Analysis of the Vertical Eddy Transport of Heat in the Atmospheric Boundary Layer for the Early Period of AMTEX' 74

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Abstract

Vertical eddy heat flux was evaluated for Feb. 16 through Feb. 19, 1974 in a mesoscale square region taken near Motobu by the use of the heat budget equation. The vertical profiles of the obtained heat flux was discussed with reference to the cumulus convection activities manifested in the occurrences of macroscopic clouds or radar echoes and with comparison to the Nitta's result derived from the large scale analysis.

1. Introduction

Structure of vertical eddy transport of heat in the atmospheric boundary layer (used here as equivalent to planetary boundary layer or lower atmosphere) are investigated, for instance, by Lenshow (1970, 1973) with his aircraft measurement as well as by Nitta and Esbensen (1974) and Nitta (1975). The latter researchers derived the vertical heat flux as an unknown of the budget equation by determining its all other terms over the main area of about 500x500 km^2 set up in the GATE or AMTEX area.

Nitta's work (1975) contained some results which are not really warranted for as evidenced in the disagreements between the surface heat flux obtained in his work and that by Kondo (1975) with his aerodynamic bulk method for some cases of the early part of AMTEX' 74 period. Nitta attributed this discrepancy to the inadequacy of his kinematic analysis of the vertical velocity meanend over the area set up for analysis. The present author feels that the difficulty in performing kinematic analysis for that period might be due to the lack of the uniformity of the relevant variables in the field of analysis.

During the period from Feb. 16 through Feb. 19, the author and his colleague (1974) conducted wind observations by pilot baloon tracking and lower tropospheric sonde (LTS) observations which gave us almost continuous soundings of wet and dry temperatures and the pressure at intermittent levels at Motobu, Okinawa as a part of AMTEX '74 program. In this paper, including the above data in analysis, the author attempts to get the heat flux profile over or near one point (Motobu) instead of seeking the result in terms of averages over a wider area and to examine the result to be obtained with reference to the macroscopic feature of weather condition observed over that point.

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2. Data and method of analysis

The aerological data at Naha, Minamidaito, Naze and Keifu-maru and the LTS data at Motobu were utilized. The height limit of the LTS observation is irregular ranging from 400 m to 2400 m, but we attempted to perform the analysis up to the level as high as 1200 m, filling out the want of observations, if any, in the upper levels of Motobu data by extrapolating or estimating from Naha data. As to the analysis of heat flux from the surface we used the sea surface temperature meaned over the whole AMTEX' 74 period analysed by Kondo (1975).

The analysis was conducted for each 9 hr of Feb. 16 through Feb. 19, 15 hr and 21 hr of Feb. 16, and 3 hr of Feb. 17. The surface weather map for 9 hr each day are presented in Fig. 1. The analysis was made in the coordinate system shown in Fig. 2, starting with convert-

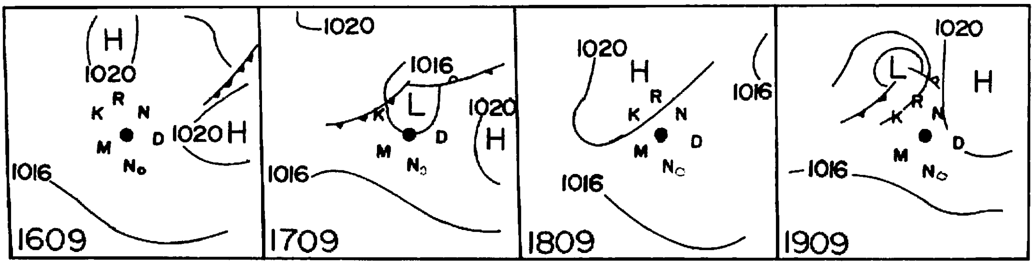

Fig. 1. Synoptic weather map for 9 hr each day Feb. 16 through Feb. 19, 1974, drawn by Japan Meteorological Agency The solid circles near the center indicate the position of Naha. D: Minamidaito, N: Naze, R: Ryofu-maru, K: Keifu-maru, M: Miyako, No: Nojima-maru.

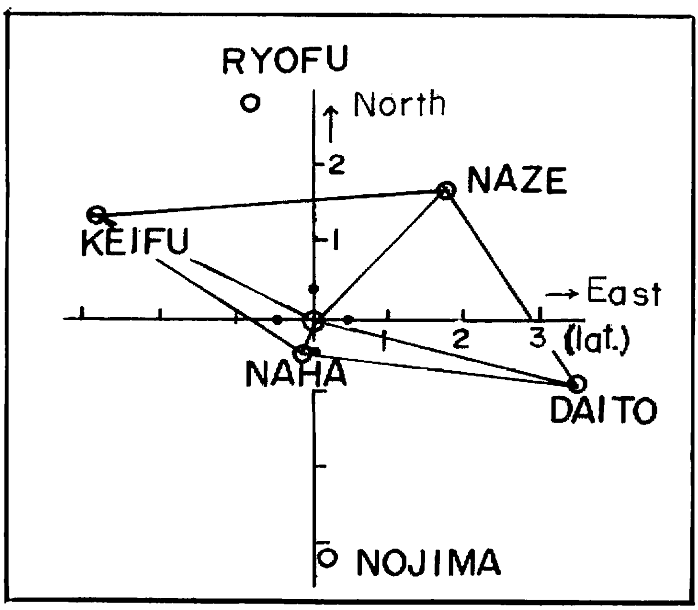

Fig. 2. The coordinate system used for analysis with the origin at Motobu.

ing the data of horizontal wind speed, air temperature and humidity reported by pressure into those by height for all the stations of the present data source. The lowest values were all assumed to refer to the height of 10 m disregarding the differences in the ground or ship-mast levels of each stations. Interpolation of the values of relevant variables was made for four positions marked by the solid points in Fig. 2 with the data at their three enclosing stations forming a triangle. These four positions are aparted from the center station (Motobu) by about 50 km. The gradients of the mean of the relevant variables were evaluated with the interpolated values at these positions. The vertical resolution of analysis is at most 200 m in the vertical direction since the aerological observations are available every about 25 mb interval in the low levels of the atmosphere.

Combining the thermodynamic equation and equation of continuity we have

$$C_p\left(\frac{\partial}{\partial t}\rho T+\frac{\partial}{\partial x}(\rho u T)+\frac{\partial}{\partial y}(\rho v T)+\frac{\partial}{\partial z}(\rho w T)\right) = \frac{dp}{dt}+Q_R+L(c-e) \tag{1}$$

, where T is air (virtual) temperature, C_p isobaric specific heat, ρ the air density, Q_R the rate of heating per unit mass caused by radiation, e evaporation rate of the liquid water in the clouds and c condensation rate per unit mass of air. Expressing a variable in terms of its mean plus fluctuation from the mean and ignoring the terms whose magnitudes are known to be small judging from the check of their order estimation (Businger and Deardorff (1968), Lenshow (1970)), Eq. (1) becomes

$$C_p\bar{\rho}\left(\frac{D\bar{T}}{Dt}+\bar{w}\frac{\bar{T}}{\bar{\Theta}}\frac{\partial\bar{\Theta}}{\partial z}+\frac{\partial}{\partial z}\overline{w'T'}\right) = L(c-e) \tag{2}$$

$$\frac{D}{Dt} = \bar{u}\frac{\partial}{\partial x}+\bar{v}\frac{\partial}{\partial y} \tag{3}$$

, where the variables with bar indicate their mean and those with primes the fluctuation from the mean. Conservation of the moisture is written as below

$$-L\bar{\rho}\left(\frac{D\bar{q}}{Dt}+\bar{w}\frac{\partial\bar{q}}{\partial z}+\frac{\partial}{\partial z}\overline{w'q'}\right) = L(c-e) \tag{4}$$

, where q is specific humidity. The notations used without explanations in Eqs. (1) through (4) have conventional meanings. Multiplying Eq. (4) by L, latent heat of condensation and subtracting it from Eq. (2) we have

$$-\bar{\rho}\frac{\partial}{\partial z}(C_p\overline{w'T'}+L\overline{w'q'}) = \bar{\rho}\left(\frac{D}{Dt}+\bar{w}\frac{\partial}{\partial z}\right)(C_p\bar{T}+L\bar{q}) \equiv Q \tag{5}$$

Integration of Eq. (5) from 0 to z gives

$$(C_p\overline{w'T'}+L\overline{w'q'})_z = (H+LE)-\int_0^z Qdz \tag{6}$$

, where H and E are the sensible heat flux from the surface and the rate of evaporation at the surface. The first term of the right hand of Eq. (6) is evaluated by aerodynamic bulk method and the second by performing the kinematic analysis in the square area (Fig. 2) with every

200 m interval in the vertical direction.

Vertical velocity was obtained from equation of continuity assuming incompressibility of the air, that is, $\overline{w} = \int_0^z \nabla\cdot V\,dz$. The local change terms of air temperature and specific

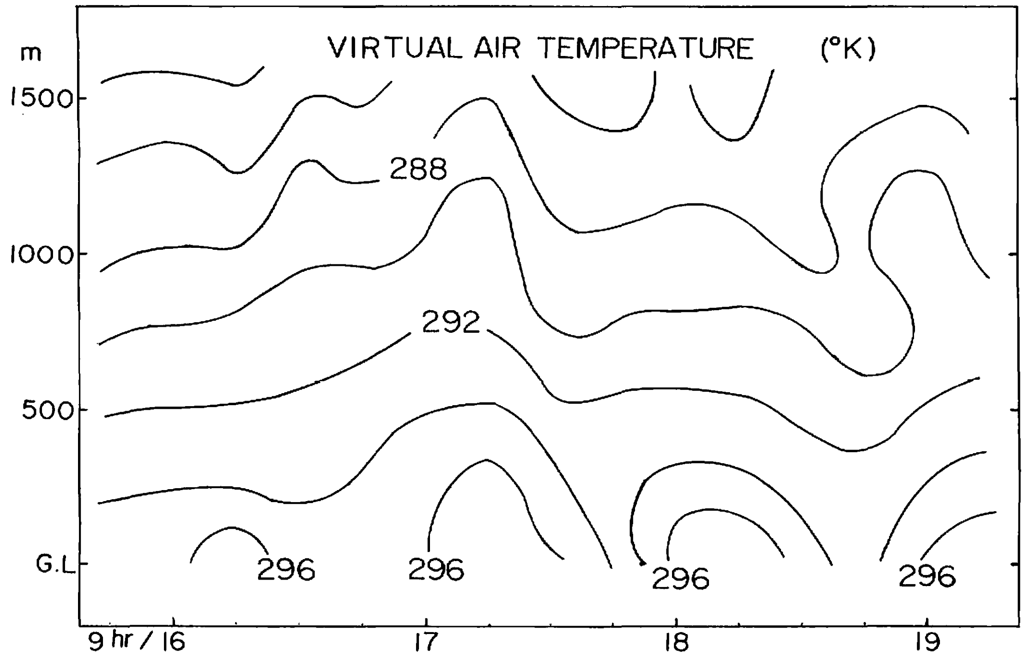

Fig. 3-(a). The time height cross section of air(virtual) temperature at Naha for the period of Feb. 16-19, 1974.

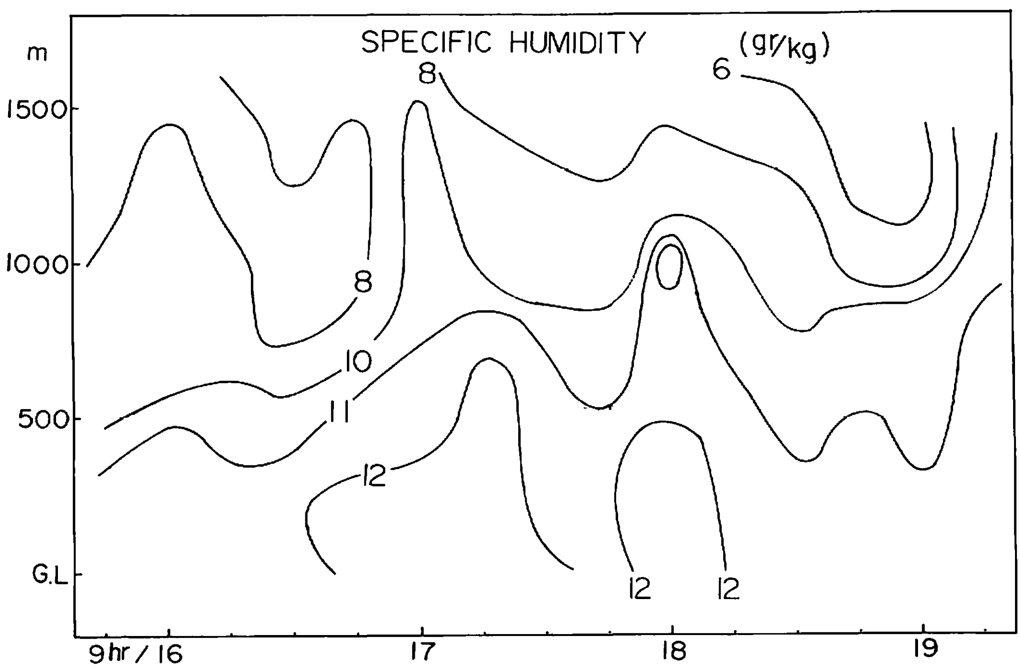

Fig. 3-(b). The same as Fig. 3-(a) except for specific humidity.

humidity were evaluated from their variation in six hours at Naha drawn in the time height cross sections (Figs. 3-(a) and 3-(b)). For this the data of Motobu was not used because their height limit as well as times of observations were irregular.

3. **Vertical velocity and eddy heat flux**

In Fig. 4 the surface streamlines are shown for the times of 9 hr Feb. 16 through Feb. 19. On Feb. 18 and Feb. 19 the air flow field is considerably uniform, whereas uniformity is hardly observed on Feb. 16 and Feb. 17. The wind direction near Okinawa Island on Feb.

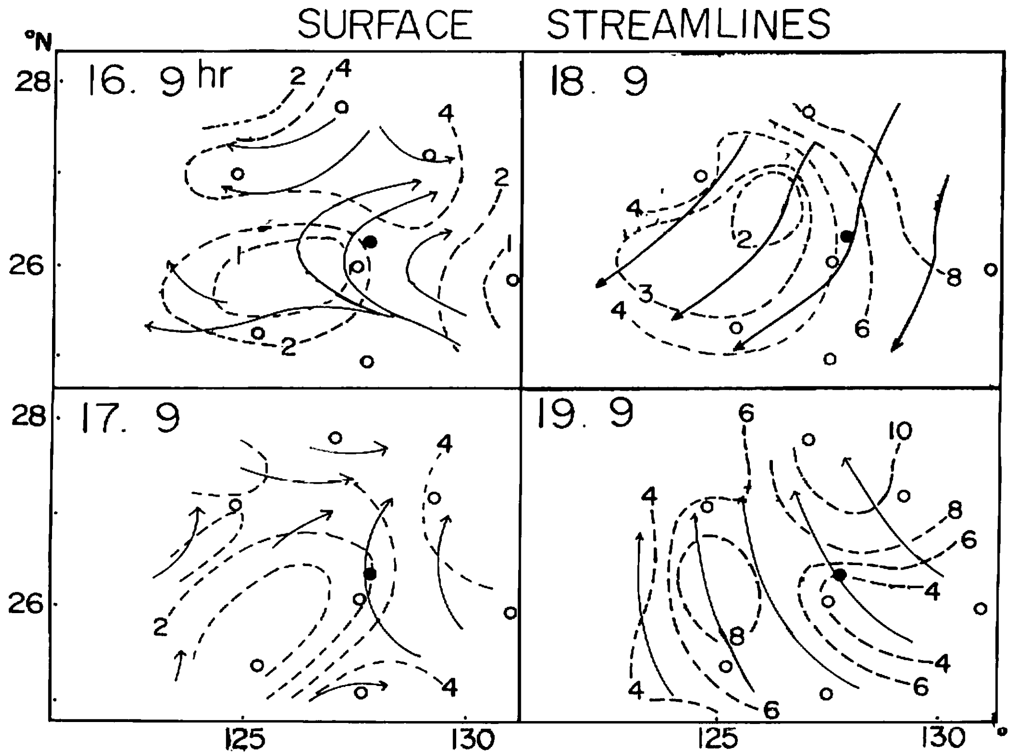

Fig. 4. Surface wind field for 9 hr each day of Feb. 16-19, 1974. Isotachs are shown by dashed lines (m/s).

18 changes cyclonically from northeast to west as the height increases, while anticyclonically from south or southeast to west on other dates. The mean wind vectors in the mesoscale square region are shown in Fig. 5.

Due to the relatively stronger surface wind and the larger sea-air temperature difference the turbulent heat transfer from the surface is dominant on Feb. 18, while it is not on Feb. 17 and Feb. 19.

The mean vertical velocity is presented in Fig. 6. At 9 hr of Feb. 16 and Feb. 18 the vertical velocity increases as the height increases. However, those on Feb. 16 show the tendency to increase linearly with height even above 1000 m but that on Feb. 18 indicate maximum upward velocity around the level of the several hundreds meter and its decreasing tendency in the upper levels. At 9 hrs of Feb. 17 and Feb. 19 the weak downward motion is

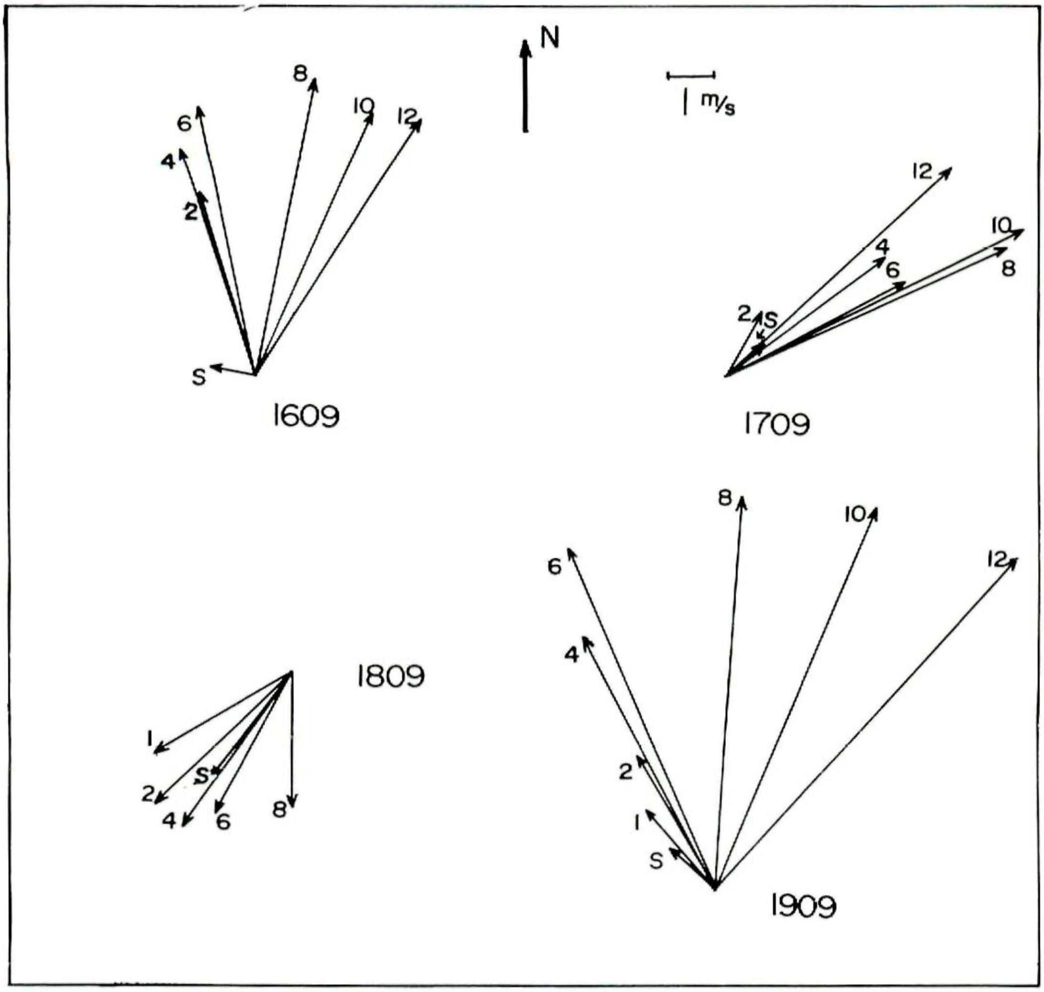

Fig. 5. Variation of the mean wind vectors with height in the mesoscale region around Motobu, for 9 hr each day of Feb. 16-19, 1974.
S denotes the surface levels and characters near the edge of vectors indicate the height level (x100 m).

observed in the entire boundary layer. The result that the upward vertical velocity at 9 hr Feb. 16 gradually decreases as time goes on and eventually the sense of vertical velocity becomes downward around 9 hr Feb. 17 showing a consistent sequential change implies the effectiveness of the kinematic technique applied to estimate the vertical velocity.

In general, the local change terms and the terms of horizontal and vertical advection consisting Q in Eq. (5) are all comparable in order of magnitude, except for the vertical advection term for Feb. 17 and Feb. 19 when the vertical velocity is generally weak in the boundary layer. To be detail, however, there are predominat terms among these varying from one occassion to other. At 9 hr Feb. 16 in the whole boundary layer the negative advection term is dominant due to the relatively strong southerly wind and this situation is roughly held until 3 hr Feb. 17. At 9 hr Feb. 17 positive local change term of especially q exceeds other

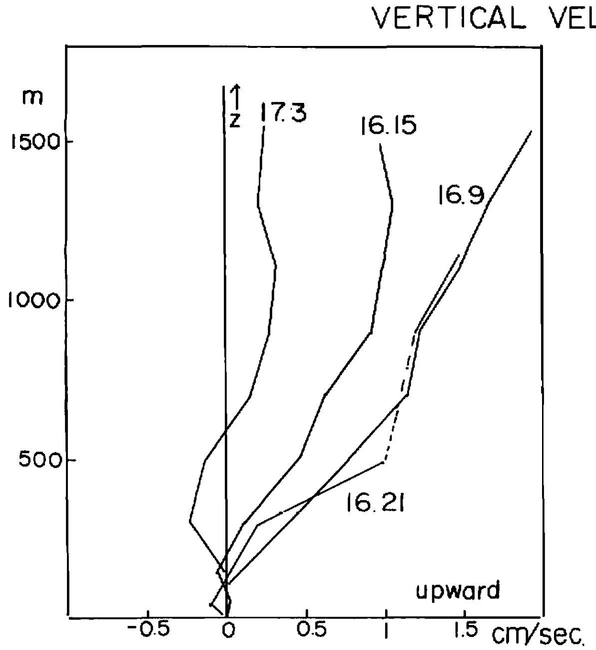

Fig. 6. Mean vertical velocity for 9 hr, 15 hr, 21 hr of Feb. 16 and 3 hr of Feb. 17 in the right and for 9 hrs of Feb. 17-19 in the left.

two terms of horizontal and vertical advection suggesting an active evaporation of the cloud droplets. At 9 hr Feb. 18 there is a larger positive local change of T in low levels which might be resulted from the diurnal variation and that of q in the upper levels with the dominant positive horizontal advection due to the northerly wind. At 9 hr Feb. 19 the larger positive local change of T which might also reflect the diurnal effect exists in low levels and the negative horizontal advection dominates in higher levels due to the strong southly wind.

As a result of the contribution of each term described above we gained the vertical profile of eddy heat flux as shown in Figs. 7-(a) and 7-(b). At 9 hr Feb. 16 the heat is transported upward in the whole boundary layer and this continues until 3 hr Feb. 17, being most typically seen at 15 hr Feb. 16 analysis. The mean of the four cases of 9 hr Feb. 16 through 3 hr Feb. 17 indicate the upward heat flux with its amount of about 5 mW/cm^2, as given by dashed curve. At 9 hr Feb. 17 the larger positive local change of q appearing in the whole layer brought about the downward heat flux. At 9 hr Feb. 18 the relatively strong northerly wind near the surface associated with the approaching of the moving high in the north of Okinawa (Fig. 1) caused the strong upward heat flux at the surface. However, this upward heat flux was rapidly suppressed as the height increases due to the strong positive local change of T and q and to the strong positive advection, and turned out to be downward heat flux increasing with height in the upper levels. Entering Feb. 19 the heat flux from the surface to the air was damped again as was for the case of Feb. 17 due to the little sea-air temperature difference relating to the warm air invasion by southeasterly flow, whereas the upward heatflux was intensified in the upper level as a result of the larger negative horizontal advection.

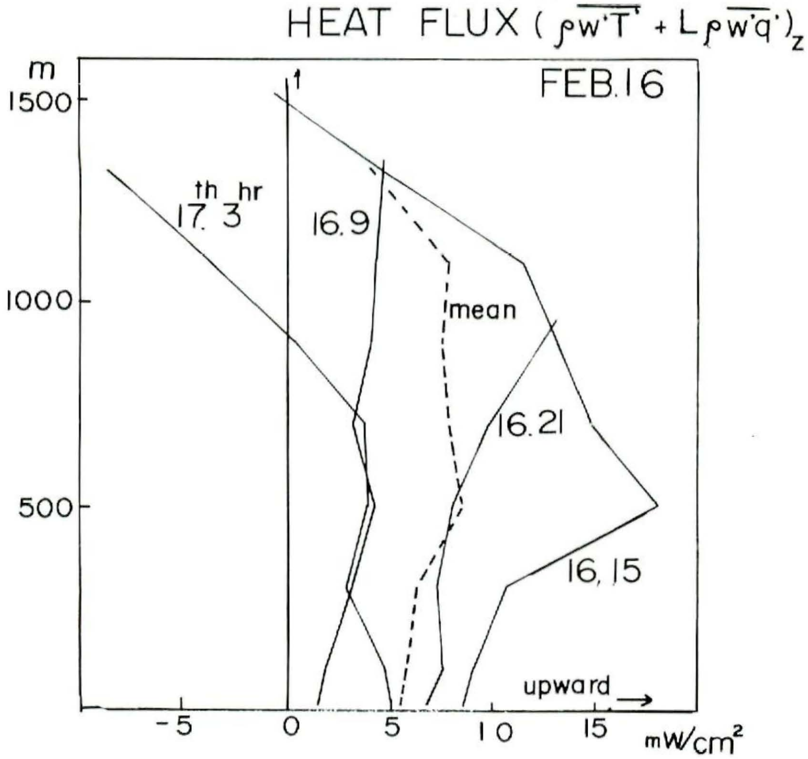

Fig. 7-(a). Eddy heat flux for 9 hr, 15 hr, 21 hr of Feb. 16 and 3 hr of Feb. 17, 1974.

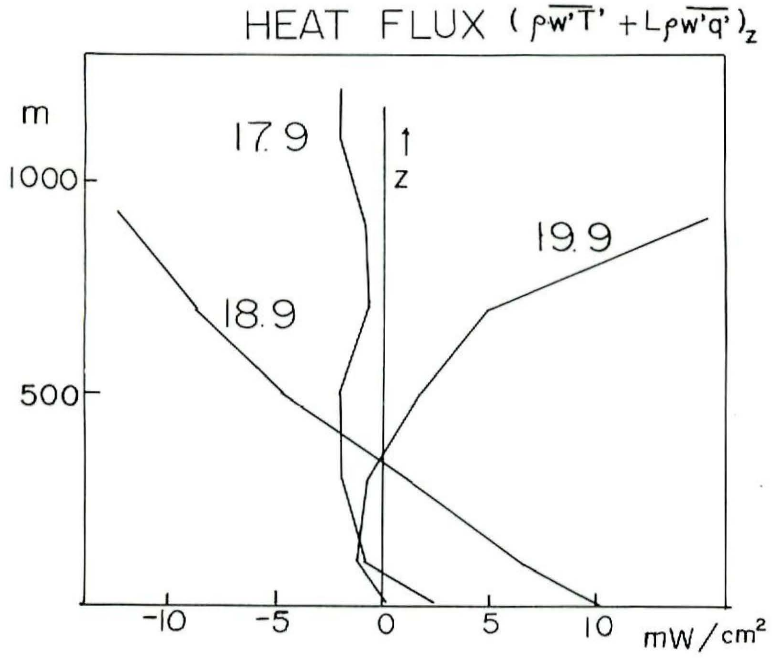

Fig. 7-(b). The same as Fig. 7-(a) except for 9 hrs of Feb. 17-19, 1974.

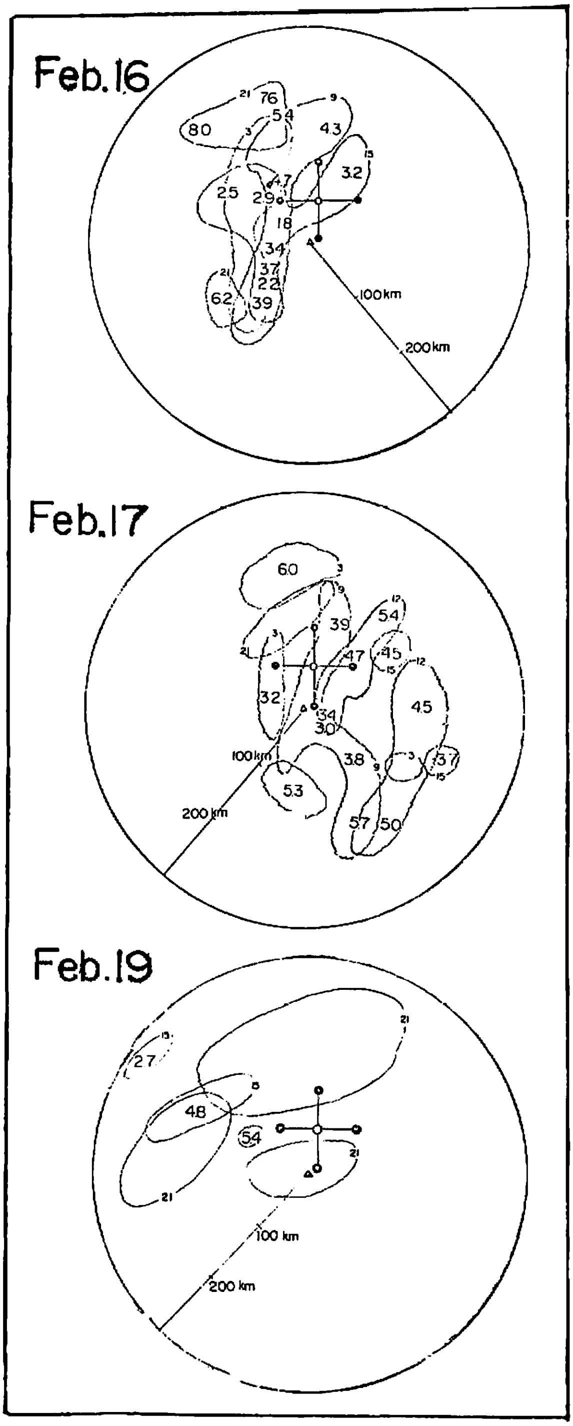

Fig. 8. Itokazu radar echo maps for Feb. 16, Feb. 17 and Feb. 19. Smaller characters denote the observation time and larger ones echo height in hundredmeter. The cross area shows the mesoscale region around Motobu used for analysis of Eq.(6).

Comparing to the result of Nitta (1975), disagreements are found in vertical velocity obtained for the cases of Feb. 16 (downward motion appeared in the Nitta's work) and in the heat flux computed for the cases of 9 hrs of Feb. 17 and Feb. 19 (strong upward and weak downward heat fluxes appeared for respective cases in the Nitta's work). As for 9 hr Feb. 18, in general, a good agreement is found in the two workers' results. It is natural that some disagreements can be expected to occur, for Nitta obtained the result averaged over the wide area surrounded by Naze, Keifu-maru, Miyako, and Minamidaito whereas the present author worked over a point Motobu.

4. Cumulus convection activity and its relation to eddy heat flux

Record of PPI radar observations at Itokazu radar site situated in southern part of Okinawa Island indicated a complete absence of echo signals during the period from 21 hr

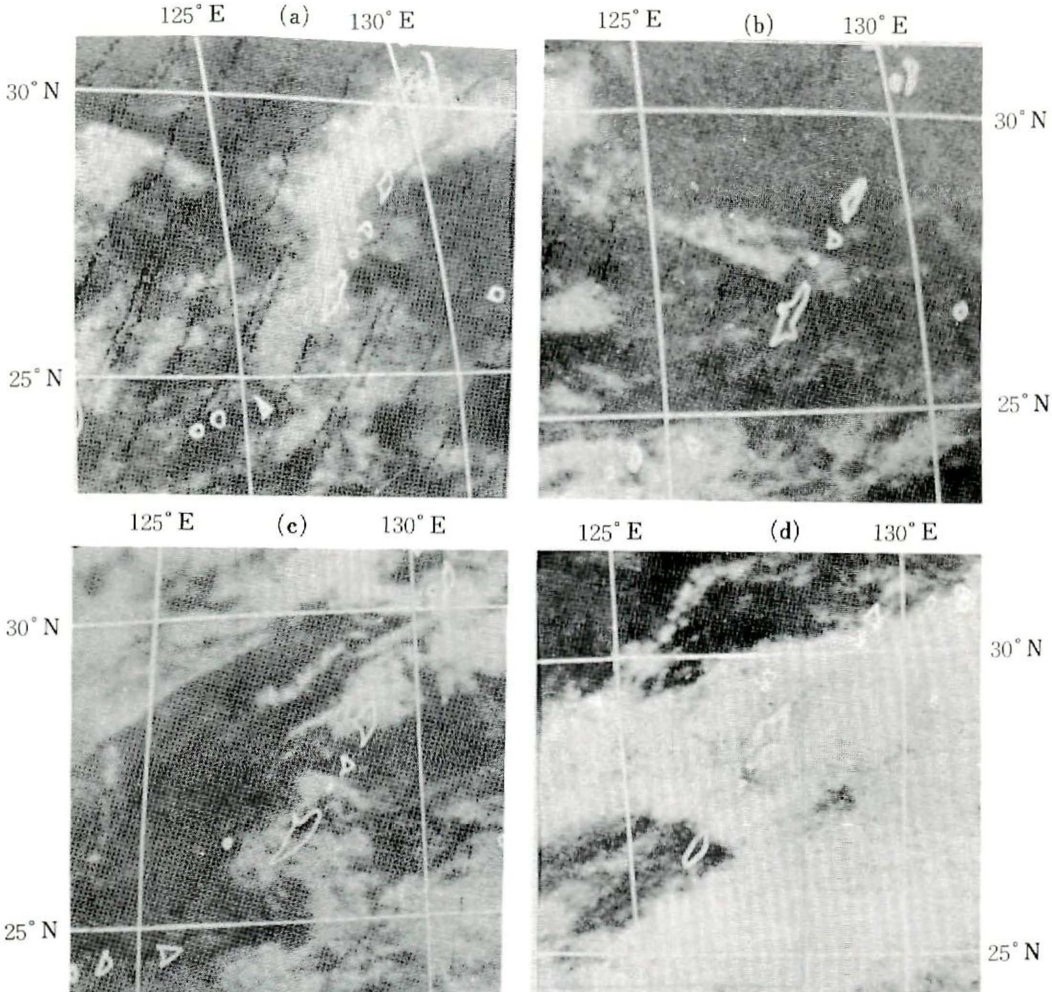

Fig. 9. The cloud pictures taken by APT Satellite over AMTEX area.
(a) for 9 hr 30 min of Feb. 16, (b) for 10 hr 17 min of Feb. 17,
(c) for 11 hr 8 min of Feb. 18 and (d) for 10 hr 56 min of Feb. 20, 1974.

Feb. 17 to 9 hr Feb. 19. Considerable intensity of the echoes from the cumulus clouds were observed on Feb. 16 and Feb. 17. In this case the clouds were not a part of the large scale of cloud system but composed of the much smaller scale of cloud-clusters frequently observed near Okinawa Island. The recovery of the echoes took place after 15 hr Feb. 19. In Fig. 8 we prepared for Feb. 16, Feb. 17 and Feb. 19 the approximate spread of the cloud clusters with estimated height of echo tops using the echo record maps available about every 3 hrs with the range of 300 km. In Fig. 9 are shown the APT satellite cloud pictures taken around 10 hr each day of Feb. 16 through Feb. 18 and that of Feb. 20 being as an alternative for Feb. 19. In Table 1 is presented the cloud amount roughly corresponding to the area shown in sattelite pictures reproduced from AMTEX '74 DATA BOOK Vol. 5. These figures and the table given above indicate that on Feb. 16 and Feb. 17 the area of active cumulus convection is concentrated in the region of less than 200x200 km^2 near Okinawa Island and that there is a large variation of cloud amount and possibly cloud height if we see them from the standpoint of wider area, say, 500x500 km^2.

Table 1. Cloud amount over AMTEX area averaged over the mesh 1 deg.x 1 deg.

N \ E	124–125	125–126	126–127	127–128	128–129	129–130	130–131	131–132
30–29	1	0	0	1	7	10	10	10
29–28	4	0	6	10	10	4	3	1
28–27	0	1	3	10	7	3	0	0
27–26	4	6	10	10	3	1	1	0
26–25	4	4	10	8	10	1	1	2
25–24	3	1	8	5	4	3	1	0
24–23	2	2	2	4	2	7	3	1

1126 JST, Fed. 16, 1974

N \ E	124–125	125–126	126–127	127–128	128–129	129–130	130–131	131–132
30–29	10	8	4	2	2	7	7	10
29–28	3	1	1	4	7	8	3	1
28–27	1	0	1	2	3	1	1	1
27–26	0	0	3	7	6	1	3	7
26–25	0	0	3	4	10	6	9	9
25–24	3	5	7	7	8	7	10	9
24–23	4	5	5	8	2	4	9	5

1023 JST, Fed. 17. 1974

N \ E	124–125	125–126	126–127	127–128	128–129	129–130	130–131	131–132
30–29	5	0	0	0	0	0	0	1
29–28	2	3	4	1	1	1	1	2
28–27	1	1	4	3	3	1	1	1
27–26	1	1	1	1	1	1	1	1
26–25	10	4	1	1	4	1	6	1
25–24	10	10	8	2	5	10	2	1
24–23	10	9	8	4	1	1	1	1

1114 JST, Fed. 18, 1974

N \ E	124–125	125–126	126–127	127–128	128–129	129–130	130–131	131–132
30–29	10	10	10	10	10	9	2	4
29–28	10	10	10	10	4	1	1	1
28–27	10	8	8	10	9	6	7	10
27–26	10	10	10	9	10	10	10	10
26–25	10	10	10	10	5	8	2	1
25–24	7	5	2	1	2	1	0	0
24–23	1	1	1	3	2	1	0	0

1102 JST, Fed. 20, 1974

The intense cumulus activity on Feb. 16 corresponds to the convergence and upward heat flux in the whole boundary layer on that date. At 9 hr Feb. 17 the weak downward heat flux is obtained although the considerably strong cumulus activity still remained around that time as figured out from the amount of cloud or radar echo. It might be reasonable for us to think that the downward heat flux preceded the disappearance of the cumulus clouds on the following day. The strong downward heat flux computed at 9 hr Feb. 18 in the upper levels might relate to the absence of cumulus clouds around that time. The intense upward heat flux at 9 hr Feb. 19 observed in the upper layer can be considered to be the sign of the recovery of the cumulus activity observed in the rest of hours of Feb. 19 and in the following days.

5. Concluding remarks

By the inclusion of LTS data at Motobu and the aerological data at Naha which are omitted from the Nitta's work the analysis in the mesoscale region taken in the neighbourhood of Motobu was made possible. The results are generally acceptable, as agreed with the Nitta's result, for the case of Feb. 18 in which the uniformity was found in the field of analysis. No assurance is given for the result for those cases of Feb. 16, Feb. 17 and Feb. 19. However, if we admit it reasonable that the upward heat flux from the subcloud layer into the cloud layer should intensify or weaken in advance of the activation or disappearance of the cumulus clouds, the result obtained for these can also be accepted.

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