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Intraseasonal Variability of Katabatic Wind Over East Antarctica and Planetary Flow Regime in the Southern Hemisphere

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The Intraseasonal variation (30- to 50-day period) of katabatic wind has been found at Mizuho plateau, East Antarctica, as a predominant mode of the subseasonal time scale variability. The atmospheric circulation in the southern middle and polar latitudes associated with this fluctuation of katabatic wind has been deduced by using the NMC gridded 500-mbar zonal wind and geopotential height field. The axisymmetric circulation pattern to Antarctica is noticeable in the anomalous zonal wind and height field. That is, the strong (weak) katabatic wind phase corresponds to the shallower and broadened (deepened and narrowed) tropospheric circumpolar vortex with weaker (stronger) westerlies over the surrounding oceans. These results strongly suggest that the intraseasonal variation of katabatic wind regime over East Antarctica is part of the modulation of planetary flow regime and meridional circulation in the southern middle and high latitudes, i.e., part of the index cycle of the southern hemisphere.

1. INTRODUCTION

The katabatic wind regime over Antarctica has been manifested as a huge drainage flow along the slope surface of the ice sheet, maintained primarily by negative buoyancy of the air near the surface, which is induced by strong radiational cooling at and near the ice sheet surface. A characteristic nature of this wind regime noted by many observations is its steadiness throughout the year [e.g., *Schwerdtfeger*, 1984], particularly in winter. The model studies by *Ball* [1960], *Parish* [1984], and others have established the theories of steady katabatic wind as a sloped boundary layer wind regime, where the Coriolis and frictional forces are balanced with the buoyancy force.

The recent model-based studies [*Egger*, 1985; *Parish and Bromwich*, 1991] have suggested that the katabatic wind regime should be part of the large-scale tropospheric meridional circulation over and around Antarctica. *Parish and Bromwich* [1991], for example, showed in a mesoscale model with the realistic orography of Antarctica that the circumpolar vortex in the upper troposphere develops rapidly in response to the cooling of the ice slopes and development of the katabatic wind regime. However, *Egger* [1985] and *James* [1987] also pointed out that the circumpolar vortex induced by the katabatic flow regime near the surface counteracts the katabatic flow and even destroyed it through the intensified pressure gradient force of the upper level. *Egger* [1992] further found the two steady state solutions of the circulation regime, one where a realistic circulation prevails under the substantial momentum transport by the circumpolar westerly waves and another one with strong upper level polar vortex but no surface easterlies (i.e., katabatic wind).

On the other hand, recent observational studies have presented ample evidences of large variance of intraseasonal (20- to 60-day period) time scale in the planetary scale circulation regime in the middle and polar latitudes of the southern hemisphere [e.g., *Graham*, 1989; *Mo and Ghil*, 1989; *Shiotani*, 1990; *Kidson*, 1991]. *Shiotani* [1990], for example, showed a dominant mode of the north-south oscillation of zonal mean circulation in the middle through the polar latitudes with the intraseasonal (30- to 40-day period) time scale. *Kidson* [1991] deduced some dominant teleconnection patterns in the time-filtered 500-mbar height field, which include the wave train patterns of wavenumber 3 or 4 and the zonally symmetric pattern involving the intensity change of the circumpolar vortex.

These theoretical and observational studies have urged us to investigate the observed temporal variability of the katabatic wind and its association with the planetary scale circulation in the southern hemisphere. This paper will address this issue particularly relevant to the intraseasonal variability, by analyzing the time series of the katabatic wind over East Antarctica and the hemispheric gridded wind and pressure field data.

2. DATA

The wind and temperature data obtained at the 30-m level of the meteorological tower of the Mizuho Station (70°42′S, 44°20′E, 2230 m above sea level (asl), which is located at the slope of East Antarctica under the typical cold katabatic climate zone [*Dalrymple*, 1966], were used as a measure of the katabatic wind. The general feature of katabatic wind over this region is described by *Inoue et al.* [1983]. The data of about 2 years from February 23, 1979, to January 7, 1981, were used, which were obtained as part of the Polar Meteorology Experiment in the south polar region (POLEX-South), Japan. The data obtained originally for every 1 min were edited to the daily mean values for the present analysis. The radiosonde observations made once or twice a week at the Mizuho Station [*Kawaguchi et al.*, 1985] were also used additionally to examine the wind and temperature profile. The National Meteorological Center (NMC) global analysis data in 5° × 5° latitude/longitude grids at 0000 GMT were adopted for the analysis of the hemispheric circulation field.

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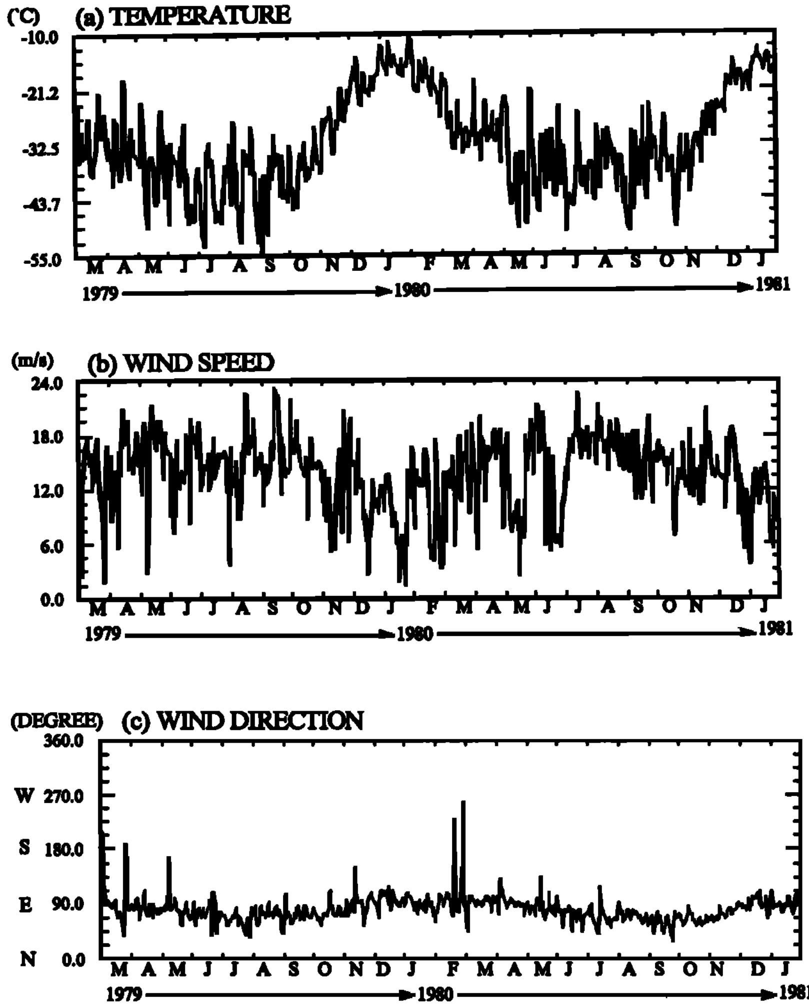

Fig. 1. Daily time series of (*a*) temperature, (*b*) wind speed, and (*c*) wind direction at Mizuho Station, East Antarctica, during the period from March 1, 1979, to January 31, 1981.

3. Spectra and Cospectra of Wind and Temperature at Mizuho Station

Figure 1 shows the time series of daily mean wind speed, temperature, and wind direction for the analysis period of 684 days (from February 23, 1979, to January 7, 1981). The wind speed shows the steadiness through the period with the mean speed of about 15 m s^{-1}, but a weak seasonal cycle is also apparent with the minima in midsummer (January). The wind direction shows the strong steadiness through the year with the direction of around 90° (i.e., from the east), indicating the characteristic of the katabatic wind at the slope of the ice sheet. The temperature shows, by contrast, a large seasonal cycle with the coreless winter [*van Loon*, 1967]. In addition, both the wind speed and the temperature series show shorter time scale fluctuation with a few days to 1- or 2-month periods.

Spectral analysis of the maximum entropy method (MEM) was applied to these time series of wind speed and air temperature to see more quantitatively the dominant periodicities. The annual cycles (represented by the 1-year plus half-year harmonics) were subtracted from the original series before applying the spectral analysis. Figure 2 shows the power spectra of wind speed and temperature. A remarkable feature that appeared commonly in the two diagrams is a predominant peak in the intraseasonal time scale within a 30- to 60-day period, though the maximum power of the two series appears in a slightly different period range from each other, i.e., the 30- to 40-day period in the wind speed but 50- to 60-day period in the temperature. There seems to be another peak of about a 10-day period in the temperature, but no corresponding peak is apparent in the wind speed.

Figure 3 shows the two components of the cross spectra between wind speed and temperature. The cospectrum (Figure 3*a*) shows one isolated positive peak at 30- to 40-day period, implying the existence of the in-phase component of the wind-temperature fluctuation of this period range. The quadrature spectrum (Figure 3*b*) shows a predominant positive peak at 40- to 50-day period, which implies that a quarter-cycle phase difference between the temperature and the wind speed is prominent in this period range.

To examine the seasonal and interannual modulation of intraseasonal variability, time series of wind speed and temperature were filtered for the 30- to 60-day period range. The butterworth filter [*Murakami*, 1979] was adopted to deduce the filtered series with the maximum response of 40-day period and a half-time response of the 30-day and 60-day period, respectively. The series of wind speed clearly shows a predominancy of this time scale through most of the analysis period but with relatively small amplitudes in spring (September and October). The series of temperature shows a significant seasonal modulation, i.e., large amplitudes in winter half years (March to September) but small amplitudes in summer half years. It seems not easy to deduce a simple phase relation between the temperature and the wind speed series, but nearly in-phase relation is apparent through most of the analysis period except March through July 1979. This result suggests that the variation of temperature of this period range is generally related to the large-scale features of the Antarctic circulation, rather than to the local or regional effect (e.g., downslope advection) of the katabatic wind, in which the wind speed is expected to be negatively correlated to the temperature anomaly. This feature will further be discussed later.

4. VERTICAL STRUCTURES OF WIND AND TEMPERATURE FIELD OF THE INTRASEASONAL TIME SCALE

By utilizing the filtered time series of wind speed (Figure 4), we identified the strong (and weak) katabatic wind phases for the intraseasonal time scale, irrespective of the seasons. The radiosonde data at Mizuho Station are, then, categorized to the strong, weak, or moderate phases. Unfortunately, as the number of radiosonde observations (about 60 times during the analysis period of the 2 years) were not sufficient for producing the composite wind and temperature profiles; typical examples for the strong and weak katabatic wind phase specified from Figure 4 is shown here. Figure 5 shows an example of the temperature and wind field profile for the strong phase (April 7, 1980) and the weak phase (April 28, 1980). In the strong case the temperature is generally high compared to the weak phase, except the near-surface layer, where strong surface inversion exists. The strong wind layer (i.e., the katabatic wind layer) in the strong phase has a depth of about 400–500 m with a maximum at 200 m above the surface (about 2200 m asl), but the wind is very weak (around 5 m s^{-1}) above 800 m from the surface. The wind direction is concentrated to NE (45°) to E (90°) in the katabatic wind layer and around E (90°) in the upper layer up to 5000 m asl. In the weak phase, by contrast, no (strong) katabatic wind layer is seen in the lower layer, and the wind speed increases with height up to about 3500 m with nearly the constant direction from W (270°). These contrastive features between the strong and the weak wind phase are more or less common in other strong and weak wind cases, which roughly correspond to the maximum and the minimum wind speed phases shown in Figure 4. That is, in the strong wind phase, the katabatic wind layer with a depth of 200–400 m is prominent with persistent easterly wind of more than 10 m s^{-1}. In the middle troposphere, the weak northeasterly wind prevails. In the weak wind phase, the westerly wind prevails throughout the troposphere with increasing wind speed with height. The temperature profile shows systematic higher values in the strong phase than in

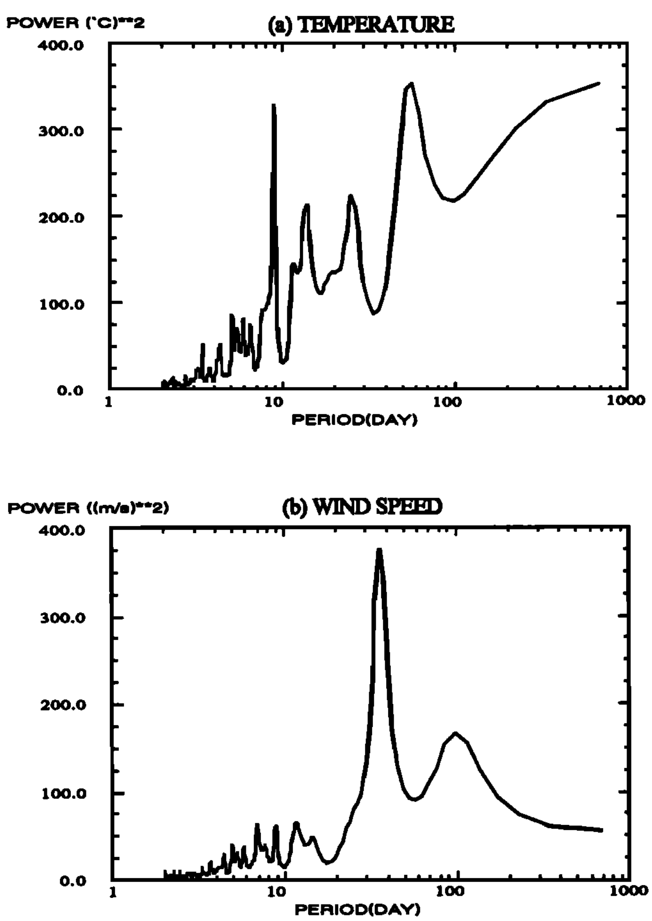

Fig. 2. Power spectra of (*a*) temperature and (*b*) wind speed at Mizuho Station for the series shown in Figure 1. The seasonal cycle is prefiltered.

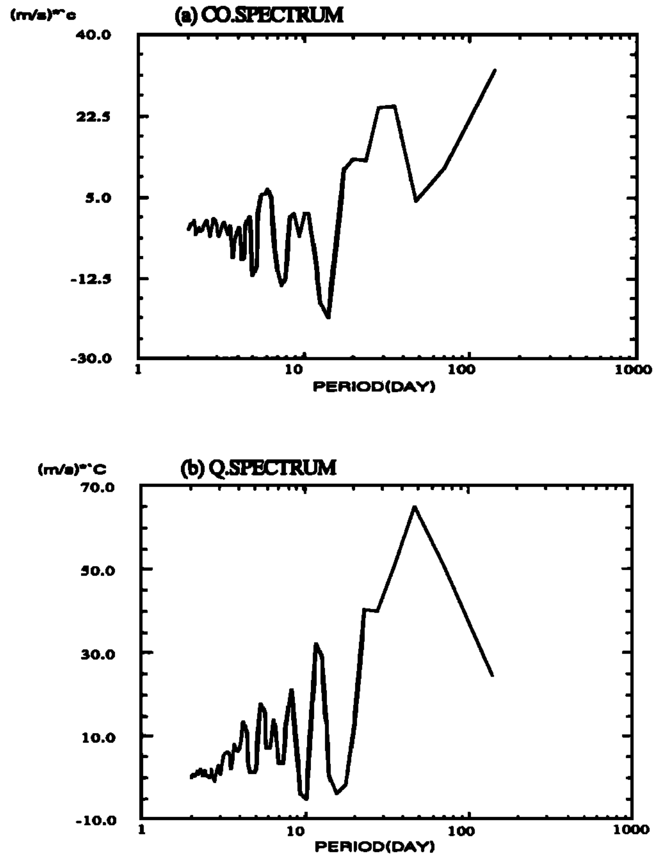

Fig. 3. Two components of cross spectra between temperature and wind speed at Mizuho Station. (*a*) Cospectrum and (*b*) quadrature spectrum.

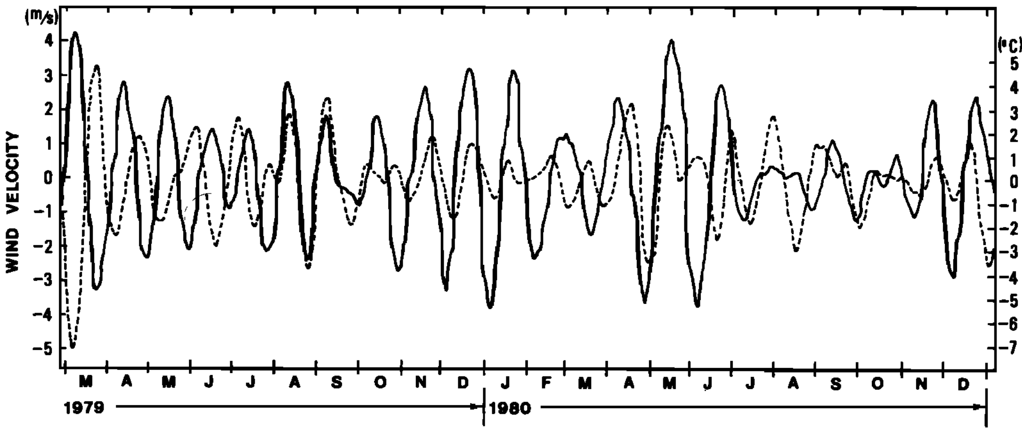

Fig. 4. Band-pass filtered time series (with period band of 30 to 60 days) of wind speed (solid curve) and temperature (dashed curve) at Mizuho Station.

the weak phase, though there seems to be no significant difference of the relative profile or lapse rate pattern. In some cases the inversion near the surface is stronger in the strong phase than in the weak phase (e.g., Figure 5), because of stronger advection of colder air from the interior of the Antarctic plateau. In this case the negative correlation, rather than the positive correlation, between the wind speed and the temperature becomes apparent, e.g., in March through July 1979. Thus the relation between the wind speed and the temperature is variable depending upon the strength of the downslope advection, though the large-scale effect seems to be dominant, as shown in Figure 4. The association of the vertical profiles over Mizuho Station with the hemispheric flow regime in the southern polar latitudes will be discussed later.

5. Composites of Planetary Flow Regime

To deduce the association between the katabatic wind variability and the planetary flow regime, the hemispheric geopotential and wind field are composited in reference to the strong and weak phases of katabatic wind shown in Figure 4. Before making composites, we produced the filtered geopotential and wind field by operating the same filter as adopted for the Mizuho Station to the original grid point data. Figure 6 shows the composite geopotential anomaly field at 500 mbar for (Figure 6*a*) strong and (Figure 6*b*) weak phases, which approximately shows a zonally symmetric structure of the anomaly field with positive (negative) anomaly over Antarctica and negative (positive) anomaly over the surrounding oceans during the strong (weak) phase.

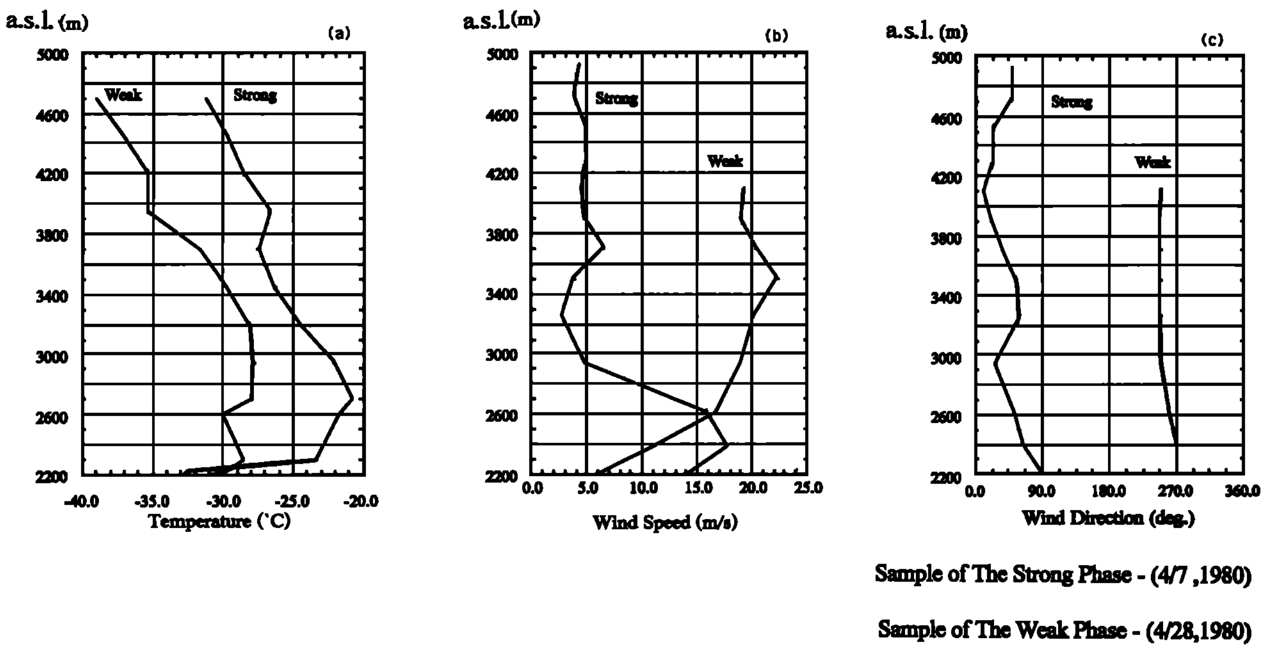

Fig. 5. Vertical structure of (*a*) temperature, (*b*) wind speed, and (*c*) wind direction for a typical case of strong and weak katabatic wind at Mizuho Station (2230 m).

This anomaly pattern implies that the circumpolar vortex is weakened (intensified) and the meridional gradient of geopotential height is slackened (steepened) during the strong (weak) phases. Consistently with this anomaly pattern of geopotential field, the zonal wind anomaly at 500 mbar (Figure 7) becomes easterly (westerly) along the coastal zone of Antarctica (about 50°–60°S) during the strong (weak) phases. Mizuho plateau is located closely at one maximum along East Antarctica in this anomaly zone. The equatorward of this anomaly zone, another zonally oriented zone of zonal wind anomaly with the opposite sign is noted, which suggests the equatorward extent (poleward shrink) of the circumpolar westerlies during the strong (weak) phases.

Figure 8 shows the composite wind vector anomaly at 500 mbar for the strong katabatic wind phase. As has been suggested in Figures 6 and 7, the anomalous anticyclonic circulation is dominated over the circumpolar vortex zone

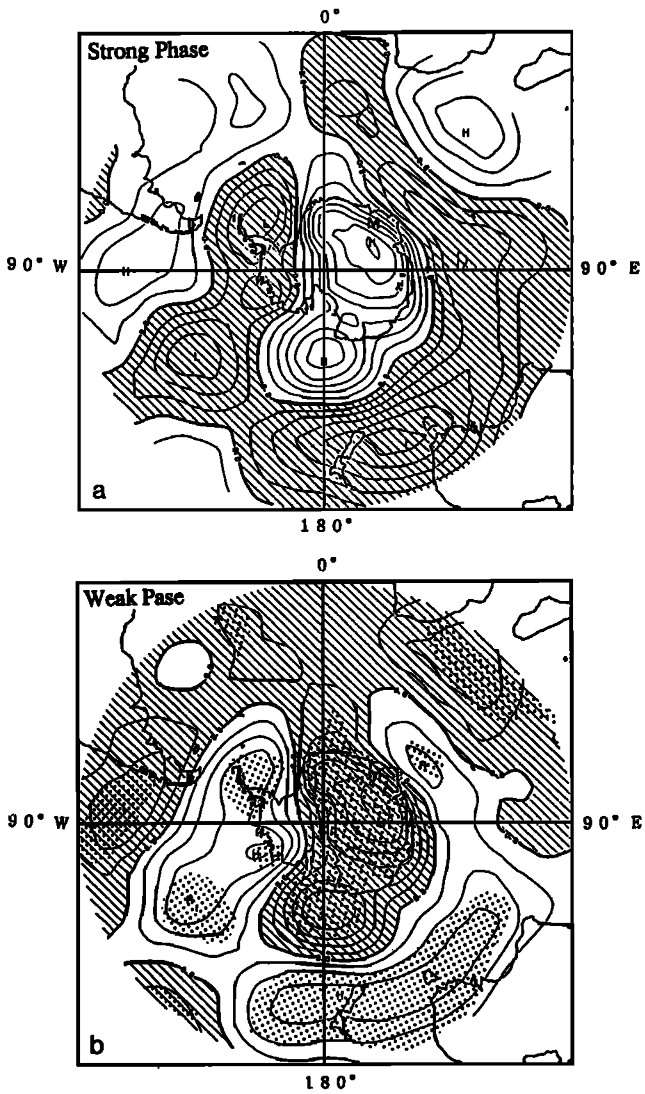

Fig. 6. Anomalous geopotential height field at 500 mbar composited for (*a*) strong katabatic wind and (*b*) weak katabatic wind of the intraseasonal time scale at Mizuho Station. Contours are 5 gpm (m) and negative values are shaded. Areas where the difference of anomalies between the strong and the weak katabatic wind phase shows 5% (or less) significant levels are dotted. The location of Mizuho Station is indicated with "M."

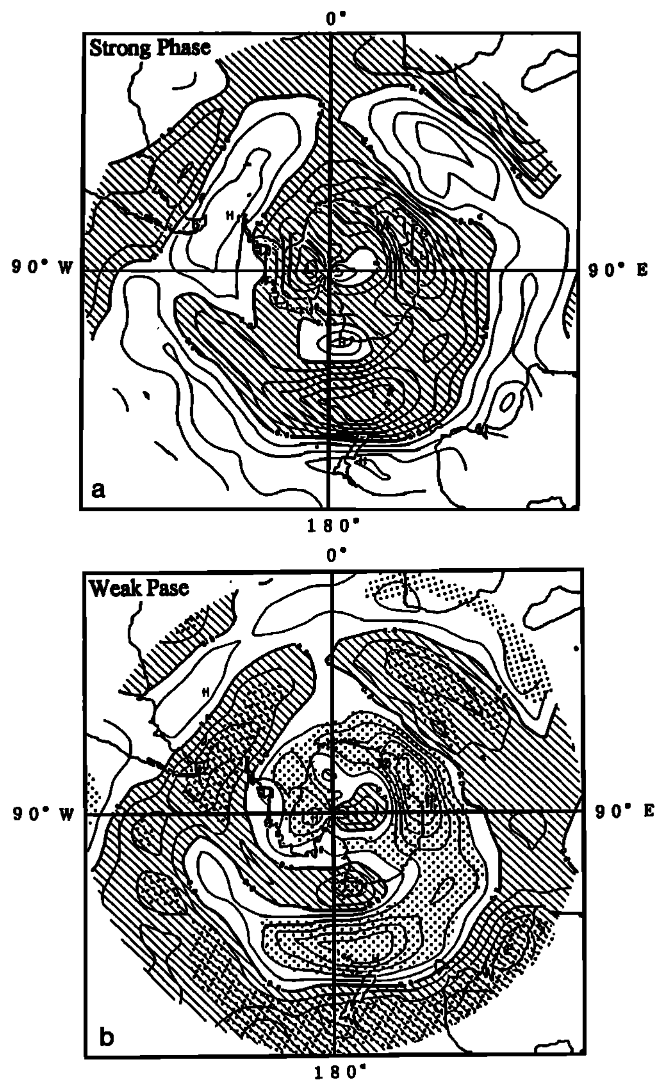

Fig. 7. Same as Figure 6 but for zonal wind. Contours are $0.5\ m\ s^{-1}$.

centered over East Antarctica. It is interesting to note that the center of the anticyclonic circulation corresponds well to the source region of mean katabatic wind regime located over the East Antarctic plateau. Another feature is a more or less zonally oriented zone of westerly anomalies along the mid-latitudes (30°–50°S), though it is less significant than the anticyclonic anomaly zone over Antarctica.

To confirm the change of the real circulation over and around Antarctica associated with the change of katabatic wind regime, the total (i.e., nonfiltered) height field at 500 mbar was composited for the two phases. Figure 9 shows the two meridional sections of 500-mbar height along the longitude lines of 45°W to 135°E and 45°E to 135°W, the latter nearly passes through the Mizuho Station at East Antarctica. During the weak phase the deepened polar vortex and the steeper meridional gradient of geopotential height along the off-coastal zone of Antarctica are apparent, as has been suggested in the anomaly field. During the strong phase, by contrast, the polar vortex is shallowed and broadened to some extent. It is noteworthy to state that locally over East Antarctica the meridional gradient is reversed in sign with a

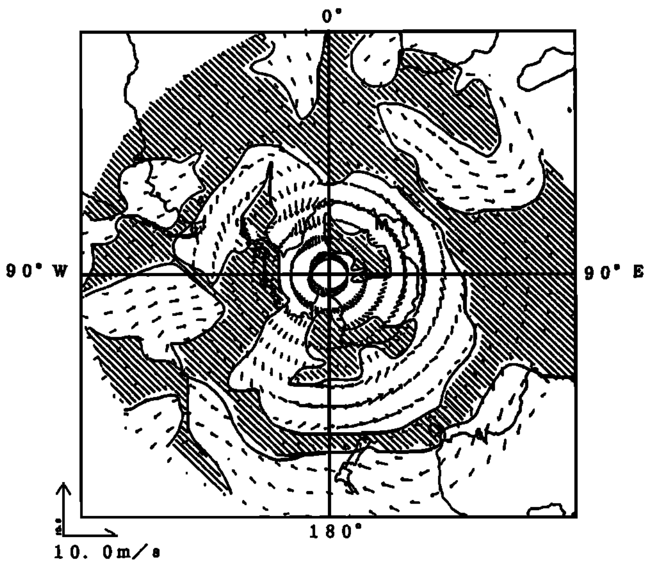

Fig. 8. Difference of wind vector at 500 mbar composited for strong and weak katabatic wind phases. Areas which are not significant (with 5% level) are shaded.

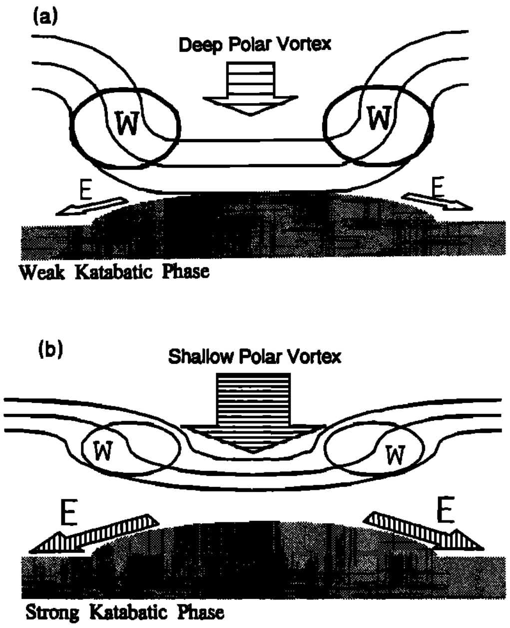

Fig. 10. Schematic diagrams of the upper tropospheric circulation over and around Antarctica for (*a*) weak katabatic wind phase and (*b*) strong katabatic wind phase.

small maximum height immediately over the highest plateau of Antarctica. This feature is particularly remarkable along the line of 45°E to 135°W (Figure 9*b*). This implies that the so-called "polar anticyclone" near the Antarctic surface develops even to the midtroposphere during the strong phase of katabatic wind regime.

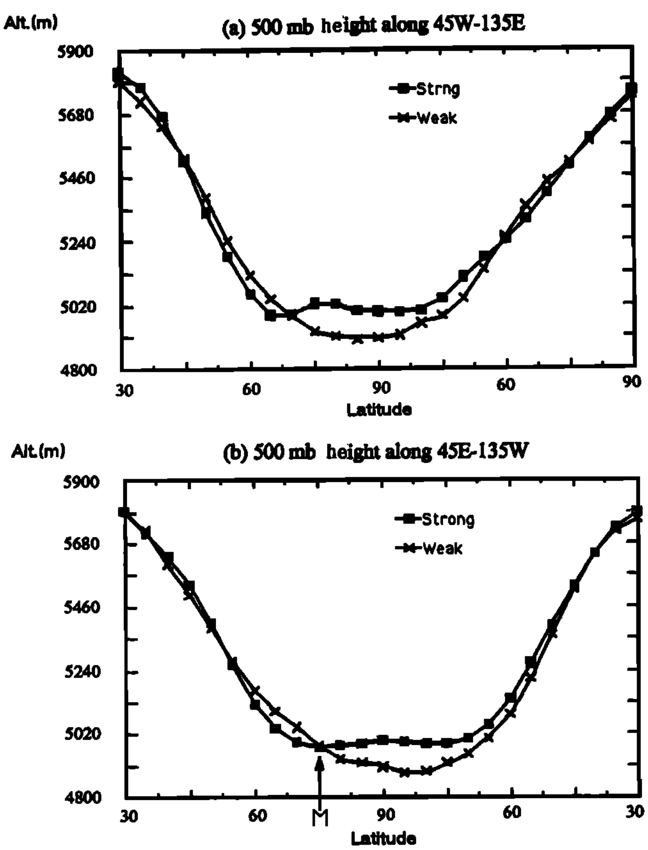

Fig. 9. Cross sections of 500-mbar height composited for strong and weak katabatic wind phase along the longitude line of (*a*) 45°W to 135°E and (*b*) 45°E to 135°W. The latitude of Mizuho Station is indicated with "M" in (*b*).

The results obtained here agree well with the vertical profile of temperature and wind field over Mizuho Station described in section 4 (e.g., Figure 5). That is, the easterly wind over Mizuho Station at 500 mbar in the strong wind phase (Figure 5) is well consistent with the anticyclonic circulation with the geostrophic easterly over East Antarctica, as shown in Figure 8. The relatively high temperature at this level seems to correspond to the relatively weak polar vortex over Antarctica. The equatorward pressure gradient over Antarctica, associated with the formation of the near-surface polar anticyclone centered over the East Antarctic plateau, may be a direct cause for the strong katabatic wind.

The composite hemispheric flow regime associated with the strong (or weak) katabatic wind at Mizuho Station strongly suggests that these anomaly flow regimes should be responsible for the anomalous state of katabatic wind not only over the Mizuho plateau but also over the whole of Antarctica, as shown in the nearly symmetric anomaly flow pattern (e.g., Figures 6 and 7) for the pole, or more exactly, for the Antarctic plateau.

6. Discussion

The intraseasonal variability of katabatic wind over Mizuho Station with about a 40-day period has been revealed to be closely related to the fluctuation of the hemispheric planetary flow regime in the southern polar and middle latitudes. The axisymmetric anomaly circulation patterns deduced from the strong (or weak) katabatic wind phases has led us to conclude that the change of katabatic wind regime over Antarctica with this time scale is directly linked with the change of intensity of the upper tropospheric circumpolar vortex over Antarctica. The relation between the upper tropospheric flow regime and the katabatic wind regime may be schematically summarized in Figure 10. It is clear that the strong (weak) katabatic wind regime is associated with the shallow (deep) polar vortex with weaker (stronger) upper westerlies. The supposed meridional circulation over the polar latitudes may be strong (weak) during the strong (weak) katabatic phase. The warm (cold) anomaly in the temperature field over Mizuho plateau during the strong (weak) katabatic phase may be fundamentally influenced by the intensity of the polar vortex. The role of adiabatic heating due to the downward motion as part of the meridional circulation may be additional, but the cold air advection from the upstreamside of the ice plateau is, in some cases, responsible for the lower temperature anomaly near the surface during the stronger katabatic wind, as pointed out earlier.

The implication of the anomalous flow patterns deduced here associated with the fluctuation of katabatic wind regime seems to be very interesting. The previous theoretical studies [e.g., *Egger*, 1985; *James*, 1986, 1989; *Parish and Bromwich*, 1991] showed that the katabatic wind regime over Antarctica plays an important role in the generation of the circumpolar vortex in the upper troposphere through the generation and transport of the vorticity in the strong easterly wind near the surface. The observational evidence that in the seasonal cycle the katabatic wind regime is strongest during winter when the circumpolar vortex is also strongest [*Schwerdtfeger*, 1984] seems to support this general idea. *James* [1986] estimated that the vorticity generated by the meridional circulation induced by the katabatic wind is comparable to that generated by the temperature gradient between the Antarctic ice cap and the surrounding oceans.

On the other hand, most of these studies also noted that the katabatic wind regime decays quickly due to the opposing meridional pressure gradient force induced by the development of the circumpolar vortex unless the northward transport of cyclonic vorticity is out of the polar domain. Recently, *Egger* [1992] further demonstrated in the axisymmetric model that two types of steady state be possible in the Antarctic meridional circulation, one where strong katabatic wind is coupled with weak upper level westerlies (or even easterlies) and another where weak or no katabatic wind is coupled with strong upper level westerlies and deep circumpolar vortex. He noted that the selection of the state depends on the strength of transport of westerly angular momentum by eddies (i.e., wave and cyclone activity) parameterized at the northern boundary of the model domain.

It is noteworthy to state that the two steady states noted by *Egger* [1992] seem to be comparable quite well to the strong and weak katabatic wind phases in the present analysis with respect to the horizontal and vertical structure of wind, pressure, and temperature field. In fact, the slackened pressure gradient (or broadened and shallowed circumpolar vortex) in the strong katabatic wind phase may correspond with the low-index type circulation over the southern high latitudes (40°–60°S) around Antarctica with intensified planetary wave activity. The deepened circumpolar vortex with stronger upper level westerlies over the surrounding oceans, by contrast, correspond to the high-index type circulation with weakened planetary wave activity. The set of the anomalous 500-mbar height patterns deduced here (Figure 6) really seems to be one (i.e., EOFs 5) of the dominant circulation patterns for the intraseasonal time scale obtained by *Kidson* [1991], who has applied the empirical orthogonal function (EOF) analysis to the filtered 500-mbar height field of 9 years (1980–1988) over the southern hemisphere. The similar pattern is also deduced by *Mo and Ghil* [1989] as the first EOFs with a dominant periodicity of 50 days.

This anomalous pattern should also be compared to the multiple equilibria of zonal mean flow of this time scale noted by *Yoden et al.* [1987] and *Shiotani* [1990]. Though they focused on the zonal mean statistics and their analysis period is different from ours, the meridional structure of zonal mean flow supposed from Figure 7 seems to be very compatible with theirs. That is, the intraseasonal variability of the katabatic wind regime described here is really part of the hemispheric modulation of the general circulation in the southern middle and high latitudes. In a sense the katabatic wind regime interacts with the planetary flow regime around Antarctica, which result in the wax and wane of the circumpolar vortex or the "index cycle" of this time scale in the southern hemisphere westerly flow. The mechanism proposed by *James* [1989] that decaying mid-latitude cyclones induce net flux of cyclonic vorticity out of the circumpolar vortex and maintain the katabatic wind seems to be very compatible with the present result. In the northern hemisphere, in contrast, the vacillation of the planetary waves is an essential mechanism of the index cycle.

One problem may be what determines the time scale of this cycle. Is it an inherent mode of the southern higher latitudes under the dynamic and thermodynamic constraints of Antarctica and the surrounding oceans? Or otherwise, does any external forcing from or interaction with the intraseasonal oscillation in the tropics [Madden and Julian, 1972] play an important role? Though there has been so far little hemispheric scale evidences for the latter case [e.g., *Shiotani*, 1990; *Kidson*, 1991], some regional scale evidences [e.g., *Yasunari*, 1981*a*, *b*] suggest the possibility of the direct interaction between the Antarctic circulation and the tropical or monsoon circulation with this time scale.

7. CONCLUSIONS

The fluctuation of katabatic wind regime with 30- to 50-day period has been noted over Mizuho plateau, East Antarctica, as a predominant mode in the intraseasonal time scale. This mode has been proved to be closely associated with the variability of the hemispheric flow regime of the middle and upper troposphere in the southern middle and polar latitudes. The strong katabatic wind phase corresponds to the weak and shallow upper tropospheric circumpolar vortex with weaker upper westerlies around it. The anticyclone seems to be formed in the near-surface level of the Antarctic ice sheet at this phase. The weak katabatic wind phase, by contrast, corresponds to the deep circumpolar vortex with stronger westerlies. The anomalous circulation pattern at the 500-mbar level associated with this change of katabatic wind regime approximately shows the axisymmetric (i.e., zonal wavenumber zero) structure, suggesting the close relation to the multiple flow equilibria of the southern westerlies [*Yoden et al.*, 1987; *Shiotani*, 1990]. These observational results have been found to be very compatible to the model results by *Egger* [1992] that two steady states of the katabatic wind regime are possible in the axisymmetric flow over and around Antarctica under the condition of momentum transport by eddies at the northern boundary.

Further observational as well as theoretical studies have to be made for understanding the role of this variability in the katabatic wind regime on the general circulation of the southern hemispheres.

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