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Hydro-Meteorological Regulation of Thermal Stratification and Its Impact on Oxygen Dynamics in Lake Maninjau

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ABSTRACT

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In tropical lakes, thermal stratification is essential for oxygen dynamics and ecosystem function, and it responds sensitively to short-term weather variation. Using high-resolution temperature profiles and weather data in 2016–2017, this study examines the effects of meteorological variability on water column stratification and oxygen levels in Lake Maninjau, a eutrophic tropical lake in West Sumatra, Indonesia. The results show that seasonal drops in air temperature were the primary factor influencing stratification in 2016, while, wind speed and sunshine duration had a greater impact on its occurrence in 2017. Furthermore, in 2016, stratification breakdown triggered full-depth mixing and a sharp drop in dissolved oxygen (DO) from >3 mg/L to <2 mg/L at 5 m depth. Generally, stratification occurs at the minimum air temperature (Tmin) of above 20.25°C. At lower Tmin, the water column can either be stratified or mixed, notably when the average wind speed (Vave) exceeds ~2.75 m/s, in which stratification tends to break down. These findings highlight how thermal and mechanical forces contribute to weakening stratification and increasing the risk of hypoxia which are detrimental to aquaculture in floating net cages, and are linked to fish kills. Recognizing these thresholds can guide risk forecasting and adaptive management of tropical lakes.

KEY WORDS: thermal stratification, dissolved oxygen, wind mixing, fish kill, Lake Maninjau.

RESUMEN

Regulación Hidrometeorológica de la Estratificación Térmica y su Impacto en la Dinámica del Oxígeno en el Lago Maninjau.

La estratificación térmica es fundamental para la dinámica del oxígeno y el funcionamiento del ecosistema en lagos tropicales, donde responde de manera sensible a los cambios meteorológicos a corto plazo. Este estudio examinó los efectos de la variabilidad meteorológica sobre la estratificación de la columna de agua y los niveles de oxígeno en el Lago Maninjau, un lago tropical eutrófico en Sumatra Occidental, Indonesia. Mediante perfiles de temperatura de alta resolución y datos meteorológicos (2016–2017), encontramos que la estratificación en 2016 estuvo influenciada principalmente por descensos estacionales de la *temperatura del aire, mientras que en 2017 respondió más a la velocidad del viento y a la duración de la radiación solar. La ruptura de la estratificación en 2016 provocó una mezcla completa de la columna de agua y una fuerte caída del oxígeno disuelto (OD) a 5 m, de >3 mg/L a <2 mg/L. En general, la estratificación persistió cuando la temperatura mínima del aire (Tmin) estaba por encima de 20.25°C. A valores menores de Tmin, la columna de agua podía estar estratificada o mezclada; notablemente, cuando la velocidad media del viento (Vave) superaba aproximadamente 2.75 m/s, la estratificación tendía a colapsar. Estos hallazgos destacan la influencia combinada de las fuerzas térmicas y mecánicas en el debilitamiento de la estratificación y el aumento del riesgo de hipoxia, condiciones perjudiciales para la acuicultura en jaulas flotantes, que se vinculan con mortalidades masivas de peces. Reconocer estos umbrales puede orientar la predicción de riesgos y la gestión adaptativa de los lagos tropicales.*

PALABRAS CLAVE: *mestratificación térmica, oxígeno disuelto, mezcla por viento, mortandad de peces, Lago Maninjau.*

INTRODUCTION

Thermal stratification is an essential physical characteristic of lakes that regulates various biogeochemical processes in the water column (Liu et al., 2020). Strong stratification limits the vertical exchange of oxygen, nutrients, and gases, thus resulting in hypoxia (low oxygen levels) in the hypolimnion and the accumulation of reduced substances from sediments (Yang et al., 2018). Weakening or breakdown of stratification, on the other hand, allows vertical mixing, which may increase oxygen levels in deeper layers. However, this process can also transport anoxic or polluted water upward, potentially decreasing oxygen concentrations in surface waters and harming aquatic life.

The dynamics of stratification are strongly influenced by climatic and geographical factors. Lakes in temperate regions typically go through clear seasonal cycles, with stratification beginning in spring and mixing occurring in autumn as the water temperature becomes more uniform. (Anderson et al., 2021, Koue et al., 2018, Magee & Wu, 2017). In contrast, tropical lakes have weaker vertical temperature gradients and respond more sensitively to daily variability of meteorological parameters, such as wind speed, air temperature, and solar radiation (Katsev et al., 2010, Santoso et al., 2018). Such short-term weather variation can significantly alter stratification strength and hydrodynamic stability, which lead to dynamic shifts in the distribution of oxygen and nutrients throughout the water column (Salas De León et al., 2016).

Abrupt stratification breakdown in eutrophic lakes has various harmful consequences, one of which is the sudden rise of anoxic hypolimnetic water to the surface, which has been linked to mass fish kill. In Lake Maninjau, a eutrophic tropical lake in West Sumatra, Indonesia floating net cage (FNC) aquaculture has been practiced intensively since 1992 (Syandri et al., 2014). Although this practice improves primary productivity and accelerates microbial decomposition, the excessive input of organic matter and nutrients from these FNCs also lowers dissolved oxygen levels, thus contributing to hypoxia in the water column (Fukushima et al., 2017, Komala et al., 2019). This condition causes the surface oxic layer to thin and the anoxic zones to expand.

Besides internal loading, weather-induced hydrodynamic changes also significantly affect thermal stratification and oxygen dynamics. Previous studies have shown that increased wind speed and decreased air temperature can enhance convective mixing and disrupt stratification in Lake Maninjau, triggering the upward transport of oxygen-deficient water (Fukushima et al., 2017, 2021). According to these studies, large convection occurs during a 3–5°C drop in temperature, while smaller convection is associated with a temperature drop of around 2°C. These studies, however, focused primarily on wind speed and air temperature and and only explored discrete temperature measurements obtained at relatively low temporal resolution, which limited their ability to assess short-term transitions between stratified and mixed states. Therefore, this present study attempts to fill the existing research gap by examining high-frequency observations of water column temperature and incorporating a wider range of meteorological factors, including solar radiation, and precipitation to more comprehensively evaluate their combined influence on surface heating in this tropical crater lake.

To investigate the role of weather-driven hydrodynamics in stratification and vertical oxygen distribution in Lake Maninjau, this study uses high-resolution time-series measurements of water temperature and dissolved oxygen (DO) along with a broader set of meteorological variables. The hypothesis is that the simultaneous occurrence of high wind speeds, low air temperature, reduced solar radiation, and heavy rainfall weakens thermal stratification, enhances vertical mixing, and increases the risk of oxygen-deficient water reaching the surface layers. This study aims to provide more profound insights into the long-term effects of meteorological factors on lake stratification stability and their implications for the dissolved oxygen levels in the surface layer.

MATERIALS AND METHODS

Study Site and Data

This study examines Lake Maninjau, (Fig. 1A), which has an average depth of 105 m, a maximum depth of 165 m, a surface area of 99.5 km²,

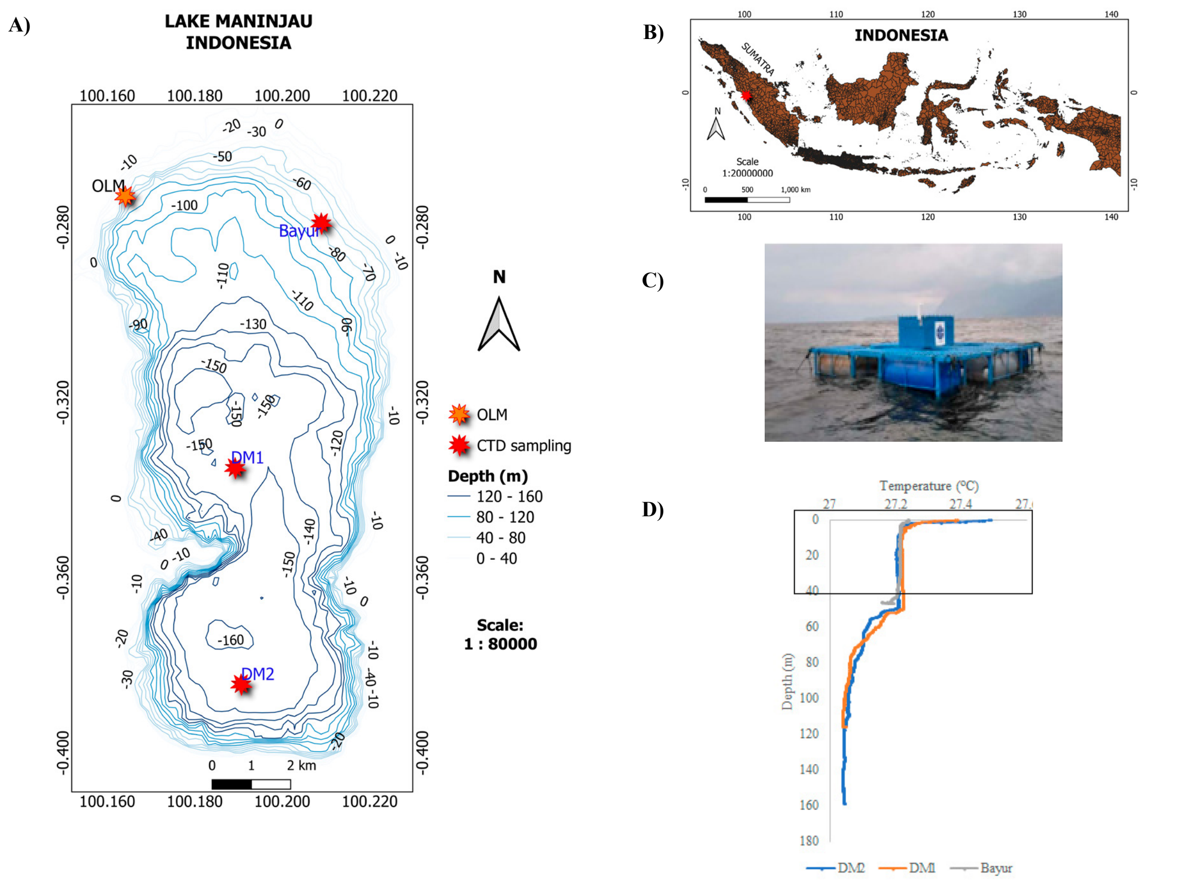

Figure 1. (A) Bathymetric map of Lake Maninjau with 10-m depth contours, showing a gently sloping northern basin and a steep southern basin. The yellow star indicates the location of the OLM buoy, and the red stars denote Bayur, DM1, and DM2, where CTD measurements were conducted on October 15, 2016. (B) Location of Lake Maninjau in West Sumatra Province, Indonesia (red marker). (C) On-line monitoring (OLM) system with temperature sensors deployed at 0.5–62 m and a DO sensor at 5 m depth. (D) Vertical temperature profiles at Bayur, DM1, and DM2 derived from CTD measurements. *(A) Mapa batimétrico del lago Maninjau con curvas de nivel cada 10 m, que muestra una cuenca norte de pendiente suave y una cuenca sur de pendiente pronunciada. La estrella amarilla indica la ubicación de la boya del sistema de monitoreo en línea (OLM), y las estrellas rojas señalan Bayur, DM1 y DM2, donde se realizaron mediciones con CTD el 15 de octubre de 2016. (B) Ubicación del lago Maninjau en la provincia de Sumatra Occidental, Indonesia (marcador rojo). (C) Sistema de monitoreo en línea (OLM) equipado con sensores de temperatura instalados a profundidades de 0.5–62 m y un sensor de oxígeno disuelto (DO) a 5 m de profundidad. (D) Perfiles verticales de temperatura en Bayur, DM1 y DM2 obtenidos a partir de mediciones con CTD.*

and a volume of 10.1 km³ (Santoso et al., 2018). The data used in the analyses include water column temperature, meteorological parameters, and dissolved oxygen (DO). Water temperature data were obtained from the Online Monitoring System (OLM) buoy deployed by the Research Centre for Limnology in late 2014 (Fig. 1C), at a distance of approximately 200 m from the edge of the lake.

Notwithstanding its location in a near-shore zone, the buoy is utilized to characterize the dynamics of temporal stratification driven by meteorological forces. The Conductivity Temperature Depth (CTD) profiles collected at offshore and near-shore stations on the same day (Oct 15, 2016) revealed only minor variations in the 0–40 m temperature structure, which were mostly due to measurement time (Fig. 1D). These results indicate the suitability of the OLM buoy for capturing temporal thermal dynamics, despite its acknowledged spatial limitations. The buoy was equipped with thermistor chains at 2-meter intervals, covering depths ranging from 0.5 to 62 m, and a DO sensor installed at a depth of 5 m.

Data on both temperature and DO were recorded every ten minutes. Temperature data were available from January 2016 to December 2017 and were averaged to daily resolution to match the meteorological dataset. Meanwhile, data on raw DO measurements were only available from January 2016 to May 2017 and were averaged into hourly means to reduce short-term variability.

Analysis Methods

Seasonal variation in meteorological parameters, was analyzed by examining the two-year dataset (2016–2017) on minimum air temperature (Tmin), maximum air temperature (Tmax), daily sunshine duration (SD), maximum wind speed (Vmax), average wind speed (Vave), and precipitation (RR). These data were obtained from the Padang Panjang Geophysics Station (0°27'58.68" S, 100°22'46.92" E), located approximately 20 km from Lake Maninjau (Indonesia Agency for Meteorology, Climatology and Geophysics/BMKG, 2022). Sunshine duration represents the period when solar radiation exceeds 120 W/m² (Hamdi, 2014; Japan Meteorological Agency, 2010).

Descriptive statistical analysis (mean values) was performed to evaluate interannual differences in meteorological parameters. For this purpose, meteorological data were aggregated to monthly averages and were used for both visualization and observation of the correlation of meteorological drivers with the monthly stratification index (SI). Furthermore, the Pearson correlation coefficient was used to measure the linear relationships between monthly meteorological variables and SI, both of which consist of continuous data (Ladd & Stabeno, 2012, Liu et al., 2019). For the analyses, missing meteorological data were not imputed, and monthly averages were derived from available observations. In cases where data on measurements of a given parameter for an entire month were unavailable, that month was excluded from the correlation analysis to prevent distortion of the statistical relationships.

In This study, thermal stratification in the water column was described using two indicators: the stratification index (Ladd & Stabeno, 2012) and mixed layer depth (MLD) (Yang et al., 2018). SI has been widely adopted in studies of lake stratification in both subtropical and tropical environments as a metric that reflects the potential energy needed to homogenize the water column, thus offering a more informative measure of stratification intensity compared to the surface–bottom temperature gradient. Meanwhile, MLD serves as a complementary physical indicator, providing the actual depth of mixing and enabling visual verification of the conditions indicated by SI. The stratification index was measured using the formulas below:

$$SI = -\int_{-h}^{0} (\rho - \bar{\rho}) g z dz \qquad (1)$$

$$\bar{\rho} = \frac{1}{h}\int_{-h}^{0} \rho dz \qquad (2)$$

Furthermore, water density was calculated from water layer temperature (T) using the following formula (Ji, 2008):

$$\rho = 999.842594 + 6.793952 \times 10^{-2}T - 9.095290 \times 10^{-3}T^2 + 1.001685 \times 10^{-4}T^3 - 1.120083 \times 10^{-6}T^4 + 6.536332 \times 10^{-9}T^5 \quad (3)$$

Where ρ: water layer density (kg/m^3), $\bar{\rho}$: average of water column density (kg/m^3), g: gravitational acceleration (m/s^2), z: water layer depth (m), h: total water column depth (m), and T: water temperature (°C).

Yang et al. (2018) defined MLD as the depth at which potential density or temperature deviates from the surface value by a specified threshold (ΔT). This study, employs the difference criterion since it is more robust and less prone to errors under conditions of small temperature fluctuations, which frequently occur in Lake Maninjau, using the ΔT of 0.2°C that provides high resolution and enables detection of weak stratification (Yang et al., 2018). The formulas used for MLD are as follows:

$$MLD = \frac{T_b - T_n}{T_{n+1} - T_n}(h_{n+1} - h_n) + h_n \quad (4)$$

$$T_b = T_s - \Delta T \quad (5)$$

Where T_s is the surface temperature, T_n and h_n are the temperature and depth of layer n, respectively.

RESULTS

Variation in Meteorological Parameters

The interpretation of interannual variability is based on the monthly evolution of meteorological parameters in 2016 and 2017 presented in Fig. 2. The averages values of Tmin and Tmax were higher in 2016 (19.92°C and 27.31°C, respectively) than those in 2017 (19.57°C and 26.99°C, respectively). However, data on Tmax for January and February 2016 were unavailable. In 2016, the values of both Tmin and Tmax were higher during the first half of the year (January–May) and gradually decreased toward the end of the year, with a slight increase in Tmin observed from mid-October to December (Fig. 2A). Conversely, Tmin was generally lower in 2017 than in 2016 and remained relatively stable throughout this year. Meanwhile, Tmax in 2017 began at lower values, increased around April–May, and then declined steadily toward December (Fig. 2B).

Regarding wind speed, this study found no significant difference in average wind speed (Vave) between the two years, with mean values of 2.07 m/s in 2016 and 2.06 m/s in 2017. Nevertheless, Vmax was higher in 2016 than in 2017, averaging 4.12 m/s and 3.54 m/s, respectively. In both years, Vave was generally higher in January–February, decreased mid-year, and then increased in December (Fig. 2C). Vmax remained relatively stable in 2017, with a sharp drop in April, followed by recovery and sustained values until the end of the year (Fig. 2D).

Similarly, there was no significant difference in sunshine duration between the two observation years, with an average of 3.41 hours in 2016 and 3.48 hours in 2017. In general, sunshine duration peaked before August, reaching around 4 hours/day in 2016 and 3.7 hours/day in 2017 (Fig. 2E). After August, it declined to below 3 hours/day in both years. Precipitation was slightly higher in 2017 than in 2016, with annual averages of 14.45 mm and 12.91 mm, respectively. In addition, it showed a clear seasonal pattern with peaks in February–March, July, and November (Fig. 2F).

Water Column Temperature Profile

Fig. 3 shows the vertical temperature profiles in 2016 and 2017, revealing two dominant thermal states: stratified and mixed. The stratification of the water column was predominantly stable in 2016, but it fluctuated and progressively became more intense intense, reaching its peak between-March and August (mean gradient 2.3°C). Stratification weakened sharply from September to mid-October, leading to a single major mixing event (mean gradient <0.3°C). As shown in the monthly stratification index displayed in Fig. 4A, a brief return to weak stratification was observed

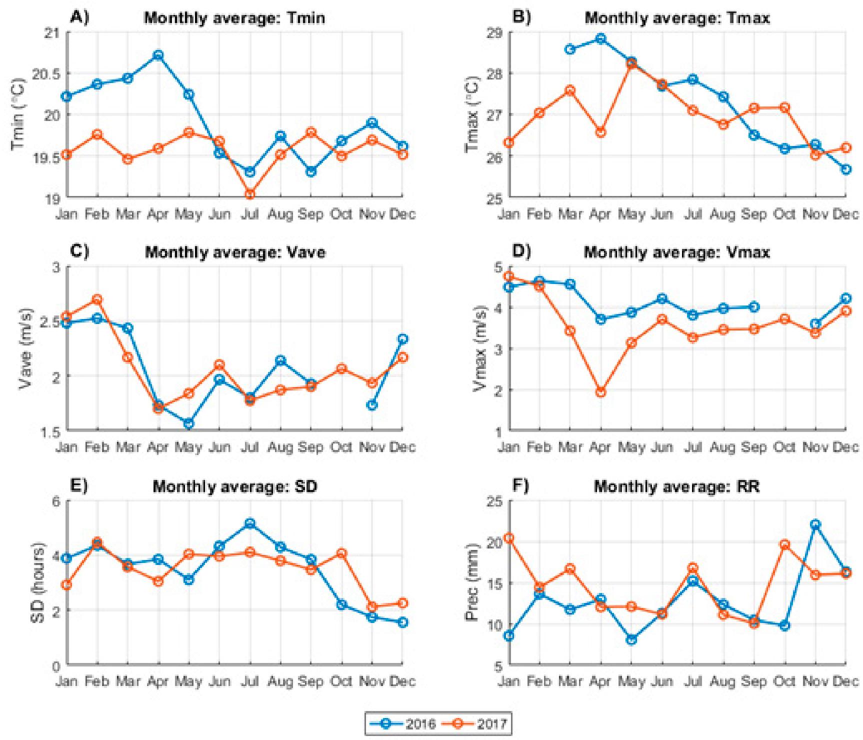

Figure 2. Monthly averages of various meteorological parameters during 2016 and 2017. (A) Minimum temperature (Tmin), (B) Maximum temperature (Tmax), (C) average wind speed (Vave), (D) Maximum wind speed; (E) Sunshine duration (SD), (F) Precipitation (RR). *Promedios mensuales de diversos parámetros meteorológicos durante 2016 y 2017. (A) temperatura mínima (Tmin); (B) temperatura máxima (Tmax); (C) velocidad media del viento (Vave); (D) velocidad máxima del viento; (E) duración de la insolación (SD); (F) precipitación (RR).*

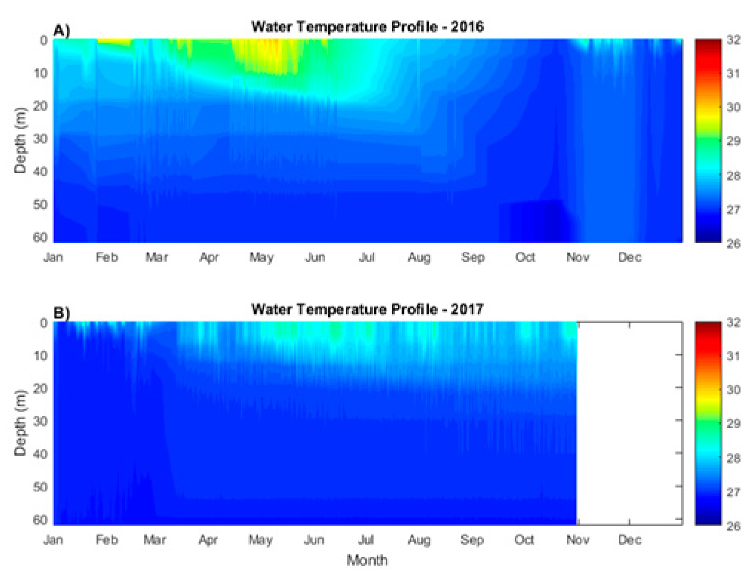

Figure 3. Vertical temperature profiles in (A) 2016, and (B) 2017. *Perfiles verticales de temperatura en (A) 2016 y (B) 2017.*

in November. Meanwhile, more frequent transitions between mixing and stratification were noted in 2017, with full mixing occurring in early January and mid-March (mean gradients of 0.5°C and 0.4°C). This was followed by the relatively strongest stratification from May to mid-August (mean gradient 1.36°C), which slightly weakened toward the end of October (gradient 0.96°C). Overall, stratification in 2017 had a less stable thermal structure and lower average surface temperatures compared to 2016, indicating a more polymictic-like behavior.

Evaluation of Water Column Stratification

To evaluate the stratification and mixing conditions of the water column, this study used SI and MLD, values derived from vertical temperature profiles in 2016 and 2017 (Fig. 3), where a high SI value indicates a stratified water column, while an SI value of near zero or negative and MLD that reaches the lake bottom describe complete mixing.

The water column exhibited stronger stratification in 2016 than in 2017 (Fig. 4A and 4B), with an average SI of 1080.00 J/m² and 788.38 J/m², respectively. In 2016, the strongest stratification occurred in May (average SI of 2393 J/m²), signifying strong thermal stability. However, a significant decline in SI was observed from May to mid-October, reaching negative values (< 0 J/m²), as displayed in Fig. 4A. This reflects the breakdown of stratification due to intense vertical mixing. During this period, the MLD progressively deepened and reached the lake bottom between August and mid-October (Fig. 4B), indicating complete mixing throughout the water column (Fig. 3B). The SI values increased after mid-October, but remained relatively low and varied until December, reflecting fluctuating stratification and mixing conditions.

In 2017, the water column was fully mixed only in early January, as evidenced by an SI value of < 0 J/m² and an MLD extending to the bottom of the lake (Fig. 4C and 4D). Stratification in this

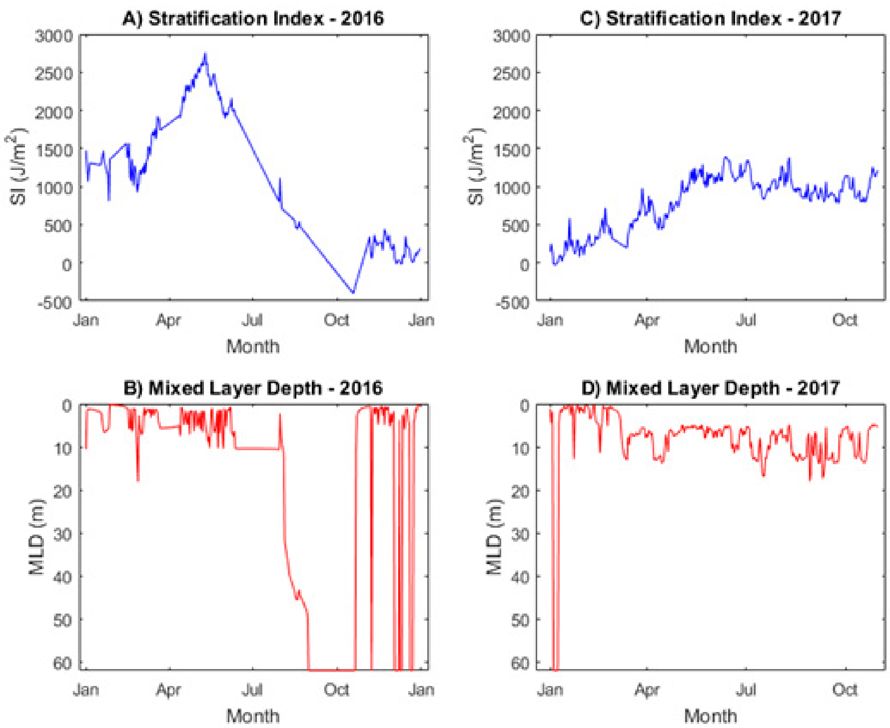

Figure 4. The Evolution of water column stratification characterized by the stratification index and mixed layer depth. (A) stratification index in 2016, (B) stratification index in 2017, (C) mixed layer depth in 2016, (D) mixed layer depth in 2017. *Evolución de la estratificación de la columna de agua, caracterizada por el índice de estratificación y la profundidad de la capa de mezcla. (A) índice de estratificación en 2016; (B) índice de estratificación en 2017; (C) profundidad de la capa de mezcla en 2016; (D) profundidad de la capa de mezcla en 2017.*

year gradually developed thereafter, reaching a peak SI of 1394 J/m² in June. No further episodes of complete mixing were observed until October. During this time, the MLD stayed at the upper 18 m, suggesting that thermal stratification persisted and vertical mixing was limited to the surface layers.

Correlation Between Meteorological Variables and SI

As shown in Table 1, the results of the correlation analysis revealed distinct patterns in the relationships between meteorological variables and SI across the two observation years. In 2016, both Tmin and Tmax showed moderately strong positive correlations with SI, whereas Vave, and RR, whereas Vmax had weak negative correlations with these variables. Overall, no parameters of wind speed and precipitation were significantly associated with SI during this year.

In contrast, the correlation structure notably differed in 2017. During this year, Vave displayed a moderately strong negative correlation with SI, while Vmax only exhibited a weak negative correlation. Among all parameters of the temperature, Tmax was the only variable that demonstrated a notable positive association with SI, whereas Tmin showed no significant relationship. Similar to that in 2016, precipitation was negatively correlated with SI in 2017, but with a stronger correlation. Meanwhile, sunshine duration (SD) correlated positively with SI in both years, although the magnitude of this relationship remained relatively weak.

Seasonal Stratification Variability

Between 2016 and 2017, there were differences in seasonal variations in SI and meteorological variables (Table 2). In 2016, the highest Tmin and SI values were observed during March–May (MAM). Conversely, the lowest SI values were recorded in September–November (SON), despite the Tmin values during these months being slightly higher than those in June−August (JJA). Meanwhile, Vave had the highest and lowest during December–February (DJF) and SON, respectively.

In 2017, the SI values was the highest during JJA and the lowest during DJF. Meanwhile, Tmin reached its highest values during SON and had its lowest during JJA. Wind conditions in this year showed a similar pattern to those in 2016, with the Vave values being the highest during DJF and the lowest during JJA.

Oxygen Dynamics and DO Patterns

Fig. 5A shows the temporal variability of dissolved oxygen (DO) in 2016 and 2017, with unavoidable gaps in data due to technical issues encountered during field operation. Missing data in 2016 account for approximately 19.25% of the total measurements up to December. Meanwhile, whereas in 2017 the proportion of missing data in 2017 is around 11%. A wide range of DO values was reported in both years, from 0 mg/L to 9.47 mg/L in 2016, and from 0 mg/L to 7.6 mg/L in 2017.

Based on the available records from 2016, the water column at 5 m depth generally exhibited increasing oxygen levels during stratification period (February − June and August), surpassing 2 mg/L. In contrast, DO levels decreased significantly between October and December, frequently approaching near-anoxic conditions.

Overall, DO levels observed in 2017 were substantially lower than those in 2016. This is likely due to more limited data availability in 2017. In addition, oxygen concentrations consistently decreased throughout this year. During March–April 2017, for instance, DO values of exceeding 2 mg/L were shown in only about 50% of measurements. During January–February 2017, on the other hand, DO levels fell below 2 mg/L in nearly all measurements (~ 100%), indicating sustained hypoxic conditions.

DISCUSSION

Dominant Meteorological Drivers of Stratification

Between 2016 and 2017, the stratification dynamics in Lake Maninjau displayed notable interannual contrasts, reflecting distinct dominant atmospheric controls. In 2016, air temperature exerted the strongest influence on water-column

Table 1. Correlation between stratification index and meteorological parameters. *Correlación entre el índice de estratificación y los parámetros meteorológicos.*

Parameter	SI			
	2016		2017	
	corr	*p*-value	corr	*p*-value
Tmin	0.605	0.037	-0.062	0.865
Tmax	0.746	0.008	0.529	0.115
Vave	-0.201	0.554	-0.713	0.002
Vmax	0.103	0.762	-0.425	0.22
SD	0.487	0.108	0.43	0.214
RR	-0.352	0.261	-0.486	0.154

Table 2. Seasonal means and standard errors of the mean (SEM) for SI, Tmin, and Vave. *Medias estacionales y errores estándar de la media (SEM) de SI, Tmin y Vave.*

Parameter	DJF	MAM	JJA	SON
2016				
SI (J/m^2)	899.65±62.43	2029.68±41.59	1164.83±57.93	45.56±24.19
Tmin (°C)	20.04±0.12	20.44±0.10	19.57±0.11	19.63±0.08
Vave (m/s)	2.46±0.10	1.91±0.10	2.00±0.09	1.86±0.10
2017				
SI (J/m^2)	254.99±21.50	732.31±31.95	1076.33±15.83	954.55±16.30
Tmin (°C)	19.63±0.13	19.60±0.09	19.43±0.10	19.65±0.11
Vave (m/s)	2.62±0.12	1.93±0.07	1.91±0.07	1.98±0.08

stability, as evidenced by moderately strong positive correlations between SI and both Tmin and Tmax. This pattern is in keeping with the comparatively high Tmin and Tmax values in early 2016 and their gradual decline throughout the year (Fig. 2A and 2B), coinciding with the weakening of stratification and the beginning of deep mixing. By mid-October, SI values were negative and MLD had reached the lake bottom (Fig. 4A and 4B), indicating complete vertical mixing.

In 2017, on the other hand, mechanical forces exerted a stronger influence on stratification dynamics. The moderately strong negative correlation between SI and average wind speed (Vave) suggests that increasing wind energy reduces thermal stability. This is particularly evident in early 2017, when full mixing occurred in the absence of noticeable seasonal cooling, associated with relatively stronger winds in January and February 2017 compared to 2016 (Fig. 2C). In contrast to 2016, Tmax was the only parameter that exhibited a significant positive correlation with SI in 2017, indicating that daytime heating continued to strengthen stratification. Nonetheless, this effect was insufficient to counteract wind-driven destratification during the early year. The subsequent alternation between stratified and mixed states of Lake Maninjau throughout 2017 resembles the behavior of polymictic lakes, in which mixing is driven by short-term meteorological variability, as observed in Lake Rotowhero, New Zealand (Brookes et al., 2013) and tropical crater lakes in Uganda (De Crop & Verschuren, 2019).

The peak SI value of 2393 J/m² observed in May 2016 reflects a substantial degree of thermal stability for a tropical lake, particularly considering that the vertical temperature gradient was only ~2.3°C at that time. On the other hand,

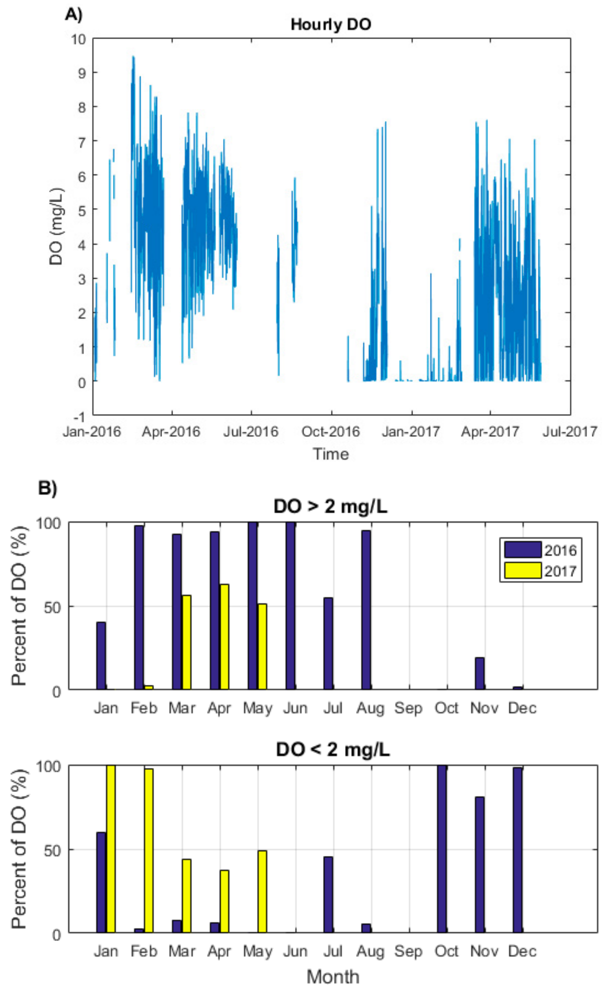

Figure 5. (A) Fluctuation of dissolved oxygen at a depth of 5 m in 2016 – 2017, (B) Monthly proportions of DO > 2 mg/L and DO < 2 mg/L at 5 m depth in 2016–2017. The blank curve in Figure 5A shows no data recorded. *(A) Fluctuación del oxígeno disuelto a una profundidad de 5 m durante 2016–2017; (B) proporciones mensuales de DO > 2 mg/L y DO < 2 mg/L a 5 m de profundidad en 2016–2017. La curva en blanco en la Figura 5A indica ausencia de datos registrados.*

the MLD-based interpretation confirms that negative SI values during mid-2016 are consistent with a fully mixed water column, these values are reasonable when compared to other systems. In Lake Matano, for example, the Schmid Stability (SS) reaches ~200 000 J/m² over the full 600-m depth, preventing complete overturning, whereas the SS value of ~5000 J/m² within the upper 100 m still allows mixing under strong wind conditions (Katsev et al., 2010). Similarly, in Lake Qiandaohu, China, where temperatures are measured to 65 m, SS reaches ~10 340 J/m² during peak stratification (July–August) when the vertical temperature difference is ~22°C, and then drops to ~429 J/m² during the cooling season (Liu et al., 2019). Within this broader context, the magnitude of SI in Lake Maninjau is line with its 60-m measurement depth and tropical climate.

The position of Lake Maninjau within the spectrum of lacustrine mixing regimes is further clarified by the timing and depth of the mixing that occurs. In 2016, a single deep mixing period from August to October produced a monomictic-like pattern of prolonged stratification interrupted by one annual overturning phase. This regime is likely influenced by a strong negative phase of the Indian Ocean Dipole (IOD), which increases cloud cover and precipitation over western Indonesia (Avia & Sofiati, 2018, Iskandar et al., 2018). The corresponding decrease in solar radiation limited daytime heating, consistent with the gradual drop in water-column temperature from late May to October. This process typically reinforces seasonal cooling and facilitates the progressive weakening of stratification until full mixing occurs. In 2017, however, stratification and mixing alternated more frequently, including partial mixing events without complete overturning after January. This is typical of tropical polymictic lakes, where mixing is intermittently triggered by short-term fluctuations in radiative and wind factors. Unlike dimictic lakes in temperate regions, which undergo winter-driven density reset, Lake Maninjau does not experience sufficiently deep cooling due to its tropical setting. Therefore, stratification dynamics in this lake are impacted primarily by the interplay between radiative heating and wind-induced turbulence.

Furthermore, short-term (diurnal) variability remains an essential control under marginal stratification conditions. Sunshine duration showed a positive but weak association with SI in both years, consistent with daytime heating strengthening stability, followed by nocturnal cooling that erodes stratification (Santoso et al., 2018). These diurnal cycles likely accumulate over weeks, setting the conditions for seasonal shifts in stability and ultimately influencing both the timing and completeness of mixing events.

Mixing–Stratification Conditions as a Function of Vave, Tmin, and SI–σ

Prior studies have reported that thermal stratification is influenced by the balance between atmospheric heating and mechanical mixing (Monismith et al., 1990, Wetzel, 2001). This present study used Tmin and Vave as the primary parameters for the reason that minimum temperature during nighttime controls surface heat loss and density stability, while average wind speed represents the dominant mechanical force that drives turbulent mixing. In the analysis, stratification condition is quantified using the $SI - \sigma$ (standard deviation), where $SI - \sigma > 0$ denotes stratification and $SI - \sigma \leq 0$ implies that the water column is mixed (Ladd & Stabeno, 2012).

Based on the figure 6, the water column generally remains stratified when Tmin is relatively high (above approximately 20.25°C), regardless of wind speed conditions. At lower Tmin values, however, the system may display either mixed or

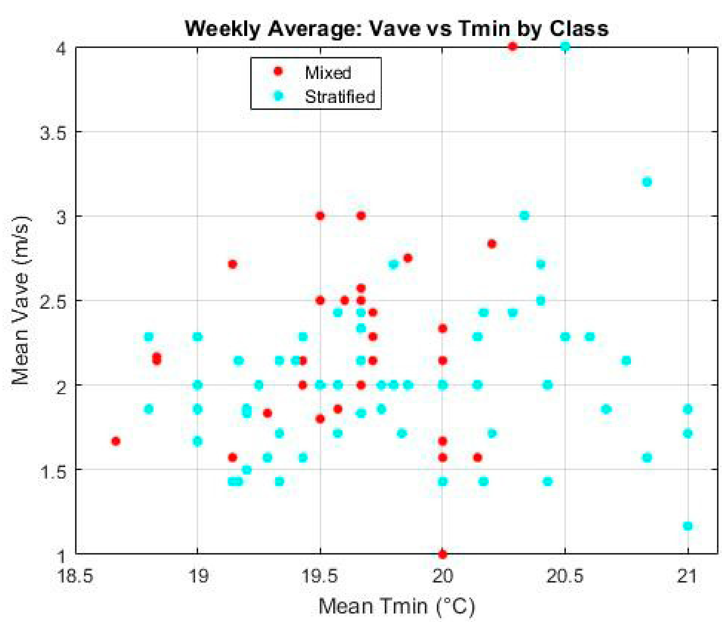

Figure 6. Minimum temperature and average wind speed coinciding with changes in the stratified and mixed status of the water column. *La temperatura mínima y la velocidad media del viento coinciden con los cambios en el estado estratificado y mezclado de la columna de agua.*

stratified states. Notably, the water column tends to shift toward mixing when the Vave value exceeds ~2.75 m/s. This indicates that wind-driven mechanical energy in this range may be sufficient to disrupt vertical density gradients.

The observed variability in stratification behavior under similar combinations of Tmin and Vave can be attributed to two key mechanisms. First, while lake stratification results from a multivariate interaction of atmospheric and limnological drivers, the plotted relationship includes only two meteorological parameters. Thus, the coexistence of mixed and stratified states within the same Tmin–Vave ranges is expected due to the influence of other factors not captured in the current visualization.

Second, the water column has thermal memory, which means that preceding meteorological forces affect subsequent mixing or stratification. For instance, the lake may remain stratified at Vave of around 2.25 m/s and Tmin ≈ 18.75°C, but it may appear mixed at the same Vave with a slightly higher Tmin (around 20°C). This scenario is plausible if strong wind events before the observation induce vertical homogenization that temporarily persists, and surface heating has not yet fully re-established stability.

Overall, this pattern suggests that Tmin and Vave act as major, but not exclusive drivers of lake stability. Nevertheless, a more complete interpretation necessitates acknowledging both prevailing atmospheric conditions and their temporal evolution, as well as contributions from other meteorological and in-lake processes that jointly regulate mixing–stratification dynamics.

The Implication of Thermal Stratification Weakening on Dissolved Oxygen Levels

Dissolved oxygen (DO) is a critical parameter of water quality, and is essential for sustaining aquatic life and supporting various biogeochemical processes in lake ecosystems. Thermal stratification strongly affects its distribution within the water column. Previous studies have reported a continuous decrease in the thickness of the oxic layer in Lake Maninjau, particularly since 1929 (Fukushima et al., 2017, Lehmusluoto et al., 1997). When thermal stratification breaks down, a thin oxic layer is highly susceptible to vertical mixing with the underlying anoxic layer, potentially leading to a sharp significant decrease in DO concentrations.

In this study, the DO measurements show a wide dynamic range at 5 m depth. This indicates a diurnal DO cycle, where night time respiration drives oxygen down to hypoxic or even anoxic levels, while daytime photosynthesis increases DO concentrations. The near-anoxic values observed more frequently in 2017 may be linked to reduced photosynthetic oxygen production due to limited solar irradiance, as indicated by the lower mean sunshine duration from January to May 2017 (3.65 h) compared to the same period in 2016 (3.89 h) (Fig. 2E). Such reduced availability of light is further supported by lower Tmin and elevated precipitation during the same months (Fig. 2F), both of which imply diminished incoming solar energy to the lake surface.

Additionally, the decreased DO levels in 2017 suggest that respiration outpaces photosynthetic oxygen generation for extended periods, causing the water column to remain vulnerable to rapid oxygen depletion (Santoso & Triwisesa, 2020). Under these conditions, even moderate mixing can transport oxygen-deficient deep water upward, accelerating the decrease in DO levels and triggering transient anoxic conditions in the upper water column.

The weakening of thermal stratification, therefore, has direct implications for lake oxygen dynamics. When stratification breaks down, whether through wind-induced mixing or surface cooling, the thin oxic layer at the surface becomes rapidly diluted by the underlying anoxic water mass, resulting a in sharp drop in DO levels. This mechanism was evident in October–December 2016 and January–February 2017, where destratification corresponded with DO concentrations dropping below 2 mg/L at 5 m depth. Conversely, under stratified conditions, DO levels above 3 mg/L tend to dominate in the surface mixed layer, preventing vertical oxygen redistribution into deeper waters. Such events pose severe risks to aquaculture, as fish in floating net cages cannot escape to oxygenated waters. This is in line with the findings of a previous study by Makmur et al. (2020) that the prolonged mixing period in 2016, which coincided with the major fish kill that year, illustrates the cumulative hazard of physical mixing, hypoxia, and the upward migration of toxic sulfide (locally known as tubo belerang).

CONCLUSIONS

This study reveals that the dynamics of thermal stratification in Lake Maninjau are highly sensitive to short-term meteorological variations, with distinct interannual differences in the dominant drivers. While a drop in air temperature played a central role in weakening stratification and triggering complete mixing, whereas in 2017, wind speed exerted a stronger influence in 2017. According to the analysis of the meteorological parameter ranges, stratification typically persisted if Tmin was relatively high (above 20.25°C), regardless of wind conditions. At lower Tmin values, the water column could either be stratified or mixed. Stratification tended to break down particularly when the Vave exceeded ~2.75 m/s, implying that wind-driven mechanical energy in this range is sufficient to overcome vertical density gradients. Precipitation, on the other hand, showed no significant effect on stratification. The aforementioned conditions significantly affect dissolved oxygen levels in the upper water column, with major implications for aquaculture operations in the lake. DO levels sharply dropped during destratification, contributing to fish kill in floating net cages. These findings highlight the importance of continuous monitoring of both meteorological and limnological parameters to anticipate ecological disturbances. Furthermore, integrating weather-based thresholds into early warning systems can enhance aquaculture resilience and support sustainable lake management in tropical regions.

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AUTHOR CONTRIBUTIONS

T.J.: Conceptualization, methodology, formal analysis, writing: original draft; M.R.P.: Conceptualization, theoretical analysis, supervisor; M.A.: Conceptualization, theoretical analysis, co-supervisor; C.H.: Conceptualization, theoretical analysis, supervisor; E.T.: Data contributor, Online monitoring device installation; M.F.: Data contributor, Online monitoring device installation.

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