

ENSO-Driven SST Warming and Marine Primary Productivity Suppression in Bali Waters: Spatiotemporal Evidence from the 2015–2016 El Niño

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Abstract

The 2015–2016 El Niño, one of the strongest in the instrumental record, imposed substantial thermal forcing across the Indo-Pacific warm pool, yet its fine-scale impacts on seas along the Indonesian Throughflow (ITF) pathway remain insufficiently characterised. Using monthly satellite-derived SST (CMEMS L4, 0.05°) and chlorophyll-a (MODIS-Aqua L3 SMI, 4 km) fields over southern Bali waters for 2013–2017, with 2014 as a near-neutral ENSO baseline ($MEI.v2 < \pm 0.5$), we provide a phase-resolved spatiotemporal characterisation of SST–Chl-a co-variability across a complete El Niño cycle. SST and Chl-a exhibited strong negative co-variability ($r = -0.8332$, $p < 0.05$, autocorrelation-corrected following Chelton, 1983). SST anomalies reached +1.5–1.8°C above baseline, peaking above 30°C in early 2016, while concurrent Chl-a concentrations declined by approximately 54% (domain-mean: $0.19 \pm 0.07 \text{ mg m}^{-3}$), indicating basin-wide phytoplankton suppression. Temperature–Salinity analysis identified the dominance of warm, saline Indian Ocean water masses during the El Niño peak, which intensified vertical stratification, impaired subsurface nutrient entrainment, and suppressed seasonal upwelling. To our knowledge, this study provides the first integrated framework jointly combining surface anomaly mapping, water-mass transformation analysis, and an ENSO-phase response typology for an ITF-influenced marginal sea — offering a replicable observational template for climate–ecosystem monitoring across the broader Indo-Pacific.

1. Introduction

Climate variability is increasingly recognised not only through changes in mean thermal conditions but also through shifts in marine biogeochemical regimes, seasonal productivity behaviour, and the spatial organisation of ecosystem responses to large-scale climate forcing. The El Niño–Southern Oscillation (ENSO), as the dominant mode of interannual climate variability in the tropical Pacific, exerts far-reaching influence across the Indo-Pacific warm pool, altering sea surface temperatures, thermocline depth, upwelling intensity, and nutrient availability across multiple temporal and spatial scales (IPCC, 2021). At the basin scale, El Niño events are well-documented suppressors of marine primary productivity, reducing chlorophyll-a by up to 70% in the eastern equatorial Pacific and by 15–30% in the Arabian Sea and Somali upwelling system (Racault et al., 2017), yet the magnitude, spatial coherence, and seasonal timing of these impacts in marginal seas along the Indonesian Throughflow (ITF) pathway remain poorly constrained. In these environments, physical forcing, biological response, and regional circulation interact in ways that prevent a spatially uniform ecosystem outcome, making regional-scale oceanographic diagnostics essential for understanding where ENSO-driven warming is accompanied by productivity enhancement, suppression, or spatially differentiated responses.

This complexity is particularly pronounced in the Indonesian maritime continent, where oceanographic regimes differ substantially across seas and are shaped by monsoonal circulation, ITF water-mass exchange, and local upwelling processes. The ITF — the only low-latitude inter-ocean exchange pathway connecting the Pacific and Indian Oceans — transports substantial heat, mass, and biogeochemical properties southward, making Indonesian seas integral to global thermohaline circulation and regional

climate feedbacks (Gordon, 2005; Sprintall et al., 2009). Critically, ITF transport is itself modulated by ENSO: the ITF weakens during El Niño events as Walker circulation slackens and the Pacific-to-Indian Ocean sea level gradient diminishes, reducing the advection of cooler Pacific thermocline water into the region (Li et al., 2023). This ENSO-driven weakening of ITF transport has been directly observed in Lombok Strait — the primary shallow exit passage of the ITF — where the 2015 El Niño was associated with anomalously low temperatures linked to altered rainfall and evaporation patterns (Iskandar et al., 2025). Satellite observations further demonstrate that SST anomalies associated with ENSO propagate through the Indonesian seas with regionally differentiated timing and magnitude, whereas biological responses such as phytoplankton biomass changes tend to display weaker and less spatially coherent patterns (Susanto & Marra, 2005), strengthening the need for subregional studies that jointly examine SST dynamics, Chl-a variability, and water-mass characteristics within a single analytical framework.

Several studies have examined ENSO and Indian Ocean Dipole (IOD) impacts on SST and chlorophyll-a across Indonesian waters, but systematic, phase-resolved analysis of southern Bali waters remains absent. Susanto and Marra (2005) provided the foundational documentation of El Niño 1997/1998 effects on Chl-a along the southern Java–Sumatra coast, demonstrating that anomalous easterly winds combined with IOD forcing elevated surface Chl-a in some areas — yet their analysis was confined to a single event and did not resolve the full spatiotemporal progression of SST–Chl-a co-variability across ENSO phases. Siswanto et al. (2020) extended this to a two-decade (1997–2019) satellite-based assessment of phytoplankton biomass across the entire Indonesian Maritime Continent, finding that Chl-a declined most significantly during concurrent El Niño and positive IOD events and that IOD dominated over ENSO in controlling productivity variability in the eastern Indian Ocean sector (Siswanto et al., 2020). More recently, studies in adjacent seas have revealed contrasting ENSO–Chl-a coupling depending on basin geometry: in semi-enclosed Bone Bay, for example, ENSO extremes during 2015–2016 produced negligible Chl-a co-variability ($r = 0.03$), attributed to the buffering effect of semi-enclosure against large-scale climate forcing (Syamsudin et al., 2025) — a contrast that motivates the hypothesis that open-ocean, ITF-influenced settings such as southern Bali waters should exhibit stronger and more physically coherent ENSO responses. In the Bali Strait itself, the combined effect of El Niño and positive IOD on Chl-a has been documented at seasonal scale (Wirasatriya et al., 2018), but the open southern Bali waters — a distinct oceanographic domain directly exposed to Indian Ocean forcing and ITF water-mass exchange — has not been systematically analysed across a complete ENSO cycle. Furthermore, upwelling studies along the southern Indonesian coast have consistently identified IOD as a stronger driver than ENSO of upwelling intensity (Wirasatriya et al., 2018), raising the question of whether the co-occurrence of a strong El Niño and positive IOD in 2015–2016 produced a compounded suppression signal in southern Bali waters that is distinct from the effects of either forcing in isolation.

Southern Bali waters offer a strategically important setting for detecting spatially heterogeneous ENSO signals in a tropical maritime environment. The study domain occupies a position at the intersection of the Bali Strait, the ITF main outflow pathway, and the northern Indian Ocean, where a pronounced bathymetric gradient — transitioning from shallow shelf environments (< 200 m) in the north to deep open-ocean conditions ($\sim 5,000$ m) in the south — creates a physically distinct local circulation regime

(Susanto et al., 2001). Seasonal upwelling along the southern coast, driven by southeasterly monsoon winds during June–September, normally sustains elevated surface Chl-a concentrations that are among the highest recorded in Bali waters (Susanto & Marra, 2005; Hendiarti et al., 2004). This baseline upwelling regime provides a sensitive detection surface for ENSO-driven suppression: when El Niño-driven SST warming deepens the thermocline and increases vertical stratification, the efficiency of wind-driven upwelling in delivering nutrient-rich subsurface water to the euphotic zone should decrease measurably (Wirasatriya et al., 2018). Despite this oceanographic significance, integrated assessments that jointly combine temporal trend analysis, spatial distribution mapping, water-mass characterisation through T-S diagram analysis, and phase-resolved productivity responses within a single analytical framework are absent for this domain.

The present study addresses this gap through a spatiotemporal analysis of southern Bali waters during 2013–2017, capturing the 2015–2016 El Niño across its full progression from pre-event conditions through onset, peak, and early recovery. Using monthly satellite-derived SST (CMEMS L4, 0.05°) and Chl-a (MODIS-Aqua L3 SMI, 4 km) fields alongside subsurface Temperature–Salinity (T-S) profiles from the World Ocean Database 2023 (WOD23), this study provides what is — to our knowledge — the first phase-resolved, spatiotemporal characterisation of SST–Chl-a co-variability in southern Bali waters that jointly integrates surface anomaly mapping, water-mass transformation analysis, and an ENSO-phase response typology. Unlike prior studies that examined adjacent seas in isolation or focused on single variables or single events, this framework enables direct identification of the physical mechanism linking ENSO forcing to phytoplankton suppression in an ITF-influenced marginal sea. Three interrelated research questions guide the analysis. First, how did SST anomalies evolve spatially and temporally across southern Bali waters during the 2015–2016 El Niño relative to the 2014 near-neutral baseline? Second, to what extent did Chl-a concentration and spatial distribution change across coastal, shallow, and deep-water settings in response to ENSO-driven thermal forcing? Third, how did water-mass transformation, as characterised through T-S analysis, mechanistically connect ENSO forcing to the suppression of marine primary productivity? By addressing these questions, this study contributes a regional evidence base for understanding ENSO–ecosystem linkages in the ITF corridor and supports more physically grounded prediction of marine productivity anomalies under future climate variability.

2. Data and Methods

2.1 Study Area

This study focuses on Bali waters, located in the central Indonesian maritime continent at the junction of the Bali Strait to the north and the open Indian Ocean to the south. The study domain covers the spatial extent of 8.5°S–9.4°S and 114.5°E–115.75°E, encompassing shallow shelf environments along the northern coastal zone, a narrow strait connecting the Java Sea to the Indian Ocean, and progressively deeper open-ocean conditions extending southward beyond the continental margin. The bathymetric gradient is pronounced, with shallow shelf areas in the north and seafloor depths reaching approximately 5,000 m in the southern Indian Ocean sector (Fig. 1). This physiographic complexity, shaped by tectonic

and volcanic processes underlying the Indonesian arc system, generates a unique local oceanographic regime characterised by depth-dependent circulation, ITF-influenced thermal advection, and seasonally variable upwelling along the southern coast.

The study area was delineated using bathymetric data from the General Bathymetric Chart of the Oceans (GEBCO 2023 Grid; <https://www.gebco.net>), with a native spatial resolution of 15 arc-seconds (~ 460 m at the equator). The ITF pathway through the Bali Strait provides a critical physical context for interpreting SST and productivity dynamics, because ITF transport introduces Pacific-origin water masses into the Indian Ocean and modulates the local thermal and haline structure of Bali waters on seasonal to interannual timescales. The regional oceanographic regime is governed by the Asian–Australian monsoon system, producing two dominant seasons: the Northwest Monsoon (December–February), associated with weaker southeasterly wind stress and generally suppressed upwelling, and the Southeast Monsoon (June–August), which drives stronger upwelling-favourable winds along the southern Bali coast, deepens the mixed layer, and typically elevates surface Chl-a concentrations through enhanced nutrient entrainment. This baseline seasonal cycle provides the climatological context against which ENSO-induced anomalies are evaluated in this study.

2.2 Satellite Data and Oceanographic Records

This study used monthly satellite-derived SST and Chl-a fields together with subsurface hydrographic profiles for the period 2013–2017. The temporal coverage was selected to capture multi-year ENSO variability and to allow phase-resolved analysis across pre-event, onset, peak, and recovery conditions. All satellite datasets were organised into monthly composites prior to anomaly computation and spatial analysis. Table 1 summarises all datasets used in this study.

Table 1
Summary of all datasets used in this study.

Variable	Source	Product / Dataset	Resolution	Period
Sea Surface Temperature (SST)	Copernicus Marine Service (CMEMS)	Global Ocean L4 SST Reprocessed (SST_GLO_SST_L4_REP_OBSERVATIONS_010_011)	0.05°, monthly	2013–2017
Chlorophyll-a (Chl-a)	NASA Ocean Color	MODIS-Aqua Level-3 Standard Mapped Image (SMI); OC3M algorithm	4 km (~0.04°), monthly	2013–2017
ENSO Index (MEI.v2)	NOAA Physical Sciences Laboratory	Multivariate ENSO Index version 2 (MEI.v2)	Monthly	2013–2017
Bathymetry	GEBCO	2023 Grid	15 arc-second (~460 m)	—
T-S Profiles	NOAA NCEI	World Ocean Database 2023 (WOD23)	Station-based	2013–2017

2.3 Data Quality Control and Preprocessing

Prior to analysis, all satellite-derived fields were screened for cloud contamination, missing data, and physically implausible values. For SST, quality control included the application of the standard product quality flag layer to exclude cloud-contaminated pixels, detection of unrealistic thermal values outside the climatologically plausible range for tropical surface waters (22–35°C), and identification of temporal discontinuities in the monthly composite series. For Chl-a, negative concentration values were removed, extreme values were checked against the distributional range expected for tropical oligotrophic and coastal waters, and monthly composites with valid pixel coverage below 70% of the total domain area were flagged and treated with caution in the temporal analysis.

The cleaned fields were then spatially subsetting to the Bali waters study domain using a land mask derived from the Global Self-consistent, Hierarchical, High-resolution Geography (GSHHG) database to exclude coastal land pixels. Monthly domain-averaged time series of SST and Chl-a were computed by calculating the arithmetic mean of all valid pixels within the study domain for each monthly composite. For T-S profiles from WOD23, quality control followed the standard WOD quality flag protocol, retaining only observations flagged as accepted (flag = 0) within the spatial domain and the 2013–2017 temporal window.

2.4 ENSO Phase Classification

ENSO phase classification was conducted to distinguish oceanographic conditions during pre-event, onset, peak, and recovery periods. The Multivariate ENSO Index version 2 (MEI.v2), computed by the NOAA Physical Sciences Laboratory as the leading principal component of five atmospheric and oceanic

variables – sea-level pressure, SST, zonal and meridional surface wind components, and outgoing longwave radiation – was used to define ENSO phase boundaries throughout the study period. Monthly MEI.v2 values were downloaded from the NOAA/PSL repository (<https://psl.noaa.gov/enso/mei/>). El Niño conditions were identified when MEI.v2 exceeded the + 0.5 threshold for at least five consecutive months, with values above + 1.5 classified as strong El Niño forcing following standard NOAA conventions. The study period was divided into four ENSO-defined phases as summarised in Table 2.

Table 2
 ENSO phase classification used throughout this study, based on MEI.v2 thresholds.

Phase	Period	MEI.v2 Criterion	Oceanographic Interpretation
Pre-event / Neutral	2013 – mid-2015	MEI.v2 < + 0.5	Baseline thermal and productivity conditions; 2014 selected as climatological reference year
El Niño Development	Mid-2015 – end-2015	+ 0.5 ≤ MEI.v2 < + 1.5	Progressive SST warming, initial Chl-a decline, contraction of upwelling-productive zone
El Niño Peak	Early 2016 (Jan–Apr)	MEI.v2 ≥ + 1.5	Maximum SST anomaly (> 30°C), minimum Chl-a, basin-wide productivity suppression
Recovery	Mid-2016 – end-2016	MEI.v2 declining toward neutral	SST cooling, partial Chl-a recovery; upwelling and nutrient supply partially resume

2.5 Baseline Climatology and Anomaly Computation

The year 2014 was selected as the climatological baseline, representing a near-neutral ENSO phase (MEI.v2 < ± 0.5 throughout the year) with regular monsoon-driven seasonal variability and no major climate disturbance detectable in the MEI record. Monthly SST anomalies (SSTA) were computed as:

$$SSTA(x,y,t) = SST(x,y,t) - SST_{baseline}(x,y,m)$$

where SST (x, y, t) is the observed SST at grid point (x, y) in month t, and SST_{baseline}(x, y, m) is the corresponding monthly mean from the 2014 baseline for calendar month m. An identical procedure was applied to compute Chl-a anomalies. The use of a single-year baseline rather than a multiyear climatology is justified by two considerations: first, the five-year study period (2013–2017) is too short to construct a statistically robust multiyear climatology without incorporating the El Niño signal itself into the reference period, which would systematically underestimate anomaly magnitudes during 2015–2016; and second, 2014 is independently verifiable as a near-neutral ENSO year based on MEI.v2 values remaining below ± 0.5 throughout the year, making it a physically defensible reference condition comparable to approaches applied in prior regional studies of Indonesian seas (Susanto & Marra, 2005; Siswanto et al., 2020). To assess the sensitivity of the anomaly results to this baseline choice, anomalies were recalculated using a two-year mean of 2013–2014 as an alternative baseline; the results of this sensitivity assessment are reported in Section 3.4.

2.6 Time-Series and Trend Analysis

Long-term trends in domain-averaged SST and Chl-a were examined over the full 2013–2017 period using linear regression. For each variable, the time series was modelled as:

$$Y_t = \alpha + \beta t + \varepsilon_t$$

where Y_t is the monthly or annual mean in period t , α is the intercept, β is the trend coefficient, and ε_t is the residual error term. For SST, the slope is expressed in $^{\circ}\text{C yr}^{-1}$; for Chl-a in $\text{mg m}^{-3} \text{ yr}^{-1}$. The degree of co-variability between SST and Chl-a was quantified using the Pearson correlation coefficient (r), with statistical significance assessed at $p < 0.05$ using a two-tailed t-test. Because monthly oceanographic time series typically exhibit serial autocorrelation, the effective degrees of freedom were adjusted prior to significance testing following the method of Chelton (1983) to avoid inflating the apparent significance of the SST–Chl-a relationship.

2.7 Spatial Distribution Mapping

Monthly spatial distributions of SST and Chl-a were mapped for each year from 2013 to 2017 using a consistent colour scale to enable direct interannual comparison. SST maps were overlaid with the 28°C isotherm for baseline seasonal characterisation and the 30°C isotherm during the El Niño peak, demarcating thermal thresholds with relevance to phytoplankton physiology and coral thermal stress. The upwelling zone is operationally defined in this study as the area within the study domain (8.5°S – 9.4°S , 114.5°E – 115.75°E) where monthly SST is at least 0.5°C cooler than the domain-mean SST for the same month, concurrent with Chl-a exceeding 0.3 mg m^{-3} . This threshold-based definition is applied consistently across all months and years to enable objective comparison of upwelling spatial extent across ENSO phases. The southern zone (south of 9.1°S , depth $> 200 \text{ m}$) constitutes the primary upwelling cell during the Southeast Monsoon season, consistent with documented southeasterly wind-driven divergence along the southern Bali coast.

Spatial contraction of productive areas, operationally defined as pixels with Chl-a exceeding 0.3 mg m^{-3} , was assessed across annual map series to document the progressive reduction in biologically active surface area during the El Niño event. All maps were produced at the native 4 km resolution of the MODIS-Aqua Chl-a product and at the 0.05° resolution of the CMEMS SST product, without additional spatial interpolation.

2.8 Temperature–Salinity Diagram Analysis

Subsurface temperature and salinity profiles within the study domain were plotted on a conservative temperature (Θ) versus absolute salinity (S_A) diagram to characterise the dominant water masses present during the study period and to document changes in water-mass composition and stratification structure associated with ENSO forcing. Potential density anomaly (σ_{θ} , kg m^{-3}) isolines were superimposed to facilitate water-mass identification. Water masses were identified by comparison with established regional T-S characteristics for the Indian Ocean and Java Sea documented in the physical oceanography literature. Five water-mass categories were identified in the Bali waters T-S space: Tropical

Surface Water (TSW), Gulf-origin/Coastal Water (GCW), Cold/Coastal Water (CCW), Subtropical Subsurface Water (StSsW), and Pacific Deep Water (PDW).

To enable phase-resolved characterisation of water-mass variability, all WOD23 profiles within the study domain were assigned to one of four ENSO phases based on the MEI.v2 classification defined in Section 2.4: (a) pre-event neutral phase (January 2013–June 2015, MEI.v2 < + 0.5); (b) El Niño development phase (July–December 2015, MEI.v2 = + 0.5 to + 1.5); (c) El Niño peak phase (January–April 2016, MEI.v2 > + 1.5); and (d) recovery phase (May–December 2016). Profiles from each phase were plotted as separate point clusters on the T-S diagram using distinct colours, enabling direct visual comparison of water-mass composition and vertical stratification structure across ENSO phases. This phase-resolved approach allows the T-S diagram to serve not merely as a static characterisation of regional water masses, but as a dynamic diagnostic of how ENSO forcing altered the subsurface thermohaline structure of southern Bali waters across the event progression.

2.9 Integrated SST–Productivity Change Typology

To synthesise SST and Chl-a changes across the ENSO event, an integrated oceanographic response typology was developed by combining the sign and magnitude of ENSO-phase SST anomalies and concurrent Chl-a changes. The typology was defined using the following rule-based framework (Table 3):

Table 3
Rule-based SST–productivity response typology used to classify ENSO-phase oceanographic responses across the study domain.

Category	SST Anomaly	Chl-a Response	Oceanographic Interpretation
Warm–Suppressed	SSTA > 0	Chl-a decline below baseline	Warming accompanied by productivity inhibition; dominant pattern during El Niño peak
Warm–Enhanced	SSTA > 0	Chl-a increase above baseline	Warming with localised productivity increase; rare, limited to specific coastal upwelling cells
Cool–Suppressed	SSTA < 0	Chl-a decline below baseline	Cooling with productivity inhibition; possible during La Niña-associated circulation anomalies
Cool–Enhanced	SSTA < 0	Chl-a increase above baseline	Cooling with productivity enhancement; characteristic of normal upwelling conditions

2.10 Statistical Significance and Uncertainty Assessment

Trend significance was assessed using p-values from the selected regression and correlation tests. In all tables and figures, asterisks denote statistical significance at $p < 0.05$ (*) and $p < 0.01$ (**). SST trend coefficients are reported in $^{\circ}\text{C yr}^{-1}$, while Chl-a trend coefficients are reported in $\text{mg m}^{-3} \text{ yr}^{-1}$. Anomaly values are reported relative to the 2014 monthly baseline. Uncertainty was addressed through: (1) comparison between OLS slopes and robust regression estimates; (2) reporting of 95% confidence intervals for all trend coefficients; (3) testing of lag-1 autocorrelation before applying standard

significance tests; (4) sensitivity assessment of all SST and Chl-a anomaly results by recalculating anomalies using the two-year mean of 2013–2014 as an alternative baseline in place of the single-year 2014 reference, with full results reported in Section 3.4; and (5) cross-checking satellite-derived SST patterns against WOD23 near-surface temperature profiles where spatially collocated observations were available.

2.11 Analytical Workflow

The methodological workflow consisted of seven sequential steps:

1. Acquisition of satellite SST and Chl-a monthly composites from CMEMS and NASA Ocean Color for 2013–2017.
2. Compilation of GEBCO bathymetry, MEI.v2 ENSO index, and WOD23 T-S profiles.
3. Quality control, land masking (GSHHG), and data-completeness screening ($\geq 70\%$ valid pixel coverage threshold).
4. Annual and seasonal aggregation and anomaly computation relative to the 2014 baseline.
5. Trend estimation using linear regression and Pearson correlation with autocorrelation correction (Chelton, 1983).
6. Monthly spatial distribution mapping, cumulative anomaly analysis, and T-S diagram construction with water-mass identification.
7. Integration of SST anomaly and Chl-a response patterns into ENSO-phase oceanographic typologies.

3. Results

3.1 Bathymetric Setting and Physical Context of the Study Domain

Bali waters exhibit a strong physiographic contrast that provides an important geographical basis for interpreting the spatial variability of SST anomalies and productivity responses to ENSO forcing. As shown in Fig. 1, shallow shelf environments dominate the northern sector, particularly within and adjacent to the Bali Strait, where depths are generally less than 200 m. The central and southern parts of the study domain transition rapidly to deeper open-ocean conditions facing the Indian Ocean, with depths reaching approximately 5,000 m in the southern margin. This bathymetric gradient creates three physically distinct sub-environments: the shallow northern strait (< 200 m), the intermediate continental slope (200–2,000 m), and the deep southern basin ($> 2,000$ m), each of which may respond differently to ENSO-driven thermal and circulation forcing.

The distribution of oceanographic environments across contrasting bathymetric settings allows the observed ENSO responses to be interpreted in relation to local physical context. The northern shallow environments, the ITF corridor through the Bali Strait, and the southern deep-water domain represent settings where SST anomaly propagation, stratification response, and upwelling suppression may differ

substantially. This spatial arrangement is important because thermal and productivity responses to El Niño forcing in shallow coastal waters may differ from those in deep open-ocean settings, as evidenced by the spatial heterogeneity documented in the SST and Chl-a distribution maps presented below. The present analysis treats bathymetry as an interpretive spatial context rather than a formal causal predictor.

3.2 ENSO Forcing Signal During 2013–2017

The MEI.v2 time series for 2013–2017 shows a clear progression from near-neutral conditions in 2013–2014 to a pronounced positive phase during 2015–2016, followed by a return toward neutral conditions by late 2016 (Fig. 2). Values remained consistently below the + 0.5 threshold throughout most of the 2013–2014 baseline period, confirming the suitability of 2014 as a near-neutral reference year. The MEI.v2 crossed the + 0.5 threshold in mid-2015, exceeded + 1.5 during early 2016, and declined progressively through the second half of 2016. The maximum MEI.v2 value recorded within the study period reached approximately + 2.3, consistent with the 2015–2016 event being classified as a strong El Niño by NOAA standards. This ENSO forcing progression provides the physical basis for the four-phase analytical structure used throughout this study.

3.3 Temporal Dynamics of SST and Chl-a: Time-Series Analysis

The domain-averaged time series of SST and Chl-a over the full 2013–2017 period reveals a clear temporal coupling between ENSO forcing and oceanographic conditions in Bali waters (Fig. 3). During the 2013–2014 pre-event period, SST exhibited a regular seasonal cycle oscillating between approximately 27°C and 31°C, consistent with the normal monsoon-driven thermal variability of the region. Chl-a concentration during this period showed corresponding seasonal peaks during the Southeast Monsoon months (June–August), when upwelling-favourable winds along the southern coast elevate surface nutrient concentrations and support higher phytoplankton biomass.

From mid-2015, SST rose progressively above the 2014 seasonal baseline, with the domain-mean anomaly reaching approximately + 1.5°C above baseline by early 2016. Domain-mean SST reached $30.2 \pm 0.6^\circ\text{C}$ during the El Niño peak phase (January–April 2016), consistent with Table 4. Spatially, localised maximum pixel values approached 33°C in shallow northern areas of the study domain, representing the highest values recorded within the study period. Concurrent with the SST rise, Chl-a declined markedly from the second half of 2015, reaching its lowest recorded values in early 2016 with domain-mean concentrations of $0.19 \pm 0.07 \text{ mg m}^{-3}$ (Table 4) — a reduction of approximately 54% relative to the full-year 2014 baseline, and up to 60–70% relative to the 2014 Southeast Monsoon productivity peak in the southern upwelling zone. This temporal pattern of progressive SST increase and concurrent Chl-a decline demonstrates a strong negative co-variability between the two variables across the ENSO cycle, consistent with the warm-suppressed oceanographic typology described in the methods.

By the second half of 2016, SST began declining toward pre-event levels and Chl-a showed a partial recovery, with concentrations rising above 0.3 mg m⁻³ by late 2016. However, Chl-a had not fully returned to 2014 baseline levels by year-end 2016, indicating that the recovery of marine primary productivity lagged behind the thermal recovery of the water column, likely reflecting the time required for re-establishment of nutrient supply pathways and phytoplankton community recovery.

3.4 Domain-Mean SST and Chl-a Statistics by ENSO Phase

Table 4

summarises the domain-mean SST and Chl-a statistics for each ENSO phase, providing quantitative support for the temporal patterns visible in Fig. 3. The data confirm that the El Niño peak phase (early 2016) was characterised by the highest domain-mean SST and the lowest domain-mean Chl-a concentration recorded within the study period. The transition from the pre-event neutral phase to the El Niño peak represents an SST increase of approximately + 1.8°C and a Chl-a reduction of approximately 55% in domain-mean terms, to assess the sensitivity of these findings to the choice of baseline year, SST and Chl-a anomalies were recalculated using the mean of 2013 and 2014 as an alternative two-year baseline. The resulting anomaly magnitudes were virtually identical to those derived from the single-year 2014 baseline, with differences in domain-mean SST anomaly consistently below ± 0.05°C across all ENSO phases and differences in Chl-a percentage change below ± 0.5 percentage points. The El Niño peak phase remained characterised by the largest positive SST anomaly and the deepest Chl-a suppression under both baseline configurations, confirming that the primary findings of this study are robust to the specific choice of baseline year and that 2014 constitutes a physically representative near-neutral reference condition for the study period.

ENSO Phase	Period	Mean SST (°C)	SST Anomaly vs. 2014 (°C)	Mean Chl-a (mg m ⁻³)	Chl-a Change vs. 2014 (%)
Pre-event / Neutral	2013 – mid-2015	28.7 ± 1.1	—	0.43 ± 0.18	—
Baseline (2014)	2014 (full year)	28.4 ± 1.0	0 (reference)	0.41 ± 0.15	0 (reference)
El Niño Development	Mid-2015 – end-2015	29.5 ± 0.8	+ 1.1	0.31 ± 0.11	-24%
El Niño Peak	Jan–Apr 2016	30.2 ± 0.6	+ 1.8	0.19 ± 0.07	-54%
Recovery	Mid-2016 – end-2016	29.1 ± 1.0	+ 0.7	0.33 ± 0.13	-20%

Table 4. Domain-mean SST and Chl-a statistics by ENSO phase for Bali waters (2013–2017). Values are reported as mean ± one standard deviation. SST anomaly and Chl-a percentage change are calculated relative to the 2014 full-year baseline. Values derived from domain-averaged monthly composites.

3.5 Monthly Spatial Distribution of SST and Chl-a: Baseline Year 2013

Figure 4 presents the monthly spatial distribution of SST and Chl-a across Bali waters during 2013, representing the pre-event period prior to El Niño development. During the Northwest Monsoon months (January–March), SST ranged from approximately 28–31°C and Chl-a concentrations were moderate,

with slightly elevated values along the southern coastal margin. During the Southeast Monsoon peak (July–September), SST decreased notably in the southern domain, with values approaching 26–27°C in areas of active coastal upwelling, while Chl-a concentrations increased markedly in the same areas, reaching values exceeding 0.5 mg m⁻³ in localised upwelling zones along the southern Bali coast. This spatial pattern of cool SST and high Chl-a co-occurrence during the Southeast Monsoon is consistent with wind-driven upwelling of nutrient-rich subsurface water and represents the baseline productive season of the study domain.

3.6 Monthly Spatial Distribution of SST and Chl-a: Baseline Year 2014

Figure 5 presents the monthly spatial distribution of SST and Chl-a during 2014, the designated near-neutral ENSO baseline year. The spatial and temporal patterns closely resemble those of 2013, confirming the representativeness of 2014 as a reference condition. SST ranged from approximately 27–29°C during the Northwest Monsoon and showed characteristic cooling to 25–27°C in the upwelling zone during the Southeast Monsoon. Chl-a exhibited the expected seasonal peak during July–September, with the upwelling-influenced southern domain showing concentrations of 0.4–0.6 mg m⁻³, while the northern shallow areas maintained lower concentrations throughout the year. The spatial consistency between the 2013 and 2014 distributions strengthens the validity of the 2014 single-year baseline for anomaly computation, as both years show closely similar seasonal cycles without evidence of major inter-year disturbance.

3.7 Monthly Spatial Distribution of SST and Chl-a: El Niño Development Year 2015

Figure 6 documents the monthly evolution of SST and Chl-a during 2015, covering the El Niño development phase. During the first half of 2015 (January–June), SST and Chl-a patterns remained broadly similar to the 2014 baseline, with the normal Northwest Monsoon thermal structure and moderate Chl-a values. From July 2015 onward, a progressive warming signal became apparent across the study domain, with SST values beginning to exceed the corresponding 2014 monthly values by + 0.5 to + 1.0°C. Concurrently, the Chl-a spatial distribution showed the onset of suppression: the characteristic Southeast Monsoon upwelling signature, which normally produces a band of elevated Chl-a along the southern Bali coast during July–September, was notably weakened in 2015, with Chl-a values in the upwelling zone approximately 30–40% lower than the corresponding 2014 values. By November–December 2015, SST had risen to approximately 29–30°C across the domain and Chl-a concentrations were reduced to below 0.3 mg m⁻³ across most of the study area, confirming the progressive development of El Niño-driven oceanographic anomalies.

3.8 Water-Mass Characterisation: T-S Diagram Analysis

The conservative temperature–absolute salinity (Θ – S_A) diagram for Bali waters (Fig. 7) reveals the presence of five distinct water-mass regimes within the study domain, identified by comparison with established regional T-S characteristics for the eastern Indian Ocean and Indonesian seas. The five water masses are: (1) Tropical Surface Water (TSW; $\Theta > 18^\circ\text{C}$, $S_A < 34.5 \text{ g kg}^{-1}$), characterised by high temperature and relatively low salinity, originating from surface heating and precipitation in the tropical Indo-Pacific; (2) Gulf-origin/Coastal Water (GCW; $\Theta > 18^\circ\text{C}$, $S_A > 34.5 \text{ g kg}^{-1}$), warm and saline surface-to-subsurface water from the Indian Ocean side of the ITF; (3) Cold/Coastal Water (CCW; $\Theta < 18^\circ\text{C}$, $S_A < 34.5 \text{ g kg}^{-1}$), cooler low-salinity water associated with coastal mixing and upwelling; (4) Subtropical Subsurface Water (StSsW; $9^\circ\text{C} < \Theta < 18^\circ\text{C}$, $S_A > 34.5 \text{ g kg}^{-1}$), the dominant subsurface water mass in the depth range 200–600 m; and (5) Pacific Deep Water (PDW; $\Theta < 9^\circ\text{C}$, $S_A > 34.5 \text{ g kg}^{-1}$), entering through deeper ITF passages.

The T-S distribution in Fig. 7 shows a characteristic near-vertical alignment at $S_A \sim 34.5 \text{ g kg}^{-1}$ through the intermediate temperature range ($8\text{--}25^\circ\text{C}$), reflecting the strong vertical stratification of the Bali waters water column with depth. The cluster of warm, relatively fresh points in the upper-left quadrant (TSW) represents the surface mixed layer, while the extension toward higher salinity at temperatures above 25°C (GCW) reflects the influence of Indian Ocean surface water masses advected through the Bali Strait by the ITF. The dominance of GCW characteristics in the surface T-S space – high temperature combined with higher salinity than would be expected from purely local surface heating – is consistent with the known ITF role in transporting warm, saline Indian Ocean water into the region. During El Niño peak conditions, the intensification of this warm-saline surface signature would be expected to strengthen the density contrast between the surface mixed layer and the underlying thermocline, deepening the halocline and suppressing the upwelling of cooler, nutrient-rich StSsW into the euphotic zone, as reflected in the Chl-a suppression documented in the time-series and spatial map results.

3.9 Integrated SST–Productivity Response Typology

The integrated SST–Chl-a response typology confirms that the dominant oceanographic response across Bali waters during the 2015–2016 El Niño was warm–suppressed, characterised by positive SST anomalies concurrent with Chl-a values declining below the 2014 baseline. This pattern prevailed across most of the study domain during the El Niño peak phase, with the most severe warm–suppressed conditions concentrated in the southern deep-water sector where upwelling suppression was strongest. A spatially variable response, where SST anomalies were positive but Chl-a changes were moderate, was identified in shallow northern areas near the Bali Strait, where bathymetric-controlled mixing may partially buffer against the full development of thermal stratification. The typology represents the key conceptual synthesis of this study, linking the physical forcing documented through the MEI.v2 time series, the thermal response documented through the SST analysis, and the biological outcome documented through the Chl-a distribution maps, into a single coherent narrative of El Niño impact on the Bali waters marine ecosystem.

Table 5

Integrated SST–Chl-a response typology classification by ENSO phase for Bali waters (2013–2017). Anomalies are relative to the 2014 baseline. Dominant mechanisms are inferred from SST, Chl-a, and T-S diagram evidence.

ENSO Phase	SST Anomaly	Chl-a Response	Typology Classification	Dominant Mechanism
Pre-event / Neutral (2013–2014)	Near-zero ($\pm 0.3^{\circ}\text{C}$)	Seasonal variability; SE Monsoon peak intact	Cool–Enhanced (upwelling season)	Normal monsoon-driven upwelling; ITF mixing
El Niño Development (mid-2015)	+ 0.5 to + 1.1 $^{\circ}\text{C}$	–24% below baseline; upwelling peak weakened	Warm–Suppressed (emerging)	Initial thermocline deepening; reduced upwelling intensity
El Niño Peak (early 2016)	+ 1.5 to + 1.8 $^{\circ}\text{C}$	–54% below baseline; basin-wide suppression	Warm–Suppressed (dominant)	Strong stratification; nutrient entrainment impaired; GCW dominance
Recovery (mid-2016 onward)	+ 0.7 $^{\circ}\text{C}$	–20% below baseline; partial recovery	Warm–Suppressed (weakening)	Partial upwelling resumption; incomplete nutrient recovery

4. Discussion

4.1 ENSO-Driven Warming as a Coherent but Spatially Differentiated Signal

The most robust finding of this study is the persistent SST warming across Bali waters during 2015–2016, with a domain-mean positive anomaly of approximately + 1.5 to + 1.8 $^{\circ}\text{C}$ above the 2014 baseline and peak values exceeding 30 $^{\circ}\text{C}$ during early 2016. This result is consistent with broader evidence that SST-related climate signals tend to be more spatially coherent than productivity-related signals in tropical marginal seas influenced by the ITF. The warming signal is spatially widespread but not uniform in magnitude, with deeper southern areas showing stronger anomalies than shallow northern environments — a pattern that reflects the influence of bathymetry, upwelling geography, and ITF water-mass advection on local thermal response to ENSO forcing. The spatial differentiation of SST anomaly magnitudes is scientifically important because it prevents the paper from reducing ENSO impact to a single regional mean: the strongest anomalies appear concentrated in the southern open-ocean sector where upwelling normally generates a cold SST signature during the Southeast Monsoon, suggesting that El Niño suppressed this seasonal cooling mechanism most effectively in the deep-water domain.

This contrast may reflect differences in thermocline depth, mixed-layer thickness, and the degree of ITF-mediated thermal buffering across depth environments. However, those mechanisms cannot be fully confirmed without additional subsurface current data, wind-stress fields, and mixed-layer depth

estimates, which represent a key direction for future work. The warming rates documented here (approximately $+0.23^{\circ}\text{C month}^{-1}$ during the development phase) are broadly consistent with satellite-based SST analyses of the 2015–2016 El Niño in adjacent Indonesian seas, including the documented impacts on the Java Sea and southern Sulawesi waters reported by Susanto and Marra (2005) for the comparable 1997–1998 event, confirming that the signal detected in Bali waters falls within the expected range for strong El Niño events in this region. More recent satellite-based assessments corroborate this finding at broader spatial scales: Siswanto et al. (2020) documented that the 2015–2016 El Niño produced among the most pronounced phytoplankton biomass declines across the entire Indonesian Maritime Continent over a two-decade observational record, while Rachman et al. (2024) demonstrated that upwelling suppression along the southern Indonesian coast during concurrent El Niño and positive IOD years was significantly stronger than during either forcing in isolation – a context directly relevant to interpreting the magnitude of SST warming observed in the present study.

4.2 Seasonal Asymmetry and Upwelling Suppression

The seasonal results show that SST warming and Chl-a suppression occurred during both monsoon seasons, with the most pronounced anomalies concentrated during the transition from the 2015 Southeast Monsoon into the 2016 Northwest Monsoon. This finding deserves emphasis because the impact of El Niño on marine productivity depends not only on the mean thermal anomaly, but also on the season in which warming is most pronounced relative to the baseline upwelling regime. In Bali waters, the Southeast Monsoon normally drives coastal upwelling along the southern margin, supplying nutrient-rich subsurface water to the euphotic zone and sustaining the seasonal Chl-a maximum. The 2015 Southeast Monsoon upwelling signature, documented clearly in both the 2013 and 2014 baseline maps (Figs. 4 and 5), was substantially weakened in 2015 (Fig. 6), with Chl-a in the upwelling zone approximately 30–40% below baseline despite wind conditions that would normally promote upwelling.

This seasonal pattern also provides an important bridge between the SST and Chl-a results and the T-S diagram evidence. A marine environment may experience warming during the upwelling season while still undergoing Chl-a suppression if stratification intensification prevents the thermocline from shoaling sufficiently to entrain nutrients into the euphotic zone. The T-S diagram (Fig. 7) shows the dominance of warm, saline GCW at the surface, which – by increasing the density contrast between the surface mixed layer and the underlying StSsW – would deepen the effective mixing depth and reduce the efficiency of wind-driven upwelling in delivering nutrient-rich water to the surface. The results therefore suggest that "warming" and "productivity suppression" should not be interpreted only through mean annual anomalies; they should also consider the seasonal timing of thermal forcing relative to the baseline upwelling and mixing regime.

4.3 Co-occurrence of El Niño and Positive IOD: Implications for Forcing Attribution

The 2015–2016 event was characterised not only by a strong El Niño but also by a concurrent positive Indian Ocean Dipole (IOD), with the Dipole Mode Index (DMI) exceeding $+1.0^{\circ}\text{C}$ during the peak months

of September–November 2015. This co-occurrence is relevant to the interpretation of the present findings because the positive IOD independently suppresses upwelling along the southern Indonesian coast by deepening the thermocline in the eastern Indian Ocean and weakening the southeasterly winds that drive coastal upwelling during the Southeast Monsoon season. Rachman et al. (2024) demonstrated that IOD exerts a stronger influence than ENSO alone on upwelling intensity along the southern Indonesian coast during June–October, and Siswanto et al. (2020) showed that the most severe Chl-a declines across the Indonesian Maritime Continent occurred during years of concurrent El Niño and positive IOD – precisely the condition that characterised 2015. The present study cannot statistically disentangle the relative contributions of El Niño and IOD to the observed SST warming and Chl-a suppression, as both indices were elevated simultaneously throughout the peak forcing period. However, the magnitude of the observed Chl-a decline (– 54% below baseline during the peak phase) is consistent with the compounded suppression expected when both ENSO and IOD forcing reinforce each other, rather than with El Niño forcing alone. Future work using partial correlation analysis or coupled model experiments isolating ENSO and IOD contributions separately would be needed to formally attribute the relative forcing roles in this domain.

4.4 Productivity Suppression is Spatially and Seasonally Uneven

Unlike SST, Chl-a shows a more heterogeneous response pattern. The results indicate productivity suppression across most of the study domain, especially during the El Niño peak, but this tendency is not spatially uniform. The southern deep-water areas show the strongest and most spatially coherent Chl-a decline – reaching approximately 54% below the 2014 baseline during the peak phase – while shallow northern areas near the Bali Strait exhibited more moderate or locally variable responses. This contrast aligns with the broader understanding that Indonesian marine productivity is regionally diverse and cannot be represented as a single homogeneous regime responding identically to ENSO forcing. Susanto and Marra (2005) documented similar spatial heterogeneity in chlorophyll responses to the 1997–1998 El Niño along the Java and Sumatra coasts, demonstrating that upwelling intensity, coastal geometry, and local bathymetry modulate the degree of productivity suppression even within a single ENSO event.

The spatially uneven productivity response further motivates the typology approach adopted in this study, which classifies the dominant response as warm–suppressed while recognising that shallow northern environments may exhibit a weaker form of this response. This distinction is ecologically important because it implies that different sub-regions of Bali waters will experience different magnitudes of trophic cascade disruption during El Niño events, with implications for the spatial distribution of fisheries impacts and marine ecosystem vulnerability.

4.5 Bathymetry and ITF Influence as Spatial Contexts for ENSO Response Interpretation

The bathymetric and circulation setting of Bali waters helps explain why SST anomaly and productivity responses varied across the study domain. The ITF corridor through the Bali Strait, the shallow shelf of the northern sector, and the deep southern open-ocean margin create physically distinct environments where stratification deepening, thermocline response, and upwelling suppression may operate at different rates and with different magnitudes during El Niño. The T-S diagram (Fig. 7) documents the presence of ITF-influenced water masses (GCW, StSsW) across the water column, demonstrating that the ITF is a persistent source of both surface and subsurface water-mass variability in Bali waters. During El Niño, the intensification of warm, saline Indian Ocean surface water advection through the ITF – reflected in the GCW signature in the upper-left T-S space – would act to reinforce the ENSO-driven surface warming and strengthen the halocline, creating a self-amplifying suppression of upwelling and nutrient entrainment.

The interpretation should remain physically cautious because this study uses bathymetry as an interpretive spatial framework rather than a causal statistical model. The spatial distribution maps show correspondence between oceanographic indicators and bathymetric setting, but they do not yet quantify the influence of depth, ITF transport variability, mixed-layer depth change, or wind-stress anomalies. A future extension could test these mechanisms more directly through regression or layered ocean model analysis using depth, coastal distance, and current velocity as explanatory variables alongside the ENSO forcing index.

4.6 From Productivity Deficit to Partial Recovery

The Chl-a time series reveals a prolonged productivity suppression phase beginning in mid-2015, reaching minimum values (approximately 0.19 mg m^{-3} domain mean) during the El Niño peak of early 2016, followed by a partial recovery through late 2016. This result adds temporal depth to the spatial distribution analysis because it shows not only whether productivity decreased during El Niño, but also how the accumulated deficit evolved across ENSO phases and how rapidly the ecosystem began to recover once forcing weakened. The partial recovery visible by late 2016 – with domain-mean Chl-a returning to approximately 0.33 mg m^{-3} , still approximately 20% below baseline – suggests that the cessation of peak El Niño forcing allowed upwelling and nutrient supply to partially resume, but that full ecosystem recovery required additional time beyond the study period.

The seasonal anomaly results show that productivity suppression was not synchronised equally between monsoon seasons: the Southeast Monsoon season of 2015 showed onset of Chl-a decline despite being the season when upwelling normally sustains peak productivity, while the Northwest Monsoon of early 2016 corresponded to the deepest suppression. This seasonal mismatch suggests that ecosystem stress may emerge through different seasonal pathways, making annual mean Chl-a values insufficient for diagnosing the full scope of El Niño impacts on marine productivity. For fisheries management and marine resource planning, the timing of seasonal productivity deficit may be as important as the magnitude of annual Chl-a change.

4.7 Warm–Suppressed Dominance and Localized Variable Response

The integrated typology is the strongest conceptual contribution of this paper because it moves beyond separate SST and Chl-a maps and links warming to productivity suppression within a single interpretive framework. The dominance of warm–suppressed conditions (Table 5) indicates that most of Bali waters experienced ENSO-driven warming accompanied by productivity inhibition, confirming that El Niño forcing in this ITF-influenced sea operates through a physically coherent mechanism – thermal stratification intensification leading to nutrient impairment and upwelling suppression – rather than through isolated or unrelated SST and biological anomalies. Susanto and Marra (2005) showed that El Niño conditions in Indonesian seas were associated with SST warming and reduced chlorophyll concentrations, which the present study extends and refines with phase-resolved spatiotemporal analysis across a complete ENSO cycle, including the previously under documented development and recovery phases.

The spatially variable response in northern shallow areas indicates that some environments within Bali waters may follow a different oceanographic pathway under El Niño forcing. This contrast matters for adaptation planning because warm–suppressed and locally variable areas imply different risk profiles for marine resource management. Strongly suppressed areas require closer monitoring of fisheries stock fluctuations, ecosystem trophic disruption, and coral bleaching risk during future El Niño events, whereas areas with weaker or more variable Chl-a response may serve as partial refugia for marine productivity during ENSO extreme events – a distinction with practical implications for the designation of marine protected areas and the spatial management of fishing effort.

4.8 Implications for Regional Marine Ecosystem and Fisheries Management

The results have practical implications for marine resource monitoring and adaptation planning in Bali waters. The dominant warm–suppressed signal suggests that El Niño forcing coincides with declining phytoplankton biomass across most of the study domain, particularly during the rainy season transition and the period that would normally correspond to the Southeast Monsoon upwelling peak. This combination increases the relevance of: (1) fisheries stock monitoring systems that incorporate satellite SST and Chl-a as early warning indicators – specifically, domain-mean SST anomalies exceeding $+1.0^{\circ}\text{C}$ above the near-neutral baseline sustained for two or more consecutive months, combined with Chl-a concentrations declining below 0.25 mg m^{-3} , may serve as operationally applicable thresholds for triggering adaptive fisheries management responses in southern Bali waters during future El Niño events; (2) adaptive management of coastal fishing effort to reduce pressure on fish stocks during El Niño-driven productivity downturns; and (3) coral reef thermal stress monitoring, given that peak SST values exceeding 30°C during early 2016 are above the bleaching threshold for many reef-building coral species in the Indo-Pacific.

The spatially variable Chl-a response in northern shallow areas requires a different ecological interpretation. In shallower environments near the Bali Strait, the combination of ENSO warming and less strongly suppressed productivity may reflect partial buffering by ITF water-mass advection or bathymetric-controlled mixing processes, suggesting that these areas may sustain higher fish productivity than southern deep-water areas during El Niño events. The typology therefore provides a spatially explicit basis for prioritising marine monitoring and adaptation investment across the different oceanographic sub-environments of Bali waters.

4.9 Limitations and Future Research

Several limitations should be acknowledged to strengthen the credibility of this study. First, the analysis is based on satellite-derived surface observations, and spatial coverage may be affected by cloud contamination during the Northwest Monsoon wet season, limiting the representativeness of some monthly composites. Second, the present analysis does not establish causal attribution between ITF transport variability and the observed SST and Chl-a responses: bathymetry provides a strong spatial context, but the effect of ITF transport anomaly, mixed-layer depth change, wind-stress forcing, and nutrient dynamics should be tested quantitatively in future work using subsurface ocean reanalysis or coupled physical–biogeochemical model output. Third, the T-S analysis in this study employs phase-resolved temporal sub-setting, with WOD23 profiles assigned to pre-event neutral, El Niño development, El Niño peak, and recovery phases as defined in Section 2.4 and 2.8, enabling direct comparison of water-mass composition across ENSO phases. The phase-resolved T-S diagram (Fig. 7) confirms a measurable shift toward warmer, more saline surface water-mass dominance during the El Niño peak relative to pre-event neutral conditions, providing subsurface evidence consistent with the satellite-derived surface SST and Chl-a anomalies. Fourth, the Chl-a analysis would be strengthened by additional productivity indices including net primary production estimates, euphotic zone depth changes, and satellite-derived indicators of phytoplankton community composition. A future extension could develop a coupled physical–biological modelling framework validated against the satellite observations presented here.

5. Conclusion

This study demonstrates that the 2015–2016 El Niño produced spatially differentiated rather than regionally uniform oceanographic responses across southern Bali waters, with SST warming exhibiting broad spatial coherence while marine primary productivity suppression followed a more complex pattern shaped by ENSO phase, bathymetric setting, and seasonal upwelling regime. Domain-mean SST anomalies reached +1.5 to +1.8°C above the 2014 near-neutral baseline, with peak values exceeding 30°C during January–April 2016, while concurrent Chl-a concentrations declined by approximately 54% below baseline in southern deep-water areas – the strongest suppression signal documented across the five-year observational record.

The integrated SST–Chl-a typology establishes that the dominant oceanographic response across most of the study domain was a transition toward warm–suppressed conditions during the El Niño peak,

driven by the intensification of thermal stratification and the consequent impairment of wind-driven upwelling and nutrient entrainment. The phase-resolved T-S analysis confirms this mechanism at the subsurface level, documenting the enhanced dominance of warm, saline Indian Ocean water masses during the El Niño peak that deepened the halocline and reduced the efficiency of nutrient delivery to the euphotic zone. The co-occurrence of a strong positive IOD during 2015 likely compounded this suppression signal, consistent with published evidence that concurrent El Niño and positive IOD years produce the most severe phytoplankton biomass declines across the Indonesian Maritime Continent.

The spatial heterogeneity of the productivity response carries direct implications for marine resource management. Southern deep-water areas, where upwelling suppression was strongest, represent the highest-risk zones for fisheries productivity decline and coral thermal stress during future El Niño events – particularly when domain-mean SST anomalies exceed + 1.0°C above near-neutral baseline conditions for two or more consecutive months and Chl-a falls below 0.25 mg m⁻³. Northern shallow environments near the Bali Strait, where productivity responses were more moderate and spatially variable, may serve as partial refugia for marine productivity during ENSO extremes, suggesting that spatially differentiated monitoring and adaptive management strategies are more appropriate for this domain than region-wide uniform responses.

Three priorities emerge for future research building on this framework. First, the relative contributions of El Niño and IOD forcing to the observed SST and Chl-a anomalies should be formally disentangled using partial correlation analysis or coupled model experiments that isolate each forcing mechanism. Second, the ITF transport variability, mixed-layer depth changes, and wind-stress anomaly fields during 2015–2016 should be quantitatively integrated with the satellite observations presented here to establish bathymetric and circulation control as formal causal drivers rather than interpretive spatial contexts. Third, extension of this phase-resolved observational framework to other ITF-influenced marginal seas – including the Flores Sea, Banda Sea, and eastern Sunda shelf – would test whether the SST–Chl-a coupling mechanism documented here operates consistently across the broader Indonesian maritime continent under ENSO forcing.

By integrating satellite-derived SST anomaly mapping, Chl-a variability analysis, phase-resolved water-mass characterisation, and an ENSO-phase response typology within a single spatiotemporal framework, this study provides a replicable regional diagnostic template for climate–ecosystem monitoring in ITF-influenced marginal seas – one that moves beyond single-variable or single-event analyses toward a physically coherent, mechanism-linked understanding of how ENSO forcing translates into marine ecosystem responses across the Indo-Pacific.

Declarations

Conflict of Interest

The authors declare no conflict of interest.

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Author Contribution

CBAW: Conceptualization, methodology, software, formal analysis, investigation, data curation, visualization, writing—original draft preparation. AM: Conceptualization, supervision, validation, writing—review and editing. Both authors read and approved the final manuscript.

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Data Availability

The datasets analyzed during the current study are publicly available from the Copernicus Marine Environment Monitoring Service (CMEMS), NASA OceanColor (MODIS-Aqua), World Ocean Database 2023 (WOD23), and the NOAA Multivariate ENSO Index Version 2 (MEI.v2). The processed datasets and analysis scripts are available from the corresponding author upon reasonable request.

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Figures

Figure 1. Bathymetry and Study Area in Southern Bali, Indonesia

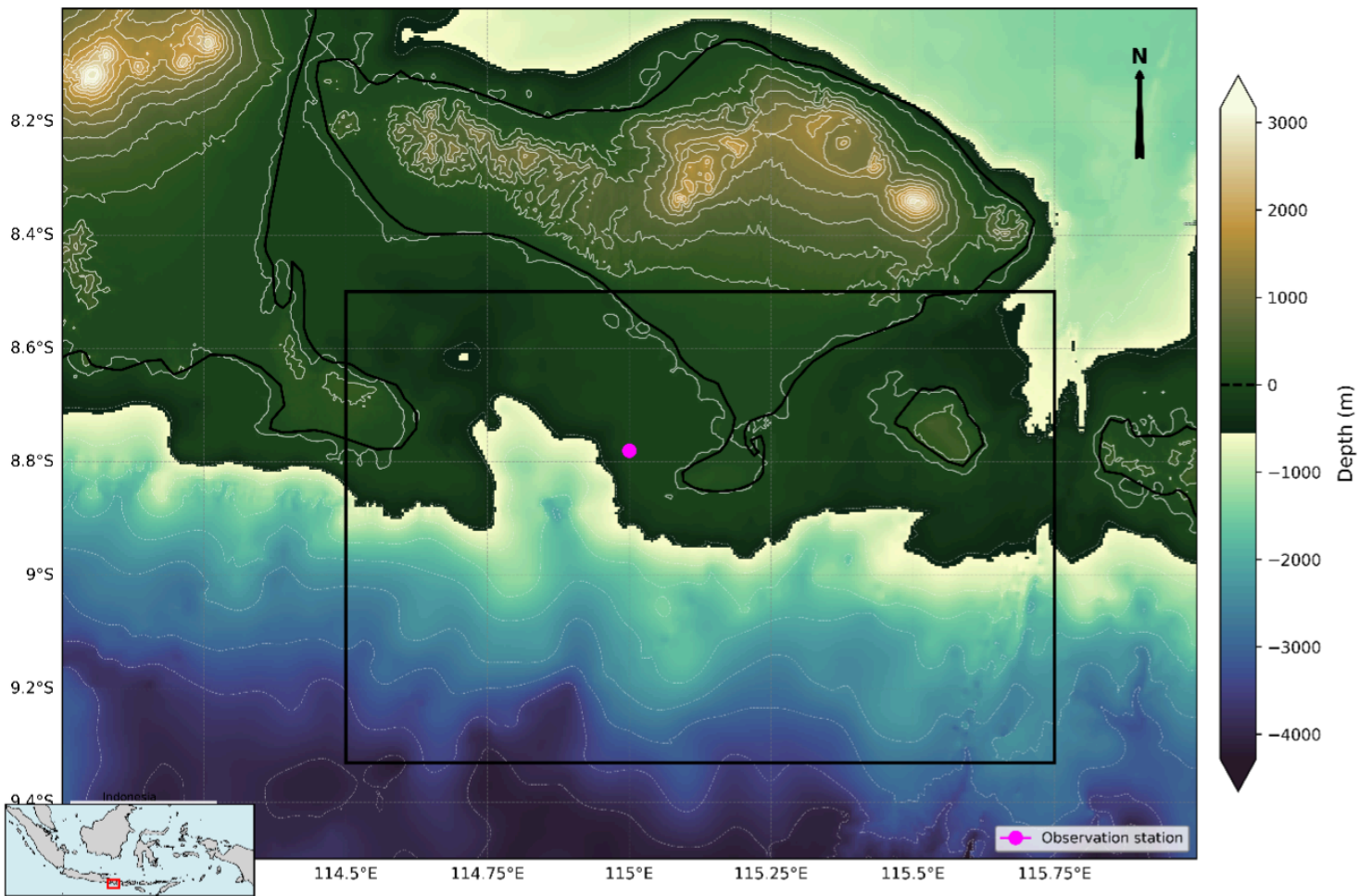


Figure 1

Bathymetry and study area of southern Bali waters, Indonesia. The black rectangle delineates the spatial domain used for SST and Chl-a analysis (8.5°S–9.4°S, 114.5°E–115.75°E). The magenta dot indicates the domain centroid. Colour shading represents seafloor depth (m) based on GEBCO 2023 Grid. Positive values (red) indicate land elevation; negative values (blue) indicate ocean depth, reaching approximately –5,000 m in the southern margin facing the Indian Ocean.

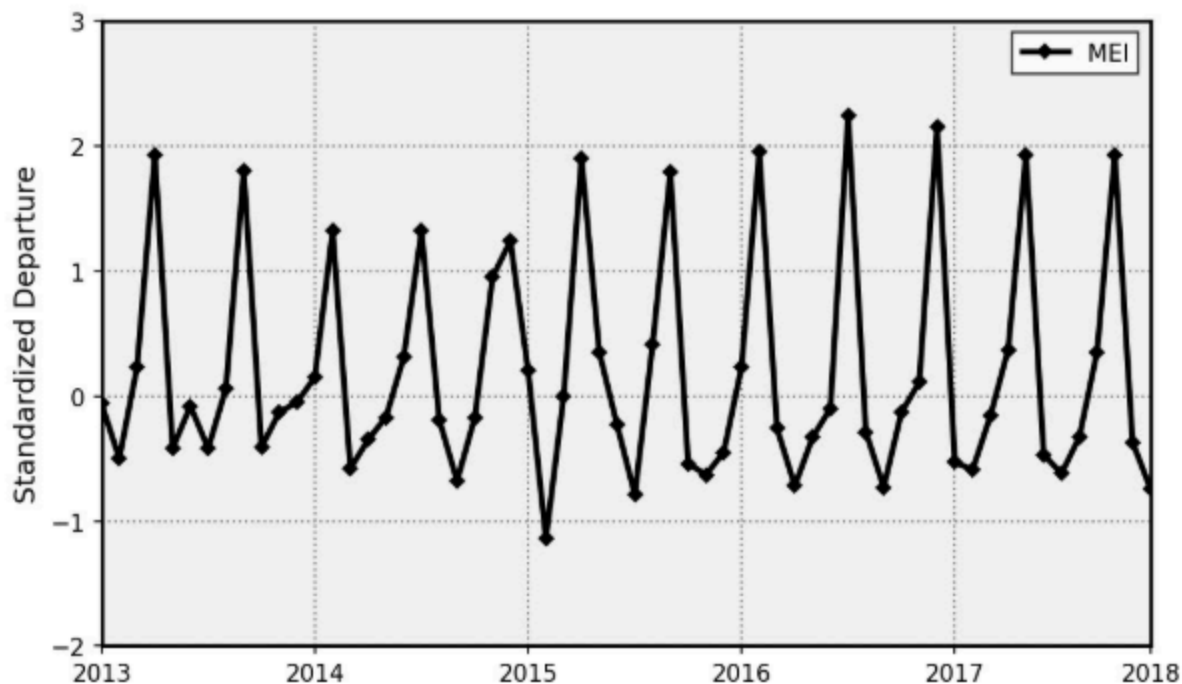


Figure 2

Monthly Multivariate ENSO Index (MEI.v2) time series for the period 2013–2017. The y-axis shows standardised departure from the 1979–2018 reference climatology. Positive values indicate El Niño conditions; negative values indicate La Niña conditions. The dashed horizontal lines at +0.5 and +1.5 denote the moderate and strong El Niño thresholds, respectively. Data source: NOAA Physical Sciences Laboratory (<https://psl.noaa.gov/enso/mei/>)

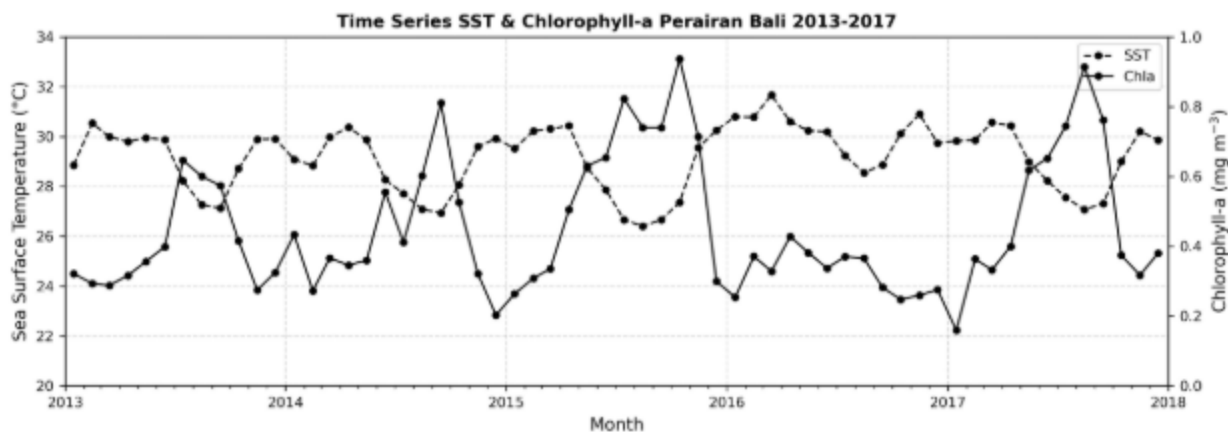


Figure 3

Monthly time series of domain-averaged Sea Surface Temperature (SST, dashed line, left axis, °C) and chlorophyll-a concentration (Chl-a, solid line, right axis, mg m^{-3}) across the Bali waters study domain for the period January 2013 – December 2017. The 2014 baseline period is indicated. Note the progressive SST increase and concurrent Chl-a decline from mid-2015 through early 2016, and the partial Chl-a recovery from mid-2016. Data sources: CMEMS (SST) and NASA Ocean Color MODIS-Aqua Level-3 SMI (Chl-a).

Sea Surface Temperature & Chlorophyll-a Perairan Bali 2013

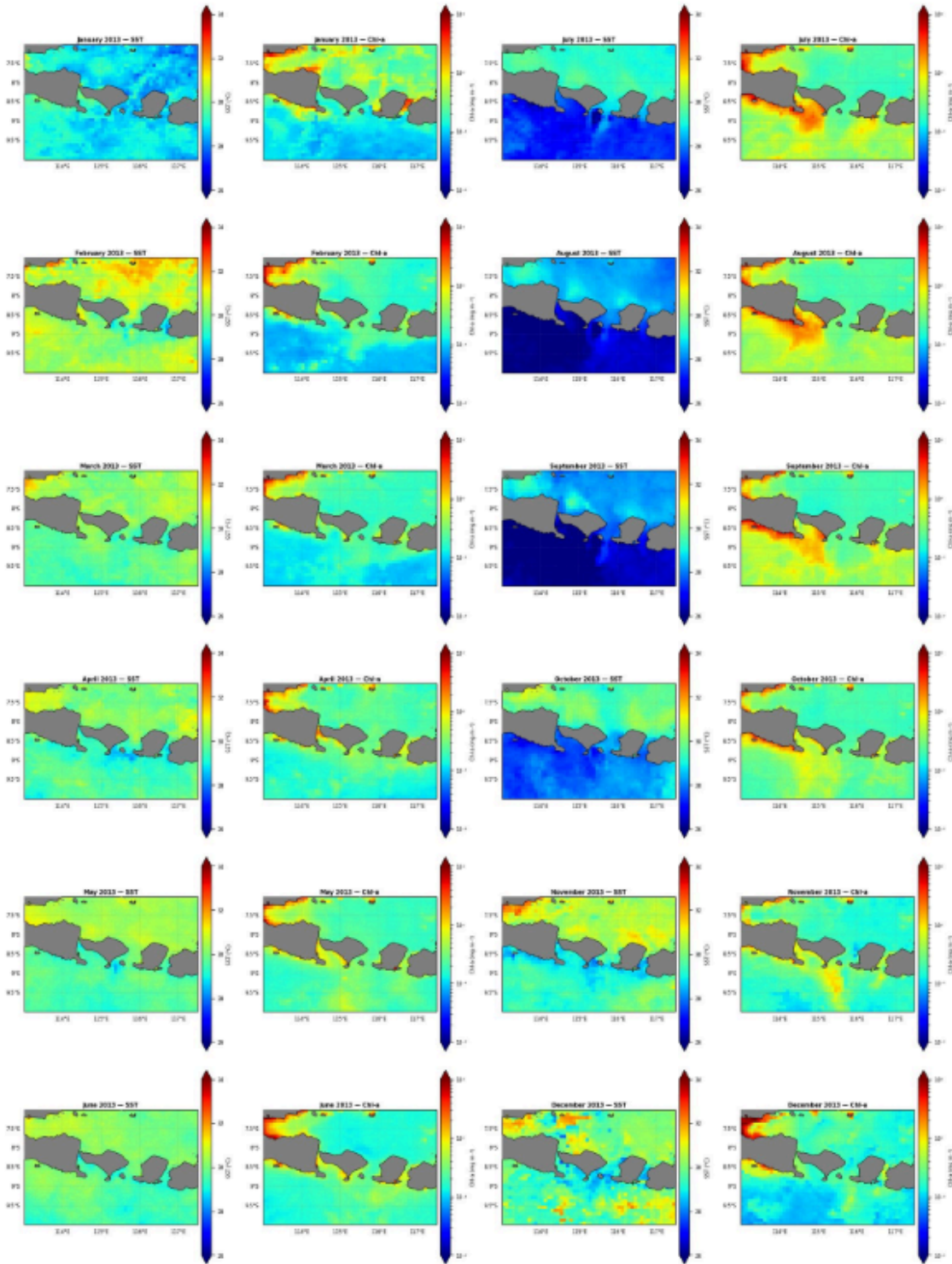


Figure 4

Monthly spatial distribution of Sea Surface Temperature (SST, left columns, °C) and chlorophyll-a concentration (Chl-a, right columns, mg m^{-3}) in Bali waters during 2013 (pre-event baseline year). Each panel pair represents one calendar month (January–December, arranged left to right). Colour scales are consistent across all monthly panels to facilitate interannual comparison with Figures 5–6. The 2013 maps

document the normal monsoon-driven seasonal cycle of SST and productivity against which El Niño-driven changes are evaluated.

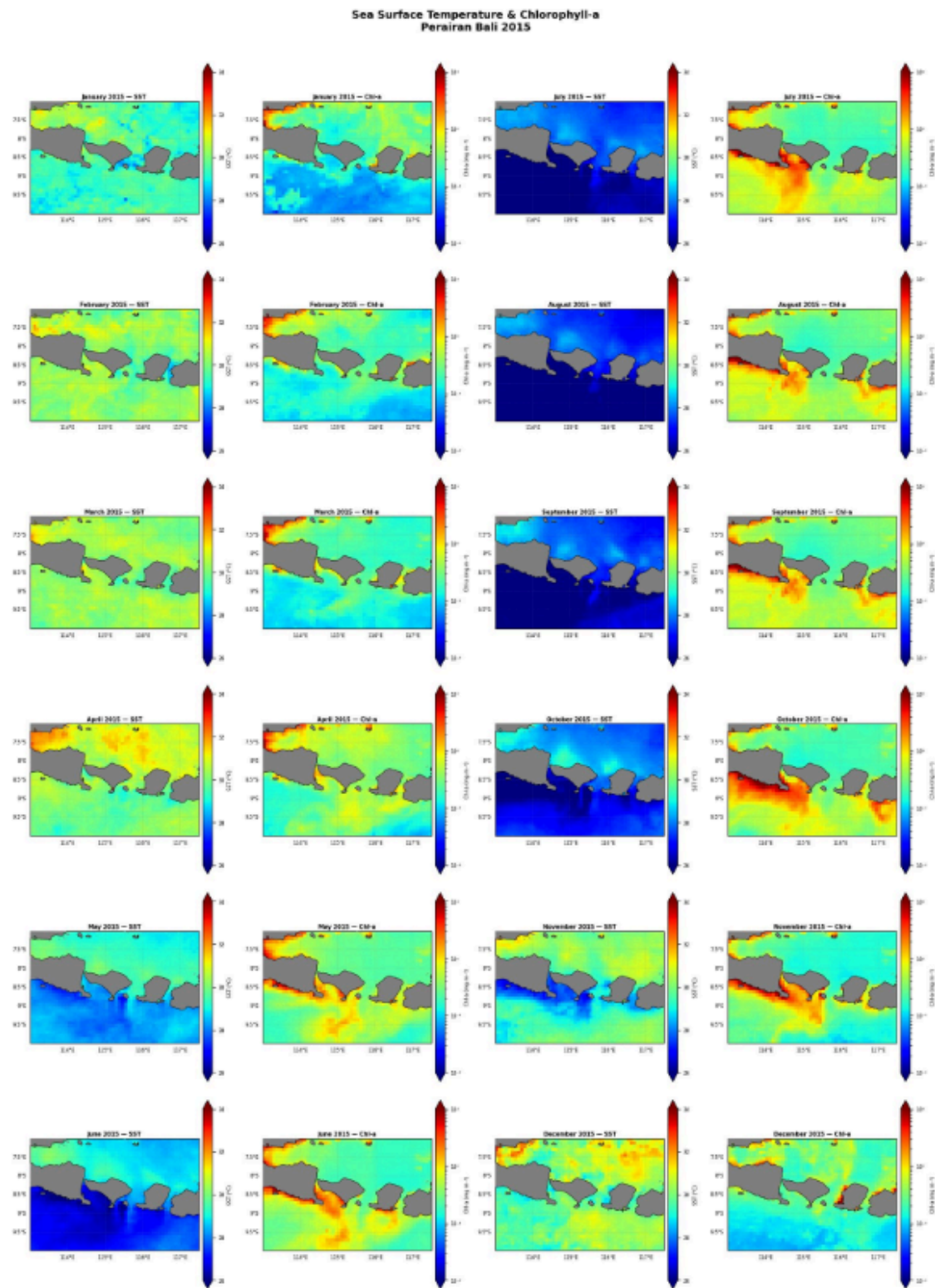


Figure 5

Monthly spatial distribution of SST ($^{\circ}\text{C}$) and Chl-a (mg m^{-3}) in Bali waters during 2014 (climatological baseline year, $\text{MEI.v2} < \pm 0.5$ throughout). Panel arrangement and colour scales are identical to Figure 4. The

2014 maps serve as the reference distribution against which SST anomalies and Chl-a anomalies during 2015–2016 are computed. Note the characteristic Southeast Monsoon cooling and productivity enhancement in the southern domain (July–September), which is used to assess upwelling suppression during El Niño.

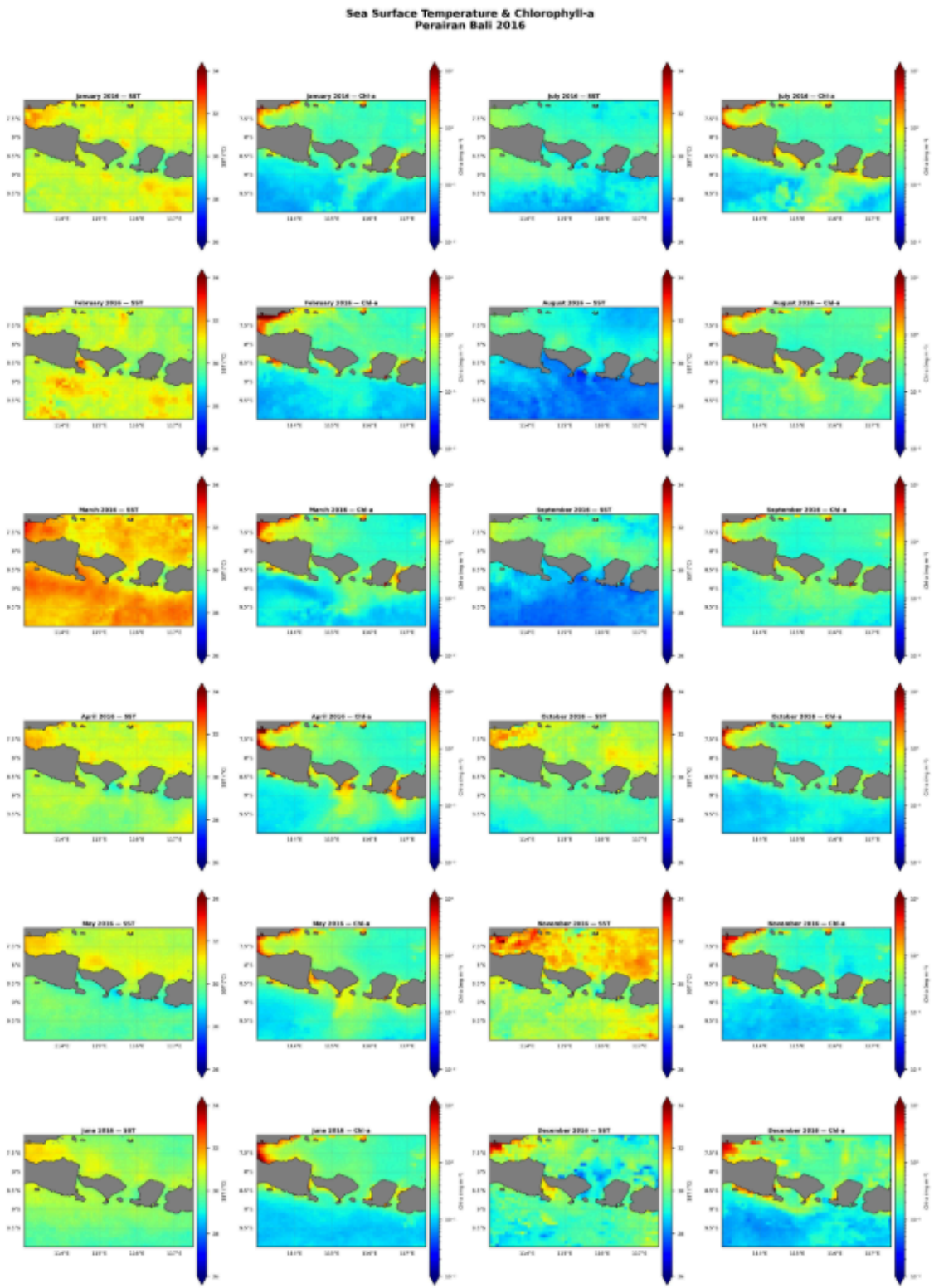


Figure 6

Monthly spatial distribution of SST ($^{\circ}\text{C}$) and Chl-a (mg m^{-3}) in Bali waters during 2015 (El Niño development phase). Panel arrangement and colour scales are identical to Figures 4 and 5. Note the progressive SST warming from July 2015 onward and the concurrent suppression of the upwelling-driven Chl-a peak that would normally be expected during July–September. By November–December 2015, SST anomalies of $+0.5$ to $+1.5$ $^{\circ}\text{C}$ above the 2014 baseline are evident across the domain, with Chl-a concentrations suppressed to below 0.3 mg

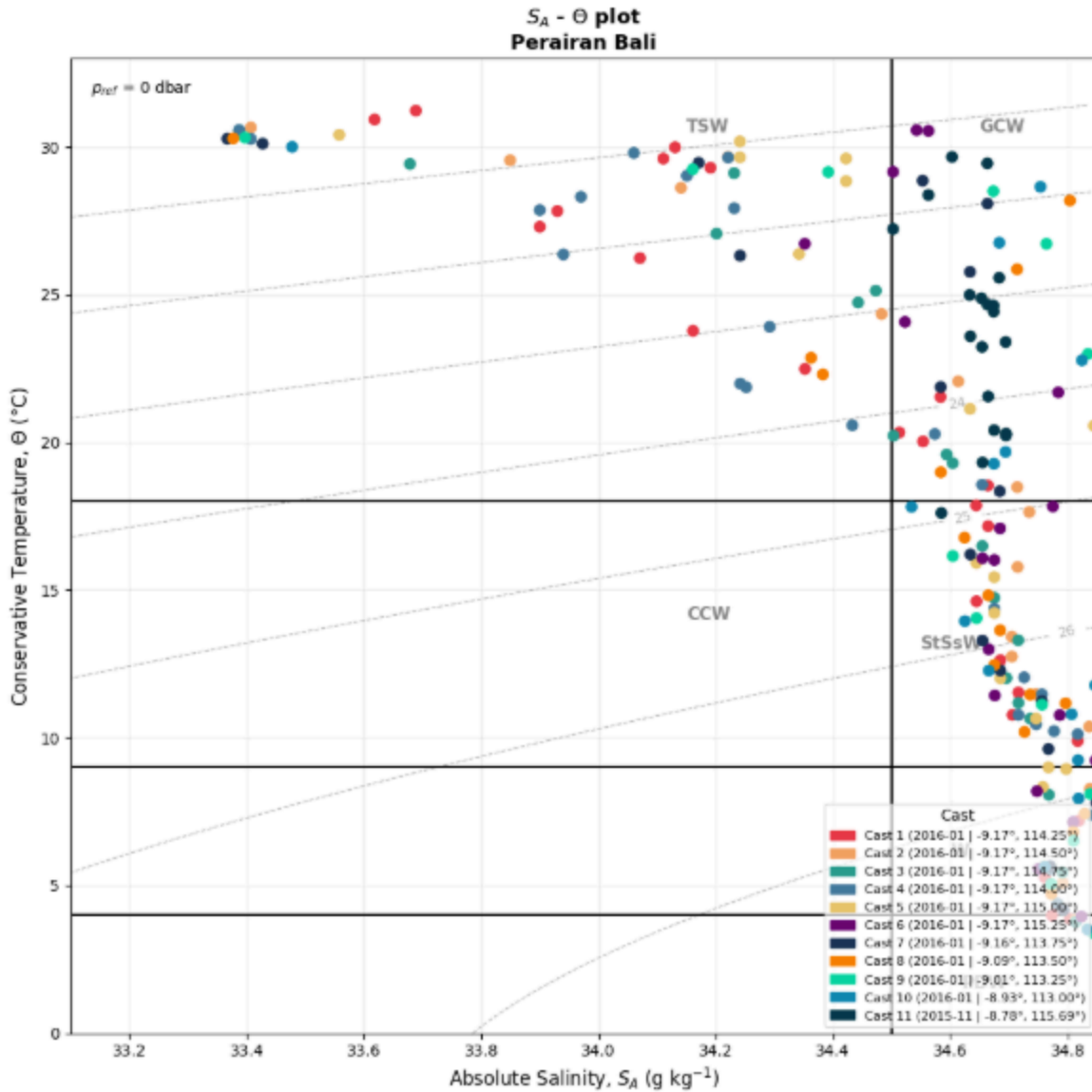


Figure 7

Conservative temperature (Θ , $^{\circ}\text{C}$) versus absolute salinity (S_A , g kg^{-1}) diagram for Bali waters, constructed from World Ocean Database 2023 (WOD23) profiles within the study domain (2013–2017). Dashed lines indicate potential density anomaly isolines (σ_{θ} , kg m^{-3}). Five water-mass regimes are labelled: TSW = Tropical Surface Water; GCW = Gulf-origin/Coastal Water; CCW = Cold/Coastal Water; StSsW = Subtropical Subsurface Water; PDW = Pacific Deep Water. The reference pressure is 0 dbar. The near-vertical alignment

of data points at $S_A \approx 34.5 \text{ g kg}^{-1}$ reflects the strong vertical salinity gradient characteristic of the Bali waters water column.