Proc. NIPR Symp. Polar Meteorol. Glaciol., **5**, 104–112, 1992

OPEN WATER AND THE CIRCUMPOLAR TROUGH IN THE ANTARCTIC

Hiroyuki ENOMOTO[1] and Atsumu OHMURA[2]

[1] *Kitami Institute of Technology, Koen-cho 165, Kitami 090*
[2] *Department of Geography, Swiss Federal Institute of Technology, Winterthurerstr. 190, CH-8057, Zürich, Switzerland*

Abstract: The extent of open water area in spring and time of rapid retreat of the sea ice area in late spring are important characteristics of the sea ice area in the Antarctic. The present study investigates relationships between atmospheric conditions and open water extent. In the present study, the position and intensity of the circumpolar trough are used as a measure of atmospheric conditions over the sea ice area. When the circumpolar trough is intense, it tends to be located at higher latitudes along the Antarctic coast. In such cases, the open water in spring increases and the time of significant retreat of the sea ice edge in late spring tends to be delayed.

1. Introduction

Sea ice area and open water area are important factors for polar climate (GOODY, 1980; ENOMOTO and OHMURA, 1991; WELLER, 1980). The heat and vapor transported from the ocean to the atmosphere through open water can strengthen atmospheric convection (SMITH *et al.*, 1990). On the other hand, a cyclonic circulation over the open water causes the pack ice to diverge (CAMPBELL and RASMUSSEN, 1972; HIBLER, 1974; WADHAMS, 1986). A positive feedback process with the open water extent is expected (CARLETON, 1981, 1988, 1989). This study attempts to find relationships between the sea ice distributions and the atmosphere.

The circumpolar trough characterizes the atmospheric circulation in the lower troposphere around Antarctica (VAN LOON, 1967; HSU and WALLACE, 1976; STRETEN, 1980). This study discusses possible interactions between sea ice and the atmosphere in this latitudinal zone.

2. Data

Two data sets are used in this study. The sea ice data set used in this study is the Navy-NOAA Joint Ice Center (JIC) Digital Sea Ice Data (DS I) (BARRY, 1986; ENOMOTO and OHMURA, 1990, 1991). The data between 1973–1984 are used in this study.

Digitized atmospheric data for the Southern Hemisphere, produced by the Australian Bureau of Meteorology (DS II) are used in the present study. These hemispheric data are digitized on a 47×47 spherical polar coordinate grid for the Southern Hemisphere. Regression analysis between these grid point data and sea ice indices are performed. The monthly mean charts for the period 1973–1984 are drawn from this data set and used to locate the circumpolar trough.

3. Circumpolar Trough

The circumpolar trough is one of the most characteristic synoptic weather fea-

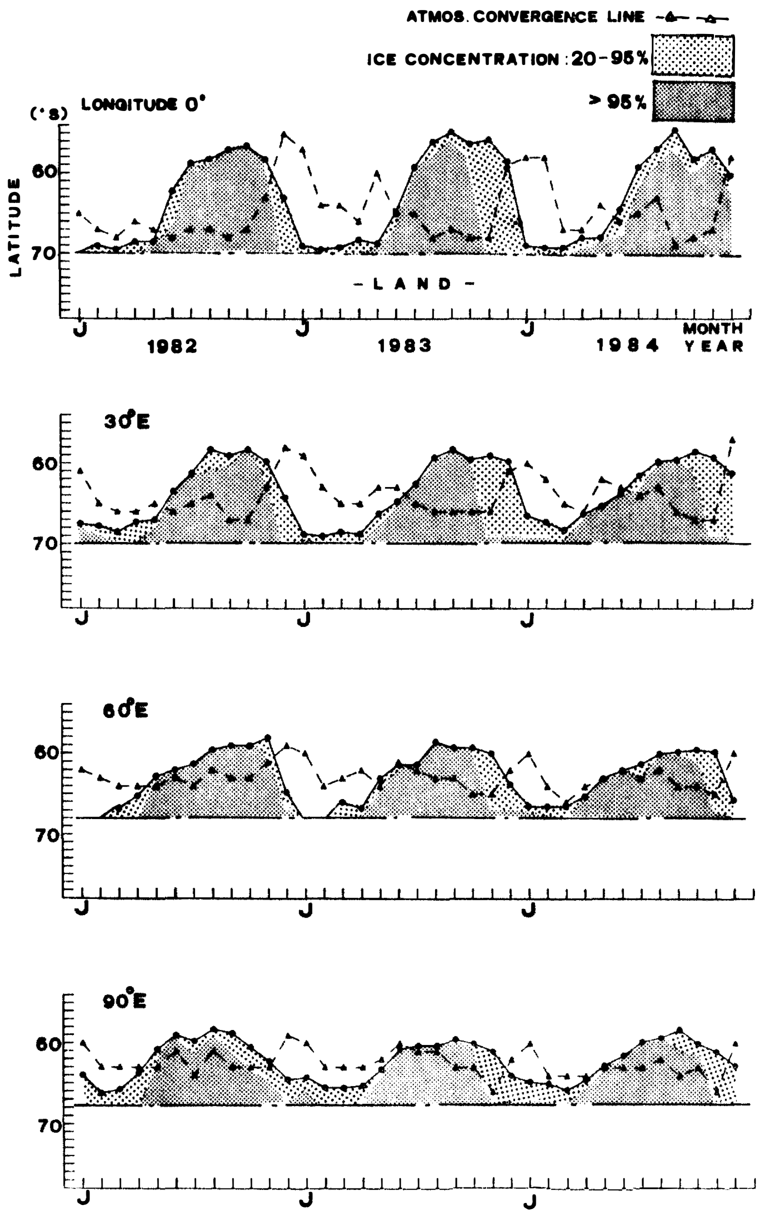

Fig. 1. Monthly fluctuations of the sea ice edge (solid line) and the circumpolar trough (dashed line) for every 30° in longitude (ENOMOTO and OHMURA, 1990). The sea ice edge and the circumpolar trough crosses twice a year, in spring and autumn. After the crossing in spring, the sea ice edge retreat drastically. The open water area increases when the circumpolar trough is located in the higher latitudes in winter, then, in early spring, it becomes its maximum before the crossing. Examples for some sectors are shown here. Same tendencies can be observed in the other longitudinal sectors.

tures around Antarctica. It is located in almost the same latitudinal zone as the sea ice edge. Figure 1 shows the monthly mean positions of sea ice edge and circumpolar trough from 1982 to 1984 (ENOMOTO and OHMURA, 1990). The circumpolar trough and the sea ice edge cross twice a year in autumn and spring. Retreat of the sea ice edge at the crossing in spring is significant. At this crossing period, the mean wind field over a large part of the sea ice area changes from westerly to easterly. North of the corresponding trough, where the westerly wind is dominant, the pack ice is transported to the north by the wind due to the Coriolis force. Thus, the sea ice area near the edge tends to diverge. South of the circumpolar trough, the opposite tendency is expected or, at least, the divergence is weak. These tendencies are apparent in the Weddell and Ross Sea sectors where the seasonal variation of the trough is great.

Although the influence of changes in the wind field can be seen in Fig. 1, the influence of the stationary wind field is also important for the sea ice distribution. In the Bellingshausen Sea and along Wilkes Land, the trough is rather stationary. The latitudinal range of the seasonal change is about half of that in the Weddell Sea (ENOMOTO and OHMURA, 1990; see also STRETEN, 1980). The Antarctic divergence line in the circumpolar ocean is located along the circumpolar trough (USSR MINISTRY OF GEOLOGY, 1966), and its position in the Wilkes Land sector is close to the continent. Circumpolar cyclones pass in a narrow latitudinal zone along the coast in this sector (ENOMOTO and OHMURA, 1990), therefore circumpolar trough is located near the coast. Although discussions are limited to a time scale of a few months in this study, for further study sea ice and atmospheric fluctuations on a shorter time scale should be described since the sea ice field breaks up on a time scale of few weeks (ENOMOTO and OHMURA, 1991).

A half-yearly cycle is observed in various fields in the atmosphere in mid-high latitudes in the Southern Hemisphere, in pressure (VAN LOON, 1967, 1972), in wind

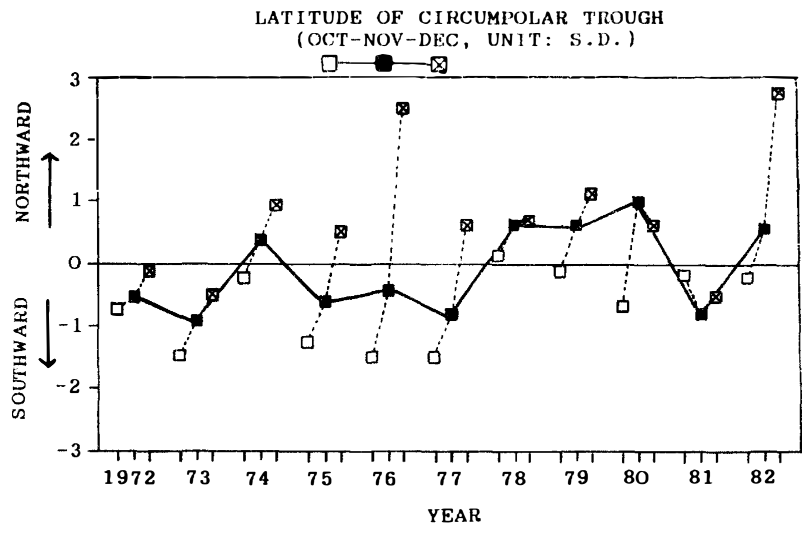

Fig. 2. Northward shift in spring and its year-to-year fluctuations of latitudinal positions for the circumpolar trough. The zonal mean positions in spring (October, November and December) are shown for each year. The positions are indicated by deviations from the mean position of all data shown in this figure (unit: standard deviation).

(VAN LOON and ROGERS, 1984). A significant northward shift of the circumpolar trough in spring appears due to part of those half-yearly cycles. The year-to-year fluctuations of the northward shift of the circumpolar trough are shown in Fig. 2. The zonal mean latitudes of the trough in October, November and December for each year are compared in this figure. The trough positions fluctuate with about a 2-year cycle. The circumpolar trough seems to be linked to a quasi-biennial oscillation (QBO) in the atmosphere (TRENBERTH, 1975, 1981; VAN LOON and ROGERS, 1984; MEEHL, 1987). TRENBERTH (1981) described the temporal and spatial structure of atmospheric pressure in the Southern Hemisphere and extracted the atmospheric fluctuation associated with the QBO. The circumpolar trough fluctuation in Fig. 2 reflects the polar part of the QBO in the atmosphere which was described by TRENBERTH (1981). Therefore, for the study of the sea ice fluctuation, some hemispheric conditions like the QBO and their influences to the circumpolar region should be described.

4. Open Water Area

In spring (October), the freezing rate of sea ice begins to decrease, however, the sea ice area tends to maintain its maximum extent (ENOMOTO and OHMURA, 1990). A sparse sea ice area appears in this season. The open water in the sea ice area begins to increase in winter (July) while the sea ice is still expanding, then an expanded but low compactness sea ice area appears. Therefore, the sea ice area can response immediately to changes in the wind field.

The period of the crossing is an important factor for the fluctuation of the open water area since the mean wind field alters by the crossing. Comparing the crossing period in 1982 and 1983 indicated in Fig. 1, it can be seen that the crossing occurred later in 1983, and a larger amount of the open water existed in 1983. The year-to-year fluctuation of the maximum open water area in spring is expected to be affected by the duration of the divergence in sea ice area. This duration is linked to the intensity of the circumpolar trough, since the circumpolar trough tends to be located in higher latitudes when the trough is deep. Therefore, the pack ice can diverge for a longer period when the trough is intense in late winter. Using a longer period data set (DS II), these relationships are examined. Regression analyses are done on the open water and pressure field. The annual maximum open water area, which occurs usually in November, is used as an index. Figure 3 shows the distribution of correlation coefficients. A negative value indicates decrease of atmospheric pressure at the corresponding grid point in the case of larger open water area. A significant negative correlation are appeared in the Weddell Sea sector. This is because the open water area in the Weddell Sea sector contributes greatly to the total open water area in the whole Antarctic.

5. Discussion

5.1. *Retreat of the sea ice boundary*

The position of the circumpolar trough fluctuates seasonally in relation to its intensity. When the intensity is large (*e. g.*, lower pressure), the trough is located at

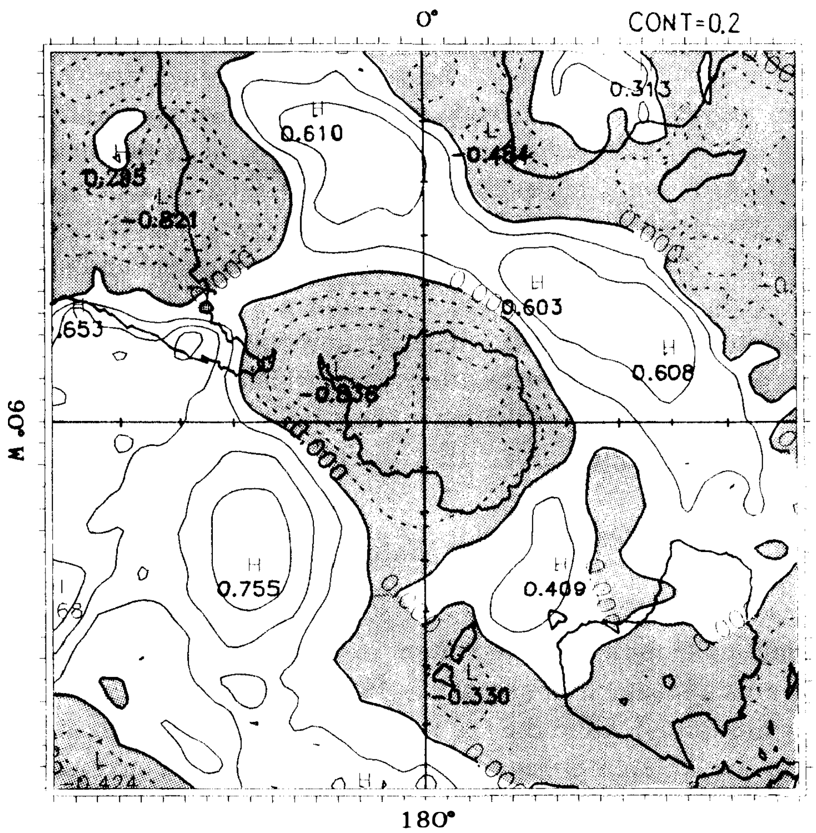

Fig. 3. Distribution of correlation coefficient between the annual maximum of the open water area totaled in the whole Antarctic and the sea level pressure (SLP) at each grid point. The negative value indicates that the SLP at the corresponding point in October is low in the case of large amount of the open water area. A center of negative correlation is appeared in the Weddell Sea sector.

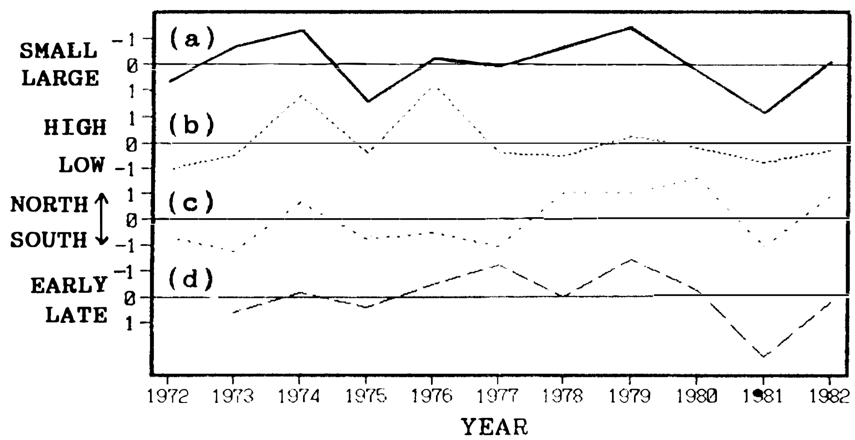

Fig. 4. Comparisons between (a) annual maximum of the open water area, (b) intensity and (c) latitudinal position of the circumpolar trough and (d) period of retreat for the sea-ice edge. The units are standard deviations. The scales are reversed for (a) and (d). Positive value in (d) indicate delay of the date. In the case of intense circumpolar trough, its position is located in the higher latitudes. The open water area increases and the period of the retreat of sea-ice edge tends to delay in such case.

higher latitude and tends to stay near the Antarctic Continent for a longer duration. Consequently the period of northward shift of the trough is delayed. Figure 4 compares the annual maximum of the open water area, the intensity of circumpolar trough and the period of the beginning of retreat.

In the Southern Hemisphere, atmospheric circulation with a wavenumber zero structure, in which changes in the pressure field occur simultaneously at all longitudes, is often observed (ROGERS and VAN LOON, 1982; KAKEGAWA *et al.*, 1986; YODEN *et al.*, 1987). Thus the present study uses a zonal mean value to indicate the atmospheric conditions. The monthly mean positions of the circumpolar trough were calculated from the latitudes in each longitudinal sector by spacing 45° of longitude from the weather charts. These weather charts were drawn using DS II.

The sea ice edge is often observed to retreat stepwise, with rapid retreat at the start of the melting season. The period of rapid retreat was obtained from the rate of decrease for the total sea ice area using DS I. In this study, the period of rapid retreat is defined as the week of the first large retreat when the retreating rate increases as much as one order of magnitude compared with the rate in previous weeks. The year-to-year fluctuation of the period of rapid retreat shows fluctuations similar to those of the open water area and the circumpolar trough. These similarities can be observed on a temporal scale of one month.

5.2. Atmosphere over open water

Changes in the open water area can be a control factor for an atmosphere-ocean coupled climate system in the polar region. Due to difficulties of direct observation of atmospheric conditions over sea ice, atmospheric processes are rarely known. An extreme case of open water is polynyas in the Weddell Sea (ZWALLY *et al.*, 1983; COMISO and GORDON, 1987; MOTOI *et al.*, 1987). STEFFEN and OHMURA (1985) observed the influence of open water on the atmosphere in the Arctic. In the Antarctic, no direct observation over the polynya has been done. The present study attempts to find evidence of the Weddell polynya in the atmospheric data available. Using the temperature data in DS II, composite maps of the surface temperature field in October were made. Figure 5 shows the difference between the mean temperature field in October for the cases of Weddell polynya (3 cases) and no Weddell polynya (8 cases) (polynya minus no polynya). The largest difference (positive) appears as a warm spot in the monthly-mean temperature of October in the Weddell Sea region. The surface temperature at this spot is as much as 4°C higher in the case of Weddell polynya. This result from monthly-mean data seems to indicate anomalous conditions which persist for a longer period. Anomalous open water could cause heating of the lower atmosphere. Although the accuracy of the position of the spot is limited since the observation points for the atmosphere are coarsely distributed, some anomalous atmospheric conditions are expected to have existed at nearby in the observation points.

Interactions between the sea ice and atmosphere are rarely known. The circumpolar trough is located in the area of the Weddell polynya (ENOMOTO and OHMURA, 1990); therefore, influence of cyclonic wind or wind-driven current on the polynya is expected. The influence of the large polynya on the atmospheric circulation, how-

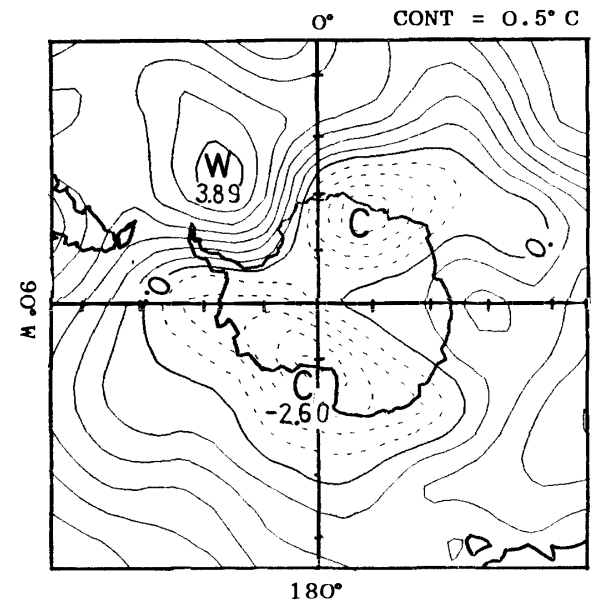

Fig. 5. Composite map of the temperature fields at surface in October. Influences of the Weddell polynya on the surface temperature is focused here. The differences in temperature are calculated between the mean temperature field in October for the case of appearances of the Weddell polynya (3 cases) and that for the case of no Weddell polynya (polynya minus no polynya). Solid and dashed lines show increase and decrease of temperature, respectively. A warm spot as much as about 4°C in the monthly-mean temperature (October) is appeared in the Weddell Sea when polynyas occurred.

evre, could not estimated. For further studies, direct observations should be done.

7. Conclusions

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

1) The year-to-year fluctuations of position and intensity of the circumpolar trough affect sea ice conditions. The period of retreat of the sea ice edge seems to be influenced by the intensity of the circumpolar trough. The crossing period for the sea ice edge and the circumpolar trough is delayed when the trough is deep.

2) As year-to-year fluctuations of the circumpolar trough seem to show a quasi-biennial oscillation, the open water condition could fluctuate, reflecting this oscillation.

3) As an extreme case of open water, the Weddell polynya was considered. In the case of appearance of the Weddell polynya, the surface temperature is calculated to be as much as 4°C higher than no-polynya case.

Acknowledgments

The authors are indebted to Prof. K. IWASAKI at Hokkaido University for preparing atmospheric data sets. The sea ice data was provided from the World Data Center A for Glaciology, Boulder, Colorado. This study was aided by Grant-in-Aid No. 02740207 for Encouragement of Young Scientists from the Japanese Ministry of Education, Science and Culture.

References

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

CAMPBELL, W. J. and RASMUSSEN, L. A. (1972): A numerical model for sea ice dynamics incorporating three alternative ice constitutive laws. Sea Ice, ed. by H. KARLSSON. Reykjavik, National Research Council, 176–187.

CARLETON, A. M. (1981): Ice-ocean-atmosphere interactions at high southern latitudes in winter from satellite observation. Aust. Meteorol. Mag., **29**, 183–195.

CARLETON, A. M. (1988): Sea ice-atmosphere signal of the Southern Oscillation in the Weddell Sea, Antarctica. J. Clim., **1**, 379–388.

CARLETON, A. M. (1989): Antarctic sea-ice relationships with indices of the atmospheric circulation of the Southern Hemisphere. Clim. Dyn., **3**, 207–220.

COMISO, J. C. and GORDON, A. L. (1987): Recurring polynyas over the Cosmonaut Sea and the Maud Rise. J. Geophys. Res., **92** (C3), 2819–2833.

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.

ENOMOTO, H. and OHMURA, A. (1991): Fluctuations of sea ice extent in the Antarctic. Proc. NIPR Symp. Polar Meteorol. Glaciol., **4**, 58–73.

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

HIBLER, W. D., III (1974): Differential sea ice drift II, comparison of mesoscale strain measurement to linear drift theory predictions. J. Glaciol., **13**, 457–471.

HSU, C.-P. F. and WALLACE, J. M. (1976): The global distribution of the annual and semiannual cycles in sea level pressure. Mon. Weather Rev., **104**, 1597–1601.

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

MEEHL, G. A. (1987): The annual cycle and interannual variability in the tropical Pacific and Indian Ocean regions. Mon. Weather Rev., **115**, 27–50.

MOTOI, T., ONO, N. and WAKATSUCHI, M. (1987): A mechanism for the formation of the Weddell polynya in 1974. J. Phys. Oceanogr., **17**, 2241–2247.

ROGERS, J. C. and VAN LOON, H. (1982): Spatial variability of sea level pressure and 500 mb height anomalies over the Southern Hemisphere. Mon. Weather Rev., **110**, 1375–1392.

SMITH, S. D., MUENCH, R. D. and PEASE, C. H. (1990): Polynyas and leads: An overview of physical processes and environment. J. Geophys. Res., **95** (C6), 9461–9479.

STEFFEN, K. and OHMURA, A. (1985): Heat exchange and surface conditions in the North Water, Northern Baffin Bay. Ann. Glaciol., **6**, 178–181.

STRETEN, N. A. (1980): Antarctic meteorology: The Australian contribution, past, present and future. Aust. Meteorol. Mag., **28**, 105–140.

TRENBERTH, K. E. (1975): A quasi-biennial standing wave in the Southern Hemisphere and interrelations with sea surface temperature. Q. J. Meteorol. Soc., **101**, 55–74.

TRENBERTH, K. E. (1981): Interannual variability of the Southern Hemisphere 500 mb flow: Regional characteristics. Mon. Weather Rev., **109**, 127–136.

USSR MINISTRY OF GEOLOGY (1966): Atlas Antarktiki. Vol. 1. Red. Sovetskaya Antarkticheskaya Ekspeditsiya. Moskva, Glavnoe Upravlenie Geodezii i Kartografii MG SSSR, 225 p.

VAN LOON, H. (1967): The half-yearly oscillations in middle and high southern latitudes and the coreless winter. J. Atmos. Sci., **24**, 472–486.

VAN LOON, H. (1972): Pressure in the Southern Hemisphere. Meteorol. Monogr., **35**, 59–86.

VAN LOON, H. and ROGERS, J. C. (1984): Interannual variations in the half-yearly cycle of pressure gradients and zonal wind at sea level on the Southern Hemisphere. Tellus, **36A**, 76–86.

WADHAMS, P. (1986): The seasonal ice zone. Geophysics of Sea Ice, ed. by N. UNTERSTEINER. New York, Plenum Press, 825–992.

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

YODEN, S., SHIOTANI, M. and HIROTA, I. (1987): Multiple planetary flow regimes in the Southern Hemisphere. J. Meteorol. Soc. Jpn., **65**, 571–586.

ZWALLY, H. J., COMISO, C., PARKINSON, C. L., CAMPBELL, W. J., CARSEY, F. D. and GLOERSEN, P. (1983): Antarctic Sea Ice, 1973–1976: Satellite Passive-Microwave Observations. NASA Sci. Tech. Inf. Rep., **SP-459**, 206 p.

(Received November 15, 1990; Revised manuscript received March 18, 1991)