# COOLING EFFECT OF SEA SURFACE TEMPERATURE OF TOKYO BAY ON URBAN AIR TEMPERATURE

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**Abstract**

Sea surface temperature (SST) and air temperature were measured with high spatial and temporal resolutions in situ in Tokyo Bay between November 2006 and September 2007. We examined how Tokyo Bay reduces urban air temperature in summer, by analyzing these data together with the data of Japan Meteorological Agency observation network in Tokyo Wards. The cooling effect of sea breeze on urban air temperature is significant in coastal region. The effect gradually decreases with distance from the coast and almost diminished at about 20 km inland. Therefore, the horizontal gradient of air temperature over the land intensified with increasing wind speed.

**Key words:** sea surface temperature, Tokyo Bay, urban air temperature

## 1. INTRODUCTION

Sea surface temperature (SST) is one of the key parameters for understanding air-sea interaction process. 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 on the sea breeze circulation in coastal areas. However, many weather forecast models currently use, as their input data, objectively analyzed SST data which 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. It has been believed that Tokyo Bay will have more or less influence on atmospheric environmental issues such as the heat island phenomenon and heavy rainfall, through the land-sea breeze mechanism (e.g., Yoshikado 1992; Kobayashi et al. 2007). However, the magnitude of the diurnal variation of SST in Tokyo Bay, and the impact of SST to the urban atmosphere are not well understood due to a lack of reliable SST data from this region.

The purpose of the present study is to investigate the impact of SST on the urban atmosphere based on a unique observation system to detect the diurnal variation of SST. Particularly, the mechanism of the cooling effect of sea breeze on urban air temperature is investigated based on the weather data observed over the bay and the urban Tokyo.

## 2. OBSERVATION

### 2.1. Site description

Tokyo Bay is adjacent to Tokyo metropolitan area, and only the entrance to the south is open to the Pacific Ocean (Fig. 1). The water surface area of the bay is approximately 960 km$^2$. The north-south and east-west lengths of the bay are approximately 50 km 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.

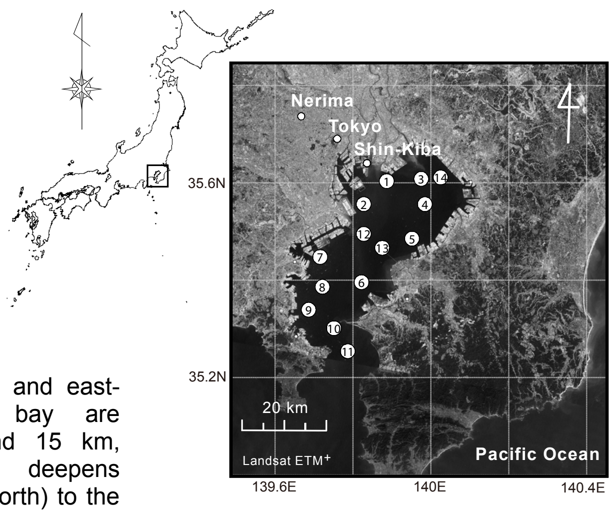


Fig. 1 Observation sites
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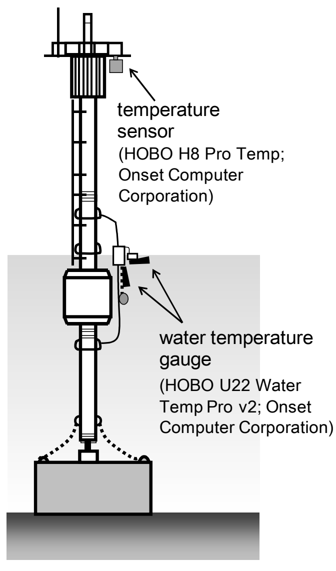


Fig. 2 The instrumental set-up on a beacon

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### 2.2. Observation system and data processing

Both the SST and the air temperature were measured in situ on buoys, beacons, and offshore structures at 14 observation points (Fig. 1). The observations were continuously made from 1 November 2006 to 24 September 2007. The SST and air temperature data were recorded every 10 minutes and averaged over 60 minutes. Figure 2 shows the setting of the instruments each site. The SST was measured at the depths of 1 cm and 20 cm below the sea surface using floats. In the present investigation, SST from the depth of 1cm was used. When SST at the depth of 1 cm was missing, SST at the depth of 20 cm was used instead. The difference of SST between the two levels was smaller than the accuracy of the sensor (± 0.2 °C). The air temperature measured at site-dependent reference heights, which varied from 3.7 to 12.8 m above the mean sea level.

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. Using these wind data, the measured air temperature was adjusted to air temperature at 10 m height using Kondo (1975).

The air temperature over the land was collected at three weather stations, i.e. Shin-Kiba, Tokyo, and Nerima, in the Tokyo metoropolitan area. The Shin-Kiba, Tokyo and Nerima weather stations are located approximately 0.2 km, 10 km, and 20 km inland from Tokyo Bay (Fig. 1). The air temperature data from these stations were collected at a height of 1.5 m.

## 3. RESULT

### 3.1. Dependency of SST on wind speed

The relationship between SST and air temperature can be classified into three seasonal modes: winter (November - February), summer (May - September), and transient (March – April); each mode was associated with the seasonal stability condition of the near-sea water (Oda and Kanda, 2009). SST in summer strongly depends on the local energy balance due to the stably stratified bay water, which is caused by strong radiative heating on the water surface and that suppresses vertical mixing. 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 and intensifies due to sea breeze during the daytime. To study the daytime relationship between SST and air temperature with the predominant wind conditions from non-rainy days, the SST and air temperature data collected from the following time period and conditions were analyzed: from 1100 to 1500 JST, southwesterly wind over the bay, and 0 mm hourly precipitation. Figure 3 shows the relationship between SST and air temperature. The SST becomes lower than the air temperature when the wind speed is higher than approximately 5 m $s^{-1}$.

The dependency of the difference between the SST and the air temperature, [SST - Air temp.], on the wind speed is shown in Fig. 4. This result suggests that the heat sink of Tokyo Bay becomes more significant under windy conditions. Under windy condition SST is lower than the air temperature whereas under calm condition SST is higher than the air temperature. Additional investigation of the same datasets revealed that the wind dependency of [SST – Air temp.] is priorly coming from the response of SST to wind conditions (Oda and Kanda, 2009).

Figure 5 shows the vertical profile of the water temperature at the head of the bay (Chiba light beacon; 35.6 °N, 140.2 °E) which is operated by Japan Coast Guard and with the wind vector at the same time. This figure indicates that the thermocline was formed at the deoth of about 4 m below the sea surface during weak wind, whereas it was vanished when the wind speed increases. The change of water temepratur under strong wind condition is mainly attributed to the vertical mixing of sea water since the direct influence of the solar insolation limited only upper layer of the ocean. Moreover, high salinity water of the mouth of the bay was

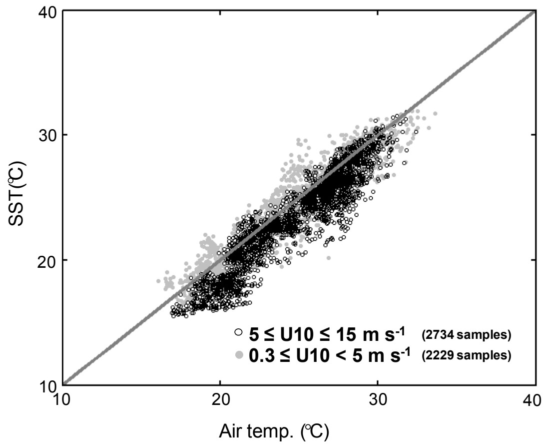



Fig. 3 The relationship between SST and air temperature over Tokyo Bay

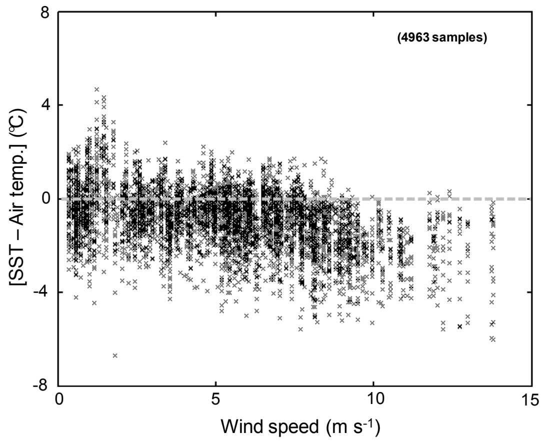



Fig. 4 The relationship between [SST – Air temp.] and wind speed

drifted to the head of the bay when the strong wind blows from the south (private communication from Dr. Yagi). In other words, it can be said that water with the lower SST at the mouth of the bay is transported to the head of the bay. In addition, the enhanced latent heat fluxes due to the increasing wind speed are also important factors to decrease SST (Oda et al., 2006).

The combined results from avobe results infer that strong southwesterly wind leads to a decrease of SST in the bay due to the following three effects; the first is the enhanced turbulent mixing of water and the resulting upward transport of sub-surface water with lower temperature, the second is the drifting of water with lower SST by the strong southwesterly wind from the mouth of the bay to the head of the bay, and the third is the increasing of upward latent heat flux. Therefore, the bay may potentially function as a heat sink.

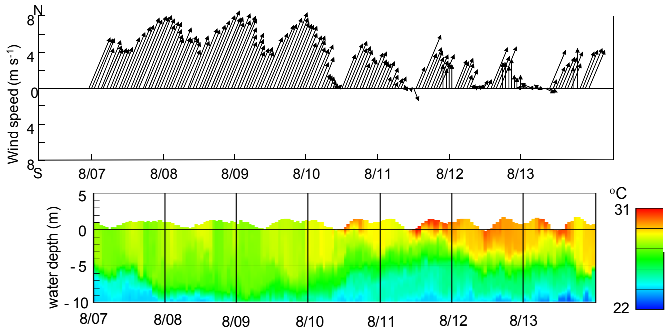



Fig. 5 The vertical profile of water temperature at the head of the bay, and the wind vector. The data source of lower figure is the Monitoring Post [Tokyo Bay Watch System] (Japan Coast Guard).

## 3.2. Cooling effect of sea breeze

We focused on the air temperature variation over the land to investigate how Tokyo Bay sea breeze has an influence on the urban atmosphere. The observation points, Shin-Kiba, Tokyo, and Nerima, are located at about 0.2km, 10km and 20km inland from the coast, respectively.

Figure 6 shows the dependency of difference air temperature between land ($Ta_{land}$) and bay ($Ta_{bay}$) on wind speed. To study the effect of sea breeze on $Ta_{land}$, the SST and air temperature data collected from the following time period and conditions were analyzed: from 1100 to 1500 JST, 0 mm hourly precipitation, southwesterly wind over the bay and southeasterly wind over the land. The horizontal air temperature gradient from Shin-Kiba to Nerima becomes large with increasing wind speed (Fi g. 6). It is interesting to note that the increase of the wind speed from the bay does not decrease the difference of $Ta_{land}$ to $Ta_{bay}$, but rather increase. It is opposite to the general idea that strong advection will reduce the horizontal temperature gradient.

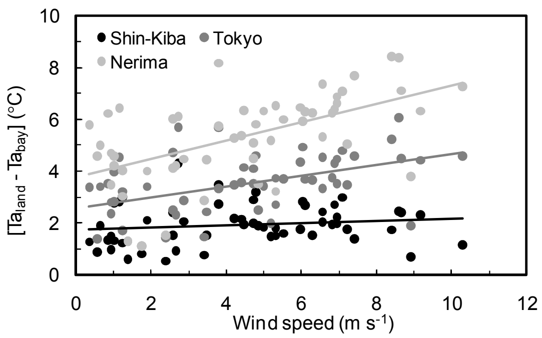



Fig. 6 The relationship between [$Ta_{land}$ – $Ta_{bay}$] and wind speed.

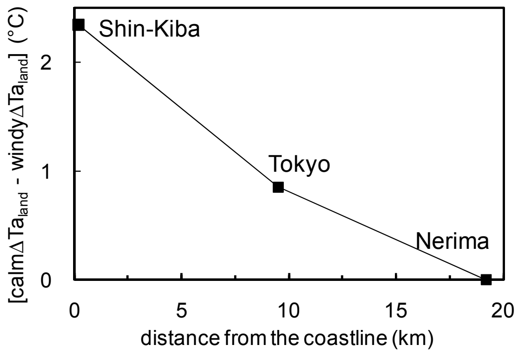
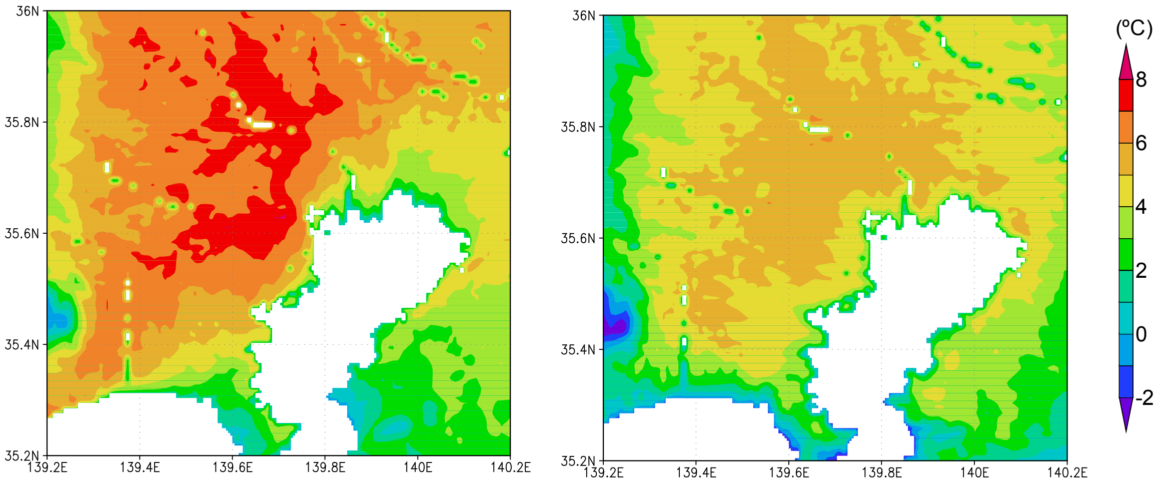



Fig. 7 The relationship between [calm$\Delta Ta_{land}$ – windy$\Delta Ta_{land}$] at the three observation stations and the distance from the coastline.

Figure 7 shows the difference between the mean dirunal amplitude of $Ta_{land}$ ($\Delta Ta_{land}$) in the case of windy and calm condition at the three observation stations, specifically: the amount of time with direct sunshine (i.e., non-cloudy) divided by the number of hours between sunrise and sunset exceeding 0.6, southwesterly wind over the bay, and 0 mm daily precipitation. Windy and calm conditions pertain to daytime (from 1100 to 1500 JST) wind speed of 5 - 15 m $s^{-1}$ and 0.3 - 5 m $s^{-1}$, respectively. The influence of wind speed on air temperature does not appear in Nerima located at about 20 km inland from the coast. In Shin-Kiba close to the shore, the diurnal amplitude of the air temperature decreses with storong wind. These air temperature decrease are probably due to the SST decrease (negative sensible heat flux) with strong wind speed (Fig. 4). The trend of the decreasing maximum air temperature (i.e., diurnal amplitude of air temperature) with increasing wind speed at this site is associated with low SST values and is consistent with the transport of low temperature air by strong southwesterly wind.

The effect of the wind speed is also investigated using numerical simulation. Figure 8 illustrates the spatial pattern of [$Ta_{land}$ - $Ta_{bay}$] on the day with strong wind (9 August 2007, 1300 JST) and weak wind (11 August 2007, 1300 JST), which are the results of the numerical simulation using WRF model under actual SST observed from this observation. As mentioned previously, on windy day, the sea breeze from the bay increases the horizontal air temperature gradient from the coast to inland. The strong sea breeze will bring the warmed air affected by the ground surfaces into further inland.




Strong wind _8/9 1300 JST    Weak wind _8/11 1300 JST

Fig. 8 [$Ta_{land}$ – $Ta_{bay}$] on the day with strong and weak wind.

As a result, the cooling effect of Tokyo Bay on urban air temperature in summer will be described below: As the strong south westerly wind over the bay enhances turbulent mixing at the water surface, more sub-surface 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. Thus, the air temperature rise over the bay is suppressed because Tokyo Bay functions as a heat sink. Cool sea breeze decrease the $Ta_{land}$ along the coastal region at the comparable rate as the decrease of $Ta_{bay}$. Cooling effect, however, gradually decrease with distance from the coast and almost diminished at about 20 km inland (Nerima). Therefore, with increasing wind speed, the horizontal $Ta_{lnad}$ gradient from the coast is intensified.

**5. CONCLUSION**

Tokyo Bay lowers urban air temperature in summer by increasing with the wind that blows over the bay's surface. The mechanism of the cooling effect of sea breeze is as follows.

1) The strong southwesterly wind over the bay in summer decreased the SST due to enhanced turbulent mixing at the water surface. It also decreased SST due to the drifting of the lower SST from the mouth of the bay to the head of the bay, and the increasing of latent heat flux.
2) The decreased SST drives negative sensible heat fluxes over the bay, thus decreases air temperature.
3) The cooled sea breeze from the bay decreases the air temperature over the land along the coast to a value comparable with that of air temperature over the bay, but no effect was detected at 20 km inland.
4) The horizontal gradient of air temperature over the land intensified with increasing wind speed.

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