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# INTERANNUAL FLUCTUATIONS OF SEA ICE EXTENT IN THE ANTARCTIC AND ASSOCIATED ATMOSPHERIC CONDITIONS

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***Abstract:*** Interannual fluctuations of sea ice extent might occur reflecting the interactions among the ice sheet, sea ice and polar atmosphere. This paper focuses on possible atmospheric driving forces for sea ice fluctuations. It is seen from synoptic correlation maps that, in the case of larger sea ice extent, the circumpolar trough is located in the lower latitudes in October. As significant relationship is found also between temperature rise over Antarctica and increase of sea ice area. The implication is that the mean wind field changes due to northward shift of the trough. Thus an outburst of cold air from the continent seems to strengthen the advection of ice pack to lower latitudes and freezing in specific sectors. The temperature rise observed in East Antarctica is due to the advection of warm air. The variations of the circumpolar trough are important for changes in sea ice extent. Long-term fluctuations of the pressure and wind fields in the Southern Hemisphere are described in this study. The fluctuations of circumpolar trough are observed to reflect large-scale atmospheric fluctuations.

## 1. Introduction

The annual maximum of sea ice extent in the Antarctic shows large interannual variations. CAVALIERI and PARKINSON (1981) investigated the extent and decay of the sea ice area. They attempted to understand physical processes and atmospheric influences on sea ice movement on a large scale. The physical processes are complicated due to interactions between the atmosphere and the sea ice. Some statistical approaches have been tried concerning this problem. CARLETON (1989) researched on the relationships between the sea ice extent and atmospheric indices (see also WEATHERLY *et al.*, 1991). JONES *et al.* (1986a, b) and JONES (1990) described the global temperature changes, and discussed the evidenced changes in Antarctic temperature. RAPER *et al.* (1984) pointed out that the temperature over Antarctica shows a parallel fluctuation with sea ice extent. Note that the correlation is positive. That is, sea-ice extent expanded largely when the temperature over the Antarctica was high.

The atmosphere–sea ice–ice sheet interactions are of great interest in studying the polar climate. We try to derive a hypothetical model from the statistical studies. Climatic influences of sea ice cover may be characterized by its area, fractions of open water and their seasonal changes. The change in fractions of the open water on associated atmospheric conditions was discussed in ENOMOTO and OHMURA (1992), and the importance of the circumpolar trough in November was emphasized. This paper investigates relationships between the extent of sea ice and atmospheric conditions: air temperature, wind and pressure. The sea ice extent seems to fluctuate with a longer time-scale from a few years to decades. This paper indicates the long-term fluctuations of the circumpolar trough, that seems to affect the interannual fluctuations of the sea ice extent.

## 2. Data Sets

Sea ice area is calculated using Navy-NOAA Joint Ice Center (JIC) Digital Sea Ice Data (BARRY, 1986; ENOMOTO and OHMURA, 1990, 1991). This study compares the interannual fluctuations of the maximum sea ice extent and atmospheric conditions from 1973 to 1984. The atmospheric data compiled by the Australian Bureau of Meteorology are available in this study. The atmospheric data have the 47 × 47 data-grids adapted on a spherical polar coordinate chart of the Southern Hemisphere. The annual maximum of sea ice area tends to occur in October. This study uses the monthly-mean data of surface air temperature, pressure (500 hPa height) and wind at 500 hPa level in October.

## 3. Sea Ice Extent and Polar Atmosphere

Synoptic correlation analyses were performed using time series data of the interannual fluctuation of the maximum sea ice extent. Each grid point of the atmospheric data has a time series of each atmospheric factor. The correlation coefficients are calculated between these atmospheric data at each grid point and the index shows the total area of sea ice. The coefficients of each data-grid are mapped to reveal the synoptic structures of associated atmospheric factors.

Figure 1 shows the result for the surface air temperature. The dotted area indicates the negative correlation. That is, air temperature was low in this area when the sea ice expanded largely. The area with negative correlation is distributed around the Antarctica. The relationships are strong in the longitudinal sectors of 40°E and 210°E. These two sectors are where the sea ice expands largely; thus, this result shows that cooling in these sectors increases sea ice production and/or decreases the melting rate. Although this map alone cannot show whether the low air temperature causes the ice extension or *vice versa*, anomalies in the atmosphere are considered to cause the changes in sea ice. This is because similar patterns are observed also at upper atmospheric levels, and the influence of sea ice is considered to be limited to the lower atmosphere.

An other interesting feature is the large positive correlation over Antarctica. The correlation coefficient in the inland part of East Antarctica is calculated to be 0.948. RAPER *et al.* (1984) also reported parallel fluctuations between the mean temperature over Antarctica and sea ice extent, using temperature data

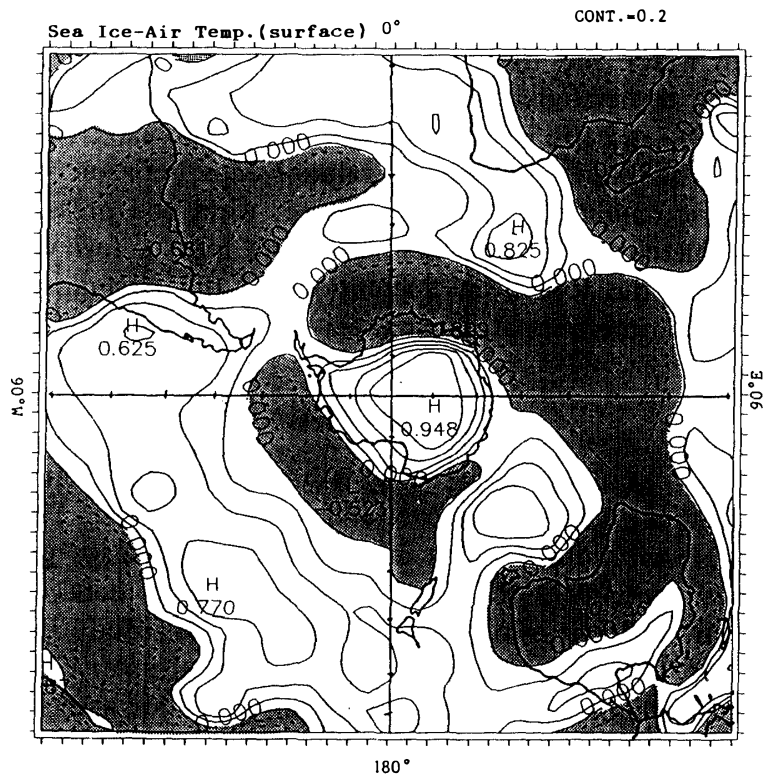


*Fig. 1. Distribution of correlation coefficient calculated between surface air temperature of each data grid at October and the maximum sea ice extent. The dotted area indicates negative correlation. In the case of large sea ice extent, temperature was low over the sea ice cover, while temperature was high over Antarctica. The area with lower temperature around Antarctica is possibly due to the divergence of cold-air from Antarctica.*

from meteorological observations over Antarctica. To understand the changes in air temperature in Antarctica associated with sea ice extent, we need to investigate the influence of changes in the atmospheric circulation. Relationships between the sea ice extent and the wind field are investigated in the same manner. Figures 2a and 2b show the results for the meridional and zonal wind components, respectively. Positive correlation in Fig. 2a indicates the increase of the north wind component when the sea ice area increases. In the case of large sea ice extent, the south wind at three sectors over Antarctica becomes strong, as shown with solid arrows in Fig. 2a. A decrease of air temperature is observed off the coast of these areas, possibly due to the strengthened out-burst of cold air from the continent. One of those key sectors is located near Syowa and Asuka Stations around 45°E; therefore more precise investigations are expected using the observational data in this sector. South wind also blows the pack ice off Antarctica, which may contribute to the larger extent of sea ice. However, Fig. 2a shows that the stronger south wind need not occur in all sectors along the coast of Antarctica. There seem to be sectors in which the wind is more effective in blowing the ice-pack and freezing.

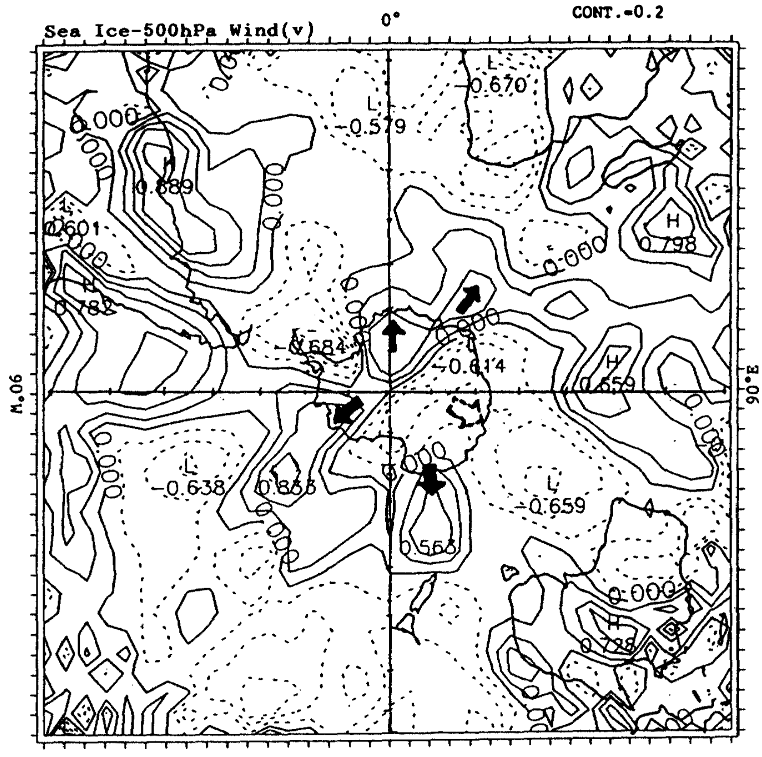


*Fig. 2a. Relationships between sea ice extent and the meridional wind field. Correlation was calculated in the same manner as for Fig. 1. In the case of large sea ice extent, south winds in three sectors over the Antarctica were strong (solid arrows). There are some effective sectors for blowing ice-pack broadly. The wind speed need not increase in all longitudes around Antarctica for large sea ice extent. In East Antarctica, the south wind decreased (dashed arrow), this causes frequent warm air advection from the north, therefore the temperature rises.*

As the air temperature decreases along the coast of Antarctica (Fig. 1), divergence of the cold air from Antarctica seems to occur. In such a case, the associated vertical circulation over Antarctica could be strengthened (PARISH and BROMWICH, 1991). Therefore, the air temperature may rise due to adiabatic heating. Other possible causes for temperature rise over the Antarctica may be changes in the air advection, which can affect the air temperature distribution greatly. Negative correlations occur over East Antarctica as shown with dashed lines and dashed arrow in Fig. 2a. As the mean wind in this area is from the south, this correlation indicates decreases in the frequency or strength of the south wind. The decrease of monthly-mean south wind implies the frequent occurrence of warm air advection from the north. This may cause increase of temperature over Antarctica shown in Fig. 1. Along the coast of East Antarctica around 90°E, the increases of the surface air temperature and the north wind, which limit the expansion of the sea ice, are indicated (Fig. 1). Decrease of sea ice area in this sector would not contribute to the change in total sea ice area in

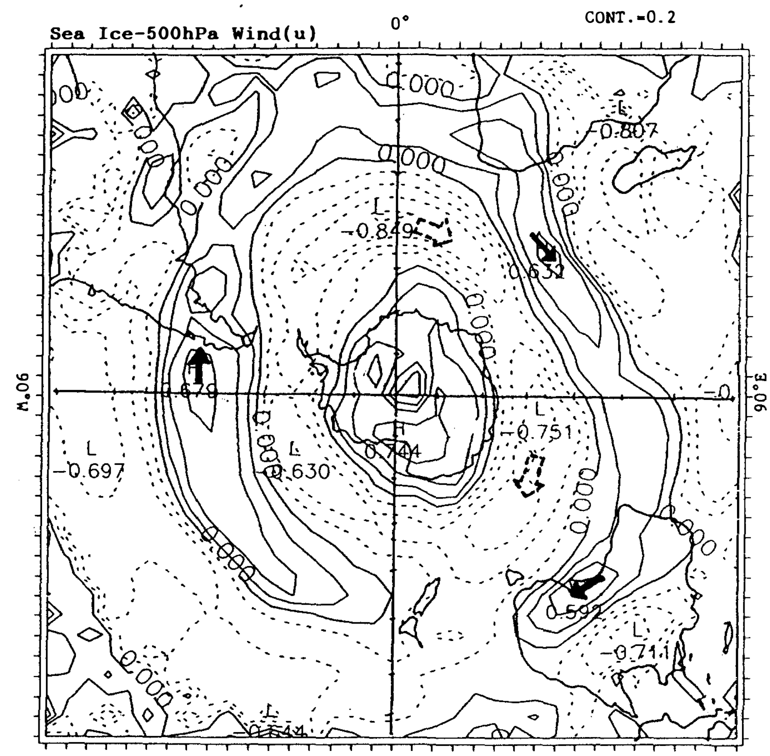


*Fig. 2b. Relationships between sea ice extent and the zonal wind field. Calculations were done in the same manner as for Fig. 2a but with the west wind component. The westerlies are stronger in middle latitudes (solid arrows) and weaker around the Antarctica (dashed arrows) when the sea ice expands largely. As the dominant wind is westerly at the 500 hPa level and easterly at the surface, the positive correlation over the Antarctica indicates increase in west component at 500 hPa level and the decrease of east component at the surface. The meridional air flow might be strengthened over the coastal zone. This pattern could occur when the mean wind-field shifts northward.*

the Antarctic. The area of sea ice in this sector is limited due to a stable low pressure area located near the coast (ENOMOTO and OHMURA, 1992).

The westerly wind is strengthened in the middle latitudes and weakens around Antarctica when the sea ice expands greatly (Fig. 2b). Positive correlation over the Antarctic coast implies an increase of the west wind component in this zone. The easterly, the mean wind at the surface in this zone could become strong. This structure indicates a northward shift of the mean wind field in middle latitudes. On the other hand, the zonal air flow becomes weak and the meridional air flow becomes strong around Antarctica. Increase of longitudinal variation, that is, meandering of wind seems to contribute to the large sea ice extent.

## 4. Discussion

### *4.1. Sea-ice extent and circumpolar trough*

The circumpolar trough characterizes the atmospheric circulation around Antarctica. Changes in positions and intensities of the circumpolar trough should be related to changes in the temperature and wind fields. The latitudinal position of the circumpolar trough in November was emphasized as it affects the decay of the sea ice area and fraction of open water in the sea ice area (ENOMOTO and OHMURA, 1992). In November, the circumpolar trough shifts to the lower latitudes drastically; then the relative position of the circumpolar trough and the northern limit of sea ice extent are altered. Therefore, the mean wind field over the sea ice limit changes from westerly to easterly. This change could cause the sea ice area to shrink. The drastic shift of the trough in November is remarkable evidence of the seasonal cycle in the polar atmosphere.

On the other hand, the month of October is considered to be the key month for the annual maximum of sea ice extent. The circumpolar trough is located over the sea ice area near the coast in October. Figure 3 shows the results of a

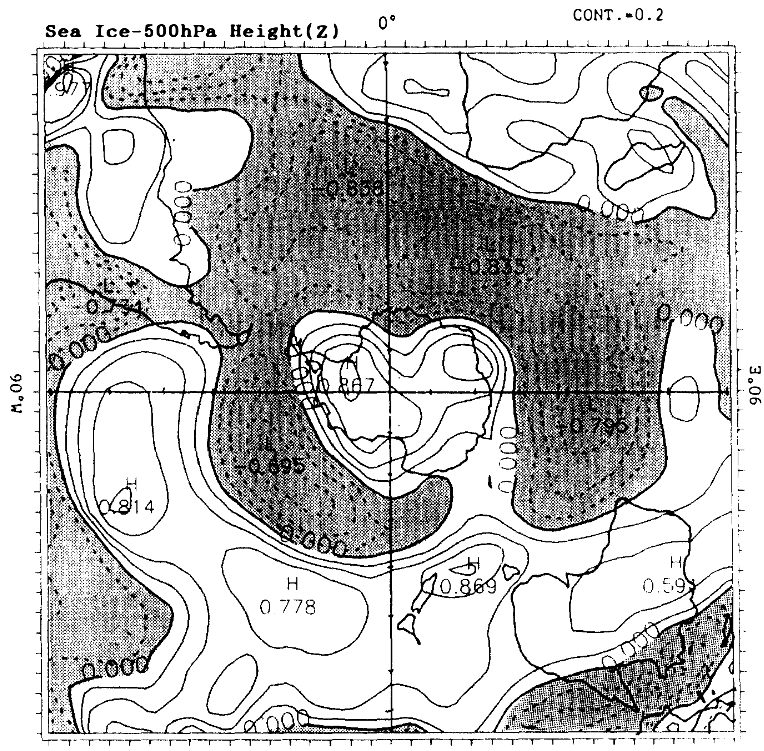


*Fig. 3. Same as Fig. 1, but with the atmospheric pressure field (500 hPa height). Atmospheric pressure decreases in middle-high latitudes in the case of large sea ice extent. The centers of decreased area are located north of the mean latitudes of the circumpolar trough. This synoptic correlation map, therefore, indicates the northward shift of the circumpolar trough. The strong south wind shown in Fig. 2a occurs west of the low pressure center.*

correlation analysis between atmospheric pressure (500 hPa height) and sea ice area. The atmospheric pressure decreases in October in middle-high latitudes when the sea ice extent is large. The centers of decreased area are located north of the mean latitudes of the circumpolar trough in each longitudinal sector. Therefore, this synoptic correlation map indicates that the northward shift of circumpolar trough in October is related the large sea ice extent.

Around Antarctica the meridional pressure gradient is weak; thus meandering of the air flow and increase of the meridional wind component tend to occur. Thus sea ice is transported to lower latitudes frequently. Expansion of the sea ice field can occur more easily than compressing of the sea ice field. Thus, the sea ice area is believed to expand when the mean centers of low pressure around Antarctica are located at the positions indicated in Fig. 3. The south winds shown in Fig. 2a occur in the western part of those low pressure areas. Although the period of drastic shift of the circumpolar trough affects the sea ice in November, the meridional circulation around Antarctica in October affects the tendency of expansion of sea ice area.

The shifts of circumpolar trough seem to occur concurrently in all sectors. Therefore, zonally-averaged pressure conditions can be used as a useful index for circumpolar atmospheric conditions. However, when we consider the physical processes for sea ice distribution, we should observe the atmospheric conditions on a regional scale as shown in Fig. 2. Figure 4 summarizes the relationships between sea ice extent and the circumpolar trough. The trough intensities were calculated by averaging the lowest pressure in eight sectors, at intervals of 45° in longitude. The circumpolar trough tends to locate in higher latitudes when it is strong. When the annual maximum area of sea ice increases, the circumpolar trough shifts northward and its intensity is weak. From 1976 to 1980, the sea ice area was relatively small and the decay of the sea ice edge tended to occur earlier (ENOMOTO and OHMURA, 1992).

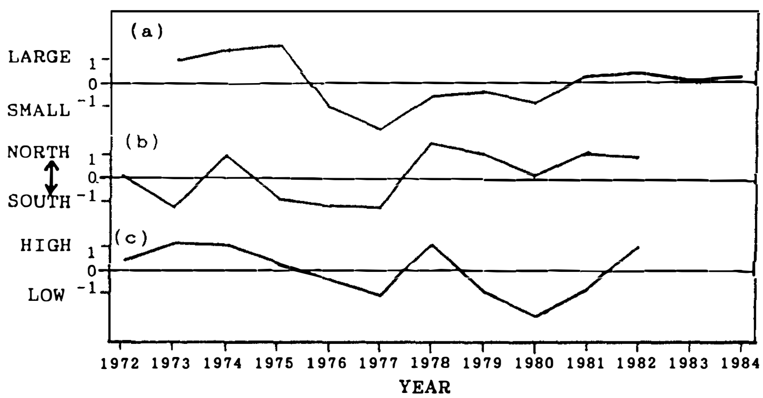


*Fig. 4. Comparisons between (a) the annual maximum of the sea ice extent, (b) the latitudinal position and (c) the intensity of the circumpolar trough in October. The units are standard deviations. In October, the area of sea ice tends to reach its annual maximum. The intensities of trough were average of lowest pressure around the Antarctica.*

### 4.2. *Circumpolar trough and southern atmosphere*

Whereas the previous sections of this paper discuss atmospheric conditions in a specific month, October, this section discusses long-term fluctuations of the atmosphere. Figures 5a and 5b show the zonal mean 500 hPa hight and wind (u-component). The zonally-averaged values are used in this analysis. A low path

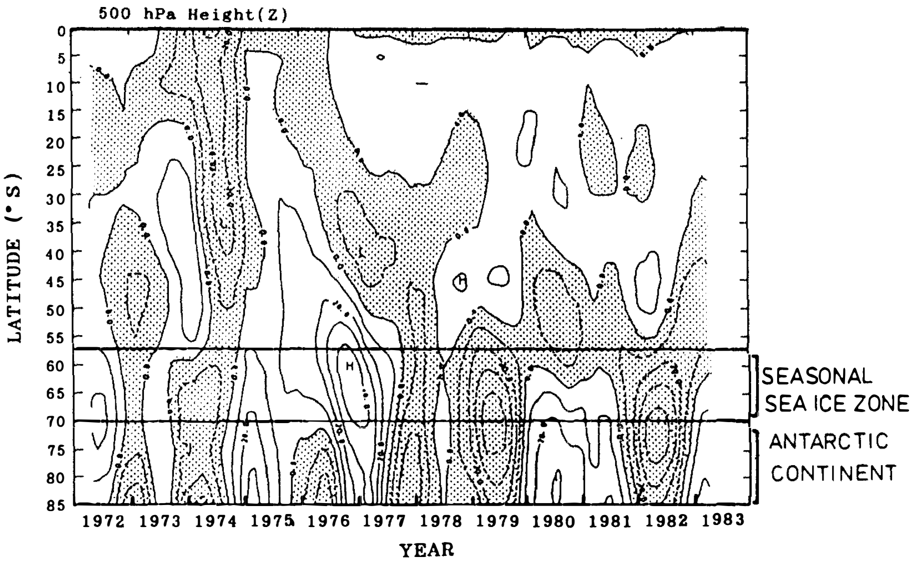


*Fig. 5a. Latitude-time section of 500 hPa height in the Southern Hemisphere. This figure shows the zonal mean 500 hPa height after filtering short-term fluctuations less than nine months out.*

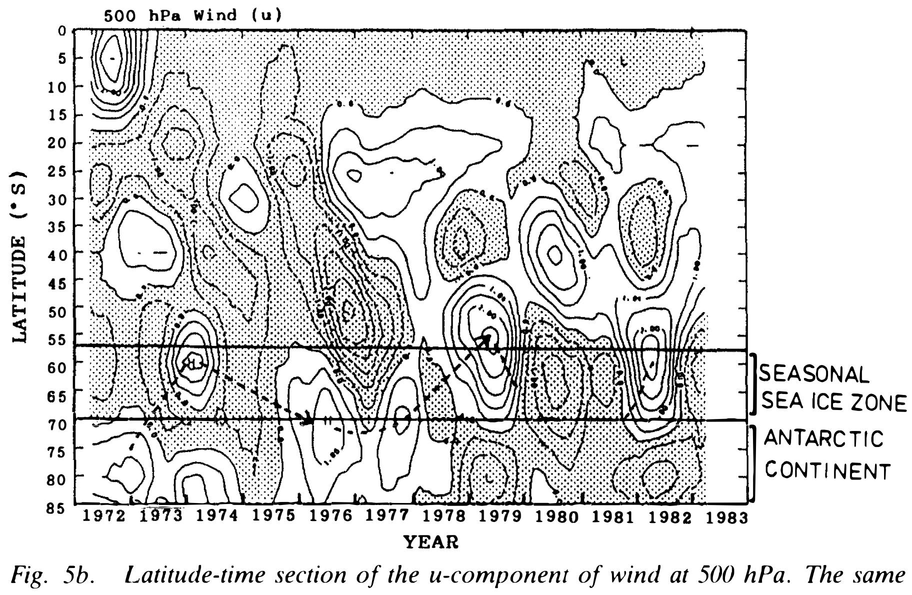


*Fig. 5b. Latitude-time section of the u-component of wind at 500 hPa. The same filter as Fig. 5a was used for this figure. Corresponding to the area with large latitudinal gradient that can be observed in Fig. 5a, the u-component increases. The latitudes of strong westerlies fluctuate, reflecting shifts of the latitudinal positions of circumpolar trough indicated in Fig. 4. The zone of large anomalies tends to locate either at sea ice edge or coast of Antarctica (dashed arrow). In the middle 1970s, the strong wind zone located along coast of Antarctica, and the area of sea ice decreased.*

filter was applied to eliminate short-term fluctuations of less than nine months. The anomalies seem to fluctuate with about a 2-year cycle, *e.g.*, quasi-biennial oscillation (QBO) (TRENBERTH, 1975, 1981; MEEHL, 1987).

The westerly (u) component increases in this zone with a large meridional gradient at 500 hPa height (Fig. 5b). The strong westerly zone between Lat. 50°S and 70°S appeared in the years 1973–1974, 1975–1976, 1978–1979 and 1981–1982. These long term fluctuations could occur on a hemispheric scale. MEEHL (1987) showed evidence of relationships between SST (sea surface temperature) anomalies and the significance of annual cycles in the atmosphere in the tropical regions. He noted 1974, 1976, 1979 and 1982 as the years of weak annual cycle, accompanying a warmer SST in the eastern Pacific region and strong circumpolar trough around Antarctica. This tendency in the circumpolar trough can be observed also in Fig. 5b. This idea is interesting since it could relate the tropical and polar atmospheric processes. Figure 5b shows alternative patterns of positive and negative values along the meridional direction. For example, the pattern in 1979 is remarkable, that is, negative values in Lat. 85°–70° and Lat. 40°–30°, positive values in Lat. 70°–40° and Lat. 30°–15°. This pattern indicates that meridional shifts of atmospheric circulation occur on a hemispheric scale. This evidence may support MEEHL's idea.

The area of increase in u-component tends to locate either Lat. 55°S–60°S or Lat. 70°S, as shown with dashed arrow in Fig. 5b. As these latitudinal zone correspond to either sea-ice edge or coast of Antarctica, strong interactions at ice surface seems to occur. This latitude range is higher than those of double westerly jet (YODEN *et al.*, 1987). Investigations on causes of these shifts over sea-ice area are future problems.

## 5. Conclusions

The influences of atmospheric conditions in October on sea ice extent were focused in this study. The results can be summarized as follows:

1) Strong south winds in some sectors are important for expansion of sea ice area. However, the strong south wind need not blows in all longitudes around Antarctica, to increase the total area of sea ice extent. There are specific sectors that affect the sea ice extent greatly. Such wind blows pack ice and cools the corresponding sectors.

2) The intense anticyclone over Antarctica and the northward shifts of circumpolar trough seem to appear concurrently, and affect extent of the sea ice area. Meridional circulation is predominant around Antarctica; and such atmospheric condition could strengthen the transport of sea ice to lower latitudes.

3) The air temperature over Antarctica shows a significant correlation with the interannual fluctuations of sea ice extent, but the coefficient is positive. That is, when the surface air temperature over the continent increases, the sea ice expands. This is possibly because advection of warm air from lower latitudes occurs in East Antarctica.

4) The interannual fluctuations of position and intensity of the circumpolar trough in October are useful indicators of atmospheric conditions affecting sea ice extent. The positions of the circumpolar trough vary in association with atmospheric circulation on a hemispheric scale.

5) The long-term fluctuations of wind around Antarctica show shift of positions with large anomalies corresponding to either sea-ice edge or coast of Antarctica.

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