Mean Heat Fluxes at Dok Island

Choi Yong-kyu[1*], Choi Hyo[2] and Lee Yong-hwa[1]
1. East Sea Fisheries Research Institute, National Fisheries Research and Development Institute, Gangneung, 210-861, KOREA
2. Atmosphere & Oceanic Disaster Research Institute, Dalim Apt. 209, Songjungdong, Gangneung 210-140, KOREA
*uniproto@korea.kr

Abstract
Based on the monthly weather report of Korea Meteorological Administration (KMA) and the daily sea surface temperature (SST) data from the Korean Oceanographic Data Center (KODC) during 2000-2008, mean heat fluxes were estimated at Dok Island. The mean SST ranged from 9.2℃ to 26.2℃, mean air temperature (AT) ranged from 2.5℃ to 27.6℃. The lowest SST was 6.8℃ (January 6, 2003) and the highest SST was 29.0℃ (August 13, 2005). The lowest AT was -4.6℃ (December 6, 2008) and the highest AT was 32.0℃ (August 18, 2007). Net heat flux was transported from the air to the sea surface during March to October and it ranged from 133.7 Wm^{-2} to 260.5 Wm^{-2}. Long wave radiation was shown to be from 19.8 Wm^{-2} to 91.5 Wm^{-2} with the minimum value in July.

Sensible heat flux ranged from -29.7Wm^{-2} to 100.1 Wm^{-2} with a minimum value in April. Latent heat flux ranged from 15.2 Wm^{-2} to 89.9 Wm^{-2}. The phase of heat exchange changed from cooling to heating at the start of March and from heating to cooling at the start of November. Using factor analysis, the net heat flux showed a positive relationship in SST, AT and relative humidity and a negative relationship in air pressure and wind in which factor 1 explains 56 % of variation.

Keywords: Heat Fluxes, Dok Island, Sea Surface Temperature, Air Temperature.

Introduction

Temperature variations are indications of heat transfer by absorption of solar energy, loss by evaporation, currents etc. The size and characteristics of the variations in temperature depend on the net rate of heat flow into or out of a water body[1]. For most purposes, we can assume that all the heat enters the ocean at the sea surface. The only other significant source of heat is the earth itself. However, the 0.05 Wm^{-2} that reaches the ocean through the floor of the ocean is small compared to the average value of nearly 200 Wm^{-2} of the sun's radiative energy that is absorbed by the surface layer of the ocean[2].

The East Sea is an unusual ocean system characterizing warm and cold regions divided by a polar front. It has been called a mini-ocean. Dok Island is located in the middle of the East Sea. It can be said that oceanographic phenomena near Dok Island is representative of the East Sea even though oceanographic characteristics can vary widely in an ocean system. Recently, an advanced climatology was described which focused on this area; warm eddy, cold eddy and oceanographic conditions etc.[3-6]

*** Author for Correspondence**

Around Dok Island, biological production is high due to the inflow of upwelled water from the eastern coast of the Korean peninsula[6]. According to this flow path, the area near Dok Island also forms one of the main migration routes of Japanese common squid[7]. These phenomena definitely are influenced by the temperature. So, the heat flux determining the temperature variation can be said to be one of the important factors.

Based on the heat flux estimation, some researchers have referred to the relation between heat flux and distribution of temperature in the East Sea of Korea/Japan Sea[7], Gulf of Maine[8], upwelling in the Gulf of Oman[9] and the northern California shelf[10] and the flow regime in the Bering Sea[11,12] respectively. The heat flux in the East Sea was modeled by Kang[13]. The mixed layer depth (MLD) was explained using heat flux in the East Sea[14]. Moreover, seasonal and temporal variations of heat flux were explained in the East Sea[15-18].

This research on the large scale could be viewed as too coarse because it looked at the whole East Sea instead of more regionally to better define the oceanographic characteristics. It would be more meaningful to know the air-sea interaction at a point of the middle site over the East Sea. Therefore, the purpose of this study is to estimate the air-sea interaction at Dok Island considered being a representative location of the East Sea in general.

Study area

Dok island is a volcanic island consisting of two large islets, Dong and Seo islets and 89 small rocky outcrops. The area of islets and rock outcrops is about 187,554 m^2. The area and height of Dong islet are 73,297 m^2 and 98 m respectively and Seo islet, 88,740 m^2 and 168 m respectively. It is about 87 km from Ulleung Island and about 217 km from Jukbyon, the closest place on the Korean peninsula (Fig. 1).

It is an oceanic climate with an annual mean air temperature of 12°C, comprising 1°C in winter and 23°C in summer. The annual mean wind speed is 4.3 ms^{-1} and the wind direction is usually from the southwest in summer and northeast in winter. The annual mean precipitation is about 1,240 mm and fog frequently occurs around island.

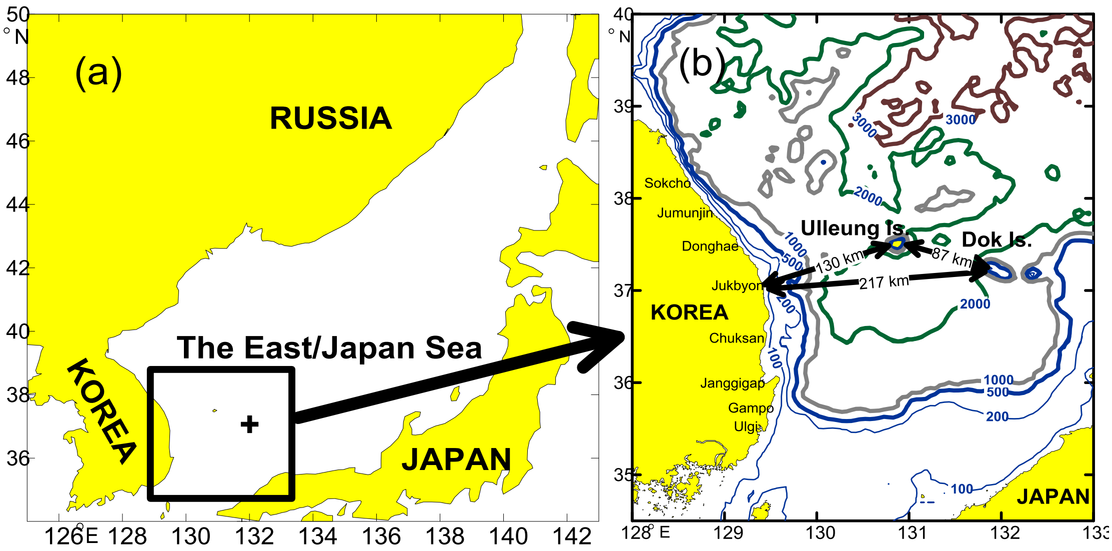

Figure 1: (a) Locations of Dok Island (cross) (b) observation sites of sea surface temperature and air temperature (Dok Island) and meteorological factors (Ulleung Island)

Data and analysis

Data: Sea surface temperature was observed from November, 1998 to December, 2008 by Kyongbuk Provincial Police Agency. The data was archived in the Korean Oceanographic Data Center (KODC) and sea surface temperature and air temperature were downloaded from http://kodc.nfrdi.re.kr/page?id=obs_03_01. The data sets were used for estimating heat fluxes during the 9 years from 2000 to 2008. The meteorological data for heat fluxes was taken from the Korean Meteorological Administration (KMA). The factors affecting heat fluxes such as cloud amount, atmospheric pressure, relative humidity and wind speed were acquired through the following web address: http://www.kma.go.kr/weather/observation/data_monthly.jsp.

The meteorological data at Ulleung Island were used because there is no weather station on Dok island. To see the relationship between the weather factors and each of the heat flux terms, we conducted a factor analysis with the SYSTAT 9.0, statistical software package.

Analysis: The formulas for estimating heat fluxes may be written as:

$$Q_{sfc} = Q_s - (Q_b + Q_h + Q_e) \quad (1)$$

where Q_{sfc} is the net heat flux through the sea surface, Q_s is the solar radiation (short wave radiation), Q_b is the long wave radiation (back radiation), Q_h is the sensible heat flux and Q_e is the latent heat flux.

The solar radiation flux (Q_s) was estimated by:

$$Q_s = Q_i\,(1-\alpha)(1-0.7C) \quad (2)$$

where Q_i is the solar radiation reaching the top of the atmosphere, α is the albedo at the sea surface (=0.06) and C is the cloud amount in tenths[19].

where

$$Q_i = 345 + 180\cos(\omega t - 173°) \quad (3)$$

where ω is $2\pi/365$ day^{-1} and t is the day of the year[20].

Long wave radiation flux was calculated from the formula:[21]

$$Q_b = \varepsilon\sigma T_s^4(0.39 - 0.00495E_a)(1-0.6C) + 4\varepsilon\sigma T_s^3(T_s - T_a) \quad (4)$$

where ε is the emissivity of water (=0.97), σ is the Stefan-Boltzman constant (= 5.7 × 10Wm^{-2}K^{-4}), E_a is the air vapor pressure, T_s and T_a are absolute sea surface and air temperatures respectively. Sensible and latent heat fluxes were given by:

$$Q_h = \rho_a C_P C_H (T_s - T_a) W \quad (5)$$

$$Q_e = \rho_a C_E L_V (q_s - q_a) W \quad (6)$$

where ρ is the air density (1.25 kgm^{-3}), C_P is the specific heat capacity of air (1004 JkgK^{-4}), C_H and C_E are the transfer coefficients of sensible and latent heat. The value of each of the coefficients was taken as 1.2×10^{-3} and 1.0×10^{-3} respectively. W represents the wind speed (ms^{-1}) and L_V is the latent heat of evaporation (2.5×10^6 Jkg^{-1}), q_s and q_a are the specific humidity of sea water and air respectively.

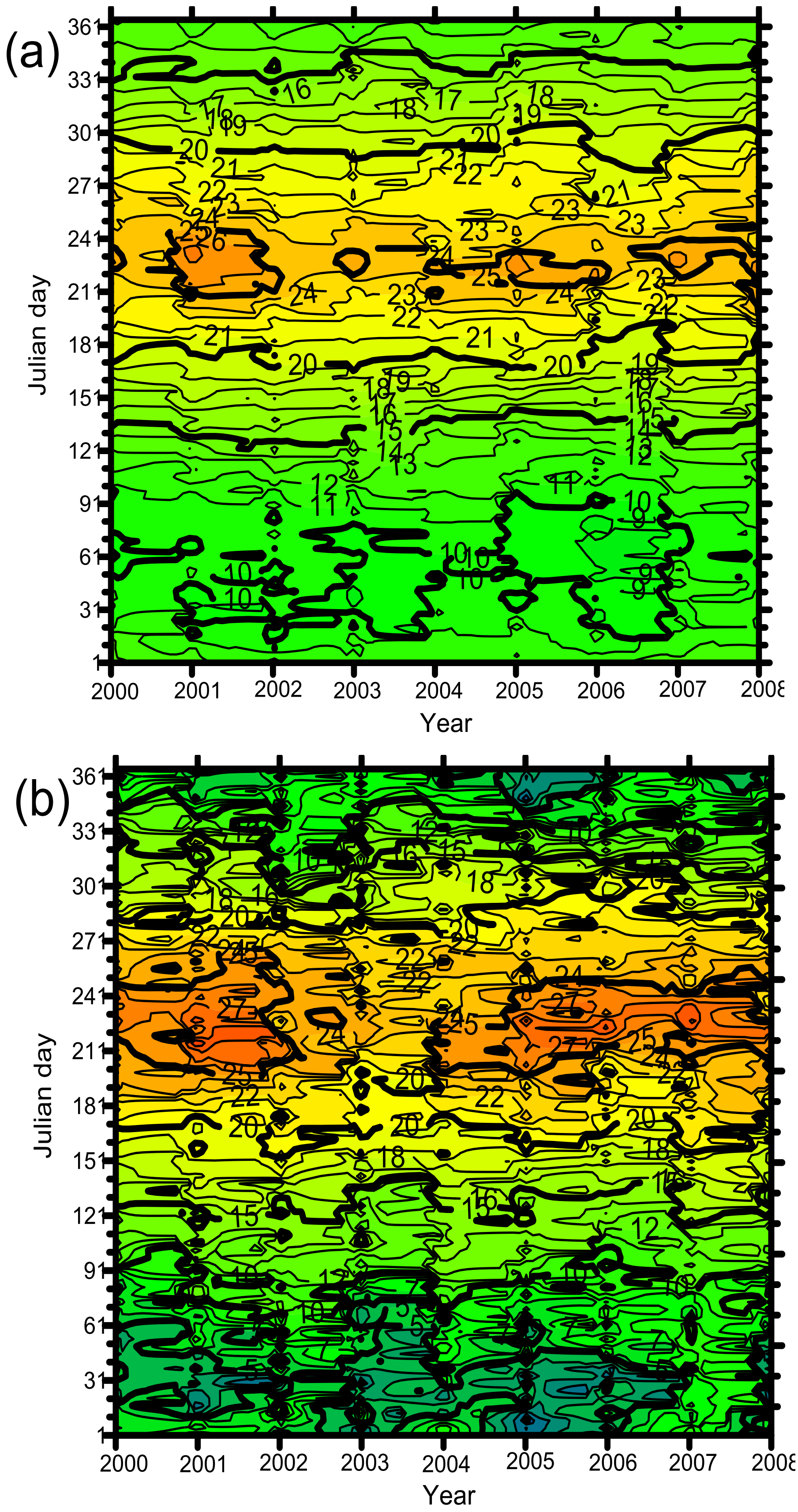

Figure 2: Daily variations of (a) sea surface temperature and (b) air temperature during 2000-2008

Results and Discussion

Fig. 2 shows sea surface temperature and air temperature at Dok Island from 2000 to 2008. Maximum sea surface temperature was 29.0°C (August 13, 2005), minimum sea surface temperature was 6.8°C (January 6, 2003). Maximum air temperature was 32.0°C (August 18, 2007), minimum air temperature was -4.6°C (December 6, 2008). The maxima sea surface temperature (day 221 or August 9) occurred about 10 days after maxima of air temperature (day 231 or August 19). On the other hand, minimum sea surface temperature was delayed about 30 days after the minimum air temperature.

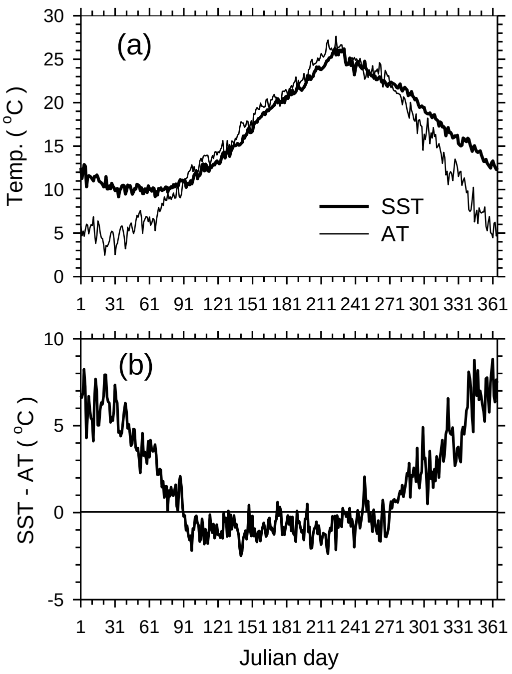

Figure 3: (a) Mean sea surface temperature (thick line) and air temperature (thin line) 2000 to 2008 and (b) the difference between sea surface temperature and air temperature. The positive values indicate that sea surface temperature is higher than air temperature

To see the variation of sea surface and air temperature, the mean values of sea surface temperature and air temperature are shown in fig. 3. The average annual ranges of sea surface and air temperature were 17.1°C and 25.2°C respectively. Sea surface temperature became higher than air temperature in April 1 (day 91) and it became lower than air temperature in September 21 (day 271).

The highest difference between sea surface temperature and air temperature was 8.8°C on December 27. It is interesting that the difference between sea surface and air temperatures was 2.5°C during the period that sea surface temperature was lower than air temperature (April 1 to September 21). These differences between sea surface and air temperatures induce the heat transfer from the air (sea) to the sea (air) by latent and sensible heat fluxes.

Fig. 4 shows daily mean variations of cloud amount, atmosphere pressure, relative humidity, and wind speed which affect the heat flux terms. The mean cloud amount was large ranging from 5.0 to 8.8 from July to August (day 182-243) and small ranging from 2.6 to 7.3 from March 10 to May 10 (day 69-130). Atmospheric pressure was low ranging from 1003.4 to 1011.7 hPa from June to August (day 152-243) and high at 1015.0 to 1023.7 hPa from December to February (day 335-59).

Relative humidity was high ranging from 71.5 to 89.3% from July to September (day 181-273) and low ranging from 53.8 to 75.5% from March to April (day 60-120). Wind speeds ranged from 2.9 to 5.7 ms^{-1} from March to April (day 60-120) and weaker ranging from 1.8 to -4.7 ms^{-1} from June to August (day 152-243). During summer, the cloud amount is large, atmospheric pressure is low and relative humidity is high.

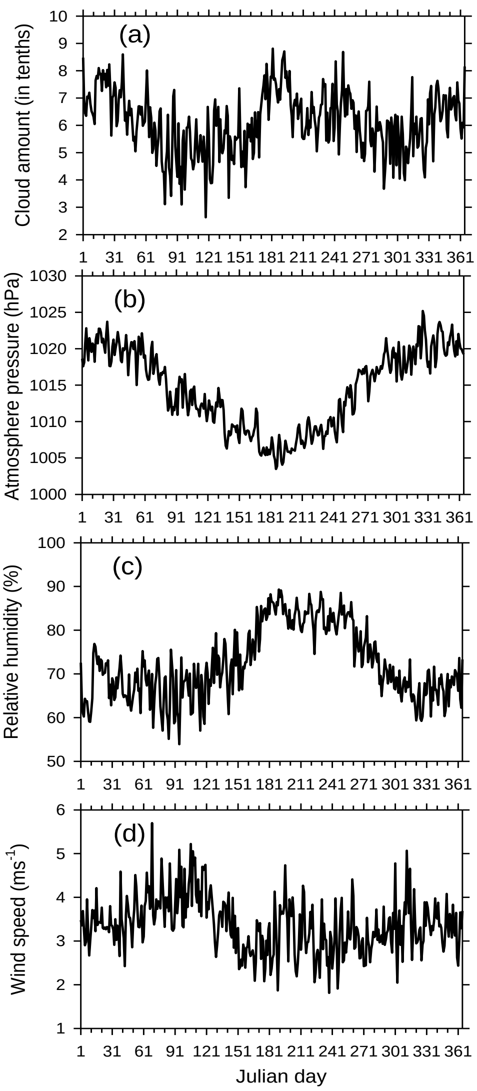

Figure 4: (a) Mean atmosphere pressure, (b) mean relative humidity, (c) mean wind speed and (d) mean cloud amount

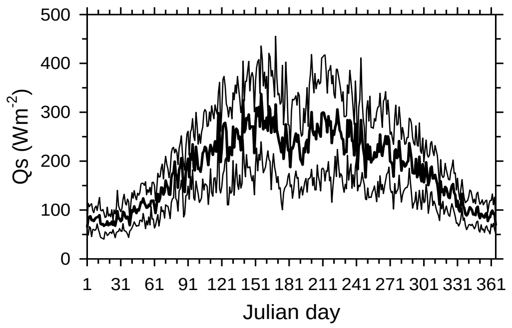

Figure 5: Mean solar radiation (thick line) and standard deviation (thin line)

These values represent the monsoon that is the rainy season in this area. The daily mean variation and standard deviation of solar radiation are shown in figure 5. Short wave radiation ranged from 64.3 Wm^{-2} to 337.6 Wm^{-2}. The short wave radiation was high ranging from 200.4 to 337.5 Wm^{-2} from May to June (day 121-181) that is, prior to the rainy season.

Also, the standard deviation was larger from May to June (ranging from 40.7 to 147.8 Wm^{-2}) than in any other season. Insolation is the largest in May[17] and Kim[22] concluded that solar radiation is not a function of latitude but dependent on cloud cover around the Korean peninsula during the rainy season.

The variation and standard deviation of each of the heat flux terms, namely, net heat flux (Q_{sfc}), long wave radiation (Q_b), sensible heat flux (Q_h) and latent heat flux (Q_e) are shown in figure 6. Positive values of net heat flux (Q_{sfc}) and negative values of long wave radiation (Q_b), sensible heat flux (Q_h) and latent heat flux (Q_e) denote heat transfer from the air to the sea respectively.

Net heat flux was transferred from the air to the sea from the beginning of March (day 70) to the beginning of November (day 312). Net heat flux reached an annual maximum in June and daily mean value amounts reached 201.3 Wm^{-2} in June. During the middle of November to the middle of March, there was net heat flux transfer from the sea to the air. The lowest value of net heat flux was -133.7 Wm^{-2} on December 22 (day 356).

Hirose et al[17] estimated that the annual mean heat flux ranges from 133 Wm^{-2} in May to -296 Wm^{-2} in December and Na et al[18] stated that the maximum heat loss occurs in January in the East Sea. Park et al[16] inferred that the sign of net surface heat flux changes from negative to positive in March and from positive to negative in September and concluded that heat loss is large in the southern part of the East Sea and Ulleung Basin. The difference between values and periods in this study and other studies seems mainly due to the study area chosen. Other studies chose the whole East Sea for the estimation of heat fluxes compared to our single station flux estimation at Dok Island.

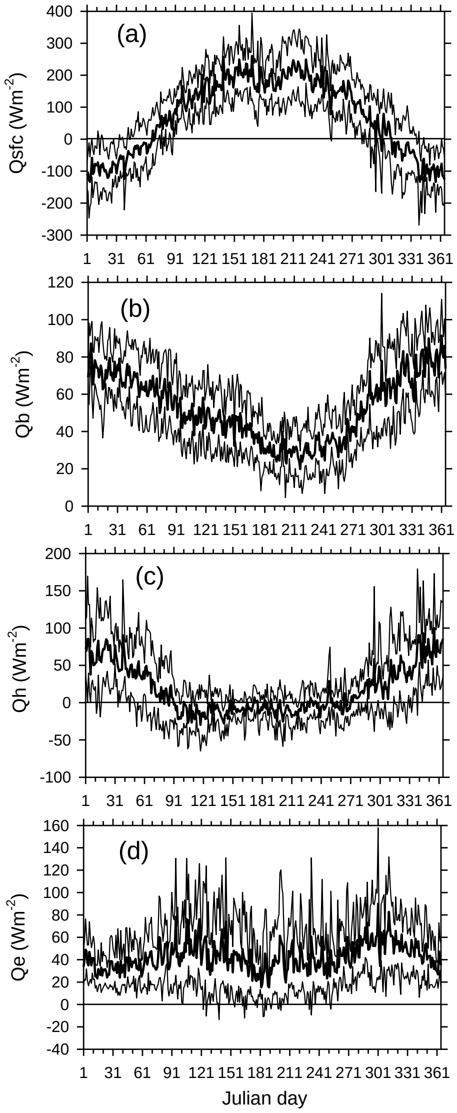

Figure 6: Same as in figure 5 except for (a) net heat flux (Q_{sfc}), (b) long wave radiation (Q_b), (c) sensible heat flux (Q_h) and (d) latent heat flux (Q_e).

Long wave radiation varied from 19.8 Wm^{-2} to 91.5 Wm^{-2} and the range was lowest at 29.2 and 39.8 Wm^{-2} in June and July (day 152-212). The standard deviation of long wave radiation was lowest in the range 4.9 to 36.1 Wm^{-2} of the heat flux terms. Long wave radiation variation is smallest by both area and season of the heat flux terms. The sensible heat flux ranged from -29.7 Wm^{-2} to 100.1 Wm^{-2} and exhibited negative values from April to September (day 91-273) which represents heat absorption from the air. The standard deviation of sensible heat was 2.8 to 98.1 Wm^{-2}.

Latent heat flux varied from 15.1 Wm^{-2} to 89.9 Wm^{-2}. In November, the latent heat flux ranged from 43.0 Wm^{-2} to 82.7 Wm^{-2} and the monthly mean value was highest at 56.5 Wm^{-2}. All of these fluxes showed a distinct seasonal variation. Kang[13] concluded that the latent heat increases with the sea surface temperature but the back radiation and sensible heat decrease as the SST increases as shown in figure 6.

Net heat flux has a negative relationship with air pressure and wind explaining 56% variation in factor 1 (Fig. 7). Na et al[18] showed that the net heat flux comes mostly from the turbulent fluxes which are strongly dependent on the wind speed. This implies that net heat flux varies conversely with wind speed and air pressure.

Table 1
Harmonic Analysis of Sea

Terms	Cosine functions
SST	16.6 + 0.5cos(ωt-76.8)
AT	15.0 + 1.2cos(ωt-166.0)
Q_{sfc}	73.0 + 26.9cos(ωt-187.8)
Q_b	52.5 + 5.4cos(ωt-298.1)
Q_h	17.4 +14.7cos(ωt-12.3)
Q_e	42.5 + 10.1cos(ωt-234.4)

Table 1 shows the results of harmonic analysis of sea surface temperature (SST), air temperature (AT), net heat flux (Q_{sfc}), long wave radiation (Q_b), sensible heat flux (Q_h) and latent heat flux (Q_e). The amplitude was large at 26.9 for net heat flux and small at 5.42 for long wave radiation. The phase of 187.8° between net heat flux and 12.3° for sensible heat flux was nearly opposite.

Conclusion

For this study on the mean heat fluxes at Dok Island, the mean annual range was 17.1℃ (9.1-26.2℃) in sea surface temperature and 25.2℃ (2.4-27.6℃) in air temperature. The average annual mean values of net heat flux, long wave radiation, sensible heat flux and latent heat flux were 73.0 Wm^{-2}, 52.5 Wm^{-2}, 17.4 Wm^{-2} and 42.5 Wm^{-2} respectively thus giving an annual mean heat surplus of -39.4 Wm^{-2}. This value is about two fifths of that concluded by Na et al[18] and about four fifths of Park et al[16] and Hirose et al[17]
.
Also, Kang et al[15] inferred that the annual mean cooling rate is 60 to 90 Wm^{-2} in the southern and northern parts of the East Sea and about 30 Wm^{-2} in the middle part. Dok Island is located close to the middle of the East Sea so the annual mean heat surplus there would be a reasonable estimation. The results of the other studies indicate a negative value in annual mean heat flux. This implies that the East Sea supplies heat to the atmosphere on an annual mean basis. The studied area around Ulleung and Dok Islands is a highly productive region and migration route for squid[6-7]. Oceanographic conditions nearby to Dok Island vary from season to season or year to year. The area around Dok Island experiences cold eddies as well as warm eddies[3-5].

Such oceanographic conditions could be detected by temperature variations in the first instance. We estimated the mean heat fluxes at Dok Island based on the fundamental factor, temperature. The negative value of surplus heat flux may be compensated for by the movement of a warm eddy or Tsushima warm current. This aspect will be investigated in the near future. Furthermore, we anticipate that the estimation of short term variations in sensible and latent heat fluxes related to the occurrence of the cold and warm eddies at Dok Island will be conducted.

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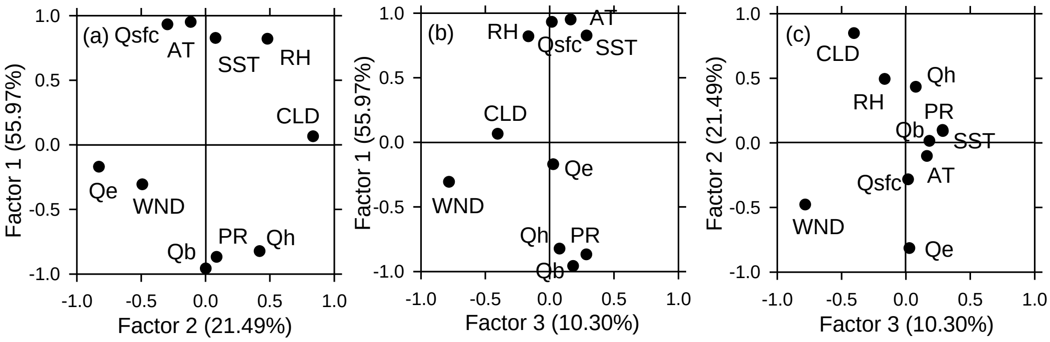

Figure 7: Factor analysis with (a) factor 1 and 2, (b) factor 1 and 3 and (c) factor 2 and 3 in each pair. RH is the relative humidity, CLD cloud amounts, WND wind speed, PR air pressure, respectively

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