On the Meridional Circulation over the East Antarctic Coast during the winter of 1976

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東南極沿岸における 1976 年冬期の子午面循環

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要旨．東南極大陸の斜面から沿岸にいたる地域の大気循環を，主として 1976 年冬の昭和基地周辺について考察した．同じ東南極でも，トラフやリッジの位置によって，時間と場所で子午面循環の様子が非常に異なっている．昭和基地の対流圏上部では，冬の卓越風は西～南西風であるが，風速は南風の時に大きくなり，一時的な渦輸送も，定常的な渦輸送と同じく大気の南北交換に重要であることがわかった．波動の振幅が増大する時は，ブロッキング高気圧が作られやすく，北東風の頻度も増すことが確かめられた．対流圏下部では，大部分が海から内陸へ向かう北成分の風であり，特に，900 mb 付近に風速の極大値をもつことが多い．このことに関しては，昭和基地の東の地形の効果が考えられる．

Abstract: The circulation of the atmosphere over the East Antarctic periphery is discussed mainly on the basis of the data of Syowa Station during the polar night of 1976. According to the location of a through or a ridge, the meridional circulation changes with time and place In the upper troposphere over Syowa the prevailing wind is W–SW in the winter, while the southerly wind increases its speed. It is pointed out that trasient eddy transportation is as well significant as the standing one for the meridional air mass exchange The blocking high formed in the meridionally developed wave contributes to the increase of the NE wind. In the lower troposphere the major part is occupied by the northerly component having a maximum wind speed around 900 mb. Effects of topography east of the station are inferred.

1. Introduction

Arctic and Antarctic areas work as two main heat sinks in the atmospheric general circulation, though the process of energy exchange with the lower latitudinal atmosphere is very different. The winter circulation, which is supposed to be most effectively influenced by the great heat sink of polar regions in each hemisphere, is shown by the mean 500 mb height contour map in Fig. 1. In the northern hemisphere, the westerly wave forms semi-permanent amplified troughs over East Asia and East America due to the

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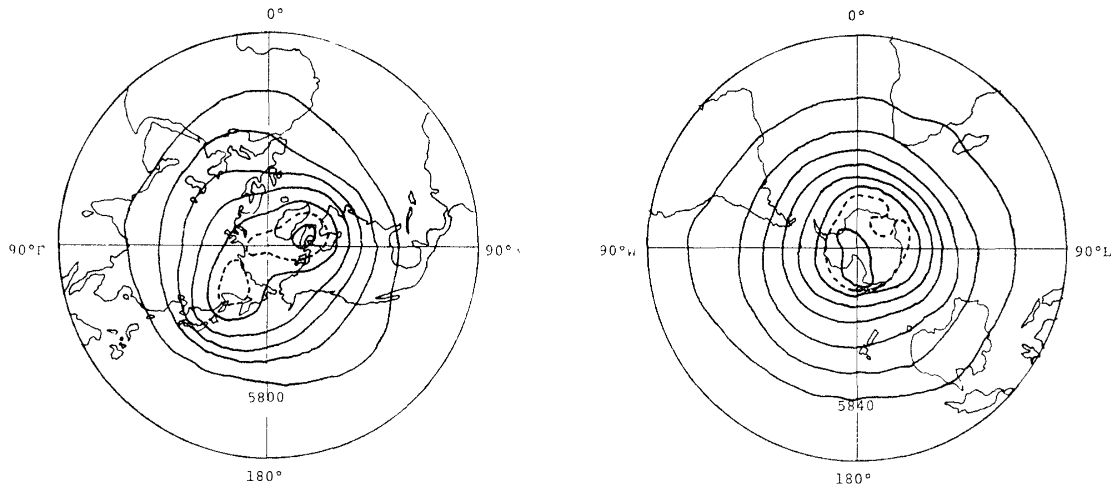

Fig. 1. Mean winter 500 mb charts. Left: Northern hemisphere for January. Right: Southern hemisphere for July. Redrawn from PALMEN *and* NEWTON*'s text (1969) with contour interval of 16 gpm.*

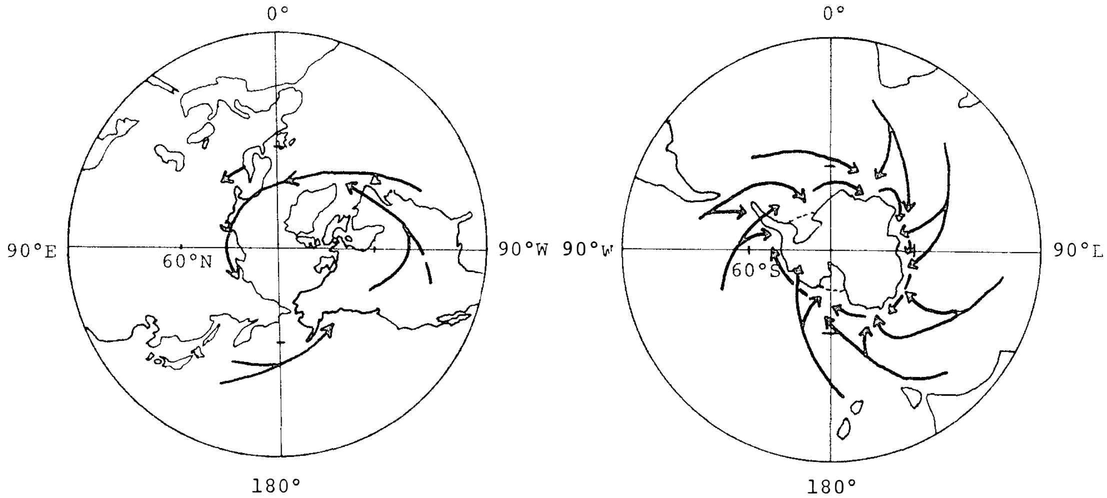

Fig. 2. Trajectories of cyclone. Left: The main tracks for North Polar region (after PALMEN *and* NEWTON*, 1969). Right: For Antarctica in 1958 (after* ASTAPENKO*, 1959).*

orographic effect of the Himalayan and Rocky Ranges. The lack of large scale mountains and wide land areas in mid-latitudes produces the symmetrically zonal circulation of the southern hemisphere (PALMEN and NEWTON, 1969). The cyclone tracks in both polar regions are shown in Fig. 2. There are two main tracks which correspond to the upper troughs in the North Polar region, namely, Aleutian and Icelandic lows. However, there are no significantly preferred tracks of cyclone in Antarctica (ASTAPENKO, 1959). It can be imagined that the air mass over Antarctica is exchanged with that of lower latitudes more through transient eddies than standing ones.

The exchange process of air mass over Antarctica is not clearly known due to the lack of inland data. WHITE and BRYSON (1966) suggested the meridional circulation which has an inflow to the continent above some 600 mb level and an outflow to the lower latitude below it during the polar night, assuming the cylindrical boundary centered on the South Pole. They considered that the disagreement of the observed radiative cooling with the local cooling of free atmosphere is explained by the vertical motion and additional adiabatic compression

However, the South Pole centered asymmetries are unrealistic either in shape and relief of the Antarctic Continent or in the atmospheric circulation. The deviation from the zonal flow in winter is eminent in West Antarctica as seen in Fig. 1, where orographically induced large cyclones play a major role in the air mass exchange (BUGAEV and MUSAELJAN, 1966). Over East Antarctica, on the other hand, the meridional circulation would be expected to be composed of outflow from the plateau near the surface and inflow at the upper level (KOBAYASHI and YOKOYAMA, 1976). Since the meridional circulation mechanism is rather different in both sectors, as mentioned above, the discussion in this paper will be confined to the circulation over East Antarctica.

2. Meridional Circulation over East Antarctica

The major part of East Antarctica is occupied by the plateau elevated more than 3000 m a.s.l. as shown in Fig. 3. RUBIN (1960) has shown that outflow from the plateau below 700 mb and inflow above it up to 250 mb prevail in June through the cylindrical

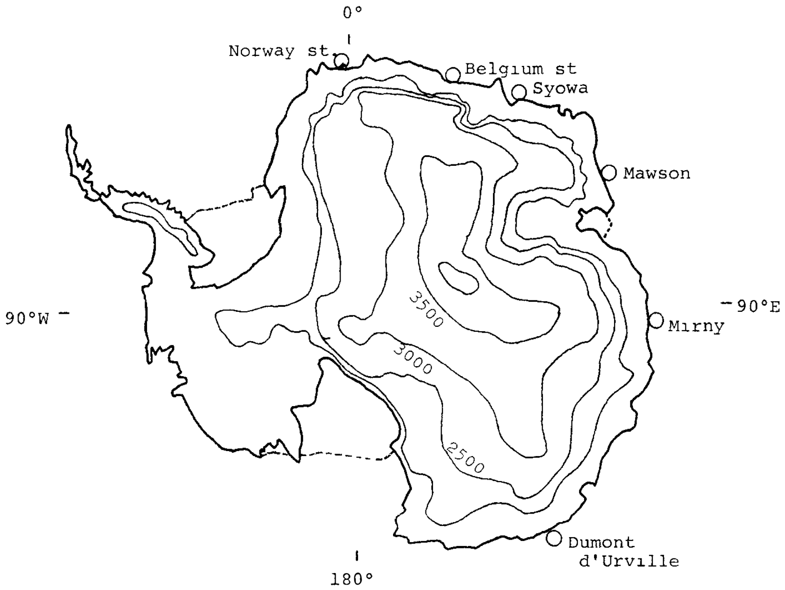

Fig 3 Antarctic relief and the location of stations along the East Antarctic coast. Contours are drawn with 500 m intervals above 2000 m.

boundary surrounding the plateau, by averaging the wind aloft data of ten stations along it. Although this agrees rather well with WHITE's result, RUBIN further mentioned that the meridional wind component is different in each station and that throughout the troposphere the outflow prevails over the eastern flank of the plateau and the inflow over the western one.

The meridional component of wind aloft in June over the East Antarctic coastal stations, which RUBIN used in his paper, is shown in Fig. 4, together with the data of Syowa Station (JAPAN METEOROLOGICAL AGENCY, 1976). The vertical wind profile in Fig. 4 can be classified into four types.

1) Inflow throughout the troposphere; Mawson.
2) Outflow throughout the troposphere; Norway Station, Belgium Station, Mirny.
3) Inflow in the lower troposphere and outflow in the upper one; Syowa.
4) Outflow in the lower troposphere and inflow in the upper one; Dumont d'Urville

The simple meridional circulation model mentioned in Section 1 is supported by the fact that the outflow in the lower troposphere prevails over every station except Syowa and possibly Mawson, but is not supported by the prevailing outflow in the upper troposphere except over Dumont D'Urville and Mawson. It is suggested that the actual

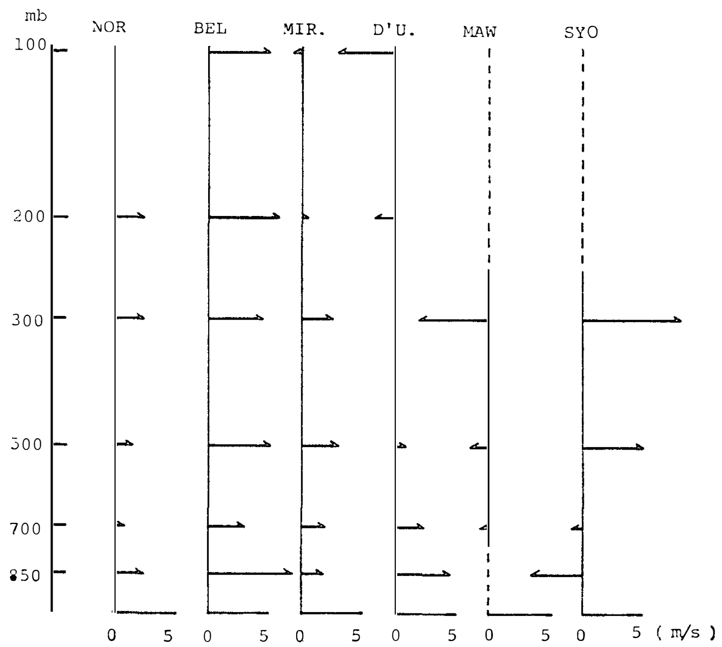

Fig 4 Mean meridional wind over the East Antarctic coastal stations for June 1958 except Syowa Station (JAPAN METEOROLOGICAL AGENCY, 1976) Positive sign shows outflow from the continent Negative shows inflow. For the location of each station see Fig 3

meridional circulation over the coastal region varies with locality.

The wind aloft over Mirny, which RUBIN has investigated, is outflow from the continent throughout the troposphere in June, but it veers to inflow in July. According to RUBIN this is explained by the shift of the trough axis. If we consider the role of standing eddies in the meridional circulation over East Antarctica, as RUBIN suggested, the wind data at Syowa Station are suitable for the analysis. Since, in East Antarctica, deviation from the zonal flow is eminent over Syowa Station as shown in Fig. 1, the relation between the variations of the meridional circulation and the axis of a trough or a ridge can be examined appropriately. The result of LETTAU (1969), in which upper outflow and lower inflow and *vice versa* in the layer from surface to 350 mb over the periphery of his idealized continent do not present except 0°–90° sector, may associate with this.

3. Meridional Circulation over Syowa Station

The mean monthly meridional wind component during the coldest four months from June to September is calculated from the data of 1976 (JAPAN METEOROLOGICAL AGENCY, 1976) and shown in Fig. 5. Outflow and inflow take place above and below the 700 mb level except for August. This is rather different with the analysis of 1972 (INOUE *et al.*, 1978), namely, not only the monthly time lag is found in two results but

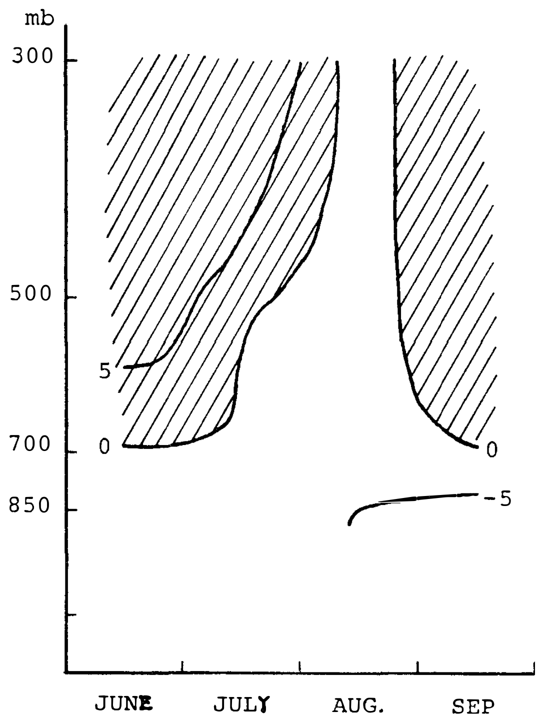

Fig 5. Mean meridional wind over Syowa Station from June to September, 1976 Unit is m/s Southerlies are shaded

the domain and intensity of outflow are larger in 1976. This can be interpreted as a result of year-to-year variations of the axis location, depth or stationariness of the trough as suggested by RUBIN.

The frequency distribution of wind direction on the 500 mb surface in 1976 is shown in Fig. 6 to examine the relation between the variation of the meridional wind and that of the zonal one. The dominant concentration is found in the west or southwest and smaller in the northeast in mean winter wind rose. The monthly wind rose from June to September is also shown in Fig. 7. The dominant wind direction is west or southwest in June, and east or northeast in July. The same concentration in both directions is found in August, thence the dominance in the southwest reappears in September. The veer of wind direction from July to August on the 500 mb surface as shown in Fig. 5 is explained by the increase of the NE wind frequencies in these months. It is noteworthy that the frequency concentration of SW wind in June and September suggests the location of a standing trough in the east of Syowa Station and that the increase of NE wind in July and August suggests the occurrence of blocking high in westerly wave in the east of Syowa.

The mean wind speed with direction distinction is also shown in Figs. 6 and 7. The maximum wind speed is seen in the sections of 0°–30° and 180°–210°, which veers counterclockwise from wind direction frequency peaks in Fig. 6. Wind speed peak in the northern section is seen in every month, which is invariant with around 10 m/s, while that of the southern section decreases fairly in August. The latter results in the mean meridional wind veer to the north in August as shown in Fig. 5. The violent southerly wind in June, July and September, which is around 20 m/s, contributes to the strong outflow from the continent in the upper troposphere over Syowa Station. The

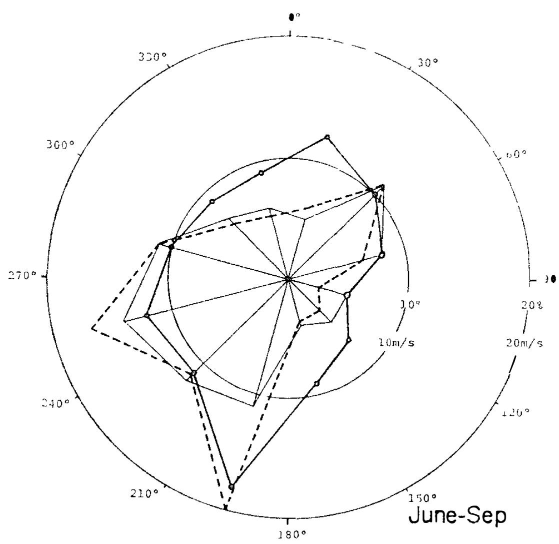

Fig 6 The frequency distribution of wind direction (solid line linking the radial solid line from the center), wind speed (solid line linking the black circle) with direction distinction of 30° interval on the 500 mb surface over Syowa Station for June to September 1976 The scale of inner circle shows 10% and 10 m/s Outer circle 20% and 20 m/s For the broken line see text

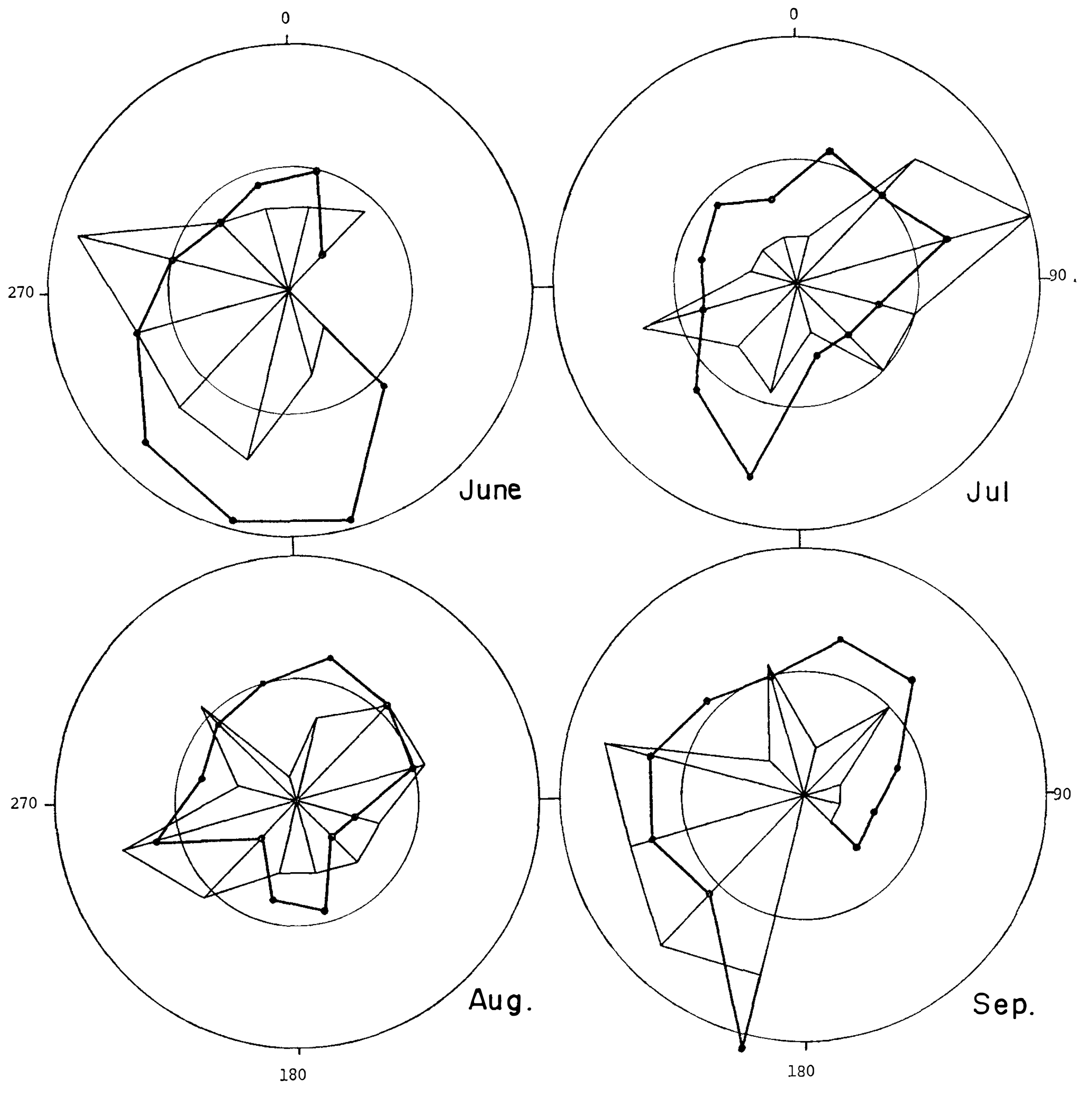

Fig. 7 Same as Fig. 6 except for June, July, August and September.

mean wind multiplied by frequency in each direction distinction is also shown by a broken line in Fig. 6. This value, though the scale is not expressed in Fig. 6, is considered to represent the magnitude of air mass exchange. Southerly, westerly and in smaller value northeasterly winds are dominant. It can be inferred that the active air mass exchange is caused by southerly and northeasterly winds as well as westerly wind. This result leads to the hypothesis that the transient eddies are as well important as the standing ones for air mass exchange.

The time change of wind speed and direction shall be reported in the following section to examine the role of the transient eddies.

4. The Variations of Wind Aloft over Syowa Station

The daily variations of wind speed and direction in June, which is considered to be the most representative month of the disagreement of the peaks between the maximum speed and the direction frequency of wind thence it can be appropriate to examine the contribution of transient eddies, are shown in Fig. 8. The wind direction and speed are correlated reversely well with the ten-odd days periodicity. In other words, the northerly wind is weak, while the southerly wind is strong. This results that the peak of maximum wind speed accompanied by a violent air mass exchange occurs in the southerly wind as shown in Fig. 6.

Daily variations of the 500 mb height and the mean sea level pressure are also shown in Fig. 8. The very good correlation obviously found between these two values suggests that the surface low or high has a large vertical structure. The relation between wind and pressure is not clear, but roughly it can be said that strong and weak winds correspond to low and high pressures respectively

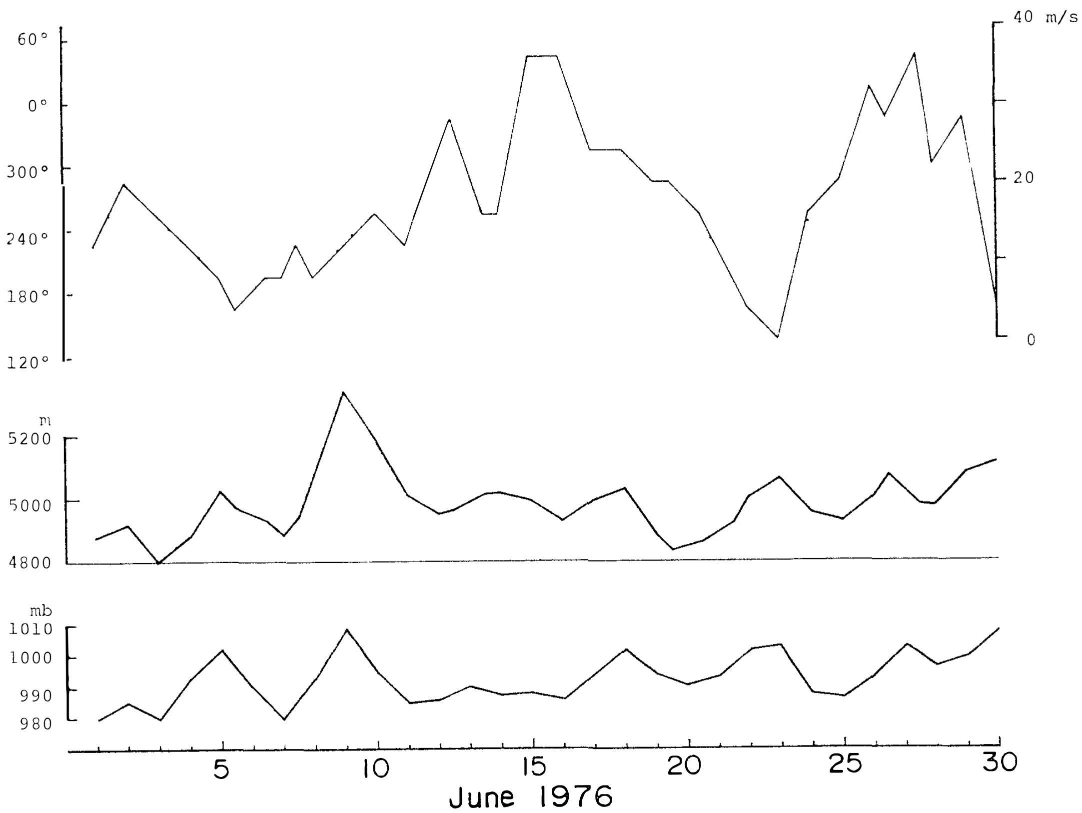

Fig 8 Above Wind direction (solid line) shown by the scale on the left side and wind speed (dotted line) shown by the scale on the right side on the 500 mb surface over Syowa in June 1976 Middle Height of 500 mb surface Below Sea level pressure

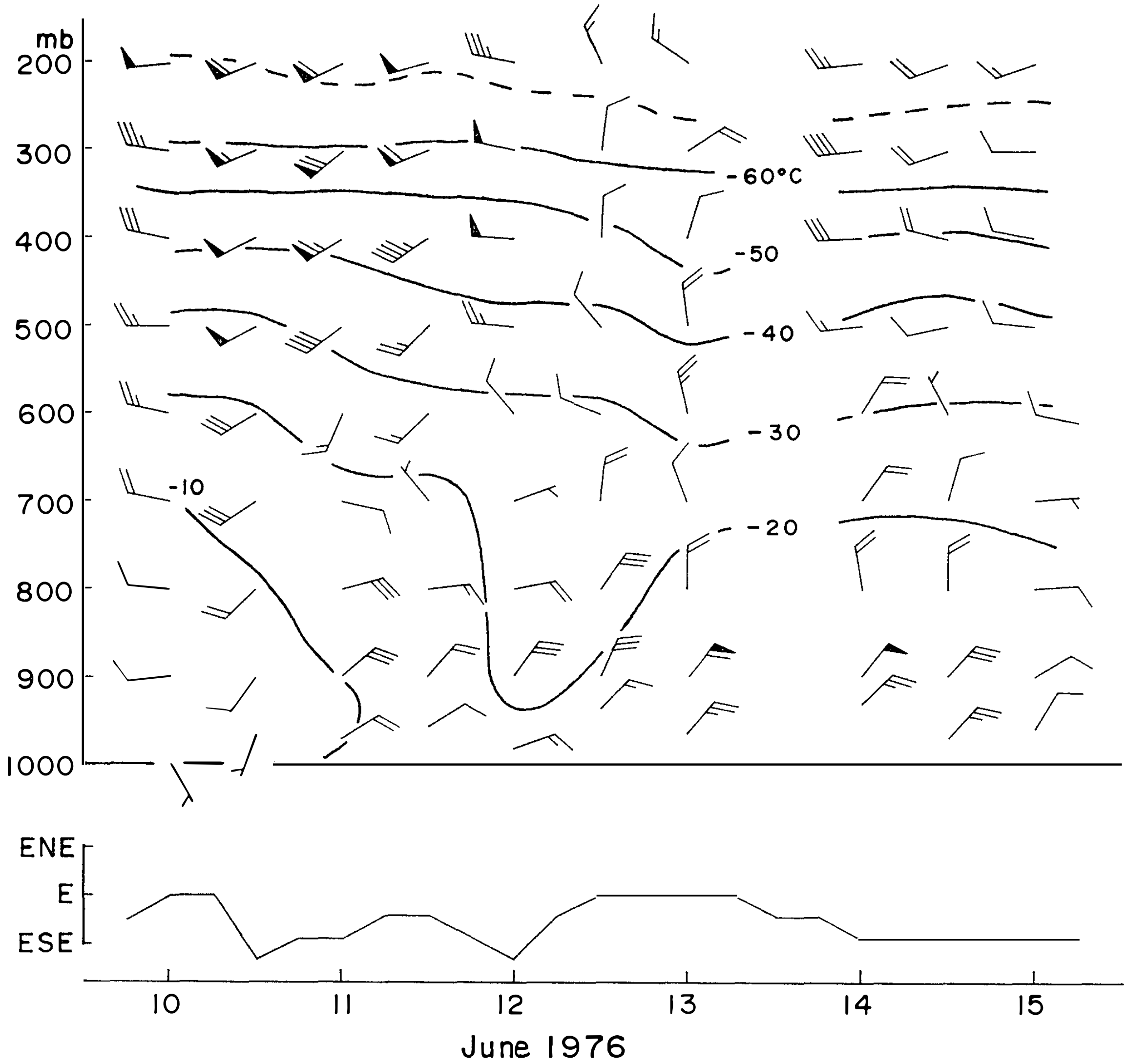

Fig 9. Above: Time section of wind and temperature aloft over Syowa from June 10th 00Z to 15th 00Z, 1976. The broken line shows tropopause. Below. Surface wind direction at Mizuho Station during the same period

To examine the vertical profile of meridional wind, the time section of wind aloft from the 10th to the 15th June, during which the northerly and the southerly winds alternated frequently, is shown in Fig. 9. Westerly flow prevailed throughout the troposphere on the 10th, then it veered to easterly and the speed increased in the lower troposphere from the 11th eminently below the 800 mb level. Upper winds also veered clockwise from the 12th to the 13th, then the northerly wind prevailed throughout the troposphere. Upper westerlies were made up again on the 14th, but the violence of lower northerlies did not abate until the 14th.

Air temperature, shown in Fig. 9, begins to decrease gradually from the lower troposphere on the 10th and abruptly on the 12th. In the upper levels the lowest temperatures appeared on the 13th

The surface wind direction at Mizuho Station (Nishio and Kawaguchi, 1977), which is located at 2230 m a s.l. and 250 km inland from Syowa, is also shown in Fig. 9 It is said that ESE is the direction of cold katabatic wind and ENE wind is under the influence of a synoptic scale disturbance at Mizuho (Inoue *et al*, 1978). The cold katabatic wind prevailing from the 10th to the 12th at Mizuho can be assumed to have prevailed over the plateau Although the typical katabatic wind never occurs at Syowa, it is more likely to exist on the Prince Olav Coast which runs NE from Syowa (Morita and Murakoshi, 1960) The cold air mass outflowing from the plateau to the coast may have been transported by offshore northeasterly and caused the abrupt temperature drop in the lower troposphere over Syowa

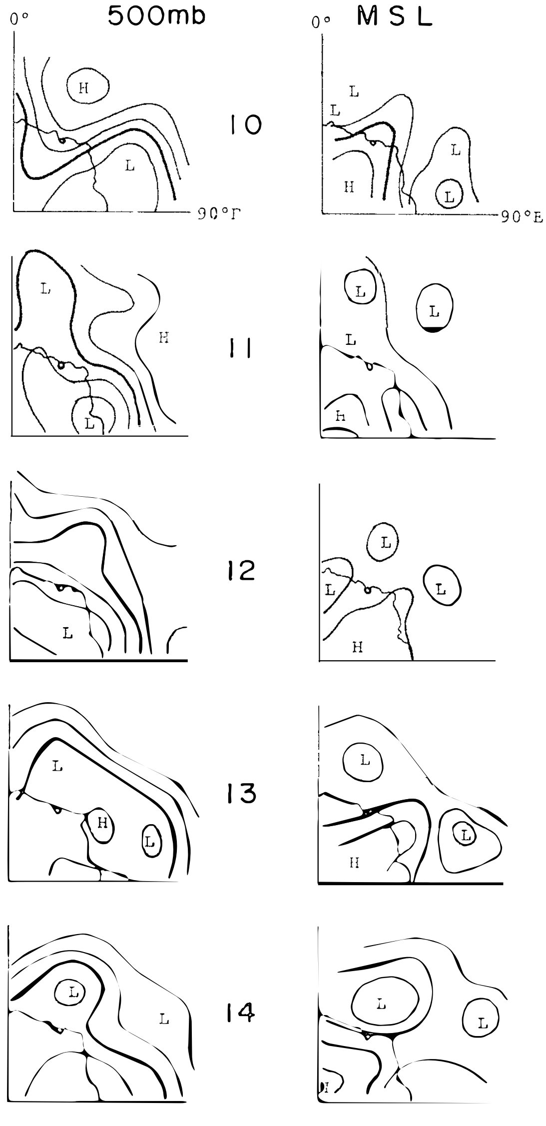

Fig. 10 Daily weather map at 00Z from 10th to 14th June, 1976. Left 500 mb. Right: Mean sea level of 0°–90° sector over Antarctica Bold solid line shows 5040 m and 1000 mb respectively. Location of Syowa Station is shown by open circle in each map

The 500 mb and mean sea level charts from the 10th to the 14th (BUREAU OF METEOROLOGY, AUSTRALIA, 1976) are reproduced in Fig. 10 to examine the above-mentioned matter. The alternative variation of upper level wind between west and southwest from the 10th to the 12th is due to the northeast-ward movement of the ridge which was located over Syowa on the 10th and the subsequent approach of a trough from west. This is replaced by a rather peculiar flow pattern on the 13th. Namely, the anticyclone was formed over east of Syowa on the 13th and it developed into a ridge afterwards. This caused the veer of the upper level wind to the northerly breeze. As already seen in Fig. 8, sea level depression and high correspond well to the upper trough and the ridge respectively. The offshore cyclogenesis and anticyclogenesis at sea level correspond to the upper depression and the ridge on the 13th. The increase of wind speed from the 11th to the 14th is supposed to be caused by the offshore cyclogenesis over northwest of Syowa. Another cyclogenesis over northeast of Syowa caused the anticyclogenesis over east of Syowa. The meridionally developed ridge or blocking high is tend to be formed near Syowa, because not only depressions which have the circular trajectory along the coastal line take up or fill up but those which have meridional tracks also converge there (ASTAPENKO, 1959). The surge of cold air mass over the continent towards the deepening cyclone is inferred from the temperature drop as mentioned above. However, since the contours of isobars are not exactly drawn over the plateau due to its elevation and lack of data, it is difficult to mention a favorable pattern for such a cold air surging.

The vertical wind profiles in Fig. 9 show various patterns. They can be classified into four groups same as previously mentioned in Section 2 by the vertical distribution of the meridional wind component;

1. Northerly throughout the troposphere (*e.g.* 12Z12th)
2. Southerly throughout the troposphere (*e.g.* 12Z10th)
3. Southerly in the upper troposphere and northely in the lower one (*e.g.* 00Z11th)
4. Northerly in the upper troposphere and southerly in the lower one

or into the following four patterns by the vertical profile of scalar wind below 500 mb;

A. Decrease towards lower level (*e. g.* 12Z10th),
B. Maximum value around 900 mb (*e. g.* 00Z12th),
C. Maximum value around 6–700 mb,
D. Generally weak wind, no significant profile.

4, C and D are not shown in Fig. 9. The wind profiles from June to September, 1976 are classified by the above-mentioned categories and tabulated in Table 1.

As for the meridional wind component, 1 and 3 are predominant. Namely, northerly wind throughout the troposphere reaches 45 percent of the total cases and, as for the lower troposphere alone, nearly 80 percent are occupied by northerly. Such an

Table 1. Classification of vertical profiles of wind aloft over Syowa during the winter of 1976; A–D based on the meridional wind component, and 1–4 on the scalar wind speed For details see text.

	A	B	C	D	Total
1	3	31	7	9	50 (45%)
2	12	1	4	3	20 (18%)
3	5	20	4	8	37 (33%)
4	2	1	0	2	5 (4%)
Total	22 (20%)	53 (47%)	15 (13%)	22 (20%)	112

overwhelming predominance of northerly in the lower troposphere is well reflected in Fig. 5. On the other hand, upper northerly, also occupying nearly half of the cases (49%), is less reflected due to its weakness as mentioned in Fig. 8. As for the scalar wind profile, nearly 50 percent of the cases are occupied by case B. In the lower troposphere alone, 96 percent are northerly (1 and 3) for this case. This is rather an abnormal concentration considering the month-to-month change of atmospheric circulation. The topography of Antarctic periphery near Syowa, *i. e.* NE–SW running steep coastal line, may affect the occurrence of maximum wind near 900 mb in the case of northerly wind. The southerly does not produce such a peculiar concentration of the scalar wind profile

5. Conclusions

The meridional air mass exchange over East Antarctica is expected to approach the idealized model mentioned in Section 1. However, the actual meridional wind over the coastal station in East Antarctica in June 1958 does not resemble such a flow model. Moreover, the mean meridional wind pattern varies with the station locality, month and year, too. The analysis over Syowa Station during the polar night in 1976 shows the flow pattern reverse to this model. Inflow to the continent prevails below 700 mb. Outflow and infow are almost equal above it, but netflow is outwards from the continent except in August due to the increased intensity of outflow.

The dominant direction of SW–W winds on the 500 mb surface is due to the favorably located upper trough. The secondary peak of NE wind is caused by the transient ridge formed east of the station However, the dominant wind speed of southerly suggests that the active air mass exchange occurs when a trough or a ridge developed. Namely, the role of both standing and transient eddies is important for air mass exchange Although this is concluded through the analysis of wind aloft data over Syowa, a different type of circulation is expected over another station where a trough or a ridge behaves differently. The role of a trough or a ridge can be very important in the air mass exchange between the Antarctic coast and the offshore area regardless of time and place.

The northerly and southerly frequencies in the upper troposphere are almost same, but 90 percent are northerly in the lower one. The prevailing easterly in the lower level may be distorted along the coastal line (MORITA and MURAKOSHI, 1960). This northeasterly having a maximum value around 900 mb with extreme concentration is also inferred to be affected by topography.

The knowledge is deficient on the air mass exchange between the plateau and the coast, which is the basis of the idea concerning the moisture transportation to inland. It is said that mass flow over inland station is regarded substantially to be the same as the extension from the coastal value (LETTAU, 1969). However, the data of 0°–90° section are still scarce. The regional investigation of the atmospheric structure between coast and plateau is highly desired.

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