Observed Sea Surface Temperature of Tokyo Bay and Its Impact on Urban Air Temperature

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ABSTRACT

Sea surface temperature (SST) and air temperature were measured in situ in Tokyo Bay. These measurements were made with high spatial and temporal resolutions between November 2006 and September 2007. The analysis of these data revealed 1) the seasonal and diurnal variations of SST and air temperature, and 2) the physical process by which Tokyo Bay lowers urban air temperature in summer. The following were the major findings obtained: 1) the diurnal amplitude of SST was as large as 5.5°C; 2) abrupt increases of SST occurred at the head and mouth of the bay that were due to heated water discharge and the Kuroshio, respectively; 3) the values of the satellite-based objectively analyzed SSTs were higher than those of the in situ SSTs, especially in winter; 4) the relationship between SST and air temperature was classified into three seasonal modes—winter, transient, and summer—and each mode was associated with the seasonal stability condition of the near-surface water; 5) the strong southwesterly wind over the bay in summer decreased the SST mainly because of increased turbulent mixing at the water surface, thereby increasing downward sensible heat flux up to 2 × 100 W m⁻²; 6) the lower SSTs in summer lowered the air temperature, but only for the urban atmosphere near the coast, and no effect was detected at 20 km inland; and 7) the horizontal gradient of air temperature over the land intensified with increasing wind speed.

1. Introduction

Sea surface temperature (SST) is one of the key parameters for understanding air–sea interaction processes. In the field of global climatology, air–sea interactions at time scales of longer than a day have been thoroughly studied, and the impact of SST on the seasonal or annual climate is now widely accepted (e.g., Bjerknes 1969; Horel and Wallace 1981). However, in regional meteorology, the importance of air–sea interaction is less recognized. This is because the diurnal change of SST and its impact on the regional atmosphere is assumed to be negligible because of the large heat capacity of water. Some recent studies have shown that this assumption is not always valid. In coastal regions, diurnal amplitudes of SSTs exceeding 5°C have been observed both from in situ and satellite observations (e.g., Flament et al. 1994; Yokoyama et al. 1995). Kawai and Wada (2007) reviewed the impacts of diurnal SST variation on the atmosphere at various time scales, and suggested the potential importance of diurnal variations of SST for the sea-breeze circulation in coastal areas. Yang and Slingo (2001) reported that a strong diurnal signal of continental convection can be detected as far as several hundred kilometers offshore in the Bay of Bengal and its adjacent ocean, and that this signal is modified by the diurnal variation of SST through the land–sea breeze circulation. Pullen et al. (2007) discovered in their simulation that the spatiotemporal variability of coastal SST near New York City, New York, induces internal boundary layer (IBL) formation, sustained and deepened by turbulent kinetic energy advected from adjacent land areas. Kawai et al. (2006) investigated the influence of diurnal SST warming on the local atmospheric circulation over Mutsu Bay in Japan, and demonstrated that a large diurnal SST increase causes the land–sea breeze circulation to become significantly weaker, resulting in higher surface air temperatures over coastal land. Despite these recent findings of air–sea interactions in regional-scale meteorology, many weather forecast

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models currently use, as their input data, objectively analyzed SST data that do not include diurnal variations even when these models are applied to the atmosphere near the coast.

In this study, we focus on the impact of SST variations of Tokyo Bay on the atmosphere of urban Tokyo. Some pioneering studies of urban climate suggested potential influences of SST on the urban atmosphere. Phenomena that are potentially influenced by SST through the land–sea breeze mechanism include the heat island effect and heavy rainfall (e.g., Yoshikado 1992; Fujibe 2003; Kobayashi et al. 2007). Recently, Holt et al. (2009) reported that realistic variations in SST (i.e., warm Tokyo Bay or local upwelling) produce subtle sea-breeze variations that dramatically impact tracer distributions. However, the magnitude of the diurnal variation of SST in Tokyo Bay and the impact of SST on the urban atmosphere are not well understood because of a lack of reliable SST data from this region.

The purpose of the present study is twofold: 1) to evaluate the seasonal and diurnal variations of SST and air temperature in Tokyo Bay with high spatial and temporal resolutions, and 2) to investigate the impact of SST on urban air temperature.

2. Observation

a. Site description

Tokyo Bay is mostly surrounded by industrial areas, and only the entrance to the south is open to the Pacific Ocean (Fig. 1a). The Tokyo metropolitan area is densely built-up and extends to the northwest from the bay.

The water surface area of the inside bay is approximately 960 km². The north–south and east–west lengths of the bay are approximately 50 and 15 km, respectively. The bay deepens gradually from the head (north) to the mouth (south), and the mean water depth is approximately 15 m (Fig. 1b). Dominant seasonal winds are northeasterly in winter and southwesterly in summer.

b. Observation system and data processing

1) IN SITU DATA

Both the SST and the air temperature were measured in situ on buoys, beacons, and offshore structures at 14 observation points (Fig. 1a). The observations were continuously made from 0000 JST (UTC + 9 h) 1 November 2006 to 2300 JST 24 September 2007. The SST was measured by water temperature gauges (HOBO U22 Water Temp Pro v2, Onset Computer Corporation) at the depths of 1 and 20 cm below the sea surface using floats to maintain the gauges in position in response to complex wave motions. The air temperature was measured by temperature sensors (HOBO H8 Pro Temp, Onset Computer Corporation) at site-dependent reference heights, which varied from 3.7 to 12.8 m above the mean sea level. The SST and air temperature data were recorded every 10 min and averaged over 60 min. The data recovery rate of SST and air temperature at most of the sites was more than 90%.
In addition to the air temperature data collected over the bay from the 14 locations above, the present study analyzed the air temperature data collected by the Japan Meteorological Agency at 3 weather stations (Shin-Kiba, Tokyo, and Nerima) on the land in the Tokyo metropolitan area. The Shin-Kiba, Tokyo, and Nerima weather stations are located approximately 0.2, 10, and 20 km inland from Tokyo Bay (Fig. 1a). The temperature data from these stations were collected at a height of 1.5 m. At these weather stations, wind direction data were also collected. The heights of the anemometers are 18.2, 74.5, and 7.9 m at Shin-Kiba, Tokyo, and Nerima, respectively.

Intensities of shortwave and longwave radiation were measured using a CNR1 net radiometer (Kipp & Zonen), which was powered by a solar battery system (solar panel: HIP-55172; battery: PS100, Campbell Scientific, Inc.) at 12.8 m above mean sea level. These radiation measurements were made at site 14 between 22 November 2006 and 20 September 2007.

Finally, wind velocity data were collected in situ at the height of 42.5 m at site 13 by the Ministry of the Environment of Japan. These wind data were adjusted to a height of 10 m using the method of Kondo (1975). This method iteratively adjusts the wind speed at the observational height to that at 10 m assuming a logarithmic wind profile and using an empirical formulation of the bulk transfer coefficient in neutral conditions. The wind speed adjusted to 10 m was then used to adjust the air temperature measured over the sea to 10 m. The air temperature adjustment was made by calculating the drag coefficient for heat and assuming a logarithmic profile of air temperature. For the sea level data at Yokosuka, those provided by the Japan Oceanographic Data Center were used.

2) SELECTION OF SST DATA FOR ANALYSIS

Accurate measurements of the temperature just at the sea surface are quite difficult because of the presence of a cool skin layer and/or a warm layer below the surface (e.g., Fairall et al. 1996; Robinson 2004). In the present observations, the observed difference between the SST from the depth of 1 cm (SST\textsubscript{1cm}) and the SST from the depth of 20 cm (SST\textsubscript{20cm}) was smaller than the accuracy of the sensor (±0.2°C) in all seasons, thus no temperature gradient was observed between the two depths within the accuracy of the sensors. Kawai and Kawamura (2000) suggested that the SST measurements may be influenced by turbulent mixing induced by the platform on which the SST is being measured (i.e., the platform effect). The turbulent mixing reduces the temperature gradient near the surface and may cause the vertical temperature profile to be constant near the platform. The platform effect might have contributed to the lack of measurable difference between SST\textsubscript{1cm} and SST\textsubscript{20cm}.

To estimate the error of the in situ SST, the in situ SST was compared to the SST derived from the infrared radiometer (SST\textsubscript{skin}) at site 14. The value of SST\textsubscript{skin} was calculated using the Stefan–Boltzmann law:

\[
\text{SST}_{\text{skin}} = \left[ \frac{L \uparrow - (1 - \varepsilon) L \downarrow}{\sigma Y} \right]^{1/4},
\]

where \( L \uparrow \) and \( L \downarrow \) are upward longwave (infrared) radiation emitted from the surface and downward longwave radiation, respectively; \( \sigma \) is the Stefan–Boltzmann constant, \( 5.67 \times 10^{-8} \) (W m\(^{-2}\) K\(^{-4}\)); and \( \varepsilon \) is the infrared emissivity, set to 0.98 in the present study.

On average, SST\textsubscript{skin} was lower than in situ SST by 0.03°C with a root-mean-square difference (RMSD) between them of 0.95°C. The accuracy of the infrared measurements by the CG3 pyrgeometer is ±20 W m\(^{-2}\). Because an error of 5 W m\(^{-2}\) in the infrared measurement results in an error of 1°C in the calculated temperature, the difference between in situ SST and SST\textsubscript{skin} was within the combined accuracy of the two instruments. Based on this result and the comparison of SST between 1- and 20-cm depths above, the use of SST\textsubscript{1cm} was considered appropriate in the present study. When SST\textsubscript{1cm} was missing, SST\textsubscript{20cm} was used instead. The values of SST\textsubscript{20cm} were used for approximately 14% of the entire observational period.

3) GLOBAL SST DATA

Three objective analysis datasets of global SST derived from satellites were used in the present study: the Real-Time, Global, Sea Surface Temperature (RTGSST) [Thiébaux et al. 2003; National Centers for Environmental Prediction (NCEP)], the Merged Satellite and In Situ Global Daily Sea Surface Temperatures (MGDSST) [Sakurai et al. 2005; Japan Meteorological Agency (JMA)], and the New Generation Sea Surface Temperature for Open Ocean (NGSST-O) (Guan and Kawamura 2004; Tohoku University, Japan). RTGSST and MGDSST are used for the Weather Research and Forecasting Model (NCEP 2008) and the JMA Meso-Scale Model (JMA 2007), respectively. The specifications of the analyzed SST data are summarized in Table 1. In addition to the objective analysis datasets, a multichannel SST dataset derived from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) was used in the analysis. This dataset is available from the Northwest Pacific Region Environmental Cooperation Center. The resolution of the data is 1.1 km in the horizontal, thus significantly higher than those of the objective analysis datasets.
3. Result

a. Seasonal and diurnal variation of SST and air temperature

Figure 2 shows the seasonal change of the spatial patterns of in situ SST in Tokyo Bay. The values shown are the monthly mean values of SST from nonrainy days. Nonrainy days are defined as days with no daily precipitation (0 mm) according to four weather stations (Tokyo, Yokohama, Chiba, and Kisarazu) operated by the Japan Meteorological Agency around the bay. SST at the head of the bay (north) is lower than that at the mouth of the bay (south) in winter, and vice versa in summer. The monthly mean minimum temperature appeared in February, and the monthly mean maximum temperature was observed in August. In April, the values of SST became spatially uniform. The seasonal variation of SST observed in the present study is consistent to those reported in previous studies (e.g., Unoki 1985). This spatial gradient of SST in the north–south direction is primarily related to the topography of the seabed (Fig. 1b) and the resulting total heat capacity of the water column. As a result, SST at the head (north) becomes lower in winter and higher in summer than that at the mouth (south).

SST is secondarily influenced by water exchange between the bay and the Pacific Ocean as will be discussed.
further in section 3d. In winter, SST in the northwestern portion of the bay tends to be low because of cool river water flowing into the bay. A high-SST spot forms at the northeastern portion of the bay throughout the year. This spot probably originates from heated water discharge from industrial activities [see section 3b(1)]. The spatial patterns of air temperature over the bay are similar to those of SST throughout the year (not shown). However, the annual temperature range of the air over the bay is larger (20.3 – 35.1°C) than that of the sea surface (9.3 – 33.1°C), and the spatial variability of the monthly averaged air temperature is smaller than that for the monthly averaged SST except in April.

Figure 3 illustrates the monthly averaged spatial distribution of the difference between SST and air temperature—SST – air temperature. Tokyo Bay becomes a heat source for the atmosphere between November and March, and this effect is the largest in December. In contrast, the mouth of the bay becomes a heat sink starting in May. Seasonal variations of SST and air temperature at the mouth of the bay are smaller than those at the head of the bay (Fig. 2). However, the seasonal variation of SST – air temperature at the mouth of the bay is larger than that at the head of the bay.

The monthly statistics of SST and air temperature for the rainy and nonrainy days are shown in Fig. 4a. On rainy days, the diurnal range of SST is quite small in all seasons. The diurnal range of SST in August was relatively large probably because there was only one rainy day in August and the precipitation on that day was low. On the other hand, on nonrainy days, the diurnal range of SST is larger than 1.0°C in summer (Fig. 4a) and less than 0.5°C in winter, indicating a distinct seasonality. In winter, the bay water is unstable because of the radiative cooling at the surface. The unstable stratification in the water generates strong vertical mixing of the water (see section 3d). Accordingly, the small diurnal range of SST is observed even on nonrainy days in winter.

The daily minimum SST tends to appear at 0500–0600 JST, and the daily maximum SST tends to occur at 1300–1400 JST (not shown). Some studies have reported that the amplitude of the diurnal SST variation reaches 5°C in extreme cases (e.g., Flament et al. 1994; Yokoyama et al. 1995). In the present study, the maximum amplitude of the daily SST variation, observed on 24 July 2007 in Tokyo Bay, was 5.5°C at site 4 (Fig. 4b). On this day, the amplitude of the daily SST variation averaged over the entire bay was 2.9°C (Fig. 4b). The day, 24 July 2007, was warm with a maximum air temperature of 31.5°C and followed a few days of cloudy and rainy weather. The large amplitude of the diurnal variation of SST may be attributable to the combined effects of freshwater
influx from precipitation on the preceding days and daytime solar heating, which results in a strong density stratification of the upper layer of the seawater (Soloviev and Lukas 1997). This result suggests that the diurnal variation of SST strongly depends on atmospheric forcing due to solar radiation. Previous studies (e.g., Price et al. 1987; Webster et al. 1996) showed that the diurnal variation of SST is influenced by the wind speed, thus the dependency of the diurnal variation of SST on the wind speed at Tokyo Bay will be discussed in section 4a.

b. Singular phenomena

1) EFFECT OF HEATED WATER DISCHARGE

It was frequently observed that SST at site 5 abruptly increased more than 2.0°C (Fig. 5). The abrupt increase of SST occurred at irregular time intervals and was more likely in the daytime. Site 5 was located near a thermal power plant, approximately 1.8 km from its freeing port. The power plant generates up to 3.6 million kW of electric power (Agency for Natural Resources and Energy of Japan 2008), then discharges water that is approximately 7°C warmer than the water taken in by the power plant at the rate of approximately 162 m³ s⁻¹ (about 45 m³ s⁻¹ per 1 million kW). According to the amount of heated water discharged into a bay, the extent of the area in which the water temperature is affected by the discharge can be estimated. For the present power plant, the area subject to a water temperature rise of 1°C extends to 3 km from the freeing port (Agency for Natural Resources and Energy of Japan 1999, see Table 2 in their appendix). Thus, the abrupt increase of SST at site 5 was probably caused by heated water discharge from the thermal power plant.

2) TIDAL VARIABILITY

The variation of SST at the mouth of the bay (site 11) matches well with the variation of the sea level, that is, the tidal variability (Fig. 6). In winter, SST at the mouth is higher than that at the head (section 3a). Moreover, at high tide, the SST at the mouth of the bay is higher than that at other sites because of the high SST of the Pacific Ocean. At low tide, the SST at the mouth of the bay is approximately the same as that at the head.

As is well known, the height of the oceanic tide is largely determined by four dominant constituents: the principal lunar semidiurnal tide (M₂ constituent; 12.42-h period), the principal solar semidiurnal tide (S₂ constituent; 12.00-h period), the luni-solar diurnal tide (K₁ constituent; 23.93-h period), and the principal lunar diurnal tide (O₁ constituent; 25.82-h period) (e.g., Unoki and Kubota 1996). With observations made 1 km away from the shoreline of Sagami Bay in Japan, Kondo et al. (1972) detected a semidiurnal variation of water temperature at a depth of several meters below the surface, but not closer to the sea surface; at the sea surface, the diurnal variation was dominant. In contrast, Fig. 6 and an FFT analysis of the current SST dataset (not shown) indicate

![Fig. 4.](image1)

![Fig. 5.](image2)
that the semidiurnal variation of SST is present at the sea surface at the mouth of Tokyo Bay. At the head of the bay, the diurnal change of SST is dominant at the sea surface.

3) INFLOW OF THE KUROSHIO

The Kuroshio (warm current) flows northward along the coastline of Japan, and occasionally approaches or recedes from the coastline for several days. Sometimes, an abrupt increase of water temperature at the mouth of the bay occurs because of an intrusion of warm Kuroshio water into Tokyo Bay (Hinata et al. 2000). Here the effects of this large-scale current on the SST of Tokyo Bay are investigated. Figure 7a shows the variations of SST at the mouth of the bay over the entire observation period. An abrupt increase of approximately 2.5°C in SST (marked by a circle in Fig. 7a) was observed at the same time that the Kuroshio was approaching the coastline. This abrupt increase is probably attributable to the direct influence of the current, since the temperature of the current is quite large.

Figure 7b shows the time series of SST from the time period around the abrupt increase of SST. While SST at the mouth of the bay (site 11) increased by approximately 2.5°C as discussed above, SST at the head of the bay (site 4) and at the middle of the bay (site 12) increased by 1.0°C according to the 25-h moving average data. This result suggests that the entire surface of Tokyo Bay is warmed directly by the Kuroshio on the time scale of several days. The influence of the current in the hourly variation of SST is evident only at the mouth of the bay (site 11) where the fluctuations of SST correspond well with the tidal variation. At the beginning of the event, the amplitude of the fluctuation is larger than 3.0°C because the difference in SST between the bay and the current is quite large.

c. Comparison between in situ SST and satellite SST

The in situ SST data are compared with three sets of objective analysis data of global SST derived from satellites: RTGSST, MGDSST, and NGSST-O. The SST data for the open ocean from these datasets are highly accurate: the bias and RMSE against SST estimated from independent buoys were −0.02°C and 0.56°C for RTGSST (Gemmill et al. 2007), 0.04°C and 0.38°C for MGDSST (Sakurai et al. 2005), and −0.01 and 0.95 K for NGSST-O (Guan and Kawamura 2004), respectively. In contrast, the objective analysis SST data do not accurately capture the SST values near the coast. The sources of the objective analysis SST data include the SST values measured in situ and those measured by infrared and microwave sensors on satellites. However, there are few in situ data values available near the coast. In addition, the resolution of microwave sensors is low, thus microwave SST values are affected by contamination due to signals from the land (Guan and Kawamura 2003). These factors contribute to the limited accuracy of the objective analysis SST data near the coast in all seasons.

To illustrate the limitations of the objectively analyzed SST data near the coast, we will compare our in situ SSTs to the objectively analyzed SSTs. This comparison is useful since some current weather forecasts for coastal regions and some regional models for atmospheric research use the objectively analyzed SST products as input. Figure 8 shows the seasonal variations of the in situ SST and the objectively analyzed SSTs derived from satellite for Tokyo Bay. In this figure, “in situ SST” indicates the daily averaged values of the in situ SST data spatially averaged over all sites. As for the objectively analyzed SSTs, the values of SSTs from 6, 8, and 46 pixels are averaged for RTGSST, MGDSST, and NGSST-O, respectively. Among the three objectively analyzed SST datasets, only the resolution of NGSST-O is high enough to include a pixel within the bay. All satellite SSTs are significantly higher than the in situ SSTs in winter while they are approximately the same as the in situ SSTs in summer. The maximum positive biases of the satellite-based SSTs in winter are 6.8°C for RTGSST, 5.3°C for MGDSST, and 8.5°C for NGSST-O. Large differences between the in situ SSTs and the objective analysis SSTs in winter are attributable to the limitation of infrared radiometers in cloudy conditions, in addition to a lack of in situ SST data near the coast and the limited resolution of microwave sensors as discussed above. The SST data from infrared radiometers...
on satellites are often used as a data source for objective analysis SST data. Infrared radiometers can retrieve SSTs even near the coast with a high horizontal resolution of 1.1 km. The SST data derived from NOAA AVHRR are similar to the in situ SST data both in magnitude and spatial pattern (Fig. 9). However, the acquisition rate of SSTs by infrared radiometers becomes low with increasing cloud cover (Guan and Kawamura 2003). Because cloud cover increases over Tokyo Bay and its surrounding area in winter, the limited acquisition rate of SSTs by infrared radiometers has a significant influence on the limited accuracy of the objective analysis SST values in winter.

Because of the limitations of satellite instruments as discussed above and the lack of available in situ data, the objective analysis data of global SST are sometimes unavailable near the coast. When this occurs, the global objective analysis SST data near the coast are often given the value of the water temperature in the Pacific Ocean, resulting in large biases. These large biases of the satellite SSTs near the coast are problematic especially in mesoscale weather predictions for coastal regions. In summer, although the objective analysis data of SSTs are reasonably accurate on a daily basis because of the small SST difference between the bay and the ocean, the data are unable to capture the diurnal variation of the SST, which exceeds 5°C under certain wind speed and radiative forcing conditions as shown in the in situ data (section 3a). Such diurnal variations of SST near the coast need be incorporated into mesoscale weather prediction models to improve their forecast accuracy.
**d. Seasonal dependency in the relationship between SST and air temperature**

Figure 10a shows the relationship between SST and air temperature at the 14 sites from the entire observation period. Only data from hours with 0 mm of precipitation are used. The relationship between SST and air temperature can be classified into three seasonal modes: winter (November–February), summer (May–September), and transient (March–April).

The three modes are characterized by different ensemble diurnal patterns of SST and air temperature (Fig. 10b) and wind conditions (Fig. 10c). The three modes are also influenced by the seasonal stability conditions of the near-surface water and the resulting circulation in the bay, as well as by the seasonal atmospheric stability conditions. The characteristics of the three modes can be summarized as below:

1) **Winter mode**: SST is always higher than the air temperature and never below a critical value of approximately 9°C, even when the minimum air temperature is less than 0°C. This relatively high value of SST is associated with vertical mixing. In winter, strong radiative cooling generates unstable stratification under the surface, and the resulting vertical mixing transports the warmer water upward from the bay bottom. The warmer seawater at the bottom originates from heat advected horizontally through the mouth of the bay from the Pacific Ocean (Yagi et al. 2000).

2) **Summer mode**: while SST is comparable to the air temperature, the daytime SST tends to be slightly lower than the air temperature. SST is mostly determined by the local energy balance near the surface due to the stably stratified bay water, which is caused by strong radiative heating on the water surface and that suppresses vertical mixing. As in winter, heat is horizontally advected into the bay from the ocean. However, the advected heat has little influence on the SST in the bay because the oceanic water advects below the stable thermocline into the bay (Yagi et al. 2000). Thus, the diurnal pattern of SST is determined by one-dimensional heat balance, similar to that of the land surface temperature.
3) Transient mode: this mode occurs in the transitional period between the winter and summer modes. While the values of SST in the transient mode remain similar to those in the winter mode, the air temperature increases by approximately 1.8°C. This observation is attributable to the difference in the heat capacities of the air and seawater.

In summary, in contrast to the variation of land surface temperature, the variation of SST depends not only on the energy flux to the water surface, but also on the stability conditions under the water surface.

4. Discussion—Does Tokyo Bay have a cooling effect on urban air temperature?

a. Dependency of SST on wind speed

As described in sections 3a and 3d, SST in summer strongly depends on the local energy balance due to the stable stratification of the water at the surface. Because the local energy balance is influenced by the local air-sea interaction, which depends on the surface wind speed, the effect of the surface wind speed on SST in summer is investigated in this subsection.
In summer, the southwesterly wind is dominant at the bay (Fig. 10c) and intensifies because of sea breeze during the daytime. To study the daytime relationship between SST and air temperature with the predominant wind conditions from nonrainy days, the SST and air temperature data collected from the following time period and conditions were analyzed: from 1100 to 1500 JST, southwesterly wind from 157.5° to 247.5° over the bay, and 0-mm hourly precipitation. The selected data were further classified into two groups using a threshold wind speed of 5 m s⁻¹, because some preceding studies suggest changes in diurnal SST variations when the wind speed exceeds 5 m s⁻¹. The SST behaviors that occur during high wind conditions include the disappearance of the skin layer (Konda et al. 1994), the absence of diurnal warming of the near-surface layer (Soloviev and Lukas 1997), and a small amplitude (approximately 1 K) of the diurnal variation of SST (Kawai and Kawamura 2002). The relationship between the two groups of SST and air temperature data is shown in Fig. 11. When the wind speed is higher than approximately 5 m s⁻¹, SST becomes lower than the air temperature. Therefore, a critical wind speed appears to exist around the wind speed of 5 m s⁻¹ for the SST to become lower than the air temperature.

Figure 12 shows the dependency of the sensible heat flux on the wind speed. The sensible heat flux $H$ was estimated from

$$ H = c_p \rho C_H U (SST - T_a), $$

where $c_p$ is the specific heat of air at constant pressure, $\rho$ is the air density, $U$ is the wind speed at a 10-m height, and $T_a$ is the air temperature at 10 m. The bulk transfer coefficient for air, $C_H$, was estimated using Kondo (1975). The sensible heat flux becomes more negative with increasing wind speed (Fig. 12), suggesting that the role of Tokyo Bay as a heat sink becomes enhanced under windy conditions. The 25-h moving averaged values of SST, air temperature, and wind velocity (Fig. 13) clearly show that SST is lower than the air temperature under windy conditions (the first half of the period) whereas SST is higher than the air temperature under calm conditions (the second half of the period). In addition, the amplitude of the SST variation is larger than that of the air temperature variation in Fig. 13. This observation indicates that the wind dependency of $SST - T_a$ originates mainly from the response of SST to wind conditions. The combined results of Figs. 12 and 13 suggest that strong southwesterly wind leads to a
decrease of SST. There are three possible mechanisms for the decrease of SST. First, enhanced turbulent mixing of water transports subsurface water of lower temperature upward to the surface. Second, water with lower SST is transported by the strong southwesterly wind from the mouth of the bay to the head of the bay. Third, upward latent heat flux increases in Tokyo Bay with strong southwesterly wind (Oda et al. 2006). Therefore, the bay may potentially function as a heat sink. This has a positive implication for mitigation of the heat island effect in Tokyo because the southwesterly wind from the bay is expected to transport air with low temperature to the Tokyo metropolitan area.

b. Dependency of air temperature over land on wind speed

To investigate the influence of the sea breeze from Tokyo Bay on the atmosphere of urban Tokyo in summer, characteristics of the air temperature over land were investigated. The air temperature over the land was collected at three weather stations [i.e., Shin-Kiba, Tokyo, and Nerima; see section 2b(1); Fig. 1a] in the Tokyo metropolitan area. To study the relationship between wind speed and the difference in air temperature between the land and the bay, the relevant data from the following time period and conditions are analyzed: from 1100 to 1500 JST, 0-mm hourly precipitation, southwesterly wind over the bay from 157.5° to 247.5°, and southeasterly wind over the land from 135° to 180°, and with 0-mm hourly precipitation.

c. Interaction between SST and sea breeze

The above investigation on the dependency of SST and air temperature on wind speed (sections 4a,b)

FIG. 13. Time series of the 25-h moving average of SST values, air temperature, and wind speed for the time period between 7 and 14 Aug 2007. The values of SST and air temperature used in the 25-h moving average are those averaged over all sites on the bay. Black line: SST; gray thick line: air temperature; gray thin line: wind speed.

FIG. 14. The relationship between the difference in air temperatures between the three observation stations on land and the bay and the wind speed. The data used were from daytime (from 1100 to 1500 JST), with southwesterly wind over the bay (from 157.5° to 247.5°) and southeasterly wind over the land (from 135° to 180°), and with 0-mm hourly precipitation.
neglected the influence of SST on the wind speed. The wind speed over the bay is determined mainly by the synoptic wind field and the sea-breeze circulation. SST may have an influence on the sea-breeze circulation, and thus the total wind speed over the bay. However, little research has been conducted on the impact of SST on the sea breeze (Kawai and Wada 2007) in contrast to the large number of observational and numerical studies on the influence of urban areas on the sea-breeze circulation (e.g., Kusaka et al. 2000; Kanda et al. 2001; Ohashi and Kida 2001; Freitas et al. 2007). Recently, Holt et al. (2009) demonstrated that realistic variations in SST (i.e., local upwelling or higher SST in Tokyo Bay than in the adjacent ocean) produce subtle variations in the sea breeze. Since the atmosphere is influenced by the sea surface through the heat fluxes (Zhang 2005), the magnitudes of some of the heat fluxes in Fig. 12 may be sufficiently large to affect the sea breeze. However, large negative sensible heat fluxes occur in windy synoptic conditions. Therefore, even if the sea breeze is modified by SST, this effect is masked by the strong synoptic wind. Further numerical studies including realistic sensible and latent heat fluxes over the sea surface as in Fig. 12 are necessary to confirm this speculation.

To summarize, Tokyo Bay lowers urban air temperature in summer by interacting with the wind that blows over the bay’s surface. As the strong southwesterly wind over the bay enhances turbulent mixing at the water surface, more subsurface water of low temperature is transported upward and decreases the SST. Moreover, when the strong southwesterly wind is present, water with lower SST is transported from the mouth of the bay to the head of the bay, and the upward latent heat flux also increases, contributing to the decrease of SST. The decreased SST drives negative sensible heat fluxes over the bay, and thus decreases air temperature. Therefore, Tokyo Bay functions as a heat sink. The cooled sea breeze from the bay decreases the values of $T_{a_{\text{land}}}$ along the coast to a value comparable with that of $T_{a_{\text{bay}}}$ (Figs. 15b,c). The cooling effect of Tokyo Bay on the urban air, however, gradually decreases with the distance from the coast and is almost negligible at approximately 20 km inland (Nerima). Therefore, with increasing wind speed, the horizontal air temperature gradient between the shore and inland becomes intensified.

5. Concluding remarks

Seasonal and diurnal variations of SST and air temperature were measured in situ at 14 sites across Tokyo Bay. As for the seasonal change of the spatial pattern of SST, SST at the head of the bay was lower than that at
the mouth of the bay in winter, and vice versa in summer. The spatial gradient of SST in the north–south direction was primarily attributed to the topography of the seabed and the resulting total heat capacity of the water column. The diurnal amplitude of the SST was larger than 1.0°C in summer, and an amplitude of the daily SST as large as 5.5°C was observed. Tokyo Bay was also affected by singular phenomena of SST. Abrupt increases of SST occurred at the eastern part of the head and the mouth of the bay due to heated water discharge from a thermal power plant and intrusion of the Kuroshio, respectively.

Seasonal variation of the SST observed in situ was compared to that of the objective analysis data of SST derived from satellites: RTGSST, MGDSST, and NGSST-O. In winter, the values of these satellite-based SSTs were much higher than those of the in situ SSTs. The maximum positive bias of the satellite-based SSTs was 6.8°C for RTGSST, 5.3°C for MGDSST, and 8.5°C for NGSST-O. This bias is attributable to two points. First, the SST acquisition rate from infrared radiometers becomes low during winter because of the increased cloud cover over Tokyo Bay and its surroundings. Second, when near-coast SST data values cannot be estimated by satellites because of their instrumental limitations, these values in the global SST objective analysis dataset are often given the values of the water temperature in the Pacific Ocean. In summer, the satellite-based SSTs were approximately the same as the in situ SSTs on a daily basis. However, the objective analysis SSTs are unable to capture the diurnal variation of the in situ SSTs, which exceeded 5°C under certain wind speed and radiative forcing conditions. These biases of the objective analysis data of satellite-based SSTs near the coast are problematic especially for mesoscale weather predictions in coastal regions.

The stability of the bay water changed from season to season. Accordingly, the relationship between SST and air temperature varied seasonally. The SST–air temperature relationship was classified into three seasonal modes: winter (November–February), summer (May–September), and transient (March–April). In the winter mode, SST was always lower than the air temperature because warm water below the surface was transported upward by bay-scale vertical mixing because of unstable stratification in the water. In the summer mode, SST was comparable to the air temperature although the daytime SST tended to be slightly lower than the air temperature. In summer, the bay water was stably stratified because of the strong radiative heating on the water surface. The stable stratification suppressed vertical mixing; thus SST was mostly determined by the local energy balance near the surface. The transient mode corresponded to the transitional regime between the winter and summer modes. SST was approximately the same as that in the winter mode, while the air temperature was higher than that in the winter mode.

Furthermore, in the summer mode, SST decreased in the presence of strong southwesterly wind, and Tokyo Bay had a cooling effect on the urban air temperature in the Tokyo metropolitan area. As the strong southwesterly wind over the bay enhanced turbulent mixing at the water surface, more subsurface water of low temperature was transported upward and decreased the SST. In addition, when the strong southwesterly wind was present over the bay, water with lower SST was transported from the mouth of the bay to the head of the bay, and the latent heat flux was also enhanced. These effects also contributed to the decrease of SST. The decreased SST drove negative sensible heat fluxes over the bay, and thus decreased air temperature. The cooled sea breeze from the bay decreased the air temperature over the land along the coast to a value comparable with that of the air temperature over the bay. The cooling effect of Tokyo Bay on the urban air, however, gradually decreased with the distance from the coast and was almost negligible at approximately 20 km inland. Therefore, with increasing wind speed, the horizontal air temperature gradient between the shore and inland became intensified.

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