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PRELIMINARY ANALYSIS OF TEMPERATURE CHANGES DUE TO SYNOPTIC SCALE DISTURBANCES AT SYOWA STATION, ANTARCTICA IN WINTER

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Abstract: The Antarctic surface air temperature often increases severely in winter when a synoptic scale disturbance comes close and then decreases after it goes away. The mechanism of these temperature changes is analyzed from the data observed at Syowa Station, Antarctica in 1993 by the 34th Japanese Antarctic Research Expedition (JARE-34). For this purpose, fifteen cases each are selected for both the prominent warming and the succeeding cooling events in winter.

The magnitude of changes in temperature due to destruction or reformation of the surface temperature inversion during the events is estimated from comparison of the vertical temperature profiles above Syowa Station before and after each event. Its contribution amounts to about half of the observed change in the surface temperature.

The horizontal advection of sensible heat is calculated from the thermal wind shear relation. It is shown that the horizontal advection of warm and cold air are observed in the warming and the cooling events, respectively. It is estimated from the average heat budget that there should be an upward current of 0.2 to 0.8 cms^{-1} during the warming events and a downward current of less than 0.4 cms^{-1} during the cooling events in the 850 to 300 hPa layer.

1. Introduction

The Antarctic air temperature on the surface fluctuates greatly in winter. It often increases more than 20°C in only a few days. These temperature changes have been reported as the effect of synoptic scale disturbances by several previous studies. NAKAJIMA *et al.* (1981) detected that the common period of 15 days was predominant in the surface temperature variation at Syowa Station and in the surface wind speed variation at both Syowa and Mizuho Stations from the spectrum analysis and noted that these periodicities correspond to those of the predominant synoptic scale disturbances. ISHIKAWA and KOBAYASHI (1983) indicated a significant negative correlation between the surface temperature at Mizuho Station and the surface pressure at Syowa Station resulting from synoptic scale disturbances. KIKUCHI *et al.* (1988) noted that the sudden warming and the gradual cooling in winter at the Advance Camp in the interior region, East Antarctica correlated to the cloud amount at Mizuho Station. ENOMOTO *et al.* (1995) found that temperature fluctuations with 5-day and 10-day scales were in-phase between the dome and the coastal regions and also in-phase with the pressure fluctuations at Syowa Station. KAWAGUCHI *et al.* (1982) investigated the surface temperature inversion at Mizuho Station and indicated that the passage of a synoptic scale disturbance destroyed the inversion and caused an increase of the surface temperature. They also found that the destruction was caused not merely by the strong wind but by frontal passage, that is, the advection.

However, the previous studies have indicated only the nature of these temperature changes due to synoptic scale disturbances qualitatively but not their quantitative mechanism. In this study, these temperature changes at Syowa Station are analyzed from two viewpoints. One is the contribution of destruction and reformation of the surface temperature inversion to the temperature change, described in Section 3.1. The other is the heat budget in the free troposphere including the contributions of the horizontal advection, long wave radiation and vertical motion, described in Section 3.2.

2. The Analyzed Data and Periods

The variations in the temperature have been analyzed from the data obtained by JARE-34 in 1993. Figure 1 shows the time series of the temperature on the surface and the standard levels of 850, 700, 500 and 300 hPa at every 3 and 15 LT in the winter of 1993 (from 21 March, the autumnal equinox, to 23 September, the vernal equinox). Severe increases in the surface temperature of about 20°C during 2 or 3 days often appear. Prominent warming events that showed increases in the surface temperature exceeding 15°C during a few days have been selected. Fifteen events selected are shown in Fig. 1. The beginning and end of the events are determined from minima and maxima in the time series of surface temperature and are shown by squares in Fig. 1. Each of these events accompanies the approach of a synoptic scale disturbance. Figure 2 is the weather chart at 15 LT on 14 August, 1993 compiled by the Japan Meteorological Agency, which

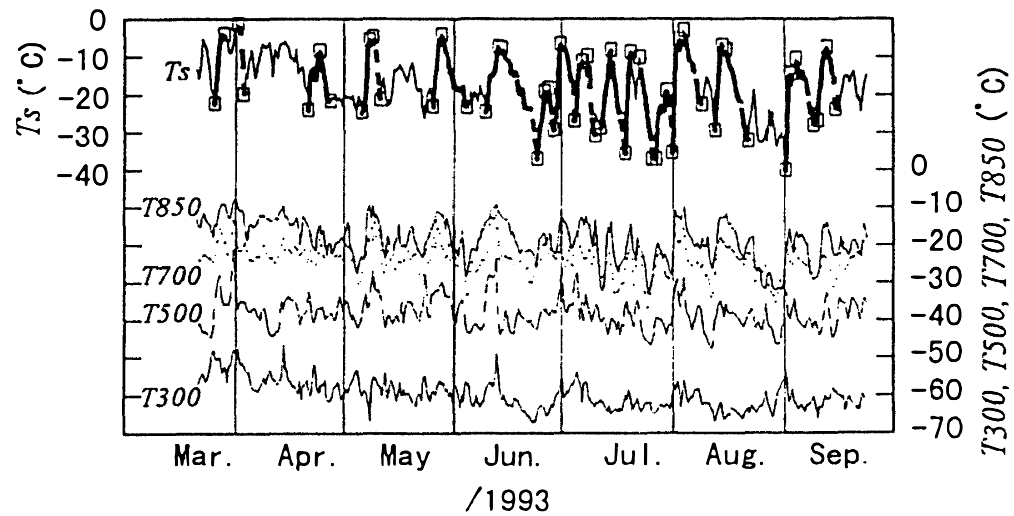

Fig. 1. Temperatures on the surface (T_s) and the standard levels of 850 (T850), 700 (T700), 500 (T500) and 300 hPa (T300) at Syowa Station at every 3 and 15 LT in the winter of 1993 (from 21 March, the autumnal equinox, to 23 September, the vernal equinox). Thick solid and broken lines represent the warming and cooling events selected in this study, respectively. Squares represent the beginning and end of those events. (Note that T_s is referenced to the left-hand ordinate and the others (T850, T700, T500 and T300) are referenced to the right-hand ordinate.)

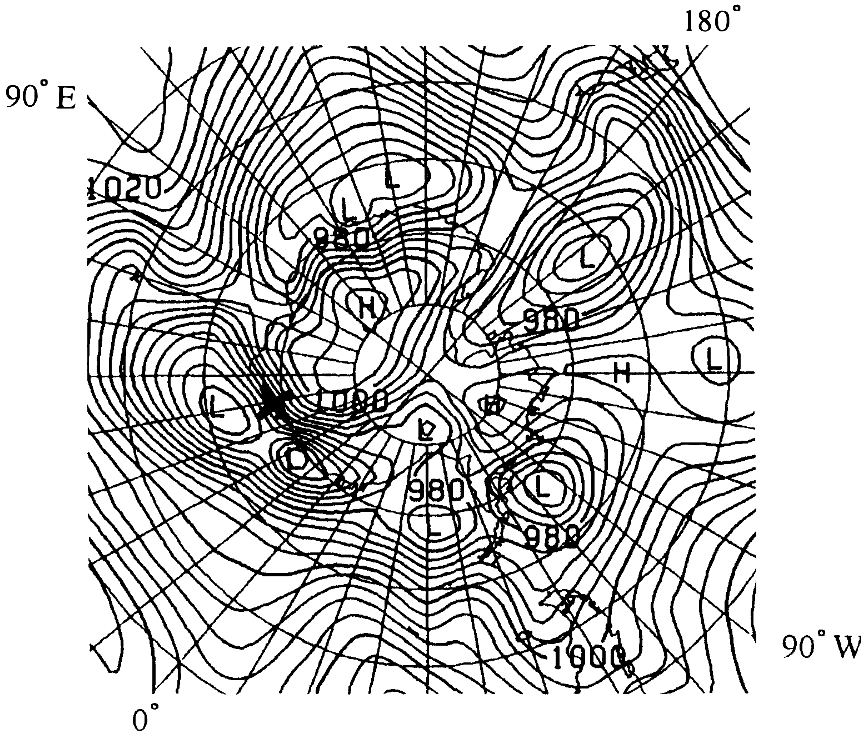

Fig. 2. The surface weather chart in the Southern Hemisphere at 15 LT on 14 August 1993, toward the end of a warming event. The cross (×) indicates the location of Syowa Station.

is an example appearing toward the end of the warming events. Fifteen periods have also been selected as the succeeding cooling events as shown in Fig. 1.

The average increase in the surface temperature is 20.6°C during 2.3 days for the fifteen warming events and the average decrease is 19.6°C during 3.9 days for the fifteen cooling events. So the average change of the surface temperature is estimated to be 20.1 °C for both the warming and the cooling events.

3. Analysis and Discussion

3.1. Contribution of the surface temperature inversion

Changes of vertical temperature profiles above Syowa Station are compiled in Fig. 3. Data on both the standard and the significant levels at every time are plotted. The composite profiles are compiled from only the standard level data for four cases, which are the beginning and end of the warming and cooling events. It is obvious that the surface temperature inversion has been destroyed during the warming events and re-formed during the cooling events. The intensity and thickness of the inversion are defined as the difference between the maximum temperature in the troposphere and the surface temperature, and as the altitude where the maximum temperature appears, respectively. The average intensity and thickness of the inversion are 10.8°C and 796.2 m before the 15 warming events, and 9.5°C and 1019.3 m after the 15 cooling events, respectively. The average change of surface temperature due to the passage of distur-

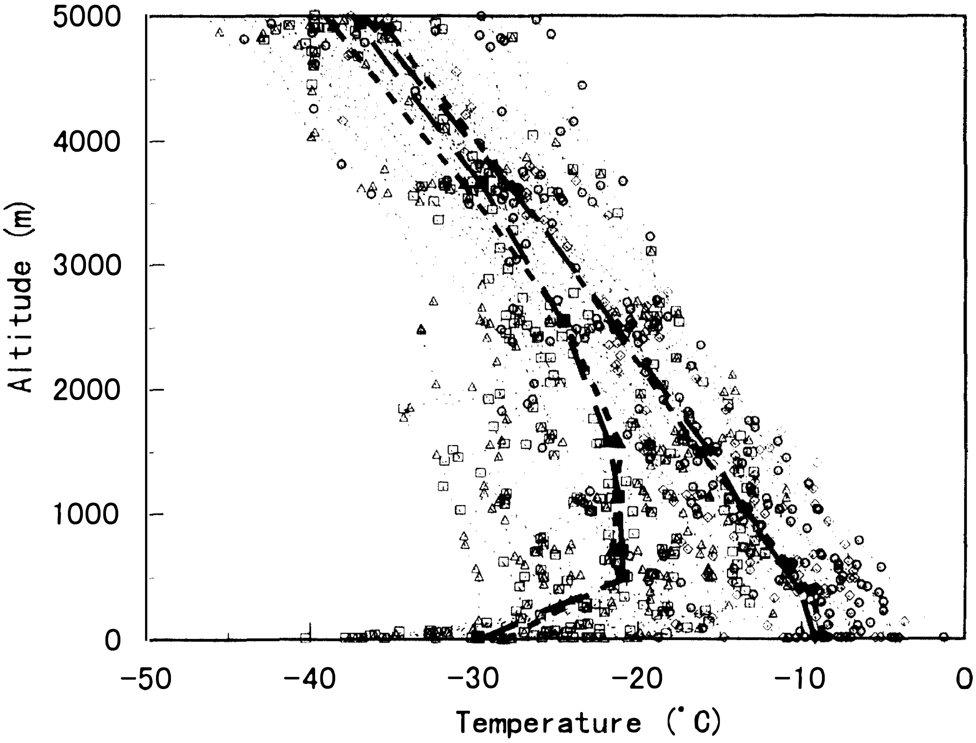

Fig. 3. Variations of vertical temperature profiles above Syowa Station. Temperatures on the standard and the significant levels are shown by different symbols: the beginning (□) and end (◇) of warming events, and the beginning (○) and end (△) of cooling events. Composite profiles compiled from only standard level data are shown by thick broken lines for warming events and thick dotted lines for cooling events, with black symbols for every case.

bances is estimated to be 20.1°C in Section 2. This change is separated into two parts. One is a change due to destruction or reformation of the surface temperature inversion, and the other is related to the whole troposphere. The change of the surface temperature due to the change of the inversion is estimated to be 10.2°C on average in both the warming and the cooling events. It is concluded that about half of the change in the surface temperature is due to destruction or reformation of the surface temperature inversion.

The temperature variations coupled with the disturbances are exaggerated at lower levels near the surface due to this contribution of the change of the inversion. The smaller surface temperature fluctuation in summer is due partly to the absence of the inversion. However, although it has been well known that a stronger temperature inversion grows in the interior region of Antarctica (KAWAGUCHI *et al.*, 1982), a significant difference cannot be seen in the amplitude of the surface temperature fluctuation between Syowa Station and the Relay Point for Dome Fuji Station (ENOMOTO *et al.*, 1995). It would be a very interesting problem how the mechanism of this fluctuation differs between the coastal and the interior regions.

3.2. The heat budget in the free troposphere

In Fig. 1 and Fig. 3, it can be seen that the temperature changes during warming and

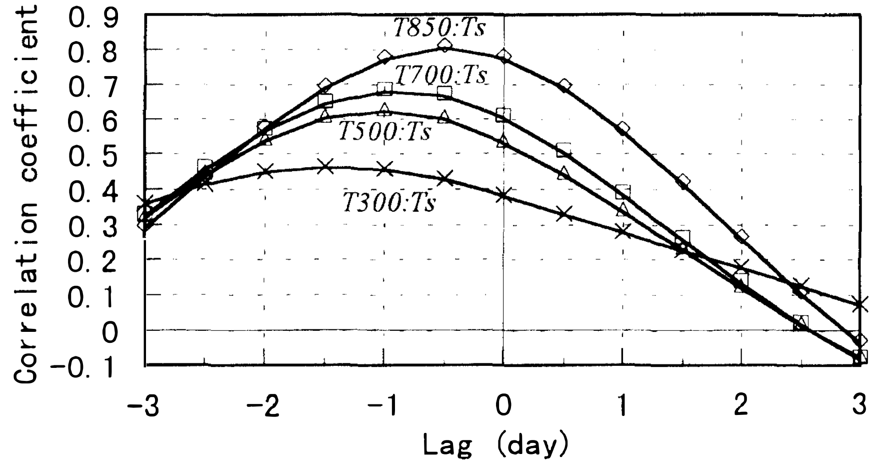

Fig. 4. Cross-correlation of temperature between the surface and upper layers in winter. The variation components of 3 to 20 days period are used. Minus value of lag represents delay of T_s.

cooling events not only in the boundary layer where the inversion exists but also in the free atmosphere below the 300 hPa level although the changes become smaller in the upper layers. Figure 4 shows the cross-correlation of the temperature fluctuation between the surface and the upper layers at Syowa Station due to disturbances in winter. The correlation becomes weaker in the upper layers and the fluctuation on the surface is delayed 0.5 to 1 day from the upper layers.

The heat budget in the free atmosphere, Antarctica for the polar night consists of three major components, which are the contributions of the horizontal advection, the long wave radiation and the vertical motion (SCHWERDTFEGER, 1984). The horizontal advection of sensible heat over Syowa Station can be calculated by the thermal wind shear relation (SCHWERDTFEGER, 1984; TAKAO and KAMATA, 1995). The thermal wind shear is defined as

$$\mathbf{v}_1-\mathbf{v}_2=(R/f)\ln(p_1/p_2)\cdot\mathbf{k}\times\nabla_p\bar{T}, \qquad (1)$$

where $\mathbf{v}_1$ and $\mathbf{v}_2$ represent the wind vectors on the standard level of air pressure, p_1 and p_2, respectively, $\nabla_p\bar{T}$ the horizontal gradient of the average temperature between those two standard levels, R the gas constant of air, f the Coriolis parameter and $\mathbf{k}$ the vertical unit vector. Assuming that the average wind, $(\mathbf{v}_1+\mathbf{v}_2)/2$ carries sensible heat corresponding to $\nabla_p\bar{T}$, the heating rate by horizontal advection, $\Delta T(HA)/\Delta t$ is calculated as

$$\Delta T(HA)/\Delta t = -\int_{t-\Delta t/2}^{t+\Delta t/2}\frac{\mathbf{v}_1+\mathbf{v}_2}{2}\cdot\nabla_p\bar{T}\mathrm{d}t = \frac{f\Delta t}{R\ln(p_1/p_2)}(u_2v_1-u_1v_2), \qquad (2)$$

where (u_1,v_1) and (u_2,v_2) represent the eastward and the northward components of $\mathbf{v}_1$ and $\mathbf{v}_2$, respectively. The calculated values of the heating rate by the horizontal advection are summarized in Table 1 on average through each layer (850–700, 700–500 and 500–300 hPa) and during each period (a whole year, winter, the warming and the cooling events of 1993). There is weak advection of warm air, around 1°Cday^{-1}, on average during a whole year or winter. On the other hand, there is relatively active advection of warm air in the warming events and weak advection of cold air in the cooling events.

Table 2 and Table 3 show the average heat budget in the free troposphere during the warming and cooling events, respectively. $\Delta T/\Delta t$ represents the actual heating rate observed by radiosondes, and $\Delta T(HA)/\Delta t$ the heating rate calculated from horizontal advection, the same as in Table 1. $\Delta T(LR)/\Delta t$ represents the rate of heating (cooling) by long wave radiation, quoted from MIYAUCHI and OHKAWARA (1992), who summarized the average vertical profiles of the cooling rate by the long wave radiation measured with radiometersondes for 356 times from March to October during 1966 to 1988 above Syowa Station. $\Delta T(VM)/\Delta t$ represents the heating rate due to vertical motion, calculated as the residual, that is $\Delta T/\Delta t-\Delta T(HA)/\Delta t-\Delta T(LR)/\Delta t$.

These values of $\Delta T(LR)/\Delta t$ have been summarized in different cases from the warming and the cooling events, which were cloudless, overcast and all data, using data in different periods from this study. Generally, the warming events correspond to periods when the weather changes from cloudless to overcast as disturbances approach and contrary for the cooling events. However, rates of cooling by long wave radiation under overcast and cloudless conditions show small differences. The change in the amount of water vapor, which itself is small because of low temperature, also gives small differ-

Table 1. The average heating rate due to horizontal advection through each layer and during each period in 1993 above Syowa Station calculated from the thermal wind shear relation (°Cday^{-1}).

	In a whole year (365days)	In winter (187days)	In the 15 warming events (35days)	In the 15 cooling events (58.5days)
850–700 hPa	0.58	1.70	9.28	−2.60
700–500 hPa	0.66	0.42	3.72	−1.28
500–300 hPa	1.50	1.08	4.96	0.14

Table 2. The average heat budget above Syowa Station in the fifteen warming events expressed in the heating rate (°Cday^{-1}). The individual terms are explained in the paper.

	$\Delta T/\Delta t$	$\Delta T(HA)/\Delta t$	$\Delta T(LR)/\Delta t$			$\Delta T(VM)/\Delta t$		
			all	cloudless	overcast	all	cloudless	overcast
850–700 hPa	2.34	9.28	−1.22	−1.15	−1.41	−5.73	−5.80	−5.54
700–500 hPa	0.90	3.72	−1.05	−0.82	−1.39	−1.78	−2.01	−1.43
500–300 hPa	0.22	4.96	−0.61	−0.46	−0.82	−4.13	−4.28	−3.92

Table 3. Same as Table 2, but in the fifteen cooling events.

	$\Delta T/\Delta t$	$\Delta T(HA)/\Delta t$	$\Delta T(LR)/\Delta t$			$\Delta T(VM)/\Delta t$		
			all	cloudless	overcast	all	cloudless	overcast
850–700 hPa	−1.34	−2.60	−1.22	−1.15	−1.41	2.48	2.41	2.67
700–500 hPa	−0.84	−1.28	−1.05	−0.82	−1.39	1.49	1.26	1.83
500–300 hPa	−0.54	0.14	−0.61	−0.46	−0.82	−0.07	−0.22	0.14

ences in them over Antarctica (CERNI and PARISH, 1984). So it is suggested that the average contribution of long wave radiation to the heat budget should be generally shown by the average of those values. The detailed change in the radiation budget for each case should be considered in the future.

The turbulent transfer of heat is neglected in this heat budget. The change of potential temperature, θ, is deduced from the conservation of the potential temperature, removing the advection term.

$$\frac{\partial \bar{\theta}}{\partial t} = -\frac{\partial \overline{w'\theta'}}{\partial z}, \tag{3}$$

where the over bar represents the average value, the prime the deviation and w is the vertical velocity. The vertical flux of the turbulent transfer of heat, Q is expressed as

$$Q = \rho C_p \overline{w'\theta'} = -\rho C_p K \frac{\partial \bar{\theta}}{\partial z}, \tag{4}$$

where ρ represents the density of air, C_p the specific heat at constant pressure and K the eddy diffusivity. Therefore,

$$\frac{\partial \bar{\theta}}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial \bar{\theta}}{\partial z}\right) = K \frac{\partial^2 \bar{\theta}}{\partial z^2}. \tag{5}$$

Accordingly, the heating rate expressed in the potential temperature by the turbulent transfer of heat can be estimated as shown in Table 4 by using K=0.1 m^2s^{-1} after SCHWERDTFEGER (1984). As its absolute value is less than 0.05 $Kday^{-1}$ during both the warming and the cooling events through the layers of 850–300 hPa, it is suggested that the contribution of the turbulent transfer should be much less than the other three terms in the heat budget and may be neglected.

Table 4. The heating rate expressed in the potential temperature, $\partial\bar{\theta}/\partial t$ by the turbulent transfer of heat above Syowa Station at each time ($Kday^{-1}$).

	The warming events		The cooling events	
	the beginning	the end	the beginning	the end
850–700 hPa	−0.019	−0.016	0.010	−0.049
700–500 hPa	−0.009	−0.005	−0.004	−0.004
500–300 hPa	0.002	0.009	0.007	0.004

In this study, the contribution of latent heat is also neglected in the heat budget because the water vapor is small over Antarctica (SCHWERDTFEGER, 1984). However, synoptic scale disturbances would accompany the phase change of water, so the contribution of latent heat should be taken into consideration in the future.

Figure 5 (a) and (b) show the same relation as Table 2 and Table 3, respectively. It is seen that the vertical motion appropriately compensates for the temperature change due to horizontal advection during both warming and cooling events. The vertical velocity in

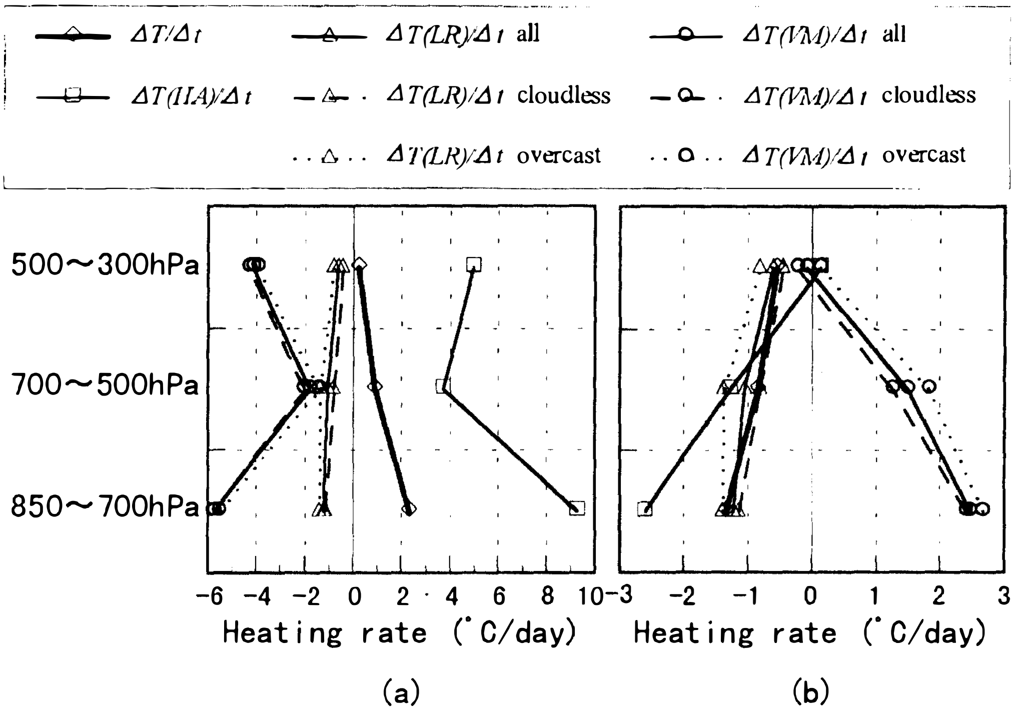

Fig. 5. The average heating rate due to the individual terms in free troposphere above Syowa Station during warming (a) and cooling (b) events, the same as shown in Table 2 and Table 3, respectively.

Table 5. The average vertical velocity above Syowa Station in the warming and cooling events estimated from the heat budget (cms^{-1}).

	The warming events		The cooling events	
	cloudless	overcast	cloudless	overcast
850–700 hPa	0.69	0.78	−0.29	−0.38
700–500 hPa	0.24	0.19	−0.15	−0.24
500–300 hPa	0.51	0.48	0.03	−0.02

each case is estimated as shown in Table 5 by using the dry adiabatic lapse rate for the cloudless case and the moist one after LIST (1949) for the overcast case. The estimated values are upward currents of 0.2 to 0.8 cms^{-1} during warming events and downward currents of less than 0.4 cms^{-1} during cooling events.

4. Conclusions

About half of the change in the surface temperature, rapid increase and decrease due to synoptic scale disturbances at Syowa Station, is shown to be the contribution of destruction and reformation of the surface temperature inversion. Because of this contribution, the temperature change is greatest on the surface and significant only in winter.

It is shown that in the free troposphere above Syowa Station, with the passage of disturbances, large positive horizontal advection of sensible heat is observed associated with surface warming events. Warming by advection is largely compensated for by cooling due to upward motion with additional long wave cooling, resulting in warming in the free troposphere. The heating rate is larger in the lower layers and amounts to several °Cday^{-1} through the 850–700 hPa layer. In the cooling phase following a warming event, cooling by horizontal advection of sensible heat is compensated for by heating due to downward motion, and cooling proportional to long wave cooling is observed. The cooling rate is larger in the lower layers. It has been reported that there is a weak downward current over Antarctica on average (SCHWERDTFEGER, 1984), but there should be quite a different circulation of atmosphere during the passages of disturbances. The temperature change and the vertical motion estimated from the heat budget coupled to the passage of synoptic scale disturbances in winter are given in this report.

Future progress should be made in more precise estimation of the individual terms in the heat budget and also in study over a wider area including the interior region.

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