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Beyond the maximum gradient: a consecutive-threshold criterion for nitracline detection in the Northwestern Indian Ocean

M. J. Princy · K. Nandakumar · P. K. Vrinda · Rupam Kalita · Aneesh A. Lotliker

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Abstract
Depth of the nitracline is an important indicator of the vertical distribution and availability of nitrate in the upper ocean. While the conventional definition of the nitracline as the depth of maximum nitrate gradient (dN/dz) has been widely accepted, this study introduces a complementary consecutive-gradient criterion to detect the onset of a sustained nitrate gradient zone. A total of 358 profiles from five Bio-Argo floats in the northwestern Indian Ocean, were analysed. Further, the nitracline depth was derived using three different. Methods maximum gradient, single threshold, and consecutive threshold method. Of the three, the consecutive-threshold method provides a consistent approach for detecting the onset of a sustained nitrate gradient zone. It maintains a continuous nitrate gradient and is less affected by random spikes or noise. Hence, a consecutive gradient criterion is proposed for nitracline detection, defining the depth where $dN/dz \geq 0.1$ µmol kg−1 m−1 is sustained over a 14 m continuous vertical span. Further, nitracline depth showed a strong association with the 26 °C isotherm (D26), which was used as an empirical thermal proxy when D26 > MLD. Under strong mixing, when D26 < MLD, the 23.5 °C isotherm (D23.5) showed a stronger association and was used as an alternative proxy. This will provide a practical thermal proxy for estimating nitracline depth in regions where direct nitrate measurements are unavailable.

Keywords Nitracline · Nitrate · Isotherm depths · Bio-Argo · Northwestern Indian Ocean

Introduction

Inorganic nitrate (NO_3^-) is the predominant form of fixed nitrogen in the ocean, serving as a key macronutrient that fuels phytoplankton growth and primary production in sunlit surface waters[1]. The vertical movement of nitrate into the euphotic zone plays an important role in ocean productivity. The nitracline is characterised by a sharp vertical gradient in nitrate concentration within the ocean's pycnocline. In this zone, nitrate is resupplied through the remineralisation of organic matter and redistributed along isopycnals by ocean circulation[2]. Its depth and shape influence phytoplankton productivity, community composition, and the biological carbon pump, which

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affects atmospheric CO_2 drawdown. Variations in nitracline depth also drive regional patterns in new production and export flux, with shallower depths enhancing nutrient mixing into surface waters.

The depth of the nitracline is influenced by the level of water-column stratification and the amount of momentum transfer caused by wind stress[3]. Additionally, it is affected by momentum transfer from below[4] and, in some instances, by vertical advection processes such as upwelling[5]. As physical mixing strengthens, the upper mixed layer extends into the nitracline, bringing nutrients into the euphotic zone[6]. This raises nutrient levels throughout the upper water column. On the other hand, when thermal stratification increases, the upper water column gets fewer nutrients, and the nitracline deepens along with the euphotic layer[7]. Thus, geographical region and associated oceanic processes play a significant role in the nitracline dynamics. The northwestern Indian Ocean is a dynamic area encompassing the Arabian Sea and adjacent basins, influenced by seasonal monsoons and upwelling systems, and bordered by Africa and Asia to the west and north, and by the Indian subcontinent and the Maldives to the east. This region is characterised by one of the most productive regions in the world's oceans[8]. Even though it is one of the smallest ocean basins, it has a wide range of biogeochemical areas. These include eutrophic, oligotrophic, upwelling, and low-oxygen environments[9]. Although numerous studies identify nitracline depth as the point of peak vertical nitrate gradient primarily based on cruise observations or model-derived datasets from other regions of the world[10–12], studies investigating nitracline depths and their variability in the northwestern Indian Ocean remain limited.

In the Arabian Sea, limited studies have addressed the nitracline, with researchers defining it using nitrate isolines at 3 µM and 1 µM[13,14] without conducting analyses to substantiate the definition. Changes in nitracline steepness, which are essential for assessing nitrate availability, remain inadequately understood due to the scarcity of high-resolution vertical data; for instance, bottle-collected data often exhibit low vertical sampling resolution. In the present study, high-resolution Bio-Argo float observations are utilised to determine the nitracline depths and their variability. In contrast to earlier research that used conventional nitracline definitions, the present study aims to propose two additional methods to identify sustained nitrate gradients and minimise sensitivity to profile-scale noise. The growing availability of high-resolution Bio-Argo nitrate observations enables a systematic evaluation of various nitracline definitions across diverse oceanographic conditions. The objective is not to replace existing definitions, but rather to assess whether alternative approaches yield a more consistent characterisation of nitracline depth and its association with upper-ocean thermal structure.

Multiple studies have established that readily available physical oceanographic variables can serve as effective proxies for subsurface biogeochemical boundaries. For instance, Prakash et al.[15] identified empirical relationships among isotherm depths (D20 and D23), sea-level anomalies, and oxycline depth in the northern Indian Ocean using Argo observations, thereby demonstrating the value of physical proxies for estimating chemically defined oceanographic features. More recently, Sridevi et al.[16] produced a climatology of nitracline depth in the Bay of Bengal and found a strong linear relationship between nitracline depth and the depth of the 26 °C isotherm (D26). However, in regions of the Arabian Sea subject to strong monsoonal forcing, such as winter convective mixing in the north and summer upwelling in the west and southeast, D26 can shoal significantly, even reaching the surface as the mixed layer deepens. Under such conditions, D26 may not reliably represent the nitracline depth, limiting its applicability as a proxy. Therefore, the present study also aims to establish a thermocline proxy for nitracline depths using high-resolution data from five Bio-Argo Profiling Floats in the Northwestern Indian Ocean (Fig. 1).

Results and discussion

Defining nitracline depths by three methods

The nitracline depth estimated from four Bio-Argo Profiling Floats (1902454, 1902455, 1902457, and 1902458) with 295 profiles exhibits substantial variability depending on the methodological approach (Fig. 2). The maximum vertical nitrate gradient $(dN/dz|max)$ method is a widely accepted approach[10–12]. Using this criterion, the

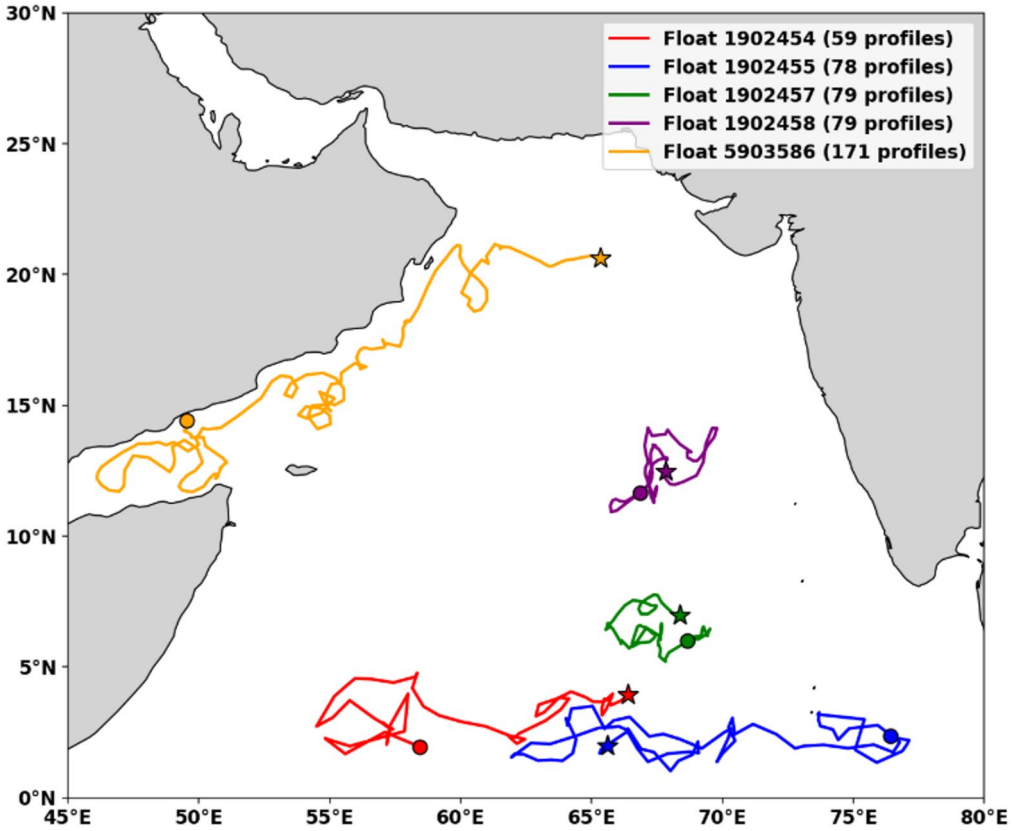


Fig. 1 Study area map showing the tracks of five Bio-Argo Floats with quality-controlled profiles from which the data are used for the analysis. Star markers indicate the starting locations of the floats, while round markers denote their ending locations.

nitracline depth is identified at greater depths, with a mean value of 90.53 m. The associated nitrate concentrations are also high, with a mean value of 12.75 µmol kg^{-1}, indicating that this method captures the depth of the strongest gradient within the deeper nitracline rather than the upper transition zone. Consequently, both nitracline depth and nitrate concentration may be overestimated and may not fully represent the onset of sustained nutrient enrichment (Fig. 2).

Since the conventional maximum-gradient method tends to identify the depth of the steepest nitrate gradient, it generally yields deeper nitracline depths and higher corresponding nitrate concentrations, potentially overlooking the upper transition into the nitracline. To address this limitation, we propose a new criterion based on a nitrate gradient threshold of $dN/dz \geq 0.10$ µmol kg^{-1} m^{-1}. To evaluate the robustness of the proposed criterion, a sensitivity analysis was performed using threshold values of 0.05, 0.08, 0.10, 0.15, and 0.20 µmol kg^{-1} m^{-1}. Representative results from eight profiles spanning the four Bio-Argo floats are presented in Supplementary Fig. 1. The analysis demonstrates that the 0.10 µmol kg^{-1} m^{-1} threshold consistently identifies the upper transition into the nitracline. In a few individual profiles, the detected depth is shifted toward the surface because of noise or isolated spikes in the nitrate profiles. However, when applied to the mean profile derived from all 295 observations, the 0.10 µmol kg^{-1} m^{-1} threshold consistently corresponds to the upper transition zone of the nitracline. This criterion yields a mean nitracline depth of 60.80 m, which is substantially shallower than that obtained using the conventional maximum-gradient method. The corresponding nitrate concentration is relatively low, with a mean value of 1.46 µmol kg^{-1}, indicating that the proposed criterion identifies the onset of sustained nitrate enrichment rather than the deeper core of the nitracline. While objective and reproducible, this approach is sensitive to weak gradients in the upper water column and tends to underestimate the true nitracline depth.

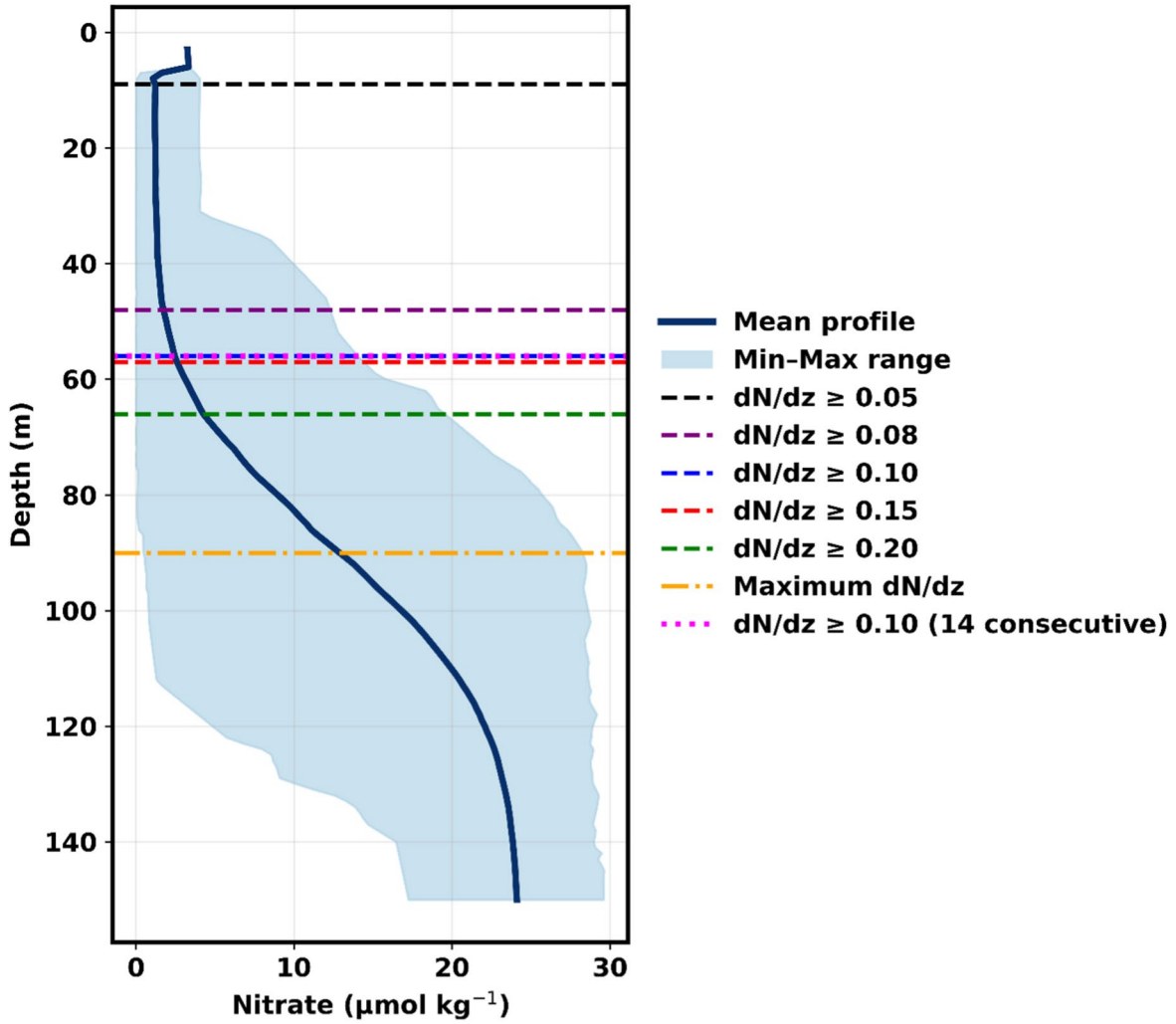


Fig. 2 Mean vertical nitrate profile derived from four Bio-Argo Profiling Floats (1902454, 1902455, 1902457, and 1902458) in the northwestern Indian Ocean. The solid blue line represents the mean nitrate concentration profile, while the shaded region indicates the minimum–maximum range of nitrate concentrations among all profiles. Horizontal dashed lines denote the mean depths identified using different nitracline depth detection criteria, including gradient thresholds of dN/dz≥0.05, 0.08, 0.10, 0.15, and 0.20 µmol kg^{-1} m^{-1}, the maximum-gradient method, and the proposed consecutive-threshold method (dN/dZ≥0.10 sustained over 14 consecutive depth observations).

A consistent and reproducible estimate of the onset of the sustained nitrate-gradient zone is obtained using the consecutive threshold criterion, defined as the first depth where $(dN/dz) \geq 0.1$ µmol kg^{-1} m^{-1} is sustained over a minimum vertical span of 14 m, corresponding to 14 consecutive 1-m depth points. This criterion identifies a mean nitracline depth of 66 m, which is deeper than the depth obtained using the 0.1 µmol kg^{-1} m^{-1} threshold method but shallower than that identified by the conventional maximum-gradient method. The corresponding mean nitrate concentration at this depth is 1.92 µmol kg^{-1}. Compared to other approaches, this method reduces sensitivity to noise and avoids biases introduced by isolated spikes, thereby providing a consistent framework for identifying the upper boundary of the sustained nitracline (Fig. 2). The overall comparison demonstrates that methodological choice strongly influences nitracline characterization, with the sustained gradient approach offering a balanced and realistic representation of the nitrate transition zone across varying hydrographic conditions. Figure 2 illustrates the differences in nitracline depths identified using nitrate gradient thresholds of dN/dz≥0.05,

0.08, 0.10, 0.15, and 0.20 µmol kg^{-1} m^{-1}, the maximum-gradient method, and the proposed consecutive-threshold method across four Bio-Argo Profiling Floats.

However, this nitracline depth estimation method has certain limitations. This analysis primarily utilises open-ocean BGC-Argo observations and does not assess the method's performance in shallow coastal environments. Additionally, transient processes such as cyclones and mesoscale eddies are known to alter nutrient distributions and nitracline structure[17]. The impact of these processes on the proposed method should be evaluated in future research. Despite these constraints, the sustained threshold criterion provides a consistent and reproducible approach for identifying the onset of the sustained nitrate-gradient in well-resolved open-ocean observations.

Seasonal variability of nitracline depth

Considering the spatial distribution of the Bio-Argo Profiling Floats in the Arabian Sea, the observed seasonal variability in nitracline depth reflects regional hydrographic differences across the northwestern Indian Ocean (Fig. 3). Floats 1902454 and 1902455, located in the western equatorial region (~1–4°N), exhibit comparatively lower seasonal variability, with nitracline depths remaining relatively consistent across seasons, generally around ~61–63 m from fall intermonsoon to winter monsoon. This relatively stable pattern likely reflects persistent stratification and weaker seasonal upwelling influence in this equatorial–southern region[18]. In contrast, Float 1902458, situated in the southern Arabian Sea (~11–14°N), shows pronounced seasonal variability, with the nitracline shoaling to about 50 m during the fall intermonsoon, deepening during the spring intermonsoon (68 m) and summer monsoon (79 m), and becoming relatively shallower again during the winter monsoon (58 m). The fall intermonsoon shows a relatively shallow nitracline, suggesting more stable stratification after the monsoon period. Similarly, during the winter monsoon, the nitracline depth again turns shallower, indicating moderate mixing influenced by northeasterly winds[14]. A similar, shallower nitracline in winter was also observed by[19] in the Arabian Sea. Float 1902457, located in the intermediate latitudinal band (~5–8°N), displays moderate

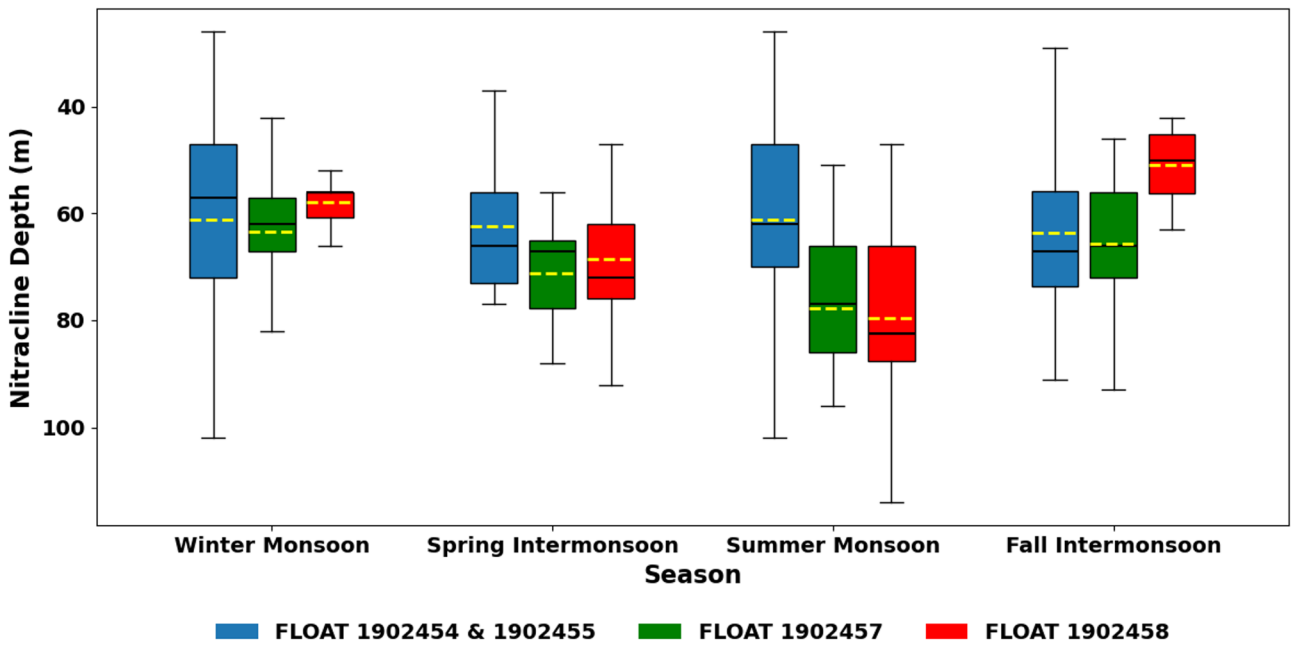


Fig. 3 Box plots showing seasonal variation of nitracline depth in four Bio-Argo Profiling Floats in the northwestern Indian Ocean. The yellow-dotted line represents the average nitracline depth for each season, and the black horizontal line shows the median (middle value) of the data. The blue box represents the interquartile range (25th–75th percentile) of the nitracline depth. The vertical black lines extending from the box are called whiskers representing the spread of the remaining data outside the interquartile range. The round dots represent outliers.

variability, with nitracline depths ranging from 66 m in the fall intermonsoon to 78 m during the summer monsoon, followed by slight shoaling in winter. Overall, these patterns suggest that floats located farther north in the Arabian Sea experience stronger seasonal modulation of the nitracline, whereas southern floats remain relatively stable throughout the seasonal cycle. The seasonal variation in nitracline depth suggests that monsoon-driven physical processes dominate its modulation, with deeper nitraclines under stronger wind forcing and enhanced upper-ocean mixing[19,20]. This interpretation is further supported by the seasonal variability of mixed-layer depth (Supplementary Fig. 2), which shows enhanced mixed-layer deepening during the monsoon seasons, consistent with intensified upper-ocean mixing and observed deepening of the nitracline. A two-way analysis of variance (ANOVA) demonstrated a significant effect of season on nitracline depth ($p < 0.001$), reflecting pronounced seasonal variability. Interannual variability was also significant ($p < 0.001$), indicating that year-to-year changes further influence nitracline depth.

Relationship of depth of nitracline and isotherm depths

The combined dataset from four Bio-Argo Profiling Floats reveals a strong positive linear relationship between the depth of nitracline and 26 °C isotherm (D26). The scatter shows clear clustering along the regression line, with a high correlation coefficient ($R = 0.89$; $n = 295$), indicating a strong association between the two variables (Fig. 4a). Previous studies have shown that D26 can serve as a thermal proxy for nitracline depth[16]. The selection of D26 was further validated through a sensitivity analysis conducted across isotherms ranging from 20 to 30 °C (Fig. 5a, b, and c). D26 showed the strongest statistical association, with the highest R value and the lowest root mean square error (RMSE) and error standard deviation. As D26 deepens from 40 m to 130 m, the nitracline depth correspondingly increases from 30 m to over 110 m. The relative distribution of data points around the regression line suggests limited scatter and consistent behaviour across different floats and sampling periods. The strong positive regression coefficient suggests that deepening of the thermocline, represented by D26, is closely associated with deepening of the nitracline. The comparable variability observed in D26 and nitracline depth suggests that temporal changes in both parameters are primarily governed by vertical mixing and the rates of organic debris remineralisation[21]. This coupling reflects the physical–biogeochemical linkage whereby thermal

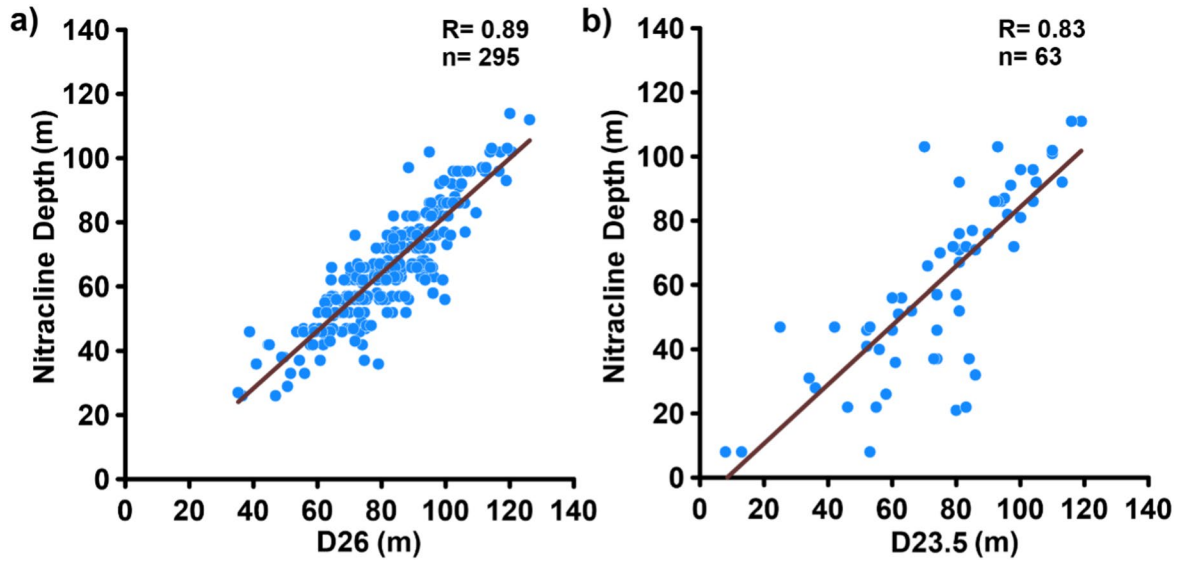


Fig. 4 Relationship between nitracline depth and isotherm depths derived from Bio-Argo observations in the Northwestern Indian Ocean. (**a**) Scatter plot showing the relationship between nitracline depth and the depth of the 26 °C isotherm (D26) derived from four Bio-Argo profiling floats in the Northwestern Indian Ocean, (**b**) Scatter plot showing the relationship between nitracline depth and the depth of the 23.5 °C isotherm (D23.5) in the western and northern Arabian Sea.

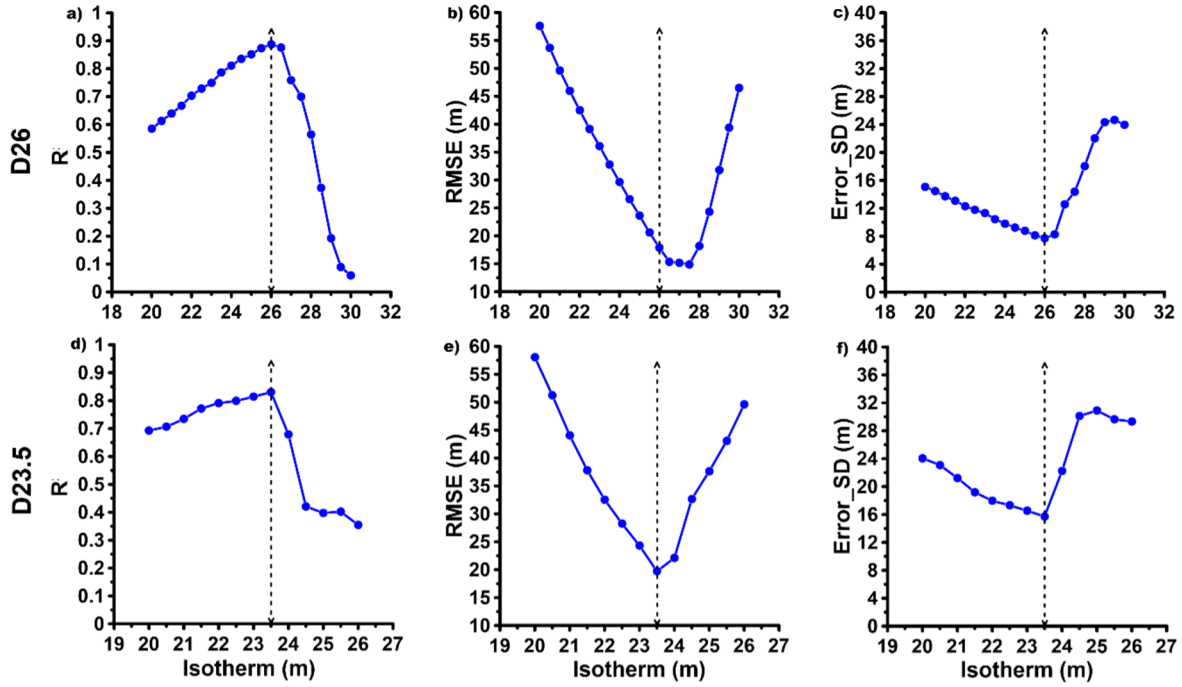


Fig. 5 Sensitivity analysis for determining the optimal isotherm depth in nitracline depth estimation. Panels (**a**–**c**) display the variation in correlation coefficient (R), root mean square error (RMSE), and error standard deviation (SD) for the D26 isotherm. Panels (d–f) present the corresponding metrics for the D23.5 isotherm. The vertical dashed line marks the selected optimal isotherm, which corresponds to the maximum R and the minimum RMSE and error SD.

stratification controls vertical nutrient distribution. Further, the strong linear relationship between nitracline depth and D26 depth suggests that variations in upper-ocean thermal structure are closely associated with changes in nutrient stratification in the study region[13]. The deeper D26 values, typically associated with enhanced stratification or downwelling conditions[22], correspond to deeper nitraclines, reflecting reduced upward nutrient flux into the euphotic zone[23]. Conversely, shallower D26 depths indicate a shoaling thermocline, which facilitates the upward displacement of the nitracline and enhances nutrient availability[24]. The high correlation across multiple floats further suggests that this relationship is regionally coherent and largely governed by large-scale physical processes such as monsoon-driven mixing, Ekman dynamics, and seasonal stratification. This coupling also highlights the utility of D26 as a potential thermal indicator of nitracline variability in the absence of direct nutrient observations. The robustness of the proposed relationship was further evaluated using 10-fold cross-validation (Supplementary Tables 1 and 2). However, due to the temporal and spatial autocorrelation of Bio-Argo profiles, these cross-validation results primarily reflect internal consistency rather than full generalizability. Validation with a larger set of independent Bio-Argo floats is recommended to enhance the applicability of the proposed criterion. However, the dynamic seasonality of the Arabian Sea limits its applicability in the northern Arabian Sea during winter and in the western and southeastern Arabian Sea during summer. The D26 reaches the surface, and a deeper mixed layer forms in these areas during the respective seasons due to monsoon-induced upwelling and winter convective mixing[25]. During these periods, D26 becomes progressively shallower as the mixed layer depth (MLD) deepens. In such cases, the nitracline estimated using the D26 proxy would lie within the MLD, which is physically unrealistic. Under these conditions, the nitracline is located deeper than the D26. Analysis of a representative float (5903586) in the western and northern Arabian Sea shows that 63 out of 171 profiles exhibit this behaviour. Correlation analysis further indicates that nitracline depth is more closely associated with D23.5 ($R = 0.83$) (Fig. 4b). A sensitivity analysis of isotherms between 20 and 26 °C further confirmed D23.5 as the optimal proxy (Fig. 5d, e, f), yielding the highest R value and the lowest RMSE and standard deviation of errors.

These findings support the selection of D23.5 under strong mixing conditions. Generally, while D26 serves as a useful empirical thermal proxy for nitracline depth across much of the Arabian Sea, its reliability diminishes in regions and seasons influenced by strong monsoonal forcing, where alternative metrics such as D23.5 provide a closer statistical correspondence. The regression equation derived from the correlation analysis is given by 1 and 2.

$$Nitracline\ Depth\ (m) = 0.8953 \times D26 - 7.4866,\ if\ D26 > MLD \quad (1)$$

$$Nitracline\ Depth\ (m) = 0.9384 \times D23.5 - 7.3966,\ if\ D26 < MLD \quad (2)$$

Comparison of nitracline detection methods using D26 as a proxy

The present study identified D26 as the most suitable empirical thermal proxy for estimating nitracline depth. To further evaluate the robustness of the three nitracline detection methods, the nitracline depths derived from each method were correlated with D26 depth (Supplementary Fig. 3). The conventional maximum-gradient method exhibited the weakest relationship with D26 ($R = 0.56$), displaying considerable scatter and a tendency to overestimate nitracline depth. The single-threshold method (dN/dz = 0.1) improved the correspondence ($R = 0.73$) and reduced the dispersion of data points. In contrast, the proposed consecutive-threshold method (dN/dz = 0.1 with CT_{14}) demonstrated the strongest agreement with the D26 isotherm ($R = 0.89$), with observations closely aligned along the regression line. The substantially higher correlation suggests that incorporating a consecutive-gradient criterion reduces the influence of isolated high-gradient spikes and identifies a more consistent estimate of the onset of the sustained nitrate-gradient zone. These findings indicate that the proposed method provides a reproducible estimate of the upper boundary of the sustained nitracline and shows stronger statistical agreement with upper-ocean thermal proxies than the other two methods.

Estimation of nitracline depth by using thermoclines

Temperature measurements are widely available in the Northwestern Indian Ocean through platforms such as Argo floats and other hydrographic surveys, whereas the nitrate observations are limited. Therefore, we used the calculated isotherm proxy to determine the nitracline in the much wider basin where nitrate observations are unavailable. A total of 16 Argo floats providing 2230 vertical profiles were used to estimate the nitracline depth in the Northwestern Indian Ocean. Nitracline depth is subsequently estimated using a conditional approach: Eq. 1 is applied when the MLD is shallower than D26, whereas Eq. 2 is employed when the MLD exceeds D26. Among the total profiles, 41 do not exhibit a detectable D26 value and are accordingly assigned a value of zero in the spatial representation (Fig. 6). The spatial distribution of D26 and the corresponding estimated nitracline depth across the study region is shown in Fig. 6. Generally, the results demonstrate that the isotherm-based method is an effective proxy for estimating nitracline depth and can be used to examine large-scale and seasonal variability in nutrient structure in the Arabian Sea. This approach significantly improves the spatial coverage of nitracline estimates and helps in understanding regional variability in nutrient distribution and its potential influence on biological productivity in the basin.

Future perspectives on nitracline variability and ecological implications

While the primary focus of this study is the characterization of nitracline depth and its relationship with isotherm-based proxies, the observed variability in nitracline structure may have broader ecological relevance that warrants targeted future investigation. Changes in nitracline depth can modify the vertical availability of nitrate to the euphotic zone and may consequently influence nutrient conditions and phytoplankton dynamics[2]. However, the present study does not include biological observations or long-term ecological assessments. Future studies

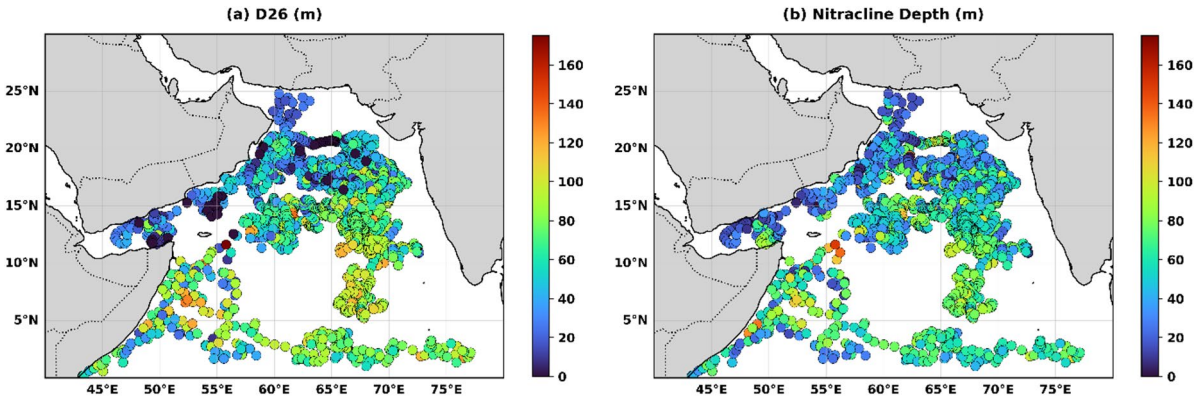


Fig. 6 Spatial distribution of (**a**) 26 °C isotherm depth (D26) and (**b**) the corresponding estimated nitracline depth in the Northwestern Indian Ocean. The nitracline depth shown in panel (**b**) was derived using Eqs. 1 and 2.

integrating extended Bio-Argo observations with nutrient, phytoplankton, satellite, and model-based datasets could investigate long-term changes in nitracline characteristics and their potential relationships with primary productivity, phytoplankton community structure, and bloom dynamics in the Arabian Sea. Such investigations would help assess whether observed changes in nitracline variability are associated with longer-term ecosystem responses.

Summary and conclusion

This paper compares three methods for calculating the depth of the nitracline in the Northwestern Indian Ocean. The conventional definition of the nitracline as the depth of the maximum nitrate gradient (dN/dz) is widely accepted and provides a useful estimate of the steepest nitrate gradient. This study introduces a complementary consecutive-threshold criterion to identify the onset of a sustained nitrate-gradient zone. The proposed approach provides a consistent and reproducible estimate of this transition complementing rather than replace existing nitracline definitions. An empirical criterion is derived by selecting a threshold for (dN/dz) and a minimum consecutive slope span. This criterion is intended to identify the upper boundary of the sustained nitracline, providing a consistent framework for nitracline detection while reducing the influence of localized profile-scale variability.

Moreover, the strong regression relationship between estimated nitracline depth and thermocline depths provide a useful practical application. Since temperature observations are widely available in the Arabian Sea from platforms such as Argo floats and hydrographic surveys, this relationship can be applied to estimate nitracline depth even in regions where nitrate measurements are unavailable. Thus, the developed regression equation provides an effective approach to extend the spatial coverage of nitracline estimates across the Arabian Sea using readily available temperature data, thereby supporting studies on nutrient dynamics and regional biogeochemical variability. In addition to its practical application, the nitracline may serve as a useful indicator of ecosystem vulnerability in the northern Arabian Sea. Climate-induced variations in nitracline depth and structure can influence the timing and efficiency of nutrient transfer from the subsurface, thereby affecting the frequency, persistence, and spatial extent of phytoplankton blooms. Therefore, the nitracline represents not only an important diagnostic biogeochemical feature but also a potential indicator of future ecosystem responses, including changes in nutrient supply and conditions that may influence harmful algal bloom development in the northern Arabian Sea.

Data sources and processing

This study utilises five available Bio-Argo profiling Float measurements from the Northwestern Indian Ocean. These floats are automated profilers equipped with biogeochemical and conductivity–temperature–depth sensors, enabling high-quality in-situ measurements at various temporal scales. We use four float measurements based on 295 profiles collected from 2023 to 2025 to determine the nitracline depths and establish a relationship between nitracline and D26 in the study area. In addition, one float (5903586) located in the western and northern Arabian Sea consists of 63 profiles used for the D23.5 relationship. The trajectories of all five floats are shown in Fig. 1. The four Bio-Argo floats were combined as they sampled the same hydrographic regime in the northwestern Indian Ocean across different seasonal conditions. Integrating observations from multiple floats expanded the range of hydrographic variability in the dataset and facilitated the development of a regionally representative nitracline–isotherm relationship. Water temperature and nitrate data from sensors on bio-Argo floats were collected from the Argo Global Data Centres (GDAC) using delayed-mode quality control[26,27]. Only data marked with quality flag 1 (Good Data) were used for further analysis. Negative values were removed. Linear interpolation was applied to adjust the dataset to 1-meter depth intervals, but only when consecutive data points were separated by no more than 6 m. The vertical nitrate gradient (dN/dz) was calculated using the central finite difference scheme. The depth of the 26 °C isotherm (D26) was estimated as the depth corresponding to the temperature value closest to 26 °C within the 25.5–26.5 °C range. Similarly, the depth of the 23.5 °C isotherm (D23.5) was defined as the depth at which temperature most closely approximates 23.5 °C within the 23–24 °C interval. The performance of each regression model was assessed using several statistical measures: the Pearson correlation coefficient (R), root mean square error (RMSE), and standard deviation of errors. Model robustness and internal consistency were evaluated through a 10-fold cross-validation procedure, with the average cross-validated R, RMSE, and error standard deviation subsequently calculated. Mixed Layer Depth was estimated using the temperature threshold method, defined as the depth at which temperature decreases by 0.2 °C relative to the value at 10 m depth[28]. Seasonal and interannual variations in nitracline depth were analysed using a two-way analysis of variance (ANOVA), with season and year designated as fixed factors and nitracline depth as the response variable. Statistical significance was determined at a 95% confidence level ($p<0.05$).

Analytical nitracline algorithms

Maximum gradient method $(dN/dz|max)$

This approach was used as the conventional method for determining the depth of nitracline. In this method, the nitracline depth is defined as the depth at which the maximum nitrate gradient occurs within the sampled depth range[3]. In this study, we adopt the location of nitracline depth (Z_n) was adopted by maximum gradient method $(dN/dz|max)$, which can be represented by $\frac{d^2N}{dz^2}\Big|_{Z_n} = 0 \quad and \ \frac{d^3N}{dz^3}\Big|_{Zn} < 0$.

Single threshold method $((dN/dz) \geq 0.1\ \mu\ mol\ kg-1\ m-1\ )$

By this criterion, the equation for the maximum gradient method, with a condition $(dN/dz) \geq 0.1$ µmol kg^{-1} m^{-1} as a threshold for determining the depth of nitracline. The selection of this threshold is usually arbitrary.

Consecutive threshold method (14 Points)

This criterion was defined to identify a sustained nitrate gradient while minimizing the influence of transient variations and sensor noise. As in the single-threshold method, a gradient threshold of $(dN/dz) \geq 0.1$ µmol kg^{-1} m^{-1} was applied, with the additional requirement that this threshold be satisfied continuously over a minimum vertical span of 14 m. Because the profiles were interpolated to 1-m depth intervals, this criterion was operationalized as

Table 1 Slope span of 4 Bio Argos selected for this study.

Float ID	No. of Profiles	Slope span range	Slope span median	Slope span mean
1,902,454	59	15–54	30	30.59
1,902,455	78	16–69	30	31.93
1,902,457	79	19–63	39	38.12
1,902,458	79	14–65	40	38.39

14 consecutive depth points satisfying the threshold. The 14-m vertical span was selected based on the minimum continuous span of the nitracline observed among the four evaluated floats (Table 1). This continuity requirement helps reduce the influence of transient variations and random spikes or noise in nitrate measurements from the Bio-Argo profiling floats and distinguishes sustained nitrate gradients from localized or diffuse variations.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-026-74941-2.

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Author contributions Princy M John: Writing original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. K Nandakumar: Validation, Methodology, Investigation, Formal analysis, Conceptualization. P K Vrinda: Methodology, Formal analysis. Rupam Kalita: Data curation. Aneesh Anandrao Lotliker: Writing – review & editing, Visualization, Supervision, Methodology.

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Data availability The Bio-Argo profile data used and analysed in the current study are publicly available from the Argo Global Data Assembly Centers (GDAC) repository at https://argo.ucsd.edu/data/data-from-gdacs/.

Declarations

Competing interests The authors declare no competing interests.

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Authors and Affiliations

M. J. Princy[1] · K. Nandakumar[1] · P. K. Vrinda[1,2] · Rupam Kalita[1,2] · Aneesh A. Lotliker[1]

✉ Aneesh A. Lotliker
aneesh@incois.gov.in

[1] Indian National Centre for Ocean Information Services (INCOIS), Ministry of Earth Sciences (MoES), Hyderabad, India

[2] Faculty of Ocean Science and Technology, Kerala University of Fisheries and Ocean Studies (KUFOS), Panangad, Kochi, India