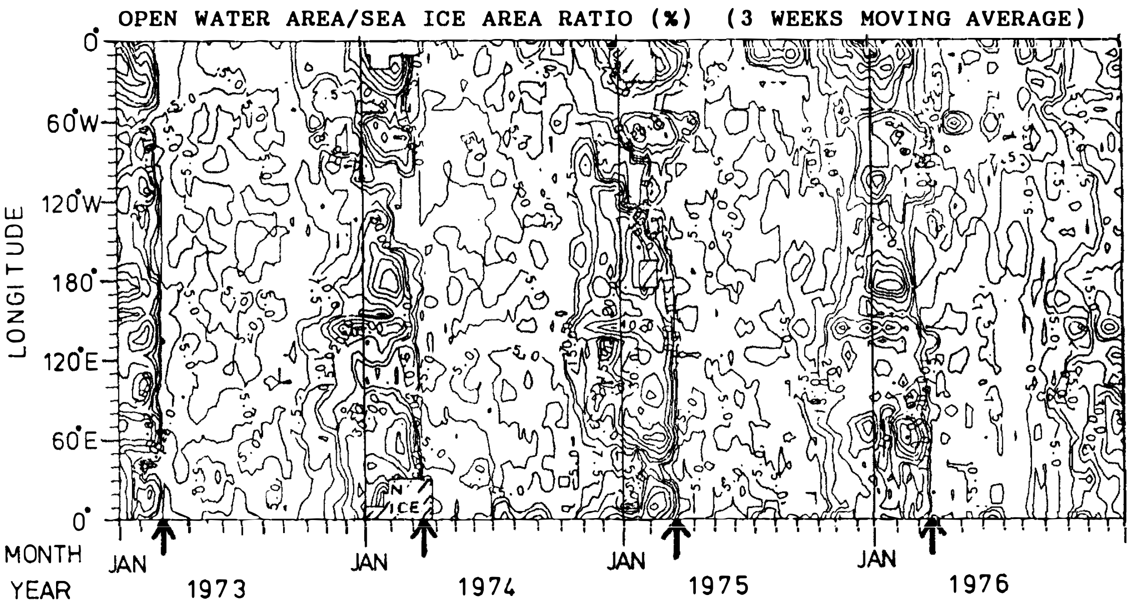


Fig. 7. Longitude-time section of the open water/sea ice area ratio (3 week moving average data). unit: %.

Fig. 7. The decrease in this ratio occurs simultaneously in many longitudinal sectors, as indicated by arrows at the beginning of advance of the sea ice area. The mean concentration of the sea ice area in almost all sectors is more than 90% during this period. This simultaneous change is most significant in 3 weeks moving-averaged data; thus, a large change in sea ice concentration occurs simultaneously at all longitudes within a period of about 3 weeks. There is, however, no evidence for a simultaneous change with characteristic time scale of 3 weeks in air temperature at the coastal zone in the Antarctic.

At the initial stage of sea ice expansion, "*pancake ice*" forms (WEEKS and ACKLEY, 1986; DUMBAR and WEEKS, 1975; STEFFEN, 1986). This type of sea ice forms rapidly, and simultaneously over a large area. This area is, however, small compared to the scale of the observed rapid formation of new ice. After the drastic change in ice concentration, the open water/ice cover ratio fluctuates only about 5–10% during the winter. During the period of retreat of sea ice area, however, the open water/ice cover ratio is highly variable, as seen in Fig. 7. Investigations should be done carefully in this problem, since new ice is difficult to detect on satellite imagery when it is forming.

From the results of weekly data (the figure is not shown here), it was observed that the open water/sea ice area ratio fluctuates largely on the time scale of one week in summer, particularly when the open water/ice covered area ratio exceeds 10–15%. This range of the ratio persists until the beginning of the ice advance. Therefore, large differences in dynamic or thermodynamic conditions in the sea ice area are expected to exist, depending on whether the ratio of open water is higher than or about equal to the threshold value of 10–15%. Sea ice dynamics is beyond the scope of the present study, but investigation of sea ice movement should be important.

A longitude-time section of the weekly change (change in open water ratio per

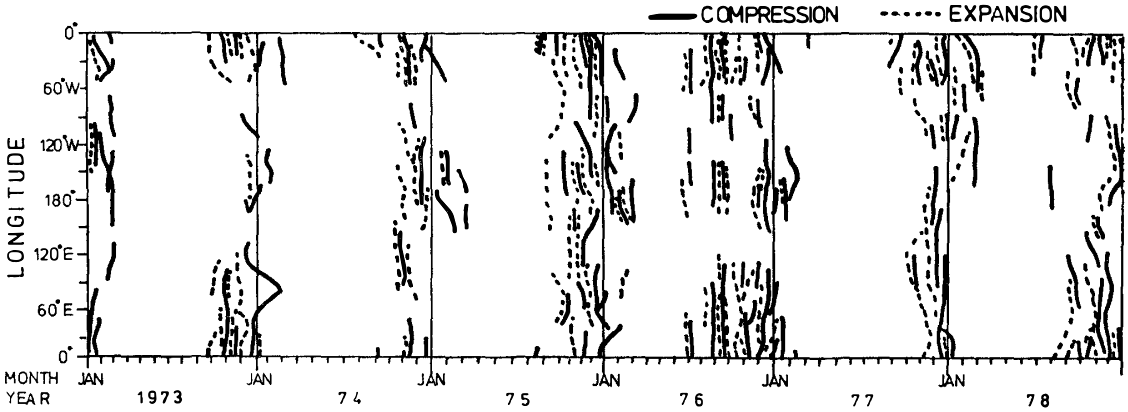


Fig. 8. Longitude-time section of the weekly change of open water area. The solid line indicates increase of open water area per unit sea ice area which implies expansion of the sea ice field. The dashed line indicates the decrease of open water area per unit sea ice area, which implies compression of the sea ice field. unit: %/week.

week) of open water area in the sea ice area is shown in Fig. 8. Large increases and decreases of open water area per week are indicated in this figure. While Fig. 7 shows the predominant change in open water area on a large scale, Fig. 8 focuses on changes on synoptic scale which can be observed frequently. It can be seen that there is frequent opening and closing of the open water area. These changes occur simultaneously over a wide area, about 90 degrees of longitude at 65°S. Strong cyclones may affect these changes. In 1976 and 1977, the annual maximum extent of sea ice area reached a minimum. Large weekly changes were observed in the preceding seasons of the annual maximum in 1976 and 1977.

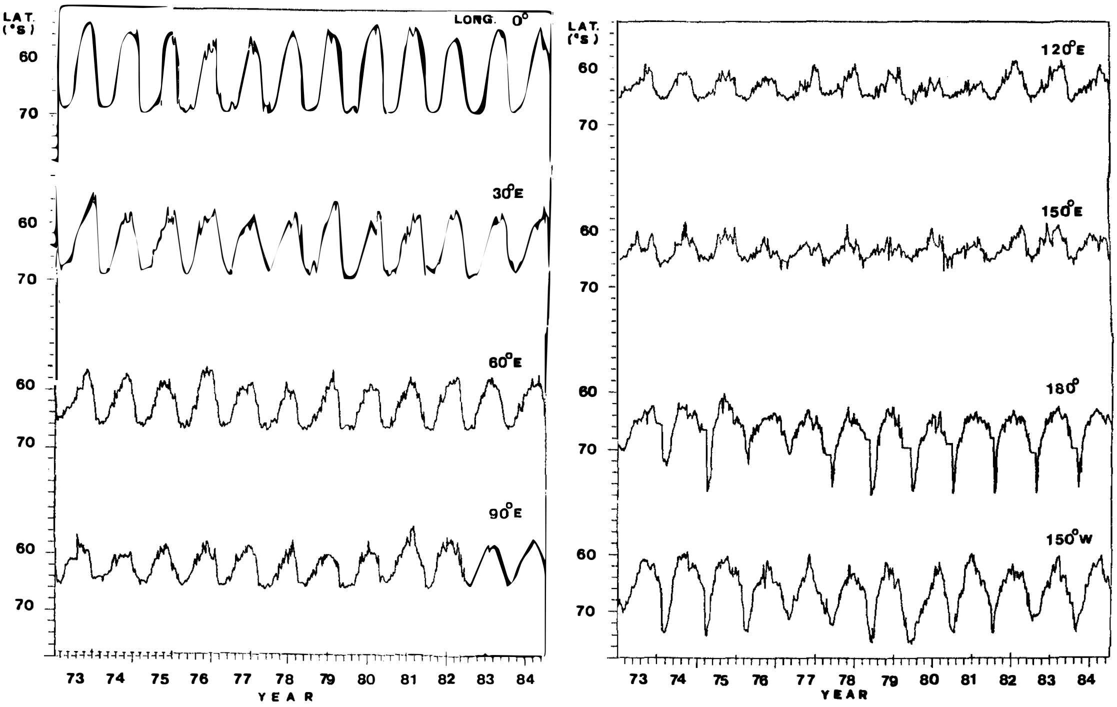
4. Ice Limit Latitude (*ILL*)

4.1. Physical meaning

The latitude of northern limit of the sea ice area is defined as the "*Ice Limit Latitude* (*ILL*)" in this study. The *ILL* is considered to be useful as a cryo-climatological index. Changes of the *ILL* imply changes in local production and advection of sea ice. The magnitude of the advection is large in the sea ice area in the Antarctic (HIBLER, 1986). To understand the drastic reduction of the sea ice area in early summer, advection, divergence and convergence of ice should be taken into account (ENOMOTO and OHMURA, 1990). Thus, although the sea ice limit is climatological information, the physical meaning of this index is complicated.

4.2. Spatial and temporal fluctuations

The fluctuation of *ILL* is obtained and shown in Fig. 9. There is large variability in the seasonal change of edge position and persistence of sea ice cover. Sudden disappearance of sea ice at Long. 180° and 60°W is caused by large longitudinal variation of sea ice extent in the Weddell and Ross Sea sectors, combined with ice advection. In winter the *ILL* tends to fluctuate in a small range near its northernmost position. This tendency of the sea ice limit to remain stable at the extreme position implies



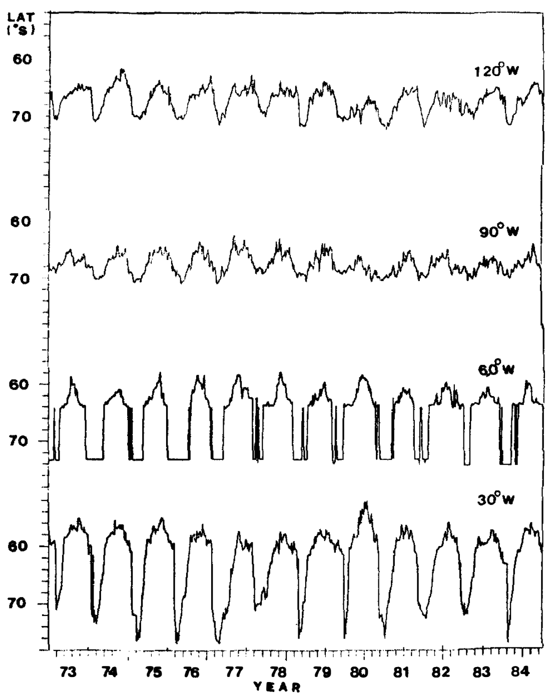


Fig. 9. Week to week change of the ice limit latitude (ILL), shown at every 30° of longitude.

equilibrium of flux and production of pack ice in the edge area (ENOMOTO and OHMURA, 1990).

Although the annual sea ice extent overall was a minimum in 1976–77, the sea ice extent varied regionally. The annual sea ice extent at 90°W is shows on opposite pattern to the fluctuation of total sea ice extent. Thus, sea ice conditions in a local area may not reflect the hemispheric fluctuation of sea ice condition. The sea ice

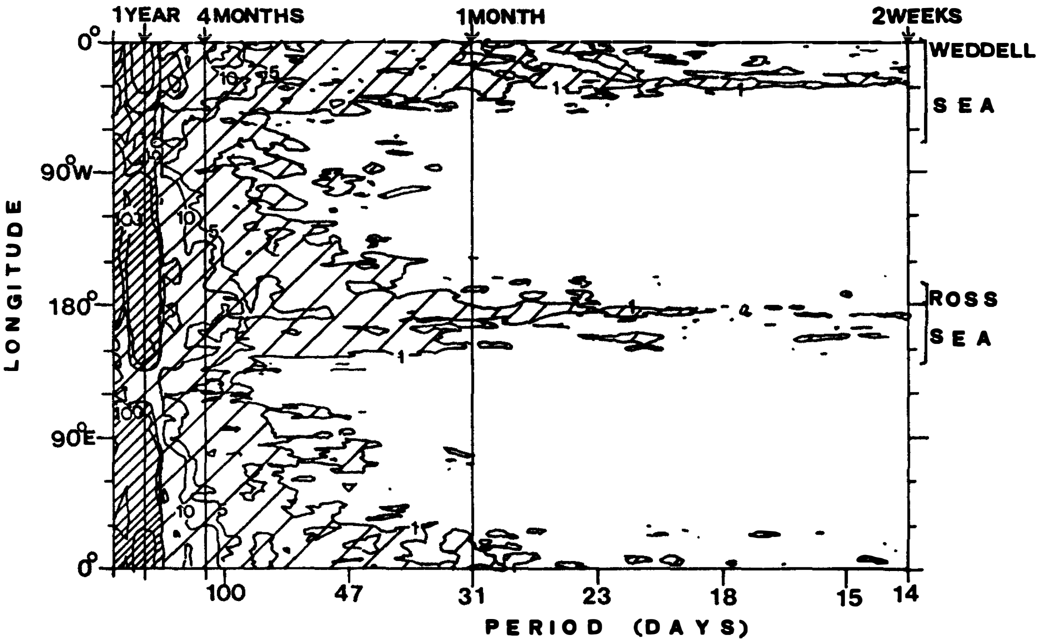


Fig. 10. Longitude-period section of the spectrum of the ILL with respect to time. The data are obtained at every 1° in longitude. Large power is indicated by hatching.

extent in this region is of particular interest, as it fluctuates with latitudinal shift of cyclone tracks (ENOMOTO and OHMURA, 1990). Fluctuations of sea ice extent may be associated with the shift of cyclone tracks around Antarctica.

4.3. *Characteristic time and space scales*

To investigate the predominant temporal and spatial scales of the *ILL*, spectral analysis is carried out for the weekly data of *ILL* using the Fast Fourier Transform (FFT) method. The temporal scale is dominated by 1 year for the fluctuations of sea ice limit latitude in all longitudes.

Predominant spatial scales are investigated using data from 1973. Throughout the year the wave numbers less than 5, which corresponds to a spatial scale of about 3600 km for latitudes around 65°, are dominant. Especially in winter larger power of spectrum is observed at these wave numbers. Figure 10 shows the results of time-spectral analysis, at every degree of longitude. The stronger power of spectrum ($>$ 1.0) are indicated by shading in this figure. In all regions, the periodicity of 1 year appears dominant, whereas regionally, in the Ross and Weddell Sea sectors, peaks of power appear also at shorter periods. This may indicate that the sea ice distribution at the sea ice margin is unsteady in these sectors compared with other sectors. These peaks of power are considered to be caused by short-term atmospheric forcing. However, time scales are expected to be longer than that of the atmosphere. The differences in kinematics of the sea ice in these sectors are considered to be due to thinning of sea ice in the Weddell and Ross Seas.

5. Movement of Sea Ice Limit

5.1. Spatial and temporal fluctuations

The weekly changes of ice limit latitudes are investigated in this section. Figure 11 shows an example which is derived at 150°W longitude. Positive values indicate net northward movement over one week. Fast movement of the *ILL*, such as 200 km/week, is sometimes observed. The direction and speed of meridional movement of the sea ice edge varies seasonally and regionally. The movement of the *ILL* is derived not only by the advection of ice mass but also by divergence or a convergence of ice mass since they change the areal concentration of sea ice.

Figure 12 shows the longitudinal variations of *ILL* movement, calculated each week of autumn and winter 1973. Large movements often appear in the Ross and Weddell Sea sectors. Sometimes the area with large movements propagates eastward. Although significant advances and their propagation are observed, there are few significant retreats. This behavior of the sea ice may reflect a uniqueness in the kinetic forcing (*e.g.*, oceanic current, gyre) or in the structure of the sea ice field (*e.g.*, large spatial variation of concentration) in the Ross and Weddell Sea sectors.

Large rates of retreat of the *ILL* are often observed in the warmer seasons, whereas in the colder season rapid advances are rarely observed. Although differences of sea ice conditions, such as an areal concentration, lead distribution, ice thickness and mean size of pack ice affect this, the main cause may be the breakup of the ice bridge between the ocean and the Weddell polynya.

5.2. Characteristic time and space scales

The predominant spatial and temporal scales of sea ice movement are investigated in a similar manner to the ice limit latitude. The investigation was done for every 10 degree of longitude. Two dominant peaks are observed at 1 year and at 3–4 weeks in almost all longitudinal sectors. In some sectors, there are peaks in the range of 100–180 days.

The temporal scale of the sea ice limit movement is longer than with the dominant periods of atmospheric eddies at 50°S (*e.g.*, 5–20 days; FRAEDRICH and KIETZIG, 1983). This is presumably due to the kinetic response time of the sea ice pack. The sea ice in

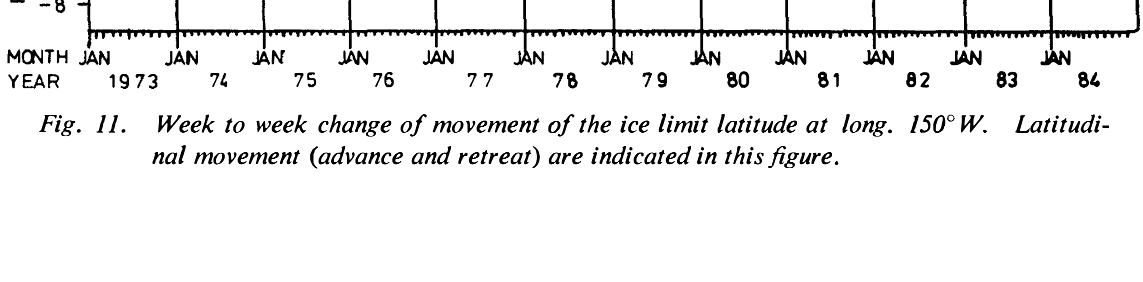


Fig. 11. Week to week change of movement of the ice limit latitude at long. 150° W. Latitudinal movement (advance and retreat) are indicated in this figure.

Table 1. Summaries of the frequency spectral analysis.

	Ice limit latitude (*ILL*)	Movement of *ILL*
Time	1 year all around Antarctica. The Ross and Weddell Seas also show peaks of power over short periods	1 year and 14–30 days (100–180 days in some sectors)
Space	Wave number ≦5=Wave length≧ 3600 km (larger power in winter)	Wave number 10–30=Wave length 1800–600 km

the Weddell and Ross Sea sectors responds to the forcing with a longer time scale of several months. Concerning the predominant spatial scale of movement of the *ILL*, the results of spectrum analysis show seasonal variations. Spectral peaks often appear between wave numbers 10 and 30, which correspond to spatial scales of 1800–600 km. Regional air flow such as cyclones may be important for sea ice movement. The results of spectral analysis for ice limit latitude and its movement are summarized in Table 1.

6. Discussion

Advances and retreats of the *ILL* with large velocity are often observed around Antarctica. Sea ice movements with large velocity occur further at their neighboring longitudes and usually propagate eastward. Propagation of the sea ice limit movement is shown in Fig. 12. This propagation does not go through all longitudinal sectors around Antarctica. This phenomenon is often restricted regionally to the

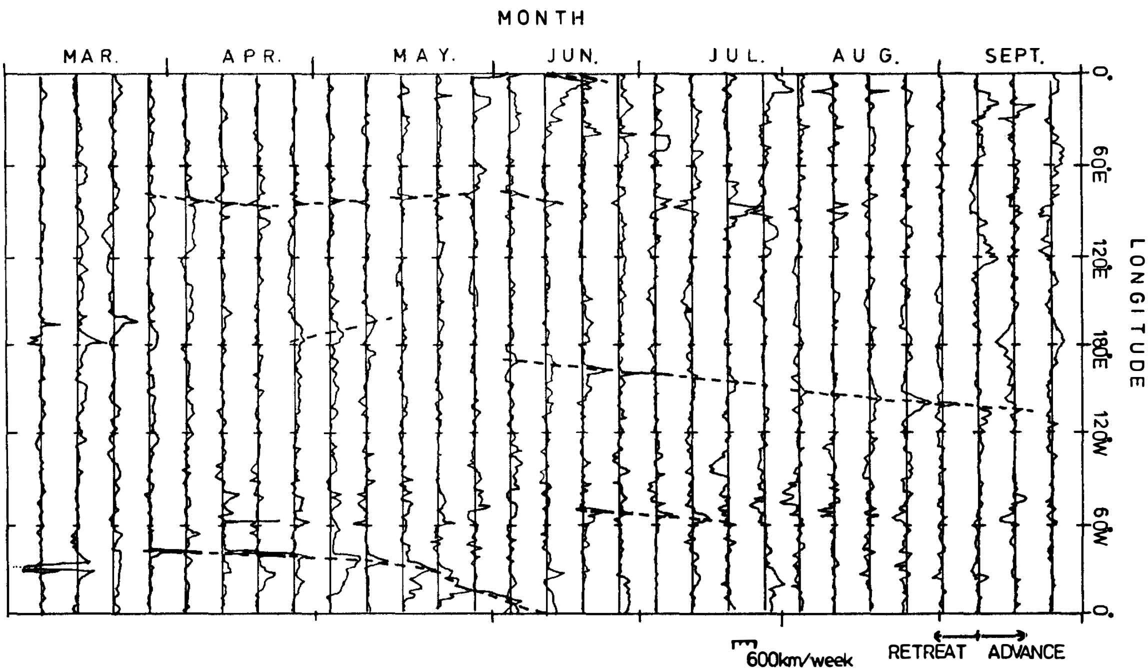


Fig. 12. Longitudinal variation of sea ice movement and its weekly changes. The dashed line indicates a propagating feature in the area with large movement of the sea ice limit in 1973.

Weddell and Ross Sea sectors, and temporally to autumn and spring. The longitudinal gradient of the large rate of movement of the *ILL* is estimated to be on the order of 10^{-5} (s^{-1}) between neighboring data points (distance 60 km). The longitudinal width of the area of large movement is, on average, 500–1000 km. This spatial scale corresponds to that of the synoptic wind field. There could be some regional differences of dynamic and thermal conditions in the atmosphere or ocean in the Weddell and Ross Sea sectors (LEMKE, 1986).

It is also expected that there are unique characteristics in sea ice itself in the Weddell and Ross Sea sectors. The sea ice area in these areas is often observed to be of low concentration. As the observed propagating feature persists for almost one month and the propagating rate is approximately 10–30 km per day (11–35 cm/s), a single coastal cyclone could not be its main forcing factor, since coastal cyclones occur more frequently with intervals less than one week and migrate much faster (several hundred km per day). Atmospheric conditions with longer time scale (one month$\sim$, see YASUNARI, 1981; KAKEGAWA *et al.*, 1986) and/or oceanic circum polar current (WHITWORTH and NOWLIN, 1987) should be considered to study this sea ice kinematic property.

CAVALIERLI and PARKINSON (1981) observed a relationship between the mean position of the coastal low pressure center and the area of sea ice advance and retreat on this time scale. STRETEN and PIKE (1980) revealed a relationship between the longitudinal position of large extent of sea ice and mean region with frequent atmospheric troughs and ridges in middle latitudes. These relationships were observed with a time scale of one month. This occurs presumably because of the kinematic response time of the sea ice movement to atmospheric forcing. The velocity of movement of the sea ice limit is very large ($>$200 km/week$=$0.3 m/s, in the latitudinal direction), more than could be produced by wind driving alone. Some changes in mass product and divergence or convergence can be expected as they change the sea ice concentration from more than 20% (sea ice area) to less than 20% (open water) or *vice versa*. Cold air advection and east-westward advection of ice mass are considered to have occurred. Such changes could produce an appearance of rapid shift of *ILL*. For further investigation, direct measurements are needed (ALLISON, 1989).

The open water area starts to increase in winter while the sea ice edge is still advancing, and reaches its maximum in spring (Fig. 3). These tendencies of the open water area are unique in the Antarctic (Figs. 5 and 6). The seasonal asymmetric extent accompanying the rapid retreat of *ILL* is affected also by these open water conditions (ENOMOTO and OHMURA, 1990). GLOERSON and CAMPBELL (1988) mentioned from the analysis of 10 years of sea ice data between 1978 and 1987 that the open water area in the Antarctic shows a decreasing trend. As the open water area affects the kinematics and energy balance concerning the sea ice area, monitoring of the open water area is as important as that of the sea ice extent.

7. Conclusions

The results of the present study can be summarized as follows:

1. The sea ice extent is stable in its maximum phase compared with its transient

stages. The sea ice limit is considered to be in dynamic and thermal equilibrium at the maximum stage; this condition persists for about two months (July–September).

2. The open water in the sea ice area begins to increase in winter (July) while the sea ice is still expanding. This results in an expanded but low concentrated sea ice area. These conditions of the open water characterize the sea ice extent and affect the kinematics of sea ice in the Antarctic.
3. The open water area in the sea ice area flucturates greatly in spring, particularly when the ratio of the open water area exceeds 15%.
4. Simultaneous freezing is observed in autumn over a wide area. It is speculated that there may be rapid change in sea ice conditions within a time scale of about three weeks. Such an event may characterize the beginning of the freezing of the southern sea.

Acknowledgments

The authors are indebted to Prof. H. C. DAVIES and Dr. K. STEFFEN at the Swiss Federal Institute of Technology (ETH) for helpful suggestions and for preparing data. Studies in Switzerland for one of the authors (ENOMOTO) were financed by a Swiss Federal Scholarship from the Swiss Federal Commission for Foreign Students (Eidgenoessische Stipendien Kommission fuer Auslaendische Studierende). The present study was supported by Research Grant No. 2.307.86 for the Project: Reevaluation of Global Heat Balance, from the Swiss National Science Foundation.

References

ACKLEY, S. F. (1981): A review of sea-ice weather relationships in the Southern Hemisphere. Sea level, Ice and Climatic Change, ed. by I. ALLISON. IAHS Publ., No. 131, 127–159.

ALLISON, I. (1989): Pack-ice drift off East Antarctica and some implications. Ann. Glaciol., **12**, 1–8.

BARRY, R. G. (1986): The sea ice data base. Geophysics of Sea Ice, ed. by N. UNTERSTEINER. New York and London, Plenum Press, 1005–1012.

CARLETON, A. M. (1983): Variations in Antarctic sea ice conditions and relationships with southern hemisphere cyclonic activity, winters 1973–77. Arch. Meteorol. Geophys. Bioklimatol., Ser. A, **32**, 1–22.

CAVALIERI, D. and PARKINSON, C. L. (1981): Large-scale variation in observed antarctic sea ice extent and associated atmospheric circulation. Mon. Weather Rev., **109**, 2323–2336.

COMISO, J. C. and ZWALLY, J. J. (1984): Concentration gradients and growth/decay characteristics of the seasonal sea ice cover. J. Geophys. Res., **89**(C5), 8081–8103.

DUMBAR, M. and WEEKS, W. F. (1975): Interpretation of young ice forms in the Gulf of St. Lawrence using side-looking Airborne radar and infrared imagery. CRREL Res. Rep., **337**, 41 p.

ENOMOTO, H. and OHMURA, A. (1990): The influences of atmospheric half-yearly cycle on the sea ice extent in the Antarctic. J. Geophys. Res., **95**(C6), 9497–9511.

FRAEDRICH, K. and KIETZIG, E. (1983): Statistical analysis and wavenumber-frequency spectra of the 500 mb geopotential along 50°S. J. Atmos. Sci., **40**, 1037–1045.

GLOERSON, P. and CAMPBELL, W. J. (1988): Variations in the Arctic, Antarctic, and global sea ice covers during 1978–1987 as observed with the Nimbus 7 Scanning Multichannel Microwave Radiometer. J. Geophys. Res., **93**(C9), 10666–10674.

GOODY, R. (1980): Polar process and world climate (A brief overview). Mon. Weather Rev., **108**, 1935–1942.

HIBLER, W. D., III (1986): Ice Dynamics. in Geophysics of Sea Ice, ed. by N. UNTERSTEINER. New York and London, Plenum Press, 577–640.

KAKEGAWA, H., YASUNARI, T. and KAWAMURA, T. (1986): Seasonal and inter-seasonal fluctuations of polar anticyclone and circumpolar vortex over Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **45**, 19–29.

LEMKE, P. (1986): Description of atmosphere-sea ice-ocean interaction. Geophysics of Sea Ice, ed. by N. UNTERSTEINER. New York and London, Plenum Press, 785–823.

PARKINSON, C. L., COMISO, J. C., ZWALLY, H. J., CAVALIERLI, D. J., GLOERSON, P. and CAMPBELL, W. J. (1987): Arctic Sea Ice, 1973–76; Satellite passive-microwave observations. NASA-SP 489, 296 p.

RASCHKE, E., Haar, T. H., Bandeln, W. R. and Pasternak, M. (1973): The annual radiation balance of the earth-atmosphere system during 1969–70 from Nimbus-3 measurements. J. Atmos. Sci., **30**, 341–364.

STEELE, M., MORISON, J. H. and UNTERSTEINER, N. (1989): The partition of air-ice-ocean momentum exchange as a function of ice concentration, floe size, and draft. J. Geophys. Res., **94**(C9), 12739–12750.

STEFFEN, K. (1986): Atlas of the sea ice types, deformation processes and opening in the ice (North Water Project). Zurcher Geogr. Schr. Dep. Geogr., Swiss Fed. Inst. Technol. (ETH), **20**, 55 p.

STRETEN, N. A. and PIKE, D. J. (1980): Characteristics of the broadscale Antarctic sea ice extent and the associated atmospheric circulation 1972–1977. Arch. Meteorol. Geophys. Bioklimatol., Ser. A, **29**, 279–299.

SUYETOBA, I. A. (1966): The dimensions of Antarctica. Polar Rec., **13**, 84, 344–347.

WEEKS, W. F. and ACKLEY, S. F. (1986): The growth, structure and properties of sea ice. Geophysics of Sea Ice, ed. by N. UNTERSTEINER. New York and London, Plenum Press, 9–164.

WELLER, G. (1980): Spatial and temporal variations in the south polar energy balance. Mon. Weather Rev., **108**, 2006–2014.

WHITWORTH, T., III and NOWLIN, W. D., Jr. (1987): Water masses and currents of the Southern Ocean at the Greenwich Meridian. J. Geophys. Res., **92**, 6462–6476.

WMO (1970): WMO Sea-Ice Nomenclature, WMO-No. 259. TP. 145, Geneva, Switzerland, 147 p.

YASUNARI, T. (1981): Influence of the Southern Hemisphere circulations of the active-break cycle of the Indian summer monsoon. Mem. Natl Inst. Polar Res., Spec. Issue, **19**, 223–233.

ZWALLY, H. J., COMISO, C., PARKINSON, C. L., CAMPBELL, W. J., CARSEY, F. D. and GLOERSEN, P. (1983a): Antarctic Sea Ice, 1973–1976; Satellite Passive-Microwave Observations, NASA Scientific and Technical Information. Report, SP-459, 206 p.

ZWALLY, H. J., PARKINSON, C. L. and COMISO, J. C. (1983b): Variability of antarctic sea ice and changes in carbon dioxide. Science, **220**, 4601, 1005–1012.

(Received December 5, 1989; Revised manuscript received March 19, 1990)