Postprint: Study on Water Temperature and Dissolved Oxygen Concentration Variations in Wuliangsuhai During the Ice-Covered Period

Authors: Zhai Jialun, Shi Xiaohong

Date: 2021-06-13T00:00:00+00:00

Abstract

The Morlet wavelet analysis method was employed to conduct trend analysis on the temperature and dissolved oxygen (DO) concentration of the under-ice water body in Ulansuhai Lake in 2019. The results indicate that: (1) Stratification was observed in lake water temperature, and simultaneously, DO concentration also exhibited stratification to varying degrees. The surface DO concentration remained constant for nearly one month, while the middle and bottom layer DO concentrations began to decrease with increasing ice cover duration, with decline rates of 0.32 mg · L-1 · d-1 in the middle layer and 0.05 mg · L-1 · d-1 in the bottom layer. (2) The primary periods of surface water temperature were 25 d and 16 d, with a period of approximately 15 d under the first primary period; the primary period of DO concentration was 23 d, with an average period of 15 d; the primary period of middle layer water temperature was 14 d, and the primary periods of DO concentration were 19 d and 7.5 d; under the first primary period, the average period of water temperature was approximately 9 d, and the average period of DO concentration was 5 d; the primary periods of bottom layer water temperature were 14 d and 2.5 d, and the primary periods of DO concentration were 24 d and 10 d. The water temperature variation period was approximately 8.5 d, and the average period of DO concentration was about 7 d. (3) The wavelet coherence spectrum results indicate that: a complex relationship exists between lake water temperature and DO concentration, with surface and bottom layer water temperatures showing an anti-phase relationship with DO concentration; at the periodic scale of 2–4 d, changes in middle layer water temperature preceded DO concentration changes by approximately 2–4 h.

Full Text

Abstract

This study employs wavelet analysis to examine trends in water temperature and dissolved oxygen (DO) concentration in the ice-covered Wuliangsu Lake during the 2019 ice-bound period (January 24–February 24). The results reveal distinct stratification in both water temperature and DO concentration beneath the ice. The DO concentration in the surface layer remained relatively stable over the month-long observation period, while the middle and bottom layers exhibited decreasing trends at rates of 0.32 $mg \cdot L^{-1}$ and 0.05 $mg \cdot L^{-1}$, respectively. The dominant period for surface water temperature variation was 25 days, with a secondary period of 16 days; under the first dominant period, the cycle was approximately 15 days. The dominant period for surface DO concentration was 23 days, with an average cycle of 15 days. For the middle layer, the dominant water temperature period was 14 days, while DO concentration showed dominant periods of 19 days and 7.5 days. Under the first dominant period, the average water temperature cycle was approximately 9 days, and the average DO concentration cycle was 5 days. In the bottom layer, water temperature exhibited dominant periods of 14 days and 2.5 days, while DO concentration showed periods of 24 days and 10 days. The water temperature cycle was approximately 8.5 days, with an average DO concentration cycle of about 7 days. Wavelet coherence spectrum results demonstrate a complex relationship between water temperature and DO concentration, with an inverse phase relationship observed between surface and bottom water temperatures and DO concentration. On the 2–4 day cycle scale, middle-layer water temperature changes preceded DO concentration changes by approximately 2–4 hours.

Keywords: Wuliangsu Lake; ice-bound period; water temperature; dissolved oxygen; wavelet transform

1.1 Study Area Overview

Wuliangsu Lake (40°36 -41°03 N, 108°43 -108°57 E) is the eighth largest freshwater lake in China, located in Urad Front Banner, Bayannur City, Inner Mongolia, at the terminus of the Hetao Irrigation District of the Yellow River. The lake exhibits a north-south elongated and east-west narrow morphology, with a current water surface area of 325.31 km^2, of which 202.2 km^2 is covered by reeds and 123.11 km^2 is open water. Water quality indicators have reached Class V or worse, indicating severe eutrophication. The proliferation of aquatic macrophytes, primarily *Potamogeton pectinatus*, and their subsequent decomposition releases nutrients while consuming substantial dissolved oxygen, leading to decreased overall DO levels. Wuliangsu Lake experiences an ice-bound period of approximately 150 days annually. Previous studies have investigated the dynamic distribution of ice-covered water bodies and their relationship with temperature during the freezing period.

1.2 Data Collection and Processing

The monitoring station was located in the central part of Wuliangsu Lake, adjacent to dense aquatic vegetation in the west and near the eastern shore, belonging to the lake' s buffer zone with relatively shallow depth and frequent, complex material exchange processes with the sediment interface. Sediment oxygen consumption accounts for approximately 70% of total water column oxygen consumption, significantly influencing overlying water DO content. Prolonged hypoxia triggers a series of environmental changes at the sediment-water interface, including the disappearance of macrobenthos and a shift from aerobic to anaerobic microbial degradation of organic matter.

Based on the actual water depth at the monitoring site, the water column was divided into surface, middle, and bottom layers. The surface layer was defined as the water body 20 cm beneath the ice; the bottom layer was defined as the region approximately 10 cm above the sediment-water interface; and the middle layer was defined at half the actual water depth. YSI probes were suspended at three depths (surface: 66 cm, middle: 130 cm, bottom: reference depth) with a monitoring interval of 10 minutes. The observation period spanned from January 24 to February 24, 2019, representing the stable ice-cover phase.

Morlet wavelet analysis was employed to analyze the periodic characteristics of water temperature and DO concentration variations. Wavelet coefficients, wavelet variance, and wavelet coherence spectra were used to reveal the patterns of temperature and DO concentration in the surface (66 cm), middle (130 cm), and bottom layers during the ice-bound period.

2 Principles of Wavelet Transform

Wavelet analysis is widely applied in research on multi-time-scale variation characteristics, aiming to obtain a complete representation of local and transient phenomena occurring at different temporal scales. Wavelet transform includes continuous wavelet transform (CWT) and discrete wavelet transform. For discrete time series data common in practical applications, the discrete form of the continuous wavelet transform is defined as:

$$W_f(a,b) = \frac{1}{\sqrt{|a|}} \sum_{t=1}^{N} f(t)\varphi\left(\frac{t-b}{a}\right)$$

where a is the scale factor, b is the time factor, and $W_f(a,b)$ represents the wavelet coefficients.

Wavelet variance is defined by integrating the squares of all wavelet coefficients for scale a across the time domain, reflecting the distribution of signal fluctuation energy with scale:

$$\text{Var}(a) = \int_{-\infty}^{+\infty} |W_f(a,b)|^2 db$$

Wavelet variance plots can identify the relative intensity of disturbances at different scales and determine the dominant time scales in the signal.

Wavelet coherence spectrum measures the degree of local correlation between two time series in the time-frequency space. Based on cross-wavelet transform (XWT) of two time series, it reveals common high-energy regions. The wavelet coherence function for time series X and Y is:

$$R_n^2(s) = \frac{|S(s^{-1}W_{XY}(a,b))|^2}{S(s^{-1}|W_X(a,b)|^2) \cdot S(s^{-1}|W_Y(a,b)|^2)}$$

where S is a smoothing operator, s is the scale, $W_X(a,b)$ and $W_Y(a,b)$ are the wavelet transforms of X and Y, and $W_{XY}(a,b)$ is the cross-wavelet spectrum.

3.1 Distribution Characteristics of Temperature and Dissolved Oxygen

Based on the monitored data, vertical distribution trends of temperature and DO concentration were plotted [Figure 3: see original paper]. The results show that temperature exhibited clear stratification, with surface, middle, and bottom layers. The surface water temperature beneath the ice ranged from -0.13 to 7.66°C, averaging 5.79°C; the middle layer averaged 6.57°C; and the bottom layer averaged -0.12°C. The highest surface temperature (7.66°C) occurred on February 2, while the lowest (-0.13°C) appeared on February 18. The middle layer reached its maximum (7.37°C) on February 3 and minimum (0.34°C) on February 22. The bottom layer peaked at 7.37°C on February 3 and reached its minimum (-0.13°C) on February 22. A stratification trend was evident, with higher temperatures in the bottom layer and lower temperatures in the surface layer.

The DO concentration profile [Figure 3: see original paper] showed different stratification patterns compared to temperature. Surface DO concentration fluctuated between 9.12–12.11 $\text{mg} \cdot \text{L}^{-1}$, averaging 10.91 $\text{mg} \cdot \text{L}^{-1}$. Middle layer DO ranged from 0.90–13.44 $\text{mg} \cdot \text{L}^{-1}$, averaging 7.14 $\text{mg} \cdot \text{L}^{-1}$. Bottom layer DO varied from 0.04–4.72 $\text{mg} \cdot \text{L}^{-1}$, averaging 1.82 $\text{mg} \cdot \text{L}^{-1}$. The surface layer showed relatively stable DO levels, while middle and bottom layers exhibited more pronounced declines over the ice-bound period. The water column displayed clear stratification into upper mixed, intermediate, and lower mixed layers.

3.2.1 Wavelet Transform Analysis of Water Temperature

To reveal the multi-time-scale variation characteristics of water temperature stratification in Wuliangsu Lake during the ice-bound period, Morlet wavelet analysis was applied. The wavelet coefficient real-part contour plot for surface water temperature [Figure 4: see original paper] shows multi-time-scale features in temperature evolution. Two distinct periodic variations were evident: 19-29 days and 9-17 days. The 19-29 day scale showed weak oscillations before February 5, then intensified, centered at 25 days and nested within the 9-17 day cycle. Wavelet variance revealed the intensity of periodic oscillations, with three prominent peaks corresponding to 25 days, 16 days, and 9 days. The maximum peak at 25 days represents the first dominant period, while 16 days corresponds to the second dominant period. The average cycle under the first dominant period was approximately 15 days, with two rising-falling transitions observed.

Middle-layer water temperature also exhibited multi-scale periodic patterns, with notable cycles of 10-17 days and 25-32 days. At the 10-17 day scale (centered at 14 days), temperature variations were pronounced with rapid alternations. The 25-32 day scale showed low-frequency, large-energy fluctuations without forming closed contours. Wavelet variance indicated the first dominant period at 14 days and the second at 25 days, with an average cycle of about 9 days under the first dominant period.

Bottom-layer water temperature showed two periodic scales: 1-6 days and 10-17 days. The 1-6 day scale (centered at 2.5 days) represented weak oscillations with stable energy, while the 10-17 day scale (centered at 14 days) showed clear alternating warm-cold cycles with a high-temperature period. Wavelet variance identified 2.5 days as the first dominant period and 14 days as the second, with an average cycle of approximately 8.5 days.

3.2.2 Wavelet Transform Analysis of DO Concentration

The wavelet coefficient real-part contour plot for surface DO concentration [Figure 6: see original paper] reveals periodic variations at 19-26 days and 7.5 days. The 19-26 day scale (centered at 23 days) showed strong energy fluctuations, while variations were minimal at scales below 7.5 days. Wavelet variance showed two peaks at 23 days and 7.5 days, with 23 days as the first dominant period and 7.5 days as the second. The average cycle under the first dominant period was approximately 15 days, with DO concentration remaining stable for the first month then decreasing from 10.18 $mg \cdot L^{-1}$ to 3.82 $mg \cdot L^{-1}$ at a rate of 0.32 $mg \cdot L^{-1} \cdot d^{-1}$. Heavy snow cover and cloudy weather reduced light transmittance to 1-5% [?], weakening photosynthesis and making respiration dominant, which consumed DO.

Middle-layer DO concentration showed periodic patterns at 15-23 days and 7.5 days. The 15-23 day scale (centered at 19 days) displayed alternating high-low concentration periods. Wavelet variance identified 19 days as the first dominant period and 7.5 days as the second, with an average cycle of about 5 days under the first dominant period. DO concentration decreased from 7.14 $mg \cdot L^{-1}$ to 1.93 $mg \cdot L^{-1}$ at 0.05 $mg \cdot L^{-1} \cdot d^{-1}$.

Bottom-layer DO concentration exhibited cycles at 19–29 days and 10 days. The 19–29 day scale (centered at 24 days) showed three high-concentration periods, while the 10-day scale showed weak energy fluctuations. Wavelet variance indicated 24 days as the first dominant period and 10 days as the second, with an average cycle of approximately 7 days. Two mutation events occurred: the first concentration drop on February 3 and the second on February 18.

3.3 Wavelet Coherence Spectrum Analysis of Water Temperature and DO Concentration

Using wavelet coherence spectrum analysis on temperature and DO data from January 24 to February 24, 2019, the phase relationships between these parameters were examined across different layers [Figure 8: see original paper]. The results show complex relationships between water temperature and DO concentration, with varying periodic patterns across the water column.

For the surface layer, a significant resonance region passed the 95% confidence test within the 3–7 day period (black contour line), with arrows pointing leftward, indicating an inverse phase relationship (negative correlation) with correlation coefficients reaching 0.8-0.95. For the middle layer, strong negative correlations emerged after February 5 within the 2–4 day period, with correlation coefficients of 0.85–0.95. Water temperature changes preceded DO concentration changes by approximately 2–4 hours. For the bottom layer, the two sequences showed strong negative correlations within the 1–3 day period after February 5, with correlation coefficients of 0.8-0.9. Overall, temperature and DO concentration exhibited negative correlations across all three layers, with the temperature phase system advancing ahead of DO concentration changes by about 2–4 hours as the ice-bound period progressed.

4 Discussion

For lakes in northern China' s cold and arid regions, the presence or absence of an ice cover fundamentally alters thermal stratification. Under ice, thermal stratification is inverted, water temperatures are lower, and atmospheric reaeration, wind-driven mixing, and atmospheric inputs essentially cease. Monitoring of ice-covered water bodies reveals that bottom layers have the highest temperatures but lowest DO concentrations, while surface layers show the opposite pattern. The surface temperature decrease results from heat loss through the ice, whereas bottom temperature increases stem from sediment heat flux [?]. Lower initial water temperatures correlate with higher potential DO storage capacity.

The vertical distribution of DO concentration is controlled not only by biochemical processes but also, more importantly, by water temperature [?]. The inverse temperature gradient (low surface temperature of -0.12°C, high bottom temperature of 6.57°C) inhibits water column convection [?], affecting DO distribution. While snow-free ice is a prerequisite for winter photosynthesis, DO production only occurs when photosynthetically active radiation is available [?]. Thus, photosynthesis is controlled by solar radiation and ice/snow cover conditions. Environmental pressures including climate, geography, eutrophication, organic pollutants, hydrology, and nutrient loading further modify DO concentrations across layers. Atmospheric reaeration and photosynthesis maintain higher surface DO concentrations, but as ice and snow cover expand, gas exchange is blocked and photosynthesis is limited, causing DO depletion. Bottom hypoxia results from sediment oxygen demand, primary productivity, external inputs, and phosphorus release. Studies have shown that sediment phosphorus release can maintain stable water column phosphorus concentrations, while suitable temperatures at the sediment-water interface support aerobic respiration by sediment organisms and benthic biota, creating bottom hypoxic conditions. Reduced DO then diffuses upward, transforming the negative correlation between middle-layer temperature and DO into a phase-advanced relationship.

The stratification of water temperature under ice leads to DO stratification. Increased water temperature reduces DO concentration, while decreased temperature increases DO solubility. Wavelet coherence spectra confirm strong negative correlations (correlation coefficients of 0.8–0.95) between temperature and DO across all layers. Low temperatures inhibit organic matter decomposition and biological respiration, helping maintain DO levels. However, as the ice-bound period continues, DO concentrations progressively decrease, and the hypoxic layer gradually expands upward from the bottom.

This study analyzed the evolution of temperature and DO concentration in Wuliangsu Lake' s stratified water body during the ice-bound period using Morlet wavelet analysis. However, the deeper coupling mechanisms between temperature and DO require further investigation using longer time series data.

5 Conclusions

1) The ice-covered water column in Wuliangsu Lake can be stratified into surface, middle, and bottom layers based on temperature and DO distribution. Average temperatures were 5.79°C (surface), 6.57°C (middle), and -0.12°C (bottom). Average DO concentrations were 10.91 $mg \cdot L^{-1}$ (surface), 7.14 $mg \cdot L^{-1}$ (middle), and 1.82 $mg \cdot L^{-1}$ (bottom). From January 24 to February 24, 2019, DO consumption increased while replenishment was insufficient, altering DO distribution throughout the water column.

2) The dominant period for surface water temperature was 25 days, with temperature undergoing two rising-falling cycles averaging 15 days each. The dominant period for surface DO concentration was 23 days, with an average cycle of 15 days. Middle-layer water temperature had a dominant period of 14 days (average cycle ~9 days), while middle-layer DO concentration showed a dominant period of 19 days (average cycle ~5 days). Bottom-layer water temperature exhibited dominant periods of 2.5 days and 14 days, with two mutation events and a cycle of approximately 8.5

days. Bottom-layer DO concentration had dominant periods of 24 days and 10 days, with an average cycle of about 7 days. Except for the bottom layer, the temperature cycles were similar across layers. High-energy zones for temperature corresponded to those for DO, indicating a positive response of DO changes to temperature variations.

3) Wavelet coherence analysis revealed complex relationships between temperature and DO concentration across all three layers, with periodic variations differing among layers. The phase relationship between temperature and DO sequences showed significant inverse correlations within 3-7 days (surface), 2-4 days (middle), and 1-3 days (bottom), with correlation coefficients of 0.8-0.95. As the ice-bound period progressed, the temperature phase system advanced ahead of DO concentration changes by approximately 2-4 hours.

References

[1] Yin Yan, Wu Zhixu, Liu Mingliang, et al. Dynamic distribution characteristics of dissolved oxygen in Qiandaohu lake and its environmental influence factors[J]. Environmental Science, 2014, 35(7): 2539-2546.

[2] Zhu Xuxu, Gao Aiguo, Wang Shiyong, et al. Distribution of dissolved oxygen in the surface water and influencial factors in Quanzhou Bay during spring and summer[J]. Journal of Xiamen University(Natural Science Edition), 2017, 56(4): 531-539.

[3] He B Y, Dai M H, Zhai W D, et al. Hypoxia in the upper reaches of the Pearl River Estuary and its maintenance mechanisms: A synthesis based on multiple year observations during 2000-2008[J]. Marine Chemistry, 2014, 167: 13-24.

[4] Xie Lei. Spatial and Temporal Variation Characteristics of Dissolved Oxygen in Stratified Small Reservoir in Front of Fushan, Qingdao[D]. Qingdao: Qingdao University, 2015.

[5] Deng Sisi. Study on Dissolved Oxygen Balance in River Network of Jiaxing Plain[D]. Hangzhou: Zhejiang University, 2013.

[6] Boehrer B, Schultzm M. Stratification of lakes[J]. Reviews of Geophysics, 2008, 46(2): 1-27.

[7] Song Shuang. Photothermal Characteristics of Wuliangsuhai And Primary Productivity of Subglacial Water[D]. Hohhot: Inner Mongolia Agricultural University, 2019.

[8] Parmar K S, Bhardwaj R. Fractal, predictability index and variability in trends analysis of river water dynamics[J]. International Journal of River Basin Management, 2014, 12(4): 285-297.

[9] Kalff J. Limnology: Inland Water Ecosystems[M]. New Jersey: Prentice Hall, 2002.

[10] Foley Brian, Jones I D, Maberly S C, et al. Long-term changes in oxygen depletion in a small temperate lake: Effects of climate change and eutrophication[J]. Blackwell Publishing Ltd, 2012, 57(2): 278-289.

[11] Huber Veronika, Wagner Carola, Gerten Dieter, et al. To bloom or not to bloom: contrasting responses of cyanobacteria to recent heat waves explained by critical thresholds of abiotic drivers[J]. Oecologia, 2012, 169(1): 245-256.

[12] Terzhevik A, Golosov S, Palshin N, et al. Some features of the thermal and dissolved oxygen structure in boreal, shallow ice covered Lake Vendyurskoe, Russia[J]. Aquatic Ecology, 2009, 43(3): 618-628.

[13] Barica J, Mathias J A. Oxygen depletion and winterkill risk in small prairie lakes under extended ice cover[J]. NRC Research Press Ottawa, Canada, 1979, 36(8): 980-986.

[14] Wilhelm Granéli. A comparison of carbon dioxide production and oxygen uptake in sediment cores from four south Swedish lakes[J]. Ecography, 1979, 2(1): 51-57.

[15] Mathias J A, Barica J. Factors controlling oxygen depletion in ice covered lakes[J]. Canadian Journal of Fisheries and Aquatic Sciences, 1980, 37(2): 185-194.

[16] Bai Qinxi, Li Runling, Li Zhijun, et al. Time series analyses of water temperature and dissolved oxygen concentration in Lake Valkea Kotinen (Finland) during ice season[J]. Ecological Informatics, 2016, 36: 181-189.

[17] Li Ming, Li Runling, Bai Qinxi, et al. Discrete wavelet analysis of variation law of dissolved oxygen concentration under ice in a Finnish Freshwater Lake[J]. Mathematics in Practice And Theory, 2015, 45(7): 149-155.

[18] Sun Biao, Li Changyou, Zhang Sheng, et al. Analysis of factors influencing the occurrence of oversaturated dissolved oxygen in total drainage ditches in Hetao irrigated area[J]. Environmental Chemistry, 2009, 28(3): 449-450.

[19] Zeng Chunfen, Huang Wenyu, Wang Weixia, et al. Distribution and its influence factors of dissolved oxygen in Tianmuhu Lake[J]. Resources and Environment in the Yangtze Basin, 2010, 19(4): 445-451.

[20] Jankowski T, David M, Livingstone, et al. Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: Implications for a warmer world[J]. Limnology and Oceanography, 2006, 51(2): 815-819.

[21] Han H G, Qiao J F, Chen Q L, et al. Model predictive control of dissolved oxygen concentration based on a self organizing RBF neural network[J]. Control Engineering Practice, 2012, 20(4): 465-476.

[22] Wang Wensheng, Ding Jing, Li Yueqing. Hydrologic Wavelet Analysis[M]. Beijing: Chemical Industry Press, 2005: 1-207.

[23] Labat D. Cross wavelet analyses of annual continental freshwater discharge and selected climate indices[J]. Journal of Hydrology, 2010, 385(1-4): 269-278.

[24] Sun Weiguo, Cheng Bingyan. Application of cross wavelet transformation to analysis on regional climate variations[J]. Journal of Applied Meteorological Science, 2008, 19(4): 479-487.

[25] Zhang Beibei, Wang Peng, Zhang Hui, et al. Correlation between sunspot activity and precipitation in the Ankang region in recent 63 years[J]. Arid Zone Research, 2018, 35(6): 1336-1343.

[26] Wang Yong, Wen Debao, Liu Yanping, et al. Effects of fog and haze weather on GPS zenith tropospheric delay and precipitable water vapor[J]. Journal of Geodesy and Geodynamics, 2014, 34(2): 120-123, 127.

[27] Zhou Y, Obenour D R, Scavia D, et al. Spatial and temporal trends in Lake Erie Hypoxia, 1987-2007[J]. Environmental Science and Technology, 2013, 47(2): 899-905.

[28] Song S, Li C, Shi X, et al. Under ice metabolism in a shallow lake in a cold and arid climate[J]. Freshwater Biology, 2019, 64(10): 1-11.

[29] Ulrike Obertegger, Biel Obrador, Giovanna Flaim. Dissolved oxygen dynamics under ice: Three winters of high frequency data from Lake Tovel, Italy[J]. Water Resources Research, 2017, 53(8): 6991-7003.

[30] Du Yanliang, Peng Wenqi, Liu Chang. A review of dissolved oxygen variation and distribution in the stratified lakes or reservoirs[J]. Journal of Hydraulic Engineering, 2019, 50(8): 990-998.

[31] Zhao Shengnan, Shi Xiaohong, Li Changyou, et al. Diffusion flux of phosphorus nutrients at the sediment water interface of the Ulansuhai Lake in northern China[J]. Water Science and Technology, 1997, 75(6): 1455-1465.

Note: Figure translations are in progress. See original paper for figures.