Budget Analysis on the Sea Effect Snow Observed along the Japan Sea Coastal Area

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Abstract

Basing on the aerological observations by smaller scale network which were set up in January of 1963, 1964 and 1965 in Hokuriku district, the Japan Sea coastal area of central Japan, the heat and moisture budgets were compared among these three years. The flux divergence of vapor assumes nearly the same values for three winters, whereas the amount of precipitation changes very much from year to year. Although the difference in the evaporation from the sea surface and that in the convective transfer are estimated to be of considerable amount, the precipitation is principally related to the net transport of condensed water either from or to the surrounding region.

The vapor import in 6 hours is compared with 6 hourly precipitation within the region. Better relation is found in the precipitation onto the downstream side stations. It is shown that the sensible heat increment is nearly twice as much as the latent heat decrement if they are computed by mean flow flux divergence. This circumstance is observed well in the cloud layer regardless to the scale of network. The surplus of the heat energy must be transported by convective activity. It is suggested that, when heavier snowfall is observed, the convective activity is so predominant that the more heat energy than that supplied from the sea surface is transported into the cloud layer.

1. Introduction

The Japan Sea plays an important role in winter time weather over Japan, especially her north western coastal region where the north westerly monsoon releases a large amount of water substances which has been stored up over the Japan Sea. Hokuriku district, the Japan Sea coastal region of the central Japan, is well known as the snowiest place and severe snow damages have been recorded quite frequently.

It was shown by Benton and Estoque (1954), Hutchings (1957) and others that the recent development of aerological network made the regional water budget analysis promising.

Obviously the cause of snowfall is to be primarily related to the air mass modification. It has long been tried to correlate the amount of snowfall with the heat supply from the Japan Sea (e.g. Ino and Nishida, 1964). While the air mass modification over the Japan Sea during winter time has been studied by many authors (e.g. Takahashi, 1940), Miyazaki (1949) investigated the interaction between air and sea from the stand point of energy budget of the sea, and Manabe (1957, 1958) and Ninomiya (1964 a, 1964 b) from that of the atmosphere. Kondo (1964) proposed a turbulent exchange formula and revised Manabe's results. Fujita and Honda (1965) summarized the ship observations of the Japan Sea. Matsumoto, Asai and Ninomiya (1963) and Ninomiya (1964 a, 1964 b) discussed the daily variation of heat and moisture with regard to the synoptic situation and they also put a special emphasis on the solid or liquid water transfer.

The redistribution of the thermodynamic energy which is supplied into the atmosphere by turbulent transfer is obviously undertaken by the activities of cumulus convections and must have a significant bearing on the large scale atmospheric motion and, at the same time, on the release of precipitation.

Aerological observation networks of smaller scale have been set up in Hokuriku district for 5 year term by the Heavy Snow Storm
Project together with other observations. Using the data of 3 years from 1963 to 1965, the net flux of sensible and latent heat is considered with special regards to the precipitation intensity and convective activity.

2. Observation and method of computing heat and water-vapor transfer

The project aerological observation was made at Wajima, Niigata and Takayama in 1963 and 1964 and at Wajima, Aikawa, Nagaoka and Toyama in 1965. As is seen from Fig. 1, the 1963 and 1964 network was located partly inland and about 2/3 of the area covers sea, while the 1965 network was located almost offshore.

The observation density is as follows. In 1963 twice a day observation in daytime (09 and 15 LST) was made for 10 day period from January 16 to 25. In 1964 three times a day observation at 09, 15 and 21 LST was made for a week from January 20 to 26. 6 hourly observation was performed in 1965 for a week from January 14 to 20 at 09, 15, 21 LST and 03 LST of the next day. Details of the network are summarized on Table 1.

Since the computations are to be made on pressure coordinate, the equations of continuity of mass, sensible heat and moisture are written as

\[
\begin{align*}
\nabla \cdot \mathbf{V} + \frac{\partial \omega}{\partial p} &= 0 \quad (1) \\
\frac{\partial c_p T}{\partial t} + \nabla \cdot \mathbf{V} c_p T + \frac{\partial \omega c_p T}{\partial p} - \omega \alpha = q \quad (2) \\
\frac{\partial s}{\partial t} + \nabla \cdot \mathbf{V} s + \frac{\partial \omega s}{\partial p} &= e \quad (3)
\end{align*}
\]

where \(T, s, \alpha, V, \omega, c_p, \text{ and } L\) are temperature, specific humidity, specific volume, horizontal velocity, vertical \(p\) velocity, specific heat on constant pressure and heat of vaporization, respectively and \(\nabla\) denotes horizontal divergence. Then \(q\) and \(e\) show heating and evaporation in the unit volume of the system.

The observable quantities are \(T, s, \alpha\) and \(V\) at each of the standard pressure levels and at the earth's surface. While \(\omega\) is to be estimated indirectly by the aid of eq. (1).

The boundary condition at the ground surface should be dealt with very carefully, when the network is located in the mountaneous region. In applying the equations to the vertical air column over the network under con-

<table>
<thead>
<tr>
<th>Year</th>
<th>Station</th>
<th>Elevation</th>
<th>Covering Area</th>
<th>Period</th>
<th>Observation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1963</td>
<td>Wajima</td>
<td>7m</td>
<td>(\times 10^8)m(^3)</td>
<td>Jan. 16~Jan. 25</td>
<td>00, 06 GMT</td>
</tr>
<tr>
<td></td>
<td>Niigata</td>
<td>6</td>
<td>136</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Takayama</td>
<td>561</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1964</td>
<td>The same as above</td>
<td></td>
<td></td>
<td>Jan. 20~Jan. 26</td>
<td>00, 06, 12 GMT</td>
</tr>
<tr>
<td>1965</td>
<td>Wajima</td>
<td>7</td>
<td>119</td>
<td>Jan. 14~Jan. 21</td>
<td>00, 06, 12, 18 GMT</td>
</tr>
<tr>
<td></td>
<td>Aikawa</td>
<td>36</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nagaoka</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Toyama</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
consideration, let us first of all integrate the equations (1), (2) and (3) vertically from the ground surface \( (p_s) \) to a certain pressure surface \( (p_i) \).

We obtain

\[
\omega_i = \omega_s + \int p_i Vdp - V_i p_i = \frac{\partial p_s}{\partial t} + \int p_i Vdp \tag{1}'
\]

\[
\frac{\partial}{\partial t} \int p_i c_p T \frac{dp}{g} + \int p_i V_c p_i c_p T \frac{dp}{g} - \frac{1}{g} \omega_c c_p T_i
\]

\[
- \int p_i \omega \frac{dp}{g} = \int p_i \frac{dp}{g} \tag{2}'
\]

\[
\frac{\partial}{\partial t} \int p_i s \frac{dp}{g} + \int p_i Vs \frac{dp}{g} - \frac{1}{g} \omega_i = \int p_i \frac{dp}{g} \tag{3}'
\]

Denoting the horizontal average over the network by bar, the averaged vertical velocity is obtained from the actual observation as follows,

\[
\bar{\omega}_i = \frac{\partial \bar{p}_s}{\partial t} + \frac{1}{A} \int \left( \int p_i Vdp \right)_n dS \tag{4}
\]

where the suffix \( n \) indicates the outward normal component along the boundary and \( dS \) and \( A \) are the line element and the area.

Let us write the second term

\[
\omega^* = \frac{1}{A} \int \left( \int p_i Vdp \right)_n dS \tag{5}
\]

which is equivalent to the total mass outflux. The suffix \( i \) indicating the value at a pressure surface under consideration is omitted from now on. Each terms of eqs. (2)' and (3)' are estimated directly or indirectly. The integrated heating and evaporation is then expressed in terms of observed field of temperature, specific humidity and wind

\[
Q = Q^* - \frac{\partial p_s}{\partial t} c_p T_s - \frac{\partial p_i}{\partial t} \int p_i \frac{dp}{g} \tag{6}
\]

\[
E = E^* - \frac{\partial p_i}{\partial t} s \tag{7}
\]

where

\[
Q^* = \frac{2}{g} \int p_i T \frac{dp}{g} + \frac{1}{A} \int p_i (Vc_p T) \frac{dp}{g} dS
\]

\[
-c_p T \omega^* - \int p_i \omega^* \frac{dp}{g} \tag{8}
\]

\[
E^* = \frac{2}{g} \int p_i s \frac{dp}{g} + \frac{1}{A} \int p_i (Vs) \frac{dp}{g} dS - s \omega^* \tag{9}
\]

The time dependent terms on the right hand side of eqs. (6) and (7) do not appear if the integration is taken for the layer in the free atmosphere.

The actual computational procedure is to approximate the integrations appearing in eqs. (5), (6), (7), (8) and (9) by linear interpolation both between stations and between successive pressure levels. The effect of mountain existing between stations is taken into consideration in a following manner on estimating the mass, heat and vapor fluxes through vertical boundary plane. The ratio of the mountain cross section appearing on this vertical boundary plane to the total area is averaged for each of the layers between successive pressure levels and is employed in obtaining the effective inflow or outflow through vertical plane.

Now it would be convenient to separate the air column into the subcloud layer and the cloud layer. Then the integrated equations of sensible and latent heat are written as

\[
\begin{cases}
Q_1 = -E_p + \frac{1}{g} \omega^c c_p T^c + Q_s + \int \omega c \frac{dp}{g} \\
E_1 = E_p + \frac{1}{g} \omega Ls + E_s
\end{cases} \tag{10}
\]

and

\[
\begin{cases}
Q_2 = C - \frac{1}{g} \omega^c c_p T^c + \int \omega c \frac{dp}{g} \\
E_2 = -C - \frac{1}{g} \omega Ls
\end{cases} \tag{11}
\]

where the suffixes 1 and 2 indicate the total value in subcloud layer and cloud layer respectively, \( Q_s \) and \( E_s \) are the supply of sensible heat and that of latent heat (evaporation), \( C \) the liberated heat due to condensation and \( E_p \) the heat due to evaporation from precipitating element. \( (1/g) \omega^c c_p T^c \) and \( (1/g) \omega Ls \) are the convective transfer of sensible and latent heat through the level of cloud base respectively and \( \int \omega c (dp/g) \) the release of potential energy caused by convection. It is known that the height of cloud base and cloud top is approximately 900 mb and 600 mb respectively on the average of wintertime cloud over the Japan Sea. Therefore it will be reasonable to take the integration domain as shown in Fig. 2. The convective transfer
Fig. 2.

is assumed to vanish at the cloud top level. Beyond this level, it was shown that error in computing divergence and, therefore, vertical velocity becomes significant because of the balloon shift if the smaller network is considered (Matsumoto and Ninomiya, 1963).

In the following discussions, we will ignore the evaporation from precipitating substance and the convective energy conversion since the air in the subcloud layer is nearly saturated over the Japan Sea and the latter is one order smaller quantity than the convective transport (see Matsumoto and Ninomiya, 1966). The pertinent equations we applied are

\[ Q_1 = Q_s + \frac{1}{g} \alpha c_p T' \]  \hspace{1cm} (10)'

\[ E_1 = E_s + \frac{1}{g} \alpha L s' \]  \hspace{1cm} (11)'

\[ Q_2 = C - \frac{1}{g} \alpha c_p T' \]  \hspace{1cm} (12)'

\[ E_2 = -C - \frac{1}{g} \alpha L s' \]  \hspace{1cm} (13)'

and

\[ M = C - P. \]  \hspace{1cm} (14)

The last equation is the integrated continuity equation of water substance, \( M \) and \( P \) being the net flux of water substance and precipitation respectively. From equations (10)\(^\prime\) ~ (13)\(^\prime\) we obtain

\[ Q_1 + Q_2 = C + Q_s \]  \hspace{1cm} (15)

\[ E_1 + E_2 = -C + E_s \]  \hspace{1cm} (16)

\[ Q_1 + Q_2 + E_1 + E_3 = Q_s + E_s. \]  \hspace{1cm} (17)

All the terms on the left hand side are computed by means of rawinsonde observations, while \( Q_s \) and \( E_s \) on the right hand side are estimated by applying the empirical formula to the air and sea surface condition.

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>1963</th>
<th>1964</th>
<th>1965</th>
<th>Ship (1965)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_a ) (Wajima, Takada)</td>
<td>-0.9°C</td>
<td>1.8</td>
<td>2.6</td>
<td>5.9</td>
</tr>
<tr>
<td>( T_s ) (Wajima, Aikawa)</td>
<td>9.5°C</td>
<td>9.1</td>
<td>9.9</td>
<td>12.4</td>
</tr>
<tr>
<td>( V ) (Wajima, Aikawa)</td>
<td>8.1 m/sec</td>
<td>5.2</td>
<td>5.9</td>
<td>6.1</td>
</tr>
<tr>
<td>( Q_s )</td>
<td>463 ly/day</td>
<td>209</td>
<td>248</td>
<td>215</td>
</tr>
<tr>
<td>( e_a )</td>
<td>3.9 mb</td>
<td>4.9</td>
<td>5.2</td>
<td>6.9</td>
</tr>
<tr>
<td>( e_s )</td>
<td>11.8 mb</td>
<td>11.5</td>
<td>12.2</td>
<td>14.1</td>
</tr>
<tr>
<td>( E_s )</td>
<td>544 ly/day</td>
<td>292</td>
<td>351</td>
<td>373</td>
</tr>
</tbody>
</table>

3. **The estimation of the evaporation and sensible heat supply at the coastal area**

The direct measurement of the fundamental parameter concerning air sea interaction at open sea was made by the maritime observation ship "Seifumaru" in 1965 surveying the area under consideration. However, in 1963 and 1964, there were no such simultaneous observations. By means of coastal sea temperature, air temperature and wind velocity let us try to estimate the sensible heat supply \( Q_s \) and the latent heat supply (evaporation) \( E_s \) from the sea surface.

In Table 2 are given the averaged air temperature \( T_a \) in °C at representative stations, Wajima and Takada, the averaged sea temperature \( T_s \) in °C at coastal stations, Wajima and Aikawa, and the averaged wind velocity \( V \) in m/sec unit at Wajima and Takada for each of 3 years' observation intervals. Applying the values mentioned above to the Jacobs experimental formula (Jacobs, 1951)

\[ Q_s = 5.5 \times V(T_a - T_s) \]  \hspace{1cm} (18)

we obtain the value of \( Q_s \) in ly/day listed in Table 2. The ship observation in 1965 is given on this table for the sake of comparison. It is seen that the \( Q_s \) evaluated indirectly from the conventional observations is quite reasonable in spite of large discrepancies in air and sea temperatures themselves. It may probably be due to the fact that air temperature is largely modified by sea temperature.

Similarly, the water vapor pressure of air \( e_a \) in mb unit, the saturated water vapor pressure at sea temperature \( e_s \) in mb unit and evaporation \( E_s \) in ly/day unit given by the Jacobs formula
are given in Table 2. It is seen that the values estimated by land observations agree considerably well with those obtained by ship observations for 1965. Therefore those values of 1963 and 1964 appearing in Table 2 will be used for the budget analysis in the following section.

4. **Comparison of the 3 years budget analyses basing on the dense rawinsonde observation network**

Let us estimate various terms in the thermodynamic equation, the continuity equations of vapor and water substance by making use of the materials obtained by small scale rawinsonde network of 1963, 1964 and 1965. The amount of precipitation is different from year to year. The year of 1963 is well known by the unprecededly heavy snowfall. On the contrary, in the next year 1964 the amount of snowfall was very small. The year of 1965 is, so to speak, an average year as far as the precipitation concerns.

The amount of precipitation relevant to the budget analysis is obtained by averaging the total amount of precipitation in selected stations during the observation period. For this purpose, we selected about 30 synoptic stations inside of the network and took the simple arithmetic average by ignoring the lack of data over sea. It does not seem to cause a serious error since the linear extrapolation from surrounding stations is approximately verified by the observations in islands. The ratio of the sea area to the whole area of the network is about 0.6 for 1963 and 1964 network and about 0.9 for 1965 network. The amount of precipitation thus obtained is as follows:

<table>
<thead>
<tr>
<th>Year</th>
<th>Amount of Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1963</td>
<td>18.1 mm/day</td>
</tr>
<tr>
<td>1964</td>
<td>4.4</td>
</tr>
<tr>
<td>1965</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Table 3.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>Waj-Tak-Niig 1.36×10^4 km²</td>
<td>Waj-Tak-Niig 1.36×10^4 km²</td>
<td>Waj-Toy-Nag-Aik 1.19×10^4 km²</td>
<td>Waj-Tat-Aki 5.67×10^4 km²</td>
</tr>
<tr>
<td>Q₁</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Q₂</td>
<td>61</td>
<td>30</td>
<td>48</td>
<td>25</td>
</tr>
<tr>
<td>E₁</td>
<td>-1</td>
<td>-4</td>
<td>-3</td>
<td>-3</td>
</tr>
<tr>
<td>E₂</td>
<td>-21</td>
<td>-20</td>
<td>-22</td>
<td>-11</td>
</tr>
<tr>
<td>Q₃</td>
<td>13</td>
<td>6</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>E₄</td>
<td>15</td>
<td>8</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>P</td>
<td>45</td>
<td>11</td>
<td>21</td>
<td>33</td>
</tr>
<tr>
<td>E₁+E₂</td>
<td>-22</td>
<td>-24</td>
<td>-24</td>
<td>-14</td>
</tr>
<tr>
<td>Q₁+Q₂+E₁+E₂</td>
<td>41</td>
<td>7</td>
<td>26</td>
<td>14</td>
</tr>
<tr>
<td>Q₃+E₄</td>
<td>28</td>
<td>14</td>
<td>25</td>
<td>14</td>
</tr>
<tr>
<td>C</td>
<td>38</td>
<td>32</td>
<td>40</td>
<td>21</td>
</tr>
<tr>
<td>M</td>
<td>-8</td>
<td>21</td>
<td>19</td>
<td>-12</td>
</tr>
<tr>
<td>-1/(\omega/c_p T^'/g)</td>
<td>11</td>
<td>5</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>-1/(\omega/Ls^'/g)</td>
<td>16</td>
<td>13</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>(Q_1/E_4)</td>
<td>0.85</td>
<td>0.72</td>
<td>0.58</td>
<td>0.85</td>
</tr>
<tr>
<td>(\omega/c_p T^'/\omega/Ls^')</td>
<td>0.65</td>
<td>0.38</td>
<td>0.36</td>
<td>0.47</td>
</tr>
<tr>
<td>(\bar{\omega})</td>
<td>-10.0</td>
<td>-4.6</td>
<td>-6.4</td>
<td>-1.4×10⁻³ mb/sec</td>
</tr>
</tbody>
</table>

Unit in ly/hour if not specified.
The various quantities which are necessary for the budget analysis are listed up in Table 3. The quantities in the first row are obtained by aerological observations and those in the second row are obtained by the surface observations. The third row is for verification. The values which are to be computed indirectly are listed in the fourth row. The last two rows are for the sake of comparison.

The fourth column is devoted to the budget of wider area which are covered by routine stations in the central Japan. The sea area is only 1/3 of the total area.

Before discussing the results, let us, first of all, see the accuracy of the computation. Eq. (17) shows that the net change of the total heat energy in the lower atmosphere \( Q_1 + Q_2 + E_1 + E_2 \) ought to agree with the total energy supply from the earth surface \( Q_s + E_s \), if the kinetic energy release due to convection is to be ignored. It may safely be said that the figures given on the third row show a good agreement, if the following circumstances are taken into consideration.

As is seen from Table 1, the 1963 and 1964 network is located in a mountaneous region where the effect of the orography is very much complicated in computing horizontal fluxes. The linear interpolation between the stations may cause errors. Furthermore the observation density of these two years is not uniform but weighted on daytime. The computations, the results of which are given in the third and the fourth column are free from these defects and it is quite natural to get much better agreements. The values of \( Q_s \) and \( E_s \) listed here are obtained by ignoring the heat supply and the evaporation from the ground surface. This may be regarded as another reason of the advantage of 1965 observation since the most part of the computation area is the sea and the observation by ship is available.

We can point out a couple of remarkable facts from Table 3. The gain of total heat energy in the atmosphere \( Q_1 + Q_2 + E_1 + E_2 \) changes very much from year to year and the amount of precipitation assumes the value similar to it. The most striking feature is found in the water vapor budget, i.e., in the fact that \( E_1 + E_2 \) has an almost constant negative value. In other words, it may be said that the amount of water vapor transported into the coastal region does not change from year to year. As a consequence, the rate of condensation in the atmosphere \( C \) is not expected to change so much as the precipitation \( P \) does. Thus the difference between these two quantities necessarily requires the transport of water substances other than vapor \( M \).

As is seen from Table 3, in the year of heavy snowfall, i.e., 1963, the region under consideration is found to be a sink of water substance and the same region becomes a source region in the following years of light snowfall. As is easily inferred, the transport of water in a form of cloud particles and possibly snowflakes has an important contribution to the amount of snowfall. Ninomiya (1964 a) studied the water substance budget over the whole area of the Japan Sea and her vicinity and showed the importance of water substance transport.

Concerning the convective transfer of sensible heat and latent heat, let us try to derive some informations on the feature of convection itself by taking three years average. We can estimate the average excess temperature and excess specific humidity by applying eq. (V) in the appendix as follows,

\[
\Delta T = 1.7 \, ^\circ C \\
\Delta s = 1.5 \, \text{gr/kg} 
\]

which in fact are realistic values for the cumulus convection.

In the fifth row are given the Bowen ratios at the sea surface and the cloud base level. It is seen that the Bowen ratio is smaller if the temperature is lower at the sea level and that the Bowen ratio at the cloud base level is smaller than that at the sea level as was suggested by Matsumoto and Ninomiya (1966).

Total supply of energy from the Japan Sea has been studied by many authors for various periods. The method of estimation is divided roughly into two categories, one by surface conditions and the other by budget in the atmosphere. First of all let us see energy supply (sensible heat and latent heat) of the monthly mean situation. Miyazaki (1949) obtained the value of 420 ly/day by means of sea budget for the winter months of 1935–1940. Manabe (1958) revised this value to be
880 ly/day. He also computed the atmospheric budget of January and February in 1955 and obtained the value of 895 ly/day. While for the particular month of heavy snowfall, January 1963, Fujita and Honda (1965) obtained the value of 947 ly/day by the surface conditions and Ino and Nishida (1964) 512 ly/day by the monthly mean surface conditions particularly at coastal stations. Attention is given specifically either to the predominant monsoon outburst situation or to the heavy snowfall situation. Manabe (1958) gave the value 1480 ly/day by making atmospheric budget computation for the predominant monsoon period from December 20, 1954 to January 3, 1955. Kondo (1964) revised this value by correcting the amount of precipitation over sea and obtained 1261 ln/day, which agrees fairly well with the value 1232 ln/day estimated by the surface condition. As to the unprecededly heavy snowfall period from January 16 to 25, 1963, the atmospheric budget analysis was made by Ninomiya (1964 a, b) and the analyses on the surface condition were made by Fujita and Honda (1965), and the obtained values are 1450 ln/day and 1180 ln/day respectively. The latter value is to be compared to the coastal value 1007 ln/day given in Table 2. It is clearly seen that the energy supply from the sea surface changes in a wide range and that the atmospheric budget computation usually gives larger value than the surface condition analysis.

The vertical distribution of $Q$ and $E$ as defined by eqs. (6) and (7) is given in Fig. 3 by full lines and broken lines respectively for each of 3 year's observation intervals. A noticeable fact is that the vertical distribution of net flux of water vapor $E$ as well as the integrated value does not change very much from year to year. The vertical distribution of vertical velocity $\omega$ is given in Fig. 4 for each of 3 year's observation intervals. The fact that the maximum upward motion is found in the lower troposphere is considered to show the averaged effect of convective motions. It is suggested that the convective activity on the average is more predominant and reaches at higher levels for the year of more precipitation.

5. **Net change of heat and moisture flux and its relation to the precipitation**

Let us discuss the time change of heat and moisture budget basing on the more reliable and the more frequent rawinsonde observations made in 1965. Since the observations were made 6 hourly, the amount of precipitation required for the budget analysis is estimated by the 6 hourly observations at selected 13 synoptic stations given in Fig. 1 (9 stations indicated by white circles together with 4 network stations).

Those 13 stations are tentatively divided into two groups, upwind side 5 stations and downwind side 8 stations, and the amount of precipitation is averaged separately for these two groups. Thus the upwind side precipitation and the downwind side precipitation are given in Fig. 5 as functions of time by dashed line and full line respectively. While the net change of moisture in the total air column...
Fig. 5. Time changes of $E_1 + E_2$ (thinner full line), upwind side precipitation (dashed line) and downwind side precipitation (heavy full line) respectively for the observation interval from 09 LST Jan. 14 to 03 LST Jan. 21, 1965. White circles show the amount of evaporation from the sea surface estimated by ship observations.

$E_1 + E_2$ is shown in this figure by a thinner full line. It is noticed that $E_1 + E_2$ is correlated to the downwind side precipitation much better than to the upwind side precipitation.* The evaporation from the sea surface estimated by ship observation is shown by circles. Since the amount of evaporation is seen to have rather uniform effect on precipi-

Fig. 6 The relation between $Q$ and $-E$ for the 100 mb layer between 700 mb and 800 mb level obtained by 6 hourly observation in 1965.

* According to the personal communication, Rikitake will soon write a paper in which the convergence in the same area is shown to be correlated to the downwind side precipitation.

Fig. 7. Time section of $\omega$ (upper figure labeled in 10^{-3} \text{mb sec}^{-1}) and $Q+E$ (lower figure labeled in ly day^{-1}(100 \text{mb})^{-1})$. Downward motion area and negative $Q+E$ area are hatched.
tation, the change of $E_1+E_2$ shows roughly the amount of condensation within the domain. Therefore the fact mentioned above seems to be quite reasonable. Furthermore remarkable discrepancies are observed between $E_1+E_2$ and upwind side precipitation, especially before the condensation takes its maximum value. These facts presumably imply the advection of condensed water.

The functional relation between $Q$ and $E$ is already studied in many papers. Matsumoto et al. (1963) pointed out that the value of $Q$ is larger than that of $-E$, implying the effect of eddy transfer. The ratio $-E/Q$ assumed then the value of about 0.5. Fig. 6 shows the relation between $-E$ and $Q$ for the convective layers. It is seen from this figure that we again have the ratio of about 0.5. This means that the total heat change $Q+E$ computed by mean field quantities changes approximately like the latent heat change $-E$ which is closely related to the amount of precipitation as is shown in Fig. 5. These circumstances will be understood physically by looking into the relation between $Q+E$ field and vertical motion field. As was pointed out by Elliott and Hovind (1965), $Q+E$ is expressed in terms of convective activity,

$$Q+E = -\frac{1}{g} \omega' (c_p T' + Ls')_p$$

similar to eqs. (12) and (13), where $c_p T' + Ls' \equiv c_p T' e'$, $T' e'$ being Robitzsch's definition for equivalent temperature of deviation field.

The vertical time sections of $\omega$ and $Q+E$ are presented in Fig. 7. The areas of upward motion and negative value of $Q+E$ are hatched. A remarkable similarity is observed between these two fields. It might be quite reasonable since $\omega$ field is considered to be also related to the convective activity (see Appendix eq. (V)). Furthermore it is well known that the vertical velocity computed by the mesoscale wind observations gives a good measure to the amount of precipitation. Summarizing these facts, it may be concluded that the precipitation is essentially the convective phenomenon without which $Q+E$, the equivalent potential temperature change due to the mean motion, is not expected to change.

Another noticeable fact is that negative value of $Q+E$ is found at those times when predominant upward motion and therefore heavy precipitation is observed. Negative value of $Q+E$ means that either the mean flow heat flux converges or, from eq. (20), the convective heat transfer is larger than the heat supply from below. In other words, when the mean flow convergence becomes larger, the convection becomes so active that it works to pump up the larger amount of heat energy than the supply from sea surface. This pumping up mechanism is often recognized in the case of heavy precipitation as a form of counter flow against the principal moisture advection.

6. Remarks

During the observation intervals in 3 winters, 1963, 1964 and 1965, we experienced fortunately the years of unpreceded heavy snowfall, less snowfall and average snowfall. We could find differences in heat and moisture supply from the sea surface, showing the contribution of sea to the amount of snowfall in its neighbouring area. However the flux divergence of water vapor has almost constant value, the equivalent precipitation being about 9 mm/day. It is obvious that the transport of condensed water in a form of cloud particle or snowflake should play important role since the precipitable water in vapor form is of pretty small amount in the low temperatures. Actually the area under consideration is found to serve as a sink region for the year of heavy snowfall and otherwise the same area is a source region of condensed water.

It is often experienced that the equivalent potential temperature does not conserve at all if only the mean flow flux is considered. Thus the eddy flux of a sub network scale should necessarily be taken into consideration. Since the network dealt with in this paper is of meso-scale, significant contributions are to be attributed to the convective activities. Introducing some informations on cumulus convection we can obtain reasonable relationships between mean flow and eddy flux.

The results derived from quantitative analyses are largely dependent on the computation scheme. One of the important problems not described in this paper is the
inconsistency in the representativeness of any quantities which are put into the relevant equations. In order to retain the consistency of three dimensional velocity field, larger number of rawinsonde stations are required.

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Appendix

Denoting the total area of the convective system, the area inside of the updraft column and the area outside of it by \( \sigma_o \), \( \sigma_c \) and \( \sigma_d \), respectively and the average value, the values inside and outside by \( \bar{\sigma} \), the suffix \( c \) and \( f \) respectively, we have

\[
\sigma_o = \sigma_c + \sigma_d \tag{I}
\]

and

\[
\sigma_o \xi = \sigma_c \xi_c + \sigma_d \xi_d \tag{II}
\]

where \( \xi \) is an arbitrary quantity. Let us define

\[
\Delta \xi = \xi - \xi_f \tag{III}
\]

the excess of the value \( \xi \) inside of a cumulus tower as compared with the outside value. Then eq. (II) is rewritten either

\[
\sigma_o \xi = \sigma_c \xi + \sigma_d \xi_f \tag{II}'
\]

or

\[
\sigma_o \xi = \sigma_c \xi - \sigma_d \xi_f \tag{II}''
\]

Now let us express the vertical eddy transfer of \( \xi \) in terms of characteristic quantities of convection. Assuming a homogeneous distribution of cumulus convections specified as above, we have

\[
\omega' = \langle \omega - \omega \rangle \langle \xi - \xi \rangle = \langle \omega_c - \omega \rangle \langle \xi_c - \xi \rangle \frac{\sigma_c}{\sigma_o}
\]

\[
+ \langle \omega_f - \omega \rangle \langle \xi_f - \xi \rangle \frac{\sigma_f}{\sigma_o}
\]

\[
= \Delta \omega \Delta \xi \frac{\sigma_f}{\sigma_o} \frac{\sigma_c}{\sigma_o} + \Delta \omega \Delta \xi \left( \frac{\sigma_c}{\sigma_o} \right)^2 \frac{\sigma_f}{\sigma_o}
\]

\[
= \Delta \omega \Delta \xi \frac{\sigma_f}{\sigma_o} \frac{\sigma_c}{\sigma_o} \tag{IV}
\]

as was derived by Yanai (1964),

or

\[
\omega' = \Delta \xi (\omega - \omega_f) \left( 1 - \frac{\sigma_c}{\sigma_o} \right) \tag{IV}'
\]

It is shown either by theoretical study (Kuo, 1965) or by observational study (Matsumoto and Ninomiya, 1966) that the area ratio of the ascending and descending region \( \sigma_c/\sigma_f \) is much smaller than unity for the ordinary condition. Therefore the eq. (IV)' may be rewritten as

\[
\omega' \xi = \Delta \xi \omega \tag{V}
\]

for the practical use since \( \omega_f \) can not be considered to play significant role.

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日本海沿岸で観測される海洋性降雪の収支解析

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北陸地方に設定した細かい観測網による高層観測資料に基づき、熱および水収支を1963, 1964および1965年の3カ年分の特別観測期間につき比較した。水蒸気の収支量はこの3冬とも殆ど同じ値を示しているが、降水量は年々非常に変っている。面からの蒸発および対流輸送量の差はかなりあるけれども、降水の変動には主として凝結した水分の輸送が関係している。

6時間間隔の水蒸気輸入量を領域内の6時間降水量と比較すると、風下側の観測点の降水量とよい関係があることが分る。平均流速による蒸散で計算すると顕熱増加量は潜熱減少量のほぼ2倍になることが示される。この関係は観測網の大きさに関係なく、とくに雲層内でよく成立っている。差引き過剰の熱エネルギーは対流活動により輸送されているものと考えられる。強い降雪が観測されるときには対流活動が盛んで、海面から補給される熱エネルギーよりも多い熱エネルギーを雲層に輸送していることが示唆される。

本研究は北陸豪雪特別研究の一環としてなされたものである。