Cooling Effect of Tokyo Bay on "Sultry Nights" with Calm Wind Conditions

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Abstract
In this study, the authors focused on light wind from the sea and its thermal environment relaxation effect during periods of calm conditions during the night when there is a concern that the urban heat island phenomenon is exacerbated. The light wind from the sea may be characteristic to urban waterfront areas where temperature increase persists throughout the day even during the night because of accumulated heat on the ground surface and artificial exhaust heat. The wind directions during periods of calm conditions at night were compared. The ratio of sea breeze to land wind near the ground level was greater than the ratio of the upper-level wind during calm conditions at night. The authors focused on the period when upper-level wind was calm. As the upper-level wind became calm, the wind direction changed from land breeze to sea breeze, and the temperature decreased as the direction of the wind changed. These observations indicated the temperature lowering effect of light wind from the sea. Previous studies of the wind system during the night generally discussed the land breeze. This study was unique in that the authors' focused on utilizing the cool light breeze from the sea at night.

Keywords: urban heat island phenomenon; sea breeze; cooling effect; sultry nights; thermal environment

1. Introduction
Securing "wind paths" and directing the sea breeze into built-up urban areas is an effective measure against the heat island effect on a citywide scale in large cities located next to the ocean, such as Tokyo. In recent years, waterfront areas in many large cities throughout Asia, including Tokyo, have undergone redevelopment accompanying large-scale land use conversion. To construct well-ventilated built-up urban areas utilizing the sea breeze, which is a valuable natural resource, and to respond to the demands of society for measures to combat the urban heat island effect, it is important to continuously accumulate the results of large numbers of related studies. There are increasing numbers of studies on the utilization of the sea breeze and cold air from river channels in the city. Related efforts include studies of the heat relaxation effects of land and sea breezes in different cities e.g., wind systems e.g., studies of urban morphology, air ventilation and the thermal environment e.g., studies of the factors and mechanisms involved in temperature development e.g., studies of impact of the actual sea surface temperature on urban air temperature e.g., all of which have provided large amounts of useful information. The authors have also been studying the actual conditions associated with wind in the streets in waterfront areas as well as the effect of the form of urban built-up areas on the thermal environment e.g.,

On the other hand, the heat island phenomenon is known to be exacerbated by calm conditions, and it is necessary to study the related phenomena under no-wind conditions. Related studies include research on cold air drainage e.g., In addition, a detailed actual survey of cold air leakage (cold air-seeping phenomena) from large-scale green spaces under calm wind conditions at night has recently been performed. In the above-mentioned study, the cold air-seeping phenomena of wind velocity from 0.1 to 0.3 m/s as well as a temperature decrease of approximately 1.0 K under a clear sky on a calm night have been observed. The method used for observation involves placing an ultrasonic anemometer-thermometer on the boundary of the green space and direct measurement of the aerial current to understand the cold air-seeping phenomena.

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Similarly, in waterfront areas of large cities showing temperature increases, the sea surface can have a certain cooling effect as a source of cool air at night when the wind is calm. However, there have been no previous surveys using highly accurate observations, and actual conditions have not been surveyed in sufficient detail. In our previous studies, we were also unable to perform analyses under calm conditions due to the technical limitations of the available measurement systems. In the present study, we used an ultrasonic anemometer-thermometer that allows the measurement of slight wind and took measurements at the Tokyo waterfront area to examine the actual state of the wind environment and the thermal environment of waterfront areas during "sultry nights" under calm wind conditions; the term "sultry night" is used by the Japanese Meteorological Agency to refer to a night when the temperature does not decrease below 25°C from late afternoon to the following morning.

2. Overview of Observation
2.1 Observation area and time period

Observations took place from 15:00 on July 28, 2008 to 09:00 on August 22, 2008 (the start date varied slightly depending on the observation point: Shibaura Wharf, from July 29; Shinagawa Wharf, from August 9). The items included in the observations were temperature, wind direction, and wind velocity. Observations were made at 53 locations around Shinagawa ward in the waterfront area in Tokyo (Fig.1.). In this measurement survey, the authors focused on the in-flow of sea breeze from Tokyo Bay; an ultrasonic anemometer-thermometer was placed at 2 locations closest to the coastline (Site A, B), with other meteorological observation equipment placed at 15 locations, mainly on roads, rivers, river channels, and open spaces running in the East-West direction, at intervals of 500 m forming a line along the East-West axis. An automatic temperature recorder was placed at 36 locations as indicated in Fig.1. at intervals of 200 m. All times indicated in this document are in Japan Standard Time.

2.2 Observation equipment

In this study, 3 types of observation equipment were used: an ultrasonic anemometer-thermometer, meteorological observation equipment, and an automatic temperature recorder. Table 1. shows the details of the observation equipment used, and Table 2. shows the accuracy of the ultrasonic anemometer-thermometer. With regard to the power source for the ultrasonic anemometer-thermometer, it was necessary for us to develop a system by which to use an accumulator battery, as there was no available AC power supply around Shinagawa Wharf. To specifically examine and evaluate measures to combat the heat island effect, it is necessary to take measurements to understand the atmospheric conditions. Therefore, securing a power supply in an outdoor setting is a major challenge in measuring the thermal environment at high resolution in urban spaces. All measurements were taken at a height of 3.5 m, including those obtained with meteorological observation equipment and automatic temperature recorders. Table 3. shows the details of sites at which ultrasonic anemometer-thermometers were placed as follows: Site A, Shibaura Wharf; Site B, Shinagawa Wharf. In this study, the mean value of the previous 5 min of data was used as the measured value for wind direction and wind velocity. The equipments used for measurement in this study were calibrated and the range and machine differences were corrected.

2.3 Existing observation points around those used in this study

Existing observation points located near the observation points used in this study include the Automated Meteorological Data Acquisition System (AMeDAS) Tokyo District Meteorological Observatory, Otemachi, Tokyo, and the Urban Renaissance Agency Shibaura Observatory. AMeDAS is referred to as Site P and the Shibaura Observatory is referred to as Site Q in this document. Valuable data from the above two locations were used to determine the weather conditions at the time of the actual survey (Table 4., Fig.2.).

![Fig.1. Overall View of the Waterfront Area of the Tokyo and Shinagawa Area](image)

**Table 1. Details of the Observation Equipment Used**

<table>
<thead>
<tr>
<th>Observation equipment used</th>
<th>Manufacturer/Monitor number</th>
<th>Observation item used in this study</th>
<th>Height at which measurements were taken</th>
<th>Time between measurements</th>
<th>Number of pieces of equipment used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic anemometer-thermometer</td>
<td>Katesat SAT-540</td>
<td>Wind direction, Wind velocity, Temperature</td>
<td>3.5m</td>
<td>5min</td>
<td>2</td>
</tr>
<tr>
<td>Meteorological observation equipment</td>
<td>Davis Vantage Pro2</td>
<td>Temperature</td>
<td>3.5m</td>
<td>5min</td>
<td>15</td>
</tr>
<tr>
<td>Automatic temperature recorder</td>
<td>ESDHC BSW-208</td>
<td>Temperature</td>
<td>3.5m</td>
<td>5min</td>
<td>36</td>
</tr>
</tbody>
</table>

**Table 2. Accuracy of the Ultrasonic Anemometer-thermometer**

<table>
<thead>
<tr>
<th>Observation equipment used</th>
<th>Range of wind velocity measurement</th>
<th>Resolution of wind velocity</th>
<th>Accuracy of wind velocity in horizontal direction</th>
<th>Range of wind direction in horizontal direction</th>
<th>Accuracy of wind direction in horizontal direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic anemometer-thermometer</td>
<td>0-60m/s</td>
<td>0.01m/s</td>
<td>±4%</td>
<td>0-540°</td>
<td>±3°</td>
</tr>
</tbody>
</table>
Table 3. Details of Sites at which Ultrasonic Anemometer-thermometers were Placed

<table>
<thead>
<tr>
<th>Sites at which ultrasonic anemometer-thermometers were placed</th>
<th>Covering of the ground surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A Shibaura Wharf</td>
<td>Asphalt</td>
</tr>
<tr>
<td>Site B Shinagawa Wharf</td>
<td>Asphalt</td>
</tr>
</tbody>
</table>

Table 4. Details of Existing Observation Points around those Used in this Study

<table>
<thead>
<tr>
<th>Existing observation points</th>
<th>Observation items used in this study</th>
<th>Height at which measurements were taken</th>
<th>Time between measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site P Automated Meteorological Data Acquisition System (AMeDAS)</td>
<td>Temperature</td>
<td>35.1m</td>
<td>10min</td>
</tr>
<tr>
<td>Site Q Urban Renaissance Agency Shibaura Observatory</td>
<td>Wind direction Wind velocity</td>
<td>87.0m</td>
<td>10min</td>
</tr>
</tbody>
</table>

![Fig.2. Existing Observation Points around those Used in this Study](image-1)

3. Wind Direction and Wind Velocity Near Ground Level at Night under Calm Wind Conditions

3.1 Definitions of terms used

Here, the wind above the urban canopy layer is called the "upper-level wind," and this was determined from the observation results obtained from Site Q. "Calm conditions" are defined as an upper-level wind velocity of \( \leq 1.0 \text{ m/s} \). "Daytime" is defined as 05:00 to 19:00, and "nighttime" is defined as 19:00 to 05:00. Taking the geography of the waterfront areas of Tokyo into consideration, the wind directions are defined as follows: North-West to North-North-East is called "North wind," North-East to East-South-East is called "East wind," South-East to South-South-West is called "South wind," and South-West to West-North-West is called "West wind." In this paper, East wind and South wind are considered "sea breeze" and North wind and West wind are considered wind from the land (Fig.3.).

3.2 Selection of periods of calm conditions during the night

Fig.4. shows the ratio of wind velocity of the upper-level wind for each hour during the actual survey. Calm conditions were observed between 00:00-10:00 and 21:00-24:00. The period 05:00-07:00 probably corresponds to the time of "morning calm." Calm conditions during the night were observed at 21:00-24:00 and 00:00-04:00. In this study, the authors focused on these calm conditions during the night.

![Fig.3. Sea Breeze and Land Wind](image-2)

![Fig.4. The Ratio of Wind Velocity of the Upper-level Wind for Each Hour (from July 28 to August 22)](image-3)

![Fig.5. The Ratio of Wind Velocity for Each Hour at Sites A under Calm Conditions (from July 29 to August 22)](image-4)

![Fig.6. The Ratio of Wind Velocity for Each Hour at Sites B under Calm Conditions (from August 9 to August 22)](image-5)

3.3 Wind direction and wind velocity near ground level under calm conditions at night

The periods with calm conditions during the night were selected as described in the previous section. To investigate the conditions of the wind near the ground level during such periods, data from Sites A and B, which are located relatively close to Site Q, were analyzed. Figs.5. and 6. show the ratio of wind velocity for each hour at Sites A and B, respectively.

During periods when the conditions were calm at night, wind with a velocity of 1.0-2.0 m/s was partly observed at Site A, but the majority of wind observed at both sites was slight with velocity in the range of 0.0-1.0 m/s.

The authors also examined the wind direction. Figs.7., 8. and 9. show the ratio of wind direction for each hour at Sites Q, A, and B, respectively, during the period of calm wind at night.
radiational cooling by the blocking effect of dense upper-level wind is from the land, a light wind from land wind was higher at ground level when conditions observations indicated that the ratio of sea breeze to nighttime low temperatures above 27°C (sultry nights) weather stations. Therefore, it is important to observe conditions close to the ground surface, which are more similar to those experienced around living spaces within the city.

4. Examining the Thermal Environment Relaxation Effect of Tokyo Bay during Periods of Calm Conditions at Night

4.1 Selection of the dates for analysis

Based on the results described in the previous section, the authors continued to examine the thermal environment of the area during the period when slight wind is blowing in from the sea during periods of calm conditions at night. Data from Site P were used to select the dates for analysis. According to the data, the latter half of the actual survey included days with localized severe rain or were partly rainy, and low temperatures dropping below 25°C on many of these days. The authors decided to use August 13, 14 and 15 as days for the analysis as all 3 days were sunny with nighttime low temperatures above 27°C (sultry nights) and all 3 days were after August 9, 2008 when all observation equipment was in place. Among the three days, the lowest temperature during the night on the 15th was 27.6°C, making it the hottest sultry night.

4.2 Selection of the period subject to analysis

Fig.10. shows the wind velocity and wind direction vector of the upper-level wind at Site Q on August 13, 14, and 15 at night from 00:00 to 09:00. The characteristics of the wind environment on each day were examined. On the 13th, the sea breeze persisted throughout the day. On the 14th, the sea breeze stopped around 03:00, showing conditions close to those during the day with a land and sea breeze cycle. On the 15th, light wind with a velocity of ≤3.0 m/s was seen throughout the day. These observations regarding the wind system corresponded to the results of our previous studies. During these three days, calm

The ratio of sea breeze to land wind was 1:1 for upper-level wind (Site Q), while the ratios at Sites A and B were approximately 7:2, respectively. Our observations indicated that the ratio of sea breeze to land wind was higher at ground level when conditions are calm at night in comparison to the upper-level wind (Figs.7., 8, and 9.). For example, even when the upper-level wind is from the land, a light wind from the sea may be seen close to ground level. This is partly because the temperature of an urban area does not decrease even at night due to the accumulated heat on the ground surface of the built-up areas as well as excess artificial exhaust heat, and the decreasing of radiational cooling by the blocking effect of dense high-rise buildings, while the surface of the sea is cool, causing a light wind to blow from the sea to the built-up areas.

For future urban planning taking natural resources into consideration, it is important to focus on the urban climate specific to urban waterfront areas where temperature increases persist even during the night. To date, the general understanding of the wind system at night was that there is a land breeze. This study was unique in that the authors focused on utilizing the cool light breeze from the sea during periods of calm conditions at night as a characteristic phenomenon of urban waterfront built-up areas with increasing temperature throughout the day due to accumulated heat on the ground surface as well as artificial exhaust heat, and the decreasing of radiational cooling.

The results of the present study indicated that the conditions close to the ground surface are affected by geography or features of the land, and are different from the prevailing wind system observed at general weather stations. Therefore, it is important to observe the conditions close to the ground surface, which are more similar to those experienced around living spaces within the city.
conditions with an upper-level wind velocity of ≤ 1.0 m/s were observed twice on the 14th from around 05:20 to 07:00 and on the 15th from around 00:50 to 01:40. The calm conditions observed on the 14th occurred after sunrise, during the period corresponding to "morning calm" and so it was decided to analyze the period from around 00:50 to 01:40 on the 15th as calm conditions at night.

4.3 Thermal environment relaxation effect of Tokyo Bay during period of calm conditions at night

Fig.11. shows the enlarged figure of Fig.10., describing the wind velocity of the upper-level wind at Site Q from around 00:50 to 01:40 on the 15th as calm conditions at night. Figs.12. and 14. show the changes in temperature and wind direction near the ground level from 18:00 on August 14 to 06:00 on August 15 at Sites A and B, respectively. The corresponding changes in temperature and wind velocity are shown in Figs.13. and 15. respectively. Fig.16. shows that the wind rose when the conditions were calm (Sites A, B). Here, the authors focused on the period during which conditions were calm, i.e., from 00:50 to 01:40 on the 15th, when the upper-level wind (Site Q) was calm. The data in Figs.12. and 14. indicate a large trend common to Sites A and B: that is, as the strength of the upper-level wind (Site Q) decreased, the wind direction changed from land wind to sea breeze, and as the wind direction changed, the temperature decreased. This is thought to indicate the temperature reducing effect of light wind blowing from the sea. The end of the period of calm upper-level wind also tended to be associated with increases in temperature at these sites.

In Figs.12. and 14. as well as Figs.13. and 15., the indicated range of temperature on the vertical axis is different according to the range of data, so the changes in the graph can be seen more easily. Next, each of Sites A and B were examined in detail.

As shown in Fig.12., the wind direction changed to sea breeze from around 01:00, and a temperature decrease of about 0.6-0.7 K was observed until about 02:30 at Site A. Fig.13. shows that when the authors focused on the period during which conditions were calm, i.e., from 00:50 to 01:40, the wind velocity was about 0.2-0.7 m/s, and the temperature decreased as wind velocity increased. The relationship between decrease in wind velocity and increase in temperature can be clearly seen at around the time when the upper-level wind(Site Q) began to blow again at about 1.0 m/s. From 01:00 to 01:30, when the upper-level wind was even weaker at about 0.0 m/s to 0.8 m/s (Fig.11.), the wind velocity at Site A tended to be stabilized at about 0.6 m/s. As shown in Fig.16., when the condition of the upper-level wind (Site Q) is calm, the direction of the breeze is from the sea.

At Site B, the wind direction changed to sea breeze from about 01:00, as seen at Site A, and a temperature decrease of 0.4-0.5 K was observed until about 02:00 (Fig.14.). Next, the authors confirmed the relationship between the wind velocity and temperature in more detail. As shown in Fig.15., when the authors focused on the period when conditions were calm, i.e., from 00:50 to 01:40, the wind velocity was about 0.0-0.1 m/s, and the temperature decreased with increasing wind velocity. Similar to Site A, the wind velocity increased around 00:50 when the upper-level wind (Site Q) became calm, and the temperature decreased.

From 01:00 to 01:30 when the upper-level wind was even weaker at about 0.0 m/s to 0.8 m/s (Fig.11.), the wind velocity at Site B was somewhat stabilized at
about 0.1 m/s. At around 01:40 when the upper-level wind (Site Q) began to blow again at about 1.0 m/s, a clear relationship was observed between the wind velocity decrease and the increase in temperature. Fig.16 shows that the wind direction during the period when the upper-level wind (Site Q) was calm was from the sea.

Figs.12. and 14. show how the wind direction switched back to landwind around 02:00-02:30 when the period of calm upper-level wind (Site Q) ended, and the temperature began to rise until around 02:30. The period with low temperature seemed to remain through the end of the period with calm wind conditions and the following period with a wind velocity of about 1.5 m/s up until about 02:40. At 02:40, the observed mean wind velocity of the upper-level wind was 2.7 m/s, and although it fluctuated, the wind velocity remained at about 2.0 m/s thereafter (Fig.10).

Fig.12. shows that after the period during which the condition of the upper-level wind (Site Q) is calm, the direction of the wind only at Site A remained the same, from the sea, but the temperature at Site A began to rise from about 02:30. It is interesting how the breeze from the sea persists, but the authors were unable to investigate this matter in more detail in this study. Site A is located at a deeper area of the Bay, and it was observed that the wind velocity at Site A was weak even when the upper-level wind was strong. The relationships between some observed results from Site A and the upper-level wind seemed characteristic of the site, probably because of geographic conditions, and further investigations taking these conditions into consideration are necessary.

4.4 Transition of temperature distribution

In the previous section, the authors focused on periods with calm upper-level wind (Site Q), and examined light wind from the sea near the ground level and its temperature reducing effect. This section discusses the changes in temperature over all observation areas during the period at which light wind from the sea was observed. The authors focused on the

![Fig.11](image1)

Fig.11. The Wind Velocity of the Upper-level Wind at Site Q from around 00:50 to 01:40 on the 15th as Calm Conditions (the enlarged figure of Fig.10.)

![Fig.12](image2)

Fig.12. The Changes in Temperature and Wind Direction from 18:00 on August 14 to 06:00 on August 15 at Sites A

![Fig.13](image3)

Fig.13. The Changes in Temperature and Wind Velocity from 18:00 on August 14 to 06:00 on August 15 at Sites A

![Fig.14](image4)

Fig.14. The Changes in Temperature and Wind Direction from 18:00 on August 14 to 06:00 on August 15 at Sites B

![Fig.15](image5)

Fig.15. The Changes in Temperature and Wind Velocity from 18:00 on August 14 to 06:00 on August 15 at Sites B
period with calm upper-level wind (Site Q) on the 15th from 00:50 to 01:40. The temperature distribution on August 15th from 00:20 to 01:20 over intervals of 20 min is shown in Fig.17.

During the period of calm upper-level wind, the thermal environment in the built-up urban areas improved, and the sizes of low temperature areas increased. The left side (west side) of the study area in the diagram has a relatively large amount of green space with a number of temples and hotels with gardens, while the central part of the study area is a business and commercial area with a terminal station and arterial highway. The low temperature area can be seen to spread from the east side closer to the coastal area as well as from the west side. As shown here, the formation of a network of low temperature areas within the urban area may segmentize the built-up urban areas with worsening thermal environment, or even improve the thermal improvement. This is an important consideration from the viewpoint of urban environmental planning, in order to make the best use of such natural resources.

This study was performed to examine the thermal environment relaxation effect of light wind from the sea during periods of calm conditions at night, when there is a concern that the heat island phenomenon will be exacerbated. This is a new view of localized natural climatic resource usage in waterfront areas of large cities where temperature increases continue throughout the day. However, further detailed studies are required to determine the frequency of calm conditions at night, along with the mechanism of action, and measurement of horizontal direction as well as range of impact of such cooling effects in built-up urban areas. As the authors were unable to measure water temperature and ground surface temperature, or to examine heat balance, the findings of this study are not necessarily sufficient for use in urban environmental planning. We plan to conduct further studies of such parameters in the near future.

5. Conclusions

In this study, the authors focused on light wind from the sea and its thermal environment relaxation effect during periods of calm conditions during the night when there is a concern that the heat island phenomenon is exacerbated. The light wind from the sea may be characteristic to urban waterfront areas where temperature increase persists throughout the day even during the night because of accumulated heat on the ground surface and artificial exhaust heat.

1. Calm conditions (wind velocity ≤ 1.0 m/s) of upper-level wind (Site Q) during the night were observed from around 21:00 to 24:00 and 00:00 to 04:00. When the authors examined the wind direction and velocity near the ground level during the period of calm conditions at night, the majority of wind velocities observed at Sites A and B ranged from 0.0-1.0 m/s, although wind velocity of 1.0-2.0 m/s was partly observed at Site A.

2. The wind directions during periods of calm conditions at night were compared. The ratio of sea breeze to land wind was 1:1 for upper-level wind (Site Q) but was 7:2 at Site A and at Site B. The ratio of sea breeze to land wind near the ground level was greater than the ratio of sea breeze to land wind of the upper-level wind during calm conditions at night.

3. The authors focused on the period of 00:50-01:40 on the 15th when upper-level wind (Site Q) was calm; there was a common trend; that is, as the upper-level wind (Site Q) became calm, the wind direction changed from land breeze to sea breeze, and the temperature decreased as the direction of the wind changed. These observations indicated the temperature lowering effect of light wind from the sea. At Sites A and B, as the condition of the upper-level wind (Site Q) became calm, the wind velocity gradually increased around 00:50, and at the same time the temperature decreased. As the upper-level wind began to blow again at about
1.0 m/s, the wind velocity gradually decreased until around 01:40 and the temperature increased. A clear relationship was seen between the wind velocity and temperature. At Site A, the wind velocity was about 0.2-0.7 m/s, and a temperature decrease of 0.6-0.7 K was observed. At Site B, wind velocity was about 0.0-0.1 m/s and a temperature decrease of 0.4-0.5 K was observed.

This study was performed to determine the conditions of the thermal environment and the wind environment of the waterfront areas of Tokyo, Japan, during sultry nights with calm wind conditions, focusing on the thermal environment relaxation effect of Tokyo Bay. This was an observational study to better understand these phenomena. Previous studies of the wind system during the night generally discussed the land breeze. The present study was unique in that the focus was on utilization of the cool light breeze from the sea during the period when the wind was calm at night. This is an important distinction between the present study and others reported previously.

6. Future Perspectives

In future studies, the authors would like to investigate the severity and characteristics of the heat island effect during the period when the wind is calm, by comparing the conditions with and without wind. In addition, a detailed analysis of the overall city weather conditions of the subject area will also be valuable to clarify the position and significance of the calm wind conditions. The authors consider this study to be fundamental research with a focus on the examination of various phenomena associated with the thermal environment relaxation effects of the sea breeze under calm conditions at night. We would like to perform further examinations in future studies, including measurement of water temperature and ground temperature, examination of heat balance focusing on the urban morphology and detailed examination of the mechanisms involved, to make the knowledge obtained in this study useful in urban environmental projects in large cities in Asian countries.

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