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# Variability of Indo-Pacific Ocean Basin Circulation and Its Impact on Climate Change

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**Abstract** This study aims to understand the complex interactions between oceanic and atmospheric processes in the Indo-Pacific region and how these interactions influence global climate patterns. The study reveals several key findings. The Indo-Pacific region exhibits significant variability in ocean circulation patterns, which are influenced by phenomena such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). The Indonesian Throughflow (ITF) plays a crucial role in modulating these patterns, with its variability linked to both local and inter-basin processes. Additionally, the study highlights the impact of basin-wide warming in the Indian Ocean on regional climate, particularly the Asian summer monsoon. The study also underscores the importance of understanding multi-decadal variability and its interaction with anthropogenic climate change. The findings of this study have significant implications for climate prediction and risk management. The variability of the Indo-Pacific Ocean basin circulation is a critical factor in global climate dynamics, influencing weather patterns, monsoon systems, and long-term climate trends. Improved understanding of these processes is essential for enhancing climate models and developing more accurate seasonal and decadal climate predictions. This study contributes to the broader effort to mitigate the impacts of climate change by providing insights into the complex interactions within the Indo-Pacific region.
**Keywords** Indo-Pacific Ocean; Climate variability; El Niño-Southern oscillation; Indian ocean dipole; Indonesian throughflow; Climate change; Monsoon; Ocean circulation

## 1 Introduction

The Indo-Pacific Ocean Basin is a critical region that encompasses the Indian Ocean and the western and central Pacific Ocean. This area is characterized by complex oceanographic and atmospheric interactions that significantly influence global climate patterns. The Indo-Pacific region is home to the Indo-Pacific Warm Pool (IPWP), which contains the warmest sea surface temperatures (SSTs) on Earth and plays a pivotal role in driving atmospheric convection and precipitation patterns (Weller et al., 2016; Windler et al., 2020). The Indonesian Throughflow (ITF) is another crucial feature of this basin, acting as a conduit for warm, fresh waters from the Pacific to the Indian Ocean, thereby influencing regional and global ocean circulation (Song et al., 2007; Feng et al., 2018).

Understanding the variability of ocean circulation in the Indo-Pacific Basin is essential for several reasons. Firstly, the region's oceanic and atmospheric dynamics are closely linked to major climate phenomena such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), which have far-reaching impacts on global weather patterns, agriculture, and ecosystems (Kajtar et al., 2017; Wang, 2019; Abram et al., 2020). Secondly, changes in ocean circulation can affect the distribution of heat and freshwater, influencing sea level rise, marine biodiversity, and the frequency and intensity of extreme weather events (Ummenhofer et al., 2021; Weller et al., 2016). Additionally, the variability in ocean circulation can modulate the hydrological cycle, impacting freshwater availability and climate risk assessments for vulnerable societies in the Indian Ocean rim countries (Weller et al., 2016; Ummenhofer et al., 2021).

This study investigate the variability of ocean circulation in the Indo-Pacific Ocean Basin and its impact on climate change. This study aims to quantify the changes in ocean circulation patterns over different temporal scales, from interannual to centennial, and identify the driving forces behind these changes, examine the interactions between the Indo-Pacific Ocean Basin and other ocean basins, such as the Atlantic and Pacific, to understand the interconnectedness of global climate systems, assess the role of anthropogenic factors, such as greenhouse gas emissions, in altering the ocean circulation and climate dynamics in the Indo-Pacific region, and provide insights into the potential future changes in ocean circulation and their implications for regional and global climate, with a focus on improving climate model simulations and predictions.

By addressing these objectives, this research aims to enhance our understanding of the Indo-Pacific Ocean Basin's role in global climate variability and contribute to more accurate climate predictions and effective climate risk management strategies.

## 2 Overview of Indo-Pacific Ocean Basin Circulation

### 2.1 Major currents and circulation patterns

The Indo-Pacific Ocean Basin is a critical component of the global ocean circulation system, influencing climate patterns and weather phenomena across the globe. The Indo-Pacific Ocean Basin is characterized by several significant currents and circulation patterns that play a crucial role in the distribution of heat and salinity, impacting regional and global climate systems. One of the most important currents is the Indonesian Throughflow (ITF), which serves as a low-latitude pathway for warm, fresh waters from the Pacific Ocean to enter the Indian Ocean. The ITF is influenced by the equatorial waveguides of both the Pacific and Indian Oceans, with its transport being stronger during La Niña events and weaker during El Niño events due to the Pacific waveguide's influence (Feng et al., 2018) (Figure 1).

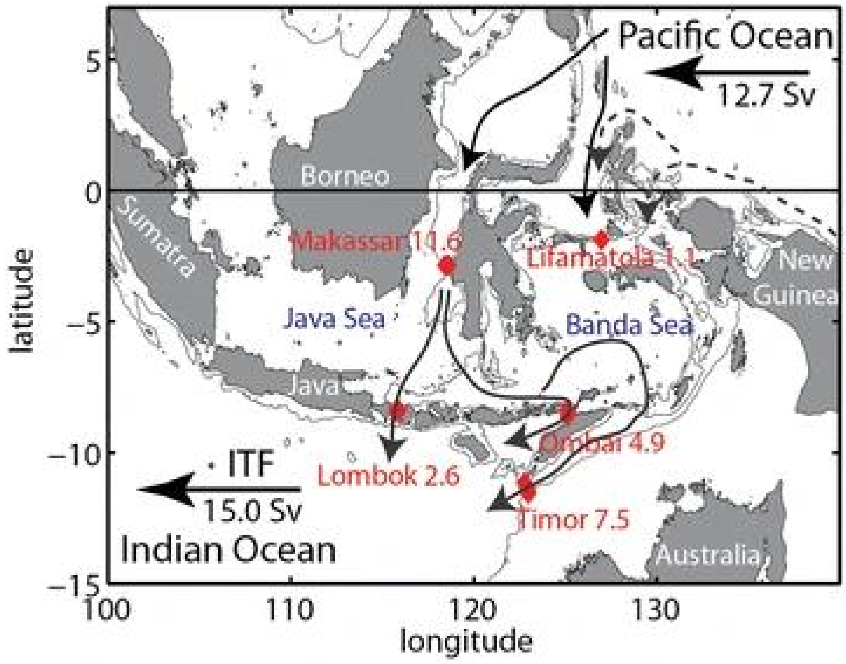


Figure 1 Transport of the currents contributing to the Indonesian Throughflow via different passages (Adopted from Feng et al., 2018)

Image caption: Transport of the currents contributing to the Indonesian Throughflow (ITF) via different passages through the Indonesian archipelago (after Wikipedia with transport values from Sprintall et al. 2009). Numbers next to current arrows indicate transport in Sverdrups (Sv) (Adopted from Feng et al., 2018)

Feng et al. (2018) depicts the pathways and transport values of currents forming the Indonesian Throughflow (ITF) as they pass through various straits and seas of the Indonesian archipelago. The ITF transports warm, fresh water from the Pacific Ocean to the Indian Ocean, playing a critical role in the global thermohaline circulation and influencing the meridional overturning of the Indian and Pacific Oceans. According to Sprintall et al. (2009), the transport values in the key passages are marked in Sverdrups (Sv), with significant contributions from the Makassar Strait (11.6 Sv) and the Lombok Strait (2.6 Sv). The ITF's estimated total transport is around 15 Sv. Understanding the ITF's variability and dynamics is essential for comprehending its impact on ocean circulation and climate, particularly in the Indo-Pacific region. This figure underscores the complexity of the ITF and its integral role in global ocean currents and climate systems.

Additionally, the Indo-Pacific Warm Pool, a region with some of the highest sea surface temperatures (SSTs) in the world, plays a significant role in global atmospheric circulation. The warm pool's properties, such as size, zonal and meridional centers, and SST, exhibit distinct seasonal and interannual variations, which are crucial for understanding the region's climate dynamics (Yin et al., 2020).

### 2.2 Seasonal and interannual variability

The Indo-Pacific Ocean Basin exhibits pronounced seasonal and interannual variability, driven by various climate phenomena such as the El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Pacific Decadal Oscillation (PDO). The ITF, for instance, shows significant interannual variability, with its transport being modulated by ENSO and IOD events. During El Niño events, the ITF transport weakens, while it strengthens during La Niña events. The IOD can offset the ENSO influences on the ITF transport during the developing and mature phases of these events (Feng et al., 2018).

The Indo-Pacific Warm Pool also demonstrates substantial seasonal and interannual variability. The Indian Ocean sector of the warm pool exhibits more vigorous seasonal oscillations in size and intensity compared to the Pacific sector. However, both sectors show comparable interannual variability, with the Indian Warm Pool having weak interannual variations and the Pacific Warm Pool exhibiting strong interdecadal variations (Yin et al., 2020).

### 2.3 Long-term trends

Long-term trends in the Indo-Pacific Ocean Basin circulation are influenced by both natural variability and anthropogenic climate change. Over the past century, the Indian Ocean has experienced significant warming, which can be attributed to human-induced climate change. However, since the 1980s, multi-decadal variability associated with the Interdecadal Pacific Oscillation has also played a significant role in modulating the region's heat and freshwater balance (Ummenhofer et al., 2021).

Climate models project a weakening trend of the ITF under global warming scenarios, primarily due to the reduction of deep upwelling in the Pacific basin rather than changes in trade winds. This weakening of the ITF could have significant implications for the Indo-Pacific Ocean circulation and global climate (Feng et al., 2018). Additionally, the Indo-Pacific Warm Pool is expected to continue warming, with the La Niña-like warming pattern dominating the tropical Pacific and a negative IOD warming pattern occurring in the Indian Ocean (Zhang et al., 2020a).

In summary, the Indo-Pacific Ocean Basin circulation is characterized by complex interactions between various currents, climate phenomena, and long-term trends. Understanding these dynamics is crucial for predicting future climate changes and their potential impacts on regional and global scales.

## 3 Drivers of Circulation Variability

### 3.1 Atmospheric forcing

Atmospheric forcing plays a crucial role in driving the variability of ocean circulation in the Indo-Pacific region. The Walker circulation, a significant atmospheric feature, has been shown to influence sea surface temperature (SST) and sea-level pressure trends, which in turn affect ocean circulation patterns. Observations indicate a strengthening of the Walker circulation, which has led to intensified warming in the Indo-Pacific Warm Pool and slight cooling in the eastern equatorial Pacific over recent decades (Wills et al., 2022). Additionally, the Indian Ocean Dipole (IOD) and the El Niño-Southern Oscillation (ENSO) are key atmospheric phenomena that modulate the geostrophic transport of the Indonesian Throughflow (ITF), with La Niña events strengthening and El Niño events weakening the ITF (Feng et al., 2018). These atmospheric forces are critical in understanding the variability of ocean circulation in the region.

### 3.2 Ocean-atmosphere interactions

The interactions between the ocean and atmosphere significantly contribute to the variability of circulation in the Indo-Pacific basin. Coupled ocean-atmosphere processes, such as those observed during glacial periods, amplify changes in the climate of the Indo-Pacific warm pool. For instance, the exposure of the Sahul shelf during glacial periods excited a positive feedback mechanism involving a stronger surface temperature gradient along the equatorial Indian Ocean and a weaker Walker circulation, leading to significant changes in ocean cooling and rainfall patterns (DiNezio et al., 2018). Furthermore, the Indo-Pacific Ocean Capacitor (IPOC) mode and the Pacific-Japan (PJ) pattern are examples of ocean-atmosphere interactions that influence regional climate variability, including the Indian Summer Monsoon Rainfall (ISMR) (Gnanaseelan and Chowdary, 2021). These interactions highlight the complex feedback mechanisms that drive circulation variability in the Indo-Pacific region.

### 3.3 Role of sea surface temperature

Sea surface temperature (SST) is a critical factor in the variability of ocean circulation in the Indo-Pacific basin. Changes in SST can influence atmospheric circulation patterns, which in turn affect ocean currents. For example, the Indo-Pacific Warm Pool has experienced intensified warming, which is consistent with the strengthening of the Walker circulation (Wills et al., 2022). Additionally, the Indian Ocean has undergone substantial heat and freshwater changes, with rapid increases in SST and ocean heat content since the 2000s. These changes are linked to both anthropogenic forcing and natural multi-decadal variability associated with the Interdecadal Pacific Oscillation (Ummenhofer et al., 2021). The variability in SST, therefore, plays a pivotal role in modulating the circulation patterns and overall climate of the Indo-Pacific region.

## 4 Impact of Circulation Variability on Climate

### 4.1 Influence on regional climate patterns

The variability in the Indo-Pacific Ocean basin circulation significantly influences regional climate patterns, particularly in the South Asian region. The Indo-Western Pacific Ocean Capacitor (IPOC) mode, for instance, induces a tripole pattern in precipitation anomalies over South Asia, characterized by strong positive precipitation anomalies over the western Ghats and Sundarbans-Bangladesh region, separated by negative anomalies over the monsoon trough region (Chowdary et al., 2019). This pattern is maintained by the anomalous western North Pacific (WNP) anticyclone and tropical Indian Ocean (TIO) warming, which affect local rainfall through mechanisms such as low-level convergence and orographic lift (Chowdary et al., 2019). Additionally, the South China Sea monsoon trough (SCSMT) exhibits interannual variability influenced by sea surface temperature anomalies (SSTAs) in the tropical Indo-Pacific, with different epochs showing varying key areas and mechanisms of influence (Zhang et al., 2020b).

### 4.2 Impact on global climate systems

The Indo-Pacific warm pool (IPWP) plays a crucial role in global climate systems by affecting major atmospheric circulations such as the Hadley and Walker circulations. Warmer SSTs in the IPWP strengthen the upward branch of the Hadley circulation, while the Walker circulation is influenced by both natural variability and global warming trends (Kim et al., 2020). The El Niño/Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are dominant modes of climate variability in the Indo-Pacific region, affecting global weather patterns through direct and indirect pathways (Behera, 2021). ENSO-induced basin-wide modes in the tropical Indian Ocean, for example, have delayed effects on climate variations in the western Pacific and adjacent Asian regions, acting like a capacitor (Behera, 2021). Furthermore, changes in sea level and SST variations in the Indo-Pacific are intrinsically linked, with climate variability modes such as ENSO, IOD, and Pacific Decadal Oscillation (PDO) significantly influencing sea level variability (Kumar et al., 2022).

### 4.3 Interaction with monsoon systems

The interaction between Indo-Pacific circulation variability and monsoon systems is complex and multifaceted. The IPOC mode, for instance, has a strong impact on the South Asian summer monsoon rainfall, with the WNP anticyclone and TIO warming playing crucial roles in maintaining regional precipitation patterns (Chowdary et al., 2019). The Indian summer monsoon rainfall (ISMR) is also influenced by various modes of interannual climate variations, including ENSO, IOD, and ENSO Modoki, which have distinct teleconnections and impacts on monsoon variability (Behera, 2021). Additionally, the IPWP affects monsoon circulations, although its impact is less pronounced compared to its influence on the Hadley and Walker circulations (Kim et al., 2020). The regional coupled ocean-atmospheric feedback mechanisms in the Indo-northwest Pacific region further enhance the variance and persistence of atmospheric variability, influencing the Asian summer monsoon (Wang et al., 2020).

## 5 Ocean Circulation and Extreme Weather Events

### 5.1 Connection to tropical cyclones

The variability in ocean circulation within the Indo-Pacific basin has a significant impact on the formation and intensity of tropical cyclones. The Madden-Julian Oscillation (MJO), a dominant mode of subseasonal variability, modulates tropical cyclones and monsoons, contributing to severe weather events across various regions including Asia, Australia, and the Americas (Roxy et al., 2019). The expansion of the Indo-Pacific warm pool has altered the MJO life cycle, which in turn affects the frequency and intensity of tropical cyclones (Roxy et al., 2019). Additionally, the Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO) are closely linked to changes in tropical cyclone activity, with positive IOD events and El Niño conditions generally leading to increased cyclone activity in the Indian Ocean (Abram et al., 2020; Kumar et al., 2021).

### 5.2 Influence on droughts and floods

Ocean circulation patterns in the Indo-Pacific basin also play a crucial role in influencing droughts and floods. The IOD and ENSO are key drivers of these extreme weather events. For instance, the strong El Niño event in 2016 and the subsequent weak La Niña in 2017 significantly impacted sea surface temperatures (SST) in the tropical Indian Ocean, leading to extreme negative and weak positive IOD phases. These phases triggered floods in the Indian subcontinent and drought conditions in East Africa (Khan et al., 2021). The variability in the South China Sea monsoon trough, influenced by SST anomalies in the Indo-Pacific, also contributes to regional droughts and floods (Zhang et al., 2020b). The interaction between the Pacific and Indian Ocean waveguides, particularly through the Indonesian Throughflow (ITF), further modulates these extreme weather events by altering the distribution of warm and cold water masses (Feng et al., 2018).

### 5.3 Case studies of notable events

Several notable events illustrate the impact of Indo-Pacific ocean circulation on extreme weather:

(1) 1997 IOD Event: The most extreme positive IOD event on record occurred in 1997, which was associated with severe droughts in Indonesia and Australia, and flooding in East Africa. This event demonstrated the tight coupling between IOD and ENSO, and its significant impact on regional climate variability (Abram et al., 2020).

(2) 2016-2017 ENSO and IOD Events: The strong El Niño in 2016 followed by a weak La Niña in 2017 led to extreme negative and weak positive IOD phases. These events caused significant flooding in the Indian subcontinent and drought conditions in East Africa, highlighting the complex interplay between ENSO and IOD in driving extreme weather (Khan et al., 2021) (Figure 2).

(3) MJO and Rainfall Patterns: The rapid warming of the Indo-Pacific warm pool has altered the MJO life cycle, leading to increased rainfall over Southeast Asia, northern Australia, and the Amazon, while causing drying over the west coast of the United States and Ecuador. This shift in rainfall patterns underscores the broader impact of ocean circulation changes on global weather systems (Roxy et al., 2019).

Khan et al. (2021) displays the yearly mean sea surface temperature (SST) anomalies in the Tropical Indian Ocean (TIO) for 2016 (a) and 2017 (b) relative to the 1981-2010 period. The black boxes represent the Western TIO (WTIO) and Eastern TIO (ETIO). Monthly SST anomaly trends are inset within the maps. In 2016, a strong Indian Ocean Dipole (IOD) event is observed, with cold anomalies in the WTIO and warm anomalies in the ETIO, peaking in September. This resulted in significant climate impacts due to suppressed atmospheric convection and enhanced surface energy flux. Conversely, 2017 experienced a weak positive IOD, with marginal SST anomalies. These SST variations influenced regional climate, highlighting the role of IOD events in climate variability. The study underscores the critical impact of SST anomalies on atmospheric conditions and regional weather patterns.

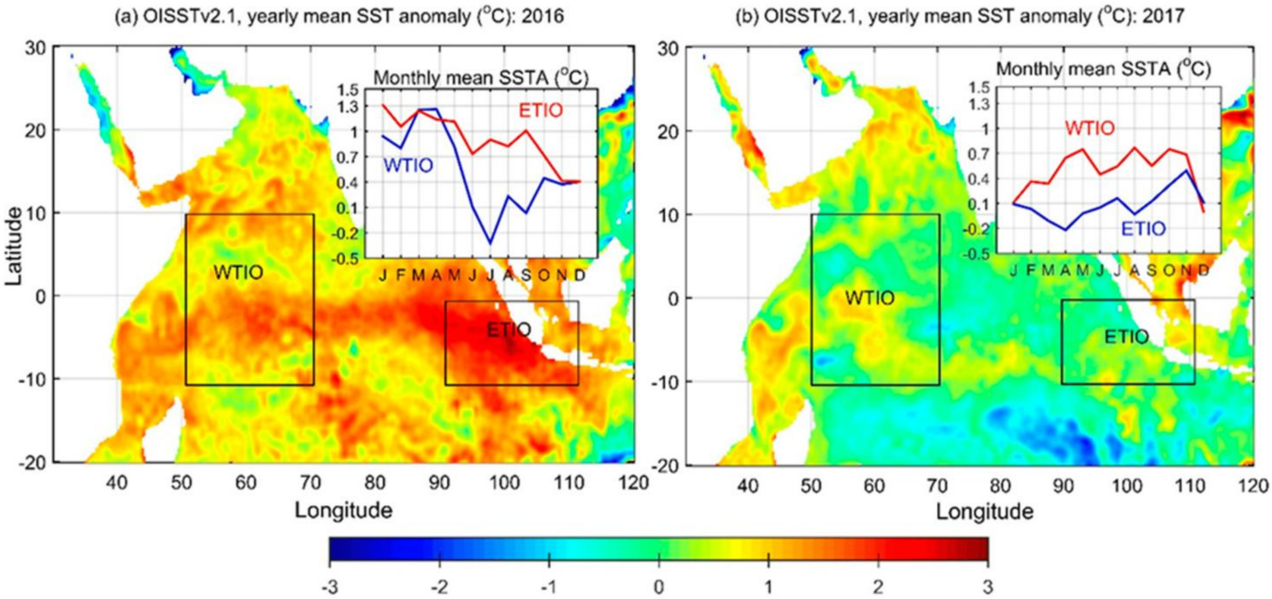


Figure 2 Evolution of SST anomalies (°C) in the TIO in 2016 and 2017 with respect to 1981–2010 reference period (Adopted from Khan et al., 2021)

Image caption: (a) yearly mean of SST anomalies in 2016, (b) yearly mean of SST anomalies in 2017. The monthly distribution of SST anomalies in 2016 and 2017 is shown within the map. The two boxes represent WTIO (10° S–10° N, 50–70° E) and ETIO (10° S–Eq, 90–110° E). Data obtained from NOAA OISSTv2.1 (Adopted from Khan et al., 2021)

These case studies underscore the critical role of Indo-Pacific ocean circulation in shaping extreme weather events, with significant implications for climate variability and change.

## 6 Modeling and Prediction of Ocean Circulation

### 6.1 Numerical modeling techniques

Numerical modeling techniques are essential for understanding and predicting ocean circulation patterns in the Indo-Pacific region. These models integrate various data sources, including in situ observations, remote sensing, and palaeo proxy networks, to simulate the complex interactions within the ocean system. For instance, the use of satellite-observed sea surface temperature (SST) data has been instrumental in examining the multi-time scale variabilities of the Indo-Pacific Warm Pool, which is crucial for understanding seasonal and interannual changes in ocean circulation (Yin et al., 2020). Additionally, climate models such as the CESM1 Large Ensemble and CMIP6 models have been employed to project changes in precipitation, low-level winds, and sea-level pressure under global warming scenarios, providing insights into the enhanced interannual variability in the region (Wang et al., 2022).

### 6.2 Challenges in prediction

Despite advancements in numerical modeling, several challenges persist in predicting ocean circulation. One significant challenge is the model biases and intermodel variability, which contribute to uncertainties in projecting climate mode changes in a warming climate (Zheng, 2019). For example, discrepancies between observed and modeled trends in sea-surface temperature and sea-level pressure highlight the limitations of current climate models in accurately reproducing historical climate patterns (Wills et al., 2022). Furthermore, the sparse observational network in certain regions, such as the subsurface of the Indian Ocean, adds to the difficulty in assessing contemporary changes and their attribution to anthropogenic or natural variability (Ummenhofer et al., 2021). The complex interactions between different climate modes, such as ENSO, IOD, and PDO, also complicate the prediction of ocean circulation patterns (Kumar et al., 2021).

### 6.3 Advances in ocean circulation models

Recent advances in ocean circulation models have improved our understanding and prediction capabilities. Enhanced climate model simulations, particularly for the Maritime Continent region, are necessary to quantify and attribute hydrological changes in the Indo-Pacific (Ummenhofer et al., 2021). The development of large ensembles for each model helps reduce uncertainty from internal variability and isolate the forced response to global warming (Zheng, 2019). Additionally, the integration of complex network methodologies and principal component analysis has provided a more comprehensive understanding of the spatiotemporal and multivariable dependencies in the Indo-Pacific climate system (Falasca et al., 2021). These advancements, coupled with sustained and enhanced observational efforts, are crucial for improving the accuracy and reliability of ocean circulation models.

In summary, while numerical modeling techniques have significantly advanced our understanding of Indo-Pacific ocean circulation, challenges such as model biases, sparse observational data, and complex climate interactions remain. Continued improvements in climate models and observational networks are essential for overcoming these challenges and enhancing our predictive capabilities.

## 7 Observational Methods

### 7.1 Satellite remote sensing

Satellite remote sensing has been instrumental in observing and understanding the variability of the Indo-Pacific Ocean basin circulation and its impact on climate change. For instance, satellite-observed Sea Surface Temperature (SST) data accumulated over multiple decades has been used to examine the multi-time scale variabilities of the Indo-Pacific Warm Pool, highlighting significant seasonal and interannual variations (Yin et al., 2020). Additionally, remote sensing datasets have been utilized to analyze the spatiotemporal variability of ocean net primary production (NPP) in the tropical eastern Indian and western Pacific Oceans, revealing complex biophysical interactions influenced by climate phenomena such as El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Kong et al., 2019). These satellite observations provide critical data for understanding the large-scale patterns and trends in ocean circulation and their climatic impacts.

### 7.2 In-situ observations

In-situ observations complement satellite data by providing detailed and localized measurements of oceanographic parameters. For example, Argo floats have been used to collect sea surface salinity (SSS) data, which, along with precipitation and evaporation datasets, help in analyzing the relationship between SSS, ocean circulation, and climate change (Du et al., 2019). Additionally, moored current meter observations in the Maluku Channel have been employed to study the interannual variability of currents in the Sulawesi Sea, revealing the influence of Indo-Pacific planetary waves on regional circulation patterns (Hu et al., 2019) (Figure 3). These in-situ measurements are crucial for validating satellite data and enhancing our understanding of ocean dynamics at finer spatial and temporal scales.

Hu et al. (2019) presents a comprehensive overview of the Indonesian Throughflow (ITF) region, highlighting the intricate connections between the tropical Pacific and Indian Oceans. Figure 1a provides a geographical context of key straits and seas within the Indonesian archipelago. Figures 1b and 1c compare sea surface height anomalies (SLA) and currents derived from the INDESO model and Aviso altimetry, showing the consistency and differences between model simulations and observational data. Figure 1d offers a detailed view of the Sulawesi Sea, illustrating current patterns and SLA with high resolution. This study emphasizes the ITF's role in global ocean circulation, influenced by planetary waves and climate variability phenomena such as ENSO and the Indian Ocean Dipole. The results underscore the importance of high-resolution modeling and observational data in understanding the dynamics of ITF and its impact on regional and global climate systems.

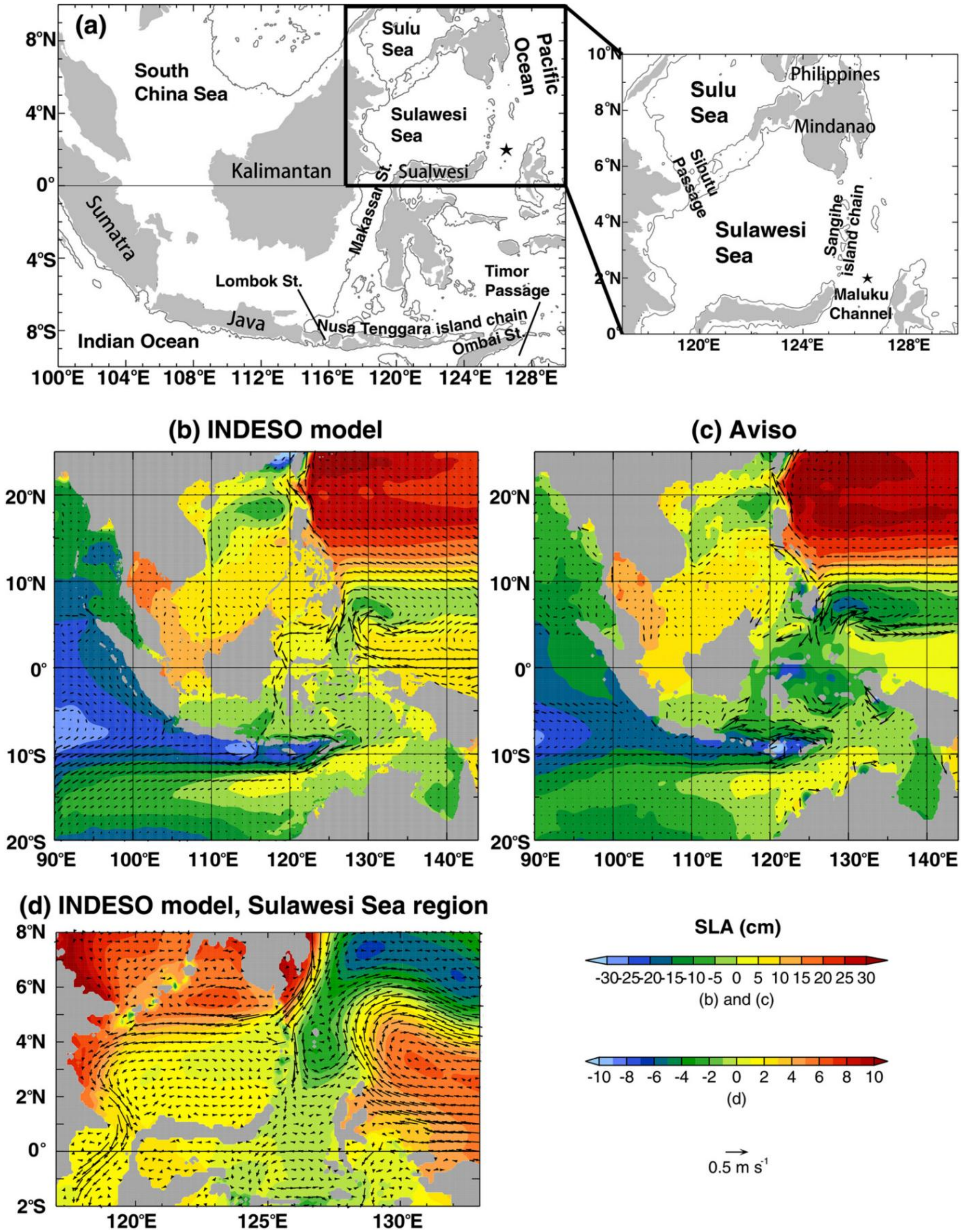


Figure 3 Sea Surface Height Anomalies and Currents in the Indonesian Archipelago (Adapted from Hu et al., 2019)

Image caption: (a) Map of the Indonesian archipelago showing the main islands and straits discussed in the study. (b) Sea surface height anomalies (SLA, cm) and surface currents (m/s) simulated by the INDESO model averaged over the 9 years from 2008 to 2016. (c) SLA and geostrophic currents from the Aviso altimetry product for the same period. (d) An enlarged portion of the Sulawesi Sea region from the INDESO model detailing SLA and current patterns. The light gray contours in (a) indicate the 200-m isobath based on NOAA's ETOPO2 dataset. The mooring location in the Maluku Channel is marked by the black star in (a). The color bar represents SLA in cm, and arrows indicate current vectors (Adapted from Hu et al., 2019)

### 7.3 Data integration and analysis

The integration of satellite and in-situ observations, along with advanced data analysis techniques, is essential for a comprehensive understanding of the Indo-Pacific Ocean basin circulation. For instance, the use of complex network methodology and principal component analysis has allowed researchers to investigate the evolution of climate modes and their connectivity over millennia, providing insights into the gradual shifts in the basin of attractions in the tropics (Falasca et al., 2021). Furthermore, the combination of remote sensing, numerical modeling, and paleo proxy networks has been employed to quantify changes in the Indian Ocean's heat and freshwater balance, highlighting the interplay between anthropogenic forcing and natural variability (Ummenhofer et al., 2021). These integrated approaches enable a more robust analysis of the intricate interactions within the Indo-Pacific system and their implications for climate change.

By leveraging both satellite remote sensing and in-situ observations, and integrating these data through sophisticated analytical methods, researchers can gain a deeper understanding of the variability in the Indo-Pacific Ocean basin circulation and its broader climatic impacts. This multi-pronged observational strategy is vital for advancing climate science and informing effective climate risk management strategies.

## 8 Human Impacts on Ocean Circulation

### 8.1 Anthropogenic climate change

Human-induced climate change has significantly impacted ocean circulation patterns in the Indo-Pacific region. The twentieth century witnessed robust surface warming in the Indian Ocean, which can be unequivocally attributed to anthropogenic climate change. This warming has led to alterations in the Walker circulation, a key component of the Indo-Pacific climate system, and has contributed to shifts in the heat and freshwater balance across the region (Ummenhofer et al., 2021). Additionally, the frequency and intensity of climate variability modes such as the Indian Ocean Dipole (IOD) have increased, further influencing ocean circulation patterns (Abram et al., 2020). These changes underscore the profound impact of human activities on the natural climate system.

### 8.2 Ocean acidification

Ocean acidification, driven by increased atmospheric CO2 levels, poses a significant threat to marine ecosystems and ocean circulation. The absorption of CO2 by the ocean leads to a decrease in pH, which can affect the health of coral reefs and other marine organisms that play a crucial role in maintaining oceanic currents and circulation patterns. Although specific studies on ocean acidification's direct impact on Indo-Pacific circulation are limited, the broader implications of acidification on marine life and ecosystem services are well-documented and suggest potential disruptions to oceanic processes (Ummenhofer et al., 2021).

### 8.3 Pollution and habitat destruction

Pollution and habitat destruction are critical human-induced factors that impact ocean circulation. The Indo-Pacific region, home to diverse marine ecosystems, faces significant threats from plastic pollution, oil spills, and coastal development. These activities can alter the physical and chemical properties of the ocean, affecting circulation patterns. For instance, pollution can lead to the degradation of coral reefs, which are essential for maintaining local ocean currents and providing habitat for numerous marine species (Ummenhofer et al., 2021). Habitat destruction, such as mangrove deforestation, further exacerbates these impacts by removing natural barriers that protect coastal areas and influence water movement.

In summary, human activities, including climate change, ocean acidification, and pollution, have profound and multifaceted impacts on ocean circulation in the Indo-Pacific region. These changes not only affect the physical environment but also have cascading effects on marine ecosystems and the services they provide. Addressing these challenges requires a comprehensive understanding of human impacts and concerted efforts to mitigate their effects on the oceanic system.

## 9 Future Research Directions

### 9.1 Identifying knowledge gaps

Despite significant advancements in understanding the variability of the Indo-Pacific Ocean basin circulation and its impact on climate change, several knowledge gaps remain. One critical area is the need for more comprehensive data on the natural variability of the Indian Ocean Dipole (IOD) before anthropogenic influences, which limits the confidence in future IOD predictions (Abram et al., 2020). Additionally, the sparse observational network in the Indian Ocean, particularly in the subsurface, hinders accurate assessments of regional-scale trends in heat and freshwater changes (Ummenhofer et al., 2021). Furthermore, the complex interactions between the El Niño-Southern Oscillation (ENSO) and other climate modes, such as the Pacific Decadal Oscillation (PDO) and the Interdecadal Pacific Oscillation (IPO), require further investigation to disentangle their combined effects on the Indo-Pacific climate system (Kumar et al., 2021; Wang et al., 2022).

### 9.2 Emerging technologies and methods

To address these knowledge gaps, the adoption of emerging technologies and methods is essential. Enhanced observing systems, including both remotely sensed and in situ observations, are crucial for maintaining and expanding the data network in the Indo-Pacific region (Ummenhofer et al., 2021). The integration of high-resolution climate models and advanced statistical techniques, such as complex network methodologies and principal component analysis, can provide deeper insights into the spatiotemporal dependencies and multivariable interactions within the climate system (Falasca et al., 2021). Additionally, the use of coral proxy networks can extend the historical record of climate variability, offering valuable context for contemporary changes (Ummenhofer et al., 2021).

### 9.3 Interdisciplinary approaches

Interdisciplinary approaches are vital for a holistic understanding of the Indo-Pacific Ocean basin circulation and its climate impacts. Collaboration between oceanographers, climatologists, and data scientists can facilitate the development of comprehensive models that incorporate both oceanic and atmospheric processes (Wang et al., 2020). Furthermore, integrating insights from paleoclimatology, such as coral records, with modern observational data can enhance the understanding of long-term climate variability and its drivers (Abram et al., 2020; Ummenhofer et al., 2021). Finally, interdisciplinary research that combines physical oceanography with socio-economic studies can better assess the implications of climate variability for vulnerable societies in the Indo-Pacific region, informing more effective climate risk management strategies (Deepa et al., 2021; Ummenhofer et al., 2021).

By addressing these future research directions, the scientific community can improve the understanding of the Indo-Pacific Ocean basin's role in global climate dynamics and enhance the predictive capabilities for future climate scenarios.

## 10 Concluding Remarks

The research on the variability of the Indo-Pacific Ocean basin circulation and its impact on climate change has yielded several significant insights. Firstly, the Indo-Pacific region has experienced substantial changes in climate mean state and variability over the Holocene, with a notable shift in the Indian Ocean's dominant climate modes. The region has also seen rapid increases in surface temperatures and ocean heat content, which are linked to both anthropogenic climate change and natural multi-decadal variability. The Indo-Pacific Warm Pool exhibits distinct seasonal and interannual variability, with significant contributions from the Indian Ocean basin-wide index. Additionally, the El Niño-Southern Oscillation (ENSO) and other non-ENSO forced variabilities play crucial roles in the region's climate dynamics. Sea surface salinity trends further indicate an intensification of the global hydrological cycle under global warming. The weakening of the Atlantic Meridional Overturning Circulation (AMOC) has also been shown to induce warming in the Indo-Pacific, highlighting the interconnectedness of global ocean systems. Historical records reveal that the Indian Ocean Dipole (IOD) has been tightly coupled with ENSO variability over the last millennium, with recent extremes being unusual but not unprecedented. The Indonesian Throughflow (ITF) is another critical component, with its variability and centennial changes significantly impacting Indo-Pacific oceanography and global climate. Finally, the Indian summer monsoon rainfall is influenced by multiple climate modes, including ENSO, IOD, and ENSO Modoki, underscoring the complex interplay of factors affecting regional climate.

Continued research in the Indo-Pacific region is crucial for several reasons. The region's climate variability has profound implications for global weather patterns, sea level rise, and regional freshwater availability. Understanding the intricate dynamics of the Indo-Pacific Warm Pool and its response to climate change is essential for improving climate models and predictions. The interplay between ENSO, IOD, and other climate modes necessitates further investigation to enhance our ability to predict and mitigate the impacts of extreme weather events. Additionally, the role of the AMOC and its influence on Indo-Pacific warming highlights the need for a comprehensive understanding of inter-basin interactions. The ITF's variability and its implications for global ocean circulation also warrant continued study, particularly in the context of future climate scenarios. Finally, the Indian summer monsoon's sensitivity to various climate modes underscores the importance of ongoing research to support agricultural planning and water resource management in the region.

Based on the findings, several recommendations for policy and management can be made. Firstly, there is a need to maintain and expand observing systems, including remote sensing and in situ observations, to monitor heat and freshwater changes in the Indo-Pacific region. Enhancing coral proxy networks and improving climate model simulations will also be critical for better quantification and attribution of hydrological changes. Policymakers should prioritize the development of early warning systems for extreme weather events, leveraging improved predictions of ENSO, IOD, and other climate modes. International collaboration is essential to address the global nature of ocean circulation changes, such as those induced by the AMOC, and to develop coordinated responses. Efforts to mitigate the impacts of climate change on the ITF and its associated oceanographic processes should be integrated into broader climate adaptation strategies. Finally, regional policies should focus on enhancing the resilience of communities dependent on the Indian summer monsoon, through sustainable water management practices and climate-smart agricultural techniques.

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The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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