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EVALUATION OF SEASONAL PATTERN OF ENERGY, WATER AND CARBON DIOXIDE FLUXES OVER TOKYO BAY

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1. INTRODUCTION

In recent years, many studies have analyzed data of micrometeorological towers that are measuring energy, water (H_2O) and carbon dioxide (CO_2) fluxes between land surface and atmosphere to increase our knowledge of surface energy balance and CO_2 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, H_2O and CO_2 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 the south 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.

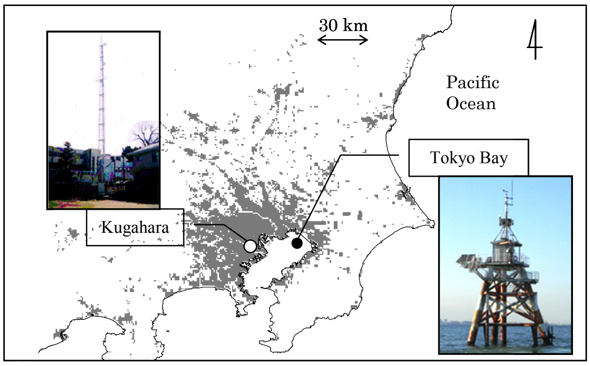

Fig.1 Environment of the study sites. Location of Tokyo Bay and Kugahara tower in Japan. Gray area indicates built-up area where artificial structures occupy significant surfaces. The data source is "Global Map" (ISCGM), available from http://www.iscgm.org/.

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, CO_2 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 CO_2 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.

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Table 1 The list of the observation equipments

Items	Tokyo Bay Instruments	Tokyo Bay sampling	Kugahara Instruments	Kugahara sampling
wind speed	3-D Sonic Anemometer (Campbell Scientific Inc., USA ; CSAT3)	10Hz non ave. Height : 12m above mean sea lebel	Ultrasonic Anemometer (Metek GmbH, Germany ; USA-1)	8Hz non ave. Height : 29m
air temperature				
CO_2 gas	Open Path CO_2/H_2O Analyser (LI-COR, Inc., USA ; LI-7500)		Open Path CO_2/H_2O Analyser (LI-COR, Inc., USA ; LI-7500)	
H_2O gas				
up/downward shortwave radiation	Pyranometers (Kipp&Zonen, Netherlands ; CM3)	1Hz 10min. ave. Height : 12m above mean sea lebel	Pyranometers (Eko Instruments, Japan ; MS-62,42)	1Hz 20min ave. Height : 25m
up/downward longwave radiation	Pyrgeometer (Kipp&Zonen, Netherlands ; CG3)		Pyrgeometer (Eko Instruments, Japan ; MS-201,202	

2.3 *Data Processing*

The fluxes of heat, water vapor and CO_2 were evaluated by the eddy covariance method every 60 minute. 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 radiant 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 Kugahra 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 ^{o}C) and highest in July and August (30 ^{o}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_2O 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.

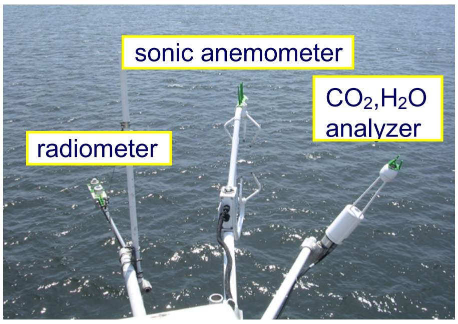


Fig.2 The installed equipments at Tokyo Bay tower

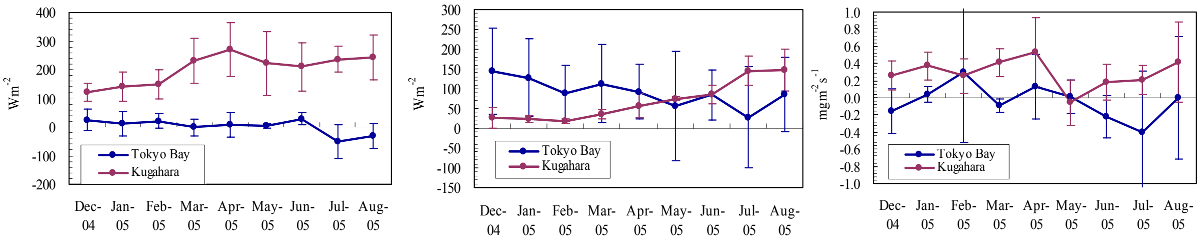
In contrast to H, latent heat flux (LE) was positive in all seasons in Tokyo Bay (i.e. Tokyo Bay was water vapor source) (Fig.3(b)). Dry air moved from the land to Tokyo Bay due to the advection or sea breeze circulation. Therefore, the evaporation would be activated in Tokyo Bay even in summer.

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),

$$G = Rn - H - LE \quad (1)$$



(a) Sensible Heat Flux (b) Latent Heat Flux (c) CO_2 Flux

Fig.3 The variation of the fluxes of (a) sensible heat, (b) latent heat and (c) CO_2

The variations of net radiation (*Rn*) and storage heat flux (*G*) are shown in Fig.4.

Rn increased from winter to summer in both sites, but summertime *Rn* in Tokyo Bay was larger than that in Kugaha. 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 *Rn* increased in summer. The large amount of energy almost equal to *Rn* 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 ms^{-1} until 3 o'clock in both the site, after that , it is 8 ms^{-1} in Tokyo Bay from 6 to 19 o'clock and 5 ms^{-1} for rest of the day in Kugahara) and 29th July 2005 (Wind direction is the south, wind speed is 1 ms^{-1} all the morning in both the site, after that , it is over 5 ms^{-1} in Tokyo Bay and 2-3 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 (*Ts-T*: surface temperature minus air temperature), *Ts* 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 [*Ts-T*].

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 *Ts* 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 *Ts*.

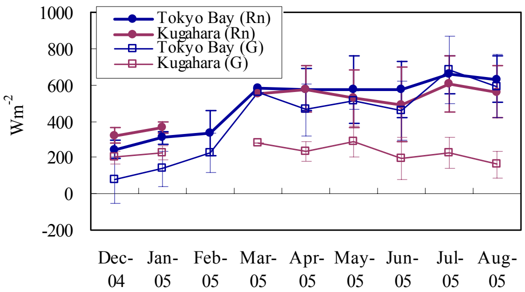


Fig.4 The variation of net radiation (*Rn*) and storage heat flux (*G*)

4.2 *Latent Heat Flux*

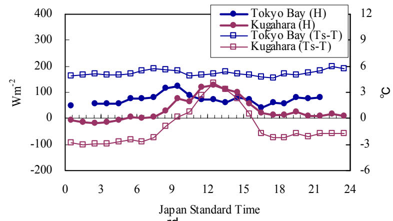
Fig.7 shows diurnal pattern of latent heat flux (*LE*).

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.

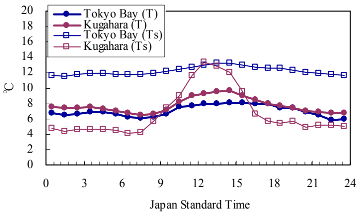
4.3 *CO_2 Flux*

Fig.9 shows diurnal pattern of CO_2 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).



(a) 23rd Dec. 2004



(a) 23rd Dec. 2004

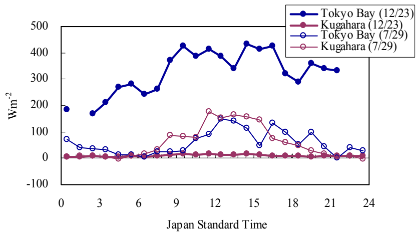
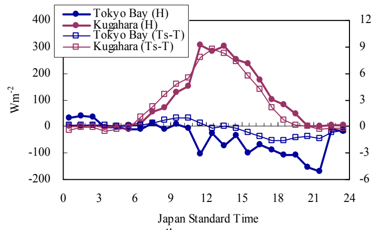
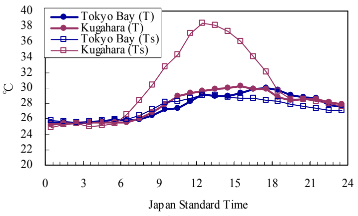


Fig.7 Diurnal variations of latent heat flux (*LE*)



(b) 29th Jul. 2005

Fig.5 Diurnal variations of sensible heat flux (*H*) and a difference of temperature (Ts-T)



(b) 29th Jul. 2005

Fig.6 Diurnal variations of air temperature (*T*) and surface temperature (Ts)

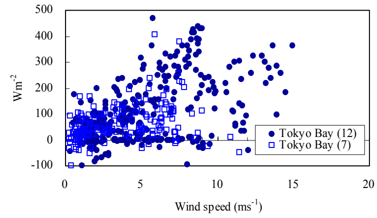


Fig.8 The relation between latent heat flux (*LE*) and wind speed

5. CONCLUSIONS

Through our observational study over Tokyo Bay, which is a closed water area next to Tokyo Metropolitan area, we found the followings. 1) Sensible heat flux *H* was positive in winter but negative in summer. It was decreasing from day to night. 2) Latent heat flux *LE* was positive throughout the day and throughout the year, especially positive *LE* was larger in winter and it was mainly dependent on wind speed. 3) CO_2 flux was negative (CO_2 sink), whereas that in suburban area was positive (CO_2 source). This result indicates that CO_2-enriched air was transported to Tokyo Bay and absorbed there.

These results suggest that the surface energy balance at 'closed' water area is influenced by sea breeze circulation and/or advection and the feature is quite different from the result in open-sea measurements.

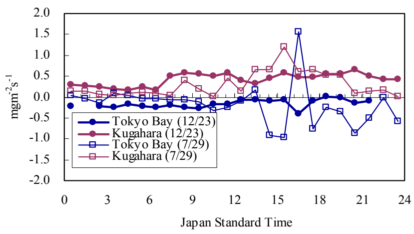


Fig.9 Diurnal variations of CO_2 flux

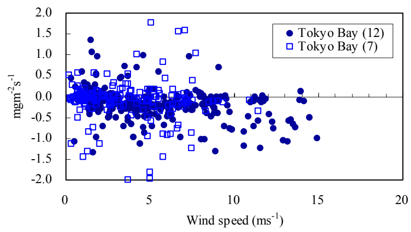


Fig.10 The relation between CO_2 flux and wind speed

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REFERENCES

Asher, W. E., Wanninkhof, R., 1995: The effect of bubble-mediated gas transfer on purposeful dual -gaseous tracer experiments, J. Geophys. Res., **103**, 10,555-10,560.

Fairall, C. W., Bradley, E. F., Rogers, D. P., Edson, J. B., Young, G. S., 1996: Bulk parameterization of air-sea fluxes for Tropical Ocean-Grobal Atmosphere Coupled-Ocean Atmosphere Response Experiment, J. Geophys. Res., **101**, 3747-376.

Ishii, H., Kanda, M., Moriwaki, R., Okuzono, K., 1999: Observational Study on The Atmosoheric Environmant over Tokyo Bay, Annual Journal of Hydraulics Engineering (In Japanese), **43**, 233-238.

Mcmillen, R. T., 1988: An eddy correlation technique with extended applicability to non-simple terrain, Boundary-Layer Meteorol., **43**, 231-245.

Moriwaki, R., Kanda, M., 2004: Seasonal and Diurnal Fluxes of Radiation, Heat, Water Vapor, and Carbon Dioxide over a Suburban Area, J. Applied Meteorol., **43**, 1700-1710.

Webb, E. K., Pearman, G. I., Leuning, R, 1980: Correction of flux measurements for density effects due to heat and water vapor transfer, Quart. J. R. Meteorol. Soc., **106**, 85-100.

WMO WDCGG, JMA, Tokyo: CO_2 concentration, Ryori, 2005, http://gaw.kishou.go.jp/wdcgg.html