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Recent advances in mid-latitude atmosphere-ocean-marine ecosystem interactions in a changing climate: From Climatic Hotspot2 to Habitable Japan

Eitarou Oka[1*] and Masami Nonaka[2]

[1]Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, Japan

[2]Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

[*]Corresponding author. E-mail: eoka@aori.u-tokyo.ac.jp; Tel: +81-4-7136-6042

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Abstract

This article reviews recent achievements in the study of mid-latitude atmosphere-ocean-marine ecosystem interactions from two Japanese research programs: the *Climatic Hotspot2* project (FY2019–2023) and the first two years of the *Habitable Japan* project (FY2024–2028). Understanding of the mid-latitude ocean-atmosphere interactions, particularly the ocean's influence on the atmosphere established in the *Climatic Hotspot1* project (FY2010–2014), has advanced through the two projects addressing changing climate and oceanic/atmospheric extreme events, such as the longest observed Kuroshio large meander from 2017 to 2025, northward meandering of the upstream Kuroshio Extension in 2023–2024, marine/atmospheric heatwaves, heavy rainfall and snowfall, and tropical cyclones. Relations between weather and its extremes over East Asia and global climate variations have also been clarified. Both projects have conducted and are conducting in-situ observation campaigns to clarify various processes in the ocean, atmosphere, and their interactions and improve numerical models. By incorporating atmospheric/marine chemistry, marine ecosystems, and fisheries as new research domains and putting more emphasis on prediction, the *Habitable Japan* project aims to answer the main question: Will mild climate and abundant water/fisheries resources persist as a basis of survival for those of us living in Japan in the future?

1. Introduction

In the tropical regions, variability of the ocean and the atmosphere is well known to tightly interact with each other to induce combined interannual variability such as El Niño/Southern Oscillation (Bjerknes 1969) and the Indian Ocean Dipole (Saji et al. 1999). Oceanic variability there induces sea surface temperature (SST) anomalies in a high SST range, a slight amount of which can affect atmospheric convection to trigger the combined variability. In contrast, it had been believed that in mid-latitudes the ocean only responds passively to atmospheric variability, and interannual variability over the mid-latitude North Pacific and its predictability come from the tropical Pacific. For example, when El Niño develops in the tropical Pacific, sea surface westerly winds are intensified and the enhanced upward surface heat flux lowers SST over the mid-latitude North Pacific (Alexander 1992), resulting in a negative correlation between the anomalies of the surface wind speed and SST.

In the early 2000s, high spatial resolution oceanic/atmospheric observations and simulations became available thanks to the development of satellite observations and high-performance computing, enabling us to discover the active roles of mid-latitude oceans in the ocean-atmosphere variability (Nonaka and Xie 2003; Nakamura et al. 2008; Minobe et al. 2008). For example, SST anomalies induced by variability of strong currents and mesoscale eddies can be correlated positively with surface wind speed anomalies, contrasting with the abovementioned relation observed on a large scale (Nonaka and Xie 2003). Since then, numerous studies have described mid-latitude ocean-atmosphere interactions and clarified their mechanisms, indicating the importance of the strong western boundary currents, their extensions, and the associated SST frontal zones (Small et al. 2008; Chelton and Xie 2010; Kwon et al. 2010; Nakamura et al. 2015; Czaja et al. 2019; Seo et al. 2023). In the international movement of investigating mid-latitude oceanic/atmospheric variability and their interactions, the MEXT (Ministry of Education, Culture, Sports, Science and Technology) Kakenhi Grant-in-Aid for Scientific Research on Innovative Areas “Multi-scale air-sea interaction under the East-Asian monsoon: A ‘hot spot’ in the climatic system” project (FY2010–2014; Nakamura et al. 2015; https://www.atmos.rcast.u-tokyo.ac.jp/hotspot/index_eng.html), later nicknamed the *Climatic Hotspot1* project, was launched nationwide in Japan, followed by similar projects in China and Europe (e.g., Xie 2013; Révelard et al. 2016). Through this project, the western boundary current regions were recognized as the hotspots of the mid-latitude climate.

In the 2010s, during and just after the end of the *Climatic Hotspot1* project, SST warming accelerated especially around Japan (Miyama et al. 2021; Minobe 2025), and extreme precipitation events became more frequent (Fujibe 2015). This motivated us to launch the Grant-in-Aid for Scientific Research on Innovative Areas “Mid-latitude ocean-atmosphere interaction hotspots under the changing climate” project (FY2019–2023; Nonaka et al. 2025; https://www.jamstec.go.jp/apl/hotspot2/index_e.html). This project, nicknamed the *Climatic Hotspot2* project, aimed to advance our understanding of the mid-latitude ocean-atmosphere interactions and to investigate how the interactions influence extreme events such as typhoons, heavy precipitation, and atmospheric heatwaves, demonstrating socioeconomical importance of understanding the interactions.

In recent years, socioeconomical activities in Japan have been further affected by ocean extremes. A large-meander path of the Kuroshio south of Japan (Fig. 1) occurred in summer 2017 and lasted beyond the historical record of 4 years and 8 months in 1975–1980, impacting fisheries in various ways (Kusaka et al. 2021). In 2023 the upstream Kuroshio Extension (KE) east of Japan (Fig. 1) meandered anomalously to the north, and the resultant marine heatwave (MHW) affected the record-breaking hot summer over northern Japan (Takemura et al. 2024; Sato et al. 2024). These events boosted us to seamlessly start the MEXT Kakenhi Grant-in-Aid for Transformative Research Areas (A) “Habitable Japan: Sustainability of atmospheric and oceanic environment as a survival basis of island country Japan” project (FY2024–2028; https://hotspot3.aori.u-tokyo.ac.jp/). In the *Habitable Japan* project, we have expanded the research domain to atmospheric/marine chemistry, marine ecosystems, and fisheries and have put more emphasis on prediction, aiming to answer the main question: Will mild climate and abundant water/fisheries resources persist as a basis of survival for those of us living in Japan in the future?

This paper summarizes representative achievements from the *Climatic Hotspot2* project and earlier results from the first two years of the *Habitable Japan* project. It also complements the preface (Nonaka et al. 2025) of the *Special Section on Midlatitude ocean-atmosphere interactions and extreme events*, which appeared in Issues 1, 3, 5, and 6 of Volume 81 (2025) of Journal of Oceanography as a collection of outputs from the *Climatic Hotspot2* project. This is because when the preface was published, most of the papers contained in the Special Section had not been accepted. In the following part, the papers from the Special Section are marked with an asterisk (*).

In this paper, an emphasis is put on in-situ observation campaigns under the *Climatic Hotspot2* and *Habitable Japan* projects, which characterize these projects. In the *Climatic Hotspot1* project, we conducted a simultaneous observation by three vessels in July 2012 to investigate the responses of the marine atmospheric boundary layer and low-level clouds to the KE front (Kawai et al. 2015, 2017; Kobashi et al. 2016; Nishikawa et al. 2016), and occupied a quasi-zonal hydrographic section along ~41ºN in April 2013 to examine the atmospheric response to the Oyashio and the formation of Central Mode Water (Kawai et al. 2019; Oka et al. 2020). To further understand various processes in the atmosphere, ocean, marine ecosystems and their interactions and improve numerical models, observation activities around Japan have been expanded in terms of season, area, parameter, and platform in association with modeling activities in the *Climatic Hotspot2* and *Habitable Japan* projects.

Section 2 introduces progress in mid-latitude ocean-atmosphere interactions, and Section 3 presents studies on the relation between the interactions and extreme events. Section 4 demonstrates results on the relation between weather and its extremes over East Asia and global climate variations. Section 5 provides outlooks.

2. Progress in mid-latitude ocean-atmosphere interactions

2.1. Impacts of oceanic frontal zones on the atmosphere

Mid-latitude oceanic frontal zones associated with strong currents affect the atmospheric storm activity by generating lower-atmospheric baroclinicity (Nakamura et al. 2008). In our research projects, the importance of oceanic frontal zones in mid-latitude air-sea interactions has been further demonstrated. Nakayama et al. (2021) found the impact of a mid-latitude oceanic frontal zone on the baroclinic annular mode (BAM), a major annular variability of extratropical eddy activity in the Southern Hemisphere. Their idealized numerical model experiments indicated that while the BAM is essentially caused by atmospheric internal dynamics, the BAM variability is amplified by a mid-latitude oceanic frontal zone by restoring atmospheric near-surface baroclinicity. Furthermore, the positive phase of the BAM is characterized by higher correlation between temperature and meridional wind fluctuations associated with transient disturbances and by meridionally more elongated disturbances, enhancing baroclinic development of the disturbances on a hemisphere scale (Nakayama et al. 2023). Ogawa and Spengler (2024) quantified the influence of mid-latitude SST fronts on the atmospheric water cycle and storm track activity. Their aqua-planet atmospheric general circulation model experiments clarified that the SST front determines the latitude of eddy moisture convergence and the associated diabatic heating, thereby energizing and anchoring the storm track. In addition, the strength of the SST gradient regulates the overall intensity of the water cycle and storm track.

It has also been revealed that surface wind convergence and precipitation are enhanced in their climatological fields around the mid-latitude western boundary currents and the associated SST frontal zones (O'Neill et al. 2003; Minobe et al. 2008; Masunaga et al. 2015). Focusing on daily scale atmospheric processes around the KE, Masunaga et al. (2020) demonstrated that a zonally extending narrow band of moderate surface wind convergence frequently emerges along the KE, and latent heating associated with ascent induced by the convergence contributes dominantly to the climatological structure. Regarding the enhanced activity of synoptic-scale, sub-weekly atmospheric disturbances along the oceanic frontal zones associated with the KE and the Gulf Stream, Okajima et al. (2024) quantified that precipitation exceeds evaporation within cyclonic domains and evaporation dominates within anticyclonic domains with the net moisture transport from anticyclonic to cyclonic domains in winter climatology, indicating that oceanic frontal zones strengthen the hydrological cycle.

The influences of the ocean on the atmosphere extend beyond the troposphere. Ando and Mochizuki (2025*) found that the Arctic sea ice influences the late-November bimodal behavior of the polar night jet, a strong stratospheric westerly wind, particularly whether it weakens or remains intense by modulating upward Rossby wave propagation. Kawatani et al. (2024) indicated that mid-latitude SST fronts can affect zonal jet strength in the mesosphere, suggesting that climate models with sufficiently high resolutions in their atmospheric and oceanic components can reduce model biases in the middle atmosphere.

In addition to the oceanic frontal zones, oceanic mesoscale eddies affect SST and the surface heat flux. Miyaji et al. (2025*) investigated the impact of mesoscale eddies on the surface heat flux from the ocean to the atmosphere over the North Pacific using an eddy detection method based on curvature vorticity (Okajima et al. 2021), and revealed net heat release from the ocean due to asymmetries in number, size, and amplitude of the associated heat flux anomalies between warm and cold eddies. They suggested that as warm (cold) eddies tend to appear more frequently on the cold (warm) side of the SST frontal zone, eddies reduce the impact of the SST frontal zone on the atmosphere by weakening the surface heat flux contrast across the zone.

Given the importance of mid-latitude oceanic frontal zones and mesoscale eddies associated with the strong western boundary currents such as the KE and the Gulf Stream, their dynamics and potential predictability have been explored. Considering the influence of oceanic intrinsic variability (Nonaka et al. 2012, 2020), an ocean prediction system was developed using an eddying ocean general circulation model initialized by an ocean reanalysis data produced by the same ocean model (Kido et al. 2022). With this system, frontal scale variability in the KE and the Gulf Stream and the associated eddy activities can be predicted with a lead time of 1–2 years (Kido et al. 2023).

2.2. Mode waters

Mode waters are characterized by its small vertical density gradient within or near the top of the permanent thermocline and are widely distributed in mid-latitude oceans (Hanawa and Talley 2001). They are formed as deep winter mixed layers and subducted to the permanent thermocline with temperature anomalies of the winter, and have been expected to be reentrained into the mixed layer in a remote area in the following winters to affect SST there. Recently, a new mechanism by which mode waters affect SST was proposed. By analyzing summer observations at the 137°E repeat hydrographic section south of Japan (Oka et al. 2018), Kobashi et al. (2021) demonstrated that thicker Subtropical Mode Water (STMW; Masuzawa 1969) is associated with a shallower seasonal thermocline on decadal timescales as STMW adjusts to conserve the potential vorticity (Xie et al. 2011). By shoaling the upper thermocline, a thick STMW lowers not only the near-surface temperature but also the mixed layer temperature (Kobashi et al. 2023) and even reduce typhoon intensity (Oka et al. 2023; Fig. 2). The shoaling effect has also been shown to influence the near-surface biogeochemical structure and primary production in the euphotic layer by the summer 137°E observation (Ono et al. 2025) and numerical simulation (Ogata et al. 2025*) as well as by shipboard and Argo profiling float observations in the North Atlantic (Nishikawa et al. 2025*). The important aspects of this mechanism are that mode waters can affect SST, or near-surface biogeochemical parameters, even without being reentrained into the mixed layer, and that it is the thickness (or potential vorticity) of mode water rather than its temperature that affects SST.

The STMW circulation has also been explored by using radiocesium (Kumamoto et al. 2014; Kaeriyama et al. 2014; Yoshida et al. 2015), which was released by the accident of the Fukushima Dai-ichi Nuclear Power Plant (FNPP1; Fig. 1) due to the 2011 off the Pacific coast of Tohoku Earthquake and 11th and the resultant huge tsunami (Aoyama et al. 2016a,b; Buesseler et al. 2017). Based on measurements in the western North Pacific in 2015–2021, Kumamoto et al. (2025*) demonstrated that temporal changes in the inventory of the FNPP1-derived radiocesium over that period were consistent with the renewal time of STMW estimated by Suga et al. (2008). Moreover, they observed the FNPP1-derived radiocesium in the tropical part of the 137°E section for the first time. This radiocesium was suggested to originate not from the subsurface STMW in the western subtropical North Pacific but from the surface water in the subarctic/subtropical boundary area in the eastern North Pacific.

Decadal variability of STMW volume is closely related to that of the KE between its stable and unstable states that lags the wind forcing over the central North Pacific related to the Pacific Decadal Oscillations (PDO; Mantua et al. 1997) by 3–4 years (Qiu and Chen 2005; Qiu et al. 2007; Oka et al. 2015, 2019). In contrast, decadal volume variability of CMW (Nakamura 1996; Suga et al. 1997) is shown to be correlated with the PDO-related wind forcing over the central North Pacific with no time lag (Iwasaka et al. 2024). Counterintuitively, when CMW is thicker on decadal timescales, it is warmer and more saline than average, because its formation region expands to the south (Iwasaka et al. 2025*). Through the effect on the upper thermocline, a decline in CMW thickness contributed to the occurrence of intense MHW over the central North Pacific in summer 2021 (Nishihira and Sugimoto 2024).

The area east of Japan is characterized by several fronts (Kida et al. 2015), high mesoscale eddy activity (Ducet and Le Traon 2001; Qiu 2002), and complex distribution of mode waters including STMW and CMW (Oka et al. 2011, 2020). Sambe and Suga (2022) demonstrated that machine learning is a useful tool for analyzing enormous amount of temperature and salinity profiles from Argo profiling floats (Wong et al. 2020) to classify mode waters in this area. Among the fronts in this area, two quasi-stationary jets, called J1 and J2 (Fig. 1), transport warm and saline subtropical waters to the subarctic regions (Isoguchi et al. 2006). As a mechanism for transporting the Kuroshio water to the starting point of J1 or J2 around 40ºN, the time fluctuations of KE are essential for J1 (Nishikawa et al. 2021; Matsuta and Mitsudera 2023), while the northern branch of the KE is the dominant pathway for J2 (Matsuta et al. 2025*). In addition, decadal variability in SST and upward surface turbulent heat flux in the transition domain around J1 and J2 is affected by variability of the Kuroshio water intrusion (Matsuta et al. 2025*).

In the *Climatic Hotspot2* project, STMW and its associated biogeochemical processes were also investigated using Argo Profiling floats equipped with biogeochemical sensors (hereafter called BGC floats), which are a powerful tool to explore the physical and biogeochemical processes and their relations in the upper ocean and across the sea surface (Riser and Johnson 2008; Johnson and Claustre 2016; Hirai et al. 2021). In contrast with earlier projects around Japan that deployed BGC floats in relatively small areas such as mesoscale eddies (Inoue et al. 2016a,b; Xu et al. 2016), we broadly deployed 13 BGC floats over the STMW distribution region. Aside from one float that did not operate, 12 floats repeated observations at intervals of one day in the initial testing period and about five days after that for 371–852 (726 on average) days to collect 92–256 (181) profiles in 2021–2023 (Fig. 3a).

These floats were equipped with ARO-FT, a new optical dissolved oxygen (DO) sensor manufactured by JFE Advantech Co. Ltd., whose installation on a group of floats had never been done. Sato et al. (2025*) developed a correction method for the float DO data using shipboard DO data obtained at the float deployment and air oxygen data collected by floats at each surfacing. While ARO-FTs exhibited a temporal drift after deployment, the corrected DO data remained within ±2% of shipboard reference data 210 days after deployment. Using these corrected data, Kawai et al. (2026) examined the aging and fate of STMW. After being capped by the seasonal thermocline in spring, the upper part of STMW is entrained into the seasonal thermocline, while the remaining lower part increases its apparent oxygen utilization rapidly in the first several months and more slowly after that, reaching 50 μmol/kg in a few years. Using the same data, Kosugi et al. (2025*) quantified oxygen fluxes between the atmosphere and the ocean. Net annual surface oxygen fluxes were upward at low latitude around 25ºN, and downward at higher latitudes around and north of ~30ºN, where oxygen was significantly undersaturated in winter in association with the STMW formation (Fig. 3b). These fluxes were also found to be strongly influenced by interannually varying wind speeds in winter. Kawai et al. (2025*) analyzed observation data from the summer 2022 cruise southeast of Hokkaido (Fig. 4; Section 2.3) and from two BGC floats drifting into the cruise area (Fig. 3a) to examine the impact of the KE-related MHW (Section 3.2) on DO distribution. They found that DO concentrations decreased near the sea surface due to warming induced by the intrusion of the Kuroshio water, while it increased in the subsurface layer because the lighter Kuroshio water overlying the denser Oyashio water pushed down isopycnal surfaces.

Four out of the 12 floats were also equipped with a SeaFET pH sensor, and two of them continued pH measurements for about a year. Using DO and pH data from these floats, Ishii et al. (2026) quantified that net community production during April–September 2021 under inorganic nutrients limitation reached 3.3 ± 0.3 and 3.5 ± 0.3 mmol C m^{-2} in the upper 100 dbar of the northwestern subtropical gyre, which strongly enhanced oxygen release and suppressed CO_2 release to the atmosphere in summer, making this region a strong CO_2 sink on an annual average. They also found that the emergence of the shallow oxygen maximum that has been ubiquitously observed below the summer mixed layer was ascribed to the near-balance among net biological oxygen production and net oxygen release to the atmosphere in the shallow oxygen maximum, greater oxygen release than biological oxygen production in the surface mixed layer above, and net respiration in the aphotic layer below. Meanwhile, Yamaguchi et al. (2024) used historical DO data to estimate the annual net community production from the surface to the winter mixed layer base in the Kuroshio-Oyashio Extension region to be 0.9 mol

C m^{-2} $year^{-1}$, which implies remarkable net respiration below 100-dbar depth and/or during winter.

2.3. Low level clouds

Low-level clouds are prevalent over eastern subtropical and mid- to high-latitude oceans. They interact with the ocean below, and have strong impacts on the Earth's radiation budget balance because they have high albedo. Because of the difficulty in projecting their future changes, low-level clouds are one of the most important sources of uncertainty in climate projections (Bony and Dufresne 2005; Stephens 2005). Koshiro et al. (2022) found that the estimated cloud-top entrainment index proposed by Kawai et al. (2017) predicts well the reduction in low-level cloud cover in the warmer climate, reducing uncertainty in climate projections.

The extensive low-level cloud deck formed in the subtropical eastern North Pacific off California has been demonstrated to have strong feedback with the underlying SST, serving as a bridge from the mid-latitude atmosphere and the tropical climate variability, making two-way interactions between the tropics and mid-latitudes (Yang et al. 2023; Miyamoto and Xie 2025). Furthermore, this low-level cloud–SST feedback was suggested to have impacts on the basin-scale ocean circulation based on numerical climate model experiments (Miyamoto et al. 2023). Specifically, reduced diabatic heating due to the low-cloud deck over the eastern North Pacific intensifies the subtropical high, and the associated wind-stress curl at the sea surface enhances the subtropical gyre and its western boundary current Kuroshio, increasing SST, upward surface turbulent heat flux, and precipitation along the Kuroshio and KE. In the western North Pacific, the base height of low-level clouds significantly changes across the SST front of the KE (Tokinaga et al. 2009; Kawai et al. 2015). Masunaga et al. (2015) revealed that the Oyashio front also affects low-level clouds by using atmospheric reanalyses, which was confirmed by shipboard and satellite observations (Kawai et al. 2019; Takahashi et al. 2021).

Low-level clouds in the summertime western North Pacific also interact with anthropogenic and natural aerosols (Sasakawa and Uematsu 2002; Sasakawa et al. 2003). Under the *Climatic Hotspot2* project, we carried out a simultaneous observation campaign of aerosols and clouds using an aircraft and a research vessel over the North Pacific southeast of Hokkaido in July–August 2022, for the first time in this area (Koike et al. 2025; Fig. 4). The purpose of this experiment was to characterize the physical and chemical properties of aerosols and to evaluate the contributions of anthropogenic and natural emissions to cloud condensation nucleus and ice-nucleating particle concentrations. The experiment also aimed to examine the vertical structure of low-level clouds.

Using seawater samples collected between the sea surface and 100-m depth at eight hydrographic stations, Yoshida et al. (2024) evaluated the applicability of a complex amplitude sensor (CAS; Moteki 2021; Moteki et al. 2023) for particle-sizing and characterization of oceanic suspended particulate matter that plays important roles in the coupling of climate and biogeochemical cycles via ocean-atmosphere interactions. The CAS-derived suspended particulate matter was classified into five major types, which were attributed mainly to diatom fragments, carbonaceous materials (likely organic matter), mineral dusts, iron oxides, and black carbon. The CAS was also applied to aerosol samples collected at 0.2–8 km altitudes in eight flights to measure the number concentrations and size distributions of mineral dust particles, which influence climate by scattering and absorbing solar and terrestrial radiation and acting as ice nuclei (Ohata et al. 2025). The average number concentration of mineral dust was 2–3 orders of magnitude lower than previously reported values near the major dust sources in East Asia, a value that was difficult to quantify using conventional methods. In addition, Adachi et al. (2025) used transmission electron microscopy for aerosol samples collected between the sea surface and 8km altitude from both the flights and cruise to characterize individual aerosol particles from different altitudes in East Asia. Their analysis revealed a wide range of compositions and mixing states of particles, both of which affect aerosol climate effects. The samples in the first period had high sea salt and mineral dust fractions, those in the second period had high fractions of potassium-bearing particles with organics and black carbon from biomass burning, and those in the last period were influenced by both sea spray and biomass burning. The overview of the campaign and other preliminary results obtained from the observation data and the associated numerical model experiments were summarized in Koike et al. (2025).

3. Mid-latitude ocean-atmosphere interactions and extreme events

Based on the understanding of mid-latitude ocean-atmosphere interactions, including those introduced in Section 2, investigations into the relation between mid-latitude ocean-atmosphere interactions and extreme events in the atmosphere and ocean have been developing. Under the changing climate, these studies are crucial for deepening our knowledge about the mechanisms behind the extreme events and using the knowledge to benefit society.

3.1. Tropical cyclones

In addition to the well-known concept that tropical cyclone (TC) activities are strongly influenced by tropical and subtropical SSTs, Nasuno et al. (2022) demonstrated that positive SST anomalies over the mid-latitude western North Pacific in the boreal summer of 2018 modulated the TC track density via large-scale atmospheric responses to those anomalies. The Kuroshio also intensifies TCs by releasing heat and water vapor to the overlying atmosphere (Kawakami et al. 2022). Moreover, Fujiwara et al. (2020a,b) found that the Kuroshio can affect the development of TCs remotely. In autumn, when low-level northeasterly winds blow over the Kuroshio toward TCs being far from and approaching Japan, water vapor evaporated from the Kuroshio south of Japan and transported to the core of the TCs can enhance the TC development. Through this mechanism, SST variability in the Kuroshio south of Japan can also affect the development of remote TCs (Fujiwara and Kawamura 2021). Similar remote influence of warm SST on the TC development was also found in the North Atlantic in association with the Gulf Stream (Fujiwara and Kawamura 2023b) and warm eddies around the Gulf Stream (Fujiwara and Kawamura 2023a).

The distance between the location of TC's lifetime maximum intensity and the nearest landmass exhibited a trend toward decrease during the last 40 years, implying an increased threat to society (Wang and Toumi 2021). By analyzing output data from both atmosphere-only and coupled atmosphere-ocean global model simulations conducted under the CMIP6 HighResMIP protocol (Haarsma et al. 2016) as part of the PRIMAVERA project, Ogawa et al. (2025) suggested that the trend is more likely attributable to natural variability in the background winds associated with the PDO or the Interdecadal Pacific Oscillation (Power et al. 1999) rather than anthropogenic warming.

While TCs develop more efficiently over high SST, they tend to induce SST cooling below their tracks, suppressing their intensity (Chang and Anthes 1979; Bender et al. 1993). Simulating local ocean-atmosphere coupling is thus important for understanding the TC development under the changing climate (Kanada and Aiki 2024). Iida et al. (2023) demonstrated that the SST cooling by TCs depends on not only the ocean conditions but also the TC characteristics, which are reasonably represented by Miyamoto et al.'s (2017) cooling parameter. Accuracy of SST products is also crucial for understanding the TC-related air-sea interactions. Nakada and Tomita (2025*) compared six satellite-based SST products and in-situ observations to find non-negligible SST biases associated with TC passages, except for J-OFURO3 (Tomita et al. 2019) that is calculated as the ensemble median of multiple SST products without spatiotemporally interpolated data. They demonstrated that the inclusion of satellite instantaneous data along with spatiotemporally interpolated products as ensemble members in J-OFURO3 reduces spatiotemporal variations in bias, enabling a more reliable representation of oceanic response to TCs. Furthermore, Tomita and Wada (2026) successfully estimated near-surface specific humidity in the vicinity of TC centers, where satellite-based retrieval has been difficult, by combining low-frequency satellite microwave radiometer channels with a neural network approach. These advances contribute to more accurate estimates of surface heat fluxes, which are essential for understanding TC-ocean interactions.

TCs approaching the southern coast of western Japan have been recently shown to cause atmospheric heatwaves in western Japan (Takahashi et al. 2026). In contrast to typical dry heatwaves caused by westward extension of the subtropical high under sunny conditions, TC-related "moist heatwaves" can occur even under cloudy conditions. Furthermore, the frequency of such moist heatwaves has increased over the past 30 years, possibly due to enhanced tropical influences.

3.2. Marine heatwaves

From the late 2010s, extremely warm conditions have been observed in the North Pacific, particularly in the Kuroshio-Oyashio region (Fig. 5a). Minobe (2025*) descried their properties and development considering not only SST anomalies but also upper ocean heat content to the 300-m depth. The warm anomalies were suggested to be induced by the northward shift of the boundary between the subtropical and subpolar gyres by the Sverdrup theory (Minobe 2025*) and by eddying ocean general circulation model experiments (Sasaki et al. 2025*). Consistently, the KE shifted northward by nearly 200 km during 1993–2021 due to the trend in the atmospheric field (Kawakami et al. 2023). In addition, the Oyashio water east of Japan had a trend toward decrease with interannual variability during 1982–2016, possibly reflecting the distribution of anticyclonic eddies that block the southward intrusion of the Oyashio (Kawakami et al. 2025*).

Furthermore, in 2023–2024, the upstream KE east of Japan meandered northward to an unprecedented extent in the era of satellite altimeter sea surface height measurement since 1993 (Ducet et al. 2000), producing SST anomalies exceeding +6ºC with enhanced upward surface turbulent heat flux and subsurface temperature anomalies as high as +10ºC off the Sanriku coast (Fig. 5b,c; Sugimoto et al. 2025*; Minobe 2025*; Fujishima et al. 2025*). This intense MHW weakened vertical stratification of the lower atmosphere, reducing low-level clouds aloft to further enhance SST anomalies (Sato et al. 2024). Using regional atmospheric model simulations, Okajima et al. (2025) quantified the impact of the MHW on the record-breaking 2023 East Asian summer heatwave (Sato et al. 2024; Takemura et al. 2024) as a compound hot-humid extreme. They demonstrated that in addition to the large-scale circulations, the prominent MHW further amplified the land heatwave as compounding high temperature and humidity by strengthening the surface radiation through changes in cloud and water vapor. They also indicated that the recent warming of the oceans around East Asia (Sato et al. 2024; Minobe 2025*) contributed to the amplification of the 2023 summer heatwave.

Through enhanced upward surface turbulent heat flux, MHWs also induce local weather extremes in Japan. The abovementioned KE-related MHW caused the record-breaking heavy rainfall in Chiba Prefecture in September 2023 (Hirata et al. 2025a) and the record-breaking heavy snowfall in Obihiro, Hokkaido in February 2025 (Hirata et al. 2025c). Warm SST associated with an anticyclonic eddy southeast of Hokkaido also enhanced heavy rainfall associated with Typhoon Hagibis (2019) along the eastern coast of the northeastern Japan (Iizuka et al. 2021). Furthermore, abnormally high SST anomalies of ~ +4ºC over the Japan Sea, together with the terrain effect of the mountain ranges of central Japan, caused an extreme rainfall event on the Japan Sea side of Japan in association with the passage of Typhoon Lan (2023) (Tsujino et al. 2024).

Regarding the MHW observed in the Gulf of Alaska in 2014–2015, called the Blob (Bond et al. 2015), Niinuma and Yasuda (2025*) revealed that warm and low-salinity anomalies formed in the central North Pacific in 2011–2012 propagated eastward and reached the Gulf of Alaska in early 2014 after being warmed by enhanced surface heat flux, reduced entrainment, and meridional heat advection. The eastward propagation of warm signal is consistent with the findings of Taguchi and Schneider (2014). Furthermore, based on a 270-year preindustrial integration of a climate model, Matsuura et al. (2025*) demonstrated that the climate modes of PDO, North Pacific Gyre Oscillation (Di Lorenzo et al. 2008), and Central Pacific El Niño (Ashok et al. 2007) underwent characteristic changes prior to the onset of MHW in the Gulf of Alaska, as suggested in previous observational and modeling studies (Di Lorenzo and Mantua 2016; Joh and Di Lorenzo 2017).

Kawakami et al. (2024) examined future changes of MHWs in the western North Pacific using high-resolution ensemble simulations that satisfactorily resolve the Kuroshio, the KE, and SST fronts. The simulation exhibited that MHWs in this region will increase and intensify toward the end of the twenty-first century in a spatially non-uniform manner. Future MHWs are less frequent and more intense in the subtropical-subarctic frontal zone with large SST variability than in other regions.

3.3. Kuroshio large meander

After a long absence since 1991 except for a one-year period in 2004–2005, a large-meander path of the Kuroshio south of Japan (Fig. 1) occurred from August 2017 through April 2025 for 7 years and 9 months, the longest period observed. This event offered a great opportunity to deepen our understanding of its mechanisms (Usui 2019) and impacts. Hirata et al. (2025b*) comprehensively reviewed the studies on the impacts of the Kuroshio large meander, including those on atmospheric heatwaves (Sugimoto et al. 2021), heavy rainfall associated with a mid-latitude cyclone (Tochimoto and Iizuka 2023), remote TC development (Fujiwara et al. 2024), and the mean precipitation in summer in the Tokai district (Sugimoto 2025*). Furthermore, the warm SST associated with the large meander and the northward meander of the upstream KE has enhanced lightning activity (Kato et al. 2025).

The Kuroshio large meander also affects subsurface ocean structure. In the region south of Japan, the warm variety of STMW formed in a local Kuroshio recirculation gyre off Shikoku survived for more than four years (Nishikawa et al. 2023), while the cold variety of STMW formed south of the KE, which occupies most of the STMW volume, has significantly decreased since the large meander began in 2017 because its westward advection was blocked by the large meander (Oka et al. 2021). Regional atmospheric model experiments demonstrated that if the Typhoon Hagibis (2019) passed over the region south of Japan in the year 2015, when the STMW thickness was at its peak, its central pressure would have been up to 9 hPa higher due to stronger SST cooling (Oka et al. 2023; Fig. 2).

The prediction accuracy of the Kuroshio is crucial for socioeconomic activities, including fisheries and marine transportation. Ohishi et al. (2025) demonstrated that ensemble forecasts based on an ensemble ocean data assimilation system more accurately captured the Kuroshio variations, particularly the transition from the non-large-meander path to the large-meander path in summer 2017, than the deterministic forecasts. The predictability limit of the ensemble forecast was estimated to be about 100–110 days, approximately one month longer than that of the deterministic forecast, indicating a significant improvement in forecast skill.

3.4. Heavy rainfall events over Kyushu

As mentioned in Section 1, heavy precipitation events have been increasing over Japan, and their frequency and severity are particularly high over Kyushu. Based on numerical experiments, Manda et al. (2022) demonstrated that the extreme heavy rainfall over Kyushu in 2017 was crucially influenced by SST warming in the East China Sea in the last four decades. They explained that the warmed SST, rather than the warmed air temperature, enhanced latent heat flux from the sea surface to intensify convection and precipitation. This mechanism agrees with that of enhanced precipitation over the Japan Sea side of Japan with cold air outbreaks above warming SST in the Japan Sea (Kawase et al. 2022). In the East China Sea, SST warming in the Kuroshio has enhanced rainfall in the Baiu rainband over the Kuroshio in June in the last four decades (Qiao et al. 2024), explaining about 35% of the enhancement (Qiao et al. 2025).

While the abovementioned studies have demonstrated that the warm ocean tends to enhance precipitation, cool SST anomalies can also affect heavy rainfall downstream. Manda et al. (2025*) investigated mechanisms of heavy rainfall event over Kyushu in August 2021 to find that cool SST anomalies in the eastern East China Sea reduced boundary layer mixing and helped maintain high convective available potential energy inflow (Tuckman et al. 2023), while warm SST anomalies in the northern East China Sea intensified mesoscale disturbances, together enhancing heavy precipitation over northern Kyushu. This provided us with a new perspective on air-sea interactions associated with complex SST distributions.

Mesoscale convection systems (MCSs) often occur in the Baiu frontal zone and can lead to disasters such as floods and landslides due to heavy rainfall. To deepen understanding of development mechanism of MCSs that occur over the East China Sea and bring heavy rainfall to Kyushu, we conducted intensive air-sea observations in the East China Sea southwest of Kyushu on June 19, 2022 by three research vessels under the *Climatic Hotspot2* project (Manda et al. 2024; Fig. 4), and observed two MCSs (Nakashita et al. 2024). The first one was accompanied by an atmospheric mesoscale disturbance, while the second one was induced by the boundary layer destabilization over the warm Kuroshio. Assimilating radiosonde data into ensemble simulations significantly improved the reproducibility for the first MCS, but hardly improved it for the second one, indicating that the predictability of MCSs over the East China Sea depends on the development mechanism, and that the incorporation of uncertainties in both the atmosphere and ocean are important for the ensemble forecasting of MCSs (Nakashita et al. 2024). The intensive observations also revealed fine structure of salinity along the Kuroshio such as a low-salinity pool in the surface layer and subsurface low-salinity patches induced by the heavy rainfall associated with the Baiu front (Takikawa et al. 2025*).

3.5. Heavy snowfall events over the Japan Sea side of Japan

Because of the crucial impact of warm SST on cold air outbreaks and the associated heavy snowfall over and around the Japan Sea, SST warming is expected to affect heavy snowfall events. Numerical experiments for a heavy snowfall event on the Japan Sea side of Japan in December 2020 clarified that the historical SST warming enhanced precipitation associated with the event through the increase of latent heat flux from the Japan Sea (Kawase et al. 2022; Fig. 6). Furthermore, a numerical experiment under the warming climate revealed that the Japan Sea polar airmass convergence zone (JPCZ; Okabayashi 1969; Asai 1988; Murakami 2019), which is a cloud band formed in the southwestern part of the Japan Sea in association with a cold air outbreak from the Eurasian continent, would shift northward and the associated snowfall would be enhanced in the northern part of Japan (Kawano et al. 2023). Actually, Kawase et al. (2026) analyzed a 5-km dynamical downscaling dataset based on the JRA-55 reanalysis (Kawase et al. 2023) to reveal that the frequency of JPCZ events has fluctuated interdecadally, and when two high-frequency periods of 1959–1971 and 2010–2022 are compared, the JPCZ shifted northeastward and its related precipitation increased in most regions on the Japan Sea side of Japan in the latter period.

Previous numerical simulations demonstrated that the JPCZ is formed by the confluence over the Japan Sea of two northwesterly airflows that split around Mt. Paektu (West and Steenburgh 2022), although such confluence had never been captured by in-situ observations. In January 2022 and January 2023, we performed intensive shipboard observations in the Japan Sea under the *Climatic Hotspot2* project (Fig. 4). The 2022 cruise encountered the JPCZ off Shimane Prefecture, and observed a sudden change in wind direction, which indicates airflow and water vapor convergences, and a strong upward surface latent heat flux associated with the Tsushima Warm Current (TWC; Tachibana et al. 2022). Based on this result, Tachibana et al. (2022) suggested that the JPCZ has a self-sustaining mechanism that further enhances the water vapor supply from the surrounding ocean (Fig. 7). The 2023 cruise encountered the JPCZ twice, off the Oki Islands and Kyoto Prefecture, the latter of which was intense, bringing heavy snowfall over many regions of Japan (TV Asahi 2023; Manuscript entitled "Heavy snow caused by Arctic air migration to subtropic sea despite warming" by Y. Tachibana et al., submitted to *Scientific Reports*). The observation captured the largest southward migration of Arctic air over the Japan Sea. The heat flux with the moisture flux from the relatively warm ocean was equivalent to the solar constant, resulting in hurricane-level wind speeds and the formation of snow clouds extending to the tropopause.

The TWC bifurcated from the Kuroshio carries warm water of the Kuroshio origin to the Japan Sea (Fig. 1). The transport of the TWC in autumn and the precipitation over the Japan Sea side of Japan in winter were positively correlated during 1997–2005 (Hirose and Fukudome 2006), although the correlation collapsed after 2006 because the interannual variation in the TWC transport has been dominated by its offshore branch (Yokomatsu and Kida 2025*). Kida et al. (2021) demonstrated that the TWC transport has increased in association with a northward (onshore) shift of the Kuroshio path south of Japan, through sea-level rise along the southern coast of Japan that propagated anticyclonically along the coast to Kyushu as coastal trapped waves. Furthermore, Usui and Hirose (2025) proposed a mechanism that interannual-to-decadal ocean heat content variability in the Japan Sea, which controls the surface heat flux there, is forced by the KE variability including its long-term northward shift (Kawakami et al. 2023), through adjustments of the sea level along the Japanese coast and the TWC transport (Fig. 8).

4. Relation between weather and its extremes over East Asia and global climate variations

Weather extremes in East Asia including Japan are affected not only by mid-latitude air-sea interactions but also by global climate variations. To examine physical processes in global climate variability that control the interannual fluctuations in the summertime heavy rainfall in Kyushu, Mochizuki (2024b) analyzed d4PDF, a set of large-ensemble simulations using a global atmospheric model (Mizuta et al. 2017). The top 1-percentile values of summertime heavy daily rainfall were mainly associated with TC activity due to summertime SST warming over the tropical Pacific, while the top 10-percentile values were closely related to large-scale horizontal moisture transport anomalies due to changes in the North Pacific subtropical high (NPSH), which was usually accompanied by Indian Ocean basin warming (IOBW; Xie et al. 2009, 2016) subsequent to the wintertime El Niño events (Fig. 9). Mochizuki and Ando (2025) further assessed factors contributing to the decadal modulation of the relation between the NPSH and IOBW. In 1982–2001, the IOBW-related SST anomalies in the tropical Indo-Pacific Oceans, which overall represent the well-known characteristics of the Indo-western Pacific Ocean capacitor effect (Xie et al. 2016; Kosaka et al. 2021), cooperatively enhanced the NPSH. In 2002–2021, on the other hand, the suppressed and westward-shifted SST anomalies in the tropical Pacific Ocean and the resultant changes in the diabatic heating of cumulus convection suppressed the NPSH enhancement.

To investigate the multiyear potential predictability of wintertime heavy precipitation potentials in East Asia, Mochizuki (2024a) analyzed initialized decadal hindcasts of the global climate model to detect that high-latitude multidecadal variability and the so-called trans-basin variability (McGregor et al. 2014; Chikamoto et al. 2015) are the major predictive components of SST variability beyond interannual timescales. An additional analysis of d4PDF revealed that when SST around the maritime continent is higher in association with the trans-basin variability, the anomalously low pressure in the northwestern Pacific enhances low-level cold air transport due to the winter monsoon, and the resultant weaker baroclinicity in the lower atmosphere reduces storm activity and wintertime heavy precipitation potential in East Asia. Yamazaki et al. (2024) examined the impacts of large meandering of westerly jet, i.e., atmospheric blocking, over East Siberia on the JPCZ that brought heavy snowfall in Fukui in February 2018. They conducted sensitivity experiments with a mesoscale weather model using the Japanese regional reanalysis data (Fukui et al. 2024) to demonstrate that the blocking caused a large-scale southward intrusion of cold air outbreaks associated with the East Asian winter monsoon, thereby substantially contributing to the JPCZ development. For future changes of Northern Hemisphere wintertime waviness including the meandering of westerly jet, Yamamoto and Martineau (2024) analyzed the budget of local wave activity (Huang and Nakamura 2016) with HighResMIP models to demonstrate that the waviness will decrease over much of the hemisphere, which is consistent with future decrease in atmospheric blocking shown by Davini and D'Andrea (2020). This is primarily because upward surface sensible heat flux will increase in high latitudes due to sea-ice loss and decrease over mid-latitude oceans, together weakening baroclinicity and thus the low-level atmospheric meridional heat flux that is the source of local wave activity. They also presented that high-resolution models mitigate this reduction by better resolving western boundary currents and their associated surface heat fluxes, indicating that both western boundary currents and polar changes are crucial for future projections and their uncertainties.

Shiozaki et al. (2021) revealed the teleconnection patterns associated with warm and cold winters in East Asia during El Niño events. While their analysis was affected by atmospheric internal variability and could not quantitatively demonstrate the remote forcing from the tropics, Shiozaki et al. (2024) successfully suppressed the influence of internal variability by using d4PDF and quantitatively estimated the forced response from the tropical Indo-Pacific Oceans, in which the differences in the development process of El Niño are a key factor. Early developing El Niño events induce strong Indian Ocean warming, which excites the Western Pacific teleconnection pattern and leads to warmer winters in East Asia. In contrast, late developing El Niño events are accompanied by weaker Indian Ocean warming, the absence of the Western Pacific pattern, and dominance of the Pacific-North American (PNA) pattern, resulting in colder winters. In addition to the tropical oceans, extratropical oceans also affect the formation and maintenance of teleconnection patterns. By conducting coupled and uncoupled large-ensemble global model simulations, Mori et al. (2024a) found that two-way atmosphere-ocean coupling in the extratropics amplifies the variability of major teleconnection patterns, elucidating the underlying mechanism. In particular, the PNA pattern becomes stronger when the atmosphere and ocean are coupled (Mori et al. 2024b). The impact of PNA-driven mid-latitude SST anomalies on the PNA itself is sensitive to the presence or absence of air-sea coupling, suggesting that traditional atmospheric general circulation model experiments, which have been commonly used to examine the effects of mid-latitude SST anomalies, may have underestimated their influence on the PNA.

5. Outlooks

Two years have passed since the ongoing *Habitable Japan* project began. In addition to advanced understanding of mid-latitude ocean-atmosphere interactions and their relations to extreme events and global climate variations, we are obtaining results that align with the project's new targets. For example, in contrast to the common idea that combined oceanic and atmospheric variability in the tropics impacts phenomena in mid-latitudes (Sections 1 and 4), the influences of mid-latitude variability to the lower latitudes have not been well understood. Recently, studies on this topic have advanced significantly, such as those on the connection via the Pacific meridional mode associated with the low-level cloud–SST feedback (Section 2.3), as well as those on the impact of the oceanic meridional overturning circulation on the Hadrey Cell and the meridional shift of the Intertropical Convergence Zone through the zonal-mean global energy balance (e.g., Xie 2023). In addition, by conducting large-ensemble atmospheric general circulation mode experiments, Miura and Tanimoto (2026) demonstrated that positive SST anomalies in the KE region weaken the trade winds over the subtropical North Pacific and rise SST there, which may further affect the combined oceanic and atmospheric variability in the tropics.

We are also having results on fisheries. Oceanic fronts have long been recognized as biological hotspots aggregating organisms from phytoplankton to top predators and attracting fisheries (Sims and Quayle 1998; Woodson and Litvin 2015). However, Xing et al. (2026a) clarified that fishing activity in the frontal zones are only 5–20% higher than non-frontal zones. Moreover, species-specific local thermal preferences yield 15–70% differences in fishery distributions between the colder and warmer sides of the front, indicating that the fronts act as a barrier. This suggests that the hotspot (aggregation) effect of the ocean front on its either colder or warmer side should be higher than previous studies, which averaged the fish distributions over both colder and warmer sides. For sustainable fisheries, dynamic marine protected area setting that takes the frontal structure into consideration seems essential. As for long-term temporal variability, SST regime shifts, which are large, abrupt transitions between sustained warm and cold states that occur on decadal to interdecadal timescales, are known to modulate marine ecosystems (Kawasaki 1983; Mantua et al. 1997). Xing et al. (2026b) demonstrated that the frequency and amplitude of SST regime shifts, accompanied by fish biomass regime shifts, have increased by 130–140% across global large marine ecosystems over the past 150 years, to a higher extent in the Northern Hemisphere. They also projected that without mitigation, anthropogenic warming will increase the frequency of regime shifts by 130–180% by the late 21st century.

Following the *Climatic Hotspot2* project (Sections 2.2, 2.3, 3.4, and 3.5), we have conducted and are conducting a variety of in-situ observations in the second and third years of the *Habitable Japan* project to clarify various processes and refine numerical models. We organized field campaigns by two vessels off the Sanriku coast and a land station at Otsuchi twice in June–July 2025 and June–July 2026, to examine the impact of the KE-related MHW (Section 3.2) on the Yamase winds and marine ecosystems (Fig. 4). In the area of intensive shipboard observations using expendable CTDs and radiosondes, SST anomalies of ~+3ºC remained in the first year, while SSTs were closer to the climatological normal in the second year. We have also revisited the Japan Sea in January–February 2026 to clarify the mechanism by which the oceanic Polar Front contributes to heavy snowfall, and have just revisited the East China Sea west of Kyushu in June–July 2026 to observe air-sea interactions associated with the

Baiu front and the Kuroshio warm water tongue (Fig. 4).

To clarify the impact of atmospheric deposition on marine ecosystems in the western North Pacific subtropical region, we started continuous observation of aerosols and rain at Chichijima Island in September 2024 (Fig. 4). We also started continuous observation of clouds using a ceilometer at Suzu facing the Japan Sea in May 2025 to explore the boundary layer structure. Furthermore, to discuss the relation between wave history and surface mass exchange flux, we have developed a sea spray optical particle counter, and have conducted and are going to conduct integrated observations of meteorological and wave conditions, heat, gas, and particle fluxes, and the sea-surface microlayer at Tanabe, Wakayama and on research vessels.

Regarding profiling float observations, Hayashida et al. (2025) demonstrated that the chlorophyll-a structure obtained by BGC floats from various projects in the western subtropical North Pacific since around 2018, characterized by subsurface chlorophyll-a maxima persisting throughout the year, corresponds reasonably to the satellite and shipboard measurements. They argued that to improve biogeochemical predictions, we need to deploy more BGC floats and develop a data assimilation method that combines float, satellite, and shipboard measurements. Thus, in the *Habitable Japan* project, we have just deployed five BGC floats with DO, pH, chlorophyll-a, and turbulence sensors in the Kuroshio and KE regions in June–July 2026 to clarify biological production and decomposition at the ocean surface.

In addition to the in-situ observations, we are creating data assimilation methods that overcome discontinuities in the atmospheric and oceanic fields around Japan to reproduce atmosphere-ocean-marine ecosystem coupling processes in the models, thereby improving prediction skills. Furthermore, we are expecting that our clarification of oceanic/atmospheric variations and changes will lead to the elucidation of local processes (weather, marine environment in coastal areas and around islands) and terrestrial environment and activities (hydrology, terrestrial ecosystems, agriculture, health, energy, social systems, etc.) related directly to human life, as well as their predictions. In cooperation with other domestic, foreign, and international research activities, we will connect disciplines from weather to fisheries to answer our main question: Will mild climate and abundant water/fisheries resources persist as a basis of survival for those of us living in Japan in the future?

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Declarations

Conflict of interest: The authors declare no conflicts of interest.

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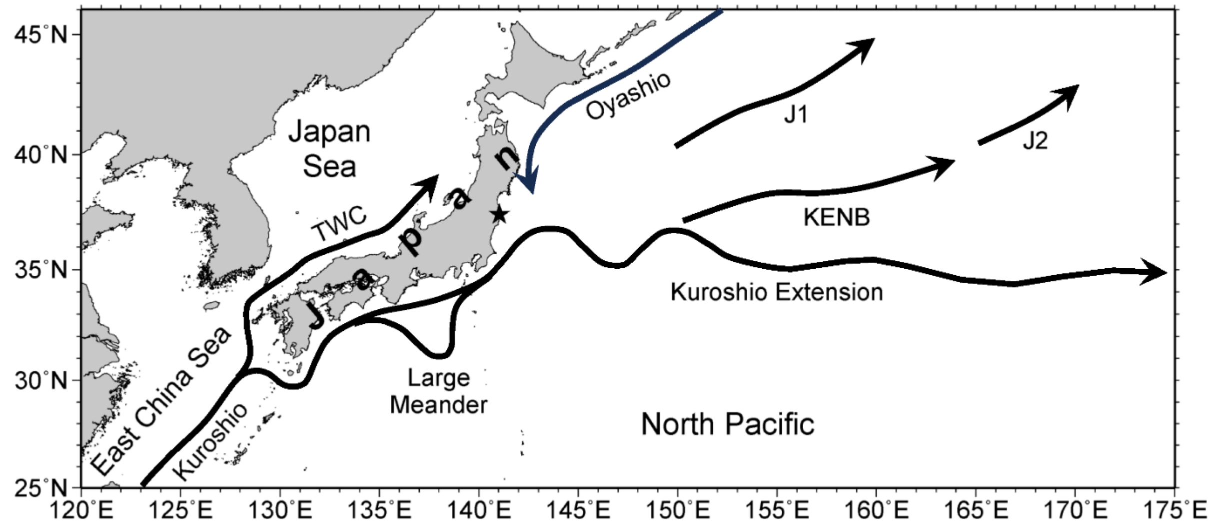

Fig. 1 Major ocean currents around Japan. TWC Tsushima Warm Curren, KENB the northern branch of the Kuroshio Extension. J1 and J2 are the quasi-stationary jets transporting warm and saline subtropical waters to the subarctic regions (Isoguchi et al. 2006). The black star denotes the Fukushima Dai-ichi Nuclear Power Plant.

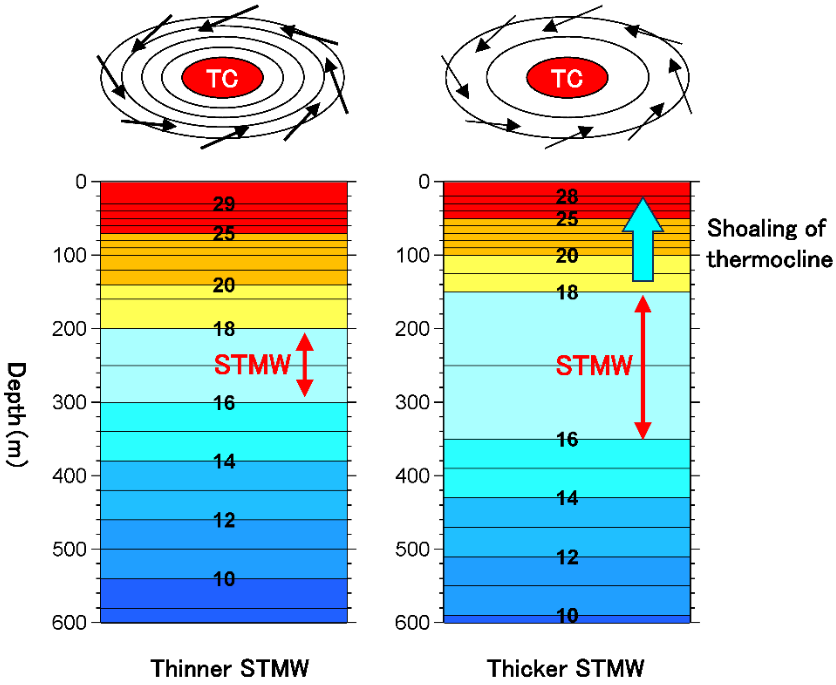

Fig. 2 Schematic representation illustrating that a thicker STMW reduces upper ocean heat content and tropical cyclone (TC) intensity.

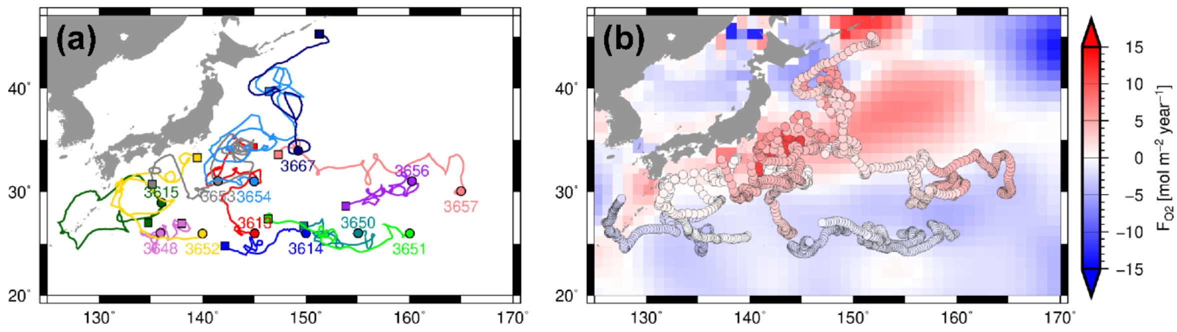

Fig. 3 **a** Trajectories of 12 BGC floats deployed under the *Climatic Hotspot2* project. Circles and squares present the locations of deployment and last surfacing, respectively. The number indicates the last four digits of the seven-digit World Meteorological Organization identifier following the first three digits of "290" (after Kosugi et al. 2025*). **b** Net annual surface oxygen fluxes for each float. Positive values indicate flux from the atmosphere to the ocean. The background denotes the climatology of the fluxes calculated from World Ocean Atlas 2023 (Reagan et al. 2024). After Kosugi et al. (2025*).

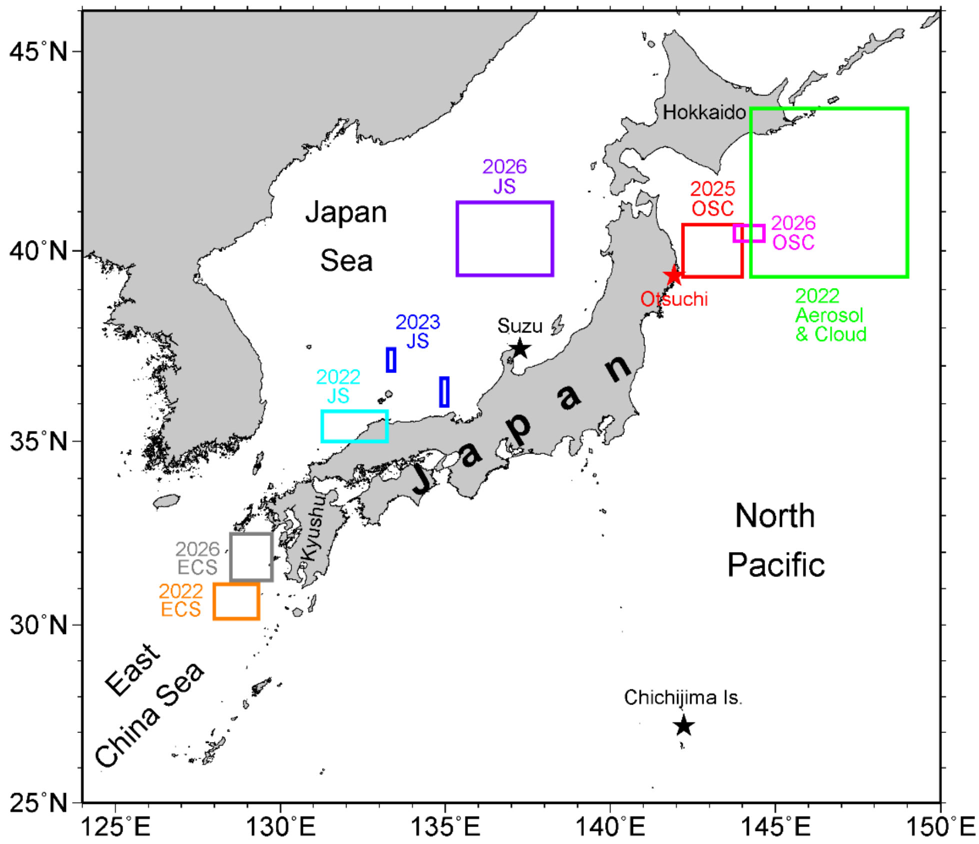

Fig. 4　Locations of completed and ongoing observations under the *Climatic Hotspot2* and *Habitable Japan* projects, except for those using profiling floats.　Rectangles indicate areas of intensive shipboard observations: the East China Sea observations in summer 2022 (orange) and summer 2026 (grey), the Japan Sea observations in winter 2022 (cyan), winter 2023 (blue), and winter 2026 (purple), the Off the Sanriku Coast observations in summer 2025 (red) and summer 2026 (magenta), and the aerosol and cloud observation southeast of Hokkaido in summer 2022 (green).　The red star denotes the land station at Otsuchi in cooperation with the Off the Sanriku Coast observations.　The black stars represent the stations at Suzu and Chichijima Island where continuous observations of aerosol, rain, and cloud are being performed since September 2024 and May 2025, respectively.　【岩本さん待ち】

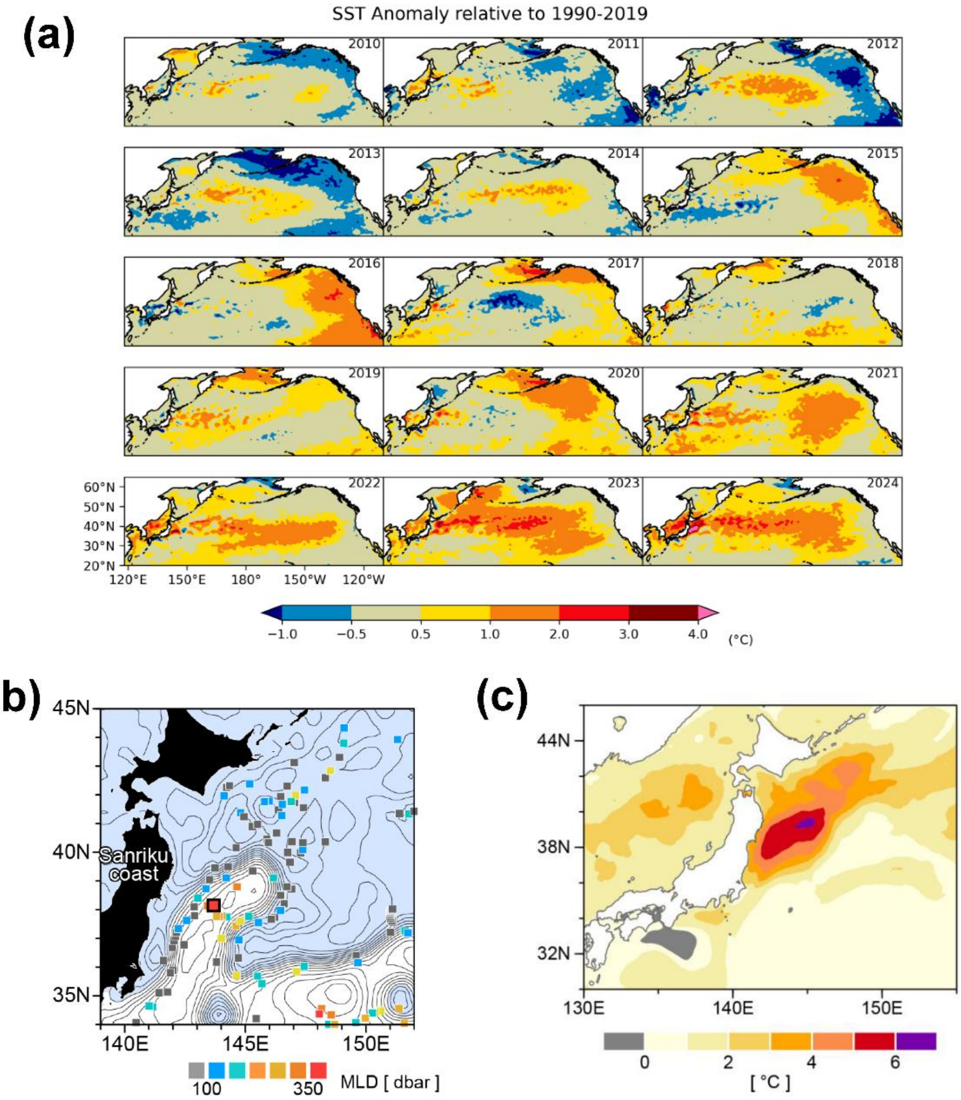

Fig. 5 **a** Annual mean SST anomalies from 2010 to 2024, relative to 1990–2019 climatology (after Minobe 2025*). **b** Sea surface height map for March 1st, 2024 with an interval of 0.1 m (light blue shading is for sea surface height < 0.8 m). Colored squares represent mixed layer depths during February–March 2024 from Argo profiles (after Sugimoto et al. 2025*). **c** Average of monthly SST anomaly for April 2023–August 2024, relative to 1982–2011 around Japan (after Sugimoto et al. 2025*).

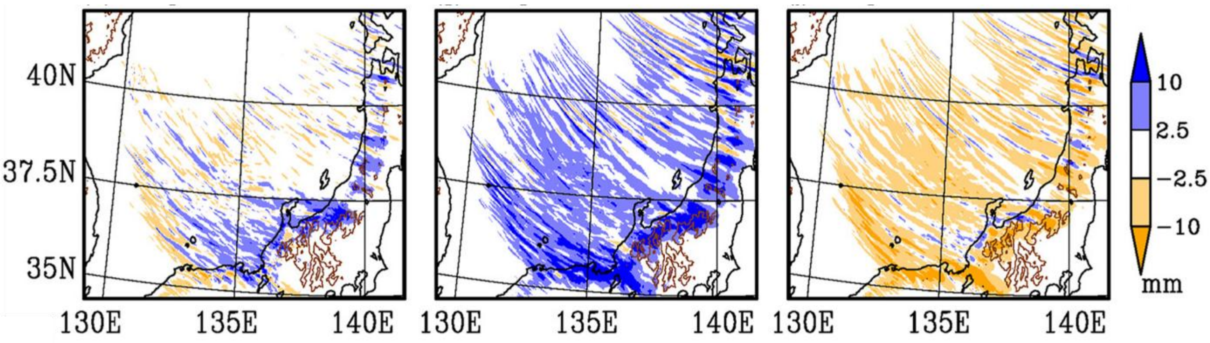

Fig. 6 Precipitation differences accumulated from 00Z 14 to 00Z 18 December 2020 attributed to both of the historical atmospheric and SST warming (left), to SST warming (middle), and to atmospheric warming (right). After Kawase et al. (2022).

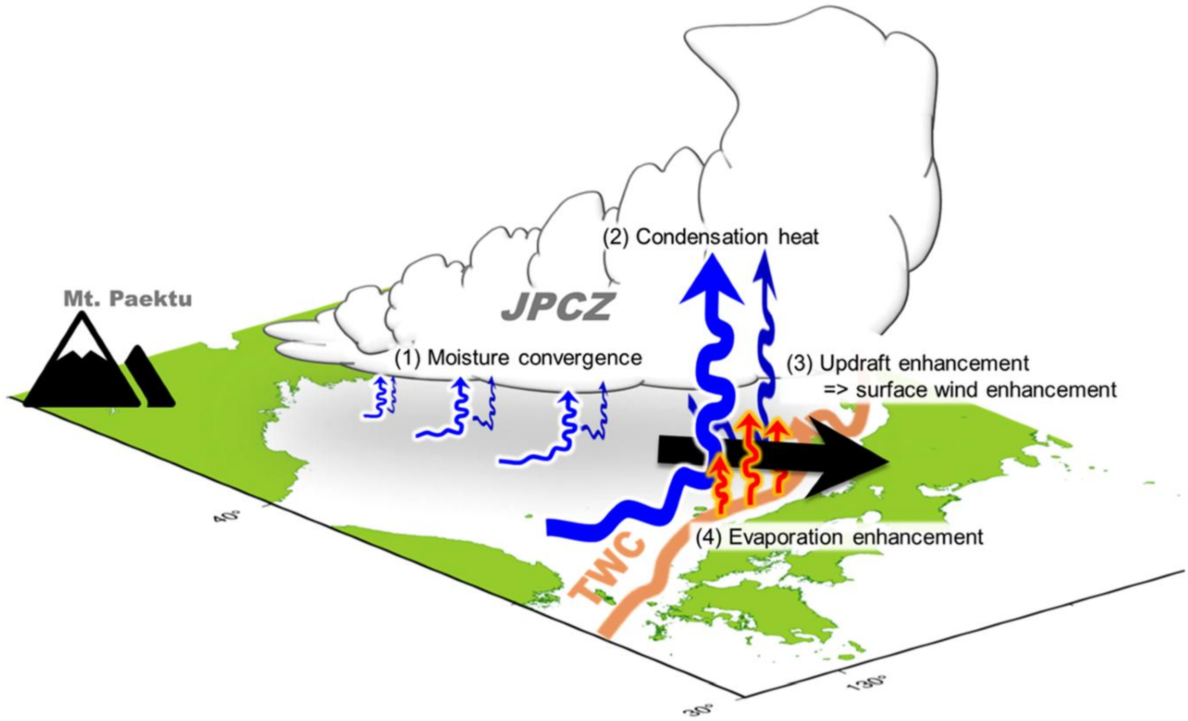

Fig. 7 Schematic representation illustrating the self-sustaining mechanism of the JPCZ. (1) Moisture from many branches converges to form a large moisture flow. This has a structure of an atmospheric river. (2) The JPCZ gains buoyancy from the condensation heat of the water vapour, and the convergence thus strengthens the updrafts. (3) The enhanced updrafts further strengthen the horizontal convergence of winds, i.e., enhanced wind speeds. (4) The enhanced wind speed further increases evaporation from the ocean and moisture convergence. Therefore, the JPCZ with the structure of atmospheric rivers has a self-sustaining mechanism. After Tachibana et al. (2022).

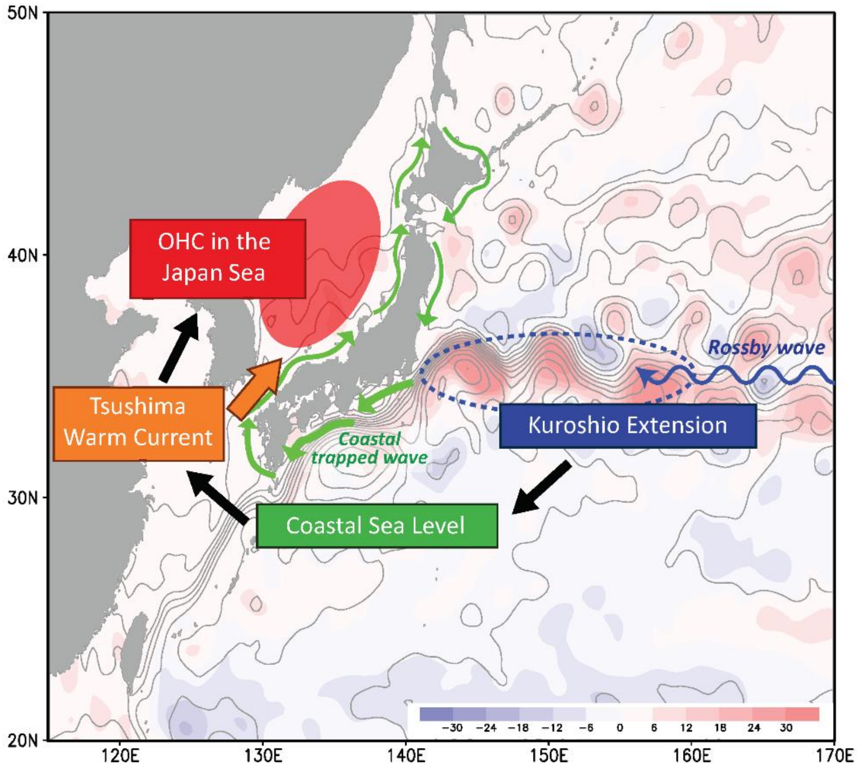

Fig. 8 Schematic representation illustrating the mechanism for interannual-to-decal ocean heat content (OHC) variability in the Japan Sea. The relation between variabilities in the KE, coastal sea level, TWC, and OHC in the Japan Sea is presented. Background contours and shades indicate the annual mean sea surface height for 2012 and its anomaly (after Usui and Hirose 2025).

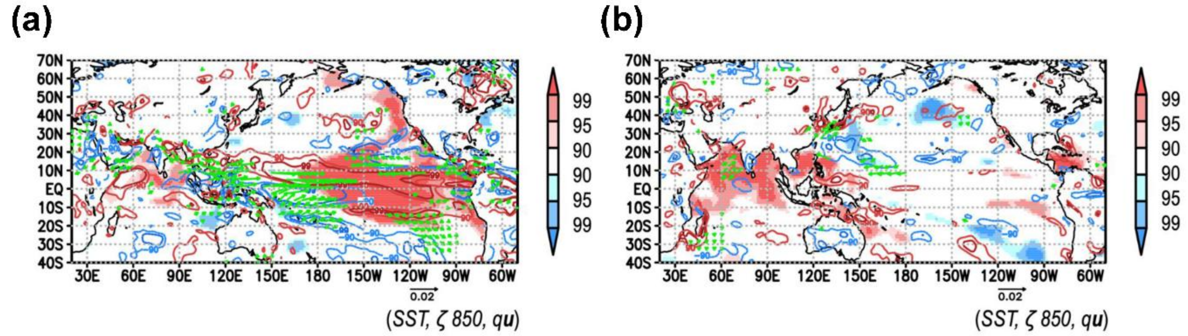

Fig. 9 Correlation coefficients of SST anomalies (shades) and vorticity at 850 hPa (contours) relative to the top 1-percentile (**a**) and 10-percentile (**b**) values of the daily rainfall potential on Kyushu during the period of June–August from 1981 to 2010. The plotted values indicate areas where the positive (warm colors) and negative (cool colors) correlation coefficients are significant at the 99, 95, and 90% confidence levels. Green vectors denote the regression values of the horizontal moisture transport at 850 hPa in areas where the regression values of both the zonal and meridional components were significant at the 90% confidence. After Mochizuki (2024b).

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