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Heat Balance of the East China Sea during the Air

Mass Transformation Experiment

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Abstract

Transfers of heat and momentum in winter for the East China Sea and adjacent seas were estimated by means of an aerodynamic bulk method under diabatic conditions. It is found that at the Kuroshio region the sensible and latent heat losses (H+IE) are primarily compensated for by the heat convergence caused by the oceanic eddy and/or current trans-port. The secondary contribution to the heat balance is due to the net flux radiation and the oceanic heat storage. On the basis of heat balance consideration, the thermal diffusivity of the ocean of K= 1.0* 108 cm2 s-1 is obtained for a period of about one month. There is also suggested that in the Yellow Sea there occurs a counterclockwise circulation of water. The average value of H + IE over the AMTEX area for the entire period of AMTEX

'74 is by about 10 to 20% smaller than the climatological normal value for the corresponding
period. The value of H+IE estimated by the present aerodynamic method agrees in general with those obtained by the atmospheric budget computations by Nitta (1976) and Murty (1976) for both the period of AMTEX '74 and AMTEX '75. During an intense cold-air outbreak the very large amount of latent heat of about 500 to 800 W m-2 is supplied to the atmosphere over the Kuroshio, while only a small amount is supplied to the atmosphere
over the shallow seas of the continental shelf. The Bowen ratio (H/IE) is about 0.7 to 0.8 over the Yellow Sea, whereas it is 0.3 to 0.4 over the AMTEX region, and 0.1 to 0.2 over
the sub-tropical ocean.

1. Introduction

The Air Mass Transformation Experiments
(AMTEX) were carried out during the two
periods from the 14th to 28th February 1974 and
from the 14th February to 1st March 1975 in the sea areas of Southwest Islands of Japan for several aims. One of these aims is to evaluate the heat transfer from the sea surface into the

air, especially in areas where the air-mass trans-formation is active. In the preparatory research for this purpose, Kondo (1975) developed an aerodynamic bulk technique which can be applied to evaluating the turbulent fluxes in the diabatic atmosphere such as that over the AMTEX sea
areas.

The objective of the present paper is to eval-uate each component of the heat balance at the sea surface by the use of the extensive observa-tional data as reported from the Ocean Stations of research vessels, the fishing and merchant ships, and the routine weather stations in the AMTEX

and adjacent regions. Since the heat balance equation implies that the sum of the total loss of heat (i.e., radiation, sensible and latent heat) from the sea surface and the heat storage in the ocean is compensated for by the convergence of heat due to the oceanic turbulence and current, it is possible to obtain the oceanic convergence of heat as a residual from the equation of heat balance. This finally enables us to evaluate the horizontal thermal diffusivity of the ocean.

2. The region and method of analysis

2.1 Heat balance equation

The equation of the heat balance of the ocean is given by

H+lE-Rn+S=Fe+Fk, (1)

where

Rn=(1-r)S*+*(L*-*Ts4) , (2)
and

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and in these equations H is the sensible heat
loss, lE the latent heat loss, Rn the net radiation
gain, S the ocean storage of heat (local change
in heat content of the ocean); Fe and Fk the flux
convergence of oceanic heat transport due to the
lateral eddy and that due to the advective current

"Kuroshio", respectively; S* and r (*0.06) the
downward solar radiant flux and the reflectivity of the sea surface, respectively; L* and *(*0.96) the downward atmospheric radiation and the emissivity of the sea surface, respectively; *Ts4 the black-body radiation corresponding to the sea surface temperature Ts, Tw the water tem-perature at the depth z; c and * the specific heat and the density of water, respectively. In cases where the depths of the bottom are more than 100 meters, the integration (Eq. 3) is practiced for the range from the sea surface to the depth of 100 meters.
The heat transport due to the Kuroshio is, in the present paper, defined by

where anV is the volume transport in the top 100-m thickness of the Kuroshio and is obtained

by the geostrophic estimation (Stommel and Yoshida, 1972), and Tin-Tout is the difference be-tween the average water temperatures of the inflowing current and of the outflowing current of the Kuroshio at the boundaries with which

the region under consideration is enclosed.
All the terms of Eq. (1) are specifically obtain-ed, except the term Fe which is determined as being residual. When the value Fe is known,

it is possible to estimate the eddy thermal clif-f usivity of the ocean, since the integral of Fe over the area A of the sea surface is equivalent to the eddy transport of oceanic heat through the cross-sectional boundaries with which the area is enclosed. The thermal diffusivity, K, may be defined by the following expression:

where bn is the cross-sectional area of the bound-ary, and * Tw/* n the average value of the hori-zontal temperature gradient at the boundary.

2.2 Method o f calculation

There were a small number of the stations for radiation observation which were specified for AMTEX purpose, and the direct observations thus obtained are insufficient to draw up a de-tailed distribution of radiation flux over the whole

region of the AMTEX and adjacent seas. So the empirical formulae are employed, too. (See Ap-pendix 1.) The radiation flux can be obtained in terms of the daily mean values of air tempera-ture, vapor pressure, amounts of the low, middle and high clouds; and of the latitude of the station and the solar declination. Table 1 shows some

examples of comparison between the observed radiations ([1], [2] and [5]) and the calculated ones ([3], [4] and [6]) at seven stations: in the

places Naze, Minamidaitojima, Okinawa and
Ishigakijima, and on board the ships, Ryofu,
Keifu and Nojima, where the direct observations
were carried out. The value presented in the last
line of this table is the difference of S*+L*
between the observed and calculated radiations.

Table 1. A comparison between the observed radiation and the calculated one for 15 to 27 February 1974. S*: downward solar radiation (W m-2), L*: downward long-wave
radiation (W m-2). 100 W m-2=206ly day-1.

Note: (a) After Naito et al. (1976) for 14 to 27 February 1974; (b) According to
Yasuda (1975), it might be possible that the radar anthena on board obstructed
the sky radiation.

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From this comparison, the magnitude of possible
error in calculated radiation may be about 10
to 20 W m-2. Such a magnitude of error is es-
sentially negligible in comparison with those of
the other terms (shown later) in the heat balance
equation.
The turbulent transports of heat (H and lE) and momentum (*) at the sea surface were estimated by use of the aerodynamic bulk co-efficients under diabatic conditions (Kondo, 1975). In that case the daily means were used for the following meteorologic parameters: wind speed, air temperature and vapor presure. The errors in the fluxes obtained by use of these param-eters, which were averaged over long intervals of time, are of essentially negligible magnitude, provided that the time intervals over which the meteorologic data were averaged were no more than one day or so (Kondo, 1972; Jobson, 1972).

2.3 Data

Fig. 1 shows a map of the East China Sea and adjacent regions, of which the present analysis is made. The continental shelf extends over the

greater part of the region. The warm "Kuroshio" flows toward northeast along the edge of the continental shelf (along the contour line of about 200-m depth). The AMTEX area has an outline of hexagonal shape.

Fig. 1 A map of the East China Sea.

For calculating the daily mean values of the downward long-wave and solar radiation, the fol-lowing data were used: three-hourly (or every hourly if practicable) routine data reported from a number of 66 observing stations, the data from the fishing and merchant ships, and the cloud picture from the satellite.
So as to obtain the heat balance within an

overall accuracy of about 10%, it is necessary to arrange the daily mean values of the meteoro-logic elements within the limits of errors of about 1* in temperature, 1 mb in water vapor pres-sure, and 1 m s-1 in wind speed.
The large solid circles shown in Fig. 1 indicate the positions of the Ocean Weather Stations (Ryofu, Keifu and Nojima). The position (34*N, 124*E) was crowded with twenty or thirty fishing ships (FS), and so it was possible to make an average for each of the meteorologic elements reported from these FS and to use it as the data at the fourth Ocean Station.
At twelve positions marked with small solid circles, wind speeds are obtained from a relation-ship between the wind speed at 10- m height, u10, and the geostrophic wind speed, G. The dashed line of Fig. 2 indicates the relationship of u10/G versus G in neutral stabilities, which can be ob-tained from the relationship between u* and zo (Kondo, 1975) in combination with the Planetary Boundary Layer model for the wind profile (e.g., Blackadar, 1962), where u* is the friction veloc-ity, and zo the aerodynamic roughness length of the sea surface. In addition to the latter relation-

ship, the atmospheric stability was taken into account for practical calculations (see Kondo, 1977).
All the data of observed wind speeds at the four Ocean Stations and on board several fishing and merchant ships, together with the estimated wind speeds at twelve positions mentioned above are not yet sufficient enough to make a detailed distribution of the wind speeds over the whole region. Therefore, the following additional pro-cedure will be employed, too. This is a method of deducing the wind speed at the open sea by using the wind speed observed at a land station. The Planetary Boundary Layer model (e.g., Blackadar, 1962,) can predict the relationship u/G versus G from the formulation of the geo-strophic drag coefficient (u*/G) versus Rossby number (G/ f z0). The solid lines of Fig. 2 indicate the relationship between u/G and G with the parameter of z0, varing from 0.1 to 100cm, for a case of the latitude * = 26*.

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Table 2. Equivalent roughness height at the
land station.

Fig. 2 The relationship between u10/G
and G under neutral stabilities.
The dashed line is for the marine
atmosphere, and the solid lines
for the cases of land roughness.
The circle and square symbols
show the ratios of the wind speed
observed at the land station to the geostrophic wind speed.

Observed results are shown in Fig. 2, where the ratio, u/G, for Okinawa Meteorological Observatory plotted with squares, and those for Miyakojima Weather Station with circles. Here, u is the observed wind speed at the land station. Each point consists of the daily averaged data. (The geostrophic wind speed was obtained from the pressure gradients over a distance of order 200-300km. See Kondo, 1977.) From this figure we can find the apparent roughness length of the land station as z0' = 0.5cm for Okinawa and

z0' =2cm for Miyakojima. (It is naturally said that this value does not mean the roughness value in an ordinary sense.) By the same procedure the values of z0' for several stations could be obtained

as shown in Table 2. When the apparent rough-ness has been known, the correction factor which is defined by C= u10/u = (u10/G)/(u/G) = C(z0', u) can be determined as the functions of z0' and u.

(Because both the ratios of u10/G and u/G pres-ented in Fig. 2 result in two relationships u10/u vs. G and G vs. u as the function of z0' .) In this case, u10 is the wind speed at the open sea, and is not affected by the land topography. The wind speed near the position indicated by the mark+in Fig. 1 is deduced from such a pro-cedure, that is, u10 = C*u.
By making use of wind data deduced from the above several methods, together with the direct observations reported from other traversing mer-chant and fishing ships, we can draw up the daily distribution of the wind speed over the East China Sea and adjacent seas.
Fig. 3 shows the mean distribution of the water

Note: (a) u10*=1.33 * u; (b) u10*u; (c) The value is limited to 1974 and previous years, because big buildings were built up at the rear of the Okinawa Meteorological Observatory after AMTEX '74.

Fig. 3 The distribution of sea-sur-face water temperature
for AMTEX '74.

temperature at the sea surface during the AMTEX '74. This is made from all the available data for water temperature with making reference to the Ten-day Marine Report published by JMA and to the Marine Report published by Naga-saki Marine Observatory. The solid line in this figure is made from the data obtained during the

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AMTEX '74, while the dashed line is from the
data obtained in nineteen Februaries from 1942
to 1960; and the two dotted lines (of 16 and
21* isotherms) indicate the climatological dis-
tributions for February. Regarding the vertical
distribution of the water temperature, there were almost uniform temperatures within the upper layer down to about 100-m depth.
Appreciable variations in water temperature with time could not be found, excepting some fluctuating nature alike to eddies. But at the shallow sea of the continental shelf, the rate of

continuous temperature fall is about 0.5 to 1.0* per two weeks.

3. Heat and stress in connection with cold air outbreak

A typical cold air outbreak occurred during the latter half period of AMTEX '74. The tur-bulent heat exchange at the sea surface took place very actively. Fig. 4 displays the weather map (for 1500 JST) and the detailed distributions of the daily mean values (00 to 24 hrs JST) of stress, sensible and latent heat. Four figures in

Fig. 4 Weather maps (1500 JST) and the daily mean distributions of the stress * (N m-2), sensible heat H (W m-2) and latent heat lE (W m-2). The top: 22nd February 1974, the middle: 24th, and the bottom: 26th.

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the tap are for the 22nd day of the month, when
the intensely cold air mass appeared and covered
the Yellow Sea. The amount of sensible heat of
about 100 W m-2 is seen there. At the same time
the value of latent heat is almost the same as the
sensible heat.

The figures in the middle are for the 24th. The front of the cold air mass advanced to the South-west Islands. A considerable amount, over 300 W m-2, of the latent heat is seen along the Kuroshio and its neighborhood.
The figures in the bottom are for the 26th, when the whole regions have been completely covered with the cold air mass. We can see the

largest amount of latent heat of about 800 W m-2 and that of sensible heat of about 300 W m-2 at

the southwest part of the AMTEX region. A power of 1,000 W m-2 to the atmosphere is equivalent to the heating rate of about 3.5* day-1 for an air column between the sea surface and the height of 2km. [The planetary boundary layer thickness was about 2km during the AMTEX. (Ninomiya and Akiyama, 1976; Nitta, 1976).]
An interesting feature can be found from Fig. 4. Over the northern part of the region the amount of H is comparable with that of lE, whereas over the southern part of the region the amount of H is about one third or less of the

amount of lE. Such a general feature is also presented in Fig. 5 which shows the distribution of the Bowen ratio (H/lE) for the entire period of the AMTEX. '74. Over the northern part of region the ratio is about 0.7 to 0.8, whereas 0.3 to 0.4 over the AMTEX area. In general, the warmer the temperature is, the smaller the Bowen ratio is. This is attributed to the reason that the

saturation vapor pressure (es) is very low at low temperatures, but as the temperature increases, es increases exponentially, so that the ratio of the sea-air vapor pressure difference to the sea-air temperature difference takes a large value for high temperatures.
The distributions of stress are displayed in the second column of Fig. 4. An isoline for *= 0.4 N m-2 (=4 dyne cm-2) nearly corresponds to an isotach for u=14 m s-1, and thus the region with large stress moves at the head of the cold air mass. The value of 0.4 N m-2 is equivalent to the acceleration in current with a rate of 35cm s-1 day-1 for a water column of the thickness of 100m, or to the Ekman mass transport with a rate of */f= 8cm s-1*100m of the water at the

latitude of 20 degrees (where f is the Coriolis

Fig. 5 The mean distribution of
Bowen ratio for the entire
period of AMTEX '74.

factor).
In summarizing, when the intensely cold air outbreak had occurred, both the active modifica-tion of the air mass and the strong interaction between the wind and current would take place all over the region.

4. Energy exchange within the AMTEX area From each of the daily distributions for radia-tion, sensible heat, latent heat, stress and cloud amount, we can evaluate each averaged value of them over the AMTEX area of hexagonal shape. Fig. 6 shows variations with time in these values. As shown in Fig. 7, the period from the 15th to the 22nd is characterized by the warm air tern-

Fig. 6 The day-to-day variations
of the averaged quantities
over the AMTEX region.

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dashed line in Fig. 1, or nearly the same as that
for the three Ocean Stations (Keifu, Ryofu and
Nojima), the author does not wish to analyse the

'75 data in detail, but wishes only to put practice
for the three Ocean Stations. The numerical
results are presented in Tables Al and A2 (see the Appendix).

Fig. 7 The day-to-day variations of the daily mean air tem-
perature and wind speed at
the Ocean Ship Stations of
Nojima, Ryofu, Keifu and
Fishing Ships.

perature with mostly light winds, and the latter period after the 23rd by the cold air with strong winds. (See also Ninomiya, 1975, and Nitta, 1976.)
On board the ocean station vessels, Keifu and Ryofu, the air temperature fell from about 17* in the earlier period to about 7* in the latter period, and the wind speed increased from about 5 m s-1 to about 15 m s-1. At the same time, as seen in the bottom of Fig. 6, the amount of cloud increased from about 60% to about 90%. In the earlier (warm) period, the heat and momen-tum exchanges at the sea surface are very small, that is, H=21W m-2, lE=108W m-2, Rn= 68W m-2, and * = 0.06N m-2, and thus the total loss of heat from the sea surface is: H+lE-Rn=
61W m-2, which is equivalent to the cooling rate of only about 0.01* day-1 in the 100-m thick-ness of water column.
In the latter (cold) period, however, the net radiation was quite small due to plentiful clouds shutting the incoming solar radiation and due to the net loss through the long-wave radiation from the sea of relatively warm temperature which was by about 10* higher than the air temperature. On the other hand, a very large amount of turbu-lent transport took place, especially on the 25th the largest amount of averaged values of H+lE and * over the AMTEX area were 711W m-2 and 0.38N m-2, respectively. The former is equivalent to the temperature drop with a rate of about 0.15* day-1 in the 100-m thickness of water column.
The above results have been obtained from the detailed analysis of the AMTEX '74 data. Since it will be shown in the Appendix of the present paper that the averaged flux over the AMTEX area of a hexagonal shape is nearly the same as that over the square region indicated by the heavy

Fig. 8 Comparisons between the heat flux of H+lE obtained by the present aero-dynamic bulk method (solid square)
and that by the budget method (open
square) by Nitta (1976) or by Murty

(1976). (a): AMTEX '74, (b): AMTEX '75
. Both the open and solid square symbols in Fig. (a) indicate the averaged flux over the square region. The dash-ed line indicates the averaged flux, estimated by the bulk method, over the AMTEX region of hexagonal shape.
In Fig. (b), the bulk estimation is the
averaged value for the three Ocean
Ship Stations, while the budget estima-
tion is the averaged value for the
square region.

Figs. 8(a) and 8(b) are the day-to-day variations in H+lE for the AMTEX's '74 and '75, respec-tively. The solid square is the estimation by the present aerodynamic method; while the open square, for reference, is the estimation by the atmospheric budget method by Nitta (1976) and Murty (1976). The close similarity in Fig. 8 be-tween the present estimation and the budget estimation is worth notice. On inspecting Fig. 8(a) and 8(b), nearly same values are found for both the AMTEX's '74 and '75: namely, about 700-800W m-2 in the intense cold period and about

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100-200W m-2 in the warm period, respectively.
For the AMTEX '75 the half period getting
colder every day is in the reversed order, i.e., the
half period of getting colder leads that of getting
warmer; moreover, the former continued for a
longer time in comparison with the colder half period in the AMTEX '74 did, and consequently the averaged value of the flux over the entire period is about 1.5 times as large as that for the AMTEX '74: namely, H+lE = 288W m-2 for the

'74, and H+lE= 418W m-2 for the '75.

5. Heat balance of the sea

The mean distributions over the entire period with respect of the meteorologic elements and of the fluxes at the sea surface are made from

their daily distributions, and are presented in Fig. A1 (Appendix): (a) air temperature T, (b) sea-air temperature difference Ts-T, (c) cloud amount n, (d) wind speed u, (e) surface stress *, (f) downward short-wave radiation S*, (g) net flux radiation gain of the sea surface Rn, (h) sensible heat loss H, and (i) latent heat loss lE. A region with strong winds is seen over the central part of the East China Sea, and con-sequently a region with large stress is there (Figs. d and e). A small amount of net radiation along the Kuroshio is due to the large loss by the long-wave radiation from the relatively warm sea and to the plentiful clouds shutting the solar energy. Over the sea off Shanghai, on the other hand, there is a large amount of net radiation, coin-cident with cold water (small temperature dif-ference between sea and air), with less cloud amount, or with the shallow sea over the con-tinental shelf (Figs. b, c, f and g). The pattern of the net radiation is similar in general with those of the sensible heat and latent heat (Figs. g, h and i). So far as the amount of heat is concerned, the net radiation is about a half of the sensible heat or about 20% of the latent heat.
Next, we shall proceed to the main theme of the present study. As shown by Eq. (1), the total loss of heat from the sea surface, H + lE-Rn, is compensated for by the release of heat content of the ocean and by the heat flux convergence due to the oceanic current and/or eddy transport. The total loss of heat is shown in Fig. 9. Since the greater part of the total loss is composed of latent heat, the distribution of H+lE-Rn is very similar to that of lE, but shows a contrast in the intervals between isolines. Over the sea near the continent the total loss of heat is about

100W m-2 or so, while along the Kuroshio it is about 350W m-2. The latter is equivalent to the temperature fall of the water column of 100-m thickness with a rate of 2.2* month-1. Such a large rate of temperature fall has never been found near the Kuroshio.

Fig. 9 The mean distribution of the total loss of heat from
the sea for the AMTEX
'74
.

On this subject, more detailed analysis will be made. The heat storage, S, in the ocean is obtain-able from the distributions of the water tempera-ture. But it will be expected to get an erratic value, because the fine structure for the whole regions can hardly be represented satisfactorily only with a small number of the water tempera-ture data obtained during the AMTEX period. Therefore, we had better to use a climatological data with respect to the water temperature.
The cooling rate of the sea could be estimated from the normal distributions for the water tem-

perature, (with making reference to "The 10-day mean sea surface temperature of the East China Sea and the Yellow Sea" and "The oceanographic atlas of the Northern Pacific"). A resulting dis-tribution of S is shown in Fig. 10. A negative value in S means the temperature decrease with time, and positive one the temperature increase. Roughly speaking, the magnitude of S is within ± 100W m-2.

An interesting feature can be seen from this figure. Over the shallow sea of the continental shelf, i.e., the northwestern part of the East China Sea, the value is S*-100W m-2 which is a nearly compensatory magnitude for the total loss of heat from the sea surface there. On the other hand, however, over the southeastern part of the region,

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Fig. 10 The mean distribution of the heat storage of the
ocean (climatological val-
ue).

especially along the Kuroshio, there are seen the
positive values. In spite of a lot of heat loss from
the sea surface to the atmosphere, the water tem-

perature increases with time. This fact is obvious-ly caused by the effect of the current and/or eddy
transport of the ocean.
It should be mentioned that we are now being investigated on the AMTEX '74 results in respect
to the turbulent heat losses H+lE, whereas on the
climatological normal distribution in respect to the heat storage S. As shown in Appendix 3,
however, the turbulent heat losses during the
AMTEX '74 are by about 14% smaller than
those obtained from the climatological values.
Even if we disregard such a difference and put
forward the analysis, the results expected will not
be altered seriously. Thus the present author will
hereafter analyse both the quantities of the '74
results and the climatological values without any
distinction between them.
Fig. 11 shows the distribution of H+lE-Rn+
S, which is, naturally, identical with the oceanic
heat convergence. An intense convergence of heat
is seen along the Kuroshio. This feature is easily understood by common sense. In contrast with the above, over the shallow sea a small or negative
heat convergence is seen. Such peculiarity gives
us an imagination that there might be a counter-
clockwise circulation in the ocean. The current,
which crosses the isotherms from the northern
region with a cold water toward south, corre-
sponds to the negative heat convergence. This
would occur in the west half of the Yellow Sea.
However, at the east half of this sea there might

Fig. 11 The mean distribution
of the heat convergence
caused by the oceanic
eddies and/or currents.

be the northwestward current which is originated in the sea west off Kyushu Island.
Now, it is intended to estimate the total oceanic heat convergence within some region of the sea. The amount of this is equal to the heat transport through the cross-sectional boundary of the region. For the region of the whole Yellow Sea, the total oceanic heat convergence is estimated at

F=*A(H+lE-Rn+S)dA=1.7*1013W .

If we assume that this amount of heat is trans-

ported only by an ideal mono-circulation as men-
tioned above, the corresponding current speed is
found to be V1 =10cm s-1, and the consequent
time required to circulate the whole volume of
water is estimated to be t1*160 days. A sche-
matic representation is shown in Fig. 12. In the
above estimation, the current speed is defined by

V1=(c*)-1(T*n-Tout)-1(2/b (6)
where b* (= 0.24*108 m2) is the cross-sectional
area of the boundary, and T*n- Tout (=12.3-
8.8*) is the difference between the average
water temperature of the inflowing current and
that of the outflowing across the boundary "a".
And the time is obtained by

t1=A*D*(2/bn)*V1-1, (7)
where A (=42*1010m2) is the area of the sea surface, and D (=40 m) the average depth of the Yellow Sea.

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Fig. 12 Schematic representation
of oceanic heat transport
in the East China and
Yellow Seas.

In a similar manner to the above, the oceani
eddy transport across the boundary "b" is esti mated at Fe = 7.7*1013W, (Fig. 12). Since the average temperature gradient and the cross sectional area of the boundary is found to be a*Tw/*n =-1.7*10-2*km'-1 and bn =1.1*108

m2, respectively, the oceanic eddy diffusivity can be obtained to be K=1.0*108cm2 s-1. This value

of K is equivalent to the eddy speed of 30cm s-1 multiplied by the eddy diameter size of about 30km. For the sea areas near the Southwest

Islands of Japan, marine reports say that there are often found the speeds of fluctuating currents like eddies with their magnitudes of the order of 30cm s-1.

Next, the oceanic eddy transport of heat across the boundaries which are indicated by the parallel dashed lines in Fig. 12 is estimated at Fe=7.3* 1013W, and the eddy diffusivity at the boundary is K= 0.9*108cm2 s-1 (with bn =1.7*108 m2 and
* Tw/*n = -1.1*10-2*km-1). This value of K is almost similar to the value obtained at the

boundary "b".
The oceanic transport of heat through the boundary "c" is estimated at 20*1013W (=Fk+ Fe+residue). The part, Fk =11*1013W, is the heat convergence caused by the Kuroshio. Then another part, Fe+residue= 9*1013W, is the heat convergence due to the eddy and other forms of transport. (In estimating Fk through Eq. (4), the value of the temperature difference, Tin-Tout= 23.5-20.5*, and the volume transport of water, anV=0.9*107m3 s-1, were used.)

If we assume the eddy diffusivity at the bound-ary "c" to be the same as 108cm2 s-1 (with bn= 2.0*108 m2 and *Tw/*n=-0.23*10-2*km-1),
it is found that the heat transport due to the eddies across the boundary "c" is equal to 2*1013W. Thus the heat due to the other forms of transport is 7*1013W (= residue). This is roughly equiva-lent to the heat convergence caused by the cur-rent of the second 100-m thick water layer of Kuroshio. (The heat convergence to be caused by the first top 100-m thickness of the Kuroshio was defined before as Fk.)
Note that each of three regions bounded by the boundaries "a", "b" and "c" has the areas of (42*1010), 2*(42*1010) and 3*(42*1010)m2, respectively, and that the region bounded by the dashed lines has a size of area of 8.6*1010m2.
At the end of this section we shall make a

comparison of eddy diffusivities between the pres-ent estimation and the values reported by several workers. The present author has a view that an accuracy in the present K-value seems to be re-latively high, because the estimation is based on the heat budget method with "meteorologic" ob-servations. On the other hand, however, values obtained hitherto are based on the "oceano-

graphic" observations: the current, salinity and spreading-matter distributions, etc.
A comparison of the oceanic eddy diffusivity is presented in Table 3. The present value is shown in the last line of the table. All results

except those in the bottom three lines are quoted from Hidaka (1955) and Bowden (1962). Some remarks should be noted. Firstly, the results in-dicated by group (1) are obtained from the con-sideration on the current energy acquired by the circulation to be dissipated by lateral eddy vis-cosity, those of group (2) from the measurements of the horizontal Reynolds stress, those of group
(3) from the measurements of spreading matters, and those of group (4) from the model experi-ments. Secondly, the result by Ichie (1957) was obtained from the observations of current fluctua-tions in the Kuroshio for the period shorter and the region smaller than those of the present analysis. In general, the longer the period is, the larger the K-value is, because the instantaneous horizontal gradients in temperature, current speed, etc. are larger than the mean gradients for long period.
The similar feature is seen with respect to the relationship between the horizontal size, r, of the region considered and the K-value. The ratios K/r are presented in the fifth column of the

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Table 3. A comparison of oceanic eddy diffusivities.

table. Four cases of them, including the present
one, result in K/r*1cm s-1.

6. Additional results

Several years ago the present author (Kondo,
1972) mentioned that the long-period means of fluxes could not be estimated correctly by the bulk formulae with only once of calculation using the time averaged values for the same period of the wind speed, the sea-air temperature difference

and the water vapor pressure. In such cases, the effective transfer coefficients to be applied are

considerably different in general from the bulk coefficients ordinarily used, (CD, CE and CH), and display a feature of diversity according to the length of time interval over which the meteoro-logic elements are averaged and to the local con-ditions. This is simply attributed to the unsteadi-ness of meteorologic elements.
In order to show what are the differences be-
tween the correct fluxes (*, H and lE) and the
incorrect ones (*1, H1 and lE1), the ratio of the
latter to the former will be calculated. The former

is given by

Fig. 13 The distribution of the ratio of the fluxes. (a): *1/*, (b): H1/H, and (c): E1/E.

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and the latter (incorrect flux) is given by

The notation within brackets denotes the mean

value over a long period. The figures (a), (b) and
(c) of Fig. 13 are the distributions of *1/*, H1/H,
and El/E, respectively, for two weeks of the
AMTEX '74. The ratios are about 0.8-0.9 for
* 1/*, about 0.6-0.8 for H1/H, and about 0.8-0.9 for E1/E over the East China Sea and adjacent
seas.

The above results imply that if we want ap-proximate fluxes with only once of calculation using the long-period mean values of the wind speed, etc., we must use the effective transfer co-efficients (CD* etc.) about 1.1 (=1/0.9) to 1.7 (=1 /0.6) times as large as the ordinary bulk co-efficients (CD, etc.). In this case, the approximate fluxes may be obtained by

7. Concluding remarks

When the intensely cold air appears over the East China Sea, the largest amount of sensible and latent heat of about 1,000W m-2 is supplied from the Kuroshio and its neighboring seas. At the same time the wind acts the stress force of about 0.4N m-2 upon the sea surface. The former is equivalent to the temperature increase with a rate of about 3.5* day-1 for the air column of 2-km thickness, or to the temperature fall with a rate of about 0.15* day-1 for the water column of 100-m thickness. (This does not mean that the temperature really change in such a manner.) The latter is equivalent to the acceleration of the cur-rent with a rate of 35cm s-1 day-1 for the 100m thickness of water, or to the Ekman mass trans-port of water with a rate of 8cm s-1*100m. Such intense activities making a strong interaction be-tween the sea and the air have occurred at the rate of about twice a month.
On the other hand, during the warm period, which intermediately occurs between cold periods, an amount of heat loss from the sea surface is small and about 100W m-2.
In regard to the averaged values for the entire period, the total heat loss from the sea of Kuro-

shio is about 350W m-2, which is compensated for by the oceanic convergence of heat caused by the current and/or the oceanic eddy transport. The average values of fluxes over the AMTEX area for AMTEX '74 are as follows: net gain of radiation Rn = 43W m-2 (= 4.3 mW cm-2 =88 1y day-1), sensible heat H=70W m-2, latent heat l E=204W m-2, total heat loss from the sea sur-face H+lE- Rn = 231W m-2, and the momentum transfer r = 0.125N m-2 (=1.25dyne cm-2). The value of H+lE for AMTEX '74 is by about 10 to 20% smaller than the climatological normal value for the corresponding period.
On the basis of heat budget consideration, there is suggested a possibility that in the Yellow Sea there occurs a counterclockwise circulation with a current speed of about 10cm s-1, provided that the oceanic heat convergence is caused only by an idealized mono-circulation. But it is likely that some fraction of heat convergence is produced also by the oceanic eddies of the Yollow Sea, and so the current of the circulation would be slightly weaker than the value of 10cm s-1.

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and Murty of Tokyo University for providing their results by budget method for comparison. The present study was supported by Funds for Scientific Research from the Ministry of Educa-tion.

Appendix 1. Empirical formulae four radiation

The empirical formulae used in the present paper were originally developed by Kondo (1967). For the convenience of practical application, the formulae are simplified and reformed as follows:

(a) Instantaneous solar radiation on a fine day:

where Ii* is the instantaneous value of the solar

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radiation at the top of the atmosphere, * the solar
zenith angle, and e the daily mean value of vapor
pressure in mb.

(b) Daily total solar radiation on a fine day

where n is the daily mean amount of clouds, Id*
the daily total value of the solar radiation at the top of the atmosphere, and *o the solar zenith angle at noon (*o= *-*, * being the latitude, and * the solar declination).

(c) Daily total solar radiation on a cloudy day

where t is a parameter representing the cloud thickness and given by

shine that is possible at the site, and Nr/N is the appearance frequency of snowfall and/or rainy time.

Note: The original empirical formula (Kondo, 1967) for the solar radiation was formulated from the observational data obtained at the IGY '58

Stations of JMA, excluding the data at Tohoku University. The present formulae (Eqs. Al-A5) are reformed from the data at Tohoku University, excluding the data at Stations of JMA. The original formula gives rise to some overestimation in the solar radiation values, which are by about 10% larger than the values given by the present reformed formulae. The present author is afraid that this may be due to inconsistency between the calibration constants of the pyranometers of To-hoku University and of JMA used for the IGY

'58 and subsequent several years.

(d) Instantaneous and/or daily mean value of the downward long-wave radiation:

where n1, nm and nh are the daily mean amount of low, middle and high clouds, respectively, s
is the ratio of the observed number of hours of sunshine to the maximum number of hours of sun-

where h is a parameter representing the cloud height, e the daily mean value of vapor pressure in mb, and *T4 the black-body radiation at the daily mean air temperature. (In general, the instantaneous deviation of the downward long-wave radiation from its daily mean value is small, within a few percent of its daily mean, provided

Table A1. Daily mean values of u* (cm s-1), lE (W m-2) and H (W m-2) at the Ocean Stations during both of the AMTEX's '74 and '75.

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that the feature of clouds does not change all
day.)

Appendix 2. Daily mean fluxes at the Ocean
Ship Stations and the average flux
over the AMTEX region

Table Al presents the daily mean values of the friction velocity, latent and sensible heat at three Ocean Ship Stations during both of the AMTEX's '74 and '75
.

Table A2 shows a comparison between the average value of H+lE over the AMTEX area of hexagonal region (fourth column) and that over the square region (third column), or that for three Ocean Stations (sixth column), or the estimation
at the open sea off Okinoerabujima (fifth column).
The value in the second and last column are, for
reference, the estimations by the budget method
in the atmosphere by Nitta (1976) and Murty
(1976). It may be seen from this table that the

Table A2. Comparisons between the averaged value of H+lE over the AMTEX area and
that over the square area, or that for three Ocean Ship Stations, or the deduced
flux from the data at Okinoerabujima Station. (Unit in W m-2)

Table A3. The monthly mean values of H+lE as deduced from data at Okino-
erabujima from 1970 to 1974.

Note: CE*=1.9*10-3; <Ts>: the mean value for 1 February to 10 March; <T> =(2*<TFeb> +<TMar>)/3 ; and <q> = (2*<qFeb>+<qMar>)/3.

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Fig. A1. The mean distribution of the meteorologic elements and of the fluxes for the entire period of AMTEX '74. (a): air temperature, (b): sea-air temperature difference, (c): cloud amount, (d): wind speed, (e): surface
stress, (f): downward solar radiation, (g): net radiation, (h): sensible heat,
and (i): latent heat.

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values are nearly the same with each other. The
difference between their averaged values for the
entire period is very small. The values presented
in the last two columns are for the AMTEX '75.
Figs. (a) through (i) of Fig. Al are the mean
distributions for the entire period of the AMTEX '74
.

Appendix 3. An estimation of H+lE as a clima-tological value
It has been shown in Table A2 that the deduced

value of H+lE from the data of Okinoerabujima Weather Station is the representative flux over the AMTEX region. For that reason, the mean flux estimated by the same procedure for the corre-sponding period of several years might be regarded as a climatological value, approximately. The fourth column of Table A3 presents the value of H+lE, which is defined by

where CH* and CE* differ from the meaning "the bulk coefficient" in ordinary use, but are "the effective coefficient". The latter is available for

estimation of the long-period mean flux by making use of the long-period means of temperature <T>, mixing ratio <q> and wind speed <u>. For the period of two weeks of AMTEX the ef-fective coefficients for Okinoerabujima Station have been obtained as CH**CE**1.9*10-3; which are considerably larger than the bulk co-efficients in ordinary use.

Data available on request

(a) Fig. A2.
The horizontal distributions of the daily mean values of the following elements are not presented in this paper, but they are available on request: cloud amount; air temperature, water vapor pres. sure and wind speed at the 10-m height; net radi-ation, sensible heat, latent heat and stress at the sea surface for each day of the AMTEX '74.

(b) Table A4.
Daily mean values (of u10, G, u*/G, T, Ts-T
e and es-e) of three Ocean Stations for both the AMTEX's '74 and '75 are also available on re-

quest. As to the values of air temperature, water vapor pressure and sea-surface temperature, the corrections for instrumental errore have beer

made. (It should be noticed that the dry-bulb thermometer of Ryofu always indicates too higl temperatures in comparison with the special ob

servation does, and that the instrument of Nojima For the sea-surface temperature sometimes indi-c ates too low temperatures as compared with the thermometer for the special observation does.)

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冬の東支那海の熱収支と海面応力

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1974年 と1975年 の気団変質の観測(AMTEX)デ ータをもとに して,黄 海と東支那海周辺海域の熱収支 と海面応
力を,主 と して空気力学的方法を用いて評価 した。 それによる と,海 面が大気へ失なう顕熱と潜熱(H+lE)は 海洋
熱(海 洋の横方向の乱流と黒潮によって運ばれる熱)に よって,大 体補償されている。放射 と海中貯熱量は二次的な役割をはた している。 なお,そ の他の主な結果は以下の通 り。
(1)6角 形に選んだAMTEX海 域内でみる と,H+lEの 全期間の平均値は,1974年 では平年値の約86%で あ
ったが,1975年 では約132%で あ った。 これは主 として,"cold"periodの 長さのちがいによるものである。いつ
れの年も"cold"periodの 最盛日には,700～800W・m-2(=1440～16501y・day-1),"warm"periodに は
100～200W・m-2程 度である。
(2)次 に,南 西諸島には,ほ ぼ2週 間に1回 の割合で大陸から寒波がやって くるが,こ の時黒潮に沿って,最 大
1,000W・m-2に も達するほどの熱放出が見 られる。 しか し浅い大陸棚上では海洋熱の影響 も弱 く,水 温が低いこともあって,熱 放出量は少ない。 一方,風 が海面に及ぼすstreｓｓ は熱収支分布図とは異った分布であるが,最 大約
0.4N・m-2(=・4dyne・cm-2)を こえ る。 この値は100mの 厚さの海水を1日 当 り35cm・s-1の 割合で加速する
力,ま たはEkmanの 輸送で表現する と8cm・s-1×100mの 水の容積運搬速度に相当する。
(3)海 面のボーエン比(H/IE)を 調べて見ると,黄 海では0.8,黒 潮域では0.4,更 にその南方では0.1と 云 う具
合に南に行 くほど小さ くなる傾向を示す。 この事は大陸か らの寒波は北方海域で,ま つ(相 対的に),気 温が上昇 し, その後で十分水蒸気の補給を受けると云 う形で気団変質がおこっている事を意味する。
(4)熱 収支式の残余項は海洋の熱収束であるから,こ れを或る海域について積分 した熱はこの海域へ運ぼれた海
洋熱に相当する。 この値と水温水平分布から海洋熱拡散係数が1×108cm2・S-1と 評価された。
(5)熱 収支分布の形から,黄 海に反時計まわ りの循環流の存在が予測される。黄海に入る海洋熱はF=1.7×1013
Wで あ るが,こ れが,も しも単一循環流だけによるものと見なすならば,そ の循環の平均速度はV1=10cm・s-1
とな り,黄 海水の 「滞留時間」は、t1=160日,程 度 と評価される。