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Mixing regimes in a cluster of seven maar lakes in tropical monsoon Asia

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ABSTRACT
The 7 maar lakes of San Pablo are a cluster of small volcanic lakes on Luzon Island, Philippines. These lakes, which are heavily utilized for aquaculture and ecotourism, usually experience fish kills that coincide with the northeast monsoon (NEM). This study explores limnophysical processes, particularly mixing regimes, in the lakes in relation to prevailing monsoons. We monitored monthly vertical and seasonal profiles of water temperature, salinity, conductivity, and dissolved oxygen from October 2016 to December 2018. Three types of mixing regimes were observed among the lakes, which have similar surface areas but different depths: polymixis in the shallowest; warm monomixis in lakes with intermediate depth; and meromixis in the deepest. A boundary between monomixis and meromixis was identified between 36 and 62 m depth. Monthly monitoring showed seasonal mixing occurred exclusively during the NEM (Nov–Apr). We also incorporated meteorological data into the model and performed multiple regression analysis for each lake to determine the best predictor: lake stability, as indicated by the Schmidt stability (S_T). A between-lake comparison showed lake stability was strongly correlated with both air temperature and wind speed, suggesting these 2 meteorological variables are involved in establishing thermal stratification in the lakes during the southwest monsoon. This study provides insights for adaptive lake management and projections of climate impacts on these understudied tropical lake ecosystems in Southeast Asia.

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lake management; limnophysics; mixing regime; stability indices; tropical maar lakes

Introduction

Stratification and mixing are fundamental physical processes in lake ecosystems that involve the vertical transport of dissolved and particulate materials (Zhang et al. 2014) and gas exchange with the atmosphere (Åberg et al. 2010), which in turn affect ecological processes such as plankton blooms due to nutrient upwelling and mass mortality due to anoxia (Jankowski et al. 2006). Various meteorological variables can influence lake mixing and stratification: air temperature, which has been observed to affect thermal structure, mixing duration, and mixing regimes of lakes (Adrian et al. 2009); and high wind speeds, which can decrease lake stability, leading to mixing (Imberger 1994). Other factors such as physical disturbance of the water column due to heavy precipitation and subsequent river inflows from tributaries can also lead to destratification, depending on monsoon strength and timing (Jones et al. 2009, Jennings et al. 2012, Bertone et al. 2015), and catchment size (Nkiaka et al. 2016).

Within the Asian region, lakes exhibit a wide variety of mixing regimes across latitude, including boreal dimictic lakes (e.g., Lake Qinghai: Su et al. 2019), temperate monomictic lakes (e.g., Lake Biwa: Yoshimizu et al. 2010), and tropical meromictic lakes (e.g., Lake Matano: Katsev et al. 2010). While most tropical lakes are understudied, they are generally regarded as warm-monomictic and tend towards polymixis or meromixis, depending on depth (Lewis 2000). Although long-term and high-frequency monitoring of tropical lakes has increased over recent years (Herrera et al. 2011, Saulnier-Talbot et al. 2014, Santoso et al. 2018), research on limnophysics in these systems is still limited (De Crop and Verschuren 2019). In tropical Southeast Asia, especially in the Philippines, the mixing regimes of lake ecosystems are poorly understood because of limited research and equipment

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availability. As a result, most lakes in the Philippines remain understudied (Legaspi et al. 2015); thus, limnological research is warranted to address the knowledge gaps of the diverse stakeholders of these systems (Bannister et al. 2019, Mendoza et al. 2019). Luzon Island, the largest island in the Philippine archipelago, harbors >35 lakes, >50% of the natural lakes in the country (Legaspi et al. 2015). The island contains a cluster of crater lakes collectively known as the 7 maar lakes.

Here, we explore the limnophysical features of these 7 neighboring lakes and assess the influence of monsoons on their mixing regimes. In addition to the intrinsic mixing behavior of tropical lakes, local anecdotal evidence indicates the lakes experience upwelling of hypoxic/anoxic bottom waters during the northeast monsoon (NEM); therefore, we hypothesize they are monomictic. Special attention is paid to how bathymetric characteristics can shape mixing regimes by comparing the 7 lakes, which are relatively similar in surface area but differ in depth and exhibit a sufficiently narrow geographical distribution to share meteorological conditions. By incorporating meteorological data into the statistical model, we also identify any variables that might influence the mixing regimes of these lakes.

Materials and methods

Study lakes and climate

The study lakes, Palakpakin, Bunot, Sampaloc, Mohicap, Yambo, Pandin, and Calibato (Fig. 1), are distributed within a small geographical area (<35.0 km^2) in the province of Laguna, Philippines. They are relatively small (surface area <2 km^2) compared to other major Philippine lakes (surface area ≥ 50 km^2; Lehner and Döll 2004), such as Taal, Lanao, and Laguna de Bay. The lakes were formed from the phreatomagmatic explosion of Mount San Cristobal, a neighboring dormant volcano (Cordero and Baldia 2015). Based on their volcanic origin and relatively small size (diameter <2.0 km; Wetzel 2001), they were classified as maars instead of calderas. The lakes are similar in surface area but differ greatly in depth, ranging from 7.0 to 131.0 m (Table 1). Since the 1970s, the lakes have been heavily utilized for aquaculture, resulting in frequent fish kills (Brillo 2017). Because fish kills can be linked to cultural eutrophication due to nonsustainable aquaculture practices (Friedrich et al. 2014), the quasigovernmental Laguna Lake Development Authority (LLDA) has attempted to regulate aquaculture in these lakes since 1998. In compliance with the Philippine Fisheries Code, the LLDA has reduced the number of fish cages, which now only utilize 10% of the lake surface area (LLDA 2014). With government intervention, some communities living around the 7 maar lakes have shifted their livelihood from aquaculture to ecotourism, whereas others still utilize the lakes solely for aquaculture (Mendoza et al. 2019).

The Philippine climate is characterized by 2 distinct types of monsoons: the NEM (Nov–Apr) and southwest monsoon (SWM; May–Oct; Chang et al. 2005, Cinco et al. 2014), distinguished by seasonal patterns of air temperature, wind speed, and rainfall (Fig. 2). The NEM has lower annual air temperature and precipitation, whereas the SWM is characterized by high air temperature and precipitation. According to Corporal-Lodangco and Leslie (2017), the Laguna province experiences a dry season (Jan–Apr) and a wet season (May–Dec), which overlap with the NEM and SWM, respectively.

Field monitoring

Limnophysical monitoring in the study lakes was conducted monthly from October 2016 to January 2018. To examine interannual variation in mixing regimes, we continued the monitoring in the 3 deepest lakes (Yambo, Pandin, and Calibato) until December 2018. Unfortunately, the gaps in monitoring in the shallower lakes were necessary because of budget constraints.

We established monitoring points at the deepest part of each lake, determined by a digital depth sounder gauge (SM-5; Cole-Parmer, USA). Vertical profiles of water temperature, salinity, conductivity, and dissolved oxygen (DO) concentration were measured using a multiparameter water quality sonde (EXO1; YSI, USA). Salinity was automatically computed from the conductivity data as a default option of the sonde.

Meteorological data for daily air temperature, wind speed, and rainfall during our monitoring period (Fig. 2) were acquired from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) meteorological synoptic station (14.1833°, 121.2500°), the nearest weather facility to the study area (<20.0 km). Data for lake surface area were obtained from the LLDA (2014). Fetch, defined as the maximum distance wind can travel uninterrupted on the lake, was calculated as the square root of lake area (von Einem and Granéli 2010). Because lake surface area and the surrounding landscape influence the mixing regime and thermal structure (Borics et al. 2015), digital elevation models (DEMs) were used to calculate the following an index of the difference in elevation means (μ_{Diff}) between the lake surface and immediate surrounding landscape within the marginal area (1.0 km^2) of the lake perimeter, considered a topographic index of the lake landscape (Table 1).

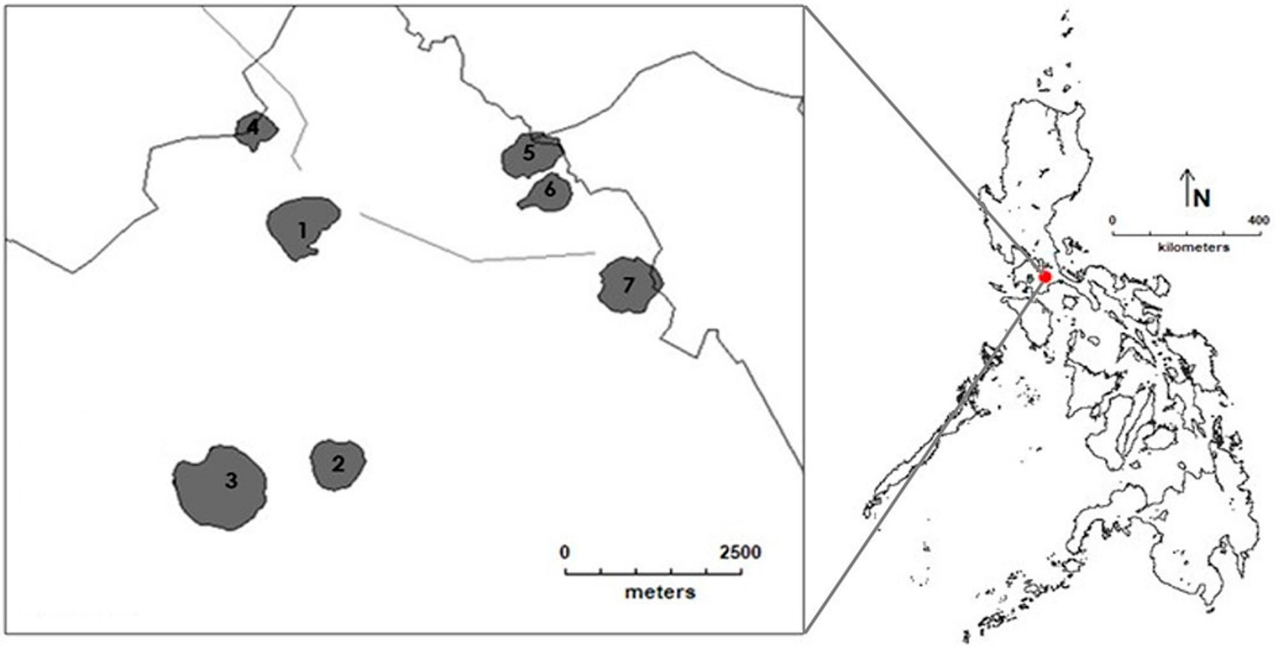

Figure 1. The 7 maar lakes of Laguna: (1) Palakpakin, (2) Bunot, (3) Sampaloc, (4) Mohicap, (5) Pandin, (6) Yambo, and (7) Calibato.

Table 1. Summary of morphological characteristics of the 7 maar lakes, arranged based on maximum depth. μ_{Diff} is a topographic index of the lake landscape (see text).

Lake	Surface area (km^2)	Maximum depth (m)	Altitude (m a.s.l.)	Fetch (m)	μ_{Diff} (m)
Palakpakin	0.48	7.0	100	693	19.8
Bunot	0.36	21.0	110	600	10.6
Sampaloc	1.04	23.0	106	1020	73.5
Mohicap	0.23	29.0	80	480	49.5
Yambo	0.31	36.0	160	557	22.4
Pandin	0.24	62.0	160	490	30.2
Calibato	0.43	131.0	170	656	41.2

Stability indices

Water density and lake stability, measured as Schmidt stability (S_T), were calculated from our monitoring data using *rLakeAnalyzer* (Winslow et al. 2019) in R. The script executes standardized methods for calculating the essential physical characteristics of a lake, including water buoyancy and interpolations of density gradients based on water temperature (Read et al. 2011). The water density profiles were initially generated to visualize the monthly evolution of density throughout the monitoring period. Salinity data were also included in the computation of water density profiles.

Because detailed bathymetry data were not available, we approximated the bathymetry of each lake using the Lake Analyzer script function *cone.ex*. The S_T, defined as the work required to mechanically homogenize a stratified lake, was derived from the following formula (Idso 1973):

$$S_T = \frac{g}{A_S}\int_0^{Z_D} (Z - Z_V)\rho_Z A_Z \partial_Z,$$

where g is acceleration due to gravity (m/s^2), A_s is lake surface area (m^2), A_Z is the lake area at depth Z (m^2), Z_D is maximum depth (m), Z_V is depth at the center of the lake (m), and ρ_Z is water density at depth Z (kg/m^3).

We used S_T values to determine if each lake underwent complete mixing. A value of 0 indicates that the water column is homogeneous in density, requiring only minimal turbulent kinetic energy to vertically mix the lake (Holzner et al. 2009). Following North et al. (2013), we assumed that complete mixing was likely if $S_T < 15$ J/m^2. We classified each of the study lakes as monomictic or polymictic if its S_T values decreased to <15 J/m^2 once or multiple times a year, respectively. Otherwise, the lake was classified as meromictic.

Statistical analysis

To examine the relationship between select meteorological factors and the mixing regime of the study lakes, we performed multiple regression analysis. First, daily air temperature, wind speed, and rainfall data were transformed into monthly averages and incorporated into the model as predictor variables to investigate which parameter is empirically most related to lake stability, indicated by S_T, as response variables over the entire study period. If strong correlations ($r > |0.7|$) were observed among predictor variables, residuals of one predictor variable regressed against another were calculated to avoid multicollinearity, which increases uncertainty in the multiple regression analysis.

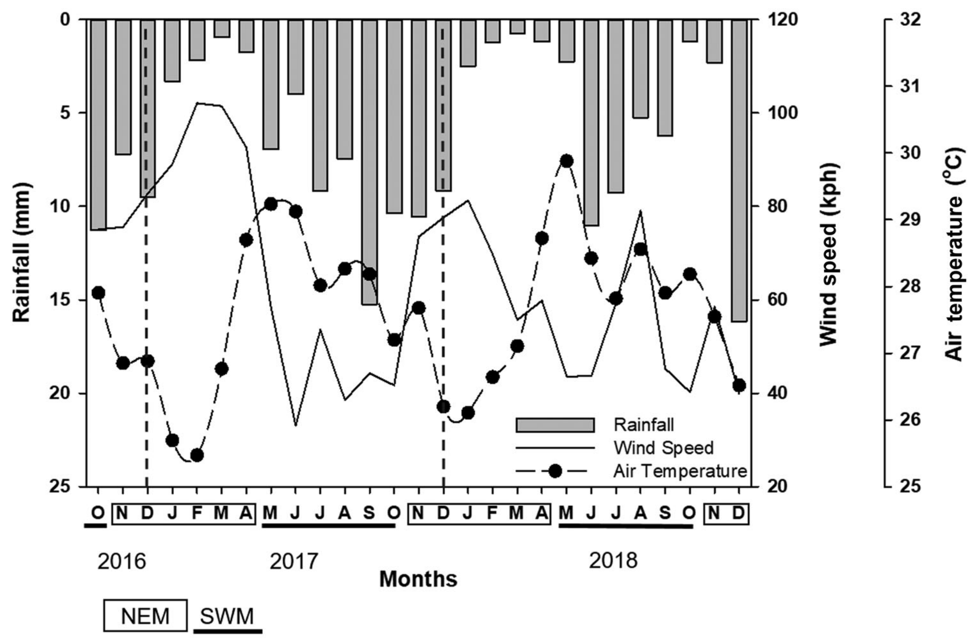

Figure 2. Summary of the meteorological parameters of interest throughout the sampling period. Northeast monsoon (NEM) is Nov–Apr and southwest monsoon (SWM) is May–Oct.

Second, we used multiple regression analysis to examine the effects of unpredictable physical disturbances, such as typhoons occurring during the SWM, on the stability of each lake. The average and maximum values were calculated for each month (30D) and for different time periods (2 weeks [14D], 10 days [10D], 1 week [7D], 5 days [5D], and 3 days [3D]) before the day of monitoring, only during the SWM. Among air temperature, wind speed, and rainfall, the variable with the highest correlation was incorporated into the model, provided that no strong correlations occurred among the predictor variables.

We used a stepwise method for model selection, adopting predictor variables at a significance level of $p \leq 0.05$. Data were $\log_{10}(x+1)$-transformed as needed to meet the assumptions of normality and equal variance.

Results

Limnophysical dynamics

During the SWM, lake waters were thermally stratified in all the study lakes, with water temperatures exceeding 30 °C at the surface (0–1 m; Fig. 3, Table 2). By contrast, lake waters were well mixed in most lakes, as depicted by the vertically homogeneous distribution of water temperature (Fig. 3) and density (Fig. 4) during the NEM, in which surface water temperature drastically decreased to 27.76 ± 1.61 °C (Fig. 3). As a consequence of alternating monsoons, surface water temperatures exhibited high seasonal variation in all lakes, whereas bottom water temperatures were seasonally stable at ~24.2–24.4 °C, except for Lake Palakpakin. Gradients of water density gradually became smaller as the NEM progressed (Fig. 4), reaching an isopycnal or near-isopycnal state throughout the entire water column during January–February.

Based on limnophysical profiling, S_T was calculated as an index of lake stability (Fig. 5). For all lakes except Lake Palakpakin, S_T remained high during the SWM, indicating high stability due to strong thermal stratification (Fig. 3b–g). However, values of S_T decreased below 15 J/m^2 once mixing occurred during the NEM, except for the deepest lakes (Pandin and Calibato). Lake Palakpakin exhibited S_T values <15 J/m^2 year-round. Therefore, the NEM and SWM could be referred to as the mixing and stratification periods, respectively. Assuming $S_T = 15$ J/m^2 to represent an approximate boundary between mixing and stratification (North et al. 2013), Lake Palakpakin can probably be classified as polymictic; Lakes Bunot, Sampaloc, Mohicap, and Yambo as warm monomictic; and Lakes Pandin and Calibato as meromictic.

In this study, we considered the following DO conditions; oxic (>4.0 mg/L), hypoxic (2.0–4.0 mg/L), and anoxic (<2.0 mg/L; Nürnberg 2002, Liu et al. 2019). The average DO concentrations at the surface (0–1 m) tended to be higher in Lakes Palakpakin and Calibato (Fig. 6; Table 2). Lake Palakpakin remained well oxygenated throughout the sampling period (≥9.0 mg/L). Interestingly, average DO concentrations (standard deviation) in the deeper parts of monomictic lakes,

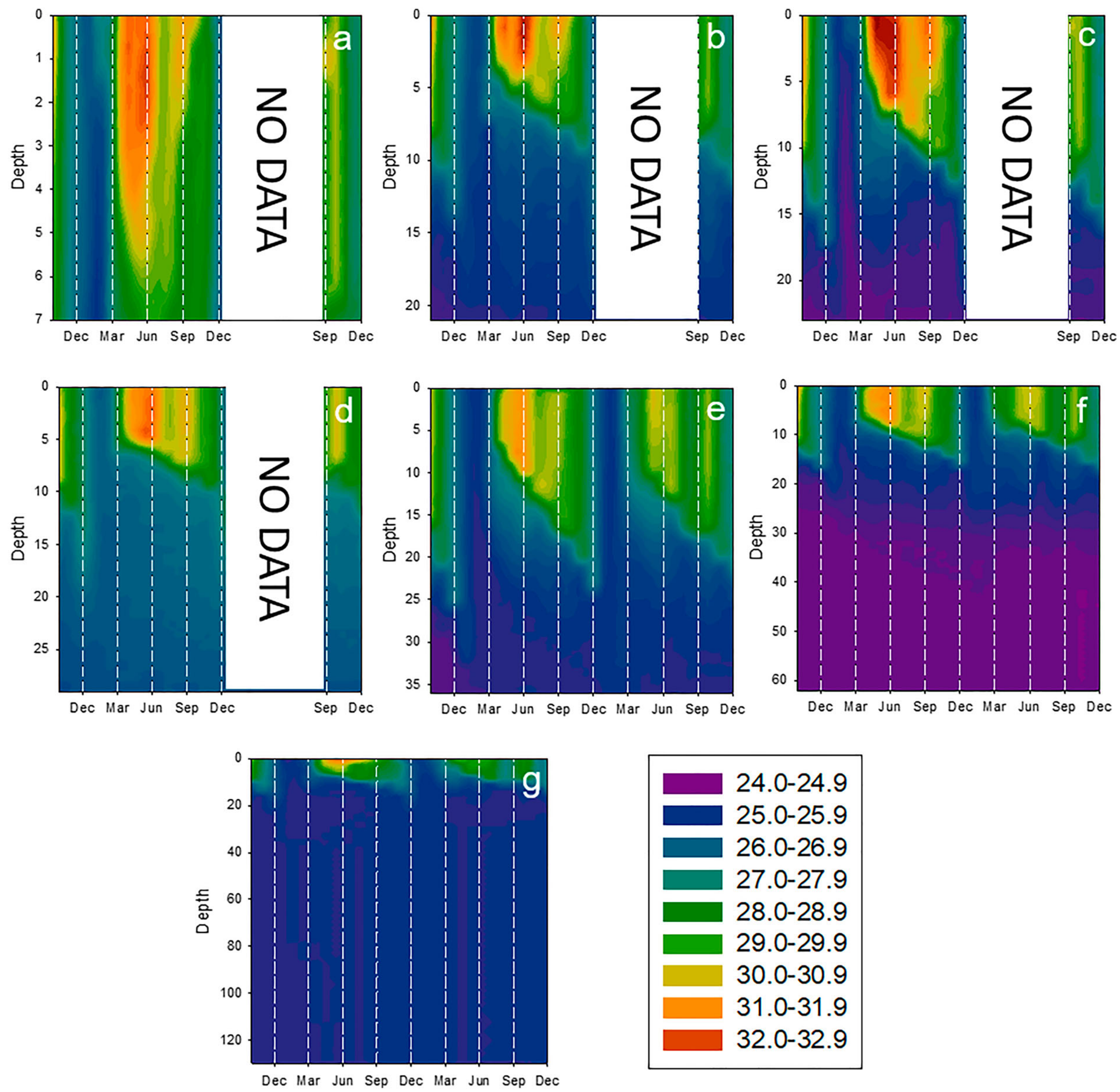

Figure 3. Monthly water temperature profiles (°C; see colored scale inset) of Lakes (a) Palakpakin, (b) Bunot, (c) Sampaloc, (d) Mohicap, (e) Yambo, (f) Pandin, and (g) Calibato (2017–2018).

Bunot (0.9 [0.9] mg/L during NEM, 1.0 [0.7] mg/L during SWM), Sampaloc (1.0 [0.9] mg/L during NEM, 1.4 [1.0] mg/L during SWM), and Mohicap (0.5 [0.4] mg/L during NEM, 0.6 [0.4] mg/L during SWM), remained anoxic during both monsoon seasons. The overall DO concentrations during the SWM were higher than those

Table 2. The mean (standard deviation) and range of water temperature and dissolved oxygen (DO) concentration in the surface (0–1 m) and bottom (1 m above lake bottom) layers of the 7 maar lakes during the monitoring period.

	Water temperature (°C)				DO (mg/L)			
	Surface		Bottom		Surface		Bottom	
	Mean (SD)	Min-Max	Mean (SD)	Min-Max	Mean (SD)	Min-Max	Mean (SD)	Min-Max
Palakpakin	28.76 (1.82)	25.8–32.1	27.90 (1.35)	25.1–30.3	9.18 (1.53)	7.0–12.7	5.1 (1.89)	1.6–9.2
Bunot	28.73 (2.03)	25.4–32.7	24.97 (0.13)	24.7–25.3	7.18 (2.72)	2.2–12.7	0.41 (0.25)	0.0–0.9
Sampaloc	29.05 (1.86)	25.9–31.9	25.43 (0.11)	25.3–25.7	7.30 (2.65)	2.6–11.7	0.45 (0.22)	0.0–0.7
Mohicap	28.98 (1.55)	26.1–31.8	25.75 (0.07)	25.6–25.9	6.61 (2.22)	1.2–10.4	0.19 (0.11)	0.0–0.04
Yambo	28.15 (1.73)	25.1–31.0	24.89 (0.16)	24.4–25.1	7.40 (1.00)	3.9–9.0	0.5 (0.58)	0.0–2.5
Pandin	28.9 (1.78)	25.2–31.1	24.28 (0.05)	24.2–24.4	7.47 (0.98)	4.5–9.4	0.06 (0.06)	0.0–0.2
Calibato	27.76 (1.61)	25.2–31.4	24.92 (0.08)	24.7–25.1	8.64 (2.48)	3.5–14.2	0.00 (0.00)	0.0–0.0

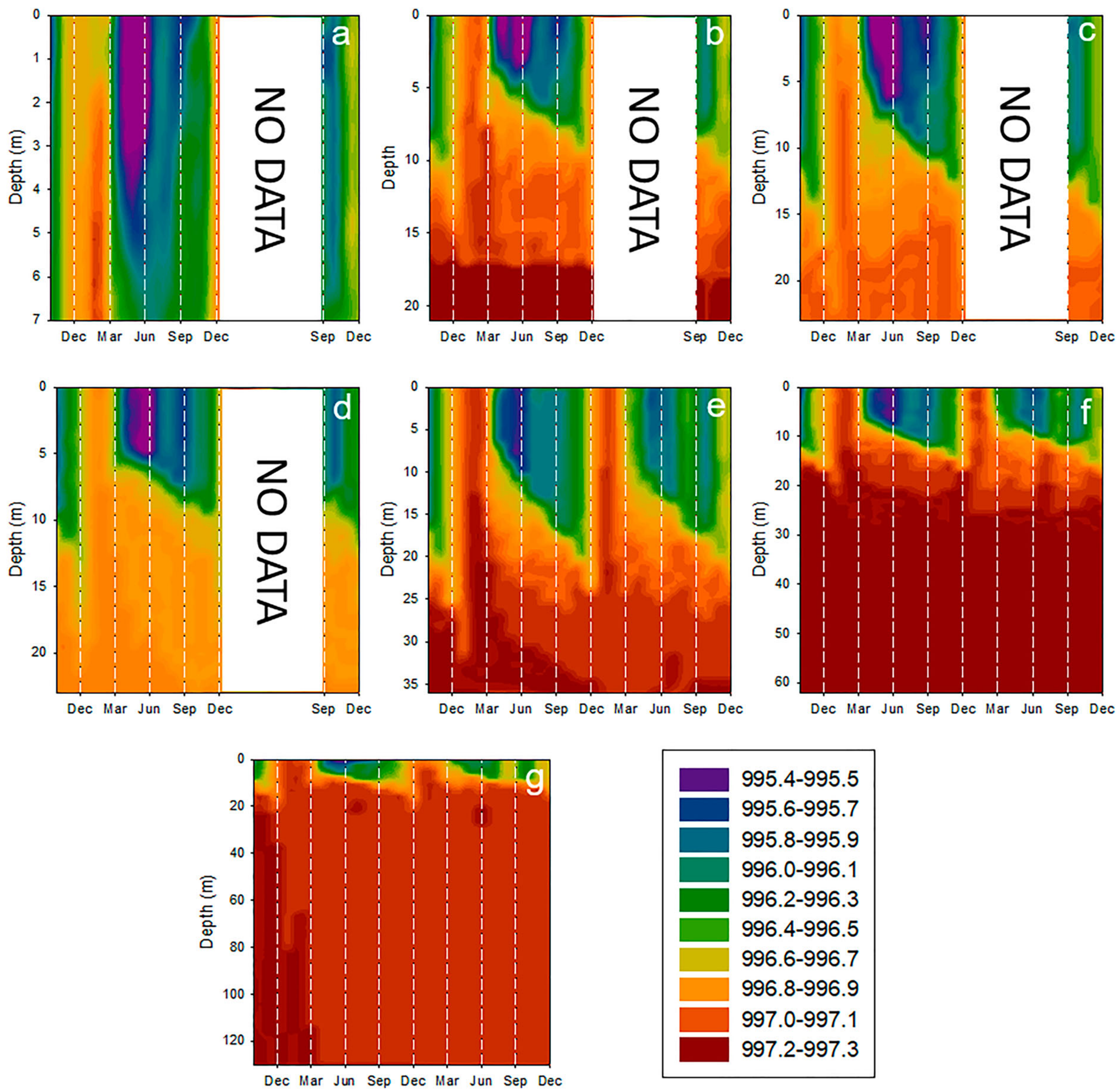

Figure 4. Monthly water density profiles (kg/m^{-3}; see colored scale inset) of Lakes (a) Palakpakin, (b) Bunot, (c) Sampaloc, (d) Mohicap, (e) Yambo, (f) Pandin, and (g) Calibato (2017–2018). NEM = northeast monsoon, SWM = southwest monsoon, and ST = Schmidt stability.

during the NEM, suggesting the gradual renewal of DO in these lakes after the mixing period. Unlike other monomictic lakes, the replenishment of average DO in the deeper parts of Lake Yambo took place immediately and resulted in a noticeable increase in concentration during the NEM. By contrast, DO concentrations in the deeper parts of meromictic lakes Pandin and Calibato remained notably low (<1.0 mg/L) throughout the sampling period.

Meanwhile, conductivity in the lakes showed no apparent temporal patterns between monsoons ($p > 0.05$; Fig. 7). Minimum values ranged from 44 to 108 mS/cm while maximum values ranged from 235 to 1368 mS/cm. In the meromictic Lakes Pandin and Calibato, the pycnocline delineating the mixolimnion and monimolimnion varied between depths (9.0–21.0 m). Meanwhile, the highest conductivity values were found on the bottom/near-bottom depths of Lakes Bunot, Sampaloc, and Mohicap (605–1368 mS/cm). Because the lakes are volcanic in origin, the high conductivity could possibly stem from volcanic activity, but other factors such as rainfall, precipitation, and groundwater seepage have also been shown to contribute to lake conductivity of maar lakes (Armienta et al. 2008). Additionally, the high conductivity measured in the lakes might also be a result of anthropogenic activities because the lakes have a long history of being used for extensive aquaculture practices (Mendoza et al. 2019).

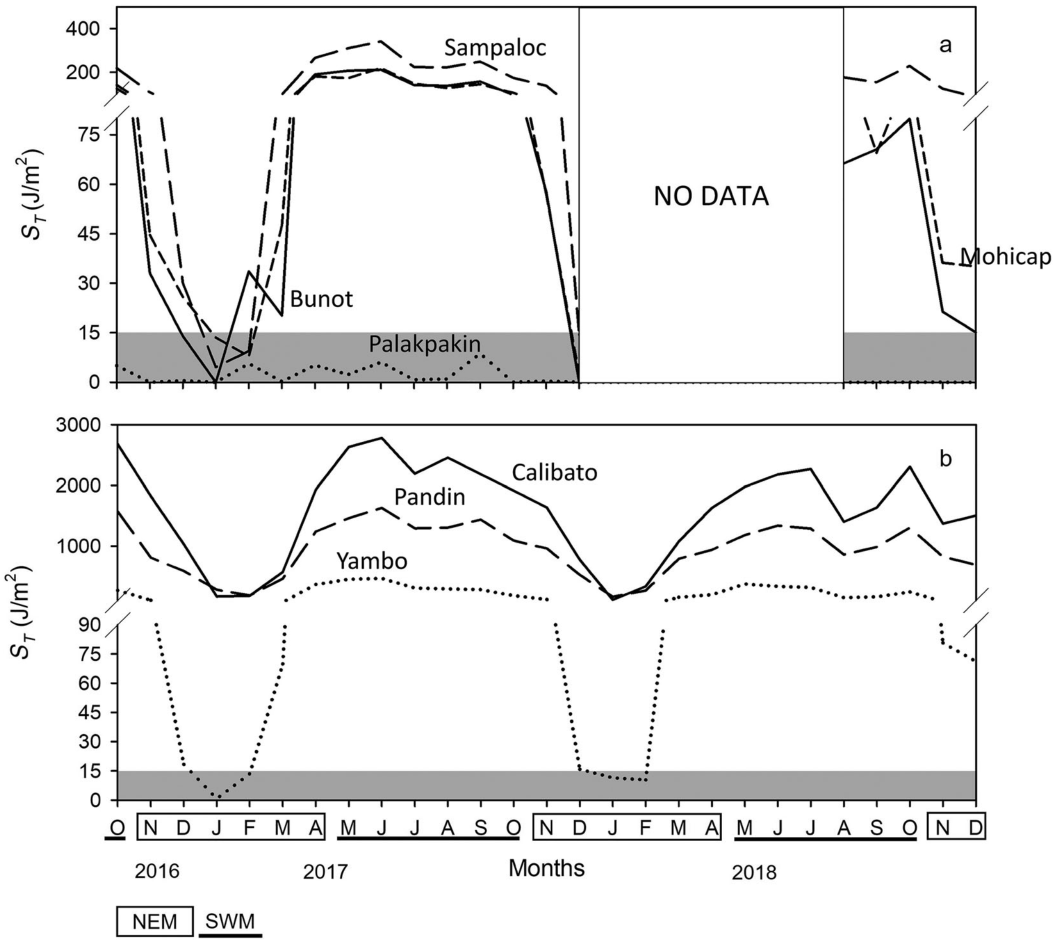

Figure 5. Monthly variation in the Schmidt stability (a, b) of the 7 maar lakes (2017–2018). NEM = northeast monsoon, SWM = southwest monsoon, and S_T = Schmidt stability.

Meteorological factors influencing the mixing regimes

Based on the multiple regression analysis performed to determine which meteorological variables are empirically most related to S_T, monthly changes in air temperature consistently and robustly accounted for the largest proportion of seasonal variation in lake stability (Table 3). Although the regression analyses for Lake Palakpakin did not yield significant models, standardized beta coefficients indicated that air temperature is the most significant parameter among all variables. Rainfall, however, only had a significant relationship with the deeper maar lakes, second only to air temperature. Meanwhile, wind speed was not significant in any model except in Lake Palakpakin.

Throughout the study period, 2 notable decreases in S_T occurred during the SWM (Jul 2017 and Aug 2018; Fig. 5). In the Philippines, the SWM is generally characterized by typhoons with strong winds and heavy rains, which may reduce lake stability. In 2017 and 2018, 22 and 21 tropical cyclones entered the Philippine area of responsibility, respectively, 4 of which arrived during July 2017 and 3 during August 2018. Thus, when examining limnophysical processes during the SWM alone, we also incorporated maximum wind speed (MaxWS) and maximum rainfall (MaxRF) into the model as predictor variables. The multiple regression analysis revealed that lake stability was more strongly related to average or maximum wind speed (Table 4), with moderate to strong negative correlations. In the deeper lakes, wind speed seemed to have the strongest relationship with S_T. By contrast, air temperature was either less important than, or replaced, wind speed as the parameter with the strongest relationship with lake stability in the shallower lakes. Rainfall was only significant in Lakes Palakpakin, Sampaloc, and Calibato.

Discussion

Mixing regimes in tropical lakes

Our 2-year monitoring of limnophysical processes in the 7 maar lakes demonstrated discrete and predictable

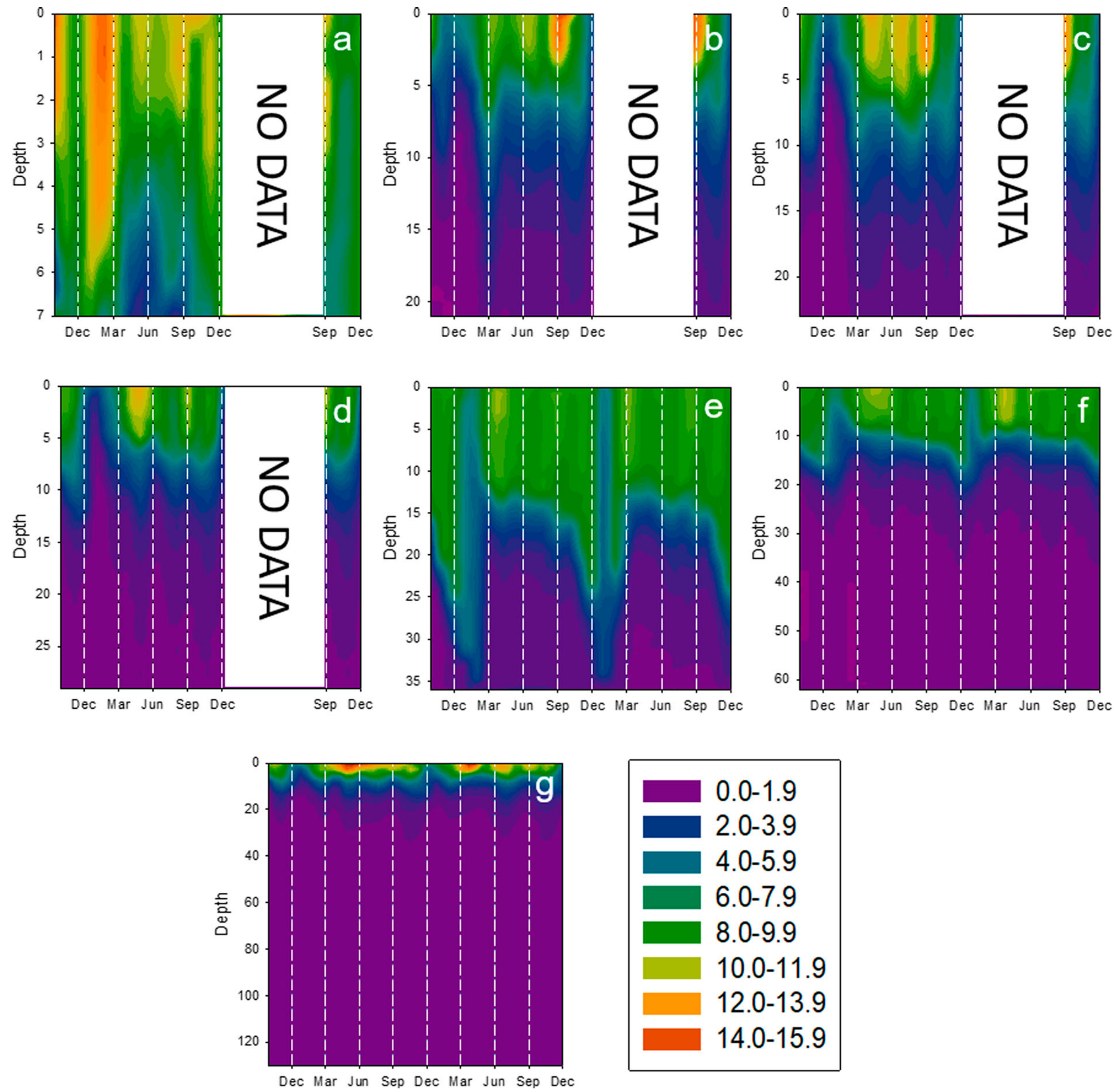

Figure 6. Monthly dissolved oxygen profiles (mg/L; see colored scale inset) of Lakes (a) Palakpakin, (b) Bunot, (c) Sampaloc, (d) Mohicap, (e) Yambo, (f) Pandin, and (g) Calibato (2017–2018).

seasonal patterns of thermal stratification and mixing under the influence of 2 types of monsoons. Because the seasonality of solar irradiance strongly controls the photoperiod and thermal cycle of lakes (Likens 2010), the monsoon-based mixing in the study lakes is reasonable.

Based on the criterion of North et al. (2013), Lakes Bunot, Sampaloc, Mohicap, and Yambo were likely fully mixed during the NEM (Fig. 3b–e, 4b–e), classifying the lakes as warm monomictic. Because the NEM coincides with hemispheric winter, convection via nocturnal heat loss during this period is immense, resulting in lakes with a negative heat budget. Moreover, DO concentrations in warm monomictic lakes are eventually replenished after the mixing period but could be depleted rapidly by a number of factors, including lower oxygen solubility and higher microbial activity (Lewis 1987, 2000).

By contrast, Lakes Pandin and Calibato remained incompletely mixed throughout the NEM (Fig. 3f–g, 4f–g). In these lakes, the mixolimnion (i.e., the upper portion) mixes akin to holomictic lakes while the monimolimnion, or deeper portion, never intermixes because of large differences in water density (Boehrer et al. 2017). As a result, in the deeper parts of the lakes the oxygen was never replenished, even after the mixing period. Based on S_T values, these 2 lakes were classified as meromictic, typical of deep tropical lakes (Katsev et al. 2017).

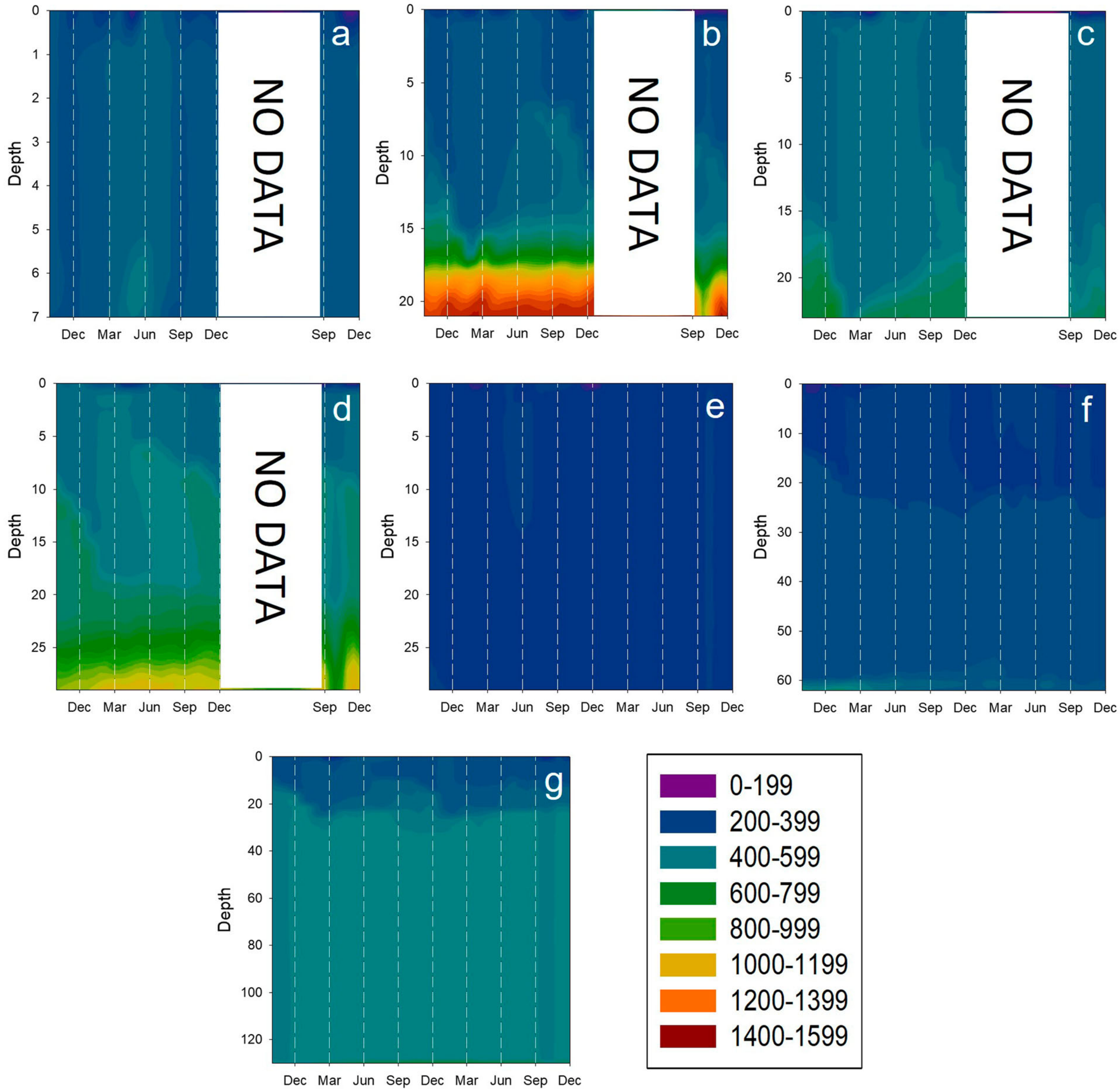

Figure 7. Monthly conductivity profiles (mS/cm; see colored scale inset) of Lakes (a) Palakpakin, (b) Bunot, (c) Sampaloc, (d) Mohicap, (e) Yambo, (f) Pandin, and (g) Calibato (2017–2018).

Because of their considerable depth, maximum S_T values were higher by 1–2 orders of magnitude compared to the other 5 lakes. Maar lakes are characteristically small and can be deep relative to their surface area. In terms of geomorphology, maar lakes are nearly perfectly circular with large volumes, allowing steeper bottom slopes (Wetzel 2001, Likens 2010). In a study of African crater lakes, Kling (1988) revealed a direct relationship between stability and maximum depth. Notably, the maximum S_T and depth values of Lakes Pandin and Calibato (1631 and 2781 J/m^2; 62 and 131 m, respectively) were comparable to those for Lakes Mbalang and Wum (1627 and 3068 J/m^2; 52 and 125 m). Lake Tanganyika, a tropical meromictic rift lake, has a maximum stability of 300 000 J/m^2. Due in part to its tremendous depth, its steep slope at the bottom depths is the main factor contributing to the immense stability of this lake (Verburg and Hecky 2009).

Given that the lake surface areas of the 7 study lakes are relatively similar, a boundary between monomixis and meromixis was delineated by a lake-depth range of 36–62 m. An exceptional case of seasonal mixing regimes was observed in the shallowest lake (Lake Palakpakin), which was classified as polymictic because the lake waters were mixed year round, as indicated by S_T values of <15 J/m^2 throughout the entire monitoring period (Fig. 5a). Additionally, Lake Palakpakin was well oxygenated throughout the sampling period. Such a

Table 3. Multiple regression analysis to test effects of meteorological factors on Schmidt stability index (S_T) through the whole monitoring period ($*p < 0.05$).

Palakpakin				Bunot				Sampaloc				Mohicap			
Predictor	β	t	VIF	Predictor	β	t	VIF	Predictor	β	t	VIF	Predictor	β	t	VIF
RF	0.21	0.838	1.268	RF	0.057	0.428	1.268	RF	0.068	0.448	1.268	RF	−0.023	−0.25	1.268
WS	0.371	1.289	1.666	WS	0.014	0.092	1.666	WS	0.031	0.177	1.666	WS	−0.136	−1.286	1.666
AT	0.529	1.995	1.412	AT	0.886*	6.253	1.412	AT	0.856*	5.336	1.412	AT	0.872*	8.966	1.412
Adj. R^2	0.055			Adj. R^2	0.73			Adj. R^2	0.654			Adj. R^2	0.873		
p	0.288			p	<0.001			p	<0.001			p	<0.001		

Yambo				Pandin				Calibato			
Predictor	β	t	VIF	Predictor	β	t	VIF	Predictor	β	t	VIF
RF	0.102	0.99	1.119	RF	0.292*	3.054	1.119	RF	0.37*	3.827	1.119
WS	−0.069	−0.562	1.578	WS	−0.147	−1.295	1.578	WS	−0.209	−1.82	1.578
AT	0.834*	7.156	1.444	AT	0.738*	6.776	1.444	AT	0.645*	5.863	1.444
Adj. R^2	0.755			Adj. R^2	0.787			Adj. R^2	0.782		
p	<0.001			p	<0.001			p	<0.001		

AT: air temperature; WS: wind speed; RF: rainfall; β: standardized coefficient, VIF: variance inflation factor.

Table 4. Multiple regression analysis to test effects of meteorological factors on Schmidt stability index (S_T) during southwest monsoon (SWM) ($*p < 0.05$).

Palakpakin				Bunot				Sampaloc				Mohicap			
Predictor	β	t	VIF	Predictor	β	t	VIF	Predictor	β	t	VIF	Predictor	β	t	VIF
MxRF14D	0.67*	2.55	1	MxWS30D	−0.71*	−4.824	1.02	AT30D	0.815*	5.465	1.003	AT30D	0.589*	4.38	1.382
				AT14D	0.497*	3.373	1.02	MxRF10D	0.475*	3.188	1.003	WS3D	−0.501*	−3.731	1.382
Adj. R^2	0.379			Adj. R^2	0.809			Adj. R^2	0.801			Adj. R^2	0.882		
p	0.34			p	0.008			p	0.001			p	<0.001		

Yambo				Pandin				Calibato			
Predictor	β	t	VIF	Predictor	β	t	VIF	Predictor	β	t	VIF
MxWS30D	−0.553*	−3.387	1.227	MxWS30D	−0.616*	−2.593	1	MxWS14D	−0.85*	−4.511	1.15
MxAT7D	0.492*	3.015	1.227					MxRF30D	0.561*	2.979	1.15
Adj. R^2	0.739			Adj. R^2	0.323			Adj. R^2	0.63		
p	<0.001			p	0.025			p	0.003		

AT: air temperature; WS: wind speed; RF: rain fall; β: standardized coefficient; Mx: maximum reading of parameter (AT/WS/RF) with reference to the number of days before monitoring; 30D, 14D, 10D, 7D, 5D, and 3D: mean values for days before monitoring, VIF: variance inflation factor.

mixing pattern can be attributed to its shallow depth (7 m).

Multiple regression analysis revealed that lake stability in the study lakes was most strongly related to air temperature (Table 3). Previous studies reported a direct effect of air temperature on seasonal variation in thermal stratification, and the stability thereof, in lakes (Robertson and Ragotzkie 1990, Coats et al. 2006, Adrian et al. 2009, Rimmer et al. 2011, Wang et al. 2019). Air temperature is likely a major factor influencing stability in the shallower lakes (Palakpakin, Bunot, Sampaloc, and Mohicap).

Despite weak correlations, the contribution of rainfall to the mixing dynamics of the deeper lakes was significant. In the tropics, deeper lakes are more likely to stratify during the wet season because of the movements of the Intertropical Convergence Zone (ITCZ). The increase in cloud cover and warmer air temperatures during this period can induce more persistent stratification in lakes (MacIntyre and Melack 2010, MacIntyre 2012). In lakes with small catchments and no significant sources of inflow, such as the 7 maar lakes in our study, mixing dynamics are controlled by either heat flux or the mechanical action of wind. Conversely, in lakes or reservoirs with considerable inflow from large tributaries or complex river systems, runoff from heavy precipitation can be significant (Ramón et al. 2013, Shenoy et al. 2021).

Unlike air temperature and rainfall, wind speed is not a significant empirical predictor of stability in the study lakes, primarily because of their relatively small size (<5 km^2) and sheltered topography. Consequently, energy inputs from wind generating surface currents are already limited compared to lakes with larger fetches (Fee et al. 1996). Although wind stress is as important as heat flux in circulation and turbulence, fetch is reduced in small lakes and resistance from the surrounding landscape is greater, thus diminishing the mixing potential of wind (Podsetchine and Schernewski 1999, Markfort et al. 2010, von Einem and Granéli 2010). Interestingly, when SWM was isolated in the model, the stability of Lakes Bunot, Yambo, Pandin, and Calibato exhibited a moderate to strong relationship to wind speed (Table 4). Furthermore, lake stability had a negative correlation with wind speed, suggesting that the greater stability of the lakes was likely a result of the lower wind speed prevailing during the SWM. Recent research has focused on the role of wind speed in lake stratification. For example, Magee and Wu (2017) observed that lake stratification was more strongly influenced by decreasing wind speeds than increasing air temperatures. Similarly, Weinke and Biddanda (2019) demonstrated persistent hypoxia due to the earlier onset of stratification stemming from periods with lower wind speeds.

Implications for adaptive lake management under climate change

Our monitoring survey demonstrated that hypoxia/anoxia developed broadly in the hypolimnion of the study lakes, except for Lake Palakpakin, during the SWM and partially or completely disappeared after mixing at the beginning of the NEM with decreasing air temperature. Vertical and seasonal variations in DO are the most critical environmental factors determining the distribution, abundance, and population viability of aquatic organisms in lake ecosystems (Stickney 2000, Ficke et al. 2007). Variation in DO is also considered a serious threat to fisheries and aquaculture because expansion or transport of hypoxic/anoxic waters often causes mass mortality (Stickney 2000, Diaz and Rosenberg 2008, Diaz and Breitburg 2009). Local anecdotes indicated that fish kills often followed a whitish upwelling with a rotting smell at the beginning of the NEM. This phenomenon can be explained by the upward advection of a hypoxic/anoxic water mass with a sulfurous odor due to mixing. Our monitoring data suggest that a higher risk of fish kills in these deeper monomictic and meromictic lakes is due to the hypoxic/anoxic upwellings.

In this study we scientifically confirmed when mixing events occurred, which can help communities better anticipate possible fish kill occurrences and minimize their impact by harvesting cage-cultured fishes before the height of overturn. In addition, a more proactive solution is reducing nutrient loading from aquaculture, which may help mitigate oxygen depletion in the hypolimnion. The local government has enacted regulations to reduce the fish cage area to a maximum of 10% of the lake surface (LLDA 2014). Although the rationale for the 10% value remains unclear, such fishery management is feasible and effective in monomictic oligotrophic lakes, in which the DO profiles can be orthograde (i.e., higher DO concentrations in deep cooler waters). By contrast, meromictic lakes are different because of a permanent and thick anoxic layer. In one of the deepest lakes, the meromictic Lake Pandin, the local lake community shifted its livelihood from aquaculture to ecotourism (i.e., toward sustainable development), with governmental support (Brillo 2017). Evidently, the classification of mixing regimes based on limnophysical monitoring is valuable for assessing the potential risks of aquaculture in tropical lakes.

Apart from sharing scientific knowledge with diverse societal stakeholders, long-term limnological monitoring can also provide novel insights into adaptive lake ecosystem management under climate change. Over recent decades, a warming trend has increasingly impacted lake ecosystems worldwide (Livingstone and Dokulil 2001, Livingstone 2003, Arhonditsis et al. 2004). Global warming reportedly lengthens thermal stratification in lakes across a wide range of climate zones (Hondzo and Stefan 1993, Elo et al. 1998, Trumpickas et al. 2009), eventually leading to hypolimnetic anoxia due to increased thermal stability and resistance to mixing (O'Reilly et al. 2003, Sahoo and Schladow 2008, Sahoo et al. 2010, Foley et al. 2012, Saulnier-Talbot et al. 2014). In our study area, some currently monomictic lakes will be more vulnerable to hypolimnetic anoxia, shifting the boundary upward (36–62 m depth) between monomixis and meromixis if the warming trend continues.

Climate change may also cause frequent and unpredictable hypoxic/anoxic upwellings during the SWM. Although our multiple regression analyses demonstrated that the lack of strong winds during the SWM has increased lake stratification, the cumulative impact of successive tropical cyclones (e.g., Jul 2017 and Aug 2018) may lower lake stability. Some climate scenarios predict that the frequency and intensity of typhoons will increase with the progression of global warming (Knutson et al. 2010, Jennings et al. 2012), and fisheries in tropical lakes may suffer from an increased incidence of unpredictable fish kills in the future, making adaptive ecosystem management more difficult. Limnophysical monitoring at a finer time resolution (i.e., on a daily or hourly scale) is needed to better understand the mechanisms controlling complex mixing regimes under physical disturbances in tropical lakes.

Conclusions

Our study provided key limnological insights into a cluster of 7 small crater lakes in the Philippines and is the first to monitor limnophysical processes in tropical lakes in Southeast Asia on a monthly scale over a period of almost 2 years. Seasonal mixing and stratification periods were observed during the NEM and SWM, respectively. Depending on depth, the lakes were classified into 3 types based on mixing regime: the shallowest lake was warm polymictic, 4 lakes of intermediate depth were warm monomictic, and the deepest 2 lakes were meromictic. Multiple regression analyses revealed air temperature to be the most significant empirical predictor of seasonal mixing dynamics in the study lakes throughout the study period. However, strong stratification of the lakes during the SWM was also found to be significantly related to the prevalence of low wind speeds. Our monitoring data provide valuable information for lake management and could help avoid fish kills due to the predictable seasonal occurrence of hypoxic/anoxic upwellings. Furthermore, our results could promote sustainable community development and better use of the ecosystem services offered by individual lakes. For adaptive ecosystem management under climate change, sustained monitoring at a finer time resolution is necessary to better understand the mixing mechanisms in tropical lakes. The measurement of additional meteorological variables (e.g., solar irradiance, evaporation rates, relative humidity) should also be considered to obtain a complete picture of the mixing dynamics of the lake.

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