NOTES AND CORRESPONDENCE

Comparison of the Kondo's Bulk Transfer Coefficient with the Recently-made Direct Observations of Fluxes on the Sea Surface

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1. Introduction

After the Air Mass Transformation Experiments (AMTEX's '74 and '75) were over, many interesting results have come out recently. One of these results is the satisfactory agreement between both the estimations of heat fluxes from the sea surface to the atmosphere by the bulk and budget methods (Kondo, 1976; Murty, 1976; and Nitta, 1976). On the other hand, several direct observations of turbulent fluxes were also made during the AMTEX by different groups at different sites. So it would be worthwhile to compare these direct observations with the bulk estimations of fluxes.

The present shorter contribution shows the comparison of the Kondo's (1975) bulk transfer coefficient with the results of the direct observations during the AMTEX and some other recent observations.

2. Comparison of the bulk coefficients

The transfers of momentum (τ), sensible heat (H) and water vapor (E) between sea and air are given by the following formulae:

$$\frac{\tau}{\rho} = -\overline{w'u'} = C_D u^2, \quad (1)$$

$$\frac{H}{C_p \rho} = \overline{w'T'} = C_H (T_s - T)u, \quad (2)$$

$$\frac{E}{\rho} = \overline{w'q'} = C_E (q_s - q)u, \quad (3)$$

where C_D , C_H and C_E are called the bulk transfer coefficients for momentum, heat and evaporation, respectively; u , T and q are respectively the wind speed, air temperature and specific humidity at a representative height above the sea surface, usually $z = 10$ m being taken as reference height,

T_s and q_s representing the surface values, and the other notations being the same as usual.

The bulk transfer coefficients are thus obtained, if the direct observations of fluxes, $\overline{w'u'}$, $\overline{w'T'}$ and $\overline{w'q'}$, (*i.e.*, the fluxes obtained by the eddy correlation technique) will be made. On the other hand, Kondo (1975) showed that these coefficients are functions of the wind speed and the sea-air temperature difference.

The difference between the coefficient [$C_{D, H, E}$] obtained from the recent observations of fluxes and the Kondo's (1975) coefficient [$C_{D, H, E}$ (Kondo)] is shown in Table 1, where the difference is defined by

$$\text{dif} = 100 \times \left[\frac{C}{C(\text{Kondo})} - 1 \right]. \quad (4)$$

Appropriate comparisons between these coefficients are made for the ranges of wind speeds of around $u_{10} \sim 10 \text{ m s}^{-1}$, because the error of the bulk coefficient for light winds will become as great as about 100 percent of the true value, if care is not taken to avoid errors (Kondo and Fujinawa, 1972).

It is noticed in Table 1 that a probable difference between the Kondo's value and the coefficients obtained from the recent observations is within a range of about $\pm 10\%$.

3. Errors in estimations of $H+LE$ over the whole AMTEX region

A satisfactory agreement has been shown between the atmospheric budget estimations (Nitta, 1976; Murty, 1976) and the bulk estimations (Kondo, 1976) of fluxes over the whole AMTEX region. The budget estimation was made from the data of the upper-air observational networks composed of four stations. Since in the lowest parts (between the surface and the 230-m height)

Table 1. Difference between the bulk transfer coefficient by Kondo (1975) and that obtained from flux observations for the $u_{10} \approx 10 \text{ m/s}$ ranges. An exceptional case from the $u_{10} \approx 10 \text{ ms}^{-1}$ is noted in the column of remarks. The diabatic transfer coefficients are for a reference height of 10 m. $\text{dif} = 100 \times [C/C - 1]$.

Author	Duration min	Sea-air temp. diff. °C	Momentum		Sensible heat		Latent heat		$H + LE$		Remarks
			No. obs. (n)	$10^8 C_D$ dif %	No. obs. (n)	$10^8 C_H$ dif %	No. obs. (n)	$10^8 C_D$ dif %	No. obs. (n)	$W \text{ m}^{-2} \%$	
Pond et al., '71	50	1	20	1.47 ± 0.26 +9	—	—	20	1.19 ± 0.17 -11	—	—	wind speed=6 m/s
Paulson et al., '72	48	1	141	1.48 ± 0.21 +10	141	1.54 ± 0.64 +17	141	1.47 ± 0.18 +9	—	—	wind speed=6 m/s(a)
Dunckel et al., '74	30	1	26	1.39 ± 0.14 0	350	1.50 ± 0.2 +16	350	1.28 ± 0.2 -3	—	—	wind speed=7 m/s(b)
Mitsuta & Fujitani, '74	60	1	6	1.22 ± 0.13 -3	—	—	—	—	—	—	wind speed=6 m/s
Müller-Glewe & Hinzpeter, '74	17	3	—	—	44	1.0 ± 0.1 -26	—	—	—	—	wind speed=7 m/s
Smith, '74	44	1	41	1.2 ± 0.20 -19	13	1.2 ± 0.5 -5	9	1.2 ± 0.3 -9	—	—	—
Wieringa, '74	10	—	126	1.40 ± 0.23 -4	—	—	—	—	—	—	—
Smith & Banke, '75	44	6	51	1.48 ± 0.3 -7	14	1.46 ± 0.4 +4	—	—	—	—	—
Naito, '77	27	3	104	1.37 ± 0.2 -10	46	1.10 ± 0.2 -17	—	—	—	—	—
(AMTEX)											
Garratt & Francy, '75	30	6	29	1.69 ± 0.31 +6	—	—	—	—	—	—	Neutral value
Garratt & Hyson, '75	30	6	—	—	334	1.2 ± 0.3 -4	239	1.6 ± 0.3 +24	—	—	C_D : Indirect method
Sahashi & Maitani, '75	60	5	33	1.55 ± 0.2 -3	160	1.4 ± 0.35 +2	—	—	—	—	Pre-AMTEX
Takahashi, '75	15	4	41	1.47 ± 0.3 -5	—	—	—	—	—	—	wind speed=8 m/s
Takeda et al., '75 {	27	4	45	1.34 ± 0.47 -12	—	—	—	—	—	—	—
Tsukamoto et al., '75	27	8	80	1.79 ± 0.72 +11	45	1.40 ± 0.2 +2	40	1.28 ± 0.4 -10	—	—	wind speed=5 m/s(c)
Yokoyama et al., '75	30	5	25	1.32 ± 0.3 -16	7	1.0	—	—	—	—	Aircraft obs.
Lenschow et al., '76	—	5	59	1.93 ± 1.42 +16	60	1.56 ± 0.53 +5	44	1.64 ± 0.39 +9	295 +4	422 +1	AMTEX '74 (d)
Nitta, '76	3.4(e)	10	—	—	—	—	—	—	—	—	AMTEX '75 (d)
Murty, '76	(13 days)	4	—	—	—	—	—	—	—	—	—
Murty, '76	(14 days)	6	—	—	—	—	—	—	—	—	—
Average, $\Sigma (\text{dif})_i / \text{No. Rep.}$				-2%		-5%		+1%			Arithmetic average
Average, $\Sigma n_i (\text{dif})_i / \Sigma n_i$				0%		+4%		+7%			Weighted average

Note: (a) After Pond et al. (1974); (b) C_H, E are due to profile technique; (c) Dissipation method; (d) Budget method; (e) It is equivalent to a flight path of about 20.5 km.

Fig. 1 The horizontal profiles of the sea-surface water temperature T_s , the air temperature T , the water vapor pressure e , and the wind speed u at the 10-m height along the straight line that passes through R. V. Keifu and Station Naze.

of the planetary boundary layer the temperature, mixing ratio and wind speed obtained at the island stations are systematically different from those obtained on board the research vessels, and accordingly the errors in the results of budget calculations must necessarily arise (Ninomiya, 1976). According to Ninomiya, this kind of error yields an underestimated value of the total amount of heat ($H+IE$) by about $19+24=43 \text{ W m}^{-2}$ for the cold period, that is the period when cold air masses burst out. The total amount of heat for the cold period is about 600 W m^{-2} , and thus this error corresponds to about +7% of the total amount of heat.

Next, we should take notice of another source of error in the budget estimation. Fig. 1 is a reproduction from one of the papers of Kondo (1976) and shows the horizontal profiles of the sea-surface temperature T_s , the air temperature T , the water vapor pressure e , and the wind speed

u at the 10-m height along the line between the research vessel Keifu and the Weather Station Naze on Amamiohshima Island. The values of T , u , etc. on the open sea off Amamiohshima Island are shown with solid circles. (The open circle indicates the primary data obtained at Naze Weather Station.) Although these meteorologic factors do not show linear profiles between the two stations, the budget method of calculation would permit to assume the linear profiles. During the cold period, in the atmospheric mixing layer, the wind, with its speed which is nearly constant and irrespective of the height, blows perpendicularly to the line connecting the positions of Keifu and Naze (Kondo, 1977), and so an approximate magnitude of the error in the sensible heat, which is caused by linear interpolation of the meteorologic factor, can be obtained as follows:

$$\Delta H \approx \frac{D}{A} \int_0^h C_p \rho (\langle Tu \rangle_{k-n} - (Tu)_{K,N}) dz, \quad (5)$$

where $A (=1.7 \times 10^5 \text{ km}^2)$ is the area of the square AMTEX region (Nitta, 1976), $D (=444 \text{ km})$ the distance between Keifu and Naze, $h (=2 \text{ km})$ the depth of the atmospheric mixed layer, $\langle Tu \rangle_{k-n}$ the averaged value of the products of T and u over the line between Keifu and Naze, and $(Tu)_{K,N}$ the average of the two $T \times u$ obtained at both the stations Keifu and Naze. (The values of T and u at the 10-m height are shown by solid circles in Fig. 1.)

If it is assumed that the value of $(\langle Tu \rangle_{k-n} - (Tu)_{K,N})$ will decrease linearly with height and tend to zero at the height of $z=h$, and so it is obtained that $\Delta H \sim 40 \text{ W m}^{-2}$. The similar procedure yields $\Delta(IE) \sim 60 \text{ W m}^{-2}$. The value of $\Delta(H+IE)$ corresponds to about -17% of the total amount of heat $H+IE$ for the cold period.

Over the horizontal profile between the islands Miyakojima and Minamidaitojima, the same kind of error amounts to about +4%.

The errors to be considered are summarized in Table 2. The error, which is caused by discarding the effect of stability on the bulk transfer coefficient due to the water vapor flux (Kondo, 1975), yields an underestimated flux by about 1%. When the daily mean values are used instead of the hourly values of T , e and u , the result shows a flux underestimated by about 1% for the bulk calculation. (The source for this kind of error was explained by Kondo, 1972.)

The value shown in the last line of Table 2 is the overall relative error between the budget and

Table 2. Summaries of the relative errors between the budget and bulk estimations of $H + LE$. The negative sign means the budget estimation smaller than the bulk estimation.

(a) Difference between the budget (Nitta & Murty) and bulk (Kondo) estimations:	+ 2%
(b) Error of the budget estimation	
(1) Error caused by making use of the data at the land stations (after Ninomiya, 1976):	+ 7%
(2) Error caused by the sub-grid scale advection	
Between the vessel Keifu and Naze Station:	-17%
Between the islands Miyakojima and Minamidaitojima:	+ 4%
(c) Error of the bulk estimation	
(1) Error caused by making use of the daily values instead of the hourly values of T , e and u :	- 1%
(2) Error caused by discarding the stability effect due to the water vapor flux:	- 1%
(3) Error contained within data processing (after Kondo, 1976):	$\pm 10\%$
Total difference between the budget and bulk estimations:	$-6 \pm 10\%$

bulk estimations of the heat fluxes over the whole AMTEX region.

4. Conclusions

During the AMTEX experiment, the estimations of the surface fluxes of the momentum, latent and sensible heat were made by both the budget and bulk methods simultaneously with the eddy correlation observations by several groups. In the present note the comparison among their results has been shown. Despite some discrepancies, a satisfactory agreement among their results may be seen though with probable differences of about $\pm 10\%$.

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海面フラックスのバルク係数 (Kondo, 1975) と 気団変質観測やその他のフラックス実測値 から得たバルク係数の相互比較

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気団変質観測ではバルク法，収支法および渦相関法（直接測定）によって海洋・大気間の熱輸送量が得られている。各々には当然の事ながら測定誤差も含まれるであろうが，その相互比較を行なってみると，平均的には，±10%程度の差で各結果は一致すると見なされる。