1. INTRODUCTION

In recent years, many studies have analyzed data of micrometeorological towers that are measuring energy, water (H₂O) and carbon dioxide (CO₂) fluxes between land surface and atmosphere to increase our knowledge of surface energy balance and CO₂ fluxes. As for ocean field, large spatial datasets were available from ship observations, and several researchers estimated the fluxes using these data (e.g., Fairall et al., 1996). However, we have little information about air-water interaction in ‘closed’ water areas such as lakes and bay, where many mega-cities have been developed in front. Therefore, it is more important to understand the impact of the closed water areas to atmospheric environment, because such areas would have a significant influence on urban climate in mega-city, which includes heat island, heavy rainfall and air pollution.

Tokyo Bay, which is adjacent to Tokyo Metropolitan area (Fig.1), is expected to mitigate the severe atmospheric environment in Tokyo. We constructed a flux measurement system in Tokyo Bay, and investigated energy, H₂O and CO₂ fluxes between the water surface and the atmosphere. The purposes of this study are to (1) evaluate the fluxes by the eddy correlation method, and to (2) understand the seasonal and diurnal pattern of the measured fluxes. Also the observational results were compared with that at a suburban area (Kugahara) in Tokyo, Japan (Fig.1).

2. METHODS

2.1 Site Description

The study sites, Tokyo Bay and Kugahara, are located in the central part of the main island in Japan. These areas belong to the monsoon region that the wind directions have the seasonal reversal. Wind blows during summer and from the north during winter.

Tokyo Bay – The measurements have been conducted at the height of 12m above mean sea level by using an existing tower (N35.6°, E140.0°) since December, 2004. The shortest distance from the land is about 3km in the direction of northeast. The seacoast region is almost an industrial area which includes a food complex, steel and a petrochemical complex.

Kugahara – The measurements have been made since May 2001 in a low-residential area, which mainly consists of densely built-up houses, paved roads and small playgrounds, in Kugahara, Tokyo (N35.6°, E139.7°). The height of a tower is 29m. There is a homogeneous residential area that the mean building height is 7.3m over 1km. The distance to Tokyo Bay tower is about 30km. Additional details on Kugahara site are given in Moriwaki and Kanda (2004).

2.2 Experimental Setup

We measured wind speeds, air temperatures, CO₂ concentrations, water vapor concentrations and radiant intensities at each site. Fluctuations of wind velocities and air temperatures were measured by a three-dimensional sonic anemometer. Concentrations of CO₂ and water vapor were measured by an open-path type infrared gas analyzer. Upward and downward shortwave and longwave radiation intensities were measured separately by using two sets of pyranometers and pyrgeometers. Table 1 shows the observation equipments which were installed at each site, and Fig.2 shows the installed equipments at Tokyo Bay tower.
2.3 Data Processing

The fluxes of heat, water vapor and CO$_2$ were evaluated by the eddy covariance method every 60 minutes. For example, data of 8 o’clock means an average of 8 to 9 o’clock (JST). Over Tokyo Bay, note that data of the radian t intensities were the instantaneous values every hour until the middle of July, and data of absolute air temperature was corrected using data at a nearest weather station, which was located in Tokyo Bay water front. The CO$_2$ and water vapor fluxes were corrected for the effect of fluctuations in air density (Webb et al., 1980). Coordinate axes were rotated so that mean vertical velocity was zero (McMillen, 1988).

For the evaluation of seasonal courses, we used data of 12 o’clock, which show clearly difference between Tokyo Bay and Kugahara due to strong radiant intensity. But we removed data due to precipitation or sensor malfunction. We analyzed the data from December 2004 to August 2005. Mean wind direction was calculated using mean wind vector. In this study we defined that upward flux was positive.

As for the evaluation of diurnal courses, we discuss the fluxes of data from December and July because each data was representative for winter and summer, respectively.

3. SEASONAL COURSE

3.1 Meteorological properties and CO$_2$ concentration

To help to understand the climatic forcing on the fluxes, we first surveyed the seasonal courses of wind speed, wind direction, air temperature, humidity and CO$_2$ concentration. As described in 2.1, the wind blew mainly from the south in summer and from the north in winter. The air temperature was lowest in February (6°C) and highest in July and August (30°C). The specific humidity was smaller in summer and larger in winter, and the CO$_2$ concentration was contrary to the variation of humidity.

3.2 Fluxes of Heat, H$_2$O and CO$_2$

The variation of the fluxes of sensible heat, latent heat and CO$_2$ are shown in Fig.3.

At Tokyo Bay, sensible heat flux ($H$) was smaller than that at Kugahara (Fig.3(a)). $H$ at Tokyo Bay was positive in winter whereas that was negative in summer. Therefore, Tokyo Bay worked as a sink of heat during summer. According to a previous study (Ishii et al., 1999), the atmosphere over Tokyo Bay was influenced by urban atmosphere due to the sea breeze circulation in summer, and thus the air above Tokyo Bay was adiabatically heated due to the subsidence flow. This would cause air temperature over Tokyo Bay to be warmer than the sea surface temperature, and therefore $H$ over Tokyo Bay tended to be negative in summer.

In contrast to $H$, latent heat flux ($LE$) was positive in all seasons in Tokyo Bay (i.e. Tokyo Bay was water vapor source) (Fig.3(b)). Dry air moved from the land to Tokyo Bay due to the advection or sea breeze circulation. Therefore, the evaporation would be activated in Tokyo Bay even in summer.

CO$_2$ flux showed seasonal variation, and it tended to be negative in general (Fig.3(c)). The CO$_2$ concentration over Tokyo Bay was about 500ppm, whereas that was about 385ppm in Ryori (WMO WDCGG , JMA), where is not affected by human activity. These results indicate that the urban air of high CO$_2$ concentration was transported to Tokyo Bay. This caused a difference of the CO$_2$ concentration between the atmosphere and the vicinity of water surface, and thus the CO$_2$ flux was downward over Tokyo Bay.

3.3 Net Radiation and Storage Heat Flux

Storage heat flux ($G$) is determined as the energy balance residual from direct observation of net all-wave radiation ($Rn$), sensible heat flux ($H$) and latent heat flux ($LE$),

$$G = Rn - H - LE$$  \hspace{1cm} (1)
The variations of net radiation ($R_n$) and storage heat flux ($G$) are shown in Fig.4. $R_n$ increased from winter to summer in both sites, but summertime $R_n$ in Tokyo Bay was larger than that in Kugahara. This was mainly due to the difference of magnitude of upward longwave radiation. Surface temperature at Tokyo Bay was much lower than that at Kugahara (not shown here) due to the difference in heat capacity. Therefore the energy-loss due to the upward longwave radiation is lower at Tokyo Bay.

$G$ in Tokyo Bay was larger in summer whereas that in Kugahara did not have significant seasonal change. The large $G$ in Tokyo Bay was because $H$ and $LE$ decreased (see 3.2) and $R_n$ increased in summer. The large amount of energy almost equal to $R_n$ was stored in Tokyo Bay in summer.

4. DIURNAL COURSE OF FLUXES IN SUMMER AND WINTER

As mentioned in 2.3, we discuss the fluxes of data from December and July. We selected two represent days; 23rd December 2004 (wind direction is the north, wind speed is $4 \text{ ms}^{-1}$ until 3 o’clock in both the site, after that , it is $8 \text{ ms}^{-1}$ in Tokyo Bay from 6 to 19 o’clock and $5 \text{ ms}^{-1}$ for rest of the day in Kugahara) and 29th July 2005 (Wind direction is the south, wind speed is $1 \text{ ms}^{-1}$ all the morning in both the site, after that , it is over $5 \text{ ms}^{-1}$ in Tokyo Bay and $2-3 \text{ ms}^{-1}$ in Kugahara for rest of the day).

4.1 Sensible Heat Flux

Fig.5 shows sensible heat flux ($H$) and a difference of temperature ($T_s-T$: surface temperature minus air temperature), $T_s$ and $T$ are shown in Fig.6. Note that surface temperature is derived from Stefan-Boltzmann law, and emissivity is 0.98 in Tokyo Bay, 1.0 in Kugahara. The variation of $H$ is corresponding to [7–7].

$H$ over Tokyo Bay tended to begin to decrease around 9 o’clock (Fig.5). $T$ in Tokyo Bay was still high even in the evening, whereas $T_s$ had a peak value around noon which is consistent with the variation of solar radiation (Fig.6). On the other hand, $T$ in Kugahara in the evening already decreased. The time lag of the temporal variation of $T$ in each site implied that warmer air which is generated in urban area was transferred to Tokyo Bay due to the advection or sea breeze circulation. This was also anticipated from the result that $T$ over Tokyo Bay had a wide daily range compared with $T_s$.

4.2 Latent Heat Flux

Fig.7 shows diurnal pattern of latent heat flux ($LE$).

$LE$ in Tokyo Bay was positive in all day, and especially in winter the magnitude was much larger (Fig.7). This is probably because in winter drier and colder air was advected to Tokyo Bay, and thus the evaporation was activated at Tokyo Bay. Fig.8 shows the relationship between $LE$ and wind speed. $LE$ over Tokyo Bay varied corresponding to wind speed especially in winter. This result suggests that wind speed was a more important factor for the magnitude of $LE$ in winter rather than radiative forcing.

4.3 CO2 Flux

Fig.9 shows diurnal pattern of CO2 flux.

$CO_2$ flux in Tokyo Bay was negative ($CO_2$ sink), whereas that in Kugahara was positive ($CO_2$ source) throughout the day. These results were attributed to that the air of high $CO_2$ concentration in the urban area was transported over Tokyo Bay due to advection in winter or sea breeze circulation in summer, as mentioned in 3.2. In recent years, several researchers have made a study on gas exchange at the air-water interface. These researchers pointed out that wind speed over about 10 ms$^{-1}$ increased gas transfer velocity (e.g., Asher, W. E. and Wanninkhof, R., 1998). As for in our observation, negative $CO_2$ flux was corresponding to wind speed, especially over 10 ms$^{-1}$ (Fig.10).
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