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Pathways to an integrated understanding of marine environments and ecosystems in the Asia-Pacific Region

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The Asia-Pacific Region (APR) encompasses a vast geographical area rich in marine biodiversity that plays critical roles in global ecological stability and climate regulation, but it also faces daunting challenges in maintaining these roles under global change. Environmental dynamics in the APR manifest regularly over a range of timescales, including storms, earthquakes, floods, and extreme heat events. Further, coastal and marine ecosystems, including extensive commercial fisheries and coral reefs, are under threat from intense resource extraction and increasingly frequent marine heatwaves. Knowledge gaps for understanding these complex systems are aggravated by substantial barriers to cross-national efforts caused by the region's vast diversity of cultures, languages, socioeconomics, politics, and management practices. Effective management of marine resources in the APR will necessitate multidisciplinary research based on continuous, region-wide observations supported by robust collaborations. In 2023, we gathered APR researchers across disciplines to discuss these issues and

find solutions during a thematic seminar and workshop program at Tohoku University in Japan. Based on the results of this program, we present a review of the current state of APR marine ecosystems, raise key questions addressable through multidisciplinary approaches, and identify future priorities for the region. We conclude that sustaining biodiversity, ecosystem functions, and climate resilience in the APR will depend on stronger interdisciplinary collaboration, better integration of biological and geophysical data, and broader access to marine observations. These efforts are both urgent and essential for supporting better science-based policy decisions to address the escalating effects of global change on marine systems across the region.

KEYWORDS

Asia-Pacific, marine science, interdisciplinary, climate change, data observations

1 Introduction

The Asia-Pacific Region (APR, as defined in this study to include Northeast and Southeast Asia and the Pacific; [Institute for Global Environmental Strategies, 2008](#)) spans an area that occupies nearly one-third of our planet's surface ([Figure 1](#)), hosts major hotspots of marine biodiversity ([Cohen and Steenbergen, 2015](#); [Gonzales et al., 2019](#)), and supports biogenic habitats including coral reefs, mangrove forests, and seagrass beds ([Williams et al., 2016](#); [Dang et al., 2021](#); [Devlin et al., 2021](#)). Healthy ocean ecosystems are critically linked to the economies of APR countries, which depend heavily on fisheries, tourism, and other marine-related activities ([Devlin et al., 2021](#)). Furthermore, local communities rely on coastal and offshore ecosystem services for their livelihoods and cultural practices ([Ross et al., 2019](#)). As a result, there are unique challenges to ocean resource management and ecosystem conservation in the APR that require not only broader awareness but also immediate attention and action.

For one, the APR is particularly vulnerable to environmental fluctuations such as synoptic storms, seasonal typhoons and monsoons, major ocean current shifts, tsunamis, and extreme heat events that manifest at varied timescales ranging from intra-annual to decadal ([Arthurton, 1998](#); [Mimura, 2008](#); [Pakoksung et al., 2022](#)). The region has been significantly affected by climate change, with sea-surface height and temperature increases exceeding global averages at 3.52 ± 1.75 cm and 0.205 ± 0.08 °C per decade ([Figures 1A, B](#)) ([Hens et al., 2018](#); [Khalil et al., 2016](#)). Furthermore, future projections under CO₂ emissions scenarios suggest further increases in sea surface temperature, precipitation, ocean acidification, and the intensity of tropical cyclones in the APR with the potential to impact marine ecosystems and socioeconomic frameworks ([Heenan et al., 2015](#)).

Furthermore, the APR, an area rich in marine biodiversity, is disproportionately threatened by both anthropogenic and environmental pressures, given that 60% of Earth's human population resides there ([Gietel-Basten, 2023](#)). Yet, a 10-year

average (2012–2023) of the Ocean Health Index (OHI), a comprehensive framework for assessing ocean health based on the sustainable provisioning of benefits and services (e.g., food, cultural and social value, jobs) ([Halpern et al., 2012](#)), revealed high biodiversity scores in the APR indicating more non-threatened species and less degradation of critical habitats relative to other components at both the global and regional scales ([Figures 1C, E](#)). However, an examination of OHI data on a year-to-year basis over the last decade reveals a steady decrease in the biodiversity component at both scales ([Figures 1D, F](#)), highlighting growing pressures on marine ecosystems. Anthropogenic causes of biodiversity loss in the APR include commodity-driven deforestation, dam construction, land-based marine pollution, and overexploitation through unregulated fishing and coastal development ([Gonzales et al., 2019](#), [Takeuchi et al., 2021](#); [Tan et al., 2022](#)). Furthermore, recent studies indicate that climate change is likely to increase the frequency of marine heat waves and natural disasters (e.g., [Emanuel, 2013](#); [Fischer and Knutti, 2015](#)). Drastic changes to marine environments in the future will likely accelerate biodiversity loss. For example, sea surface temperature in Southeast Asia is predicted to rise by 1.1–2.9 °C and dissolved oxygen levels to decline by 5–13 mmol m⁻³ over the 21st century ([Kay et al., 2023](#)). Such rapid shifts will impact sensitive biogenic habitats, alter species distribution, and threaten the food security and livelihoods of millions reliant on coastal resources.

Addressing discrete challenges necessitates sustained regional observational platforms for detecting trends and elucidating processes. International efforts have made much progress to foster this effort, including the development of the Essential Ocean Variables (EOVs) system by the Global Ocean Observing System (GOOS) to facilitate standardization of data collection worldwide. By monitoring EOVs at national and regional scales, we can better assess marine system dynamics, responses to environmental stresses, and the accuracy of forecasts ([Miloslavich et al., 2018](#)). The “Decade of Ocean Science for Sustainable Development”

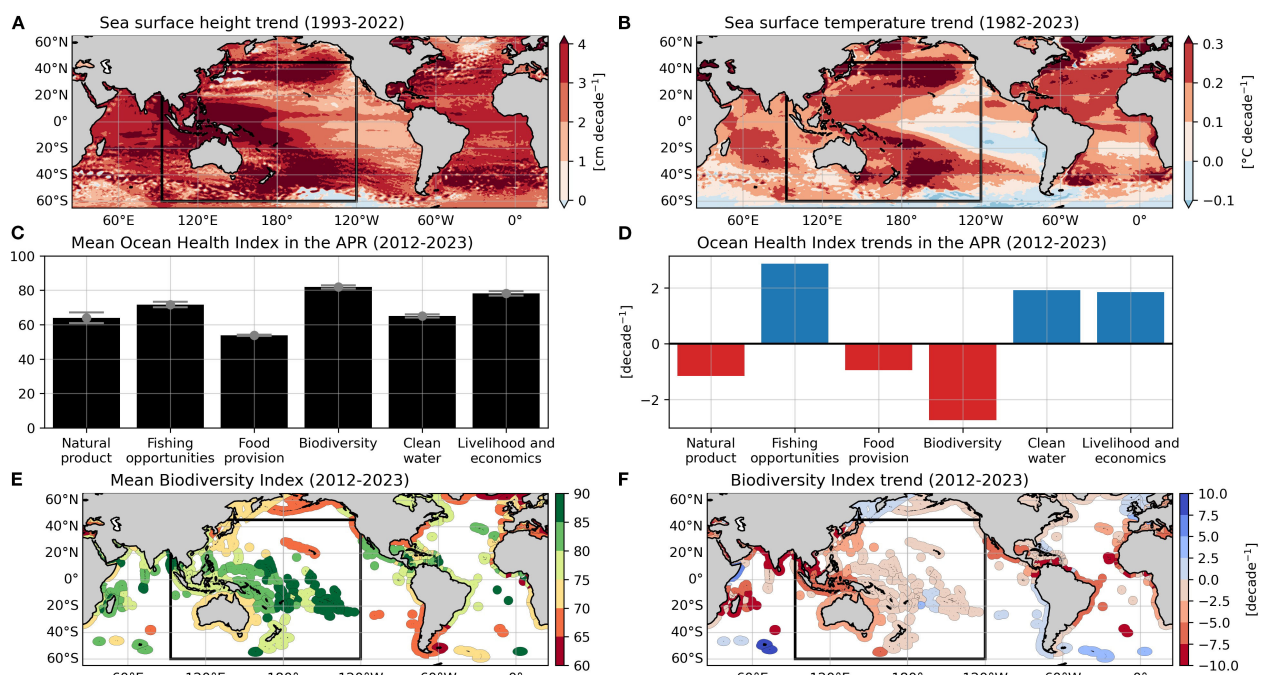


FIGURE 1

Trends of (A) sea surface height from 1993 to 2022 and (B) sea surface temperature from 1982 to 2023. (C) Average scores of Ocean Health Index (OHI) components in the APR. The error bars indicate one standard deviation of the annual mean. (D) Trends of OHI components in the APR from 2012 to 2023. (E) Average scores of the biodiversity component of the OHI. (F) Trend of the biodiversity component from 2012 to 2023. The trends are calculated by using linear regression. The black box (93°E-120°W, 60°S-45°N) indicates the APR.

(2021–2030) designated by the United Nations (UN) aims to enhance ocean resilience and sustainability, which also aligns with the broader goals of the 2030 Sustainable Development Agenda (Ryabinin et al., 2019; Venkatesan et al., 2021). Though valiant objectives, cross-national data-sharing efforts in the APR to address regional maritime issues are multifaceted due to the diversity of cultures, languages, socioeconomics, politics, and management practices (Beeson and Murray, 2020; Dang et al., 2021). The result is a general lack of publicly available regional ocean data in the APR, which can undermine the trust of both academics and policymakers (Chung, 2010; Costello et al., 2012), further hindering a comprehensive assessment of the status of those marine ecosystems.

To call attention to these particular challenges and assess the state of ocean ecosystems in this rapidly changing region, we formed an international working group of interdisciplinary early-career researchers and faculty mentors based primarily on the APR. Our aim is to foster collaboration and harness diverse perspectives from different countries, academic career levels, and research fields, including biology, ecology, oceanography, climatology, and engineering. The group convened for a thematic seminar and workshop program entitled “Integrated Understanding of Marine Environment and Marine Ecosystems” held in October–December 2023 as part of the Tohoku Forum for Creativity (TFC) Programs at Tohoku University in Japan. Here we present the core challenges and opportunities we have identified for interdisciplinary marine science opportunities in the APR. We first discuss how the adoption and proliferation of innovative and improved data sources (e.g., in

the biological and geophysical fields) are essential for developing a comprehensive understanding of marine ecosystems, and how the use of these data can help forge new research directions. We then raise key questions about the future sustainability of marine ecosystems in the APR and propose strategies to address them in light of new types of data resources made available in recent years.

2 Adoption and proliferation of varied marine data sources

Measuring EOVs and indicators at high spatial and temporal resolutions from local to regional scales is necessary to adequately monitor marine systems. Marine biodiversity monitoring has traditionally relied on direct sampling and observations of organisms, which has made regional estimates difficult in the APR. However, advances in data and monitoring technology have helped the research community to reduce costs and transcend the boundaries imposed by the complex network of exclusive economic zones (EEZs) in this region.

2.1 Automated marine geophysical and biogeochemical monitoring

Beginning in 1999, the Argo program effectively utilized autonomous floats to address regional sampling biases that lead to persistent geographical data gaps for marine variables. Argo

profiling floats measure temperature and salinity from 2000 m to the ocean surface every 10 days (Core-Argo; Riser et al., 2016; Figure 2A). These data have been used for many applications including investigations of subsurface ocean dynamics under climate change (Lyu et al., 2021) and impacts on typhoon intensity (Oka et al., 2023). BGC-Argo, which includes biogeochemical and optical sensors, was developed over the last decade to collect data on oxygen, nitrate, pH, and chlorophyll-a, as well as downwelling irradiance for deep and remote areas (Claustre et al., 2020; Figure 2B). These data have been used to monitor seasonal net primary production (Yang et al., 2021), the influence of oceanic eddies on subsurface biogeochemistry (Xiu and Chai, 2020; Chen et al., 2021), and the timing of seasonal phytoplankton blooms (Mignot et al., 2018). Both Core and BGC-Argo have transformed *in situ* marine data collection in the APR by enabling consistent subsurface monitoring of physical and biogeochemical properties across previously undersampled regions (e.g., He et al., 2022; Chamberlain et al., 2023).

However, data coverage remains limited in regions with shallow waters (<2000 meters) and near continental shelves, such as the Gulf of Thailand, the Indonesian seas, and waters north of Australia (Figure 2A). One example of addressing this gap is the deployment of floats specialized for shallow waters such as those in the Natuna Sea, Karimata Strait, and Java Sea in Indonesia (24th Argo Steering Meeting; <https://argo.ucsd.edu/organization/argo-meetings/>). Furthermore, BGC-Argo coverage remains extremely limited in the APR, particularly in Southeast Asia, where observations are sparse or entirely absent (Figure 2B). One practical pathway to improve data availability in the APR is through OneArgo (Owens et al., 2022), a global initiative to unify and expand coverage by incorporating Core, Deep (reaching 6000 meters), and BGC-Argo floats into one integrated system, which should support more comprehensive monitoring of ocean dynamics and ecosystem change in the APR. However, OneArgo deployments in this region must also navigate legal and diplomatic considerations, particularly regarding the deployment of floats that may drift into EEZs (Belbeoch, 2006). The process of deploying Argo floats in or near EEZs requires advance notification to coastal states, which can present challenges for achieving full regional coverage.

2.2 Biodiversity surveys and environmental DNA

There is a pressing need for more *in situ* biodiversity data on marine organisms in the APR to fill knowledge gaps that cannot be addressed solely with remotely sensed data. The APR contains many marine biodiversity hotspots for varied taxonomic groups (Roberts et al., 2002; Von Rintelen et al., 2017), but compared to the terrestrial realm, many of these marine groups remain poorly described, and some of the most data-deficient groups are the most diverse in the APR (Allen, 2008). For example, zooplankton are ecologically important but remain understudied due to their complex life cycles, diel and seasonal migrations, and limited taxonomic expertise (Bandara et al., 2021; Pappalardo et al.,

2021). Coral species boundaries also remain unclear, particularly in the Coral Triangle, hindering our ability to assess the full diversity of associated marine fauna (Hoeksema, 2017). Although recent advances in metabarcoding techniques offer promising tools to improve species detection, their effectiveness in the APR is still limited by sparse regional reference libraries and a lack of comprehensive specimen records (Moutinho et al., 2024; Jintsu-Uchifune and Yamamoto, 2016). This has resulted in extreme underrepresentation of APR marine species in large genomic, biogeographic, and taxonomic databases (e.g., NCBI, GBIF, OBIS, FishBase, SeaLifeBase, WoRMS). Described marine species are also in dire need of updates, as many are known only from perfunctory descriptions and sparse museum specimens from decades ago. These issues are caused in large part by a decline in active taxonomists who can identify species new to science (Engel et al., 2021). Thus, many resident species known to local communities and fisheries remain invisible to science and conservation assessment protocols like the IUCN Red List. However, new taxonomic efforts in the APR over the last 20 years have contributed to the description of hundreds of new fish species at a steady pace per year, resulting in over 4,500 new descriptions from 2010 to 2024 (Eschmeyer et al., 2010; Fricke et al., 2024).

Environmental DNA (eDNA) analysis has helped us assess biodiversity from communities using seawater and other indirect samples to identify resident organisms, including species that cannot be easily observed during field work (Beng and Corlett, 2020; Othman et al., 2023; Cahyani et al., 2024). These data have been used to track ecosystem responses to climate anomalies (Berry et al., 2019) and improve management of rare and invasive species (Eva et al., 2016; Madduppa et al., 2021), thus having both economic and biomonitoring significance (Moutinho et al., 2024). In addition, metabarcoding surveys targeting universal gene markers and metagenome skimming facilitate the detection and identification of many organisms (Porter and Hajibabaei, 2018; Garlapati et al., 2019; Hidaka et al., 2024), and these techniques can be adapted for eDNA to enhance taxon detection with time and cost efficiency, even for samples taken from sediment for deceased organisms (Takahashi et al., 2023). It must be noted that reference libraries are essential for detecting species from eDNA samples, especially for poorly known groups, but genomic data on marine species is sparse throughout the APR besides in Australia and New Zealand (De Jong et al., 2024). Therefore, while eDNA approaches can be useful for tracking the presence and possible range of known species and identifying the relative abundance of DNA from unknown sources, they will not be sufficient for reconstructing full communities until genomic sampling and taxonomic deficiencies noted above are fully addressed.

Regional efforts to develop streamlined eDNA collection protocols, expand sampling targets and reference databases, reduce sample processing and data sharing times, and implement long-term archiving practices are all essential for facilitating efforts that can fill baseline knowledge gaps regarding biodiversity in the APR. Examples of large-scale projects in the region include the OceanOmics project (minderoo.org/resources/oceanomics/), which focuses on advancing eDNA analysis techniques and developing

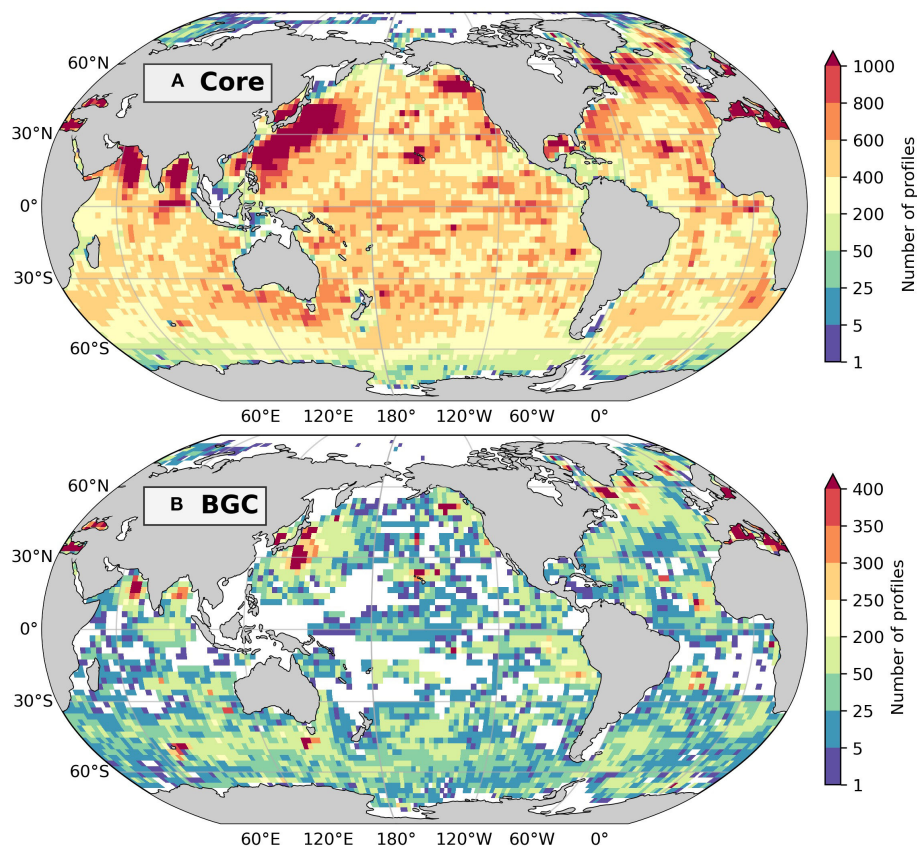


FIGURE 2

The total number of Argo profiles from 2000 to 2023 for temperature and salinity only (Core Argo; **A**) and additionally for biogeochemical variables (BGC-Argo; **B**) at 2.5° resolution (~275 km at the equator). White areas indicate grid cells with no available profiles for this time frame. As oxygen is the most consistently measured biogeochemical variable, only profiles that have quality-controlled (QC flags 1, 2, 5, and 8) oxygen data are shown in (**B**).

genomic reference libraries for Australia, and ANEMONE (All Nippon eDNA Monitoring Network), which maintains an open database of eDNA data for fish species in Japan and is now also expanding to include other partners in the APR and beyond (oceandecade.org/actions/anemone-global/). Continued efforts to accumulate and share eDNA data publicly for the APR will help accelerate consistent monitoring, resulting in more accurate biodiversity assessments of the region and the discovery of new species.

2.3 High-resolution remote sensing data for coastal ecosystem monitoring

In the APR, where remote and complex coastal areas often lack sustained programs for *in situ* sampling, high-resolution satellite data provide essential, repeatable observations. These data include ocean surface variables such as sea-surface temperature, chlorophyll-a concentration, turbidity, and ocean color, providing critical insights into the conditions of key ecosystems. For example, high-resolution satellite data can reveal changes in mangrove health over time in the APR, aiding national reporting on carbon stocks and supporting coastal climate mitigation strategies (Sakti et al.,

2020; Roy et al., 2024). Satellite data have also been used to map coral resilience and forecast temperature anomalies for the APR, crucial for anticipating and managing bleaching events (Knudby et al., 2013; Smith and Spillman, 2019). Using the Allen Coral Atlas, a global database of high-resolution reef habitat maps developed using satellite imagery, Lyons et al. (2024) demonstrated that the APR contains the largest global extent of shallow coral reefs, with Indonesia, the Philippines, and Papua New Guinea at the top of the list.

To support evidence-based management and biodiversity conservation across the APR, satellite observations should be integrated into regional monitoring systems, ideally using machine learning workflows. In addition, strategies should be explored to link satellite-derived indicators to local measurements from management efforts such as fisheries, mangrove restoration, and coral reef protection.

2.4 Incorporating geophysical data into biodiversity models

Despite growing access to ecological and environmental data, biodiversity models still rarely incorporate geophysical processes

that play critical roles in shaping marine ecosystems, particularly in the APR. While variables such as sea surface temperature or salinity are commonly included, more complex physical dynamics such as ocean currents, eddy activity, and upwelling are overlooked but could prove important to biodiversity models. For example, [Santora et al. \(2021\)](#) combined long-term biodiversity data for the California coast with physical drivers such as upwelling variability, source water changes, and marine heatwaves to enhance species distribution models and inform ecosystem forecasting. [Ackiss et al. \(2013\)](#) provided a rare example for the APR, showing how geophysical processes, such as the Mindanao and Halmahera eddies, can shape biodiversity by creating genetic breaks in reef fish populations through limited larval dispersal, thus highlighting how physical oceanographic processes shape marine biodiversity patterns. While the value of such integrative approaches is clear, the scarcity of related studies for the APR highlights opportunities to fill significant research gaps through interdisciplinary research.

Future progress will depend on bold new research initiatives featuring collaboration between physical oceanographers and ecologists to integrate geophysical variables into biodiversity models. Development of dynamic models that mechanistically link geophysical forcings to biodiversity and ecosystem function and their application to generate specific testable hypotheses could stimulate targeted oceanic observations to obtain the geophysical data needed. Given the dynamic nature of the physical marine environment in the APR, such research is expected to help answer lingering questions about spatiotemporal patterns of biodiversity in the region.

3 Key questions addressed by new data opportunities

Here we identify key questions concerning the rapidly changing APR that, while being crucial to address, can only be effectively solved by integrating insights from multiple disciplines.

3.1 How do changing oceanic physical processes impact the diversity and dynamics of marine life?

Oceanic physical processes, influenced by climate change, are reshaping marine life in the APR. Decadal modes of climate variability, such as the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) have been shown to alter sea-surface temperature, salinity, and ocean circulation, which in turn shift the distributions and abundance patterns of key commercial species across the Indo-Pacific region ([Wu et al., 2022](#)). The increasing frequencies of marine heatwaves and harmful algal blooms are also leading to habitat degradation and species redistribution around the APR ([Oliver et al., 2018](#); [Kang et al., 2021](#)). Marine species are closely tracking shifting temperatures, particularly in warm tropical waters like the Central Pacific Basin, raising the risk of local extirpations where species already live near

their thermal limits ([Lenoir et al., 2020](#)). Moreover, the impacts of climate change in the APR are highly variable—different regions have exhibited vastly different levels of coral bleaching that vary based on climate extremes but also geography, disturbance history, and water movement, making predictions challenging ([McClanahan et al., 2019](#)).

In addition, it is becoming clear that APR reefs respond differently to climate change than those in other parts of the world, with inconsistent bleaching patterns across depth and weak or absent correlations with thermal stress variability. This variability is likely influenced by the region's high coral richness and genetic diversity, as well as complex environmental conditions, which can mask or alter expected responses to warming and other stressors ([Schlesinger and van Woesik, 2023](#)). Together, these observations highlight the need for a more regionally informed understanding of how climate-driven ocean changes are affecting marine ecosystems in the APR. The variability in responses suggests that global trends may not hold uniformly in this highly diverse and dynamic region. Addressing this complexity will require greater integration of biological and physical data, expanded long-term monitoring, and a stronger focus on local environmental and ecological contexts. As marine ecosystems across the APR continue to face rapid change, improving our ability to detect, interpret, and respond to these shifts will be essential for effective conservation and management.

3.2 Which intensifying extreme events in the marine realm are most concerning?

As the climate continues to warm, the APR has experienced an increasing number of climate-related disasters, which may reflect a rise in the frequency and intensity of extreme events, combined with increased human exposure and vulnerability ([Thomas et al., 2014](#)). Understanding whether these events are accelerating and which types pose the greatest risk is critical for anticipating the region's ecological and socio-economic vulnerabilities. The frequency and intensity of extreme weather events across the APR have been increasing, including heatwaves ([Fischer and Knutti, 2015](#)), heavy rainfall ([Kharin et al., 2013](#)), and severe droughts ([Dong et al., 2024](#)). This also includes events that directly threaten coastal infrastructure and livelihoods such as tropical cyclones ([Webster et al., 2005](#); [Emanuel, 2013](#)), tsunamis ([Suppasri et al., 2011](#); [2018](#); [Pakoksung et al., 2022](#)), and sea-level rise ([Dasgupta et al., 2009](#); [Hoeke et al., 2013](#)). The rise in extreme marine weather events poses serious and often compounding risks to biodiversity and ecosystem dynamics in the APR. Marine heatwaves can cause widespread coral bleaching and mortality, which in turn destabilizes reef-associated food webs and reduces habitat complexity ([Leggat et al., 2019](#); [Fordyce et al., 2019](#)). Similarly, increased frequency of flooding and cyclones can lead to physical damage to critical habitats like mangroves and seagrass beds, disrupt reproductive cycles of marine species, and favor opportunistic or invasive organisms over long-established communities ([Biswas et al., 2012](#); [Asbridge et al., 2018](#)). These stressors may also accelerate shifts in

species distributions and traits, selecting for faster-growing, more heat-tolerant species while driving local declines or extinctions of more specialized organisms (Mellin et al., 2024).

As these extremes become more common, the resilience of ecosystems may erode, making recovery slower and less predictable, which highlights the urgent need to factor extreme event dynamics into conservation planning and marine management strategies. In our view, failing to integrate the growing frequency and severity of extreme events into conservation and management strategies risks weakening marine ecosystem stability in the APR, which will detrimentally affect food security, coastal protection, and livelihoods for millions (Vinke et al., 2017). Without urgent and coordinated efforts to build resilience through ecosystem-based adaptation, early-warning systems, and environmentally sustainable development, the APR may face cascading socio-ecological crises that severely threaten its future sustainability.

4 Discussion

The APR hosts some of the world's marine biodiversity hotspots, including the Coral Triangle, that support ecosystem services critical to both regional and global human wellbeing. Uniquely, the impacts of climate change on the APR often diverge from global patterns due to its complex oceanography and high biodiversity. This calls for region-specific approaches to marine research and conservation that go beyond global models and are tailored to the APR's distinctive ecological and environmental dynamics.

Inconsistent data sharing remains a cross-cutting problem that hinders efforts to understand and manage marine ecosystems in the APR. Differences in scientific culture, technical capacity, and political sensitivities around sovereignty and resource control all limit collaboration and access to ecological data. Even when data exists, they are often fragmented or siloed within national institutions. Many key questions about ecosystem change, species responses, and climate resilience in the APR can only be answered through the integration of diverse datasets across disciplines, from physical oceanography to molecular ecology. Without shared, high-quality data, our ability to detect patterns, predict outcomes, and guide effective action remains severely constrained. New approaches to data-sharing aided by technology can help (e.g., Pendleton et al., 2019), but resolving data limitation issues in the APR will also require coordinated action among scientists and policymakers to strengthen existing channels for sharing data and building new ones. One example of how these challenges can be addressed is the international Argo program, which coordinates the deployment and management of ocean-observing floats across more than 30 countries (Wong et al., 2020). The program ensures that data collected by these floats are rapidly checked and made publicly available within about 24 hours, followed by more thorough quality control procedures carried out over the floats' operational lifespans to ensure long-term reliability. Argo follows FAIR (Findable, Accessible, Interoperable, and Reusable) data principles and is supported by regular international meetings that align standards and practices. This combination of coordination,

open data sharing, and ongoing quality assurance provides a useful model for strengthening data systems and regional cooperation in the APR.

A productive way forward is to build on regional initiatives that are already redefining how marine science is approached in the Asia-Pacific. This effort aligns with the goals of the World Premier International Research Centre Initiative-Advanced Institute for Marine Ecosystem Change (WPI-AIMEC), recently established at Tohoku University and Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and a satellite campus at the University of Hawai'i, Manoa. WPI-AIMEC brings together researchers across disciplines to better understand and forecast marine ecosystem responses to environmental change, with a global scope but a particular focus on the Northwest Pacific. As part of WPI-AIMEC's activities, our group contributes to an international, interdisciplinary effort to understand marine biodiversity and ecosystem change, where rapid environmental shifts demand regionally focused, fusion science approaches. Institutes like WPI-AIMEC illustrate the power of integrated marine ecosystem approaches that bring together oceanographers, climate scientists, and ecologists to address complex challenges from multiple angles. By combining physical and biological data across disciplines and borders, such efforts help generate more comprehensive insights into ecosystem change and resilience. Collaborative frameworks like this are essential for turning fragmented observations into coordinated action and for ensuring that science meaningfully supports the long-term health of marine ecosystems and human wellbeing across the APR.

Data availability statement

All datasets used in this study are publicly available. Core and BGC Argo float data, along with associated metadata, were obtained from the Global Data Assembly Centre (Argo, 2024). Sea surface temperature data from NOAA's OISST v2.1 product are available at <https://www.ncei.noaa.gov/products/optimum-interpolation-sst> (Huang et al., 2021). Ocean Health Index (OHI) data can be accessed via the <https://oceanhealthindex.org/> (Halpern et al., 2012). Merged satellite altimetry products are provided through the EU Copernicus Marine Service (European Union-Copernicus Marine Service, 2021).

Author contributions

HA: Data curation, Visualization, Writing – original draft, Writing – review & editing. SY: Supervision, Writing – original draft, Writing – review & editing. JK: Supervision, Writing – original draft, Writing – review & editing. AA: Writing – original draft. SA: Writing – original draft. EG: Writing – original draft. HI: Writing – original draft. EL: Writing – original draft. YL: Writing – original draft. GN: Writing – original draft. PP-P: Writing – original draft. FS: Writing – original draft. CA: Writing – original draft, Writing – review & editing. DA: Writing – original draft. AB: Writing – original draft, Writing – review

& editing. UD: Writing – original draft, Writing – review & editing. TF: Writing – original draft. FH: Writing – original draft. MK: Writing – original draft. TM: Writing – original draft. CP: Writing – original draft. LS: Writing – original draft, Writing – review & editing. TSh: Writing – original draft, Writing – review & editing. SS: Writing – original draft, Writing – review & editing. PS: Writing – original draft, Writing – review & editing. CA-R: Writing – original draft, Writing – review & editing. AW: Writing – original draft, Writing – review & editing. TSu: Funding acquisition, Project administration, Writing – original draft.

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