Three-Dimensional Analysis of a Cold Front
Associated with Meso-scale Disturbances

by

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Abstract

A three-dimensional analysis of a cold front with squall lines was made, using 6-hourly aerological data around Japan on 12th and 13th Dec., 1957. A squall front was analysed in front of the cold front, where the direct circulation was prominent. A strong southerly low-level jet was observed ahead of the cold front. Estimation of the order of magnitude of each term on the equation of motion was made, which showed strengthening or weakening of southerly jet \( v \) was mainly due to the horizontal advection. As to the change of \( u \)-momentum, the ageostrophic wind component was large and comparable with the horizontal advection term.

The actual wind followed the geostrophic one with a lag time of several hours, which caused large ageostrophic wind components.

The pattern of the observed rain fall amount coincided with the expected one computed by the total amount of liberated heat by condensation.

1. Introduction

Recently, the 'meso-scale disturbance' is widely considered important for the heavy rains in summer or the high winds in winter. It is often called a squall line or an instability line found ahead of a cold front, in the warm sector of a cyclone.

The main features of the generation and the maintenance of a squall line are that (1) the squall line generates around the cold front and moves more rapidly than the front (Newton 1950). Its life time is, in general, about fifteen hours at most (2) a meso-scale high pressure cell is often observed along the squall line (Fujita 1955), (3) the vertical structure of the warm sector of the cyclone is extraordinarily unstable (Breliand 1958); a large amount of warm and moist air plunges into the warm sector at the lower level, and (4) a southerly low level jet stream is mostly observed, where the anomaly of the actual wind from the geostrophic one is very large (Matsumoto and others 1962).

We have many important subjects left to be considered.

Ordinarily, the vertically unstable field can not be maintained for a long time.
A small-scale thermal convection generates there, which stabilizes the field. What causes the field to be maintained so unstable for such a long time?

What are the features of the vertical circulation around the squall line? According to the analysis of C.W. Newton (1950), in his study of the structure and mechanism of prefrontal squall lines, a strong upward current existed ahead of the squall front, while a general descent of air from above the polar front and a very pronounced descent in the region within a distance of 20-30 miles behind the squall front, were deduced from the analysis of wet-bulb potential temperature and the distribution of moisture or the cloud system.

What is the mechanism of the generation and the maintenance of the low-level jet stream? And what is the role of this jet in the generation of meso-scale disturbances or the heavy rains? It may now be an established fact that one of the most significant phenomena is the existence of a lower southerly jet when the heavy rains are observed in summer. According to the results obtained by the staff members of Meteorological Research Institute, this jet-like current lasted for more than a week with a several hundred kilometers width, corresponding to the heavy rains from June 24th to 30th in 1961 around Japan. The remarkable feature was that the maximum velocity was above 50 knots in the jet core at about 800 mb level in spite of summer. And in this case, the vertical circulation around the jet core was one of indirect sense.

Newton showed that a significant factor for squall line formation is the unbalance between thermal wind and actual wind shear, which Y. Sasaki has supported by his study in ‘a numerical experiment of squall-line formation’ (1959). And he also suggested that the role of a strong southerly flow at low level may be indirect and appears to be important for supplying moisture from ocean areas, while the mechanism of the jet stream, being supergeostrophic, was left unsolved.

Does the baroclinic instability play an important role in the squall line activity? Should we think this phenomenon as a gravitational wave as M. Tepper has stated applying the hydrodynamic shock theory by Freeman?

There are three subjects to be considered: to construct a three-dimensional structure of a squall line, and to pursue its whole life time; to study the mechanism of development or maintenance of the squall line in its meso-scale domain (within 100 km); and to analyse the large-scale field with meso-scale disturbances. How is the correspondence between the actual wind and the pressure system? How does the heat released by condensation have an effect on the development of the system? As a preliminary work, it may be necessary to know the balance between each term in the equation of motion and that in the thermodynamical equation.

The first subject will be described in §3 and §4. In §5 and §6, the third problem will be discussed. The second theme could not be taken up because of the sparseness of the data.

2. Data sources and its treatment

In this paper, the three-dimensional analysis of a cold front with squall lines is presented, which followed the major cyclone moving northeastwards with a velocity of 80 km/hour over the Japan Sea on 12th and 13th of Dec., 1957.

As this period belonged to ‘the world day’ in the International Geophysical Year,
we could obtain 6-hourly radiosonde and pilot balloon observations.

The aerological observation stations being sparse in time and space, it is very difficult to construct a detailed structure of the meso-scale disturbance. In this paper, the following technique was adopted to analyse the field with disturbances.

1) A detailed vertical-time section was constructed in every observation station. Every significant-level observation was used so as to find the inversion, front, or any other disturbances. When constructing the isobaric weather map, the time-to-space transformation was used, if necessary.

2) The identification of a cold front or a squall front was made by making use of the ascent curves on the emagram, depending on the principle of continuity or conservation of quality with time and space as to the disturbance.

3) As for the surface analysis, the abundant hourly data were used. In addition to it, we could also use the self-recording data.

4) Based on these data and the preliminary analysis, the isobaric weather maps were constructed in every 50 mb interval from surface to 500 mb level. For the purpose of numerical computation, every quantity was read at grid points with 100 km distance.

![Fig. 1. Station map. The inner rectangular shows the region subjected to detailed analysis. Mesh used for calculation.](image-url)
Domains analysed and used for calculation are shown in Fig. 1.

In order to make clear the mechanism of the low-level jet, estimations of divergence, vertical $p$-velocity, and each term in the equation of motion and also in the thermodynamical equation were made every six hours from 21 JST 12 Dec. to 21 JST 13 Dec., while the jet stream was strong. For the calculation, a finite difference method as has been used in routine work of numerical weather prediction was adopted. The derivative of any quantity was substituted by the centered difference.

The values of the horizontal divergence were computed as

$$D = \frac{m}{2 \cdot D S} (u_1 - u_3 + v_2 - v_4),$$

where $u$ and $v$ are the eastward and the northward wind components relative to the new rectangular co-ordinate on the map projected by the Lambert method. The origin of this co-ordinate is at 35.0°N. and 135.0°E. shown in Fig. 1. And $m$ is the magnification factor, $D S$ is the distance between grid points (100 km). The vertical $p$-velocity $\omega = \frac{\partial p}{\partial t}$ was computed by successive addition of the horizontal divergence by the continuity relation,

$$\omega(I, J, K+1) = \omega(I, J, K) + \frac{\rho(K) - \rho(K-1)}{2} (D(I, J, K) + D(I, J, K+1)),$$

$$\omega_0 = (\frac{\partial p}{\partial t} + V \cdot F_h p)_{z=h},$$

where $\omega(I, J, 1)$ means the $p$-velocity on the surface $\omega_0$, $p$ the surface pressure at the station, $V$ the horizontal velocity, $F_h$ the horizontal derivative along the surface, $(I, J, K)$ means the mesh points in $(x, y, p)$ coordinate, $\rho(K)$ the pressure on $K_{th}$ level.

3. Surface analysis

At the incipient stage (about 21 JST, 12th), a remarkable plunge of warm air was observed ahead of the cold front in the warm sector of the cyclone. A weak temperature drop and pressure rise were found at about 100 km in front of the cold front. The rainy areas were already observed corresponding to the cold front and squall line, respectively. Meanwhile, the wind field showed a strong southerly jet-like current at the center line of the warm tongue. The maximum velocity reached 40 knots on the surface.

Figs. 2-a, 2-b, 2-c shown the horizontal time section at 30°N between 13° and 140°E of sea-level pressure (mb), southerly jet by north-southward component (m/sec), and the corresponding geostrophic wind component (m/sec) on the surface, respectively.

The pressure-gradient greatly increased about 200 to 300 km ahead of the cold front, where the maximum value of geostrophic wind exceeded 30 m/sec. In the mean time, the actual jet stream appeared about 12 hours after the occurrence of the maximum geostrophic wind, which is to be investigated in detail afterwards.

Accordingly, the actual wind was weaker than the geostrophic one (subgeostrophic) at the squall line in the incipient time, while supergeostrophic wind blew after the squall line had disappeared.
Fig. 2a. Horizontal time section along 30°N between 130°E and 140°E of sea level pressure (+1000 mb).

Fig. 2b. Wind velocity by the north-south component (m/sec) on the surface.

Fig. 2c. The corresponding geostrophic wind component (m/sec). The left side numeral means the time (JST). The double line shows the cold front on the surface.

Fig. 3. Surface map at 00 JST 13th (mature stage). Thick solid line shows the pressure, thick dotted line the temperature, single thick line the cold front, doubled thick line the squall front.
At about 00 JST, 13th, the meso-scale disturbance entered into the mature stage shown in Fig. 3. In order to identify the squall line around Japan, it is necessary, in most cases, to use the self-recording data, for the high pressure cell or the temperature drop is not so remarkable. But in this case, the meso-high was so marked stretching northeast to southwestward with 500 km length and 200 km width, the squall line was easily identified by the pressure jump, temperature drop, showers, thunders, and/or strong wind by using the hourly data. In addition, some of the self-recording data were referred to, which showed marked pressure jump with more than 3 mb/10 min. at several stations.

Fig. 4 shows the propagation of the squall line and the cold front thus decided.

4. Cross section analysis

1) Vertical time section

In the first place, we should find out the disturbances or the fronts above ground and identify them. For this purpose, the ascent curves of several stations on the emagram were used. Some of them are shown in Figs. 5a-5c, where the capital letters underneath show the station name, each four numerals the day and the time (JST).

In Fig. 5-a, we can see a distinguished discontinuity layer or inversion layer denoted by S. This may be a kind of fronts, which we call the secondary fronts in this paper. Under these fronts, another inversion layer denoted by W is easily recognized. This is a warm front associated with the cyclone in question. Next, in Fig. 5-c, we can also find out the secondary front S rather in the upper layer. Besides, a marked inversion layer or stable layer named C is expressed on the emagram. This is a cold front or a main polar front.

On the time between these shown in Figs. 5a and 5c, another stable layer, denoted by I in Fig. 5b, is identified which is neither a cold front, a secondary front nor a warm front. We can make sure of this by comparison of the potential temperatures of the stable layers or by the lapse rate analysis. This may be a squall front continuing to the instability line on the surface.
The characteristic potential temperature of each layer is about

\[ 310^\circ K \sim 296^\circ K \] for secondary front
\[ 300^\circ K \sim 292^\circ K \] for squall front
\[ 292^\circ K \sim 284^\circ K \] for warm front
and
\[ 296^\circ K \sim 284^\circ K \] for cold front respectively.

Fig. 6 shows the vertical time section at Kagoshima where the squall front could be detected in the lower layer. The marked main polar front has divided the whole air mass into two parts. The squall line on the surface passed Kagoshima at about 23 JST on the 12th, while the cold front at about 03 JST on the 13th, which was made sure by making use of the hourly data of the stations in Japan.
Fig. 7. East-west cross section along 35°N. The same for Fig. 6.
The identification of the squall front in the free atmosphere is generally very difficult as its time scale and horizontal scale are small. But in this case, using the sequence of 6-hourly aerological data at Kagoshima, we could find two series of temperature discontinuity from ground to 700 mb level both between 21 on 12th and 03 on 13th, and between 03 and 09 on 13th. The former was the squall front and the latter the cold front. There existed a stable layer between 700 mb and 770 mb, corresponding to the squall front on 03, 13th, which seemed to prolong and contact with the cold front on that level.

Another characteristic feature was that the strong lower southerly jet-like current existed just in front of the squall front, whose maximum wind velocity exceeded 20 m/sec in the north-south component.

2) East-west cross section

As the squall line or the cold front stretches in the direction of SW to NE or SSW to NNE, the east-west cross sections are shown in Figs. 7 and 8. To draw this cross section, the vertical time section and ascent curve at each station were used thoroughly. The hatched area in the Figs. means the frontal zone. The thin solid lines show the temperature, the thick solid lines the observed wind velocity in the north-south direction. Thus the wind and temperature field were drawn independently of each other, but their correspondence was fairly good nevertheless. And also the divergence pattern corresponded to the frontal system (Fig. 9). At 2100, 12th., it was a divergence field rather than convergence around to cold front, while there was found a strong convergence zone from surface to 600 mb in the middle layer around the squall front. This may suggest the existence of a strong upward current over the squall front, and the downward current over the cold front.
Fig. 9. Divergence pattern and the vertical motion along 35°N.

The dotted area shows the convergence zone (divergence in $10^{-4}$ sec$^{-1}$), the thin solid arrow the streamline relative to the movement of the frontal system. Thin solid lines show the vertical $\rho$-velocity (C.G.S.)

Fig. 10. Potential temperature (solid, °K) and mixing ratio (dotted, gm/kg) at 35°N.
At 0300 13th, the squall line on the surface was going to dissipate and could hardly be detected except for the weak stable layer over Kagoshima and Yonago in the middle layer, contacting with the cold front. But the divergence pattern showed a distinguished convergence zone in the lower layer over the squall line on the surface (Fig. 9-b).

Fig. 10 shows the potential temperature (thin dotted lines, deg. K) and the mixing ratio (thick solid, gm/kg) around the fronts. The jet was found warm and moist, and also the upper air had become wet where the upward motion was distinguished, (Fig. 9) and the dry air existed in the region of downward motion. A life time of the jet stream thus could be pursued from developing to dissipating stage as shown in Figs. 7a to 8b.

On the 35°N cross section, the jet which was strongest at 03 JST had weakened already, and the position of its core revealed itself rather in the upper layer (600 mb) at 09 JST. However, the strongest flow in the whole period was observed at this time (09 JST) on the 37°N cross section in the lowest layer near 950 mb (Fig. 8a).

5. Estimation on the equation of motion

In order to make clear the mechanism of the strong jet at low level, an estimation of the order of magnitude of each term on the equations of motion was made. The equations are

\[
\frac{\partial u}{\partial t} + V \cdot F u + \omega \frac{\partial u}{\partial p} - f(v - v_g) = F_x,
\]

\[
\frac{\partial v}{\partial t} + V \cdot F v + \omega \frac{\partial v}{\partial p} + f(u - u_g) = F_y,
\]

where \( u_g \) and \( v_g \) represent the geostrophic wind velocity in its east-west, and north-south component respectively. \( F_x \) and \( F_y \) mean the frictional force.

Comparison of the wind with the pressure gradient showed us that the strong jet itself was nearly geostrophic at the incipient stage. And the contrast of super- and sub-geostrophic wind was prominent at the east and west side of the jet, respectively (21 JST, 12th) (Fig. 11-a). Six hours later, the strong wind region had spread over the whole warm sector of the cyclone. The strongest wind exceeded 30 m/sec on 850 mb level. (Fig. 11b). As Fig. 11c shows, the strongest wind region appears to have concentrated in a narrow area surrounded by the warm- and cold-front near the center of the cyclone (09 JST, 13th). The jet over Wajima, being undoubtedly supergeostrophic, blew into the center of the cyclone nearly perpendicular to the isobar.

Now the results of order estimation of the magnitude of each term in the equation of motion are described below for the east-west vertical cross section on 37°N between 130°E and 140°E, 09 JST, 13th.

Figs. 12 show the horizontal advection \( (V \cdot F u) \), Fig. 12a, the vertical advection of u-momentum \( (\omega (\partial u/\partial p)) \), Fig. 13b, the ageostrophic wind component \( (f(v_g - v)) \), and Fig. 12c, on the 37°N-east-west vertical cross section at 03 JST, 13th.
Fig. 12-d shows the expected velocity change \( \frac{\partial u}{\partial t} \) calculated by the equation of motion assuming that the frictional force is neglected \( (F_x=0) \).

As for the comparison of this expected velocity change with the observed one, the actual changes from 03 JST to 09 JST and from 09 JST to 15 JST are shown in Figs. 12-e and 12-f. In spite of the rough estimation under a lot of assumption, these patterns correspond considerably well with each other, except for their magnitude.

Similar results were obtained for the \( y \)-component in Fig. 13. The most effective term on the expected change of \( u \)- or \( v \)-momentum was the advective term \( \mathbf{V} \cdot \nabla u \) or \( \mathbf{V} \cdot \nabla v \), respectively. Results shown in Figs. 12 and 13 tell us that the order of magnitude of each term is roughly described in Tables 1 and 2.
Fig. 12. Order estimation of each term in the equation of motion on $u$-component along 37°N vertical section 09 JST 13th (C.G.S. unit)

Table 1.

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$\left( \frac{\partial u}{\partial t} \right)_{obs}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$V \cdot p u$</td>
<td>0.3</td>
</tr>
<tr>
<td>$\omega \cdot \frac{\partial u}{\partial p}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$f(v_{g}-v)$</td>
<td>0.3</td>
</tr>
<tr>
<td>$\left( \frac{\partial u}{\partial t} \right)_{exp}$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 2.

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$\left( \frac{\partial v}{\partial t} \right)_{obs}$</td>
<td>0.2</td>
</tr>
<tr>
<td>$V \cdot p v$</td>
<td>0.4</td>
</tr>
<tr>
<td>$\omega \cdot \frac{\partial v}{\partial p}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$f(u-u_{g})$</td>
<td>0.1</td>
</tr>
<tr>
<td>$\left( \frac{\partial v}{\partial t} \right)_{exp}$</td>
<td>0.4</td>
</tr>
</tbody>
</table>

(in C.G.S. unit)
The horizontal advection term $\mathbf{V} \cdot \mathbf{F}u$ or $\mathbf{V} \cdot \mathbf{F}v$ is likely to cancel with the vertical advection term $w(\partial u/\partial p)$ or $w(\partial v/\partial p)$, respectively.

The distinguished strengthening or weakening of the southerly jet $v$ was mainly due to the horizontal advection $\mathbf{V} \cdot \mathbf{F}v$; while, as to the change of $u$-momentum, the ageostrophic wind component $f(v_g - v)$ was comparable with the horizontal advection term $\mathbf{V} \cdot \mathbf{F}u$ in the equation (1), but the former does not always cancel with the latter. We will now discuss the cause of this large non-geostrophic wind.

One of the most difficult points on the estimation was that we had only data observed 6-hourly, which is nearly the same as the time scale of the disturbance. Accordingly the observed velocity change, $\partial u/\partial t$ or $\partial v/\partial t$, was generally smaller than the expected one in magnitude.

To complement this disadvantage, we show the correspondence between actual wind observed hourly and the geostrophic one calculated 3-hourly at the station on the surface (Figs. 14 and 15).

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Fig. 13. Same as Fig. 12 but for $v$-component.
On the surface, the actual wind was below 50% of the geostrophic wind velocity owing to the effect of surface friction. And the Figs. 16 show the 6-hourly sequence of wind velocity in the north-south component (solid line) and of the corresponding geostrophic wind (dotted line) along the latitude between 130°E and 140°E both at 850 mb level (lower) and at 500 mb level (upper), from 21 JST, 12th to 13th. The interesting feature was that the magnitude of these two winds was nearly equal but with some difference in phase in the lower layer.

At the incipient stage (21 JST 12th), the actual wind was stronger to the east of the geostrophic jet. At 03 JST 13th, the wind was nearly geostrophic or a little super geostrophic, but the pattern of the two winds was fairly the same. Six hours later, when the maximum jet appeared over Wajima, this extraordinary jet was completely ageostrophic and lay to the west of the geostrophic jet core. And again several hours after these two winds nearly coincided with each other. It seemed to us that the actual wind was oscillating around the geostrophic jet core with about 30 hours' period, which caused the strong ageostrophic wind. While the period of the pure inertia oscillation is about 18 hours in this domain and the period of inertiagravity wave is generally less than the pure inertia oscillation, which means that this prominent oscillation can not at once be identified as the inertia wave.

This distinguished oscillation was seen only in the lower. At 500 mb level, the actual wind was always nearly geostrophic.
Fig. 16. Correspondence between actual wind (solid) and geostrophic one (dotted) along latitudes between 130°E and 140°E.
6. Estimation on the thermo-dynamic equation

There is no doubt that the strong upward current induces the condensation in the lower and middle layers. Y. Sasaki pursued a life time of a squall line in its early stage and concluded that the role of liberation of latent heat may be important in its developing stage, having an effect on the change of the pressure system.

In this paper estimations of the individual change of potential temperature, and also the change of mixing ratio of water vapour were made by the equations

\[
Q_t = \frac{C_p}{\left(\frac{P_0}{\rho}\right)^{\gamma-1}} \left(\frac{\partial \theta}{\partial t} + \mathbf{V} \cdot \nabla \theta + \omega \frac{\partial \theta}{\partial \rho}\right),
\]

\[
Q_v = -L \left(\frac{\partial q}{\partial t} + \mathbf{V} \cdot \nabla q + \omega \frac{\partial q}{\partial \rho}\right),
\]

\[\gamma = C_p/C_v,\]

Fig. 17. Heat sources and sinks \(Q_t\) and \(Q_v\) \(\times 10^{-4}\) cal/gm·sec) on the vertical cross section along latitudes 35°N or 37°N.
where $C_p$ is the specific heat of air under constant pressure, $C_v$ the specific heat under constant volume, $L$ the latent heat of condensation, $\theta$ the potential temperature and $q$ the mixing ratio of water vapor. Local changes were substituted by the forward difference of 6 hours.

Figs. 17a to 17d and 17e to 17f show the distribution of heat sources and sinks $Q_i$ or $Q_e$ on the vertical cross section along the latitude 35°N and 37°N respectively. The estimated values of heat sources by the two methods were fairly similar to each other. The maximum heat liberation was about 2 cal/gm. hr, where the upward motion was prominent.

Figs. 18 illustrate the contribution of each term in the equation to the heat sources $Q_i$. A local warming was seen in the region of ascending motion during 03 JST 09 JST ahead of the cold front. But after 09 JST an eminent cooling was found in the rear of the front.

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Fig. 18a. Local change of the first term (proportional to potential temperature change) in the equation (3) $\times 10^{-4}$ cal/ gm • sec) from 0300 to 0900, 13th.

Fig. 18a'. Same as 18a but for 0900 to 1500.

Fig. 18b. Same as 18a but for the advection term.

Fig. 18c. Same as 18a but for the vertical advection term.
Fig. 19a. Observed rain fall amount from 2000 to 2100 12th, (mm/hr)

Fig. 19a'. Expected rain fall amount at 2100 (mm/hr)

Fig. 19b. Same as 19a but for 0200 to 0300, 13th.

Fig. 19b'. Same as 19' but for at 0300.

Fig. 19c. Same as 19a but for 0800 to 0900, 13th.

Fig. 19c'. Same as 19a' but for at 0900.
The most effective term on the heat sources was certainly of the vertical advection \( \omega(\partial\theta/\partial p) \), which nearly coincided with the \( Q_t \).

The observed precipitation was compared with the total amount of liberated heat calculated and converted to the equivalent precipitation (mm/hr) (Figs. 19). The pattern of the expected rain fall amount coincided with the observed one except for the slight difference in the position of the rainy area and in its quantity.

7. Concluding remarks

A strong ageostrophic wind was analysed and the oscillation of actual wind around the geostrophic jet core was found, whose mechanism is yet uncertain. It is desired to investigate this using more abundant data as to time and space scale.

The pattern of the observed rain fall amount coincided well with the expected one computed by the total amount of liberated heat by condensation. But the positions of these two rainy areas were slightly different. At the initial stage, the actual rain fall was at the rear of the expected one. At 03 JST these two areas nearly coincided. This fact might suggest a relation similar to the oscillation of actual wind around geostrophic wind.

It should be regretted that in this paper we could not take up the mechanism of squall line formation and development, the relation between the two winds, and so on in a meso-scale discussion. These should be dealt with in near future on the basis of special observation for meso-scale disturbances.

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References

MATSUMOTO and others, 1962: Analysis of heavy rains with low level jet during early summer 1961 (to be published).
中規模擾乱を伴った前線の三次元解析

千秋 誠夫

1957 年 12 月 12 日から 13 日にかけて日本を通過した、スコールラインを伴った前線の解析を、6 時間ごとの高层データを用い行なった。寒冷前線の前面にスコールフロントが解析され、そのまわりでは直接循環が認められた。寒冷前線の前面は強い南よりの下層ジェットが見られた。運動方程式の各項の大きさの時間を行なったところ、南よりジェットの強化は主に水平移流の項によることが示された。
実測風は数時間のおくれをもって、地衡風に追従し、そのことが強い非地衡風成分をもたらした。
実測雨量パターンは凝結による潜熱から計算したパターンとよく一致した。