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IS IT TROPOSPHERIC SUDDEN WARMING?

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ABSTRACT

In this study, we carried out a quantitative heat budget analysis of the polar tropospheric in and around Alaska for the winter of 1988/89. The winter was abnormal with respect to a drastic variation of temperature. The surface minimum tempetature in the interior of Alaska was lower than -40° C during two weeks in late January. This cold situation was suddenly replaced by extremely warm weather during February, especially in northern Alaska. It has warmed by 40° C within a week, which is comparable to the stratospheric sudden warming.

The result of the heat budget analysis shows that the severe cold in late January is caused by an anomalous reduction in warm advection of sensible heat. The cold spell is followed by abnormally warm weather in February with enhanced warm advection associated with a blocking formation over the North Pacific. We find that the sudden warming in the troposphere after the cold spell is initiated by an adiabatic warming due to a mechanical compression similar to the stratospheric sudden warming. It is suggested by these results that this phenomenon may be regarded as tropospheric sudden warming in high latitudes.

1. INTRODUCTION

Stratospheric sudden warming is an extraordinary phenomenon which we cannot observe in the troposphere. Temperature increases more than 40° C within a week, which never happens in the troposphere(see Matsuno, 1971; Matsuno and Shimazaki, 1981). Our recognition of weather is, however, sometimes misleading when we always live in the middle latitudes. We can find a number of mysterious weather phenomena in the arctic and subarctic.

The Alaska winter of 1988/89 was unusual with respect to the drastic temperature variation. A number of new record low temperature at the surface were reported in interior Alaska at the end of January. Among these new records were -60.0° C at Tanaka and -59.4° C at McGrath.(The all-time state record is -62.2° C set in 1971 at Prospect Creek.) In the beginning of February, this extremely cold air mass in the lower troposphere over Alaska began to slide southeast through Canada to the northern United States. As the cold air mass passed through these regions, many new record low temperatures were set. In contrast to the cold conditions developing in the northern United States, Alaska warmed dramatically in early February. The temperature has indeed increased more than 40° C within a week at the weather station in Barrow Alaska. During this period, a warm maritime air mass was transported over Alaska via enhanced meridional flow induced by pronounced atmospheric blocking over the North Pacific. The maritime warm air was combined with a strong downslope flow over the Alaska Range and Brooks Range to produce very warm monthly mean surface temperature at Fairbanks and

Barrow(see Tanaka and Milkovich, 1990).

The surface temperature variations in January and February 1989 for Barrow and Fairbanks are shown in Fig.1. The 1989 winter included two weeks of temperature below -40°C in late January at both locations. We realize that the 1989 cold spell was a long and intense one in comparison to those in the last decade. In contrast, the warm monthly mean temperature for February at Barrow was really abnormal. The monthly mean temperature was 18°C warmer than normal, which is more than four times greater than the standard deviation of the long-term monthly mean(see Walsh and Chapman, 1990). The probability of such an episode is just once in ten thousand events. The unusual winter 1988/89 in and around Alaska offers an interesting opportunity of the quantitative heat budget analysis in investigating the nature and valiability of the polar air mass.

The objectives of the present study is to conduct a quantitative assessment of the extreme temperature variation of the polar troposphere in and around Alaska during the abnormal winter of 1988/89. We are especially interested in the cause of the sudden warming in the troposphere, exceeding 40° C within a week(see Fig.1). The questions to be addressed include: Why did the persistent cold snap occur? Why was the cold spell suddenly replaced by an abnormal warm spell in February? How did thermodynamic terms vary associated with the extreme temperature variation?

In order to answer these questions, we first analyzed the horizontal and vertical extension of the rapid temperature variations. We found that the temperature variation is not confined to the lower troposphere. Instead, it is an entire tropospheric phenomenon in and around Alaska. We then performed a quantitative heat budget analysis over the analysis domain in the troposphere, using upper air meteorological data provided by the National Meteorological Center(NMC). We examined the time series of the fundamental thermodynamic terms. The results of this heat budget analysis will show the most prominent thermodynamic factor responsible for the extreme temperature variation during the winter of 1988/89. It will be shown that the sudden warming after the severe cold is caused by an adiabatic compression similar to the stratospheric sudden warming to some extent. The result suggests that the phenomenon may be regarded as tropospheric sudden warming.

2. DATA AND THE ANALYSIS METHOD

We obtained the NMC grid-point global analysis data for the period of 1 December 1988 through 28 February 1989 from the National Center for Atmospheric Research. The data consist of twice daily(0000 and 1200 UTC) meteorological variables on the 2.5° by 2.5° longitude latitude grids at the mandatory vertical levels from 1000mb to 50mb. The original data were reduced to 5° by 5° grid data in this study.

Using a pressure coodinate in the vertical, the first law of thermodynamic energy equation represented by enthalpy may be written as:

Time change of temperature
= horizontal advection
+ adiabatic process due to vertical motion
+ diabatic process

The daibatic process includes radiative heating, latent heat release, and diffusive vertical transport of sensible heat among others. In the present study, the diabatic term was evaluated by a residual balance of the heat budget equation. The latent heat release and shortwave radiation appear to be small in the extreme cold, high-latitude environment. Since the surface snow cover over the continent behaves as an efficient insulator, the vertical eddy sensible heat transport from the ground may be considered as secondary effect. Hence, the residual term of the diabatic process may be regarded primarily as radiative cooling due to longwave radiation toward the space.

The analysis domain of the present heat budget analysis has been determined by observing a characteristic vertical and horizontal extension of the temperature variation. According to the analysis of the vertical profile of the temperature change, the warming is not confined to the lower troposphere, but is extending over the whole troposphere. Figure 2 describes the 700mb temperature changes for the warming period. The values are the difference in 15-day mean temperature between the end of January and the beginning of February. The maximum warming occurred over interior Alaska, showing a temperature increase of 20°C. The horizontal extension of the 10°C contour encloses an area of 50°-80°N, 160°E-110°W. With these results we set the domain of the present heat budget analysis to be a closed area of 55°-75°N, 110°-180°W, as is shown by the shaded area in Fig.2. The analysis domain extends from the surface to 50mb in the vertical.

3. RESULTS

The results of the heat budget calculations are presented in this section for the severe cold in the latter half of January and the subsequent abnormal warm weather in February. Figure 3a shows a time series of enthalpy(sensible heat) integrated over the analysis domain defined in Fig.2. The 5-day running mean of the time series is also presented by thick lines. Temporal variations are superimposed on the low-frequency variation. The enthalpy decreases from a peak in mid-December to a minimum in late January. It increases rapidly at the beginning of February and remains at a high level during the month. The time series for the entire tropospheric change reasonably reflects Alaska's abnormal weather near the surface in Fig.1. Hence, the examination of the tropospheric integral appears to be the most meaningful method of assessing the unusual temperature variation during the winter.

The time series of the thermodynamic terms appearing in the heat budget equation are presented in Figs. b-e. The sensible heat advection is, in general, positive, thereby raising the temperature. About 100W/m^2 of heating occurs before the cold spell. The advection decreases in January, and it becomes negative at the end of January. In February, the advection increases rapidly as meridional flow due to the blocking formation dominates. Adiabatic warming due to vartical motions provides a relatively small contribution except for the period at the very end of January. When the cold spell ended, strong adiabatic warming in excess of $300W/m^2$ occurred, and the Pacific blocking formed. This increase in adiabatic warming accounts for the major warming as seen in the tendency term. The extraordinary sea-level pressure of 1078.4mb was recorded during this period. It should be noted that the adiabatic warming due to the vertical motion occurred before the blocking formation and advective warming in the present case study. The blocking developed during the occurrence of the significant downward motion over the domain as discussed by Colucci(1985). The residual of the heat budget is expected to be negative since it represents a dominant radiative cooling of the air column. The results are consistent with the expectation, except for the period of January. The short-term variations in the residual are considerably small in comparison to the other terms. The cooling is reduced during the cold spell and is enhanced during the warm spell; thus agreeing with the nature of longwave radiation. Since a temperature profile tends to approach radiative equilibrium, the radiative cooling is strong when it is warm, but the cooling is weak when it is cold.

The result of the heat budget clearly indicates that the sudden warming in the troposphere is caused by the adiabatic compression due to the vertical motion. The domain-average vertical p-velocity(omega) is illustrated in Fig.4 for a series of 10-day averages during the analysis period. Since omega was negative during January, there was an ascending motion for the domain average. Then, omega became strongly positive at the end of January and early February, compressing the air by the downward motion. The values decreased in mid-February. The time variation of omega seems to be consistent with the actual temperature change during the warming period. Evidently, the rapid temperature increase is caused by the adiabatic compression.

4. CONCLUSION AND DISCUSSION

The Alaska winter of 1988/89 was unusual with respect to the drastic temperature variation. The surface weather stations observed a warmer than normal December, two weeks of -40°C during January in interior Alaska, and an extremely warm February in northern Alaska. The temperature variation is not confined to the lower troposphere, but it is an entire tropospheric phenomenon in and around Alaska. The rapid temperature increase by 40°C within a week is comparable to the stratospheric sudden warming.

The results of the present heat budget analysis are summarized as follows.

1) A heat budget for the three-month average in and around Alaska is maintained by a balance of advective warming($36W/m^2$), adiabatic warming due to decending motion($19W/m^2$), and radiative process(residual term, $-54W/m^2$). The results agree with previous studies(e.g. Nakamura and Oort, 1988; Fortelius, 1989).

2) The severe cold in Alaska during late January was induced by

an anomalous reduction of warm air advection resulting from a persistent zonal flow pattern in the middle latitudes. Cold advection near the surface from Siberia accelerated the cooling. It is important to note that the domain-averaged vertical motion was upward during the cooling period. There was a persistent cooling due to the adiabatic expansion in the lower troposphere caused by the large-scale ascending motion.

3) The subsequent abnormal warming in February was caused by the unusual adiabatic compression. The warm air advection due to the strong meridional flow associated with a blocking formation in the North Pacific occurred after the adiabatic warming.

It is well known that the stratospheric sudden warming occurs by an adiabatic compression due to a descending motion(Matsuno, 1971). Vertical propagations of transient planetary waves and their breakdown at a critical layer are responsible for the stratospheric sudden warming. The decelerated polar night jet by the wave-mean flow interaction causes the warming by means of its mechanical compression. The present heat budget analysis shows that the sudden warming in the troposphere is caused by the similar mechanism as the tropospheric sudden warming in a sense that both are the results from the adiabatic compression. Therefore, the phenomenon may be regarded as tropospheric sudden warming. It is a local warming in high latitudes, which is a great contrast with the stratospheric sudden warming over the stratospheric polar cap. Expected mechanical work involved during the warming is substantially larger in the tropospheric sudden warming because of the density stratification. The reason for the unusual descending motion, which seems to be related to a strong convergence near the tropopause, is still an open question. The dynamical curiosity is great, and more observational analysis is needed as a future study.

ACKNOWLEDGMENT

This paper is dedicated for Professor Toshie Nishizawa on his retirement from the Institute of Geoscience, the University of Tsukuba. A professor should not work for money, fame, and power, but should work for motif, faith, and peace. Professor Nishizawa has been a strong man in pursuit of his faith supported by his noble philosophy. He has demanded us a deep physical insight and the need of basic study for variety of atmospheric phenomena. I have enjoyed discussion with him along which I can learn his fresh insight for a commonly observed phenomenon in our daily life. He always loves man, the earth, and the society, so he can lead a number of outstanding successors. I am delighted to have been one of his students. I would like to celebrate his excellent accomplishment today.

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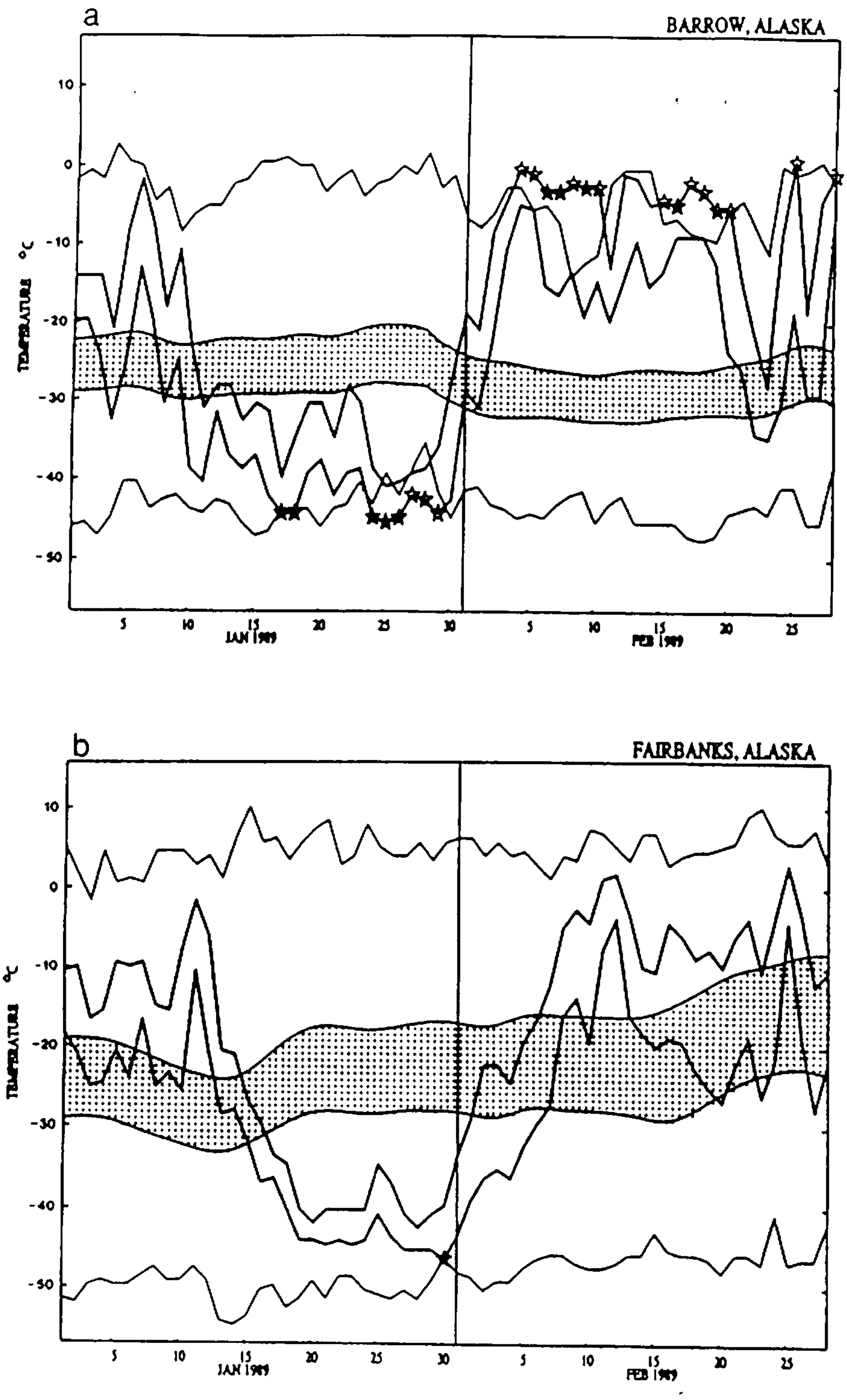

Fig. 1. Time series of daily high and low temperatures (thick lines) during January and February 1989 at (a) Barrow Alaska and (b) Fairbanks Alaska. The shaded area denotes the 30-year mean normal and the upper and lower thin lines denote the record temperatures during the 30 years. The new records are marked by star symbols.

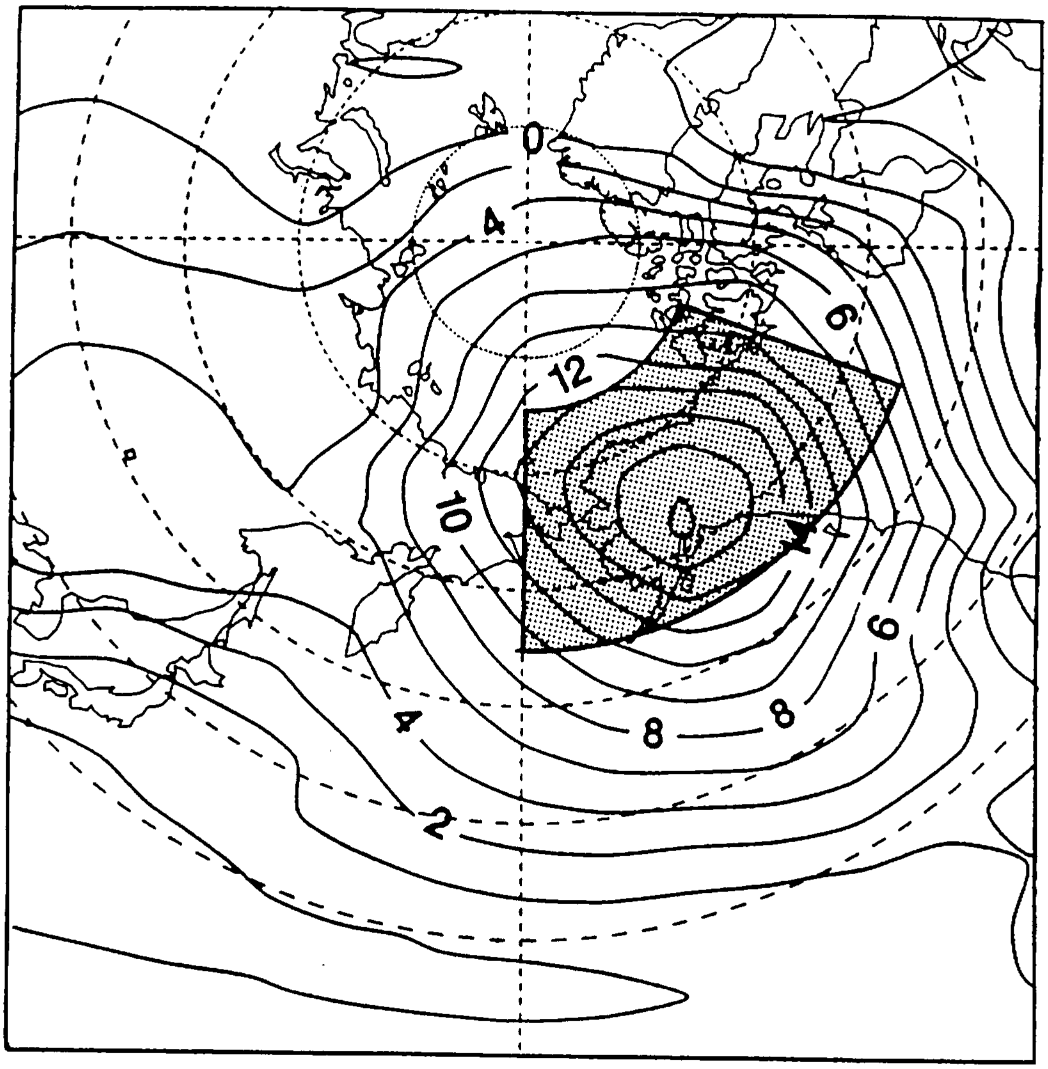

Fig. 2. Temperature change ($^\circ K$) at the 700 mb level for the warming period. The values are the difference of the 15-day mean temperatures between the end of January and the beginning of February. The hatched area represents the analysis domain for the present heat budget analysis.

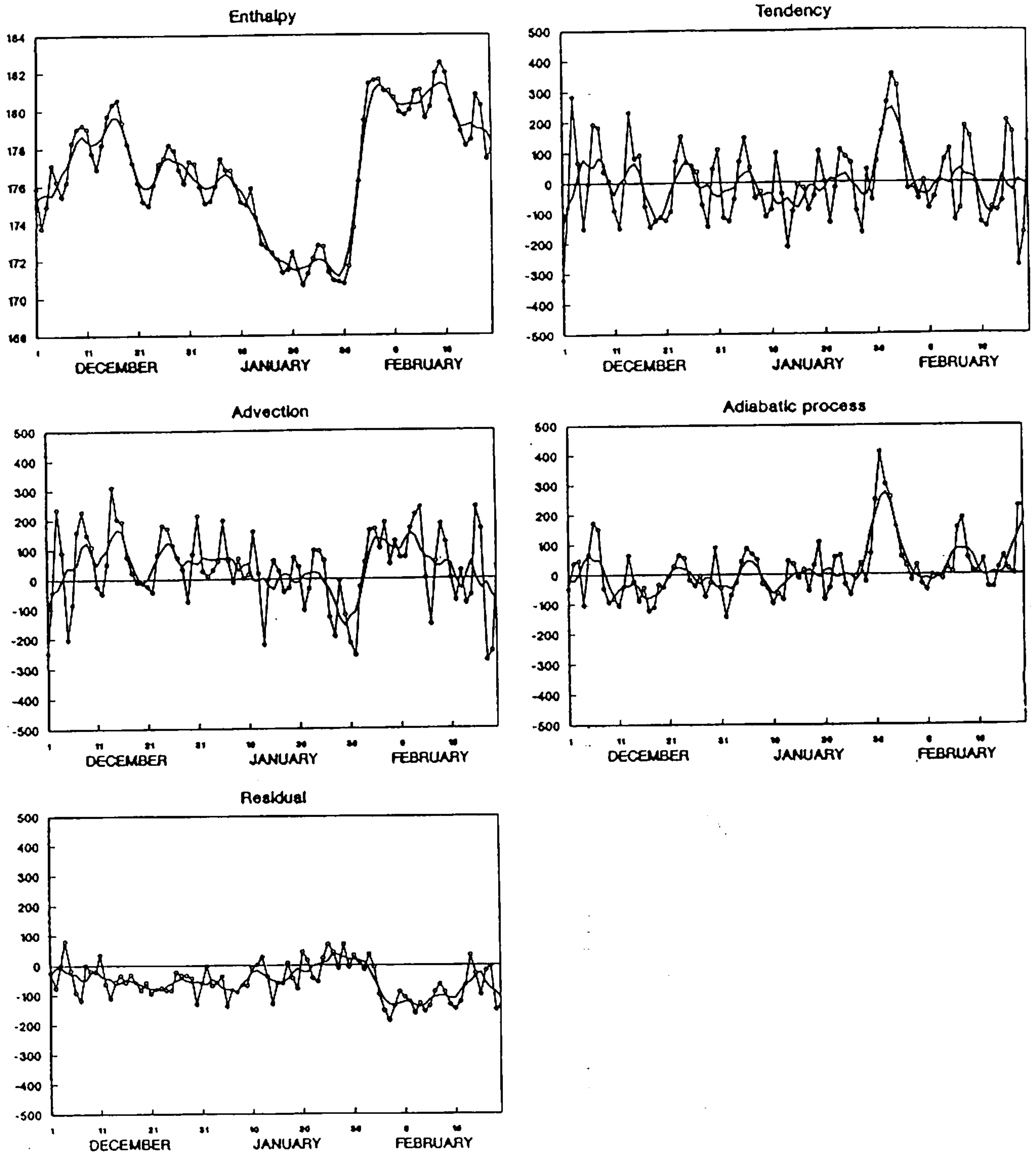

Fig. 3. Time series of (a) enthalpy, (b) its tendency, (c) its advection, (d) adiabatic warming, and (e) diabatic process (residual of the heat budget) during the winter of 1988/89. The thick lines are the 5-day running mean of the original time series. The units are $10^7 J/m^2$ for (a) and W/m^2 for (b) through (e).

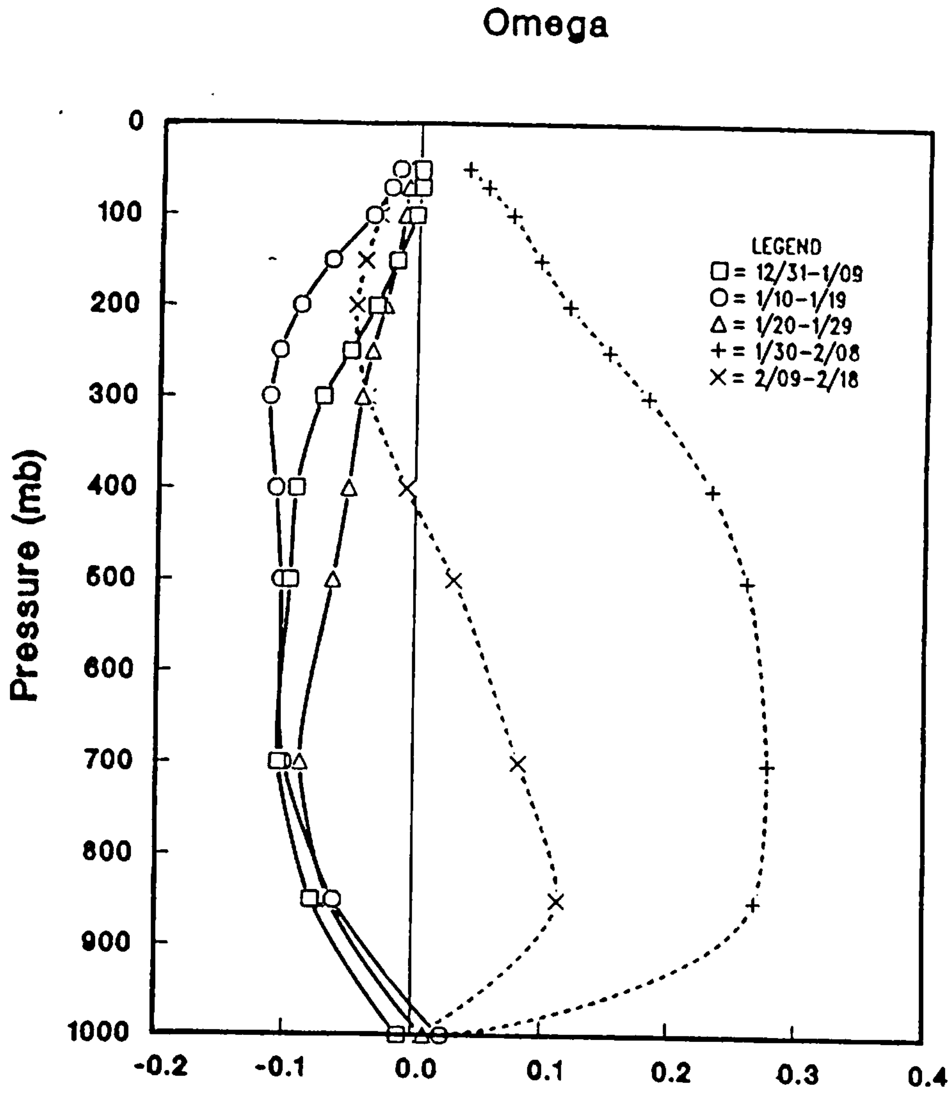

Fig. 4. Vertical profiles of omega over the analysis domain for 10-day averages during the winter of 1988/89. The units are *μbar/s*