Conceptual models of dissolved carbon fluxes *considering* interannual typhoon responses *under extreme climates* in a two-layer stratified lake: *interannual typhoon responses* *under extreme climates*

Hao-Chi Lin, Keisuke Nakayama, Jeng-Wei Tsai, and Chih-Yu Chiu

1 Department of Geography, National Taiwan University, Taipei City, Taiwan
2 Graduate School of Engineering, Kobe University, Kobe City, Japan
3 Graduate Institute of Bioresources, National Pingtung University of Science and Technology, Pingtung, Taiwan
4 Biodiversity Research Center, Academia Sinica, Taipei City, Taiwan

* Corresponding author: Keisuke Nakayama (nakayama@phoenix.kobe-u.ac.jp)
Abstract

Extreme climates affect the seasonal and interannual patterns of carbon (C) distribution in lentic ecosystems due to the regimes of river inflow and thermal stratification within lentic ecosystems. Typhoons rapidly load substantial amounts of terrestrial C into smaller subtropical lakes (i.e., Yuan-Yang Lake, YYL, Taiwan), renewing and mixing the water column. We developed a conceptual dissolved C model and hypothesized that allochthonous C loading and river inflow intrusion may affect the dissolved inorganic C (DIC) and dissolved organic C (DOC) distributions in a small subtropical lake under these extreme climates. A two-layer conceptual C model was developed to explore how the DIC and DOC fluxes respond to typhoon disturbances on seasonal and interannual time scales in YYL, while simultaneously considering autochthonous processes such as algal photosynthesis, remineralization, and vertical transformation. To compare the temporal patterns of fluxes between typhoon years (2015–2016) and non-typhoon years (2017–2018), monthly field samples were obtained and their DIC, DOC, and chlorophyll a concentrations measured. Monthly field samplings were conducted to measure the DIC, DOC, and chlorophyll a concentrations to compare the temporal patterns of fluxes between typhoon years (2015–2016) and non-typhoon years (2017–2018). The results demonstrated that net ecosystem production was 3.14 times higher in the typhoon years than in the non-typhoon years in YYL. These results suggested that loading of allochthonous C was the most crucial factor affecting the temporal variation of C fluxes in the typhoon years because of changes in the physical and biochemical processes, such as photosynthesis, mineralization, and vertical transportation. However, the lowered vertical transportation rate shaped the seasonal C in the non-typhoon years due to thermal stratification within this small subtropical lake.
1. Introduction

The Intergovernmental Panel for Environmental Changes Sixth Assessment Report (IPCC AR6) (2021) suggested that, by 2050, not only is air temperature going to increase by at least about 1.5°C but high-intensity storms and drought events will become more frequent as a result of global warming and climate change. In freshwater ecosystems, extreme climates may change the mixing regimes of freshwater columns (Kraemer et al., 2021; Maberly et al., 2020; Woolway et al., 2020), heat wave events (Woolway et al., 2021a; Woolway et al., 2021b), droughts (Marcé et al., 2019), and floods (Woolway et al., 2018). Freshwater ecosystems store around 0.32 to 1.8 Pg C yr⁻¹, which is approximately equivalent to shallow coastal areas. These freshwater ecosystems provide important services for human sustainability, such as acting as processing hotspots in regional carbon (C) cycling (Aufdenkampe et al., 2011; Cole et al., 2007; Engel et al., 2018; Lauerwald et al., 2015; Raymond et al., 2013). Extreme weather events might induce stronger seasonal thermal stratification from spring to summer and longer overturns from autumn to winter, thereby changing C distribution and transportation within water bodies (Kraemer et al., 2021; Olsson et al., 2022a; Woolway et al., 2020). The responses of C fluxes in small lakes (lake area < 1 km²) are sensitive to climate change due to the ease with which C mixes within water columns (Doubek et al., 2021; MacIntyre et al., 2021; Winslow et al., 2015). Moreover, storms induce dramatic changes in thermal stratification and water inflows (Lin et al., 2022; Olsson et al., 2022b; Vachon and Del Giorgio, 2014; Woolway et al., 2018). River inflows and wind turbulence released mix allochthonous C from sediments into the water column after storm events in small stratified lakes (Bartosiewicz et al., 2015; Czikowsky et al., 2018; Vachon and Del Giorgio, 2014). However, small lakes account for 25% to 35% of the total area of the earth's surface lakes (Cole et al., 2007; Downing et al., 2006; Raymond et al., 2013). Compared to the case in larger lakes, our understanding of C fluxes in small lakes remains uncertain because small lakes have usually been ignored in calculations of C fluxes on a global scale (Cole et al., 2007; Raymond et al., 2013). Thus, elucidation of the C fluxes in small lakes in extreme weather/climate conditions is key to optimizing estimations of global C fluxes in extreme climates.

Understanding the influences of physical, hydrological, and biogeochemical processes on the fate of C fluxes in smaller lake ecosystems is challenging work (Aufdenkampe et al., 2011; Cole et al., 2007; Raymond et al., 2013; Tranvik et al., 2009; Vachon et al., 2021; Woolway et al., 2018). This is not only because of difficulties in measurement but also because of the complexity of the interactions between factors and processes associated with C fluxes. Dissolved inorganic carbon (DIC) concentration is an important factor in estimating CO₂ fluxes within lake ecosystems (Smith, 1985). Among C fluxes in a freshwater body, the partial pressure of CO₂ (pCO₂), defined as CO₂ emission across
Typhoons might significantly impact the C distributions within the water columns in subtropical regions (Chiu et al., 2020; Lin et al., 2022). Kossin et al. (2013) investigated global storm events with an accumulated rainfall of about 50 mm, which accounts for approximately 10%–40% of precipitation in a subtropical typhoon event. Additionally, some studies have found not only that extreme rainstorms would impact the dissolved carbon in large lakes and catchments due to weathering (Sun et al., 2021; Zhou et al., 2023), but also that typhoon disturbances quickly mix, renew, or dilute the water in small subtropical lakes (Kimura et al., 2012; Kimura et al., 2017; Lin et al., 2022). However, the complex interactions between biogeochemical and physical regimes for autochthonous and allochthonous C introduce uncertainty in elucidating the complete patterns between typhoons and dissolved C. In subtropical freshwater ecosystems, DOC concentration is a vital factor in describing variances in mineralization and remineralization rates for dissolved C (Lin et al., 2022; Shih et al., 2019).
seasonal and interannual patterns of C fluxes during typhoon disturbances. River intrusion not only controls the C fluxes, algal biomass, and nutrient loading, but also influences the length of stratification and hydraulic retention times (Lin et al., 2021; Lin et al., 2022; Maranger et al., 2018; Nakayama et al., 2020; Olsson et al., 2022a; Olsson et al., 2022b; Zwart et al., 2017; Vachon and Del Giorgio, 2014). Therefore, we hypothesized that allochthonous C loading and river inflow intrusion might affect DIC and DOC distributions (Fig. 1). Further, autochthonous processes in small subtropical lakes, such as algal photosynthesis, remineralization, and vertical transportation, must also be considered (Fig. 1). Here, we tested our hypothesis developing two-layer conceptual C models to assess C flux responses to typhoon disturbances in small subtropical lakes.

2. Materials and methods

2.1 Study site

YYL is a shallow (mean water depth: 4.3 m) and oligotrophic (total phosphorus: 10-20 μg-P L⁻¹; total nitrogen: 20-60 μg-N L⁻¹) subtropical mountain lake (Chou et al., 2000; Tsai et al., 2008; Wu et al., 2001) on Chi-Lan Mountain at around 1,640 asl in north-central Taiwan (24.58° N, 121.40° E) (Fig. 2a). Its water is brown because of its humic acid content (colored dissolved organic matter: 20–50 ppb QSE; with specific ultraviolet absorbance at 254 nm assessed by a portable fluorometer (model C3; Turner Designs, Sunnyvale, CA, USA); mean pH: 5.4). YYL is surrounded by old-growth trees such as Chamaecyparis formosensis, Chamaecyparis obtusa var. formosana, and Rhododendron formosanum Heiml (Chou et al., 2000). Annual precipitation is over 3,000 mm yr⁻¹, and typhoon precipitation contributes up to half of the total precipitation in YYL (Chang et al., 2007; Lai et al., 2006). Due to the rapid renewal of the water body, the water retention time (or residence time) was around 4.4 days in typhoon Megi from 27 September to 1 October 2016 (Lin et al., 2022). The water surface temperature ranges from 15 to 25 °C during March to August, and the water column overturns in September (Kimura et al., 2012; Kimura et al., 2017; Lin et al., 2021) (Fig. 2a). The concentrations of DIC, DOC, dissolved O₂ (Lin et al., 2021), total nitrogen, total phosphorus, nutrients (Chiu et al., 2020; Tsai et al., 2008) and bacteria composition (Shade et al., 2011) increase within YYL from autumn to winter. YYL has been registered as a long-term ecological study site by the Ministry of Science and Technology (MOST) of Taiwan since 1992 and it became part of the Global Lake Ecological Observatory Network (GLEON) in 2004.

2.2 Water sampling and chemical analysis
We collected water quality samples (DOC, DIC, and Chl a) at water depths of 0.04, 0.50, 1.00, 2.00, and 3.50 m at the buoy site (Fig. 12). From January 2015 to December 2018, we measured the water surfaces for six river inflows and one outflow each month using a horizontal van Dorn bottle (2.20 L, acrylic). We also measured the water surfaces of six river inflows and an outflow monthly using a horizontal van Dorn bottle (2.20 L, acrylic) from January 2015 to December 2018 (Fig. 12). These samples were collected using a portable hand pump and glass microfiber filter papers (47 mm GF/F, nominal pore size 0.70 μm; Whatman, Maidstone, Kent, UK) to obtain filtrate samples. Water samples were stored at around 4°C in a refrigerator until analysis. Samples were analyzed using an infrared gas detector to detect DIC and DOC concentrations with persulfate digestion (model 1088 Rotary TOC autosampler;OI Analytical, College Station, TX, USA). The filter papers were kept refrigerated in opaque bottles at around -25°C in a refrigerator until the samples were analyzed using a portable fluorometer (model 10-AU-005-CE; Turner Designs, Sunnyvale, CA, USA) with specific wavelengths were 430 nm (blue) and 662 nm (red). In the laboratory, the filter papers were extracted with methanol to obtain Chl a concentration. These samples were analyzed for less than 72 h to prevent light and chemical degradation.

2.3 Data analysis and numerical modeling

Three water quality variables (DIC, DOC, and Chl a) were compared between different layers (upper and lower layers), years (typhoon years and non-typhoon years), and seasons (spring, summer, autumn, and winter). First, we separated our investigation data into typhoon years and non-typhoon years as described in Sect. 2.3.1. Next, we developed a conceptual equations model to generate continuous DIC and DOC data at the upper and lower layers as shown in Sect. 2.3.2. This helped us understand the transportation, photosynthesis, and remineralization rates between seasons and between typhoon and non-typhoon years (see Sect. 2.3.2).

2.3.1 Typhoon and non-typhoon years

We collected meteorological data from a meteorological tower located about 1.0 km from YYL (Lin et al., 2021; Lin et al., 2022). Data on rainfall (model N-68; Nippon Electric Instrument, Tokyo, Japan) and wind speed (model 03001, R.M. Young, Traverse City, MI, USA) were stored in a datalogger (model CR1000; Campbell Scientific, Logan, UT, USA) for every 10 min. River discharge (Q_{in}, m³ d⁻¹) was estimated every 10 min using the rainfall data and a water depth meter (model HOBO U20; Onset Computer, Bourne, MA, USA) at the end of a river inflow (Fig. 12) using the Manning formula. Transparency was estimated using Secchi disc data measured at local times (GMT+08:00) from 10:00 to 14:00.

As Table 1 shows, four strong typhoons were recorded, contributing a total of 2,254 mm
of precipitation in all 24 months of 2015 and 2016, this accounted for 35.6% of the annual precipitation. However, no typhoon rainfall was recorded at YYL in 2017 and 2018; the total precipitation in that 2-year period was around 2,537 mm. There was no significant difference in average water depth between 2017 and 2018 (Table 1). The average discharge was less than 774 m³ d⁻¹ in 2017 and 2018. Thus, we considered 2015 and 2016 as typhoon years, and 2017 and 2018 as non-typhoon years.

2.3.2 Conceptual two-layer DIC and DOC model

Nakayama et al. (2010) successfully developed a conceptual two-layer dissolved oxygen model based on strong wind turbulence at Tokyo Bay. Lin et al. (2021) pointed out that thermal stratification that inhibits vertical C flux between the upper and lower layers in shallow stratified lakes makes it possible to develop conceptual two-layer C models (Lin et al., 2022; Nakayama et al., 2022). The phytoplankton and remineralization effects on DIC and DOC fluxes (dDIC/dt and dDOC/dt, mg-C L⁻¹ d⁻¹) were considered in a conceptual two-layer equation model as shown in Equations 1–4. The fluxes in the upper layer (from the water surface to 2.5 m water depth) were calculated as follows:

\[
\frac{dDIC}{dt} = \frac{Q_0DIC - Q_{out}DIC_U - V_U\alpha_{PCLU}Chl_U + V_U\alpha_{ML}DOC_U + A_I\omega_U(DIC_L - DIC_U)}{C_U} + \frac{A_{BF}DIC}{C_U} + Pa_U
\]

\[
\frac{dDOC}{dt} = \frac{Q_0DOC - Q_{out}DOC_U - V_U\alpha_{PCLU}DOC_U + V_U\alpha_{ML}DOC_U + A_I\omega_U(DOC_L - DOC_U)}{C_U} + \frac{Q_LDOC}{C_U} + Pb_U
\]

Those in the lower layer (from 2.5 to 4.0 m water depth) were calculated as follows:

\[
\frac{dDIC}{dt} = \frac{Q_LDIC - V_L\alpha_{PCLU}Chl_U + V_L\alpha_{ML}DOC_U + A_I\omega_U(DIC_U - DIC_L)}{C_U} + \frac{A_{BF}DIC}{C_U} + Pa_L
\]

\[
\frac{dDOC}{dt} = \frac{Q_LDOC - V_L\alpha_{PCLU}DOC_U + A_I\omega_U(DOC_U - DOC_L)}{C_U} + \frac{Q_L}{C_U} + Pb_L
\]

\[
V_{total} = V_U + V_L
\]

\[
Q_{in} = Q_U + Q_L
\]
where, as shown in Table 2, total lake volume \((V_{\text{total}}, 53,544 \text{ m}^3)\) comprises parts to the upper layer \((V_U, 45,456 \text{ m}^3)\) and to the lower layer \((V_L, 8,808 \text{ m}^3)\) (Equation 5), and where the lake surface area \((A_U)\) is 36,000 m² and the bottom of the lake area \((A_B)\) is 3,520 m². The interface is 2.5 m vertically, and the interface area \((A_I)\) is 7,264 m² in YYL. The water depth is not only steady but also changes. However, the change in water depth varied ranged from 4.56 to 4.66 m steadily during the typhoon period (Chiu et al., 2020; Lin et al., 2022). Therefore, we can assume that the changes in lake volumes and areas were negligible. The coefficient \(C_U\) with a value of 1000, used to establish is a coefficient value (>1000) to establishing a standard unit for \(F_{\text{CO}_2}\) (mg-C m⁻² d⁻¹), considering the air–water \(\text{CO}_2\) exchange by Fick’s law as follows:

\[
F_{\text{CO}_2} = k_{\text{CO}_2} \cdot K_H (p_{\text{CO}_2 \text{water}} - p_{\text{CO}_2 \text{air}})
\]

(7)

where \(k_{\text{CO}_2}\) is the gas transfer velocity from empirical wind speed equations (Cole and Caraco, 1998; Jähne et al., 1987; Smith, 1985; Wanninkhof, 1992). \(K_H\) is Henry’s coefficient calculated by water temperature empirical equations (Plummer and Busenberg, 1982). \(p_{\text{CO}_2 \text{air}}\) (μatm) is the \(\text{CO}_2\) partial pressure in the atmosphere using air pressure data (Lin et al., 2021; Lin et al., 2022), and the atmospheric \(\text{CO}_2\) concentration is assumed to be 400 ppm. \(p_{\text{CO}_2 \text{water}}\) (μatm) is the \(\text{CO}_2\) partial pressure at the water surface around 0.04 m water depth from water quality data (temperature, pH, DIC concentration at the water surface. The empirical equation (Cai and Wang, 1998) was also followed by Lin et al. (2021). \(F_{\text{CO}_2}\) contributed approximately half of the net ecosystem production (NEP) across the water surface to the atmosphere in YYL (Lin et al., 2011). Further, because sediment carbon may be an important flux into shallow subtropical lakes, the sediment C flux \((BF_{\text{DIC}}, BF_{\text{DOC}}, \text{mg-C L}^{-1})\) in the lower layer was considered (Lin et al., 2022).

We assumed that the river discharge and outflow discharge \((Q_{\text{in}}, \text{m}^3 \text{ d}^{-1})\) are in a quasi–steady state \((Q_{\text{in}} = Q_{\text{out}}\)), dividing into upper discharge \((Q_U, \text{m}^3 \text{ d}^{-1})\) and lower discharge \((Q_L, \text{m}^3 \text{ d}^{-1})\) (Equation 6). Lin et al. (2021) showed that the buoyancy frequencies in YYL were 0.011 ± 0.004 s⁻¹, 0.013 ± 0.004 s⁻¹, 0.006 ± 0.003 s⁻¹, and 0.007 ± 0.004 s⁻¹ from spring (March–May), summer (June–August), autumn (September–November), and winter (December–February), respectively, inhibiting the vertical profile of DIC mixed due to stratification. We estimated the percentages of \(Q_U\) and \(Q_L\) based on the buoyancy frequency following Lin et al. (2020 and 2022). \(Q_U\) values were 75%, 80%, 45%, and 50% of \(Q_{\text{in}}\) for spring to winter, and \(Q_L\) values were 25%, 20%, 55%, and 50% of \(Q_{\text{in}}\). The physical and biogeochemical regimes under climate change remain uncertain, such as biological compositions, mixing regimes, morphometric characteristics, and air–water energy fluxes (evaporation and transpiration) (Woolway et al., 2020). To simulate extreme climate scenarios, we shifted the ratio of \(Q_{\text{in}}\) for each season and tested the river intrusion hypothesis (Fig. 1). We established two extreme conditions: Level 1 and Level 2. Level 2 is the more extreme condition:
chlorophyll = \alpha - O_b \sum_s S_{\text{sim}}(\alpha - NSE)\sum_t\frac{1}{\alpha - M_U}(\alpha - P_A)\sum_{i=1}^{n}(\alpha - P_B)

The contributions of photosynthesis production depended on the chlorophyll a concentration (Chl_a, mg L^{-1}) and on the absorption coefficients in the upper layer (\alpha_{PU}, d^{-1}) and lower layer (\alpha_{PL}, d^{-1}). The coefficients of DOC remineralization rates in the upper layer (\alpha_{MU}, d^{-1}) and lower layer (\alpha_{ML}, d^{-1}) were also considered in the conceptual models. The \alpha_{PU}, \alpha_{MU}, \alpha_{PL}, \alpha_{ML}, w_i, BF_{DIC}, BF_{DOC}, P_A, P_B, Pa_L, Pb_U, and Pb_L were used multiple linear regression analysis. Further, these unknown values were tested by trial and error to obtain the parameters of the best-fit condition (Nakayama et al., 2022). Dividing the seasonal and nonseasonal serranoids to learn the seasonal differences. The same parameters of the best-fit condition were used to obtain the extreme conditions for Level 1 and Level 2. We used the coefficient of determination (R^2) and the Nash–Sutcliffe model efficiency coefficient (NSE) (Nash and Sutcliffe, 1970) to quantify the performance of the equation model with DIC and DOC sampling data (observation data) for each simulation as follows.

\[
NSE = 1 - \frac{\sum_{i=1}^{n}(Obs_i - Sim_i)^2}{\sum_{i=1}^{n}(Obs_i - \bar{Obs})^2}
\]  \hspace{1cm} (8)

where Obs is observation data of DIC and DOC concentrations, and Sim is best-fit data for conceptual model.

\subsection{DIC and DOC fluxes}

Net ecosystem production was defined as the difference between primary production and ecological respiration (NEP = GPP - ER) due to photosynthesis and respiration via biota (Dodds and Whiles, 2020). Given that we assumed that the C fluxes were dependent on the river inflows in YYL (Fig. 12), we estimated the NEP by end-member analysis using the C concentration of the river inflow and outflow (Lin et al., 2021; Nakayama et al., 2020) by following Equations 28–Equation 121. The upper layer NEP of DIC flux (mg C d\(^{-1}\)) was obtained from Equation 1 as follows:

\[ Q_U \text{ is 80}\% \text{ (spring), 85}\% \text{ (summer), 50}\% \text{ (autumn), and 50}\% \text{ (winter) of } Q_{in}; \ Q_L \text{ is 20}\% \text{ (spring), 15}\% \text{ (summer), 50}\% \text{ (autumn), and 50}\% \text{ (winter) of } Q_{in}. \text{ Level 1 is the condition between the present and the Level 2 condition: } Q_U \text{ is 77}\% \text{ (spring), 82}\% \text{ (summer), 47}\% \text{ (autumn), and 50}\% \text{ (winter) of } Q_{in}; \ Q_L \text{ is 23}\% \text{ (spring), 18}\% \text{ (summer), 53}\% \text{ (autumn), and 50}\% \text{ (winter) of } Q_{in}. \text{(Table 2).} \]
The upper layer flux of DOC flux (mg C m$^{-3}$ d$^{-1}$) was estimated from Equation 2:

$$\text{Upper flux}_{\text{DOC}} = C_U \alpha_M \text{DOC}_U - C_U \frac{A_I \text{DOC}_L - \text{DOC}_U}{V_U} - C_U \frac{P b_U}{V_U}$$

$$= C_U \frac{Q_U \text{DOC}_R + Q_L \text{DOC}_L - Q_{\text{out}} \text{DOC}_U}{V_U}$$

$$= C_U \frac{1}{\tau_{U}} \left( \frac{Q_U}{Q_{\text{in}}} \text{DOC}_R + \frac{Q_L}{Q_{\text{in}}} \text{DOC}_L - \text{DOC}_U \right)$$

$$\tau_{U} = \frac{V_U}{Q_{\text{in}}}$$

263 The upper layer flux of DIC flux (mg C m$^{-3}$ d$^{-1}$) was estimated from Equation 2:

$$\text{Upper flux}_{\text{DIC}} = C_U \alpha_M \text{DIC}_U - C_U \frac{A_I \text{DIC}_L - \text{DIC}_U}{V_U} - C_U \frac{P b_U}{V_U}$$

$$= C_U \frac{Q_U \text{DIC}_R + Q_L \text{DIC}_L - Q_{\text{out}} \text{DIC}_U}{V_U}$$

$$= C_U \frac{1}{\tau_{U}} \left( \frac{Q_U}{Q_{\text{in}}} \text{DIC}_R + \frac{Q_L}{Q_{\text{in}}} \text{DIC}_L - \text{DIC}_U \right)$$

264 The lower layer flux of DIC flux (mg C m$^{-3}$ d$^{-1}$) was estimated from Equation 3:

$$\text{Lower flux}_{\text{DIC}} = C_U \alpha_M \text{DIC}_L - C_U \frac{A_I \text{DIC}_U - \text{DIC}_L}{V_L} - A_B R_F_{\text{DIC}}$$

$$= C_U \frac{P b_L}{V_L} = C_U \frac{Q_U \text{DIC}_R - \text{DIC}_L}{V_L} = C_U \frac{1}{\tau_{L}} \frac{Q_L}{Q_{\text{in}}} (\text{DIC}_R - \text{DIC}_L)$$

$$\tau_{L} = \frac{V_L}{Q_{\text{in}}}$$

265 The lower layer flux of DOC flux (mg C m$^{-3}$ d$^{-1}$) was estimated from Equation 4:

$$\text{Lower flux}_{\text{DOC}} = C_U \alpha_M \text{DOC}_L - C_U \frac{A_I \text{DOC}_U - \text{DOC}_L}{V_L} - A_B R_F_{\text{DOC}}$$

$$= C_U \frac{P b_L}{V_L} = C_U \frac{Q_U \text{DOC}_R - \text{DOC}_L}{V_L} = C_U \frac{1}{\tau_{L}} \frac{Q_L}{Q_{\text{in}}} (\text{DOC}_R - \text{DOC}_L)$$

266 Thus, the total flux of DIC and that of DOC are:

$$\text{Flux}_{\text{DIC}} = \frac{V_U \text{Upper flux}_{\text{DIC}} + V_L \text{Lower flux}_{\text{DIC}}}{V_{\text{total}}}$$

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\[ \text{Flux}_{\text{DOC}} = \frac{V_U \text{Upper flux}_{\text{DOC}} + V_L \text{Lower flux}_{\text{DOC}}}{V_{\text{total}}} \]  

(144)

where, \( F_C \) is \( \frac{A_F}{V_U} F_{CO_2} \) and \( t_{ru}, t_{rl} \) are residence times (\( d \)) in the upper and lower layers, respectively. These parameters were used for the best-fit condition as shown in Table 2.
3. Results

3.1 DIC, DOC, and Chl a concentrations in the typhoon and non-typhoon years

The results of the comparisons between the two periods of typhoon years (2015 and 2016) revealed demonstrated that there were no significant differences in DIC, DOC, and Chl a concentrations between the upper and lower layers in the typhoon years 2015 and 2016, however, all these parameters differed significantly between the layers in the non-typhoon years 2017 and 2018 (Fig. 23). This is because of the typhoon-induced mixing and lower strength of thermal stratification between upper and lower layers (Lin et al., 2021; Lin et al., 2022). Overall, the average DIC \(_2\) was 2.06 mg-C L\(^{-1}\), and DIC \(_1\) was 3.66 mg-C L\(^{-1}\); the average DOC \(_2\) was 5.87 mg-C L\(^{-1}\), and DOC \(_1\) was 8.02 mg-C L\(^{-1}\); and Chl \(_2\) and Chl \(_1\) were 2.13 μg-C L\(^{-1}\) and 18.5 μg-C L\(^{-1}\), respectively. In typhoon years, the average DIC \(_2\) was 2.46 mg-C L\(^{-1}\), and DIC \(_1\) was 3.66 mg-C L\(^{-1}\); the average DOC \(_2\) was 6.10 mg-C L\(^{-1}\), and DOC \(_1\) was 8.38 mg-C L\(^{-1}\); and the Chl \(_2\) and Chl \(_1\) were 2.38 μg-C L\(^{-1}\), respectively (Fig. 23). In non-typhoon years, the average DIC \(_2\) was 1.81 mg-C L\(^{-1}\); and DIC \(_1\) was 3.28 mg-C L\(^{-1}\); the average DOC \(_2\) was 5.66 mg-C L\(^{-1}\); and DOC \(_1\) was 7.67 mg-C L\(^{-1}\); and Chl \(_2\) and Chl \(_1\) were 1.89 μg-C L\(^{-1}\) and 24.4 μg-C L\(^{-1}\), respectively (Fig. 2).

ANOVA results indicated no significant differences in DIC concentrations among seasons during the typhoon years (p-values > 0.05), suggesting a lack of statistically significant variation in DIC data across seasons. However, the ANOVA test Results of ANOVA showed that there were no significant differences between seasons in DIC, DOC, and Chl a concentrations (p-values > 0.05) that show no significant differences in DIC data among seasons in the typhoon years (Fig. 24a-d). However, the DOC concentration showed significant differences between seasons in the typhoon years (Fig. 24c-d). No significant differences between Chl \(_2\) and Chl \(_1\) were observed among the seasons (Fig. 24e-f), whereas the standard deviations (SD) of DIC and DOC were higher in summer and autumn (Fig. 24) due to terrestrial C loading (Chiu et al., 2020). In summer, the SD values of DIC \(_2\) and DOC \(_2\) were 3.51 mg-C L\(^{-1}\) and 3.69 mg-C L\(^{-1}\), respectively (Fig. 24a, c, e). In autumn, DIC \(_2\) and DOC \(_2\) had the highest SD (4.06 and 4.17 mg-C L\(^{-1}\), respectively) (Fig. 24b, d). Notably, the maximum values of DIC \(_2\) and DOC \(_2\) were 7.06 and 15.6 mg-C L\(^{-1}\) and those of DIC \(_1\) and DOC \(_1\) were 10.9 and 19.8 mg-C L\(^{-1}\), respectively, in the typhoon years (Fig. 24a-d).

Positive Pearson correlations of 0.45 to 0.80 were observed between the DIC and DOC in the typhoon years (Fig. 45a). In the non-typhoon years, the upper layer DIC \(_2\) was the only variable correlated negatively correlated with DOC in the upper and lower layers (Fig. 45b). The DIC in the lower layer was positively correlated with the Chl \(_2\) (Fig. 45) due to the abundant respiration in the lower layer (Lin et al., 2021; Tsai et al., 2008) (Fig. 5).
3.2 Performance of conceptual two-layer DIC and DOC models

The results for the typhoon years demonstrated that most of the seasonal scenarios were better fitting than the nonseasonal scenarios (Fig. 6). Under the seasonal scenarios, the DIC was around 1.5 to 5.0 mg-C L⁻¹ (Fig. 5a–b) and DIC₁ was around 5.0 mg-C L⁻¹. However, the NSE of DIC₂ was 0.73 under the nonseasonal scenarios, which was higher than seasonal scenarios (NSE = 0.71) (Table 3), because DIC₂ was elevated dramatically, by 40 mg-C L⁻¹, under the nonseasonal scenarios during the 2016 typhoon period (Fig. 6d). In the non-typhoon years (2017–2018), the best-fit values of DIC₁ and DIC₂ did not differ significantly between the seasonal and nonseasonal scenarios (R² and NSE were around 0.40 and 0.70 for R² and NSE, respectively). These results demonstrated that DIC₁ and DIC₂ in the typhoon years must use the seasonal scenarios, whereas in the non-typhoon years they should use the nonseasonal scenarios. On the other hand, the DOC under the seasonal scenarios fit our observation data (R² values were 0.91, and 0.46, and the NSE coefficients from inas equation (8) were 0.95 and 0.73 for DOC₁ and DOC₂, respectively) (Fig. 5c–h, Table 3). Thus, the results suggested that the DOC₁ and DOC₂ must use the seasonal scenarios in both the typhoon and non-typhoon years.

As shown in Table 3, the parameters for the conceptual two-layer DIC and DOC models showed different regimes between the typhoon and non-typhoon years (Table 3). In the typhoon years, the photosynthesis absorption rates coefficients (α₃L, α₃L) were negative (photosynthesis < respiration) for each season. YYL was a C source due to a large allochthonous C loading during typhoons; the respiration was elevated by around 30- to 150-fold from summer to autumn. However, the parameter values of the transportation coefficients (wT) were higher in autumn than in the other seasons (Table 3). As a result, the higher remineralization rates during typhoon disturbances from summer to autumn resulted in positive α₅L and α₅L. In the non-typhoon years, the remineralization rates were negative (Table 3). Thus, the results suggest that the conceptual two-layer C models may reasonably fit the observation data.
3.3 Interannual and seasonal NEP in YYL

The typhoon disturbances in summer and autumn played an important role in promoting the C released by YYL (Table 4). Overall, YYL released 245 mg C m\(^{-2}\) d\(^{-1}\) of DIC and 415 mg C m\(^{-3}\) d\(^{-1}\) of DOC during the typhoon years; during the non-typhoon years, it released 51.7 mg C m\(^{-3}\) d\(^{-1}\) of DIC and 22.8 mg C m\(^{-3}\) d\(^{-1}\) of DOC (Table 4). The average \(F_C\) was one to two times larger than \(\text{Flux}_{\text{DIC}}\), and 219 and 133 mg C m\(^{-3}\) d\(^{-1}\) were released from YYL into the atmosphere in the typhoon and non-typhoon years, respectively (Table 4). In summer, the upper layer exhibited declines in both DIC and DOC concentrations, with the decline in DIC being approximately 3.7 times more DIC in the typhoon years than in the non-typhoon years (Table 4). In autumn in the typhoon years, 216 mg C d\(^{-1}\) of upper layer DIC was released, but 46.1 mg C m\(^{-3}\) d\(^{-1}\) of upper layer DOC was produced. In autumn, 216 mg C d\(^{-1}\) of upper layer DIC was released; however, 46.1 mg C m\(^{-3}\) d\(^{-1}\) of upper layer DOC was produced in the typhoon years. The upper layer \(\text{Flux}_{\text{DOC}}\) was negative in the autumn of the typhoon years, when 268 mg C m\(^{-3}\) d\(^{-1}\) more \(F_C\) was released compared to autumn in the non-typhoon years. In addition, the lower layer exhibited the largest release of DIC in the outflow in the typhoon years; however, the fluxes in the lower layer were more than twice as high in the summer as in the autumn of those typhoon years (Table 4). The average total \(\text{Flux}_{\text{DOC}}\) exhibited a release of approximately 3.14 times more C in the typhoon years than in the non-typhoon years. The average total \(\text{Flux}_{\text{DIC}}\) was 3.14 times more released C in the typhoon than in the non-typhoon years. The average total \(\text{NEP}_{\text{DOC}}\) showed an increase of 62.3 mg C m\(^{-3}\) d\(^{-1}\) of DOC between the typhoon years and non-typhoon years due to the over 10-folden times higher flux in the upper layer (Table 4).

The ratios of DIC and DOC concentrations reveal the magnitudes of allochthonous DOC loading into YYL (Shih et al., 2019), and the upper and lower layers show different patterns. In the typhoon years, the upper layer ratios decreased (higher DOC loading) from summer to autumn, whereas in the lower layer, the DIC:DOC decreased from autumn to winter. In the non-typhoon years, the autumn DIC:DOC ratio was the lowest, around 0.216 to 0.351 (Table 4).
3.4 Interannual responses of DIC and DOC to typhoons

We simulated the responses of DIC and DOC flux to typhoons using conceptual two-layer C models. The results showed that the DIC was more sensitive to typhoon disturbances than DOC under the scenarios of Level 1 and Level 2 (Fig. 6-8). Overall, the C level declined in the upper layers but increased in the lower layers (Fig. 6). DIC and DOC in the upper layer tended to decline from 1.0 (Level 1) to 2.0 mg-C L⁻¹ (Level 2) (Fig. 7a, c); however, they increased to 10.0 and 20.0 mg-C L⁻¹ in the lower layer under Level 1 and Level 2, respectively (Fig. 6b, d).

The DIC concentration in the upper layer was significantly lower in the typhoon years than in the non-typhoon years during spring and autumn under Level 2 (Fig. 7a-c). Under the best-fit and Level 1 conditions, the DIC concentrations decreased significantly from winter to spring (Fig. 7c-d). The lower layer DIC values under the best-fit and Level 1 conditions differed significantly between the typhoon and non-typhoon years (Fig. 7c-h). The DIC of the lower layer under Level 2 differed significantly from winter to spring only (Fig. 7e, h).

Especially, the highest average of lower layer DIC in the lower layer values was 10 mg-C L⁻¹ under the Level 2 in spring in non-typhoon years (Fig 7e).

However, the upper layer DOC showed significant typhoon responses for each condition from winter to spring (Fig. 8a, d). The DOC of the upper layer tended to differ more significantly under the extreme climates from summer to autumn (Fig. 8b-c). The DOC of the lower layer showed different typhoon responses between the spring and the other seasons (Fig. 8c-h), and the lower layer DOC values in the lower layer under Level 2 conditions in spring showed no significant difference between the typhoon and non-typhoon years (Fig 8e).
4. Discussion

4.1 Biochemical and physical differences of DIC and DOC fluxes between typhoon and non-typhoon years in YYL

Annual total precipitation was 40% higher in the typhoon years than in the non-typhoon years (Table 1). Water retention and typhoon-induced upwelling control the dynamics of DIC and DOC during the summer and autumn (Chiu et al., 2020; Jones et al., 2009; Tsai et al., 2008; Tsai et al., 2011). The absence of typhoon-induced upwelling affected water quality data differently between the upper and lower layers (Chiu et al., 2020; Lin et al., 2022; Tsai et al., 2008; Tsai et al., 2011). During the non-typhoon period in YYL, for example, an anoxic condition at the hypolimnion may affect the efficiency of C mineralization and remineralization rates in non-typhoon years (Carey et al., 2022; Chiu et al., 2020; Lin et al., 2022; Shade et al., 2010; Shade et al., 2011). Therefore, these physical and biogeochemical processes might describe different patterns between the upper and lower layers, as revealed by the Pearson correlations (Fig. 45).

Thermal stratification and allochthonous C loading may drive the responses of fluxes to typhoons in YYL. The absolute values of fluxes were higher in the typhoon years than in the non-typhoon years (Table 4). We found that precipitation from typhoons loaded large amounts of allochthonous C into YYL during summer and autumn, which might explain the higher fluxes in autumn compared to the other seasons (Table 4). Typhoons dramatically changed the seasonal and interannual patterns of DIC fluxes due to river intrusion (Fig. 6a–b; Fig. 24), which correspond to our hypothesis (Fig. 1) and corresponds to the results of previous studies (Chiu et al., 2020; Lin et al., 2021; Lin et al., 2022). In summer, the spatial differences between layers in DIC and DOC between layers were inhibited due to strong thermal stratification, describing the positive upper net primary production and lower negative net primary production (Lin et al., 2021). The thermal stratification and anoxic condition may have been controlled by the seasonal and interannual patterns of DIC and DOC fluxes in the non-typhoon years (Tables 3–4; Fig. 56).

Additionally, because of the absence of typhoon-induced mixing and allochthonous C loading, the absolute values of total fluxes were lower in the non-typhoon years than those in the non-typhoon years (Table 4). In the typhoon years, our results showed that the typhoon-induced fluxes upwelling and loading increased by facilitated 102.2 mg DIC m⁻³ d⁻¹ and 62.3 mg DOC m⁻³ d⁻¹ in YYL (Table 4). Additionally, the CO₂ emission (fC) was 43 % higher (~83 mg C m⁻³ d⁻¹) in the typhoon years than in the non-typhoon years.
4.2  Model limitation under the extreme weather scenarios

Water temperature might be a crucial driver in controlling C fluxes in YYL (Chiu et al., 2020; Lin et al., 2021; Lin et al., 2022). We found that the fluxes and $F_{\text{CO}_2}$ in summer were usually higher than in winter (Tables 3–4) due to the higher levels of photosynthesis, remineralization, and strength of thermal stratification (Lin et al., 2021; Lin et al., 2022). With the conceptual two-layer C models (Table 3), photosynthesis absorption ($\alpha_{\text{PL}}$), remineralization ($\alpha_{\text{MU}}, \alpha_{\text{ML}}$), and transportation ($w_t$) well represented the seasonal variations in DIC and DOC data. These parameters of the conceptual two-layer C models appeared in reasonable patterns (Table 3). The higher remineralization and photosynthesis rates resulted in higher absolute values of fluxes in the autumn of the typhoon years (Tables 3–4). In the non-typhoon years, the photosynthesis rates contributed to the total fluxes (Tables 3–4). Moreover, without the typhoon-induced mixing and refreshing of the water column, anoxic conditions may occur (Carey et al., 2022; Vachon et al., 2021), which could result in negative remineralization rates in non-typhoon years. Thus, the conceptual two-layer C models well characterizes the seasonal and interannual responses of DIC and DOC fluxes to typhoons in YYL.

Under extreme weather conditions, Level 2 usually shifted to different typhoon responses for each season (Fig. 7A–D) due to extreme river intrusions. DIC changes more significantly than DOC under Level 1 and Level 2 (Fig. 6C–D), because the photosynthesis, transportation, and remineralization rates may crucially affect the seasonal and interannual patterns of DOC as well (Fig. 1). Moreover, we compared the fluxes with different model conditions as shown in Fig. 9A–D, demonstrating that the responses of $\text{Flux}_{\text{DIC}}$ to typhoons differed dramatically between Level 1 and Level 2 (Fig. 9A–C), especially, the Upper $\text{Flux}_{\text{DIC}}$ released more C in the typhoon years and absorbed more C in the non-typhoon years than Obs.
Not only were the absolute values of FluxDIC over 3 times higher in the typhoon years (Table 4), but SD was higher in the typhoon years as well (Fig. 9). Additionally, the \( F_C \) was 43% higher (~83 mg C m\(^{-3}\) d\(^{-1}\)) in typhoon years than in non-typhoon years (Table 4). Therefore, the typhoon disturbances control DIC loading and C emissions in YYL, which is consistent with our previous studies (Chiu et al., 2020; Lin et al., 2021; Lin et al., 2022).

However, DOC fluxes changed less under Level 1 and Level 2 (Fig. 9d–f), a finding that is consistent with our continuous DOC data (Fig. 7e–d). Processes such as respiration, mineralization, and sediment burial may impact DOC fluxes (Bartosiewicz et al., 2015; Hanson et al., 2015; Maranger et al., 2018). To our knowledge, photo-chemical mineralization and degradation may play a key role in shaping C fluxes because colored DOC reduces ultraviolet radiation (UVR) and active photosynthetic radiation (PAR) (Allesson et al., 2021; Chiu et al., 2020; Schindler et al., 1996; Scully et al., 1996; Williamson et al., 1999). Ejarque et al. (2021) also successfully developed a conceptual one-layer model of DOC and DIC, considering bacterial respiration, photo-mineralization and degradation in a temperate mountain lake. In addition, Nagatomo et al. (2023) suggested that the DIC might be underestimated if submerged vegetation is ignored. Thus, we suggest that photo-biochemical processes (such as photo-mineralization) and submerged vegetation should be considered in the upper layer to clarify and validate the responses of the total C fluxes under extreme climates in a two-layer stratified lake.
We successfully developed two-layer conceptual C models to obtain continuous DIC and DOC data in YYL and to simulate extreme conditions. Our conceptual two-layer C model revealed that allochthonous and autochthonous processes both accounted for C flux responses to typhoon disturbances on seasonal and interannual scales by applying our proposed two-layer conceptual C model. Without typhoons, the strength of thermal stratification was the primary driver of determinants the seasonal and interannual patterns of factor that drive DIC and DOC concentrations data's seasonal and interannual patterns of DIC and DOC. In typhoon years, our results were shown the typhoon-induced fluxes upwelling and loading facilitated 102.2 mg DIC m\(^{-3}\) d\(^{-1}\) and 62.3 mg DOC m\(^{-3}\) d\(^{-1}\) flux in YYL, respectively (Table 4). We successfully developed two-layer conceptual C models to obtain continuous DIC and DOC data in YYL and to simulate extreme conditions. In the typhoon years, the changes in seasonal river intrusion regimes in YYL resulted in a 3-fold higher total FluxDIC in the typhoon years than in the non-typhoon years. However, our model should be improved for application to under extreme climate scenarios by considering other autochthonous processes, such as sediment burial, photosynthetic and respiration), in a subtropical small lake account for the C flux responses to typhoons on seasonal and interannual time scales.

Commented [A79]: # Report 2
Typhoon disturbances or seasons?

Commented [A80R79]: Typhoon disturbances. We have clarified the sentence. Thank you.

Commented [A81]: # Report 2
Rephrase sentence:” Without typhoons, the strength of thermal stratification was the primary determinants (determinant of) the seasonal and interannual patterns of DIC and DOC concentration. Typhoon-induced upwelling and loading facilitated 102.2 mg-DIC m-3 d-1 and 62.3 mg-DOC m-3 d-1 flux in YYL, respectively.”

Commented [A82R81]: We have rephrased the sentences. Thanks for your suggestion (lines 435 to 438).
Competing interests

The authors have no conflicts of interest to report.

Acknowledgements

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Data availability

The data that support the findings of this study are adopted from our previous works, including Chiu et al. (2020), Lin et al. (2021), and Lin et al. (2022).
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Table 1. Comparison of Yuan-Yang Lake’s rainfall and hydrological records in typhoon and non-typhoon years.

<table>
<thead>
<tr>
<th>Records</th>
<th>Typhoon years</th>
<th>Non-typhoon years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time period (year)</td>
<td>2015-2016</td>
<td>2017-2018</td>
</tr>
<tr>
<td>Total precipitation (mm)</td>
<td>6,332</td>
<td>3,795</td>
</tr>
<tr>
<td>Total typhoon rainfall (mm)</td>
<td>2,254</td>
<td>0</td>
</tr>
<tr>
<td>Average water depth (m ± SD)</td>
<td>4.54 ± 1.7</td>
<td>4.51 ± 1.5</td>
</tr>
<tr>
<td>Average river discharge (m$^3$ d$^{-1}$)</td>
<td>3,717</td>
<td>2,943</td>
</tr>
<tr>
<td>Transparency (Secchi disc depth, m ± SD)</td>
<td>1.58 ± 0.45</td>
<td>1.38 ± 0.28</td>
</tr>
</tbody>
</table>
Table 2. Parameters of the two-layer conceptual model in Yuan-Yang Lake

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Q</em>&lt;sub&gt;out&lt;/sub&gt;</td>
<td>Outflow discharge</td>
<td>Daily data</td>
</tr>
<tr>
<td><em>Q</em>&lt;sub&gt;in&lt;/sub&gt;</td>
<td>Inflow discharge</td>
<td>Daily data</td>
</tr>
<tr>
<td><em>Q</em>&lt;sub&gt;U&lt;/sub&gt;</td>
<td>Upper layer discharge</td>
<td>Daily data</td>
</tr>
<tr>
<td><em>Q</em>&lt;sub&gt;L&lt;/sub&gt;</td>
<td>Lower layer discharge</td>
<td>Daily data</td>
</tr>
<tr>
<td>DIC&lt;sub&gt;R&lt;/sub&gt;</td>
<td>River inflow DIC</td>
<td>Monthly data</td>
</tr>
<tr>
<td>DIC&lt;sub&gt;U&lt;/sub&gt;</td>
<td>Upper layer DIC</td>
<td>Monthly data</td>
</tr>
<tr>
<td>DIC&lt;sub&gt;L&lt;/sub&gt;</td>
<td>Lower layer DIC</td>
<td>Monthly data</td>
</tr>
<tr>
<td>Chl&lt;sub&gt;U&lt;/sub&gt;</td>
<td>Upper layer Chl a</td>
<td>Monthly data</td>
</tr>
<tr>
<td>Chl&lt;sub&gt;L&lt;/sub&gt;</td>
<td>Lower layer Chl a</td>
<td>Monthly data</td>
</tr>
<tr>
<td>DOC&lt;sub&gt;U&lt;/sub&gt;</td>
<td>Upper layer DOC</td>
<td>Monthly data</td>
</tr>
<tr>
<td>DOC&lt;sub&gt;L&lt;/sub&gt;</td>
<td>Lower layer DOC</td>
<td>Monthly data</td>
</tr>
<tr>
<td><em>F</em>&lt;sub&gt;CO2&lt;/sub&gt;</td>
<td>Carbon emission (equation 7)</td>
<td>Monthly data</td>
</tr>
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**Constants**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td><em>V</em>&lt;sub&gt;total&lt;/sub&gt;</td>
<td>Total lake volume</td>
<td>53,544</td>
</tr>
<tr>
<td><em>V</em>&lt;sub&gt;U&lt;/sub&gt;</td>
<td>Upper layer volume</td>
<td>45,456</td>
</tr>
<tr>
<td><em>V</em>&lt;sub&gt;L&lt;/sub&gt;</td>
<td>Lower layer volume</td>
<td>8,088</td>
</tr>
<tr>
<td><em>A</em>&lt;sub&gt;S&lt;/sub&gt;</td>
<td>Lake surface area</td>
<td>36,000</td>
</tr>
<tr>
<td><em>A</em>&lt;sub&gt;I&lt;/sub&gt;</td>
<td>Interface area</td>
<td>7,264</td>
</tr>
<tr>
<td><em>A</em>&lt;sub&gt;B&lt;/sub&gt;</td>
<td>Bottom of lake area</td>
<td>3,520</td>
</tr>
<tr>
<td><em>C</em>&lt;sub&gt;U&lt;/sub&gt;</td>
<td>Coefficient of the standard unit-</td>
<td>1,000</td>
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**Unknown Constants**

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<thead>
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<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>α</em>&lt;sub&gt;PU&lt;/sub&gt;, <em>α</em>&lt;sub&gt;PL&lt;/sub&gt;</td>
<td>Coefficients of photosynthesis</td>
<td>Constant</td>
</tr>
<tr>
<td><em>α</em>&lt;sub&gt;MU&lt;/sub&gt;, <em>α</em>&lt;sub&gt;ML&lt;/sub&gt;</td>
<td>Coefficients of mineralization</td>
<td>Constant</td>
</tr>
<tr>
<td><em>w</em>&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Coefficient of vertical transportation</td>
<td>Constant</td>
</tr>
<tr>
<td><em>BF</em>&lt;sub&gt;DIC&lt;/sub&gt;, <em>BF</em>&lt;sub&gt;DOC&lt;/sub&gt;</td>
<td>Sediment DIC and DOC emission</td>
<td>Constant</td>
</tr>
<tr>
<td><em>P</em>&lt;sub&gt;AU&lt;/sub&gt;, <em>P</em>&lt;sub&gt;BL&lt;/sub&gt;</td>
<td>Equations constant at lower layer</td>
<td>Constant</td>
</tr>
</tbody>
</table>

**Extreme scenarios**

- Level 1: Best-fit scenario but change upper- and lower-layers discharges (*Q*<sub>U</sub>, *Q*<sub>L</sub>)
  - 77% (spring), 23% (spring),
  - 82% (summer), 18% (summer),
  - 47% (autumn), 53% (autumn),
  - 50% (winter), 50% (winter)

- Level 2: Change in upper- and lower-layers discharges (*Q*<sub>U</sub>, *Q*<sub>L</sub>)
  - 77% (spring), 23% (spring),
  - 82% (summer), 18% (summer),
  - 47% (autumn), 53% (autumn),
  - 50% (winter), 50% (winter)
<table>
<thead>
<tr>
<th>Level 2</th>
<th>Best-fit scenario but change upper and lower layers discharges ($Q_U, Q_L$)</th>
<th>$Q_{in}$</th>
<th>$Q_{in}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$80%$ (spring), $85%$ (summer), $50%$ (autumn), $50%$ (winter)</td>
<td>$20%$ (spring), $15%$ (summer), $50%$ (autumn), $50%$ (winter)</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Best-fit parameters of a two-layer conceptual model of DIC and DOC in Yuan-Yang Lake from 2015 to 2018.

<table>
<thead>
<tr>
<th></th>
<th>Typhoon years</th>
<th>Non-typhoon years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2015‒2016</td>
<td>2017‒2018</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>Summer</td>
</tr>
<tr>
<td>Upper layer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{CO2}$ (mg C/m$^2$ d$^{-1}$)</td>
<td>291</td>
<td>245</td>
</tr>
<tr>
<td>$a_{PU}$ (d$^{-1}$)</td>
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<tr>
<td>$Pb_{U}$ (d$^{-1}$)</td>
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<td>9461</td>
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<tr>
<td>$d_{DICU}$</td>
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<tr>
<td>$d_{DOC_U}$</td>
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<td>Lower layer</td>
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<tr>
<td>$a_{PL}$ (d$^{-1}$)</td>
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<td>-22.1</td>
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<td>$a_{ML}$ (d$^{-1}$)</td>
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<td>$Pa_{L}$ (d$^{-1}$)</td>
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<td>$Pb_{L}$ (d$^{-1}$)</td>
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<td>$BF_{DOC}$, $BF_{DOC}$ (mg C L$^{-1}$)</td>
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<tr>
<td>$d_{DICL}$</td>
<td></td>
<td></td>
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<tr>
<td>$d_{DOC_L}$</td>
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<tr>
<td>(R$^2$, NSE)</td>
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<tr>
<td>(R$^2$, NSE)</td>
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Table 4. Seasonal averages of carbon fluxes (mg C m\(^{-3}\) d\(^{-1}\)) for each season in Yuan-Yang Lake. Positive values are shown in the carbon sink (black), and negative ones show the values after carbon was released.

<table>
<thead>
<tr>
<th></th>
<th>Flux (mg C m(^{-3}) d(^{-1}))</th>
<th>Total (mg C m(^{-3}) d(^{-1}))</th>
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<tr>
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<td>(F_C)</td>
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<td><strong>Typhoon years</strong></td>
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<td>Spring</td>
<td>Average</td>
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<td>DOC</td>
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<td>-351</td>
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<tr>
<td></td>
<td>DOC</td>
<td>-</td>
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<tr>
<td>Winter</td>
<td>DIC</td>
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<td>DOC</td>
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<td><strong>Non-typhoon years</strong></td>
<td>Average</td>
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<td>DIC</td>
<td>-138</td>
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<tr>
<td></td>
<td>DOC</td>
<td>-</td>
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Fig. 1: Conceptual diagram of river intrusion (red arrows) and thermal stratification (red dashed line) dominant responses of DIC and DOC in a subtropical two-layer stratified lake under extreme climates.
Fig. 1. Sampling locations and bathymetry maps of Yuan–Yang Lake (YYL). The dark green rectangle shows the buoy station, which is located at the deepest site of the lake. The red points and white cross show the river mouths of the inflows and outflows, respectively. The gray triangle shows the location of the water depth sensor.

Commented [A91]: # Report 2
Fig 2: I would make your markers bigger on the map.

Commented [A92R91]: We have enlarged the marker as much as possible. The red arrows show the inflowing rivers. Thanks.

Commented [A93]: # Report 1
Figure 2. Inflowing rivers should be included in this figure.

Commented [A94R93]: We have enlarged the marker as much as possible. The red arrows show the inflowing rivers. Thanks.
Fig. 2. Comparisons of (a) DIC, (b) DOC, and (c) Chl a between upper (DIC\(_U\), DOC\(_U\), Chl\(_a\)_U) and lower (DIC\(_L\), DOC\(_L\), Chl\(_a\)_L) layers, grouped by typhoon and non-typhoon years. The bullet points show the water sampling data. We used a t-test to obtain the p-values. The ns show the p-values ≥ 0.05, * show p-values from 0.05 to 0.01, and ** show p-values from 0.01 to 0.001 by t-test.

Commented [A95]: # Report 2
Fig 3: should you maybe just write the p values on the respective graph panels instead of the key to the values (ns, *, **)? For example, since you use the term “nonseasonal” I think ns means that, but I do not believe that is the case...

Commented [A96R95]: We have added the p-values in the graph panels. Thank you.

Commented [A97]: # Report 1
Figure 3 I can see much higher Chl-a in the lower than in the upper layer of this lake. Higher phytoplankton biomass is usually found in the upper layer of a specific lake. Please double-check your data.

Commented [A98R97]: Thanks for your comment. We have double-checked the data set to make sure it is correct. YYL is a humic and oligotrophic lake, resulting in the low Chl. a concentration in the upper layer (Tsai et al. 2008), but we sometimes found brief algal blooms in the lower layer around the end of March.
Fig. 34. Seasonal variations of (a) upper layer DIC (DIC$_U$), (b) lower layer DIC (DIC$_L$), (c) upper layer DOC (DOC$_U$), (d) lower layer DOC (DOC$_L$), (e) upper layer Chl. a (Chl$_a$), (f) lower layer Chl. a (Chl$_a$) grouped by typhoon and non-typhoon years. The bullet points show the water sampling data. To determine the seasonality, we used one-way ANOVA to obtain the p-values. The "ns" show p-values ≥ 0.05; * show p-values from 0.05 to 0.01; and ** show p-values are from 0.01 to 0.001.
Fig. 45. Pearson correlation coefficients of DIC, DOC, and Chl. a concentration at upper layer and lower layer DIC ($DIC_U$, $DIC_L$), DOC ($DOC_U$, $DOC_L$), Chl. a ($Chl_U$, $Chl_L$) during (a) typhoon years and (b) non-typhoon years. The black crosses show insignificant values ($p$-values are $> 0.05$).
Fig. 5.6. Continuous daily DIC and DOC data at (a, b, e, f) the upper layer (DIC$_U$, DOC$_U$) and (c, d, g, h) lower layer (DIC$_L$, DOC$_L$) by using conceptual equations models. The gray lines show the interannual data, the black lines show the best fit for DIC, the red lines show the best-fit for DOC (Table 3), and the empty dots show water sampling (observation) data for each month.
Fig. 6. Continuous daily DIC and DOC data at (a, c) upper layer (DIC$_U$, DOC$_U$) and (b, d) lower layer (DIC$_L$, DOC$_L$) by using the conceptual equation model under extreme climates from 2015 to 2018. Blue lines are original best-fit data as in Fig. 6, in which the parameters of the DIC model in non-typhoon years are under the nonseasonal scenario and the others are under the seasonal scenario as shown in Table 3. Orange regions show Level 1; pink regions show Level 2.
Figure 7a. Seasonal responses of continuous (a-d) upper layer DIC and (e-h) lower layer DIC (mg-C L⁻¹) between typhoon (Typhoon) and non-typhoon (Non) years for each season as in Fig. 34. Fit (blue boxes) condition shows the best-fit data by using the conceptual two-layer C model; Lvl (yellow boxes) and Lv2 (red boxes) show the extreme climates. The empty dots show the continuous DIC and DOC data. Empty dots show the continuous DIC and DOC data. “ns”: p-values ≥ 0.05; *: p-values from 0.05 to 0.01; **: p-values from 0.01 to 0.001; ****: p-values less than 0.0001 based on a t-test. The ns show p-values ≥ 0.05, * show p-values from 0.05 to 0.01, ** show p-values from 0.01 to 0.001; **** show p-values less than 0.0001 based on a t-test.
Fig. 89. Seasonal responses of (a-d) upper layer DOC and (e-h) lower layer DOC (mg·C L⁻¹) between typhoon (Typhoon) and non-typhoon (Non) years for each season as in Fig. 78. The Fit (blue boxes) condition shows the best-fit data by using the conceptual two-layer carbon model; Lv1 (yellow boxes) and Lv2 (red boxes) show the extreme climates. Empty dots show the continuous DIC and DOC data. “ns”: p-values ≥ 0.05; *: p-values from 0.05 to 0.01; **: p-values from 0.01 to 0.001; ****: p-values less than 0.0001 based on a t-test. Empty dots show the continuous DIC and DOC data. The ns show p-values ≥ 0.05, * show p-values from 0.05 to 0.01, ** show p-values from 0.01 to 0.001, **** show p-values less than 0.0001 based on a t-test.
Fig. 9.10. Interannual (a) Upper flux$_{DOC}$ , (b) Lower flux$_{DOC}$ , (c) Flux$_{DOC}$ , (d) Upper flux$_{DIC}$ , (e) Lower flux$_{DIC}$ , and (f) Flux$_{DIC}$ (mg C m$^{-3}$ d$^{-1}$) grouped by typhoon and non-typhoon years. The Obs condition (black boxes) show the observation data as in Fig. 6.5. The Fit condition (blue boxes) shows the best-fit data by using the conceptual two-layer carbon model as in Fig. 5.6. Level 1 (yellow boxes) and Level 2 (red boxes) show the extreme scenarios as in Fig. 6.2. For the definitions of fluxes please see Sect. 2.3.3.