NOTES AND CORRESPONDENCE

Mass and Heat Balances of the Local Front over the Kanto Plain in Early Winter

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Abstract

The local front observed over the Kanto plain on December 5, 1996 has been analyzed as an example of one of those that often appear when a synoptic-scale low advances in the Japan Sea in early winter. Winds in the lower layer, blowing from the northern and western mountains since the previous night, supplied cold air to the middle of the plain. Before dawn, synoptic-scale southerly winds intensified from the south of the plain, and the local front formed along the southern margin of the cold air mass.

The southerly winds over the lifted frontal surface entrained the cold air from the lower layer and transported it northward in a “transition layer,” characterized by relatively cold southerly winds. The depths of the transition and lower layers tended to be maintained above the inland areas north of the front. The front advanced northward, corresponding to the surplus of the northward flow in the transition layer over the cold air supply in the lower layer. As a result of the persistent cold air flow, even during the daytime, the front became stationary over the middle of the plain in the afternoon.

Additionally, a very shallow (~ 50 m) structure of the frontal head existed prior to the frontal passage through the central area of Tokyo.

1. Introduction

The local front that occasionally appears over the southern Kanto plain in early winter (hereafter referred to as the front) has long been observed (Yoshino, 1961 and 1975). Recently, the formation mechanism of the front has been investigated by an analysis of routine meteorological data (Mizuno and Kondo, 1992). A series of observations have been performed to determine the three-dimensional structure of the front (Yoshikado *et al.*, 1994), and numerical models have been employed for further analyses, such as the relationship between the front and the synoptic field, and air pollution (Kondo and Mizuno, 1990; Ohara and Uno, 1997). Through these works, the basic generation mechanism of the front has been clarified as follows: (1) Nocturnal drainage flow, or mountain breeze, originating in the mountainous region to the west and north of the plain, forms a large cold air lake. (2) Due to a synoptic low propagating in the Japan Sea, warm southerly to southwesterly

winds gradually develop from south of Kanto, forming the front along the boundary of the cold air mass. (3) The mountains to the west of the plain prevent the southwesterly flow from advancing inland, particularly in the western region of the plain. Thus the front tends to form in a southwest-northeast alignment and persist for a considerably long time, even during the daytime.

However, the observations (Yoshikado *et al.*, 1994) clarified that warm southwesterly winds did not move parallel to the front, but flowed over the cold air mass. Intense mixing occurred along the elevated frontal surface due to the very strong vertical wind shear. The cold air found in the frontal zone and beneath the frontal surface was transported northeastward at a fast rate. To compensate for this loss and maintain the frontal structure during the day, a sufficient amount of cold air has to be supplied.

In this article, the front observed during December 5, 1996 is applied to estimate the amount of the cold air supply by contrast with the loss. The mountain drainage flow is examined as the source of the cold air in comparison with that during the calm morning of the previous day. Observed structure of

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Fig. 1. Surface weather charts at (a) 1800 JST on December 4 and (b) 0600 JST on December 5, 1996. The location of the low and associated fronts at 1800 JST on December 5 is shown by the faint lines in (b).

the frontal head is also discussed, because the estimation of the budget of the cold air is based on the assumption that the structure does not change even if its location shifts.

2. Data

An intensive observation was carried out at two sites from the morning of December 4, 1996, and caught the episode on December 5. One site was Urawa, 23 km northwest of Tokyo, where radiosondes were released eight times during the two days. Pilot-balloon tracking was also performed generally every hour. At Kanda, an urban site in Tokyo, similar soundings were performed. Temperature and winds measured on the Tokyo Tower (maintained by the Metropolitan Government of Tokyo), located 4 km south of Kanda, were supplementally used.

In addition to these data representing the vertical atmospheric structure, surface meteorological data from the Automated Meteorological Data Acquisition System (AMeDAS, the Japan Meteorological Agency) were employed for the analysis.

3. Synoptic condition during the episode

For the two days prior to December 5, a predominant migratory high covered the Japan Islands. The high pressure area was followed by a low that was located around the Korean Straits on the evening of December 4 (Fig. 1a). This low advanced to the middle of the Japan Sea by the morning of December 5, and the Kanto district remained on the warmer side of the system throughout the daytime.

In spite of this configuration of the synoptic systems, warm air did not actually occupy the inland

half of the Kanto plain. A cold air mass stagnated over the inland areas, and a local front formed along its southern boundary. Details of this local structure are shown in the next section.

During the evening of December 5, the low reached southern Hokkaido, with the cold front extending from the low passing over the Kanto plain (Fig. 1b).

4. Evolution of the local front

According to the AMeDAS, only the Miura and Boso Peninsulas were influenced by warm southerly winds at 0500 JST (Fig. 2). For example, SSW winds at 8 ms^{-1} and at a temperature of 15.2°C occurred at Miura (for the location, see Fig. 2), in contrast with NNE winds at 1 ms^{-1} and 7.4°C at Yokohama. The front was already recognized to be located between these sites. The location of the front at every hour was determined in this way (see following).

During the next few hours, the front shifted northward as the southerly winds somewhat intensified. The distance of the shift was greater along the western shore of Tokyo Bay, and less along the eastern shore, presumably due to the more complicated terrain of the Boso Peninsula. At 0800 JST, the front was aligned in a west-east direction, from Fuchuu in the western suburbs of Tokyo, to the central areas of Tokyo, and along the northern shore of the bay.

By 0900 JST, however, the inland advance of the front became much slower over the western region of the plain, while it accelerated over the eastern region. Consequently, the alignment of the front became oriented in a southwest-northeast direction.

Fig. 2. Hourly location of the local front, determined by the wind and temperature data from AMeDAS stations (open circles), some of which are denoted by the initial of the name: Fuchuu, Kanda, Miura, Tsukuba, Urawa, and Yokohama.

This might have been caused by the effect of the western mountains holding the cold air on the lee side against the southerly wind, along with the cold air being supplied from the northern and western mountains.

The front passed Urawa between 1300 and 1400 JST, during which time the air temperature increased from 10.1 C to 18.5 C. The temperature contrast found on either side of the front was as large as that in the early morning hours as mentioned previously, as a result of nearly equivalent warming.

5. Mass and heat transport below the elevated frontal surface

On the basis of the variations in the upper winds observed at Urawa and Kanda by pilot balloons (Fig. 3), several processes in the evolution of the front have been analyzed.

5.1 Original northerly flow

As shown in the previous section, the front was first recognized to form during the early morning of December 5. However, the northerly winds found in the northern part of the front had been observed through the previous night (Fig. 3). Furthermore, similar winds had appeared during the morning of December 4. It is considered that these winds were local winds, such as the mountain drainage flow originated from the mountains of heights of more than 2000 m to the north and west of the plain,

and were transformed into the cold inflow to the front when coupled with the synoptic-scale southerly winds during the morning of December 5. Therefore, prior to the front itself, the original structure of the northerly winds is briefly examined here.

During the morning hours of December 4, the northerly breeze persisted in the lower layers above both sites (Fig. 3), above which southerly winds were already observed, even though wind speeds were still moderate.

Details of this stage are shown in Fig. 4, where the temperature profiles were obtained from radiosonde data. The wind direction above Urawa reversed at about 400 m, while a temperature inversion extended to the same approximate height at 0804 JST, remaining as a lifted stable layer even at 1158 JST. This suggests that the mountain breeze is a gravity current that has a clearly defined upper surface.

Above Kanda, the lower northerly layer was about 350 m thick, slightly thinner than that above Urawa (*cf.*, Fig. 3).

5.2 Development of the front

The northerly breeze ceased during the afternoon of December 4, but soon reappeared, propagating from inland areas. After 2100 JST, the northerly wind above Urawa extended to heights as high as that during the morning (Fig. 3), while the upper southerly wind intensified to some degree. Above Kanda, the upper southerly wind intensified more

Fig. 3. Temporal variation of the upper winds above (a) Urawa, and (b) Kanda on December 4 and 5, 1996. In the legend, (α) denotes the horizontal wind direction from north.

rapidly, while the depth of the lower northerly layer continued to reduce before the dawn of December 5.

At 0600 JST, the southerly wind also suddenly intensified above Urawa. At the same time, the depth of the lower northerly layer decreased to less than 200 m. The depth, however, stabilized after a few hours at about 200 m, and lasted for at least four hours. The temperature and south-north wind component profiles at this stage are shown in Fig. 5a.

The two temperature profiles taken during this stage (0755 and 1158 JST) had similar shapes to each other, as a result of the nearly equivalent warming in the northerly and southerly layers. The warming in the bottom layer probably resulted from radiation balance and anthropogenic heat, while that in the upper southerly layer occurred as a result of horizontal advection.

The maximum velocity of the northerly wind did not decrease much (*cf.*, Fig. 4) in spite of the decrease in the depth. It is of special interest that the lowest part of the southerly layer, ranging from 200 m to higher than 500 m, exhibited an inversion. This is a quite different feature from that during the previous morning, considered to be a transitional layer resulting from the turbulent mixing due to the strong vertical shear along the frontal surface.

It is not very surprising that the depths of the northerly and transition layers were maintained above Urawa for the hours while the front approached. The examples of fronts shown in Yoshikado *et al.* (1994) had wide zones in which the frontal surface was nearly horizontal.

5.3 Air flow budget

During 0800–1200 JST on December 5, as mentioned in the previous section, the front was advancing in the area between Fuchuu and Urawa (*cf.*, Fig. 2). The distance between these two sites (F-U) is 23 km, and the front required nearly six hours to pass through this area. The front in this area was oriented in a direction 54 degrees clockwise from north. The distance F-U measured perpendicular to this direction is 10 km, resulting in a frontal velocity of $V_f = 1.7 \text{ kmh}^{-1}$.

Here, it was assumed that the vertical structure in the lower atmosphere was horizontally uniform, since that above Urawa did not largely vary, except for the nearly uniform increase in temperature while the front shifted northward. Vectorially averaging ($\bar{v}$) the five wind profiles in Fig. 5a, and using the morning potential temperature profile (θ) as representative since the two profiles were similar to each

Fig. 4. The vertical profiles of temperature and horizontal wind component in the south-north plane on the morning of December 4 above Urawa.

other, the cold air transport rate can be calculated by

$$\int \rho C_p |v| \sin \beta (\theta_S - \theta) dz, \quad (1)$$

where θ_S is the potential temperature of the southerly wind upper than the transition layer (represented by that at the 600 m height), β the angle between the wind and the direction of the front (*cf.*, Fig. 6), and the other symbols have conventional meanings.

The southeastward transport of cold air in the lower northerly wind (Q_N) is calculated by integrating (1) from $z = 0$ to h_N (*cf.*, Fig. 6, here 200 m). The northwestward transport in the transition layer (Q_T) is determined by integrating (1) from h_N to h_T (600 m). The value of Q_T is larger than Q_N and their difference $DQ (= Q_T - Q_N)$ corresponds to the rate of decrease of cold air at the frontal head, which is related to the velocity of the advance of the front V_f as

$$DQ = V_f \int_{z=0}^{h_T} \rho C_p (\theta_S - \theta) dz. \quad (2)$$

The relevant values obtained from (1) and (2) are $Q_T = 7.96 \text{ MWm}^{-1}$, $Q_N = 6.43 \text{ MWm}^{-1}$, $DQ = 1.53 \text{ MWm}^{-1}$ (the unit means cooling rate per width along the direction of the front), and $V_f = 1.37 \text{ kmh}^{-1}$, which roughly coincides with the observed (1.7 kmh^{-1}) mentioned previously. This means that, roughly speaking, the cold air is supplied as the lower northerly wind, entrained by the southerly wind in the frontal zone, and removed through the transition layer. As this occurs, the

front advances corresponding to the surplus of the removal of cold air over the supply.

The above calculation is based on the assumption, never completely satisfied, that the vertical structure of the front was unchanged over the area between the frontal head and Urawa while it shifted northward. In addition, the disagreement in V_f between the observed and calculated values can be related to the following factors. First, while the cold air is in the frontal zone, it can be heated by various sources, such as anthropogenic heating and insolation, although the latter was very small due to cloudy sky over the plain. Second, the cold air can experience horizontal divergence during the outflow toward the front. Third, the transition layer observed over Urawa can be traced back to far southwest regions, where the area of the cold source is supposed to be smaller than that of the northerly wind above Urawa.

A rough estimate indicates that the southward transport of cold air on the morning of December 5 (Q_N) was smaller by about 25 % than that on December 4 (*cf.*, Fig. 4, when no transition layer existed). This is a reasonable result, since it was fair and calm on December 4, and therefore the cooling over the inland region could be expected to be stronger. It should be noted that this estimation of cold air is based on the temperature relative to the upper air, and the difference in net quantity of heat was much larger. Even the smaller amount of cold air on December 5, however, proves to have been sufficient to prevent the front from penetrating inland.

5.4 Cold air at the frontal head

Above the Kanda site, the upper southerly wind extended downward before the dawn of December 5, and the lower northerly layer almost disappeared at 0545 JST (Fig. 5b). The ground-level air, however, remained nearly calm with a cold air temperature of 9.5 C, even at 0800 JST. This temperature increased to 15.0 C at 0900 JST with the onset of the southerly wind. This indicates that the frontal head was thin but persistent under the strong southerly wind.

In contrast with the very thin calm layer observed at 0545 JST, the temperature profile measured at 0617 JST (Fig. 5b) still exhibited a transition layer (*i.e.*, southerly but relatively cold) having a 350 m depth. According to the temperature data from the Tokyo Tower, it appears that the transition layer reduced to about 250 m at 0700 JST, and almost disappeared at 0800 JST.

A similar wind profile with a slight northwesterly layer was observed above Urawa at 1300 JST (*cf.*, Fig. 3a), when the surface air temperature was 12.7 C. The onset of the predominant southerly wind was observed at 1317 JST, and the air temperature increased to 18.4 C. This change was more rapid

Fig. 5. As in Fig. 4, except for the morning of December 5 above (a) Urawa, and (b) Kanda. In (b), the profiles up to 250 m denoted by the numerals from 6 to 9 (hour, JST) are the temperature measured on the tower. Velocities out of range are plotted as 20 ms^{-1} .

Fig. 6. Schematic diagram illustrating the variables in Eq. (1) for (a) the horizontal view, and (b) the vertical profile.

than that at Kanda.

Seino (1998) reported that the depth of the calm cold air layer was less than 100 m above Tsukuba, located in the eastern region of the plain (*cf.*, Fig. 2), and was maintained for several hours.

6. Discussion and conclusions

The basic mechanism for the formation of the local front above the southern Kanto plain, typically in early winter, was explained many years ago (Yoshino, 1961) as the boundary between the cold drainage flow from the central mountains and the warm maritime wind. A series of intensive observations were performed in recent years (Mizuno *et al.*, 1993; Yoshikado *et al.*, 1994), and the three-dimensional structure was clarified from several examples. In those cases, however, a considerably large variety was found in the location and dura-

tion of the fronts. For example, one front lasted only during the night, while another advanced northward during the night, returned southward during the evening, and continued through the following night. These differences depend on the supply of cold air and the duration of the synoptic-scale southwesterly wind. In particular, the drainage flow that supplies the cold air to the north side of the front is essentially a nocturnal phenomenon. Therefore, the budget of the cold air during the day is of special interest under such situations that strong southerly winds entrain the cold air along the frontal surface, even though the cold air tends to be retained on the lee side of the western mountains.

In the present case, a nearly steady structure was maintained in the air flow above Urawa, a site somewhat west of the central region of the plain, for no less than four hours. In addition, the temper-

ature contrast between the cold and warm air flow was generally maintained during the same period. This situation allowed for the evaluation of the cold air budget, neglecting the homogeneous warming of the entire system. As a result, the balance can be roughly explained by considering that the cold mountain outflow to the frontal zone is entrained into the lowest part of the warm southerly wind and turns back northward. The excess in the northward cold flux then corresponds to the northward shift of the front.

In spite of less cold outflow from the north than on the preceding day when inland radiational cooling was more intense due to clear skies, the predominant front did not extend to the north end, but stayed in the middle of the plain until mid-afternoon. This fact suggests that the front could have persisted through the following night. The synoptic-scale cold front, however, actually passed over the area and the local system disappeared by the next morning. Expected conditions for a longer persistence of the local front are: (1) more intense radiational cooling during the preceding night, (2) a cloudy sky after sunrise, which reduces heating of the cold air mass over the plain, (3) a warm southerly wind which is not excessively strong, and (4) a slowly propagating low pressure in the Japan Sea with the accompanying cold front later proceeding to the Kanto plain.

Over the central area of Tokyo, a calm cold air layer having a depth of 50 m or less persisted for a few hours, which delayed the arrival of the front at ground-level. A similar layer was found over the Tsukuba area (Seino, 1998). The persistent feature of these layers is supposed to result from the large ground roughness, as one of the major factors, particularly in the urban areas around Tokyo. For another point of view, Fig. 2 indicates that the

northward advance of the front accelerated before it reached both the Kanda and Tsukuba areas, where only thin cold air layers were present during those periods. It is reasonable that the thin cold layers were readily penetrated. At the same time, the main cold air mass, the depth of which was at least a few hundred meters, had previously moved over a wide zone. Evaluation of the dynamical balance with respect to these features will be the subject of a future work.

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初冬季の関東平野上の局地前線の気流の収支構造

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日本海沿岸を東進する総観規模低気圧に伴って初冬季の関東平野にしばしば出現する局地前線の気流構造を、1996年12月5日に観測された例について解析した。前夜からの北部・西部の山地方面から吹く下層風が平野部に冷気を供給していた。低気圧暖域の総観規模の南風が平野南部で夜半からしだいに強まり、北部からの冷気塊との間に局地前線を形成した。

南風は前線面において下層の北風が供給する冷気を取り込み、相対的に冷たい南風の「遷移層」を形成して、冷気を運び去る。前線の北側後背部で観測した各層の厚さはかなり定常的で、下層の冷気供給量に対する遷移層内の北向き冷気輸送量の過剰分は、前線の北進に伴う前線先端部の冷気量の減少にほぼ対応する。しかし、下層の冷気流は午後まで持続し、そのため前線は平野中央部に維持される。

なお、前線の先端部の構造の一例として、前線通過前の東京都心周辺では、厚さ 50 m あるいはそれ以下の冷たい弱風層が 2 時間以上持続した点が特徴的であった。