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Short Report

Keywords: marine heatwaves, atmospheric circulation, heatstroke, wet bulb globe temperature

Posted Date: June 10th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9851331/v1>

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Additional Declarations: No competing interests reported.

**Day-to-day atmospheric circulation modulated the impact of
marine heatwaves on heatstroke risk in Hokkaido in
August 2023**

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Abstract

Extreme high temperature and humidity threaten high-latitude regions that are less adapted to such conditions. While marine heatwaves (MHWs) can contribute to hot and humid conditions over land, the modulation of these impacts by the day-to-day atmospheric circulation remains poorly understood. This study focused on Hokkaido, the northernmost prefecture in Japan, to investigate how the daily atmospheric circulation regulated the distribution and intensity of MHW-related heatstroke risk during August 2023. Regional atmospheric model simulations indicated that the MHWs that developed south of Hokkaido increased the Wet Bulb Globe Temperature (WBGT) by approximately 2 °C in southern coastal areas. Backward trajectory analysis showed that the intensity of MHW-induced heatstroke risk was governed by the daily atmospheric circulation. On days when MHWs substantially impacted the WBGT in the southeastern coastal region, air parcels passed over regions with high sea surface temperatures (SSTs). Conversely, when trajectories bypassed these MHW areas, the impact remained low. These results demonstrate that the daily atmospheric circulation can determine the magnitude of heatstroke risk over land. Our findings suggest that the relative positioning of airflow pathways and the SST distribution should be considered to improve heatstroke risk prediction in coastal regions.

37 **Keywords**

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40 **Statements and Declarations**

41 **Competing Interests**

42 The authors declare that they have no competing interests.

43

1 Introduction

Occurrence of extreme heat events has been increasing worldwide, posing notable risks to natural and human systems (IPCC AR6 2021). In recent years, the global mean surface air temperature has reached record high levels, with the three warmest years occurring during 2023–2025 (World Meteorological Organization 2025). Accompanying this warming, extreme heat events have been widely observed across East Asia (Perkins-Kirkpatrick et al. 2024). In this region, in addition to high temperature events, compound hot and humid events frequently occur during summer that substantially enhance heatstroke risk (Ha et al. 2022; Deng et al. 2025). Such hot and humid conditions affected Japan in 2023, resulting in many heatstroke patients being transported to hospitals (e.g., Oka et al. 2025; Okajima et al. 2025).

Multiple processes contribute to the development of high temperature and humidity over land. Marine heatwaves (MHWs), characterized by persistently high sea surface temperatures (SSTs) (Hobday et al. 2016), can contribute to developing hot and humid conditions in surrounding land areas (Takahashi et al. 2015; Sato et al. 2024; Takemura et al. 2024; Cai et al. 2026). One possible reason for this is considered to be enhancement of the flow of warm, humid air from the ocean to land associated with

MHWs (e.g., Sato et al. 2026). During summer, these atmospheric flows are likely to vary from day to day (e.g., Wie et al. 2021). Therefore, daily atmospheric circulation variability during the summer might modulate the influence of MHWs on heatstroke risk. These processes might further exacerbate heatstroke risk in high-latitude regions, where populations are generally less adapted to extreme heat and humidity (e.g., Fujibe et al. 2018; Speizer et al. 2022).

In August 2023, Hokkaido, the northernmost prefecture in Japan, recorded surface air temperatures and specific humidity levels that were far higher than observed in previous years (Fig. 1a). Heatstroke cases in Hokkaido reached approximately 3.6 times the 2010–2024 August average during the same period (Supplement 1). During this period, MHWs developed as the warm Kuroshio Extension meandered markedly northward (Sato et al. 2024). Positive SST anomalies were observed around northern Japan, with SST anomalies exceeding 4 °C relative to the climatology in some areas on the Pacific side (Fig. 1b). Additionally, southerly winds associated with the western North Pacific subtropical high prevailed (Fig. 1c). Positive equivalent potential temperature anomalies of approximately 14 K were observed around Hokkaido (Fig. 1d).

Even under persistently high SST conditions, the surface air temperature and humidity over Hokkaido exhibited pronounced day-to-day variability. For example,

during 5–7 August, SST remained nearly constant at close to 23 °C, whereas surface air temperature decreased by approximately 2 °C and specific humidity increased by approximately 3 g kg⁻¹ (Supplement 2). This implies that MHWs alone could not explain the variability in heatstroke risk. Therefore, the modulation of the impact of MHWs on heatstroke risk in Hokkaido might have been driven by the submonthly atmospheric circulation.

Previous related studies on heatstroke risk primarily investigated the relative impacts of MHWs and synoptic atmospheric circulation separately. Consequently, the extent to which MHW-related heatstroke risk is influenced by the day-to-day atmospheric circulation remains poorly understood. Therefore, this study focused on Hokkaido in August 2023 to investigate how the day-to-day atmospheric circulation might regulate daily MHW-related heatstroke risk.

2 Data and Method

2.1 Data and Experiments

To investigate how daily atmospheric circulation variability controls MHW-related impacts on heatstroke risk, this study used the Weather Research and Forecasting

model (WRF-ARW). The details of the experiments are outlined in Supplement 3. The numerical experiments focused on the period 20 July to 31 August 2023, including a spin-up period comprising the first 12 days. The experimental domain is shown in Supplement 4. The horizontal mesh size was 5 km. Optimum Interpolation Sea Surface Temperature (OISST; <https://www.ncei.noaa.gov/products/optimum-interpolation-sst>) data were used as the lower boundary condition for the ocean. Two experiments were conducted: a realistic experiment using daily SST in 2023 (hereafter, SST23) and a sensitivity experiment using daily climatological SST for 1991–2020 (hereafter, CLIM). Both experiments were driven using the same atmospheric forcing data from the Japan Meteorological Agency mesoscale model (MSM) analysis.

2.2 Evaluation of Heatstroke Risk

The Wet Bulb Globe Temperature (WBGT) was utilized to quantitatively evaluate heatstroke risk. The WBGT is an index that measures the combined effects of air temperature, humidity, and solar radiation on the human body, and is often referred to as the heat stress index (Epstein and Moran 2006). We computed the WBGT at 2-m height using Equation (1), following the methodology adopted by the Japanese government

(Ministry of the Environment 2024):

$$WBGT = 0.1T_d + 0.7T_w + 0.2T_g \quad (1)$$

where T_d [°C], T_w [°C], and T_g [°C] represent the dry bulb temperature, wet bulb temperature, and globe temperature at 2-m height, respectively. T_w was derived using Sprung's formula as described below:

$$e(T_d) = es(T_w) - AP(T_d - T_w) \quad (2)$$

where es [hPa] and e [hPa] represent the saturation vapor pressure at T_w [°C] and vapor pressure at T_d , respectively, and $A = 0.00062$ and $P = 1013.25$ hPa are constants. We estimated the globe temperature T_g using the formula proposed by Okada et al. (2013; Equation 3):

$$T_g = \frac{S - A}{BS + CU + D} + T_a \quad (3)$$

where S , U , and T_a represent global solar radiation [W m^{-2}], wind speed [m s^{-1}], and hourly air temperature [°C], respectively. The other symbols, $A = 28.94$, $B = 0.038$, $C = 3.82$, and $D = 19.03$ are constants determined through nonlinear least squares analysis using hourly observations recorded during July and August 2023. Because observed globe temperature data are available from a single monitoring site in each prefecture (Ministry of the Environment 2024), this study determined a coefficient to approximate the observations from the Sapporo Meteorological Observatory, which represents the

measurements for Hokkaido. The coefficient of determination (R^2) for T_g was 0.95, and the root mean square error was 1.48 °C. Heatstroke risk is greater in densely populated areas; hence, the WBGT values were compared across the eight densely populated regions shown in Supplement 5.

3 Results and Discussion

3.1 Regional Differences in WBGT Associated with MHWs

First, the effects of MHW on WBGT are investigated based on the experimental results from August 2023. Figure 2 shows the spatial distribution of the August 2023 mean WBGT for observations and SST23, together with the differences between SST23 and CLIM. It is evident that SST23 successfully captures the observed pattern of higher values along the Sea of Japan coast and lower values along the Pacific coast (Fig. 2a and b). The spatial distribution of WBGT in SST23 is similar to that of SST (Figs. 1b and 2b), which suggests that SST strongly affects the overlying atmosphere. The WBGT in the southern coastal areas of Hokkaido is approximately 2 °C higher in SST23 than in CLIM, whereas the increase is less than 0.5 °C in inland regions (Fig. 2c). Figure 3 shows the differences in WBGT between SST23 and CLIM in densely populated areas. Figure 3 further

confirms the spatial pattern shown in Fig. 2c, with larger WBGT differences in the southern coastal areas than in the inland region. Specifically, WBGT at Kushiro and Tomakomai markedly increase in SST23 and exceed the heatstroke warning threshold of 25 °C on certain days, whereas it remains low throughout the month in CLIM. In contrast, in inland areas such as Asahikawa and Kitami, the WBGT difference between SST23 and CLIM is less than 1 °C on average (Fig. 3). These results indicate that the impact of high SST on heatstroke risk is weaker in inland areas than in coastal regions.

3.2 Influence of the Day-to-Day Atmospheric Circulation on WBGT Variability

To investigate the influence of the day-to-day atmospheric circulation on WBGT under MHW conditions, Kushiro is selected as a representative site for the southern coastal region, where MHW impacts on WBGT are largest among the study sites (Fig. 3). Figure 4 shows the hourly variations in WBGT for SST23 and CLIM, together with their differences. WBGT in SST23 remains persistently higher than in CLIM (Fig. 4a). After 13 August, WBGT increases abruptly in SST23 but rises only slightly in CLIM. As shown in Fig. 4b, the largest 5% WBGT difference occurs on 26–27 August (white dots), whereas the smallest 5% difference (black dots) appears on 7 August. These contrasting impacts

of SST imply that the daily atmospheric circulation regulates the magnitude of the impacts and determines whether the MHW effects are enhanced or mitigated.

The synoptic circulations during these contrasting cases, namely, the suppression case (7 August) and the amplification case (26–27 August), are shown in Fig. 5. In the suppression case, high-pressure centers are located over the western North Pacific and Sea of Okhotsk (Fig. 5a). Southeasterly winds associated with the former high pressure system and northeasterly winds associated with the latter high pressure system are directed toward Kushiro. SST anomalies are positive southeast of Hokkaido, exceeding 4 °C in some areas, whereas negative anomalies of approximately –2 °C are observed northeast of Hokkaido. In the amplification case, a high pressure center over the Sea of Okhotsk is absent, and the southerly winds around the high pressure over the western North Pacific are directed toward Kushiro (Fig. 5b). SST anomalies are positive around northern Japan, exceeding 6 °C in some areas on the Pacific side of southern Hokkaido. These different atmospheric circulation patterns might explain the contrasting influence of MHWs on coastal WBGT between the two periods. To further investigate these mechanisms, we conducted backward trajectory analysis to identify the transport pathways of the air masses, and the processes responsible for their warming and moistening. Air parcels were initialized at 10-m altitude and traced backward for 18 h.

No substantial differences are evident between the mean trajectories of SST23 and CLIM in both cases (Fig. 6). This suggests that the direct influence of MHWs on low-level winds within the numerical domain is small during the target cases, probably because the same lateral boundaries were used in both experiments. In contrast, the air parcel trajectories differ substantially between the two cases, reflecting their respective synoptic atmospheric conditions (Fig. 6). In the suppression case, air parcels pass over the ocean region to the northeast of Hokkaido, where SST is in the range 12–20 °C in SST23 and 12–18 °C in CLIM (Fig. 6a and b). Notably, SSTs along the pathways are similar between SST23 and CLIM, indicating that SSTs in 2023 were close to the climatological mean. In the amplification case, air parcels pass over regions of high SST off the Pacific coast of northern Japan, with SSTs of 23–30 °C in SST23 (Fig. 6c), i.e., substantially higher compared with those of CLIM (16–26 °C; Fig. 6d).

As air parcels travel toward Kushiro, the equivalent potential temperature (θ_e) increases in the suppression case in both SST23 and CLIM by 11.0 and 8.4 K, respectively. The rates of increase are similar, consistent with the smaller SST difference along the trajectories. In contrast, in the amplification case, θ_e decreases as the air parcels move northward, but the magnitude of the decrease differs substantially: only 2.2 K in SST23 but 14.5 K in CLIM. This indicates that the air parcels in CLIM undergo rapid loss of

moist static energy before reaching land, while those in SST23 reach Kushiro without
airmass modification. Figure 7c–f shows the upward latent and sensible heat fluxes from
the ocean along the mean trajectory. Latent heat flux dominates over sensible heat flux in
both cases (Fig. 7c–f), which indicates that latent heat supply from the ocean contributes
substantially to the moistening of the air parcels. The magnitude of the latent heat flux
from the ocean along the trajectories is substantially larger in the amplification case than
in the suppression case (Fig. 7c–f). These results suggest that differences in air parcel
trajectories associated with daily atmospheric circulation control the magnitude of
oceanic heat and moisture supply. Therefore, heatstroke risk is enhanced when air parcels
pass over MHW regions. This complex influence of MHWs, modulated by the daily
atmospheric circulation, might be a characteristic unique to northern Japan, where a
northward shift of the Kuroshio Extension and warm eddies contribute to the formation
of MHWs, coinciding with large variations in wind direction associated with synoptic
weather systems.

4 Summary

This study investigated how the day-to-day atmospheric circulation regulated the impacts of MHWs on heatstroke risk in Hokkaido during August 2023. Numerical experiments revealed that MHWs around northern Japan increased the WBGT by approximately 2 °C in southern coastal areas during this period. In contrast, the MHW-induced increase in WBGT was less than 0.5 °C over inland areas of Hokkaido. These results indicate that the influence of MHWs on WBGT is spatially nonuniform. Furthermore, daily analysis demonstrated that the influence of MHWs on heatstroke risk in the coastal city, Kushiro, differed markedly within a month. Backward trajectory analysis for Kushiro showed that air parcels passed over regions of anomalously high SST on days when the MHW impact was large. During this transit, the high SSTs provided an enhanced supply of latent heat to the lower atmosphere, reducing the cooling of the air parcels. Consequently, the air parcels maintained high θ_e until they reached the southern coast. In contrast, for a day with small MHW impact, the air parcels passed over the ocean where SST was normal or slightly higher compared with climatology, leading to a weak supply of latent heat to the air parcels. Consequently, the θ_e of the air parcels did not increase before reaching the southern coast. These results suggest that the day-to-day

atmospheric circulation determines whether the air parcels pass over MHW regions, and thus it controls the magnitude of the heat and moisture supplied to the atmosphere, leading to daily variations in the impact of MHWs on coastal WBGT.

A similar mechanism would be applicable to other coastal areas across the world and might provide useful insight for heatstroke risk assessment. As global warming progresses, MHWs are expected to become more frequent and intense, potentially elevating heatstroke risks in coastal regions. To reduce future heatstroke risk, it is important to develop region-specific heatstroke prediction systems that take into account the relative positioning between daily airflow pathways and SST distributions.

Data Availability

The original data of heatstroke cases used in this study are publicly available from the Fire and Disaster Management Agency of Japan at <https://www.fdma.go.jp/disaster/heatstroke/post3.html> (accessed on 10 May 2026). The MSM analysis data are publicly available from the Data Integration and Analysis System (DIAS) at <https://www.diasjp.net/> (accessed on 10 May 2024). The OISST data are publicly available from the NOAA National Centers for Environmental Information at <https://www.ncei.noaa.gov/products/optimum-interpolation-sst> (accessed on 10 May

2024). Hourly meteorological observation data are publicly available from the Japan Meteorological Agency at <https://www.data.jma.go.jp/gmd/risk/obsdl/index.php> (accessed on 28 December 2025).

Acknowledgments

This work was supported by JST SPRING, Grant Number JPMJSP2119. We thank James Buxton MSc, from Edanz (<https://jp.edanz.com/ac>), for editing a draft of this manuscript. This study was supported by the Japan Society for the Promotion of Science KAKENHI (Grant Number: JP24H02228; JP26K03145), the Arctic Challenge for Sustainability III (ArCS III) project (Grant Number: JPMXD1720251001), and the SENTAN program (JPMXD0722680734).

Author Contributions

T.M. and T.S. conceptualized and designed the study. T.M. conducted the data analysis and drafted the manuscript as the corresponding author. T.S. supervised the research, provided guidance throughout the study, and critically reviewed the manuscript. All authors reviewed the manuscript.

References

- Cai, F., D. Gerten, K. Zhang, T. Zhang, S. Yang, and J. Kurths, 2026: Large-scale aggregation of humid heatwaves exacerbated by coastal oceanic warming. *Nature Geoscience*, doi:10.1038/s41561-026-01952-z.
- Deng, X., L. Zhao, C. Xiao, R. Dai, Q. Xu, Y. Yao, C. Liang, L. Yao, and D. He, 2025: Heatstroke characteristics and meteorological conditions in Hefei, China: thresholds and driving factors. *BMC Public Health*, 25, 352, doi:10.1186/s12889-025-21577-y.
- Douville, H., K. Raghavan, J. Renwick, R. P. Allan, P. A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T. Y. Gan, J. Gergis, D. Jiang, A. Khan, W. Pokam Mba, D. Rosenfeld, J. Tierney, and O. Zolina, 2021: Chapter 8: Water cycle changes. In *IPCC (Intergovernmental Panel on Climate Change), Climate change 2021—The physical science basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, doi:10.1017/9781009157896.
- Epstein, Y., and D. S. Moran, 2006: Thermal comfort and the heat stress indices. *Ind. Health*, 44(3), 388–398, doi:10.2486/indhealth.44.388.
- Fujibe, F., J. Matsumoto, and H. Suzuki, 2018: Regional Features of the Relationship between Daily Heat-Stroke Mortality and Temperature in Different Climate Zones

288 in Japan. *SOLA*, 14, 144–147, doi:10.2151/sola.2018-025.

289 Geospatial Information Authority of Japan, 2024: Future Population Data by 500m mesh

290 (H30 National Bureau of Statistics Estimates) (2017). (Available online at:

291 <https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-mesh500h30.html>, accessed 20

292 Oct 2024).

293 Ha, K.-J., J.-B. Ahn, J.-Y. Lee, S.-K. Min, Y. Cha, D. Lee, and J.-H. Yoon, 2022:

294 Dynamics and characteristics of dry and moist heatwaves over East Asia. *npj*

295 *Climate and Atmospheric Science*, 5, 27, doi:10.1038/s41612-022-00272-4.

296 Hobday, A. J., and co-authors, 2016: A hierarchical approach to defining marine

297 heatwaves. *Prog. Oceanogr.*, 141, 227–238, doi:10.1016/j.pocean.2015.12.014.

298 Japan Meteorological Agency, 2023: The remarkable high temperatures in Hokkaido

299 during the summer (2023) (in Japanese). (Available online at:

300 <https://hokkaido.env.go.jp/content/000162648.pdf>, accessed 28 Nov 2024).

301 Japan Meteorological Agency, 2024: Long-Term Trends in Sea Surface Temperature

302 (Around Japan) (2024) (in Japanese). (Available online at:

303 [https://www.data.jma.go.jp/gmd/kaiyou/data/shindan/a_1/japan_warm/japan_warm](https://www.data.jma.go.jp/gmd/kaiyou/data/shindan/a_1/japan_warm/japan_warm.html)

304 [.html](https://www.data.jma.go.jp/gmd/kaiyou/data/shindan/a_1/japan_warm/japan_warm.html), accessed 28 Nov 2024).

305 Kuroda, H., and T. Setou, 2021: Extensive marine heatwaves at the sea surface in the

306 northwestern Pacific Ocean in summer 2021. *Remote Sens.*, 13, 3989,
307 doi:10.3390/rs13193989.

308 Martinez, G. S., C. Imai, and K. Masumo, 2011: Local Heat Stroke Prevention Plans in
309 Japan: Characteristics and Elements for Public Health Adaptation to Climate Change.
310 *Int. J. Environ. Res. Public Health*, 8, 4563–4581, doi:10.3390/ijerph8124563.

311 Ministry of the Environment, 2024: About the Heat Index (WBGT) (2024) (in Japanese).
312 (Available online at: https://www.wbgt.env.go.jp/doc_observation.php, accessed 11
313 Nov 2024).

314 Miyama, T., S. Minobe, and H. Goto, 2021: Marine heatwave of sea surface temperature
315 of the Oyashio region in summer in 2010–2016. *Front. Mar. Sci.*, 7, 576240,
316 doi:10.3389/fmars.2020.576240.

317 Oka, K., V. L. H. Phung, J. He, Y. Honda, M. Hashizume, and Y. Hijioka, 2025: Future
318 heatstroke mortality in Japan: Impacts of climate, demographic changes, and long-
319 term heat adaptation. *Environ. Res.*, 267, 123012, doi:10.1016/j.envres.2024.123012.

320 Okada, M., M. Okada, and H. Kusaka, 2013: Parameter adjustment and application to an
321 extension area of Okada and Kusaka's formula for the black globe temperature.
322 *Journal of Heat Island Institute International*, 8, 13–21 (in Japanese with English
323 abstract).

324 Okajima, S., Y. Kosaka, T. Miyasaka, and R. Ito, 2025: Unprecedented marine heatwave
 325 significantly exacerbated the record-breaking 2023 East Asian summer heatwave.
 326 *AGU Adv.*, 6, e2025AV001673, doi:10.1029/2025AV001673.

327 Perkins-Kirkpatrick, S., Barriopedro, D., Jha, R., Wang, L., Mondal, A., Libonati, R., and
 328 Kornhuber, K., 2024: Extreme terrestrial heat in 2023. *Nature Reviews Earth and*
 329 *Environment*, 5(4), 244–246, doi:10.1038/s43017-024-00536-y.

330 Sato, H., K. Takemura, A. Ito, T. Umeda, S. Maeda, Y. Tanimoto, M. Nonaka, and H.
 331 Nakamura, 2024: Impact of an unprecedented marine heatwave on extremely hot
 332 summer over Northern Japan in 2023. *Sci. Rep.*, 14, doi:
 333 <https://doi.org/10.1038/s41598-024-65291-y>.

334 Sato, N., T. Horinouchi, and Y. Kawatani, 2026: Recent extreme heat events with high
 335 wet-bulb temperature in Tokyo exacerbated by moisture supply from the ocean. *J.*
 336 *Meteor. Soc. Japan*, 104, 9, doi: <https://doi.org/10.1007/s44394-025-00010-3>.

337 Speizer, S., C. Raymond, C. Ivanovich, and R. M. Horton, 2022: Concentrated and
 338 intensifying humid heat extremes in the IPCC AR6 regions. *Geophys. Res. Lett.*, 49,
 339 e2021GL097261, doi: <https://doi.org/10.1029/2021GL097261>.

340 Takahashi, H. G., S. A. Adachi, T. Sato, M. Hara, X. Ma, and F. Kimura, 2015: An Oceanic
 341 Impact of the Kuroshio on Surface Air Temperature on the Pacific Coast of Japan in

Summer: Regional H₂O Greenhouse Gas Effect. *J. Climate*, 28, 7128–7144,
doi:10.1175/JCLI-D-14-00763.1.

Takemura, K., H. Sato, A. Ito, T. Umeda, S. Maeda, M. Hirai, Y. Tamaki, H. Murai, H.
Nakamigawa, Y. N. Takayabu, H. Ueda, R. Kawamura, Y. Tanimoto, H. Naoe, M.
Nonaka, T. Hirooka, H. Mukougawa, M. Watanabe, and H. Nakamura, 2024:
Preliminary Diagnosis of Primary Factors for an Unprecedented Heatwave over
Japan in 2023 Summer. *SOLA*, 20, 69–78, doi:10.2151/sola.2024-010.

Wie, J., Moon, B. K., Hyun, Y. K., and Lee, J., 2021: Impact of local atmospheric
circulation and sea surface temperature of the East Sea (Sea of Japan) on heat waves
over the Korean Peninsula. *Theoretical and Applied Climatology*, 144, 431–446,
doi:10.1007/s00704-021-03546-8.

World Meteorological Organization, 2025: 2025 set to be second or third warmest year
on record, continuing exceptionally high warming trend. (Available online at:
[https://wmo.int/media/news/2025-set-be-second-or-third-warmest-year-record-](https://wmo.int/media/news/2025-set-be-second-or-third-warmest-year-record-continuing-exceptionally-high-warming-trend)
[continuing-exceptionally-high-warming-trend](https://wmo.int/media/news/2025-set-be-second-or-third-warmest-year-record-continuing-exceptionally-high-warming-trend), accessed 15 Apr 2026)

Figure Legends

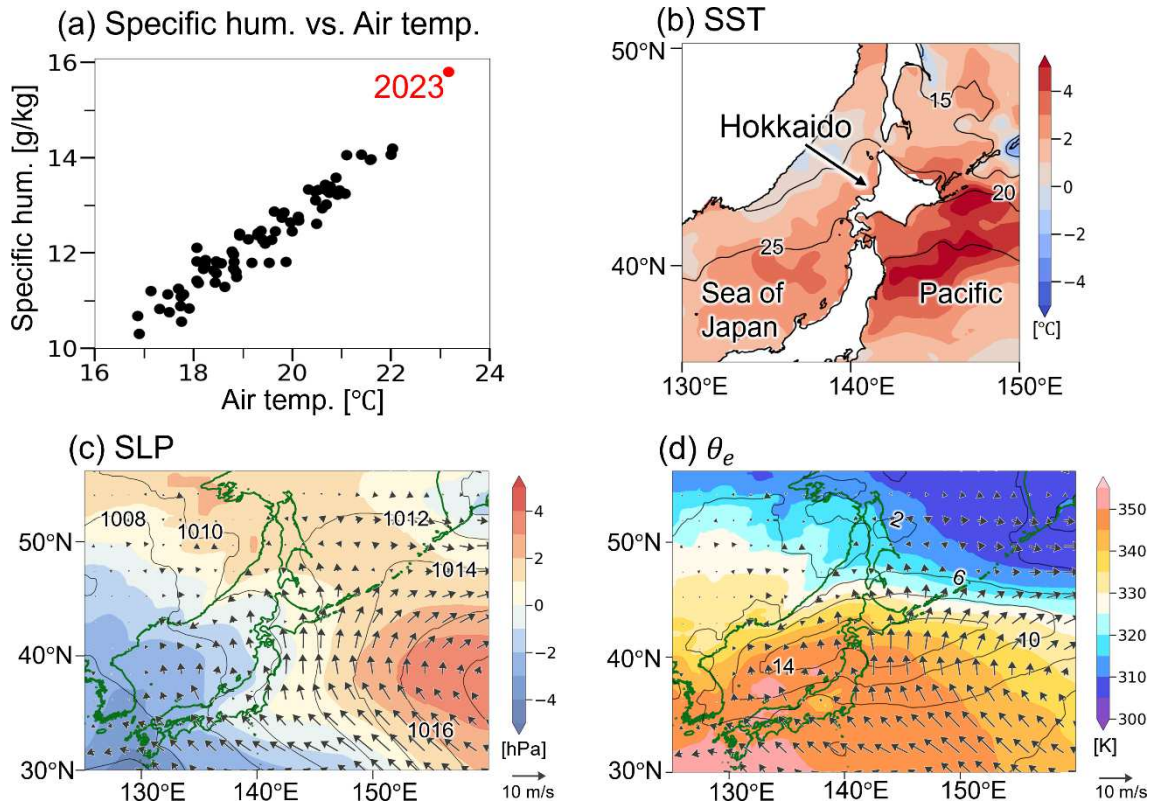


Fig. 1. (a) Scatter plot of monthly mean 2-m air temperature and 2-m specific humidity over Hokkaido (41° – 46° N, 139° – 146° E) in August during 1991–2023. (b) Monthly mean SST (contours) and its anomaly (shading) in August 2023. (c) Monthly mean sea level pressure (contours), its anomaly (shading), and horizontal wind vectors at 10-m height in August 2023. (d) Equivalent potential temperature (θ_e ; shading), its anomaly (contours), and horizontal wind vectors at 975 hPa in August 2023.

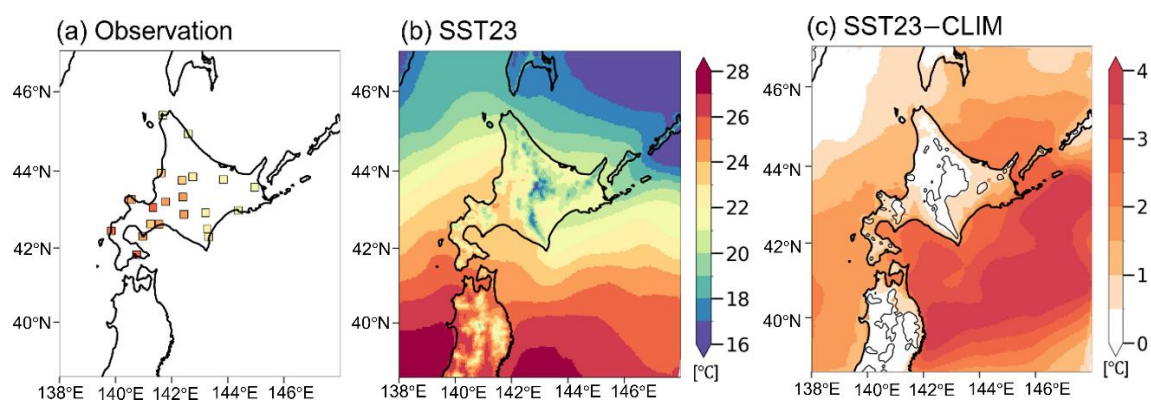


Fig. 2. (a) August mean WBGT in Hokkaido estimated from Automated Meteorological Data Acquisition System observations, (b) August mean WBGT under SST23 conditions, and (c) difference in WBGT between SST23 and CLIM (shading), with 500-m elevation contours.

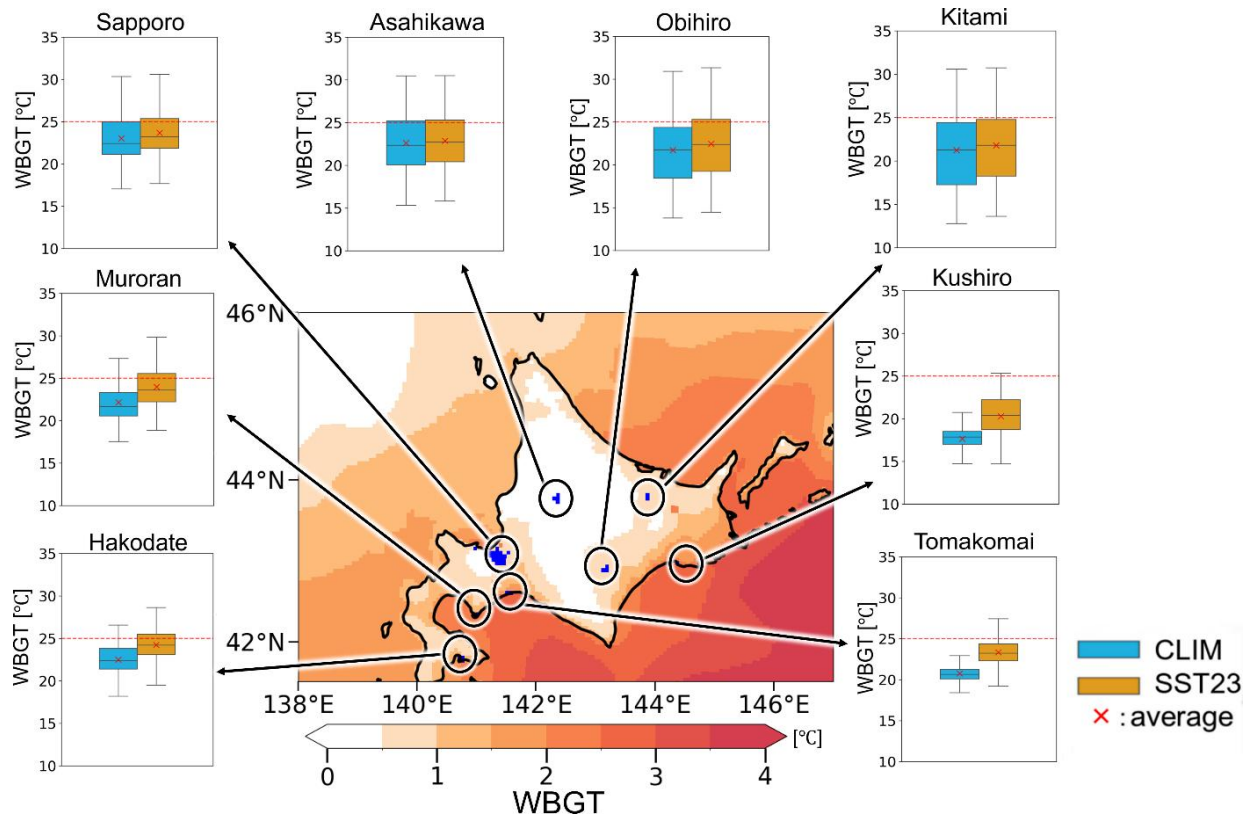


Fig. 3. Comparison of WBGT in regions with high population exposure. WBGT for CLIM and SST23 are shown in blue and orange, respectively. Boxes in the box-and-whisker plots illustrate the interquartile range of hourly values, with lines indicating the median and red crosses representing the average. Red dashed line signifies the heatstroke warning threshold of 25 °C set by the Ministry of the Environment.

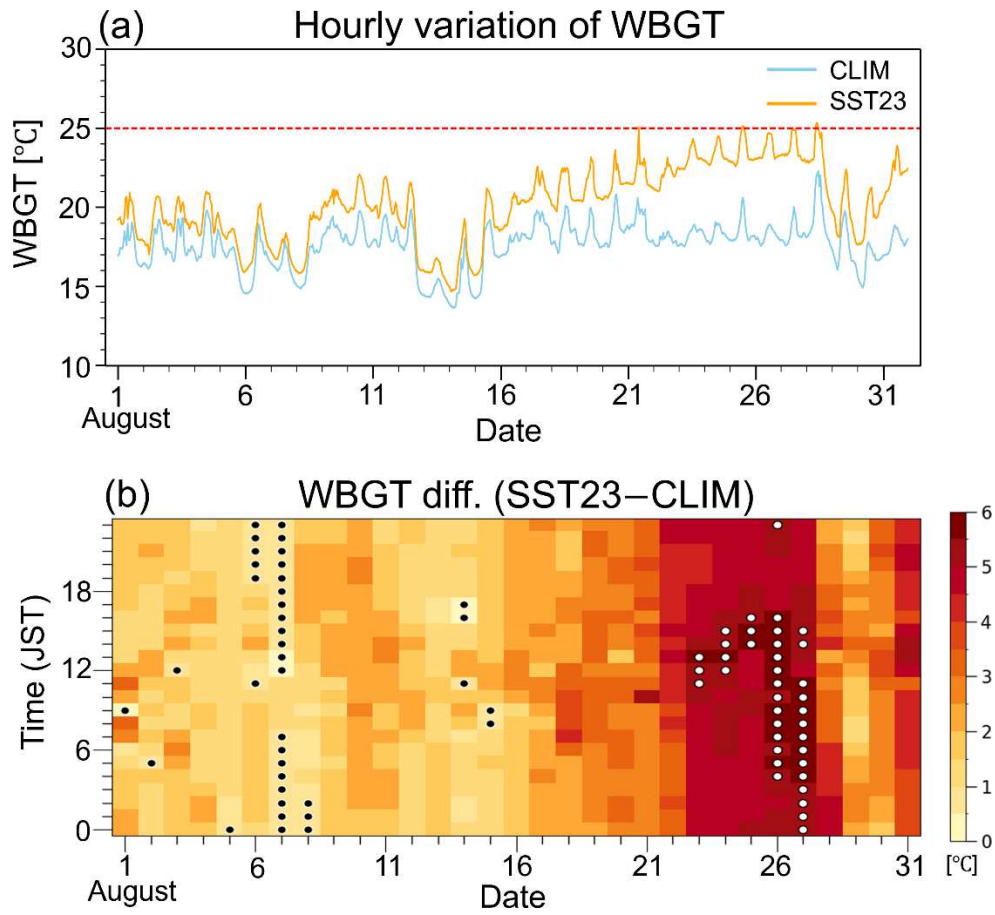
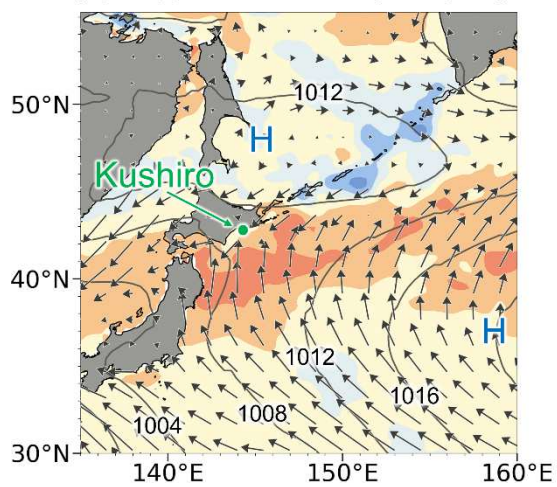


Fig. 4. (a) Hourly WBGT at Kushiro for SST23 (orange) and CLIM (light blue). Red dashed line indicates the heatstroke warning threshold of 25 °C. (b) Hourly difference in WBGT (SST23-CLIM) at Kushiro. The largest and smallest 5% of WBGT differences are indicated by white and black dots, respectively.

(a) Suppression case (7 August)



(b) Amplification case (26–27 August)

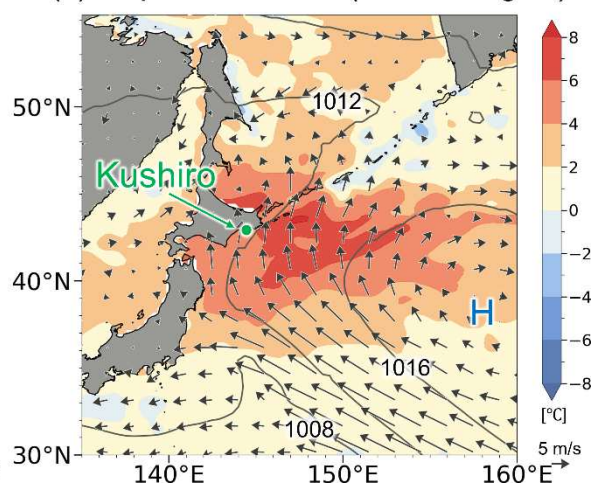


Fig. 5. Sea level pressure (contours), SST anomalies (shading), and wind vectors for (a) 7 August and (b) 26–27 August 2023.

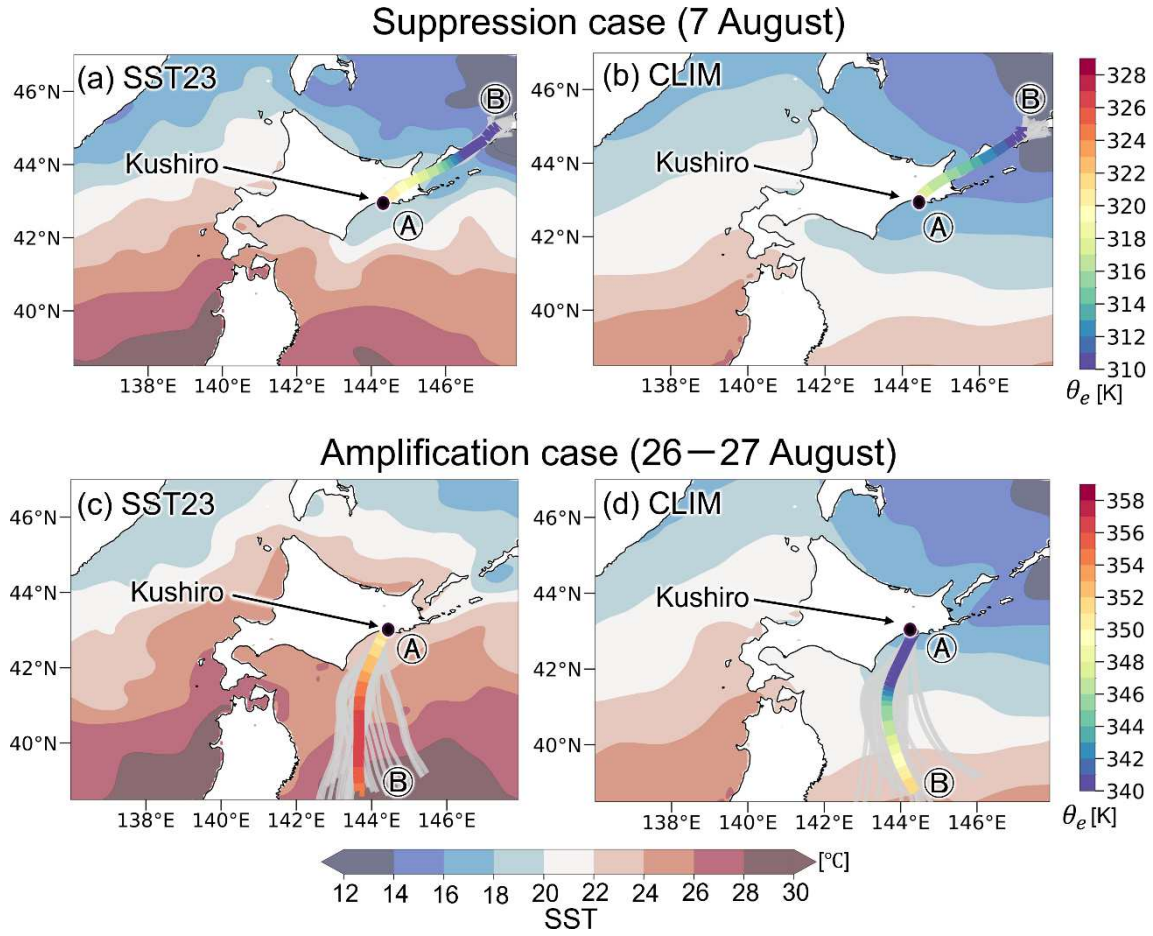


Fig. 6. Backward trajectories of air parcels from 10-m height at Kushiro, traced up to 18 h. (a) SST23 and (b) CLIM for the suppression case, and (c) SST23 and (d) CLIM for the amplification case. Shading represents the mean SST for each case. Colored solid lines indicate the mean trajectories of air parcels for each case; gray lines show individual trajectories from each time step. Color of the mean trajectory corresponds to the mean equivalent potential temperature. A and B indicate the starting and ending points of the mean trajectories, respectively.

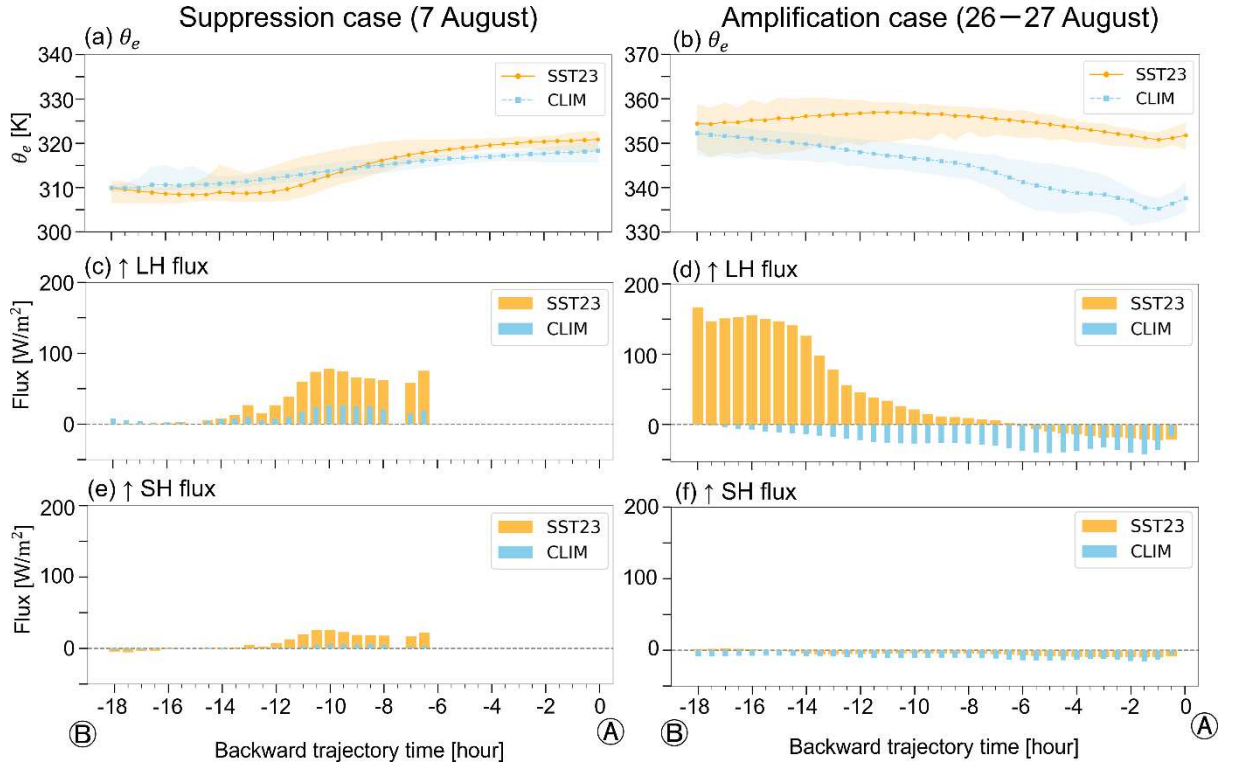


Fig. 7. Temporal variations in equivalent potential temperature (θ_e) and surface heat fluxes along the mean backward trajectories of air parcels arriving at 10-m height over Kushiro, traced back 18 h (see Fig. 6). (a), (b) Equivalent potential temperature along the trajectories for the suppression and amplification cases, respectively (SST23: orange; CLIM: light blue). Shaded areas represent the envelope defined by the minimum and maximum values among the samples. (c), (d) Upward latent heat flux and (e), (f) upward sensible heat flux along the mean trajectories for the suppression and amplification cases, respectively.

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