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Atmospheric and Oceanic Factors Affecting the Air-Sea Thermal Interactions in the East Sea (Japan Sea)

Yong Q. Kang
Dept. of Oceanograhy, National Fisheries University of Pusan, Pusan 608

東海海面 熱交換에 影響을 미치는 大氣 및 海洋的 要因

姜 容 均
釜山水產大學 海洋學科

Abstract: The atmospheric and oceanic influences on the air-sea thermal interaction in the East Sea (Japan Sea) are studied by means of an analytic model which is based on the heat budget of the ocean. By means of the model, the annual variations of heat fluxes and air temperatures in the East Sea are analytically simulated. The model shows that the back radiation, the latent heat and the sensible heat increase with the warm water advection. The latent heat increases with the sea surface temperature (SST) but the back radiation and the sensible heat dcrease as the SST increases. In the East Sea, an increase of mean SST by 1.0°C yields an increase of mean air temperature by 1.2°C. The heat storage in the ocean plays an important role in the annual variations of heat flux across the sea surface.

要約: 대기 및 해양적 요인들이 동해의 해면을 통한 열교환에 미치는 영향을 구명하기 위하여, 해양의 열수지에 근거한 해석적인 모델을 만들고, 이 모델을 통하여 동해상 해면 열교환의 각 성분과 대기 온도의 연변화를 해석적으로 재현(simulation)하였다. 모델에 의한 이론적인 결과에 의하면, 동해에서 난류에 의한 열수송이 클수록 역복사, 잠열 및 현열의 방출이 증가한다. 그리고 표면수온이 증가함에 따라 잠열은 증가하지만, 역복사와 현열은 감소한다. 동해에서 연평균 수온이 1°C 증가하면 해상 기온의 연평균이 1.2°C 증가하는 효과를 가져오며, 해양의 저열량의 크기는 해면을 통한 열교환의 연변화에 지대한 영향을 미친다.

INTRODUCTION

The heat capacity of the ocean is much larger than that of the atmosphere, and the ocean plays a very significant role in the air-sea thermal interactions. In most studies on the air-sea thermal interactions, the heat transfer across the sea surface is usually computed by empirical bulk formulas. Haney (1971), Kraus (1972), and Walker (1977), among others, discussed the empirical formulas. Heat fluxes over the North Pacific and the North Atlantic were computed by Wyrtki (1965) and Bunker (1976), respectively. In those studies, the sea surface temperature (SST) is used as an input parameter in the empirical formulas, but the oceanic heat storage and heat advection are not included in the formulas. The gross contribution of the ocean to the air-sea interaction is usually estimated by the residual or net heat flux across the sea surface.

In this paper, in order to understand the ocean's role in the air-sea thermal interactions in the East Sea (Japan Sea), an analytic model of the air-sea interaction is developed which is based on the heat budget of the ocean. The model is particulary suitable in investigating the ocean's role on the heat fluxes across the sea

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surface. The model is based on the heat budget of the ocean and it also uses empirical formulas of heat flux computations. However, the air temperature (AT) is not given as an input but is computed as an output of the model. In other words, the air-sea interaction problem is approached from an 'oceanographic' point of view rather than from a 'meteorological' one. The model is applied to the East Sea and it analytically simulates the annual variations of the AT and the heat flux components at the sea surface. A close resemblance between the 'oceanographic' simulation by the model and the 'meteorological' estimation by Maizuru Marine Observatory (MMO, 1972) supports the validity of the model. The sensitivity of various atmospheric and oceanic factors on the AT and on the heat flux components across the sea surface in the East Sea are studied in this paper.

MODEL

The model is based on the heat budget of the ocean, which can be written by

$$Q_i+Q_v-(Q_b+Q_h+Q_e+Q_t)=0, \qquad (1)$$

where Q_i is the incoming short-wave radiation reaching onto the sea surface, Q_v the horizontal advection of heat by ocean current, Q_b the effective upward back radiation, Q_h the sensible heat loss, Q_e the upward latent heat flux of evaportion, and Q_t the change rate of ocean's heat content or the heat storage rate. Each term of (1) is parameterized by the bulk method as follows.

The incoming radiation is (Gill, 1982, p. 34)

$$Q_i=Q_{io}(1-\alpha)(1-0.7C), \qquad (2)$$

where Q_{io} is the solar radiation reaching the top of the atmosphere, α the albedo of the sea surface, C the fraction of cloud coverage. The effective upward flux of long-wave radiation from the sea surface by Berliand's formula is (MMO, 1972, p. 47)

$$Q_b=\varepsilon\sigma T_s^4(0.39-0.058\sqrt{e_a})(1-0.65C^2)$$
$$+4\varepsilon\sigma T_s^3(T_s-T_a), \qquad (3)$$

where ε is the emissivity of sea surface ($\varepsilon=0.985$), σ the Stefan-Boltzman constant ($\sigma=5.76\times10^{-8}\ Wm^{-2}K^{-4}$), e_a the vapor pressure of the air in mb, T_s the absolute SST, and T_a the absolute AT.

The bulk formula of sensible heat flux is (Haney, 1971)

$$Q_h=\rho_a C_a D_h U(T_s-T_a)=A_h U(T_s-T_a), \quad (4)$$

where ρ_a is the density of air ($\rho_a=1.225\text{kg/m}^3$ at 15°C), C_a the specific heat of air, D_h a dimensionless constant for heat conduction or Stanton number ($D_h=1.10\times10^{-3}$; Smith, 1980), U the wind speed, and $A_h=\rho_a C_a D_h=1.353\ JK^{-1}m^{-3}$.

The latent heat flux of evaporation is (Haney, 1971)

$$Q_e=(0.622/p)L\rho_a D_e U(e_s-e_a)$$
$$=A_e U(e_s-e_a), \qquad (5)$$

where p is the atmospheric pressure ($p=1013\ mb$), L the latent heat of evaporation per unit mass ($L=589Kcal/Kg$), D_e a dimensionless constant for evaporation or Dalton number ($D_e=1.5\times10^{-3}$; Gill, 1982), and e_s and e_a are vapor pressures at the sea surface and at the deck height, respectively, and $A_e=(0.622/p)L\rho_a D=2.78Jm^{-3}mb^{-1}$. The vapor pressures e_s and e_a can be represented by

$$e_s=e^\circ(T_s), \quad e_a=he^\circ(T_a), \qquad (6)$$

where $e^\circ(T)$ is the saturation vapor pressure at temperature T, and h the relative humidity of the air. The latent heat flux of (5), by using (6), becomes a function of the AT, the SST and the relative humidity. The saturation vapor pressure (mb) in a temperature range of ± 40°C is given by (Gill, 1982, p. 606)

$$\log_{10} e^\circ(T) = 0.7859+0.03477T)/$$
$$(1+0.00412T). \qquad (7)$$

The heat content of the ocean, Q, and its change rate, Q_t, are

$$Q(t)=\rho_w C_w\int_{-H}^{0} T_w(z)\,dz$$

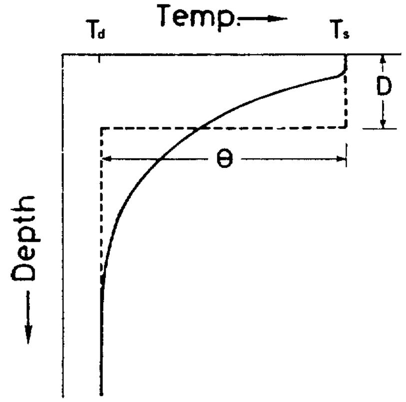

Fig. 1. Two-layer approximation of the vertical temperature distribution.

$$Q_t(t)=\rho_w C_w \frac{\partial}{\partial t}\int_{-H}^{0} T_w(z)dz, \tag{8}$$

where t is the time, z the vertical coordinate, H the depth of the ocean, ρ_w the density of sea water ($\rho_w=1000Kg/m^3$), C_w the specific heat of sea water ($C_w=1$ cal $K^{-1}g^{-1}$), and $T_w(z)$ the sea water temperature. If a two-layer approximation of $T_w(z)$ shown in Fig. 1 is used, then (8) becomes

$$Q(t)=\rho_w C_w \theta(t)D(t)+\text{const}$$

$$Q_t(t)=\rho_w C_w \frac{\partial}{\partial t}[\theta(t)D(t)] \tag{9}$$

where $D(t)$ is the thickness of the upper layer in the two-layer model, and $\theta(t)$ the difference between the surface layer temperature, T_s, and the lower layer temperature, T_d, i.e., $\theta(t)=T_s(t)-T_d$. The horizontal advection of heat by ocean current is

$$Q_v=-\rho_w C_w \int_{-H}^{0} V\partial T_w/\partial x \; dz, \tag{10}$$

where x is the downstream distance and V the current speed.

The terms Q_i, Q_v and Q_t of (1) are independent on the AT while the other terms Q_h, Q_e and Q_b are dependent on it. By substituting (3), (4) and (5) into (1) we get

$$\begin{aligned}Q_i+Q_v-Q_t=&\varepsilon\sigma T_s^4[0.39\\&-0.05\sqrt{he^\circ(T_a)}](1-0.65C^2)\\&+A_hU(T_s-T_a)+4\varepsilon\sigma T_s^3(T_s-T_a)\\&+A_eU[e^\circ(T_s)-he^\circ(T_a)].\end{aligned} \tag{11}$$

The terms in the left hand side of (11), which are independent on the AT, depend on the albedo of the sea surface, the cloud coverage, the sea water temperature, and the speed of ocean current. If the values of the incoming radiation, the heat advection, the heat storage rate, the relative humidity, the cloud coverage and the wind speed are given, then the AT can be determined from the nonlinear algebraic equaton (11).

If the difference between SST aind AT (SST-AT) is sufficiently small, then by using truncated Taylor expansions,

$$\begin{aligned}&e^0(T_a)=e^0(T_s)-e'\delta T,\\&e^0(T_s)-h\ e^0(T_s-T_a)\\&\quad=(1-h)e^0(T_s)+he'\delta T,\end{aligned} \tag{12}$$

where $\delta T=T_s-T_a$ and $e'=de^0/dT$ at $T=T_s$, we get the approximate analytic solution of (11) as

$$\begin{aligned}&\delta T(0.025\varepsilon\sigma T_s^4e'/\sqrt{he^0}+4\varepsilon\sigma T_s^3+A_hU\\&\quad+A_eUhe')\\&=Q_i+Q_v-Q_t-\varepsilon\sigma T_s^4(1-0.65C^2)(0.39-\\&\quad0.058\sqrt{he^0})-A_eU(1-h)e^0.\end{aligned} \tag{13}$$

This approximate solution is used as an initial guess for the numerical solution of (11).

SIMULATION OF AIR-SEA INTERACTION IN THE EAST SEA

The annual variations of the AT and the heat flux in the East Sea are simulated based on (11). The inputs T_s, Q_{i0}, U and D in the East Sea are approximated by time-harmonic functions as (cf. MMO, 1972)

$$T_s(°C)=15+8\cos(\omega t-240°)$$
$$Q_{i0}(W/m^2)=345+180\cos(\omega t-173°)$$
$$U(m/sec)=6.2+1.8\cos(\omega t-15°)$$
$$D(m)=38+6\cos(\omega t-31°),$$

where $\omega=2\pi/365$ day^{-1} and t is the day of the year (e.g., t of 365 means December 31). The values of other inputs, assumed constant, are $h=66\%$, $C=66\%$ (MMO, 1972), $Q=63\,W/m^2$ $=130$ ly/day (Wyrtki, 1965), $\alpha=0.33$ (Ste-

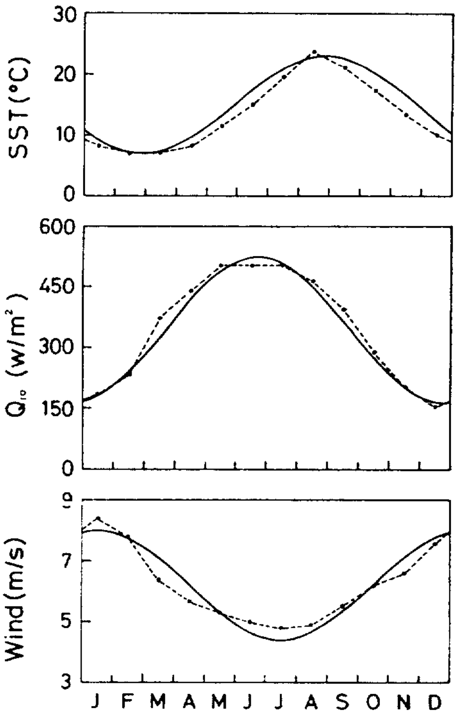

Fig. 2. Sinusoidal inputs (full lines) of the SST, the incoming radiation at the top of the atmosphere, Q_{io}, and the wind speed used in a simulation of an annual variation of air-sea interaction in the East Sea. The corresponding estimates in the East Sea by Maizuru Mar. Obs. (1972) are shown by dotted lines.

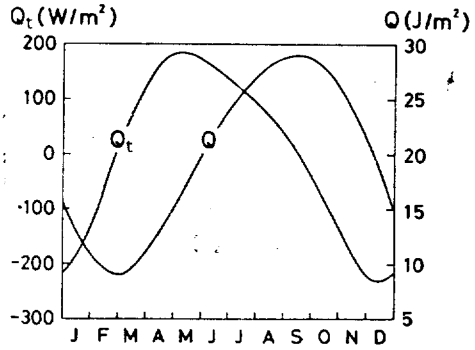

Fig. 3. Heat content, Q, and heat storage rate, Q_t, used in a simulation of the air-sea interaction in the East Sea.

phens *et al*, 1973), and $T_d=2.0°C$. The annual variations of the SST, the incoming radiation at the top of the atmosphere, and the wind speed used in the model are shown in Fig. 2

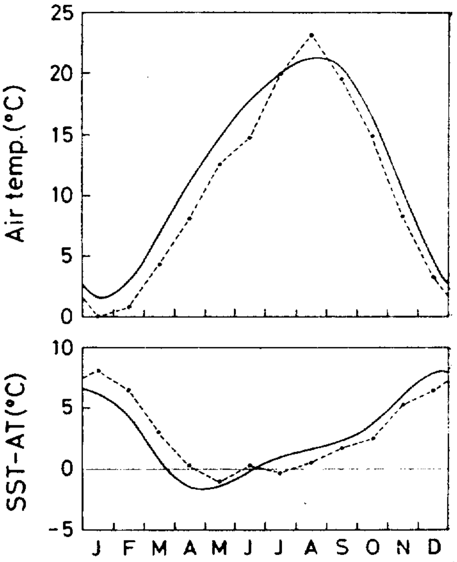

Fig. 4. Simulated annual variations (full lines) of the AT and the SST-AT in the East Sea. The corresponding observations by Maizuru Mar. Obs. (1972) are shown by dotted lines.

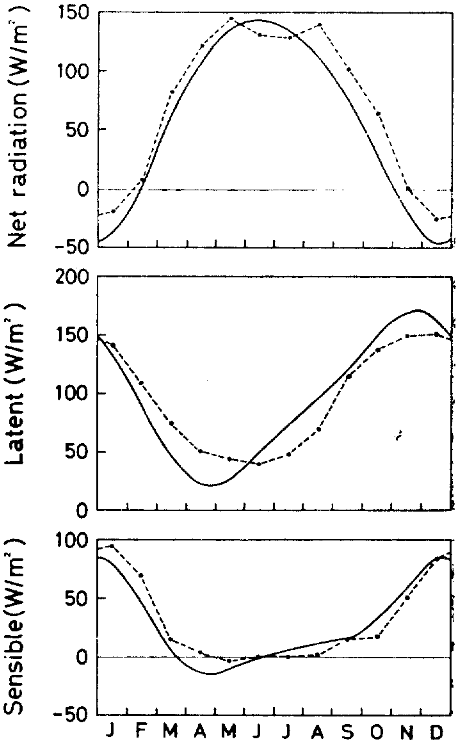

Fig. 5. Simulated annual variations (full lines) of the net radiation, the latent heat and the sensible heat of the East Sea. The corresponding estimates by Maizuru Mar. Obs. (1972) are shown by dotted lines.

by full lines. The corresponding observations or estimates spatially averaged over the East Sea by MMO (1972) are shown by dotted lines in Fig. 2. The annual variations of heat content and its change rate computed by (9) are shown in Fig. 3.

Using these inputs, the annual variation of the *AT* in the East Sea is solved from (11) by the secant method (Hornbeck, 1975), and shown by full lines in Fig. 4. The back radiation, the sensible heat and the latent heat are computed by (3), (4) and (5), respectively, and shown by full lines in Fig. 5. The corresponding 'meteorological' estimates based on the observed AT in the East Sea by MMO (1972) are shown by dotted lines in Figs. 4 and 5. Note that the simulated outputs in Figs. 4 and 5 are not sinusoidal, although the inputs are either sinusoidal or constant. Since the specified inputs are only approximate, so is the simulated outputs. However, the temporal behavior of the simulated results (full lines in Figs. 4 and 5) basically agrees with the 'estimates' (dotted lines in Fig. 4 and 5).

ATMOSPHERIC FACTORS

The sensitivity of atmospheric and oceanic factors on the AT and on the heat flux components are investigated by changing only one input parameter while keeping the others the same as those used in the simulation of the air-sea interaction of the East Sea.

Fig. 6a and 6b show the dependence of the annual means of heat flux components on the cloud coverage and the sea surface albedo, respectively. As the cloud coverage or the albedo increases, the mean incoming radiation reaching the sea surface decreases, and this decrease is compensated by decreases of sensible heat, latent heat and back radiation. The decrease of sensible

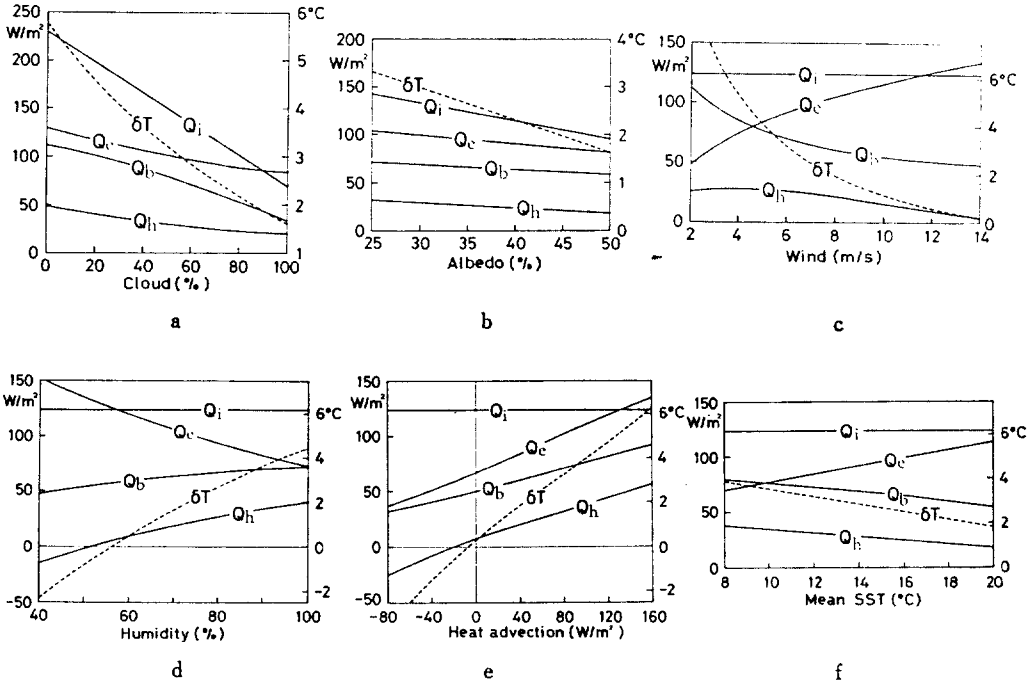

Fig. 6. Dependences of the means of heat fluxes and SST-AT on the percentage of cloud coverage (a), on the albedo of the sea surface (b), on the wind speed (c), on the relative humidity of the air (d), on the oceanic heat advection (e), and on the mean SST (f). Q_i is the incoming radiation, Q_b the back radiation, Q_h the sensible heat, Q_e the latent heat flux of evaporation, and δT the SST-AT.

and latent heats, associated with a decrease of the incoming radiation, yields a decrease in the SST-AT. Fig. 6c shows the mean heat flux components and the SST-AT as a function of wind speed. An increase of wind speed yields an increase of latent heat and a decrease of SST-AT. An increase of the latent heat with the wind speed is compensated by the decrease of back radiation and sensible heat.

Fig. 6d shows the influence of the relative humidity on the means of heat flux and SST-AT. An increase of relative humidity yields a decrease of latent heat and an increase of SST-AT. A decrease of latent heat flux, associated with an increase of relative humidity, is compensated by increases of sensible heat and back radiation. Figs. 6c and 6d suggest that an increase of the wind speed is quite analogous to a decease of the relative humidity and *vice versa*.

OCEANIC FACTORS

The roles of the ocean on the AT and on the heat flux is studied by considering the effects of the heat advection, the mean SST, the amplitude of SST, and the magnitude of oceanic heat storage rate.

Fig. 6e shows the means of heat flux components and SST-AT as functions of oceanic heat advection. The sensible and latent heats and the back radiation increase with the horizontal advection of heat by ocean currents. An increase of heat advection by 1 W/m^2 is partitioned into the increases of the latent heat, the sensible heat and the back radiation by 0.43, 0.32 and 0.25 W/m^2, respectively. The mean SST-AT is almost proportional to the advection. The mean SST is higher (lower) than the mean AT for the case of warm (cold) water advection.

Fig. 6f shows the effects of the mean SST on the means of heat flux and SST-AT. As the mean SST increases, the latent heat increases while the back radiation and the sensible heat decrease. An increase of mean SST by 1°C yields an increase of latent heat by 3.7 W/m^2. The latenl heat flux increases with the SST becuase the saturation vapor pressure increases almost exponentially with the AT. An increase of latent heat flux, associated with an increase of mean SST, is balanced by a decrease of back radiation and sensible heat. An increase of mean SST by 1.0°C yields decreases of the back radiation and the sensible heat by 2.0 and 1.7 W/m^2, respectively. Fig. 7 shows the means of AT and SST-AT as functions of mean SST. An increase of mean SST by 1.0°C brings an increase of mean AT by 1.2°C. The mean SST-AT decreases almost linearly with the increase of mean SST.

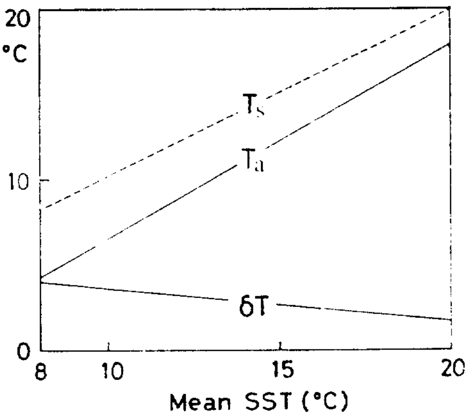

Fig. 7. Dependence of the means of AT (T_a) and the SST-AT (δT) on the mean SST (T_s). The heat storage rate is not changed.

The effects of the annual range of the SST are studied by varying the amplitude of the SST while keeping the heat storage rate the same as the reference one. The result shows that the means of heat flux, AT and SST-AT are almost independent on the annual range of SST (this result is not shown in the figure). However, the annual variations of the heat fluxes and AT depend on the annual range of SST. Fig. 8 shows the annual variations of AT and SST-AT

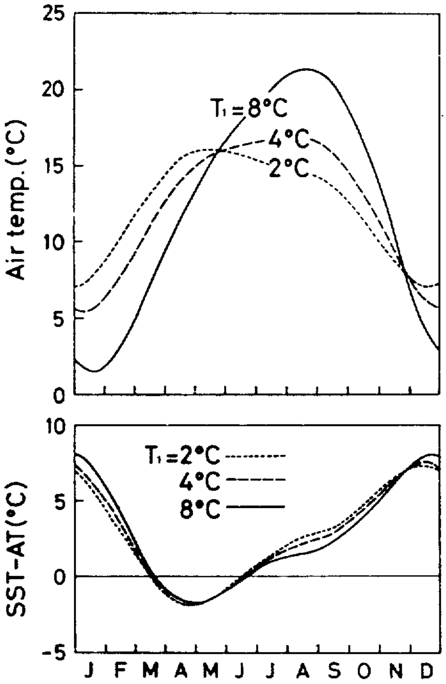

Fig. 8. Annual variations of AT and SST-AT associated with SST variations with amplitudes of 2, 4 and 8°C. The heat storage rate is not changed.

associated with the seasonal SST variation with amplitudes of 2, 4 and 8°C. This figure shows that the annual variation of AT depends strongly on the amplitude of the SST, but the annual variation of SST-AT depends only weakly on it.

Fig. 9 shows the dependence of the means of heat flux and SSS-AT on the annual range of heat storage rate. Its magnitude adjusted either by varying the amplitude of SST (the upper figure) or by varying the depth of the upper layer (the lower figure). Fig. 9 shows that the means of heat flux and SST-AT are almost independent of the magnitudes of heat storage rate. The annual variations of heat flux components and SST-AT, on the other hand, depend strongly on the magnitude of heat storage rate. Fig. 10 shows the annual variations of latent heat, sensible heat, and SST-AT associated with various magnitudes of heat storage rate. The relative heat storage rates of 10, 40, 50 and 100% with respect to the reference one of Fig. 3 are obtained by varying the depth of the upper layer. The annual variation of SST-AT for the case of the relative heat storage of 10% is almost out of phase from that of the reference one.

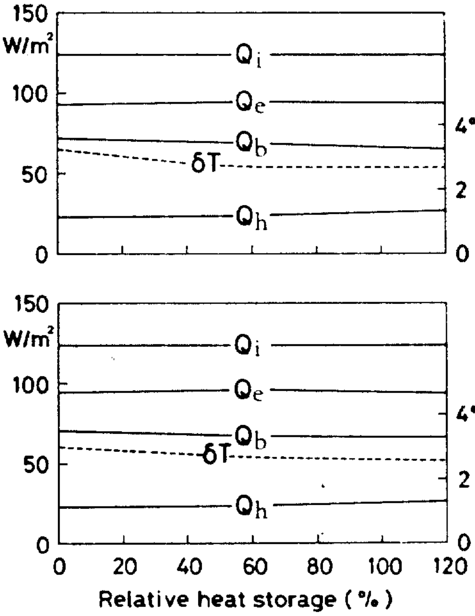

Fig. 9. Dependence of the means of heat fluxes and SST-AT on the magnitude of heat storage rate. The relative heat storage rate is changed by varying only the amplitude of SST (the upper figure) or by varying only the depth of the upper layer (the lower figure). Symbols are the same as in Fig. 6.

DISCUSSION AND CONCLUSIONS

The influences of atmospheric and oceanic factors on the air-sea interaction in the East Sea are studied in this paper through an analytic model which is based on the heat budget of the ocean. In the model the AT is not given as an input but is computed as an output. The annual variations of AT and heat flux components in the East Sea were simulated reasonably well by means of the model. The model shows the followings.

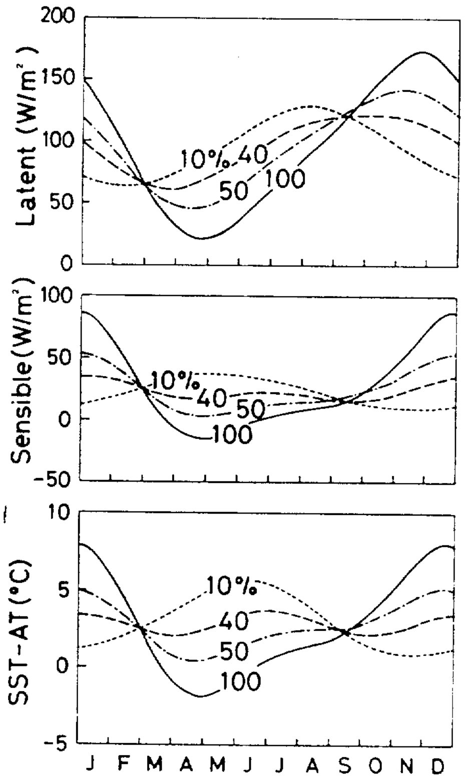

Fig. 10. Annual variations of the latent heat, the sensible heat and the SST-AT associated with relative heat storage rates of 10, 40, 50 and 100% with respect to the reference one. The relative heat storage rate is changed by varying the depth of the upper layer.

An increase of cloud coverage or albedo of the sea surface reduces the incoming radiation reaching onto the sea surface. An increase of wind speed plays a role similar to a decrease of relative humidity. As wind speed increases or relative humidity decreases the latent heat flux increases whereas the back radiation and the sensible heat decrease. An increase of the oceanic heat advection yields a results analogous to an increase of the incoming radiation. The sensible heat, latent heat and back radiation increase with the increase of incoming radiation or heat advection. As the heat advection increases, the SST-AT also increases. In fact, in the open ocean the SST-AT is maximal in regions of the Kuroshio and the Gulf Stream where the heat advection is large (Cayan, 1980).

The change in the mean SST brings significant influences on the AT and on the heat fluxes at the sea surface. For the situation of the East Sea, an increase of SST by 1.0°C yields an increase of AT 1.2°C. Although the estimates in the East Sea do not necessarily represent those in the open ocean, they give insights on the possibe effects of large scale ocean temperature anomalies on the climatic variability. Note that the mean SST can be varied without any change in the heat content of the ocean becan because the latter depends not only on the SST but also on the depth of the upper layer.

The means of AT and heat flux components are almost independent on the annual range of seasonal SST or seasonal storage of heat. However, the annual ranges of seasonal heat storage and SST play significant roles in the annual vaiation of AT and heat flux components.

The influence of the ocean's heat storage is well manifested in the annual variation of SST-AT. For the case of seasonal heat storage less than 10% of the typical ocean, the phase of SST-AT is almost opposite to that of a typical ocean. By a similar reasoning one can explain why the SST is higher than the AT in winter whereas the ground surface temperature is higher than the AT in summer (Kang, 1983). The contrast between the 'continentality' and the 'oceanality' is attributd mainly to the greatness of heat reservoir capacity of the ocean.

In this paper, the influences of atmospheric and oceanic factors on the air-sea thermal interactions in the East Sea are analytically investigated by changing only one factor while keeping the others the same as the reference ones. Such an 'artificial' change does not necessarily reflects the actual situations, because a change in one factor usually accompanies changes in other factors. For example, a change in the SST would accompany a change in the vapor pressure. The analytic approach in this paper, however, provides insights on the influences of various atmospheric and oceanic factors on the air-sea thermal interactions in the East Sea.

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REFERENCES

Bunker, A.F., 1976. Computations of surface energy flux and annual air-sea interaction cycles of the North Atlantic. Mon. Wea. Rev., 104:1122-1140.

Cayan, D.R., 1980. Large-scale relationship between sea surface temperature and surface air temperature. Mon. Wea. Rev., 108:1293-1301.

Gill, A.E., 1982. Atmosphere-Ocean Dynamics. Academic Press, Oxford, 922pp.

Haney, R.L., 1971. Surface thermal boundary condition for ocean circulation models. J. Phys. Oceanogr., 1:241-248.

Hornbeck, R.W., 1975. Numerical Methods. Quantum Publ., New York, 310pp.

Kang, Y.Q., 1983. On the temperature differernces across ground and sea surfaces in Korea. J. Korean Meteor. Soc., 19:88-95.

Kraus, E.B., 1972. Atmosphere-Ocean Interaction. Clarendon Press, Oxford, 275pp.

Maizuru Marine Observatory, 1972. Marine Meteorological Study of the Japan Sea. Japan Meteorological Agency, Tokyo, 116pp. (in Japanese)

Perry, A.H. and J.M. Walker, 1977. The Ocean-Atmosphere System. Longman Inc., London, 160pp.

Smith, S.D., 1980. Wind stress and heat flux over the ocean in gale force winds. J. Phys. Oceanogr., 10:709-726.

Stephens, G.K., G.G. Campbell and T.H. vonder Haar, 1981. Earth radiation budgets. J. Geophys. Res., 86:9739-9760.

Wyrtki, K., 1965. The average annual heat balance over the North Pacific Ocean and its relation to ocean circulation. J. Geophys. Res., 70:4547-4559.