Two Centuries of Oceanographic Data in the Indonesian Seas and Surroundings: Historical Patterns of Data Availability, <s>Trends,</s> Gaps, and Future Challenges

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Abstract. The Indonesian Seas and Surroundings (ISS) play an important role in global ocean circulation by connecting the Pacific and Indian Oceans via the global thermohaline circulation. This region regulates the exchange of water mass, heat, salinity, and biogeochemical elements, further influencing the global climate and carbon cycle. Consequently, extensive observations and surveys, particularly the in-situ measurements, have been conducted over the past two centuries. This study analyzed over 461,865 oceanographic casts from multiple international repositories, with 360,409 casts, or 21.97 % rejection, after rigorous quality control. The findings indicate that data collection was sparse and temporally limited before the early 19th century, with a marked increase beginning from the mid-20th century. Spatially, observations are heavily concentrated along major international shipping routes, including the Makassar Strait, Malacca Strait, and South China Seas, while vast areas, such as the Halmahera Sea, Timor Sea, Java Sea, and Sulawesi Sea, remain poorly detected. Temperature and salinity are the most collected data, whereas deep-sea observations, particularly below 800 meters, are critically lacking, with limited measurements of essential ocean variables such as dissolved oxygen, nutrients, and currents. Additionally, coastal regions exhibit substantial data deficiencies. Given the region's complex ocean-atmosphere interactions and unique topographic features, the current observational coverage remains insufficient to resolve the uncertainties in Indonesian Throughflow (ITF) variability, ocean heat transport, and monsoon forecasting. This study proposes to address the gaps by deploying autonomous monitoring technologies (Argo floats, gliders, moored buoys) in deep-sea and coastal regions, expanding regional observational networks, and enhancing executable data-sharing mechanisms. The raw datasets can be accessed freely from the website provided in the text, and processed datasets are preserved in data repositories with a corresponding assigned DOI. Final datasets and the computed cast per half-degree grid square with Python syntax are freely available from the Mendeley

repository. The data were in the TXT file format, and we used Ocean Data View Software (ODV Ver. 5.7.2), Python, and QGIS Software to process, visualize, and analyze the data.

1. Introduction

The Indonesian Seas and Surroundings (ISS) is one of the complex systems with unique oceanographic characteristics (Burnett et al., 2000; Susanto et al., 2010; Wijffels et al., 2008). This region is the only one at the low latitude where two oceanic basins (the Pacific and Indian Oceans) connect and interact (Hu and Sprintall, 2017; Tillinger and Gordon, 2009). Given its unique position, the ISS plays a key role in regulating and distributing heat and salinity through the Indonesian Throughflow (ITF) and monsoon currents (Bouruet-Aubertot et al., 2018; Feng et al., 2018). This tropical region is also profoundly affected by climatic factors, including the El Niño-Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and seasonal monsoon patterns (Duan et al., 2023; Garternicht and Schott, 1997; Qian et al., 2010). ~~These interactions influence weather and regional climate within sea-air interactions~~ These modes of variability influence weather and regional climate via air-sea interactions and significantly affect marine biodiversity and fisheries (Khan et al., 2024; Wisetya Dewi et al., 2020). This region is also part of the Coral Triangle, a biodiversity hotspot that supports extensive coral reef ecosystems, serves as a critical migratory route for numerous fish species, and plays a vital role in regional and global marine biodiversity (Gusviga et al., 2021; Purba et al., 2025c). However, despite the critical importance of the ISS in regulating the global ocean and climate, the data collection in this region remains inconsistent, with significant data gaps in spatial and temporal scales. In the context of ongoing climate change, understanding the dynamics of the ISS is increasingly crucial (Makarim et al., 2019). ~~The data poverty in some critical regions, including ISS, further weakens the reliability of global warming projections~~ The scarcity of observations in critical regions, including the ISS, results in limitations in the evaluation and refinement of coupled climate models, resulting in greater uncertainty in the representation of regional processes and reducing confidence in projections for these areas (Faizal et al., 2021; Freeman et al., 2019; von Schuckmann et al., 2020; Vance et al., 2019).

In the era of satellite technology, previous studies demonstrated that direct in-situ measurement using instruments is still the most reliable method to observe ocean conditions, with the advantage of interior sampling capacity and high-precision data (Buck et al., 2019; Zweng et al., 2018). In recent decades, in situ~~in-situ~~ measurements have increased exponentially, greatly enhancing our ability to monitor oceanic changes (Liu et al., 2017; Roemmich et al., 2019). Various platforms, such as Conductivity Temperature and Depth (CTD) profilers, moorings, and Argo floats, can gather continuous, long-term datasets at great depths from the surface to the deep sea, capturing the vertical structure of the ocean (Whitt et al., 2020; Woo and Pattiaratchi, 2010). Furthermore, the integrated global ocean observation system has taken the strength of in-situ and satellite technology and has been highlighted and emphasized as important (Garzoli et al., 2010; Weller et al., 2019)~~(Garzoli et al., 2010; Weller et al., 2019)~~. Despite its accuracy, the main limitation of in-situ data is its sparse and uneven coverage both in temporal and spatial scales. Due to ~~this challenge~~these limitations, ~~the analysis of~~analyzing ocean conditions in terms of climate change ~~faces the challenge~~ is challenging, particularly in archipelagic countries and the deep ocean (Beal et al., 2019).

To support data collection, several global portals provide freely available oceanographic data, including the World Ocean Database (WOD), which offers comprehensive temperature, salinity, and oxygen profiles. Another global program is the

75   Copernicus Marine Environment Monitoring Service (CMEMS), which provides simulation, reanalysis, and real-time ocean data.

Furthermore, the Argo program, which gathers temperature and salinity data from ocean profiling floats, and the Global Ocean Observing System (GOOS), which integrates data from a variety of oceanographic sources (Bax et al., 2018; Boyer et al., 2018a; von Schuckmann et al., 2019). Recently, ~~within~~ as part of the UN Ocean Decade Programmes, there have

80   been actions to increase community resilience ~~to enhance~~ by enhancing various early warning services for all communities on multi-ocean hazards. The goal is to send these warnings ~~as fast as possible in (near) real-time~~ almost instantly or in real-time. The information required for this multi-hazard early warning service (MHEWS) includes geophysical, ecological, biological, weather, climate, and anthropogenic-related ocean and coastal hazards (Pandoe et al., 2024). Meanwhile, various institutions, including universities, research centres~~centers~~, private companies, and other stakeholders, collect and store oceanographic data

85   in a specific database. However, the regulatory frameworks and administrative procedures frequently obstruct access to this information.

This study advances prior research by systematically compiling two centuries of in-situ observations, identifying critical spatial and vertical data gaps, and assessing the implications for climate modelling~~modeling~~. Unlike past efforts, we quantify the rejection rates of different datasets, analyze international contributions to ISS data collection, and highlight the

90   disproportionate underrepresentation of local research efforts. This study investigates how spatial and temporal data gaps in the Indonesian Seas impact our understanding of regional ocean dynamics and global climate models. We hypothesize that the uneven distribution of in-situ observations, particularly in deep-sea regions, coastal regions, and ITF pathways, introduces significant uncertainties in ocean heat transport assessments, climate change projections, and regional fisheries management strategies. The output of this result will align with the UN Ocean Decade (2021-2030) and Sustainable Development Goals

95   (SDGs 13 and 14) for the blue economy (Rayner et al., 2019).

2. Method

2.1. Geographic Characteristics

ISS is situated in the equatorial region where dynamic interactions between oceanographic, terrestrial, and atmospheric phenomena occur (Lan et al., 2009; Wang et al., 2017). In this paper, the ISS refers to the region spanning from

100   15 °N to 15 °S and 90 °E to 140 °E. The water depth across this region exhibits significant~~great~~ variation, where Karimata Strait and Java Seas are characterized by shallow water (<100 m), monsoonal currents, and strong tides effect (Katavouta et al., 2022; Lana et al., 2017), while the deep region goes up to 6000 m such as in the Banda Sea, the surrounding Indian Ocean and the Pacific Ocean. Due to differences in sea level, the water mass flow from the Pacific to the Indian Ocean via the

Indonesian Seas has three branches: eastern throughflow via the Makassar Strait, Maluku Seas, and western throughflow through the Karimata Strait (Putriani et al., 2019; Susanto et al., 2010). The water mass in the ISS predominantly comes from the Pacific, including the South Pacific Subtropical Water (SPSW), the North Pacific Intermediate Water (NPIW), and South Pacific Intermediate Water (SPIW) (Coatanoan et al., 1999; Li et al., 2021). While in the deep southern ISS water, the Antarctic Bottom Water (ABW) flows to the equatorial region near the Savu Seas and surroundings. On the other hand, the mixing processes in the ISS are strongly influenced by monsoonal winds, tidal forces, and internal waves (Atmadipoera and Suteja, 2018)(Atmadipoera and Suteja, 2018). The seasonal monsoons, driven by differential heating between the Asian and Australian continents, generate reversing wind patterns that control surface circulation and upwelling events (Moore et al., 2003)(Moore et al., 2003) (Figure 1Figure 1).
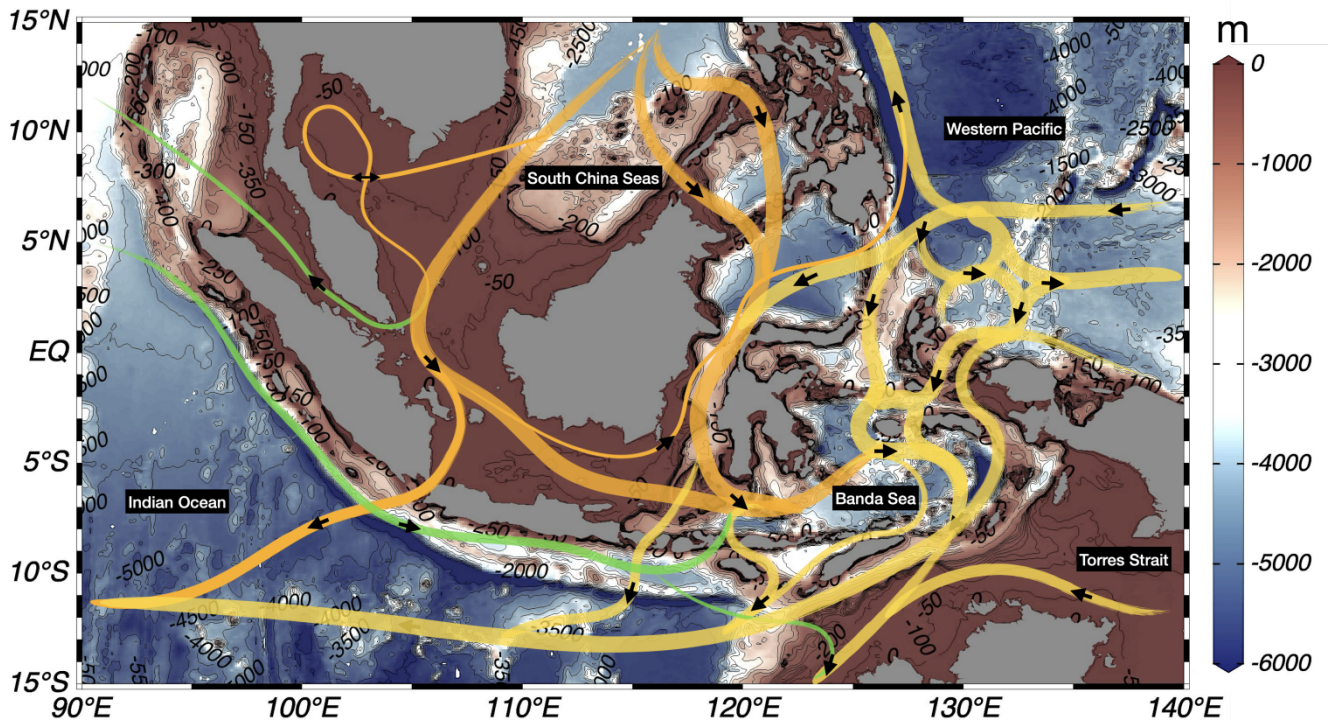
Figure 1: A map of Indonesian seas and surroundings (bathymetric derived from www.gebco.net). Schematic general circulation is presented with lines and adopted from previous findings (Burnett et al., 2000; Gordon, 2005; Shinoda et al., 2012; Susanto et al., 2010)**. Yellow lines represent water mass from the Pacific Ocean, orange lines represent water mass from the South China Sea (SCS) through the Karimata Strait, and green lines represent water mass from the Indian Ocean.**

Beyond the ITF, circulation patterns in the Indonesian seas are significantly affected by monsoonal winds, tidal forces, and large-scale climate phenomena such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Heryati et al., 2018; Horhoruw et al., 2020; Johari et al., 2021). During the boreal summer monsoon (June–September), strong southeasterly winds enhance the ITF transport, driving water southward into the Indian Ocean. Conversely, in the boreal winter

monsoon (December–March), shifts in wind patterns allow water from the South China Sea to flow into the Indonesian seas, temporarily altering the strength of the ITF. These seasonal variations influence coastal upwelling processes, particularly along the southern coasts of Java and Sumatra, which contribute to increased marine productivity (Iskandar et al., 2017; Purba et al., 2025c; Sidik et al., 2025). In addition to monsoonal influences, regional circulations play a vital role in shaping the hydrodynamics of the Indonesian seas. The South China Sea exchanges water with the Indonesian seas through the Karimata and Malacca Straits, affecting salinity and temperature distributions (Duan et al., 2023; Idris et al., 2020; Moore et al., 2003). The Torres Strait, located between Australia and Papua New Guinea, facilitates water exchange between the Arafura Sea and the Coral Sea, further impacting the broader circulation system. These complex interactions underscore the Indonesian seas as a highly dynamic environment where multiple oceanic and atmospheric processes converge.

2.2. Data Sources

A comprehensive inventory of oceanographic data sources since the 18th century is essential for understanding the variability and long-term trends in the ISS regions. Various international and national programs have contributed to collecting key oceanographic parameters, including temperature, salinity, pH, dissolved oxygen, chlorophyll achlorophyll a, and nutrients (nitrate and nitrite), using diverse observational platforms. Fortunately, several global open repositories provide open access to the in situin-situ dataset for this study (Table 1Table 1). While direct access to national government and institutional data were not available at this stage, we utilized reliable open-source data and look forward to potential future collaborations in the future with various research institutions, particularly in Indonesia, to improve oceanographic data recording in the regions. However, several valuable datasets websites from the Indonesian National Oceanographic Data Centre (NODC) and the National Scientific Repository (Repositori Ilmiah Nasional: RIN) can be accessed freely, although the data are not yet available. Also, the data from BRIN comes from various oceanographic data surveys from 1991 to the present, which were also available. Additional data from the Padjadjaran Oceanic Data CentreCenter (PODC), hosted by Universitas Padjadjaran, provides essential oceanographic data relevant to the region. Furthermore, we also searched for data or metadata that had already been published online on the official government website. These dataset sources provide in-situ data on physical, chemical, and biological oceanographic parameters, allowing for mapping oceanographic conditions and enhancing our understanding of dynamic processes in Indonesian waters (https://doi.org/10.17632/fnn6tsjckn.1).

Table 1: List of datasets, parameters, and sources of data

No.	Source and established	Variable	Depth (m)	Instrument	Country	Metadata	Raw Data

1	Argo Program (1998)	Temperature, Salinity	0 to 2000	Profiling floats	Consortium	X	X
2	GOOS (1991)	Temperature, Salinity	All layer	Gliders, Argo Floats, XBTs, Niskin bottles	Consortium	X	X
3	TAO Project (1984)	Temperature	0 to 500	CTDs	FR, JP, and US	X	X
4	INAGOOS (2005)	Temperature, Salinity, Chlorophyll-a, pH, Dissolved Oxygen, Nitrate	0 to 10	CTDs, moored buoys	ID	X	X
5	NODC	Salinity, Temperature	0 to 1200	CTD, XCTD	ID	X	
6	SEA-GOOS (1999)	Temperature, Salinity	All layer	Gliders, Argo Floats, XBTs	Consortium	X	X
7	WOD (1998)	Temperature, Salinity, pH, Chlorophyll-a, Nitrate, Nitrite	All layer	CTDs, Argo Floats, XBTs, MBTs, OSDs, PFLs, Niskin bottles	Consortium	X	X
8	RAMA Buoy (2004)	Temperature, Salinity	0 to 500	Moored buoys	CH, IN, ID, JP, and US	X	X
9	WOCE (1990)	Temperature, Salinity	All layer	CTDs, ADCPs	CA, FR, JP, and US	X	X
10	PODC (2015)	Temperature, Salinity, Chlorophyll-a, pH, Dissolved Oxygen, Nitrate	0 to 100	Niskin bottle, portable instruments	UoP	X	X

11	CCHDO (1995)	Temperature, Salinity, pH, Dissolved Oxygen	0 to 11,000	CTDs, Niskin bottles, moored and drifting buoys	Consortium	X	X
12	RIN BRIN	Temperature, Salinity	All layer	CTDs, moored and drifting buoys	ID	X	X
13	PANGAEA	Temperature, Salinity	All layer	CTDs	DE	X	X
14	COO	Temperature, Salinity	All layer	CTDs, XBTs, MBTs, Bottles, moored buoys, Profilers, Drifters, TSGs	FR	X	X

CH, FR, ID, IN, JP, and US stand for China, France, Indonesia, India, Japan, the United States of America, and UoP for the University of Padjadjaran. The technical names follow the standard rule: XBT represents the Expendable Bathythermograph, CTD represents the Conductivity-Temperature-Depth profiler, and MBT represents the Mechanical Bathythermograph.

155

In detail, the some key global projects and initiatives focusthere are key global projects and initiatives that focus on measuring in-situ data in the ISS, such as the Argo Program (https://argo.ucsd.edu), Global Ocean Observing System (GOOS) (https://goosocean.org), Tropical Atmosphere Ocean (TAO) Project (https://tao.ndbc.noaa.gov), Indonesian Global Ocean Observing System (INAGOOS), Indian Ocean Global Ocean Observing System (IOGOOS), and Southeast Asian Global Ocean Observing System (SEA-GOOS) (https://goosocean.org). The Argo Program is an initiative that deploys a global network of profiling floats to collect data on ocean conditions, including temperature, salinity, and some chemical and biogeochemical parameters from the surface to 2000 m depth. Argo floats are deployed in the outer ofISS waters, contributing to understanding ocean dynamics in the region. Meanwhile, GOOS is a permanent global system for observations, modellingmodeling, and analysis of marine and ocean variables to support operational ocean services worldwide. Indonesia participates in GOOS through regional alliances and contributes data from its waters to the global system. The TAO project and its Western Pacific counterpart, TRITON (https://www.jamstec.go.jp/jamstec/TRITON/real_time/), maintain an array of moored buoys in the tropical Pacific Ocean, measuring surface meteorological variables and oceanographic variables. The SEA-GOOS is a regional alliance under GOOS focusing on Southeast Asian waters, including Indonesia. It aims to enhance the region's ocean observations and data-sharing capacity. Indonesia is a key participant, contributing to and benefiting from regional oceanographic data. Other data used in this paper were from the World Ocean Database 2018 updated (WOD-18, https://www.ncei.noaa.gov/products/world-ocean-database) by the National Centers for Environmental Information (NCEI), RAMA Array (https://www.pmel.noaa.gov/gtmba/pmel-theme/indian-ocean-rama) by the Pacific Marine Environmental Laboratory (PMEL) of NOAA, The Hydrographic Program of the World Ocean Circulation Experiment (WOCE,

https://ewoce.org/data/index.html), CLIVAR and Carbon Hydrographic Data Office (CCHDO: https://cchdo.ucsd.edu/),
175   PANGEAE (https://www.pangaea.de/), and Coriolis Operational Oceanography (https://www.coriolis.eu.org/).

2.3. Data Filtering

       Most of the information provided is still in its raw form, and comprehensive screening was carried out to ensure there
were no duplicates, outliers, or biased data. Duplicate data can exist due to repetition of data input, use of the same source by
various data providers, and errors during data input. All data were carefully compared, and the duplicates were determined
180   based on key identifiers: ID, latitude and longitude, cruise name, and timestamps. Data with similarities in these criteria
resulted in the same actual values-; thus, it was labelled labeled duplicate data and deleted. It is necessary to eliminate all data
with errors, such as inconsistent measurements or errors in measuring devices. The data were downloaded and imported into
Ocean Data View (ODV ver. 5.7.2) (Schlitzer, 2024)(Schlitzer, 2024) to detect duplicate data, remove biased data, and show
the results. The removed temperature and salinity data were those outside Indonesian waters' characteristics, specifically the
185   temperature range of -2 to 35 °C and the salinity range of 20 to 40 psu, respectively (Purba et al., 2021; Webb, 2021)(Purba et
al., 2021; Webb, 2021). The typical pH range in the Indonesian seas generally falls between 5 and 9. The concentration of
dissolved oxygen (DO) typically varies between 3 and 8 milligrams per litre liter (mg/L). Nitrate concentrations usually range
from 0.5 to 20 μmol/L (Valdany et al., 2022). Other temperatures and salinity data are all obtained from the WOD-18, so
filtering was carried out based on quality flag 0 (accepted value) on the WOD dataset to filter out error data. The weighted-
190   average gridding interpolation method was used in scalar values, and corrections were done according to NCEI Guidance and
correction schemes (http://www. nodc.noaa.gov/OC5/XBT_BIAS/xbt_bias.html).

       The initial screening showed that the dataset comprises 461,865 casts from various oceanographic sources, of which
360,409 casts remained after screening, resulting in an overall 21.97% rejection rate. The highest rejection rate is observed in
WOD XBT (45.36%), followed by Argo Float (19.88%) and EWOCE (13.20%). This result indicates significant data filtering
195   for these sources. In contrast, datasets such as WOD OSD (0.09%), WOD MBT (0.02%), and WOD CTD (0.03%) experienced
minimal data rejection. Notably, data from Rama Buoy, NANO-DOAP, and TOA Buoy remained intact, with 0.00% rejection.
Other datasets, including PODC (7.71%), PANGEAE (4.82%), and CCHDO (3.15%), had moderate rejection rates. These
variations reflect differences in data quality across sources, with some requiring substantial filtering while others maintained
high data integrity.

200   The high rejection rate of WOD XBT (45.36%) is likely due to several factors related to data quality and instrument
limitations. XBTs (Expendable Bathythermographs) estimate depth using a fall-rate equation rather than direct measurement,
which can introduce errors due to variations in probe type, water temperature, and deployment conditions. Additionally, many
XBT datasets originate from historical observations, some of which may not meet modern quality standards, leading to more
rejected profiles. Unlike CTDs, XBTs do not measure salinity or pressure, making their data less comprehensive and more
205   prone to exclusion if supporting parameters are missing. Since commercial vessels frequently deploy XBTs, operational issues
such as improper probe deployment, variations in ship speed, or incorrect metadata can further compromise data reliability.

Lastly, the WOD-18 applies strict screening procedures to eliminate duplicates, outliers, and spurious values, and given the inherent accuracy limitations of XBTs, a significant portion of the data is filtered out during quality control (Table 2).

Table 2: Summary of oceanographic datasets used in this study, including the number of casts before and after data screening and the rejection rate for each dataset.

Number	Dataset	Number of casts		
		Raw	After screening	Rate of rejection
1.	WOD XBT	163,914	89,562	45.36%
	WOD OSD	36,063	36,029	0.09%
	WOD MBT	67,181	67,165	0.02%
	WOD CTD	12,491	12,487	0.03%
2.	PODC	2,621	2,419	7.71%
3.	Rama Buoy	14,303	14,303	0.00%
4.	Argo Float	87,422	70,040	19.88%
5.	EWOCE	70,080	60,826	13.20%
6.	NANO-DOAP	87	87	0.00%
7.	PANGEAE	3,404	3,240	4.82%
8.	CCHDO	1,523	1,475	3.15%
9.	TOA Buoy	2,776	2,776	0.00%
	Total Data	461,865	360,409	21.97%

XBT = Expendable Bathythermographs; CTD = Conductivity, Temperature, and Depth Profiler; OSD = Ocean Station Data; MBT = Mechanical Bathythermographs

The WOD-18 contributes significantly, with its subcategories including XBT, OSD, MBT, and CTD. Among these, the WOD XBT dataset, with 163,914 raw casts and 89,562 after screening, represents the most considerable contribution, followed by the WOD MBT, which shows only a minimal reduction after screening (67,181 raw to 67,165 screened). Other key datasets include the Argo Float data, with 87,422 raw casts, of which 70,040 were retained after screening, and the EWOCE dataset, which containsincludes 70,080 raw casts, reduced to 60,826 after screening. In comparison, smaller datasets such as the PANGEA, NANO-DOAP, and CCHDO represent more specific collections but are still critical to the overall database. Some datasets, like the Rama Buoy, TOA Buoy, and NANO-DOAP, underwent no reduction during the screening process, indicating high-quality, reliable initial data.

2.4. Visualization and Data Analysis

After filtering, the data were visualized to understand the spatial and temporal patterns of the collected oceanographic parameters. The collected data will be were analysed across different oceanic regions, including the Pacific Ocean, Indian Ocean, Malacca Strait, Natuna Sea, South China Sea, Makassar Strait, Java Sea, and Banda Sea. This regional approach will

helped to identify spatial and vertical data distribution, including parameter changes in oceanographic conditions, contributing to a better understanding of data in the ISS region. Visualization was carried out in three forms: surface profiles, vertical

230   profiles, and graphs representing a country's contribution to oceanographic data collection. Surface profiles were generated to illustrate the spatial distribution of oceanographic parameters across different seasons and years, helping to identify gaps in data and future research. Additionally, vertical sections were constructed to analyze subsurface data, particularly in the Indonesian Throughflow (ITF) pathways, such as the Makassar Strait, Lombok Strait, Ombai Strait, and Timor Passage. These profiles provided insights into the existing data, revealing significant gaps in deep-sea measurements, ~~significant~~particularly

235   in the water column. We generated graphs categorizing observations by country ID and instrument type to evaluate international contributions to ISS oceanographic data. All visualizations were created using Ocean Data View (ODV) version 5.7.2 and Python-based geospatial libraries, enabling high-resolution spatial mapping and time-series analysis.

We used Kernel Density Estimation (KDE) to estimate the probability density function (PDF) of a continuous random variable. This method works by placing a kernel function on each data point. These kernels are then summed to produce a

240   continuous density curve representing the underlying data distribution. The smoothness of the KDE output depends on the bandwidth parameter, which controls how much each data point influences the overall density estimate. A larger bandwidth results in a smoother distribution, while a smaller bandwidth retains more details but may introduce noise.

245

$$f(x) = \frac{1}{nh} + \sum_{i=1}^{n} K(\frac{x-xi}{h})$$

where: fx = estimated probability density function (PDF) at point x; n = number of data points; h = bandwidth (smoothing parameter); K = kernel function; xi = observed data points. The kernel function is a smooth function that determines

250   the shape of the contributions from each data point. A common choice is the Gaussian kernel:

$$K(u) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}u2}; u = \frac{x-xi}{h}$$

The bandwidth h plays a crucial role in KDE, where ~~A~~ a small h results in a density estimate that captures more details but

255   may introduce noise (overfitting), and ~~A~~ a large h produces a smoother estimate but may obscure important data features (underfitting). Furthermore, the ~~Calculation~~ calculation of data density began by creating a grid in the study area with a latitude and longitude coverage in each grid of 0.5°. The grid for which data density was calculated is a grid that completely fits the boundaries of the study area. Meanwhile, grids that did not fully enter the study area were not included in the calculation. The data density in each grid cell was calculated using the following formula:

$$D_{ij} = \frac{N_{ij}}{A}$$

Wherewhere: D_{ij} = data density in a specific grid cell (i, j); N_{ij} = number of data points inside that grid cell; A = area of the grid cell.

Since the desired unit is cast per half-degree squares and each grid that had has been created is exactly half a degree, then the formula simplifies to:

$$D_{ij} = N_{ij}$$

The data density value in each grid cell is then represented by a centroid located in the middle of each grid cell.

The data density values in the study area were further divided into six quantiles to understand more clearly how the data is distributed. The quantile classification was calculated using the following formula:

$$Q_k = F^{-1}\frac{k}{6}, \qquad k = 1, 2, 3, 4, 5$$

Wherewhere: Q_k = the actual breakpoints for the six quantiles; F^{-1} = the inverse Cumulative Distribution Function (CDF) to find out the data values contained in specificcertain cumulative percentiles: $\frac{k}{6}$ = the quantile fraction

DThe denominator 6 in the formula above was chosen because the data is divided into six quantiles. The k value has a range from 1 to 5, so it can provide five5 breakpoints to create six quantiles. To get the quantile distribution, data values were sorted from smallest to largest. Then, the percentile is selected corresponding to: Q_1 = 16.67% percentile (1/6), Q_2 = 33.33% percentile (2/6), Q_3 = 50.00% percentile (3/6, median), Q_4 = 66.67% percentile (4/6), Q_5 = 83.33% percentile (5/6). This calculation divides the dataset into six quantiles that have the same number of data points. Because density calculations up to quantile division did not consider grid cells with zero data points, new centroids were added for the grid cells with zero data points .. pointsEmpty cells are shown as 'Q0 (No Data)' and are not part of the quantile calculation. So Thus, the legend on the visualization becomes as follows: zero data points Q_0 (No Data), Q_1, Q_2, Q_3, Q_4, Q_5, Q_6.

3. Results

3.1. Summary of Data by Instruments Sampling

In general, expendable instruments such as XBT and MBT are frequently deployed, especially in the SCS region, the Malacca Strait, and from the Sunda Strait to Australia (ALKI 1). Autonomous platforms, such as drifters and profile floats, are more common in deep-ocean regions such as the Banda Seas, west Sumatera, south of Java, and northern Papua. The SCS, Savu Sea, Sulawesi Sea, and Banda Sea are regions with a small number of profile float casts. At the same time, the profile float is lacking in the Malacca Strait, Java Sea, and Arafura Sea (Figure 2Figure 2). The highest density of observations is found along major shipping routes (Indonesian Archipelagic Sea Lanes; hereinafter: ALKI), where there are three ALKI lines

in Indonesian seas, including the Malacca Strait, SCS to Sunda Strait (ALKI 1), Makassar Strait to Lombok Strait (ALKI 2),
Maluku Sea to Savu and Timor Passage via Banda Sea (ALKI 3).
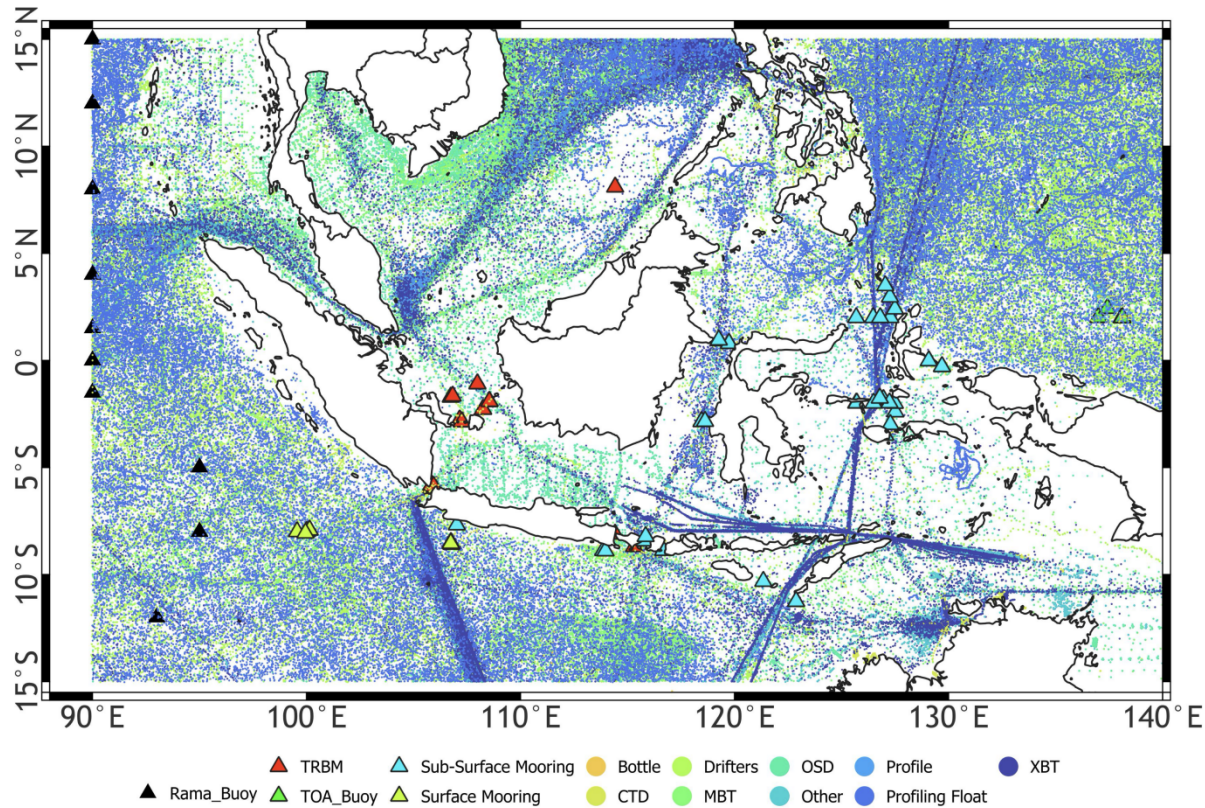
Figure 2: Spatial distribution of oceanographic data casts in the ISS region, categorized by different data collection methods. The dataset includes observations from buoys (yellow triangles), bottles (light blue), CTD (orange), OSD (cyan), MBT (red), XBT (light green), drifters (grey), profile floats (magenta), and other sources (dark blue).

The number of cast data from XBT in the Indian Ocean is 36,007, and 16,554 in the Pacific Ocean, with the most dominant location being the area approaching the Philippines. The use of MBT has better coverage in the Indian Ocean, with a total data cast of 23,660, while in the Pacific Ocean is 15,511. The distribution of drifter use in the study area is generally similar to Profile Float, where the instrument is predominantly used to collect data in the Indian and Pacific Oceans. The use of drifters in the Indian Ocean has been recorded with 14,285 data casts, while in the Pacific Ocean is 21,663. Due to the drifter's characteristics of moving with the ocean current, its coverage in the Indian Ocean is almost similar to that of the Profile Float. The SCS, Java Sea, and Banda Sea regions have much less cast drifter data. Then, data collection that falls into the OSD category tends to be mainly carried out in the SCS and Java Sea.

Oceanographic data collection using buoys is only carried out in a small part of the Indian Ocean, especially at longitude 90°E, and a small part of the Pacific Ocean, around 400 km north of Papua. Despite its small coverage, this instrument has recorded 14,334 data casts, with the most significant proportion being in the Pacific Ocean, 14,303, and the remaining 31

in the Indian Ocean. CTD is predominantly used to retrieve oceanographic data in the Pacific Ocean, with the number of data casts being 6,017, the second lowest in all categories. Meanwhile, the number of data casts in the Indian Ocean is 3,393, the second lowest of all categories. Its distribution in the Pacific and Indian Ocean is relatively even, not concentrated in certain areas. Because CTD has the second-lowest number of data casts among all categories, it fails to cover many water areas, including the Java and Arafura Seas. The number of data casts using bottles is the lowest of all categories. This instrument is only used in the Indian Ocean, the Pacific Ocean, the Makassar Strait, and the Banda Sea. Water areas other than these four areas are not covered at all. The distribution in the Indian Ocean shows only a few data collection transects, with a total of 736 data casts. The same condition is also found in the Pacific Ocean, where the data collection pattern using bottles only shows eight transects with a total of 1,290 data casts. The amount of cast bottle data in the Pacific and Indian Oceans is the lowest of all categories.

3.2. Spatiotemporal Trends of Oceanographic Observations from 1800 to 2024

The quantity of oceanographic observation stations has significantly risen over the last two centuries. The spatial distribution of oceanographic data across ISS demonstrates significant spatial heterogeneity, with higher concentrations along international shipping lanes (ALKI) and major research expeditions. At the same time, vast areas, particularly in remote archipelagic waters, lack continuous monitoring. Spatially, oceanographic data in the study area have been recorded since 1800. Oceanographic measurements continued to develop over time (Figure 3Figure 3). From 1800 to 1900, oceanographic measurements were only conducted in several limited regions, including the Andaman Seas, Sulu Seas, Eastern Indian Ocean, and around Papua. The number of measurements began to increase significantly during the period 1911-1920, particularly in the Natuna Seas and SCS, the Malacca Strait, and the Java Seas. The decade 1921-1930 witnessed the increasing measurements in the eastern ISS. The Western Pacific was much sampled in the 1930s and 1940s, likely while the ocean measurements in the SCS bloomed since the 1950s, but noticeably reduced after 2000. During World War II, most measurements were conducted in the eastern Indonesian Seas, including the Banda Sea, Savu Sea, Makassar Strait, Aru Sea, and Seram Sea.
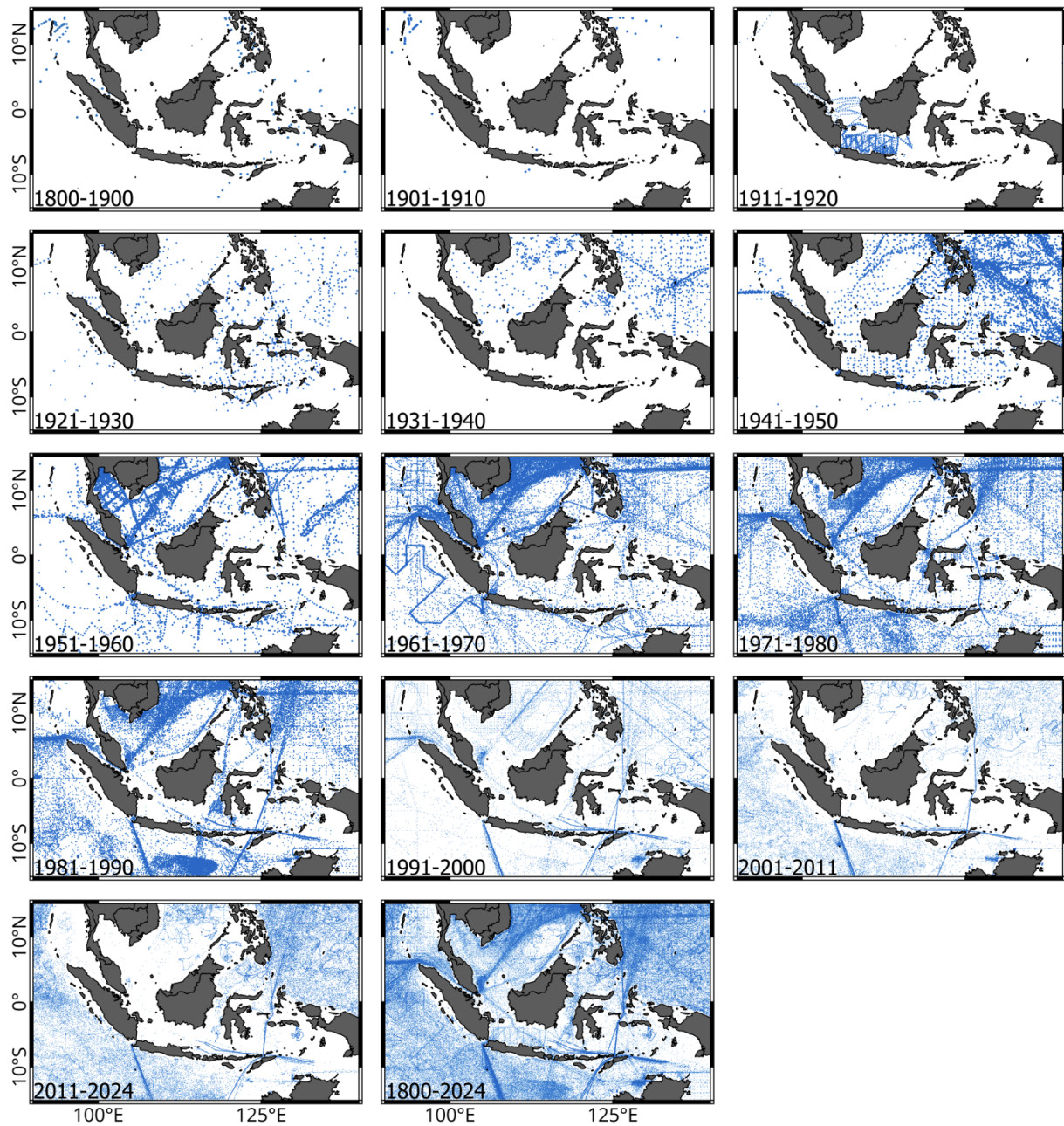
Figure 3: Spatial distribution of ocean data represented by blue dots from 1800 to 2024

Furthermore, samplings were also done in the Gulf of Thailand and the Sulu Seas near the Philippines. Since the mid-19th century, oceanographic measurements have rapidly increased, mainly due to new technology and the ~~raising~~ise of commercial and cargo ships. Global trade has a clear footprint in the spatial distribution of oceanographic data, which aligns with the shipping routes established by the ISS, specifically the ALKI. In this period, the SCS, including the Gulf of Thailand, hosted the densest concentration of data points. The region from southern Sumatra to Papua also appears to have a large distribution of data points showing the shipping lanes. Measurements in the Western Pacific Ocean have kept increasing, with dense data measurements along some shipping lanes from the Philippines. Apart from that, the three water areas that ALKI passes through also significantly increase data collection points. This can be seen in the Sunda Strait, Makassar Strait, and the ALKI III route, which stretches from the Molucca Sea (near Halmahera) to the Savu Sea (near East Nusa Tenggara). However, the latest period from 2001 to 2024 has a different distribution of data points. During this period, oceanographic data measurements in the SCS and the Gulf of Thailand decreased drastically. Not many measurements were made in these two regions, and only a few were made in the central to northern SCS. This condition was most likely caused by the monetary crisis, which resulted in economic instability in Indonesia in the late 1990s. In addition, the global COVID-19 pandemic, which resulted in many restrictions, also weakened in situ~~in-situ~~ data collection in this area. In contrast, the distribution of data points in other water areas has a higher density than in previous periods.

During the measurement period, the number of oceanographic data collection casts ~~has~~ increased from 1950 and had a relatively flat growth until 2000. A significant increase occurred between 2000 and 2005, with measurement points approaching 200,000. This increase is higher than the accumulation of previous years. After this period, oceanographic data measurements have shown a decreasing trend until 2024 (Figure 4~~Figure 4~~).
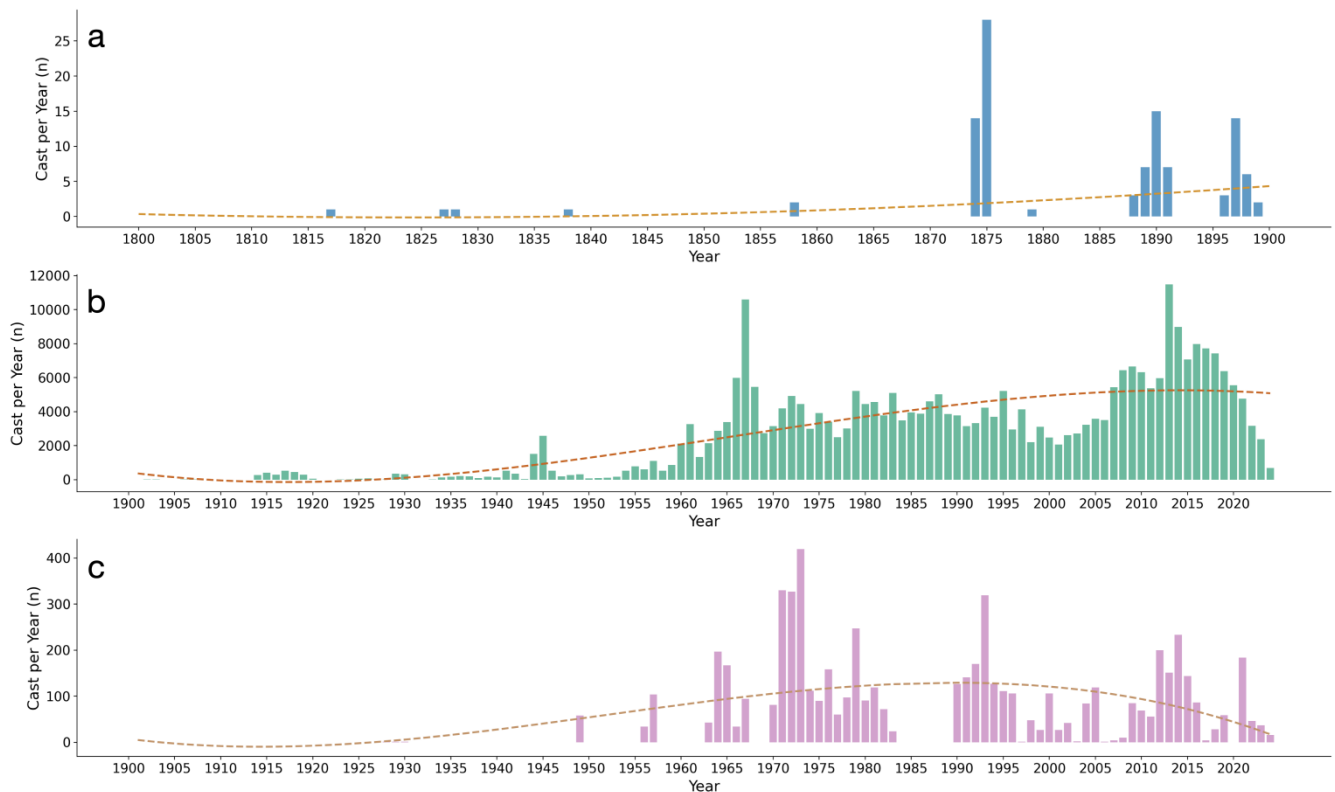
Figure 4: In-situ measurement in the ISS region from 1800 to 2024, a) range from 1800 to 1900, b) cast data from international (blue bars) and Indonesia (red bars), c) Specific to expedition or measurement by Indonesian institution. Dash lines 10-year trends.

Between 1800 and 1900, only 106 stations existed worldwide, indicative of the restricted spread and technological advancements of that era. Between 1901 and 1925, the total escalated to 2,419 stations, signifying the expanding phases of more organized and extensive oceanographic investigation. The expansion persisted consistently, resulting in the establishment of 8,273 stations from 1926 to 1950. Massive oceanographic data measurements in Indonesian waters began to be conducted in 1951. From 1951 to 1975, a substantial increase occurred, with the number of stations escalating to 68,286, driven by breakthroughs in marine technology and increased global interest in oceanic research. In a worldwideglobal perspective, until 1974, there were 1,490,000 total stations. This trend in the ISS continued from 1976 to 2000, with the number of stations increasing to 94,328.

Meanwhile, the global total station on a relatively similar temporal scale is almost 7,000,000 stations. The most remarkable significant rise in the ISS occurred in the 21st century, with the number of stations rising to 725,298 from 2001 to 2024, indicative of the global focus on ocean monitoring, satellite integration, and the enhanced accessibility of advanced observational instruments. The same condition occurred in global data recording, where the total number of stations soared to 18,625,988 stations. Massive oceanographic data measurements in Indonesian waters began to be conducted in 1951.

370   Massive oceanographic data collection in Indonesian waters started in 1951, with significant contributions from national and international research programs. The South China Sea (SCS) and the Malacca Strait had the highest number or frequency of oceanographic data measurements between the 1960s and 1990s. During this period, there was likely a significant focus on collecting oceanographic data in these regions, possibly due to research initiatives, increased regional maritime activities, exploration projects, or technological advancements in oceanography.

375

3.3. National and International Project Collaboration

The global distribution of oceanographic data reflects significant disparities in research contributions across different countries. While some nations have established extensive ocean observation programs, others remain underrepresented in global data collection efforts, particularly in developing regions. Countries like the United States, Japan, and Australia lead in
380   the number of casts, contributing valuable in-situ data to international initiatives (Figure 5Figure 5). With 92,329 casts annually, the United States shows up as the primary contributor—25.62% of all casts., and Australia with 58,508 casts (16.27%). With 52,612 casts (14.63%), Japan maintains a significant presence in the Pacific and Indian Oceans through many organizations. Furthermore, China has shown increasing engagement in oceanographic research (14,674 casts, 4.08%). From European countries, including France (2,735 casts, 0.76%), Germany (3,470 casts, 0.96%), and Great Britain (17,704 casts,
385   4.92%).
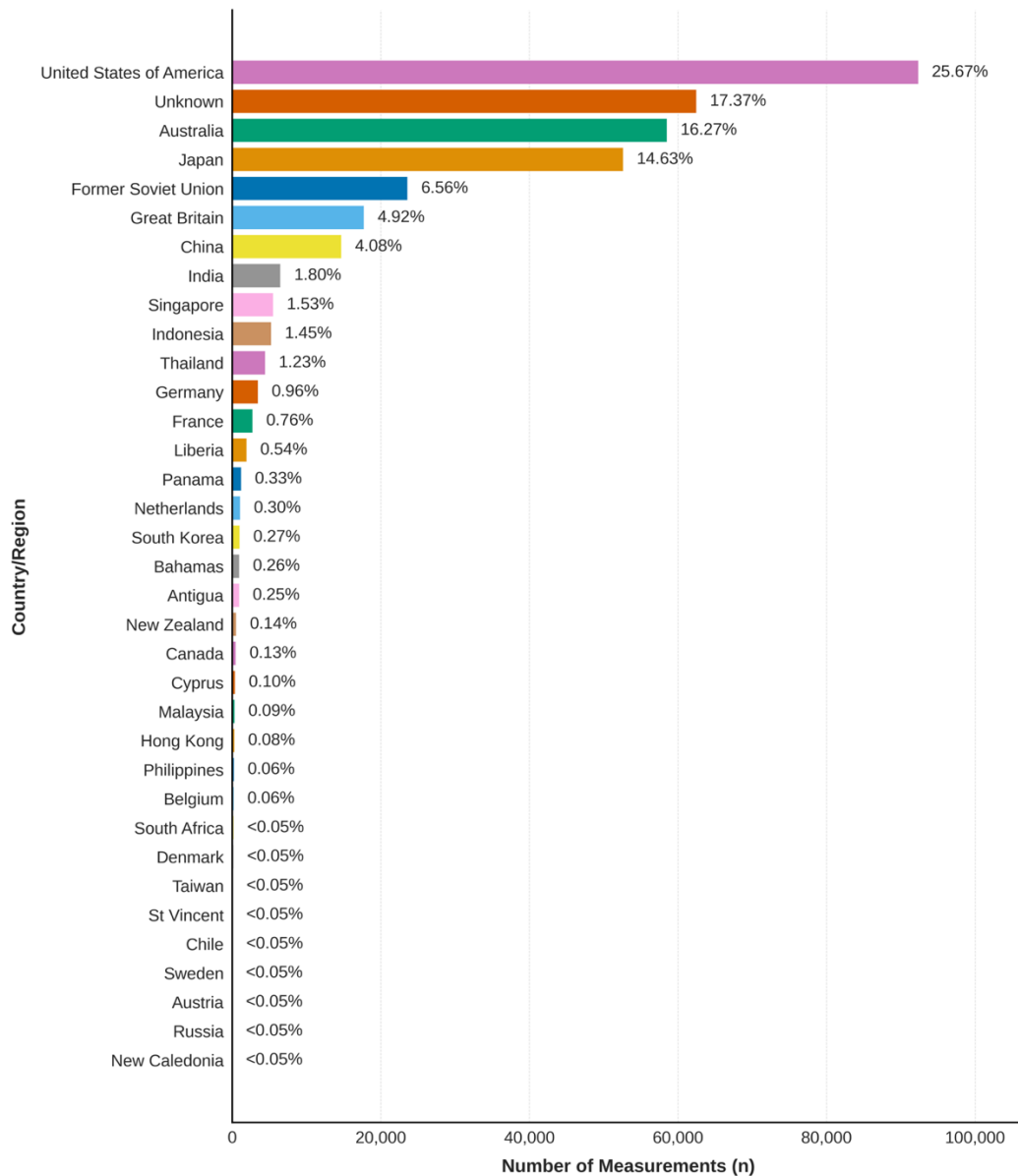
Figure 5: Number of oceanographic casts per year by country/region in the ISS regions

390 ~~The data cast contributions highlight the varying levels of oceanographic research participation across different countries. The United States leads with 92,329 casts (25.62%), and Australia with 58,508 casts (16.27%). With 52,612 casts (14.63%), Japan maintains a significant presence in the Pacific and Indian Oceans through many organizations. Furthermore, China has shown increasing engagement in oceanographic research (14,674 casts, 4.08%). From European countries, including France (2,735 casts, 0.76%), Germany (3,470 casts, 0.96%), and Great Britain (17,704 casts, 4.92%).~~

395   In Southeast Asia, Singapore (1.53%), Thailand (1.23%), and Indonesia (1.45%) have contributed to regional oceanographic datasets. Interestingly, a substantial portion of oceanographic data is categorized as "Unknown" (17.37%, or approximately 62,455 casts), which likely originates from historical datasets with missing metadata, classified military data, or contributions from private vessels and commercial ships. Additionally, some countries, such as Russia, New Zealand, and other regions/nations, show minimal data contributions (<0.05%).

400 **3.4. Variability and Frequency Distributions of Key Oceanographic Parameters**

        The KDE analysis highlights distinct oceanographic characteristics across different sea and ocean regions. The height and width of density peaks provide insights into the concentration and variability of key parameters, while multiple peaks indicate clustering around different values. Each region exhibits unique patterns, reflecting the diverse oceanographic processes at play (Figure 6).

405
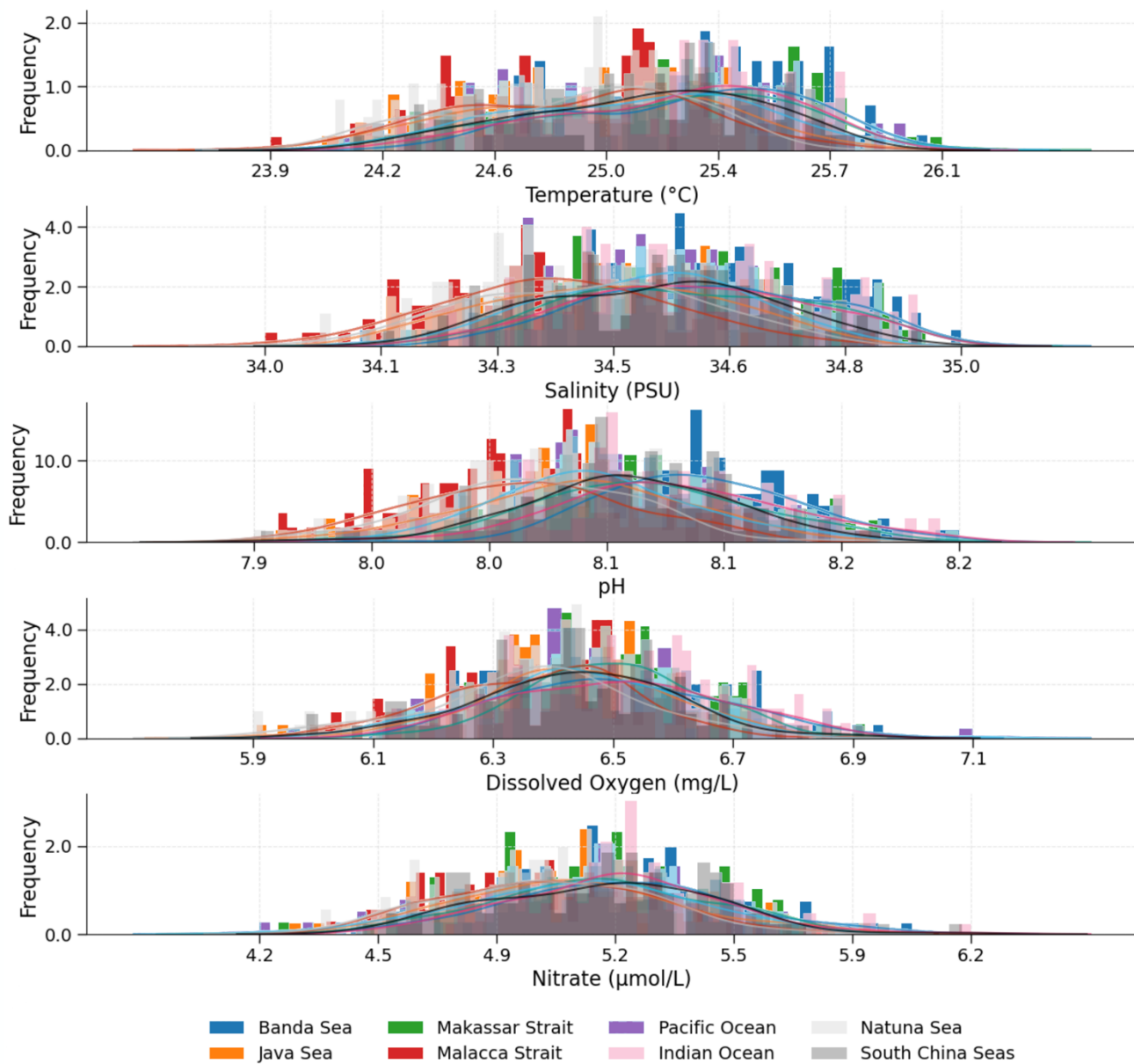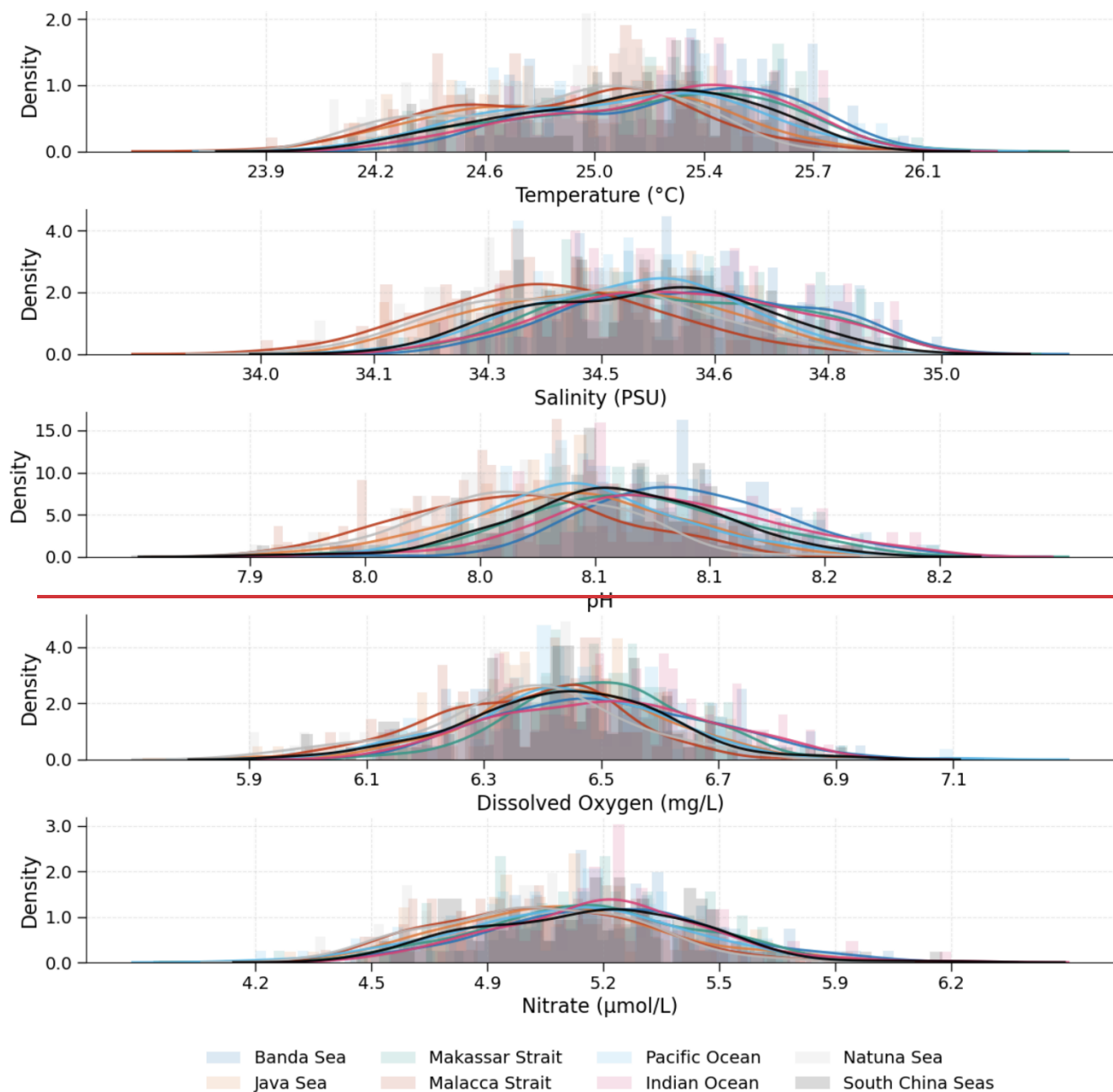
Figure 6: Distribution of five essential ocean variables by region, where the histogram (filled colours) shows data density and line colours show smoothed distribution using the KDE estimation method

The Banda Sea demonstrates consistently high values across multiple parameters. With the highest recorded average temperature of 25.25°C (24.33°C to 26.05°C), it is one of the warmest regions. This warmth is accompanied by high salinity, averaging 34.62 PSU, making it one of the more saline water bodies in the region. Furthermore, the Banda Sea has notably high dissolved oxygen levels, with a mean concentration of 5.22 mg/L. The Indian Ocean also exhibits stable, high values

across multiple parameters. With a temperature mean of 25.20°C and high salinity levels, it is a key contributor to regional climate and water mass exchanges. The Indian Ocean shows a relatively stable pH and has one of the highest nitrate concentrations, averaging 5.21 μmol/L. In contrast, the Malacca Strait exhibits lower pH, dissolved oxygen, and nitrate compared to open oceanic regions. The Natuna Sea consistently shows the lowest values across several parameters, setting it apart as a unique hydrographic region. It records the coolest temperatures, with a mean of 24.87°C, and has the lowest salinity levels, averaging 24.88 PSU. The dissolved oxygen content in the Natuna Sea is also relatively low, with an average of 6.37 mg/L.

4. Discussion

The complex circulation in the ISS is influenced by multiple drivers, including tide effects, ITF pathways, monsoon currents, IOD, ENSO, and bathymetry (Fig. 1). These phenomena are crucial for regional climate variability, fisheries productivity, and ocean-atmosphere interactions (Fadhilah et al., 2024; Qian et al., 2010). However, based on data collected from sampling stations since 1990, which mainly study specific oceanic phenomena without continuous monitoring, the understanding remains limited. Upwelling events and oceanic eddies are the most studied in the southern part of Java and are commonly associated with fisheries, IOD, and ENSO (Rachmayani et al., 2019)(Rachmayani et al., 2019). Meanwhile, research has mainly focused on eddies and the warm pool region in the northern waters of Papua (Arruda and Nof, 2003; Kashino et al., 2013). The ITF has also been the focus of studies in the Banda Sea, Makassar Strait, and Seram Sea (Prihatiningsih et al., 2021; Rugebregt et al., 2023).The complex circulation in the ISS due to many factors including tide effect, ITF pathways, monsoon currents, IOD, ENSO, and bathymetry (Fig. 1).

The data collection in ISS reflects contributions from global, regional, and national initiatives, with many programs, such as Argo, GOOS, SEA-GOOS, and WOD, operating as international collaborations, while INAGOOS and RIN BRIN represent national efforts within Indonesia. The depth range of observations varies significantly among datasets, influencing their applicability for different research objectives. Temperature and salinity are the most commonly measured parameters across all programs, providing essential data for studying ocean circulation and climate variability. However, while these two variables are well-represented, dissolved oxygen, nutrients, and pH observations are less frequently available, often exhibiting spatial and temporal gaps, particularly in coastal and deep-sea regions (Table 1). This is largely due to the higher cost, calibration needs, and historical under-prioritization of biogeochemical sensors compared to physical measurements, as well as the logistical challenges of sustained monitoring in these environments (Kolodziejczyk et al., 2024).

In general, analysis of data collected from sampling stations since 1990 reveals that these stations are strategically positioned to study specific oceanic phenomena. In the southern waters of Java, research efforts have focused on studying upwelling events, oceanic eddies, the Indian Ocean Dipole (IOD), and the El Niño-Southern Oscillation (ENSO). These phenomena play a crucial role in regional climate variability, fisheries productivity, and ocean atmosphere interactions. Upwelling events bring nutrient rich waters to the surface, supporting marine ecosystems and influencing local weather

patterns. Further east, in regions such as the Banda Sea, Makassar Strait, and Seram Sea, research has been concentrated on studying the Indonesian Throughflow (ITF). The ITF is a critical component of global ocean circulation, transporting warm Pacific waters into the Indian Ocean and influencing climate systems on both regional and global scales. Meanwhile, research has primarily focused on eddies and the warm pool region in the northern waters of Papua. This area is characterized by complex oceanographic dynamics, including mesoscale eddies that influence heat distribution, biological productivity, and atmospheric interactions. The warm pool is particularly significant as it plays a key role in global climate variability and is a heat source for atmospheric convection (Figure 7).
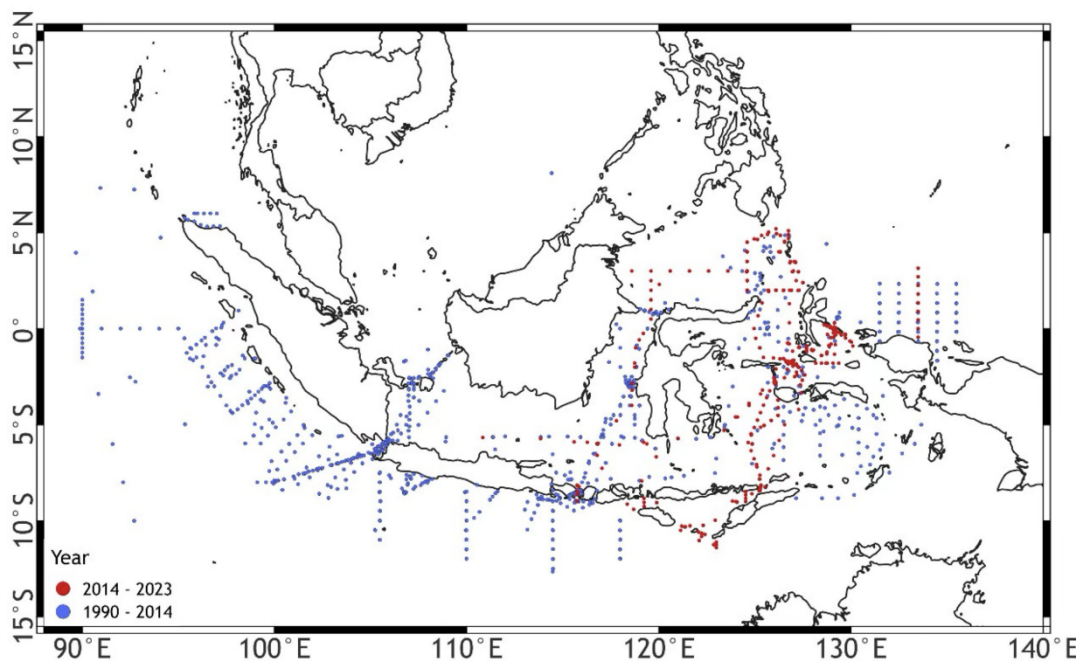
Figure 7. Data collection represents an effort of the Indonesian government, such as LIPI and BPPT, which are now integrated into BRIN as part of the organizational restructuring. Other international collaborations include IOCAS and FIO (mostly since 2014). Detailed positions and years can be found in the supplement material.

These station points (Figure 2; Figure 3) also highlight the growing interest of international researchers, especially after it was recognized that Indonesian waters play a critical role in global thermohaline circulation. sSince 1990, when intensive measurements have been conducted using Indonesian research vessels and through international collaborations, particularly in the eastern Indonesian seas, where depths exceed 4,000 m. This region is also known as a key pathway of the ITF, which is influences oceanic heat and mass exchange between the Pacific and Indian Oceanspart of the global ocean thermohaline circulation. The data collection efforts include not only scientific expeditions but also the deployment of moorings and buoys to ensure long-term observations. These Existing sampling points also indicate gaps in data coverage that cannot be addressed solely by commercial vessels operating along Indonesia's designated international shipping lanes (ALKI) (Figure 2; Figure 3). Unlike commercial ship-based observations, dedicated research deployments provide more precise and

continuous oceanographic measurements, essential for understanding climate variability, deep ocean circulation, and regional marine ecosystems.

470 ~~From t~~The dataset analyzed in this study (Table 2~~Table 2~~) is a wide array of oceanographic measurements sourced from various international programs and platforms. The WOD provided the most extensive contributions, particularly its XBT, OSD, MBT, and CTD datasets. However, post-screening, there was a substantial reduction in the XBT dataset, with~~,~~ 45% of the original data being rejected~~from 163,914 raw casts to 89,562~~, likely due to redundancy, bias, incompleteness, or poor data quality. The other factors, ~~The quality and reliability of the data may be influenced by factors~~ such as inconsistent

475 methodologies, varying instruments, or limited calibration, as data collection is also conducted through volunteers and commercial vessels (Boyer et al., 2018a). ~~Nevertheless, these contributions offer valuable information, particularly in regions with limited research coverage. Several studies used this portal data to analyse the characteristics of water mass .~~

The OSD and MBT datasets have minimum reductions, reflecting high data quality or fewer redundancies. The CTD dataset, critical for detailed temperature and salinity profiles, maintained almost all of its casts after screening, underscoring

480 its importance for oceanographic studies. The Argo Float data ~~system an essential tool for monitoring global ocean dynamics~~ provided 87,422 casts, though, after quality control, only 70,040 remained. This reduction signifies the challenge of maintaining data accuracy, especially in ~~highly variable~~complex oceanic regions like the Indonesian seas. Argo Floats, known for their autonomous measurement capabilities, remain indispensable for real-time ocean monitoring but require continuous data validation to ensure reliability.

485 Furthermore, ~~T~~the EWOCE contributed ~~many casts, with~~ 70,080 casts, ~~initially available,~~ but ~~60,826~~13% ~~casts were retained after screening~~were discarded. ~~The EWOCE data are vital for understanding the large-scale circulation patterns and their role in global climate systems, especially in regions like the Indonesian Seas that are part of the global thermohaline circulation .~~ RAMA and TOA buoy systems provided valuable stationary measurements with 14,303 and 2,776 casts, respectively. ~~These buoy systems offer consistent, long-term observations essential for detecting climate-related changes, such~~

490 ~~as shifts in monsoon patterns and ocean-atmosphere interactions.~~ In contrast, PODC (Padjadjaran Oceanographic Data Cent~~e~~re) ~~w~~as collected from scholars at Universitas Padjadjaran, and most of the data is collected near the university region, which is the West Java region, providing 2,621 raw casts, with 2,419 retained after screening (Faizal et al., 2021; Purba et al., 2022).~~and~~ The NANO-DOAP project, established in 2021, ha~~s~~d ~~small~~limi87 casts~~number of casts. However, these datasets remain essential for specific regions and parameters less covered by more extensive programs than the WOD program. The~~

495 ~~PODC, for example, provided 2,621 raw casts, with 2,419 retained after screening. This portal data were established in 2015, and primary data were collected from scholars at Universitas Padjadjaran; therefore, most data is collected near the university . Another dataset from the NANO-DOAP program, collected in Pangandaraan Bay, which faces the Indian Ocean, provided 87 casts~~. This number remained unchanged after screening, reflecting the high quality of the data. Experts carefully screened the samples after collection to ensure that only well-validated data were released~~. This ongoing program provides valuable~~

500 ~~insights into ocean dynamics, particularly in coastal regions where other instruments and satellites cannot easily reach~~ (Franz et al., 2021). From our perspective, all this portal data is vital for understanding the large-scale circulation patterns and their

role in global climate systems, especially in regions like the Indonesian Seas that are part of the global thermohaline circulation (Gould, 2003).

From historical data, we can conclude that from 1800 to the early 1900s, oceanographic observations were minimal,
505 primarily due to the limited technology and infrastructure available for ocean data collection (Fig. 3; Fig. 4). Most ocean observations during the 19th century were conducted during scientific expeditions parallel with invasion but their availability in modern databases is limited due to incomplete archiving practices and delays in data submission to national and international repositories (Bingham et al., 2002). THowever, the increase in data collection in the 1910s can be linked to technological advancements and the growing importance of understanding oceanic conditions for navigation and scientific exploration.
510 Nevertheless, World War I (1914 to 1918) and World War II (1939 to 1945) significantly shifted global priorities from scientific research, including oceanography, as most nations concentrated their resources on military and defencedefense efforts. Oceanographic activities took a backseat during these periods, particularly in Indonesia and other countries in the region, which were undergoing profound social and political changes. Despite these challenges, Indonesia and the surrounding nations maintained their civilization, gradually moving towards modernization. Early initiatives were undertaken during the
515 Snellius I Expedition from 1929 to 1930. Dr. P.M. van Riel, a Dutch scientist, conducted this expedition, which concentrated on the eastern region of the Indonesian archipelago, specifically the Lesser Sunda Islands, Banda Sea, and Molucca Sea. The expedition focusedconcentrated on the oceanographic characteristics of the region, such as seafloor mapping, currents, and water column properties, to investigate deep-sea environments (van Aken, 2005).

Oceanographic observations worldwide increased significantly between 1940 and 1970. This increase can be
520 attributed to the naval system's dependence on ocean knowledge. Interestingly, observations increased significantly in the early 1960s, from over 2,000 casts in 1960 to over 6,000 in 1967. As international cooperation and funding for oceanographic research projects increased, this trend continued into the 1970s and 1980s, with many casts. These included initiatives like the World Ocean Circulation Experiment (WOCE) and building buoys and mooring systems, which substantially contributed to data gathering, especially in under-represented areas like the deep sea and isolated archipelagic waters.
525 In Indonesia, this global momentum was mirrored by the establishment of national research institutions and the gradual development of local monitoring capacity. The founding of the Indonesian Institute of Sciences (LIPI) in 1967, later integrated into the National Research and Innovation Agency (BRIN), marked a turning point in building systematic oceanographic programs within the archipelago. Through national expeditions and collaborations with international partners, Indonesia began to fill critical gaps in observations, particularly in key regions such as the Makassar Strait and Banda Sea,
530 which form the core pathways of the Indonesian Throughflow. These efforts not only aligned with global initiatives like WOCE but also underscored the strategic importance of the Indonesian Seas to both regional and global climate systems (Figure 7).
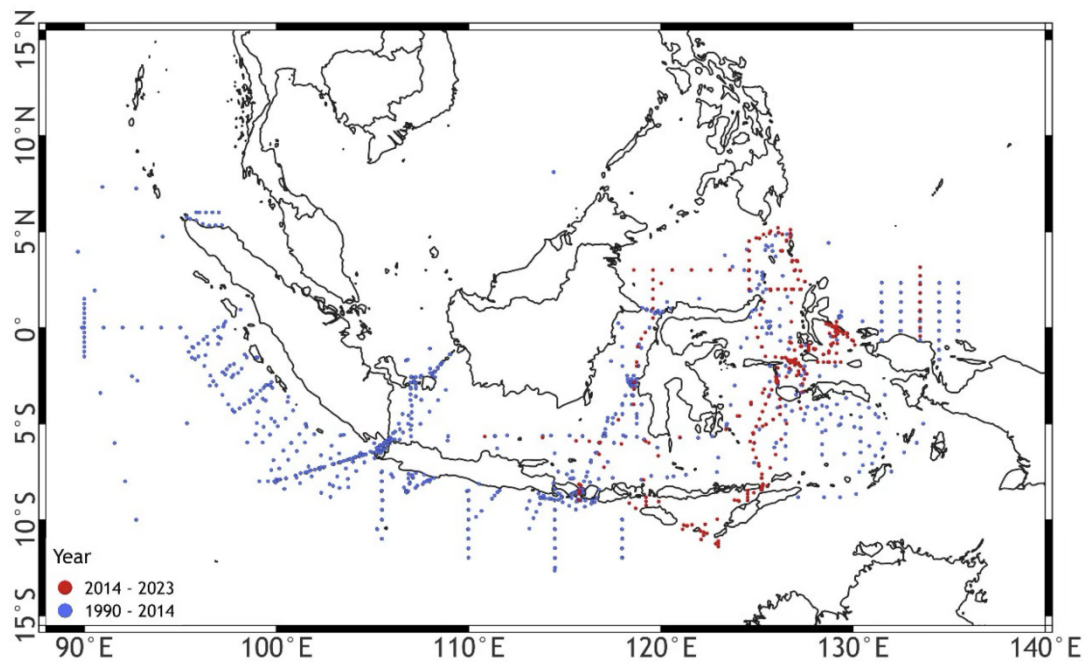
Figure 7. Data collection represents an effort of the Indonesian government, such as LIPI and BPPT, which are now integrated into BRIN as part of the organizational restructuring. Other international collaborations include IOCAS and FIO (mostly since 2014). Detailed positions and years can be found in the supplement material.

~~The founding of the Indonesian Institute of Sciences (LIPI) in 1967—now known as the National Research and Innovation Agency, or BRIN—marked the beginning of Indonesia's oceanographic research programs. Since 1970, this institution has worked to improve Indonesia's research capacities, particularly oceanology studies, marking a turning point in the nation's scientific development (Fig. 5).~~ Indonesia was able to address local environmental issues and add to global oceanographic knowledge by establishing LIPI, which was crucial in starting systematic ocean measurements, especially in its vast archipelagic waters. As a result, the 1960s symbolized Indonesia's dedication to comprehending and managing its maritime resources and signalled~~signaled~~ a global trend toward greater ocean surveillance. The establishment of research institutions in Indonesia also created new avenues for expanding oceanographic data recording capabilities in Indonesian waters, both independently and in collaboration with other institutions. ~~(Figure 7)~~.

Oceanographic casts increased sharply in 2000 and peaked in 2003 at 178,823 castings. The rise of autonomous oceanographic technology, explicitly using Argo floats, satellite-based remote sensing, and moored buoy systems like the RAMA Buoy array, correlates with technology development. By enabling continuous monitoring and allowing access to previously inaccessible locations, such as distant areas and deeper ocean layers, these technologies have completely changed the way ocean data is gathered. Following the high in 2003, the historical statistics indicate a decrease in casts. The casts decreased to 2,359 by 2023, suggesting that observations occurred less frequently. This decline may be attributed to several factors, including budget cuts in research funding, logistical challenges in maintaining long-term ocean monitoring stations, and the high costs associated with deploying and maintaining autonomous instruments in remote and deep-sea areas.

The considerable contribution highlights the US's substantial investment in oceanographic research infrastructure, including advanced satellite systems, buoys, and research vessels. Additionally, Japan is committed to studying ocean processes by providing casts at 14.6%. Japan's technological achievements and proximity to the western Pacific Ocean, which affects the Indonesian Seas, probably contribute to its significant involvement. The contributions made by both nations reflect their active participation in furthering world oceanography science. With 16.23%, Australia ranks second among all contributors. Australia's strong participation demonstrates its attention to monitoring important oceanographic processes, including the ITF and regional upwelling systems. Indonesia's close neighbour and nation with an interest in the Indo-Pacific region is Australia. With 4.07%, China is also rather important due to its extensive data-collecting activities, which show its increasing investment in marine research and scientific cooperation in the Asia-Pacific . These regional powers understand how important Indonesian waters affect world ocean circulation and temperature patterns (Figure 5Figure 5). In contrast, several underrepresented countries, such as Indonesia (6,035 casts), Malaysia (319 casts), and the Philippines (223 casts), exhibit much lower data contributions despite their crucial geographical locations.

For instance, Indonesia, situated along the vital Indonesian Throughflow (ITF) that connects the Pacific and Indian Oceans, has limited data collection activities (Sprintall et al., 2019). However, it emphasizes issues including less advanced research vessels, less research funding, and fewer operational oceanographic instruments. Strengthening Indonesia's and regional countries' position in oceanographic research is essential to ensuring that local scientists can play a significant role in studying their seas, which are vital to global climate systems. 4.91% of Great Britain and 6.54% of the former Soviet Union mention previous involvement in the oceanographic study. These nations have made significant strides in understanding Indonesian seas through their colonial or Cold War-era research projects. This under-representation suggests that there may be substantial data gaps in these important ocean regions due to resource, technological, and international collaboration issues. This disparity emphasizes how urgently nations must cooperate further and share resources to improve oceanic research (Silveira et al., 2022). Several institutions and organizations conduct marine surveys in Indonesia, although the information gathered frequently does not fully meet the comprehensive understanding of local ocean dynamics. As a result, wealthy and low-income countries have significantly different access to data, resulting in under-representation in crucial areas such as Indonesian waters. It is crucial to form alliances for future projects like mooring deployments to close these data gaps and enhance our understanding of ocean dynamics in general. This draws attention to a crucial component of Indonesia's oceanographic data collection process. The WOD efficiently leverages a range of nautical activities to collect important oceanic data, such as measurements from cargo ships, fishing vessels, commercial ships, and specialized research vessels. Especially in active shipping lanes, this varied sampling approach guarantees thorough coverage of the oceans.

Notably, most data are focused along these international shipping routes in the context of the Surroundings ISS (Fig. 6) because they represent regions of heavy maritime activity where ships naturally collect data. In contrast, in transport, this alignment with shipping channels is important. It also highlights possible data gaps in less-travelledless traveled areas, especially in isolated archipelagic waters where monitoring efforts might not be adequate. These differences in data accessibility have a significant impact on our understanding of the oceans worldwide. The absence of sufficient in situin situ

data is especially problematic for areas like the Indonesian Seas, which are essential for researching interactions between the Pacific and Indian Oceans.

590   Because simple measurement is crucial to understanding ocean dynamics, temperature and salinity are the most commonly measured parameters in oceanographic investigations (Fig. 7 - 9). For these measures, devices such as Conductivity-Temperature-Depth (CTD) sensors are frequently utilized because they are relatively easy to install and can precisely measure temperature and salinity simultaneously. These factors significantly impact marine ecosystems' physical environment, stratification, and circulation. ModellingModeling ocean dynamics, forecasting changes in marine habitats, and tackling the

595   issues brought on by climate change depend on an understanding of temperature and salinity. For instance, changes in salinity and temperature directly affect marine life, influencing food availability, breeding cycles, and species distribution. With temperature and salinity, other crucial parameters like pH, dissolved oxygen (DO), and Nitrate are also monitored. While DO levels are essential for determining the health of marine organisms, Nitrate is critical for understanding nutrient availability and primary productivity. As ocean acidification threatens marine ecosystems, pH measurements are becoming increasingly

600   important.

5. Recent Gaps and Future Research

5.1. Recent Gaps

While the ISS serves as a key region for various phenomena such as ENSO, IOD, and ITF, we further highlight the vertical gaps in data coverage and analyse the distribution of observational data. We analyse the spatial and temporal data

605   gaps, with the average cast data in the study area being 462 casts per one-degree grid square, with the highest and lowest casts on one grid being 26,244 and 1, respectively. There are several hotspots with a data cast density of more than 138 per grid: the Pacific Ocean, Indian Ocean, and SCS (Figure 8Figure 8).
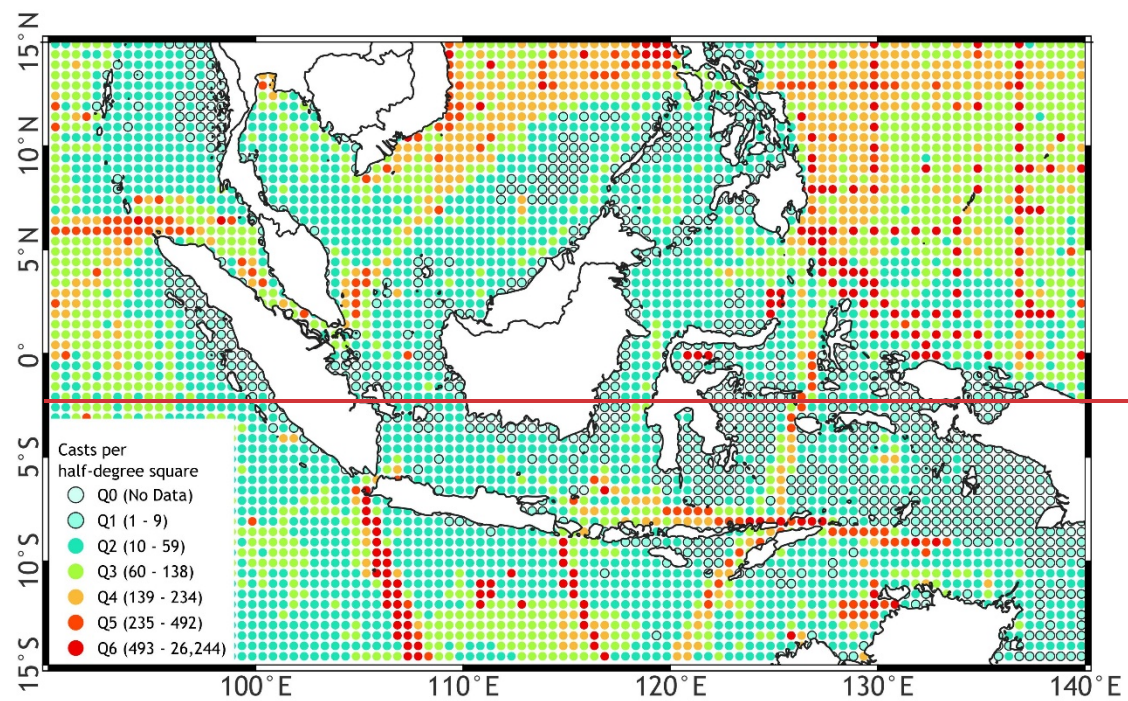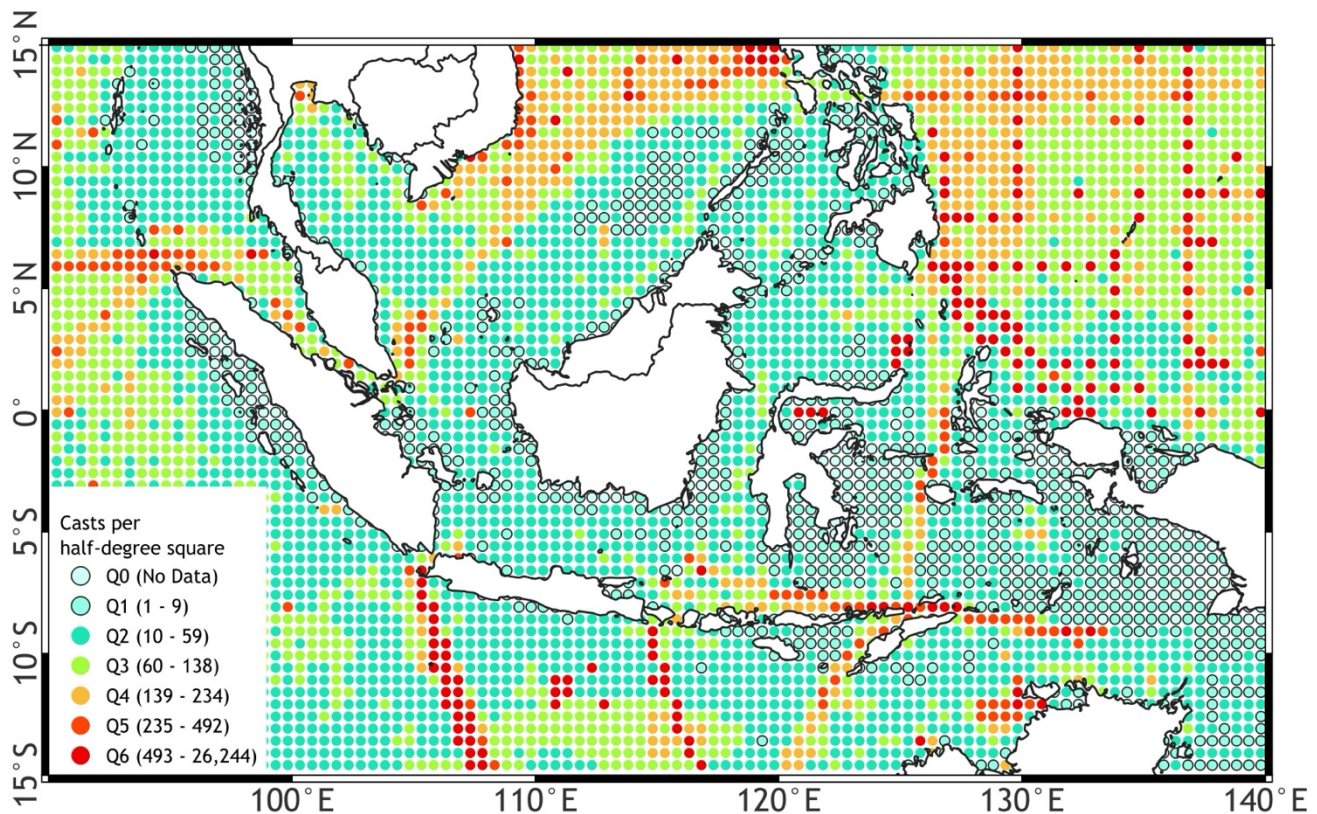
Figure 8: Spatial distribution of historical oceanographic casts per half-degree grid square in the ISS region over the observational period. Cast density is categorized into seven quantiles: Q0 (no data), Q1 (1–9 casts), Q2 (10–59 casts), Q3 (60–138 casts), Q4 (139–234 casts), Q5 (235–492 casts), and Q6 (493–26,244 casts). ~~The color scale represents the density of data casts, ranging from low-density areas (blue-light dots) to high-density areas (red dots). Black circle dots represent the area where there is a lack of data collection.~~

The Pacific Ocean has a consistently high data~~ ~~cast density among the other regions. Almost all of this area has a density at quantile 5 with a cast per one-degree grid square range of 492 to 26,244. The number of ~~cast~~ data casts in this region is 263,957, with an average of 1,027 casts per grid. Oceanographic instruments and ships collect data from this area's large number of data casts. The highest number of data casts on one grid in this region is 7,751, while the lowest is 5. The Indian Ocean has the highest number of data casts of the three hotspots, with 293,383 data casts. Even though it has a higher total cast data than the Pacific Ocean, the average cast data in the Indian Ocean is lower, 649 casts per one-degree grid square, than the Pacific Ocean because its area is large, and the distribution of data collection is not as homogeneous as the Pacific Ocean. The minimum and maximum range of casts per one-degree grid square in this region is 1 to 26,244 casts per grid. The first (26,244 casts per one-degree grid square) and ~~third~~ third-highest densities (15,647 casts per one-degree grid square) are also in this area, precisely to the south of Bali.

The SCS is the third hotspot in the study area, with 61,617 casts and an average of 392 casts per one-degree grid square. The impact of shipping lanes in this region is evident because it is very clear that the data distribution is divided into two parts. The area close to Vietnam and Peninsular Malaysia is a high-density region. Meanwhile, the part that approaches Kalimantan Island is a low-density area. The maximum value of the cast data in the SCS is 3.644. Apart from the placement of oceanographic instruments, the distribution of these hotspots is also influenced by shipping routes in Indonesian waters, ALKI. The data distribution resembles shipping routes in the western region, stretching from the SCS and the Malacca Strait to the Sunda Strait. The data distribution pattern with a data density of more than 492 resembles ALKI I. The same case can be seen in the eastern region; there is a data distribution pattern with a density of more than 492, which resembles a shipping lane that stretches from the Molucca Sea to the western Banda Sea. Then, it branches towards the west to the Savu Sea via the Timor Passage and east to the Timor Sea. This distribution pattern is identical to ALKI lines. Areas with low maritime traffic or no shipping lanes have much lower data density because methods for collecting oceanographic data by commercial ships cannot be implemented. The Andaman Sea shows cast data density in quantiles 1 to 3, with no more than 138 casts per one-degree grid square. Similar conditions appear in the Gulf of Thailand near Malaysia, the SCS near Kalimantan Island, the Sulu Sea, and the Arafura Sea. On the other hand, even though it is passed by ALKI, the Sulawesi Sea and Makassar Strait have relatively low data density compared to other areas that ALKI also passes. The density in this region is no more than 234 casts per one-degree grid square.

We also analysed the importance of coastal regions in the era of climate change. Almost 60% of the population in Southeast Asia (SEA) is on the coast and depends on the sea for their livelihood. Likewise, the SEA region is an area rich in biodiversity. Mitigation in this region must start with complete data. Four coastal areas are chosen to represent how coastal measurements have been carried out at~~in coastal areas with~~ a distance of 12 miles from the coastline. In general, coastal measurements have small quantities with uneven distribution. For example, ~~on~~ the west coast of Sumatra ~~are~~is only found on the west coast of Lampung Province, which has eight measurements and covers an area of no more than 38 km^2.

Even though the west coast of Sumatra has become a place of various international shipping lines (ALKI I), coastal measurements in the region are still very low. Java Island has a total of 16,751 measurements along its coast. There are two coastal measurement hot spots on the island of Java, namely the Sunda Strait (ALKI I route), with 1,095 cast observations, and the Bali Strait (ALKI II route), with 14,949 cast observations. The busy shipping area in these two straits means they have many casts, almost 96% of the total casts on the island of Java. The Bali Strait alone contains 89% of the cast on the island of Java. The northern and southern coastal areas of Java Island have few and uneven coastal measurements. In the north of~~northern~~ the coastal region~~area~~, measurements are generally carried out in Jakarta Bay and its surroundings. Meanwhile, in the southern coastal area, Pelabuhan Ratu Bay has relatively more coastal measurements than the rest of the south~~southern~~ coast. Recently, two coastal monitoring stations, supported by the NANO-DOAP Program, have been established in the northern and southern regions of West Java (https://nf-pogo-alumni.org/projects/global/).

Both of these stations started in 2021 and measured some of the water quality parameters. Then, the coast of Makassar (Fig. 10.c), which is in the Makassar Strait, is a busy area because there is a large port that coincides with the ALKI II route.

Even though there is much marine activity in this area, the number of coastal measurement casts is only 37—a small quantity for a water area that passes through one of Indonesia's three main shipping routes. The Arafuru Sea has the fewest coastal measurement casts of the four selected areas, with only one cast. The number of casts is minimal, considering that this region is one of the vital~~important~~ trade routes in Indonesia and is also a water area on the border of Indonesia's Exclusive Economic Zone (EEZ) and Australia's EEZ. We also assumed that most coastal monitoring efforts and data collection in the ISS region have not been conducted over the long term or with sufficient spatial coverage.

Second, while the data cover~~s~~ extensive depths, ~~it shows varying~~ availability varies across the region, with some areas providing measurements up to 6000 m, while others are limited to only 800 m. These gaps limit the ability ~~introduce significant~~to rigorously ~~uncertainties in~~evaluate ITF climate models, affecting confidence in predictions of ocean heat transport, monsoon variability, and ENSO dynamics. For example, as the main pathways of ITF, the ~~scarcity~~ limited ~~of~~ high-resolution subsurface data in the Makassar Strait and Lombok Strait constrain~~hinders~~ the ~~a~~assessment ~~of~~ ~~bility of~~ coupled climate models' performance ~~to accurately~~in simulat~~ing~~e ITF variability, which in turn impacts estimates of ~~leading to errors in~~ Pacific-Indian Ocean exchange ~~estimates~~. Similarly, t~~T~~he scarcity of deep-sea data in the ISS complicates assessments of long-term heat storage and ocean circulation changes, which are crucial for understanding regional climate feedback (Figure 8).
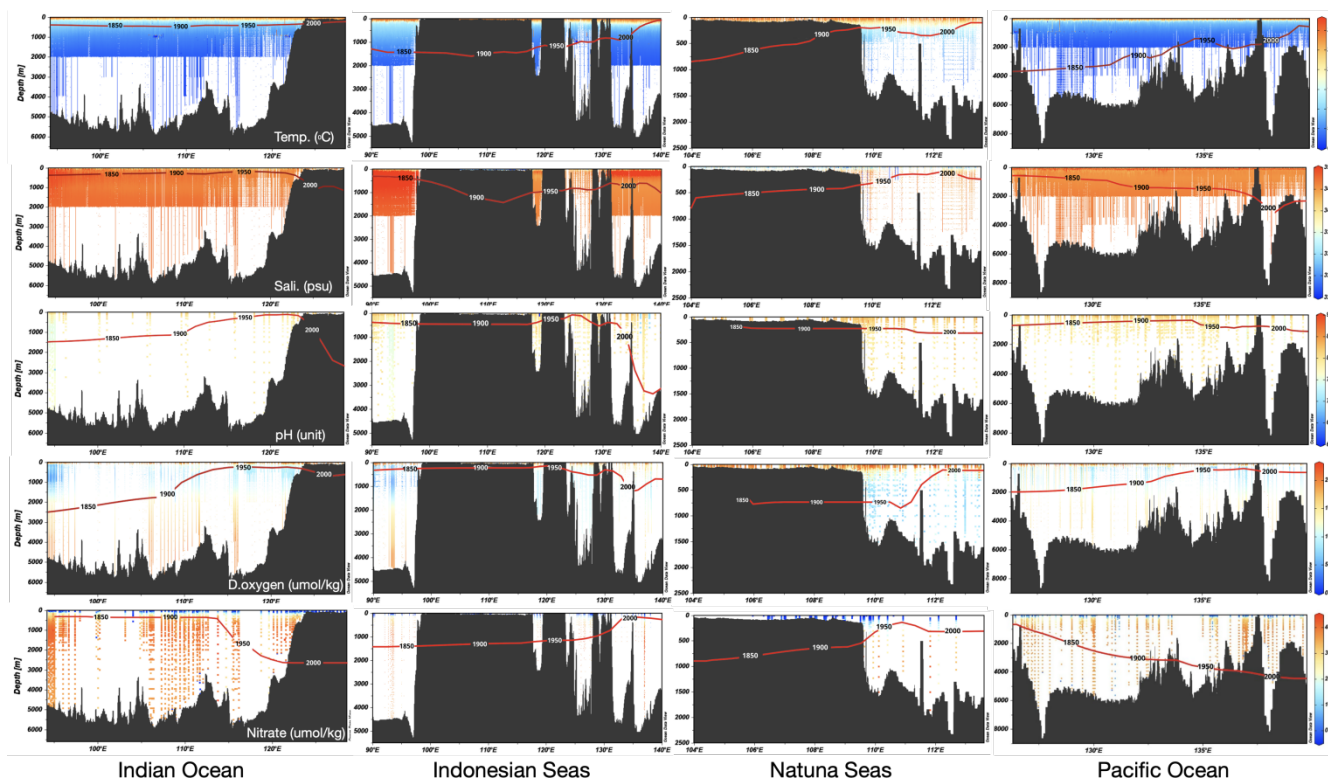
Figure 9: Vertical distribution (dots) and trends in several essential ocean variables (temperature, salinity, pH, dissolved Oxygen, and nitrate Levels) in the ISS. Red lines represent the trend measurement over the years.

5.2. Future Direction

The ISS region plays a crucial role in global ocean circulation, serving as the primary low-latitude pathway where warm, low-salinity Pacific waters flow into the Indian Ocean via the Indonesian Throughflow (ITF). However, observational gaps limit our ability to model and predict ocean variability under climate change accurately. We believe that many oceanographic measurements in the ISS region remain abundant and are scattered across various institutions, often stored in separate databases with limited accessibility. These datasets, collected by governmental agencies, research institutions, universities, and international collaborations, are crucial for understanding long-term oceanographic trends. To address these challenges, five key observational directions must be emphasized, leveraging regional and global cooperation to enhance data coverage and knowledge-sharing.

1. Synchronized Large-Scale Horizontal Observations

   Large-scale ocean monitoring is essential to understanding oceanic teleconnections, particularly how variability in the Pacific Ocean affects the Indian Ocean via the ITF. These interactions, influenced by the El Niño-Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and monsoonal cycles, impact global climate patterns, fisheries, and biodiversity. To enhance our understanding of these interactions, synchronized observations must be conducted across broad spatial scales.

2. Deep-Water and Coastal Observations

   A significant data gap exists in the deep layers of the ITF, particularly below 800 meters in key passages such as the Makassar Strait, Lombok Strait, and Timor Passage. These regions regulate ITF transport, influencing global thermohaline circulation and ocean heat distribution. However, deep-sea observations remain sparse and intermittent, limiting our ability to detect long-term changes in ocean warming and carbon sequestration. Deploying additional deep-sea Argo floats, moored buoys, and gliders within ITF pathways is essential for improving subsurface and deep-sea data coverage. Coastal monitoring initiatives, such as the NANO-DOAP Programme, play a vital role in tracking changes in Essential Ocean Variables (EOV) at different depths (Sarker et al., 2024). Expanding similar coastal monitoring networks will help bridge data gaps between large-scale oceanic processes and nearshore environmental changes. Coastal observations should be integrated with offshore data collection efforts to improve climate resilience, fisheries management, and conservation planning in Marine Protected Areas (MPAs). Long-term monitoring is crucial for detecting gradual temperature, salinity, and ocean acidification changes linked to climate change and global warming. Unfortunately, long-term observations in the ISS region remain fragmented and underfunded, creating challenges for understanding decadal ocean variability. Establishing permanent ocean monitoring stations, including deep-sea moorings and fixed observation points, is necessary to provide continuous data. These long-term datasets will improve seasonal to decadal-scale predictions and contribute to a more comprehensive understanding of climate variability. Additionally,

investments in research vessels equipped with modern oceanographic instruments will be essential for conducting systematic observations across the ISS region.

3. High-Frequency Observations

High-frequency monitoring is essential for capturing rapid oceanic changes, such as internal waves, mesoscale eddies, and tidal mixing, which influence marine ecosystems and fisheries productivity. Traditional oceanographic cruises cannot provide the temporal resolution for such short-term phenomena. Regional and global collaboration is vital for advancing real-time data collection technologies. Leveraging cutting-edge technologies, including AI-based data interpolation, machine learning for data gap-filling, and autonomous underwater vehicles (AUVs), can enhance real-time, high-resolution observations. Furthermore, integrating in-situ and satellite-based observations will improve forecasting capabilities for extreme climate events such as prolonged droughts and intensified monsoons.

4. Interdisciplinary Study

Since the existing measurement focuses on physical aspects such as temperature, salinity, and currents, an interdisciplinary approach that merges marine science, climate modelling~~modeling~~, biogeochemistry, and socioeconomics is also important. Understanding the impacts of climate change on marine ecosystems, fisheries, and coastal communities necessitates strong global collaboration across multiple disciplines. This interdisciplinary framework will provide deeper insights into the interactions between ocean circulation, climate variability, and marine ecosystems.

5. Network and Collaboration

Despite growing observational efforts, challenges in data accessibility persist due to institutional data restrictions, national security concerns, and inconsistent data management practices. Global collaboration is key to overcoming these barriers. Coordinated monitoring efforts require regional cooperation among~~collaboration among~~ countries bordering the Pacific and Indian Oceans, particularly through networks such as the Global Ocean Observing System (GOOS), the Indian Ocean Observing System (IndOOS), and the Argo Program. Beyond regional partnerships, global collaboration is critical to integrating ISS observations into worldwide climate models (Bax et al., 2018). Investing in research infrastructure, including vessels, offshore observatories, and real-time data-sharing systems, is essential for expanding Indonesia's global monitoring contributions. Furthermore, developing cloud-based data repositories and ensuring compliance with FAIR (Findable, Accessible, Interoperable, Reusable) standards will enhance global data accessibility and improve research collaboration (Meyssignac et al., 2019). Open-access data initiatives will promote transparency, allowing for more informed decision-making regarding marine resource management and climate adaptation strategies.

6. Conclusion

This study is one of the first comprehensive inventories of oceanographic observations in the Indonesian Seas and Surroundings (ISS), offering a unique analysis of the spatial and vertical data distribution throughout the region. This research

identifies critical, previously undocumented data gaps, notably in under-represented deep-sea areas and remote archipelagic regions, by combining data from numerous international programs spanning over two centuries. The study not only emphasizes historical trends in data collection but also introduces a systematic approach to data screening and validation, which ensures the reliability of future climate modelling~~modeling~~ and marine ecosystem studies. These findings are instrumental in addressing the challenges of data accessibility and coverage, setting a foundation for more equitable and inclusive oceanographic research initiatives in the era of climate change. Collecting data in this region is challenging. However, oceanographic observation stations have dramatically increased over the past two centuries, reflecting the growing recognition of oceanography's critical role in addressing environmental challenges. The acquisition of in-situ data has made substantial progress due to the advancements in autonomous technologies and international programs. Nevertheless, despite these advancements, it is essential to improve data coverage, particularly in remote archipelagic areas and deep-sea regions. Recent discoveries indicate a substantial limitation of data for depths below 800 meters, which raises concerns regarding our understanding of the critical oceanic processes in these deeper layers. Many crucial phenomena, such as temperature fluctuations, nutrient cycling, and marine biodiversity dynamics, transpire at these depths. The limited data coverage in these critical zones means our comprehension of marine ecosystems' overall condition and functioning remains inadequate. By addressing these five key observational priorities, the ISS region can significantly enhance its role in global ocean monitoring and climate research. Strengthening regional and international~~global~~ collaborations, improving deep-sea and coastal observations, utilizing advanced monitoring technologies, and ensuring open data accessibility will provide a comprehensive understanding of ocean-climate interactions. These efforts will ultimately support better climate adaptation strategies, improved forecasting of extreme events, and sustainable marine resource management worldwide.

Code and Data Availability

All the code and data are publicly available. The data used in this study are divided into two categories: pre-processed data and processed data. The pre-processed data were obtained from several publicly accessible sources, including the World Ocean Database 2018 (Boyer et al., 2018b), the Argo Program (https://argo.ucsd.edu/data/), and the Tropical Atmosphere Ocean (TAO) Project (https://www.tao.ndbc.noaa.gov/tao/data_download/search_map.shtml). TRITON counterpart and The Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA) (https://www.pmel.noaa.gov/tao/drupal/disdel/). Historical hydrographic data from the World Ocean Circulation Experiment (WOCE, https://ewoce.org/data/index.html) and the CLIVAR and Carbon Hydrographic Data Office (CCHDO, https://cchdo.ucsd.edu/). Users may use this region to download (15 °N to 15 °S and 90 °E to 140 °E). Several data points were also gathered from the Padjadjaran Oceanographic Data Centre (PODC) (https://podc.fpik.unpad.ac.id). PANGEAE (https://www.pangaea.de/), and Coriolis Operational Oceanography (https://www.coriolis.eu.org/). These datasets were downloaded in .nc or .txt formats and served as the foundational input for the subsequent analysis. The processed data, which include derived variables, statistical outputs, and visualizations, were generated during the course of this study using

standardized analytical methods. These processed datasets are preserved in the Mendeley Data repository with a corresponding assigned DOI, including those from the NANO DOAP Project (TEPAST Station) (https://doi.org/10.17632/fnn6tsjckn.1) (Purba et al., 2025d) Some of the metadata, such as the year of observation, project name, contributing institution, and instruments used, are also provided and sourced from the National Research Agency (BRIN), Institute of Oceanology, Chinese

780 Academy of Science (IOCAS), and First Institute of Oceanography (FIO) (Supplementary material). All metadata and relevant supporting files can be accessed freely in the supplementary material. The data were in the TXT file format, and we used Ocean Data View Software (ODV Ver. 5.7.2), Python, and QGIS Software to process, visualize, and analyze the data (https://doi.org/10.17632/nm5txj3fps.1) (Purba et al., 2025b). We also use Python to compute the cast per half-degree grid square with syntax freely available at https://doi.org/10.17632/mbvxs72mvd.2 (Purba et al., 2025a).

785 **Competing interest**

Each author has specific expertise and has provided a substantial contribution to this work. None of them hashave any competing interests with regard to their scientific and publishing responsibilities for this manuscript.

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