

Numerical modeling of hydrodynamics in Poyang Lake: forcing and eddy kinetic energy

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Abstract This study employed the three-dimensional MIKE model to simulate the hydrodynamic properties of Poyang Lake from October 2020 to December 2021. The model demonstrated high accuracy, with the coefficient of determination (R^2) exceeding 0.96 for water level and 0.98 for water area comparisons, indicating its efficacy in replicating the lake's hydrodynamics. Notably, the highest pressure gradient forcing was observed in March and April, aligning with increased flow rates in the Ganjiang River, affecting the east side of Poyang Lake. This period saw a distinctive pressure gradient front in the lake's central channel, potentially influencing material distribution. Eddy kinetic energy, calculated from model velocity data, peaked in May and June, and again in September and October, corresponding to changes in river flow rates. This energy was predominantly influenced by local dynamics in the lake's central area, with low frequencies and extended periods, differing from other lake regions. Furthermore, the study found a strong correlation between eddy activities and the spatial distribution of water materials, as indicated by the consistency of turbidity patterns in satellite imagery and eddy kinetic energy distributions. These findings highlight the significant impact of hydrodynamic behaviors, particularly eddy movements, on the distribution of suspended materials within Poyang Lake.

Keywords Poyang Lake, MIKE model, pressure gradient forcing, eddy kinetic energy

1 Introduction

Poyang Lake is the largest freshwater lake in China and plays a critical role in the Yangtze River basin as a pass-through, throughput, and seasonal lake. Compared to

rivers and estuaries, lakes are generally considered to have slow flow velocities and poor water exchange capabilities. However, large river-connected lakes such as Poyang Lake and Dongting Lake exhibit distinct characteristics from other lakes, such as Taihu and Chaohu (Gao et al., 2014). These large river-connected lakes have complex relationships with rivers, often displaying unique hydrodynamic features (Hu et al., 2007). Studying the intricate hydrodynamics of Poyang Lake is vital for understanding the flow dynamics in the lake area and for the protection of its aquatic ecology and water environment.

Poyang Lake is a highly dynamic lake, mainly driven by river inflows, and the hydrodynamic structure of Poyang Lake varies significantly between its flood and dry seasons, exhibiting rich and complex dynamics (Feng et al., 2012; Liu et al., 2018). The uneven change in flow state is a primary driver in the evolution of Poyang Lake's ecosystem (Lai et al., 2016). Under the influence of the river inflows, gravity-driven lake currents dominate the flow pattern (Hu et al., 2007). Poyang Lake receives runoff from five rivers and drains into the Yangtze River through the northern deep-water channel. The pressure gradient between inflow and outflow forms the lake's primary flow regime (Guo et al., 2012; Xu et al., 2023). From July to October, influenced by the river-lake relationship, when the Yangtze River level rises above that of Poyang Lake, reverse flow occurs, significantly affecting the lake's usual northward flow, causing a substantial southward backflow. However, during the dry season, the Yangtze River acts to drain the lake, lowering water levels and accelerating flow velocity (Li et al., 2017; Chen et al., 2022). Poyang Lake, located in a windy region, experiences significant wind-driven currents primarily from mid-July to late September. These currents affect the west shore of the central lake and the eastern bays, often creating noticeable circulation patterns (Yao et al., 2019; Wang et al., 2020). Research indicates

that seasonal lake clusters play a crucial role in regulating the water levels and flow rates of Poyang Lake (Li et al., 2019). Additionally, Sand mining-induced topographical changes significantly affect the lake's water level, flow, velocity, and retention time (Yao et al., 2018). Moreover, research indicates that vegetation on floodplains has a significant impact on the hydrodynamic conditions of lake areas. An increase in vegetation can affect the transport efficiency of the lake system, slow down the flow rate, raise the water level, and increase the water storage capacity of the lake. The impact of vegetation on flow velocity and outflow is more pronounced during the phases of rising and falling water levels than during the flood stage, reflecting the complex interaction between vegetation and hydrology that varies with the seasonal changes of the floodplain (Li et al., 2020a). In addition, small-scale eddies, particularly active during the reversal period, significantly impact the lake's dynamic structure in the summer and autumn seasons (Xu et al., 2023). However, the quantification of these eddies remains unclear.

Eddies are a fundamental phenomenon in fluid motion, commonly found in aquatic environments. The interaction of various physical forces often leads to the formation of eddies, which significantly impact hydrodynamics and water environments. Li et al. (2022a) observed secondary flows composed of dual counterclockwise-rotating helical structures and channel-scale circulations in Poyang Lake's outflow channels, both as composite and single channels. Ralph (2002) studied the scale and structure of eddies in large lakes. By observing water flow and near-surface temperature in Lake Superior, the study revealed the presence of widespread eddies and discussed their formation, propagation, and dissipation mechanisms, as well as their three-dimensional structure. Hamze-Ziabari et al. (2022) proposed a new method for detecting and characterizing basin-scale circulation and mesoscale eddies in Lake Geneva. The study found that horizontal movement in lake eddies is primarily influenced by wind stress, while their vertical movement structures depend mainly on the depth and strength of the thermocline. These results highlight the complexity of large lake circulation systems. Research shows that eddies can redistribute momentum and energy horizontally and vertically, significantly impacting the flow field. They facilitate the exchange between surface and deep waters, affecting the transport and distribution of temperature, pollutants, and nutrients in the water environment. In aquatic ecosystems, eddies also play a crucial role in the activities of aquatic life such as fish and the distribution of plankton (Meunier et al., 2018). Studying eddy phenomena is essential for predicting changes in the hydrodynamic environment, understanding the dynamic evolution of ecosystems, and managing water environments.

Numerical models are highly effective tools for

quantifying the hydrologic and hydrodynamic conditions of lakes. Hydrodynamic models are commonly used for quantitative analysis of changes in hydrological situations (Logah et al., 2017; Zhang et al., 2020). Hydrodynamic characteristics have always been a focus of Poyang Lake research. Extensive work has been conducted on the hydrodynamic and water environmental conditions of the lake's floodplain areas. Yao et al. (2018, 2019) established hydrodynamic models to study the potential impact of wind force and bathymetric changes on Poyang Lake's hydrodynamics. Qi et al. (2016) used the concept of water age applied to a fluid dynamics model to investigate the migration and retention processes of dissolved substances, revealing that the water age of Poyang Lake is significantly influenced by hydrological conditions. Lai et al. (2016) and Yao et al. (2022) used hydrodynamic models to study the construction of Poyang Lake's water conservancy hub, examining its potential impact on the lake's hydrology, hydrodynamics, and water environment. Li et al. (2018, 2019, 2020b) conducted studies on the water balance of Poyang Lake, analyzing the hydrological connectivity between seasonal lakes and the main lake area. They also pioneered the use of three-dimensional hydrodynamic models and statistical methods to explore the spatiotemporal variations and primary causes of thermal stability in large river-lake floodplain systems, specifically Poyang Lake in China. Numerical modeling studies focusing on Poyang Lake have mainly concentrated on three aspects: water flow characteristics (water level, depth, flow field), water environment features, and the relationship with studies in other disciplines related to lake current characteristics.

While previous studies have explored circulation conditions in Poyang Lake, there has been a lack of extensive analysis on hydrodynamic forcing characteristics and eddy kinetic energy. This study aims to fill this gap by conducting a detailed investigation into these aspects using three-dimensional model simulation results. The specific objectives are: (i) to develop and validate a three-dimensional hydrodynamic model for simulating the lake's hydrodynamic conditions, (ii) to analyze the hydrodynamic forcing characteristics in Poyang Lake, and (iii) to evaluate the spatiotemporal characteristics of eddy kinetic energy across the lake. Through this comprehensive approach, the study seeks to enhance understanding of the hydrodynamic properties and their evolution in Poyang Lake.

2 Study area and data

2.1 Study area

Poyang Lake is an important wetland ecosystem in China, located in the northern part of Jiangxi Province, on the southern bank of the Yangtze River (Fig. 1). It spans from

28°22'N to 29°45'N latitude and 115°47'E to 116°45'E longitude, covering a total basin area of $1.622 \times 10^5 \text{ km}^2$ (Lei et al., 2021). The lake area is characterized by a north subtropical monsoon climate, with significant alternation of winter and summer monsoons. The annual average temperature ranges from 16.5°C to 17.8°C. Poyang Lake extends 170 km from north to south, with an average east–west width of 16.9 km and a maximum width of approximately 74 km (Liao et al., 2020). The lake-bed topography of Poyang Lake is complex, comprising river channels, lake branches, seasonal dish-shaped lakes, and sandbars (Zheng et al., 2021). The lake is fed by five rivers within its basin—Ganjiang, Fuhe, Xinjiang, Raohe, and Xiushui—and it drains northward into the Yangtze River, functioning as a critical regulatory body for the Yangtze's flow. The lake's hydrology is significantly influenced by precipitation and the varying water levels of the Yangtze River, creating a unique natural landscape. This dynamic system exhibits clear seasonal variations, expanding into a lake during high water periods and contracting to a riverine state during low water levels.

2.2 Data

The study utilized data including the daily average flow

measurements from seven hydrological stations located on the five main rivers of Poyang Lake: Waizhou Station (Ganjiang River), Qiujiu and Wanjiabu Stations (Xiushui River), Dufengkeng and Hushan Stations (Raohe River), Meigang Station (Xinjiang River), and Lijiadu Station (Fuhe River), as shown in Fig. 1. Additionally, it included daily average water level data from Hukou Station at the lake's outlet, and Xingzi, Duchang, Tangyin, and Kangshan Stations within the lake area; as well as wind speed and direction data from Nanjishan Station. This hydrological information was sourced from the Jiangxi Provincial Hydrology Bureau. The study also utilized 5 m spatial resolution DEM (Digital Elevation Model) data of Poyang Lake, measured in 2010. The water levels and DEM data have all been converted to the data sets on the Yellow Sea base.

3 Methodology

3.1 Model description

This study employed the three-dimensional hydrodynamic model MIKE 3 (2014 version, developed by the Danish Hydraulic Institute (DHI) to study the flow

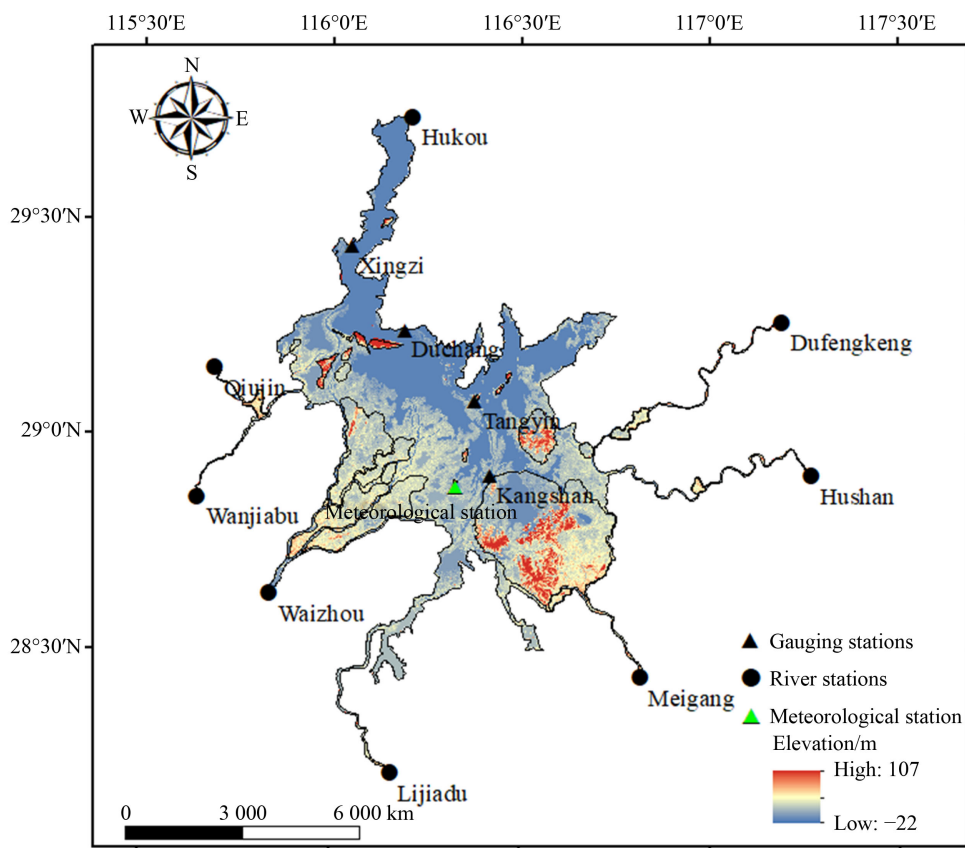


Fig. 1 The Poyang Lake catchment basin, the elevation of the lakebed (based on the 2010 Digital Elevation Model (DEM) referenced to the Yellow Sea datum, which is the water surface elevation system used in this study), and the positions of hydrological stations on the five rivers, monitoring stations within the lake area, and meteorological stations in the lake region.

characteristics and eddy features of Poyang Lake. The MIKE 3 model uses an unstructured triangular mesh to discretize the computational domain. It employs the three-dimensional incompressible Reynolds-averaged Navier-Stokes equations, utilizing a finite volume method for numerical computations, and applies the hydrostatic pressure and Boussinesq approximations. The model's three-dimensional grid is layered, allowing for stratified computations in the vertical direction and considering external forces, enabling the simulation of three-dimensional flow systems with a free surface (DHI, 2012). This model has been used to study numerous rivers, reservoirs, lakes, and estuaries, and has been proven effective in simulating transport and three-dimensional hydrodynamic processes. The fundamental equations of the MIKE 3 hydrodynamic model consist of the continuity equation and the momentum conservation equations in the x , y , and z directions. For the z -direction, a vertical σ transformation equation is used, where $x = x'$, $y = y'$, and $\sigma = (z - z_b)/h$, leading to the following transformed three-dimensional non-steady flow control equation:

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x'} + \frac{\partial hv}{\partial y'} + \frac{\partial hw}{\partial \sigma} = hS, \quad (1)$$

$$\begin{aligned} & \frac{\partial hu}{\partial t} + \frac{\partial hu^2}{\partial x'} + \frac{\partial hv^2}{\partial y'} + \frac{\partial hwu}{\partial \sigma} \\ & = fvh - gh \frac{\partial \eta}{\partial x'} - \frac{h}{\rho_0} \frac{\partial p_a}{\partial x'} - \frac{hg}{\rho_0} \int_z^\eta \frac{\partial \rho}{\partial x} dz \\ & \quad - \frac{1}{\rho_0} \left(\frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y} \right) + hF_u + \frac{\partial}{\partial \sigma} \left(\frac{\nu_t}{h} \frac{\partial u}{\partial \sigma} \right) + hu_s S, \end{aligned} \quad (2)$$

$$\begin{aligned} & \frac{\partial hv}{\partial t} + \frac{\partial huv}{\partial x'} + \frac{\partial hv^2}{\partial y'} + \frac{\partial huv}{\partial \sigma} \\ & = -fuh - gh \frac{\partial \eta}{\partial y'} - \frac{h}{\rho_0} \frac{\partial p_a}{\partial y'} - \frac{hg}{\rho_0} \int_z^\eta \frac{\partial \rho}{\partial y} dz \\ & \quad - \frac{1}{\rho_0} \left(\frac{\partial s_{yx}}{\partial x} + \frac{\partial s_{yy}}{\partial y} \right) + hF_v + \frac{\partial}{\partial \sigma} \left(\frac{\nu_t}{h} \frac{\partial v}{\partial \sigma} \right) + hv_s S, \end{aligned} \quad (3)$$

where t represents time; x' , y' , and σ are the three-dimensional coordinates in the sigma coordinate system, representing the eastward, northward, and vertical directions, respectively; η is the water surface elevation, d is the still water depth, h is the total water depth with $h = \eta + d$; u , v and w are the velocity components along the x' , y' , and σ axes, respectively; $f = 2\Omega \sin \varphi$ is the Coriolis parameter (Ω is the rotational angular velocity, φ is the geographic latitude); g is the acceleration due to gravity; ρ is the water density; s_{xx} , s_{xy} , s_{yx} , and s_{yy} are the components of the radiation stress tensor; ν_t is the vertical turbulent viscosity; p_a represents the atmospheric pressure at sea level; ρ_0 is the reference density of the water; S is the flow rate of point sources; (u_s, v_s) are the flow velocities into adjacent water bodies; F_u, F_v are the

horizontal pressure terms.

3.2 Hydrodynamic modeling

The hydrodynamic model simulation covered the period from October 2020 to December 2021, conducting a numerical simulation of the hydrodynamic processes of Poyang Lake for the entire year of 2021. The daily measured flow data from seven hydrological stations on the five inflow rivers are used as upstream open boundary conditions, while daily water level data from the Hukou Station, where the northern channel meets the Yangtze River, are used as downstream open boundary conditions. To satisfy the requirements for model stability and computational accuracy, the computational domain of Poyang Lake was determined based on the maximum water surface in May. Constrained by the Courant condition, the model's minimum time step was limited to 0.01 s, with a computational time step chosen to be 30 s. The 2010 measured (5 m \times 5 m) spatial resolution DEM elevation data were interpolated onto 20516 triangular meshes, with mesh resolutions ranging from 80 m in the river channels to 1400 m in the floodplain (Fig. 2). The model was vertically divided into 5 equidistant sigma layers, with spatial resistance specified by variable roughness heights in vegetation areas, marshlands, and permanent water bodies (Li et al., 2018).

The initial water flow velocity for the entire model domain was set to zero, and the computational domain of Poyang Lake was determined based on the maximum water surface in May. The model employed wetting and drying numerical options and followed the rule of

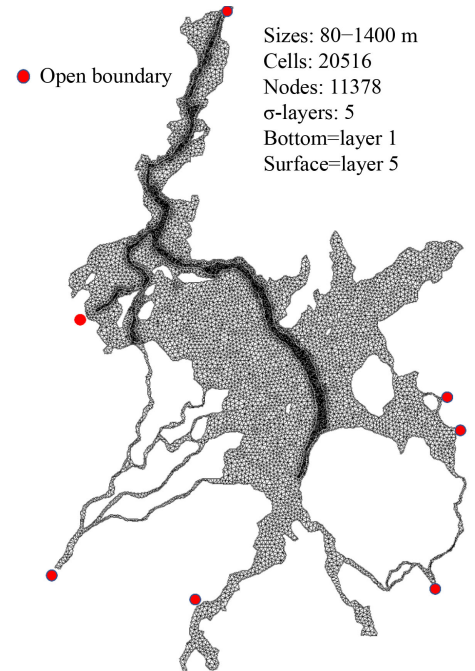


Fig. 2 Computational domain, mesh grid and open boundary for MIKE 3 model.

h_{dry} (0.005 m) < h_{flood} (0.05 m) < h_{wet} (0.1 m) (DHI, 2012). The horizontal eddy viscosity was represented by the Smagorinsky formula, and the vertical eddy viscosity by the standard k - ε turbulence model, solving the transport equations for turbulent kinetic energy and energy dissipation. Table 1 lists the other key parameters used in the current three-dimensional hydrodynamic model of Poyang Lake. These parameters are referenced from published studies on Poyang Lake by Li et al. (2017, 2018).

4 Model validations

This study employs the coefficient of determination (R^2) and root mean square error (RMSE) as evaluation metrics to calibrate the model's accuracy in terms of water level and water area. A comparison was made between daily measured water level data and model simulation data from four observation stations in the lake area: Kangshan, Tangyin, Duchang, and Xingzi. The hydrodynamic model's accuracy showed R^2 values of 0.96 at Kangshan, 0.98 at Tangyin, 0.99 at Duchang, and 0.99 at Xingzi. Regarding RMSE values, Kangshan is 0.38 m, Tangyin 0.30 m, Duchang 0.33 m, and Xingzi 0.25 m, with all

Table 1 Key parameters used in the 3D MIKE model

Parameters	Values
Smagorinsky factor for eddy viscosity	0.28
Wind friction	0.001255
Roughness heights/m	0.02–0.3
Critical CFL	0.8
Prandtl number for turbulent kinetic energy	1.0
Prandtl number for dissipation of turbulent kinetic energy	1.3

stations having RMSE values below 0.4 m. In addition, the Mean Relative Error (MRE) values were calculated. The MRE values are 2.06% for Xingzi, 2.82% for Duchang, 1.88% for Tangyin, and 2.55% for Kangshan, indicating excellent performance in amplitude and phase comparison to observed results during the simulation period, as shown in Fig. 3.

As illustrated in Figs. 4 and 5, the water body area simulated by the model and extracted from remote sensing imagery matched well. The simulation error in water area during low water levels was greater than during high water levels due to various factors. One aspect is that the simulation accuracy is affected by the computational grid size and lakebed topography, particularly in drought seasons with severe and complex boundary changes. Additionally, the accuracy of water body extraction from remote sensing is influenced by the adaptive threshold segmentation algorithm and the spatial resolution of the images, especially during periods of low water when the water body range is smaller.

Figure 6 shows the coverage of water area under different water levels during four periods in the simulation as depicted by both the model simulation and satellite imagery. Figure 6 indicates that the simulated water area of Poyang Lake in 2021 had good consistency with remote sensing images in terms of spatiotemporal variation patterns, particularly during high water levels. The comparisons and analysis demonstrate that the modeling results are reliable and have high confidence.

5 Results and analyses

5.1 Hydrodynamic forcing

Poyang Lake experiences significant seasonal variations. These include pronounced annual cycles in water level,

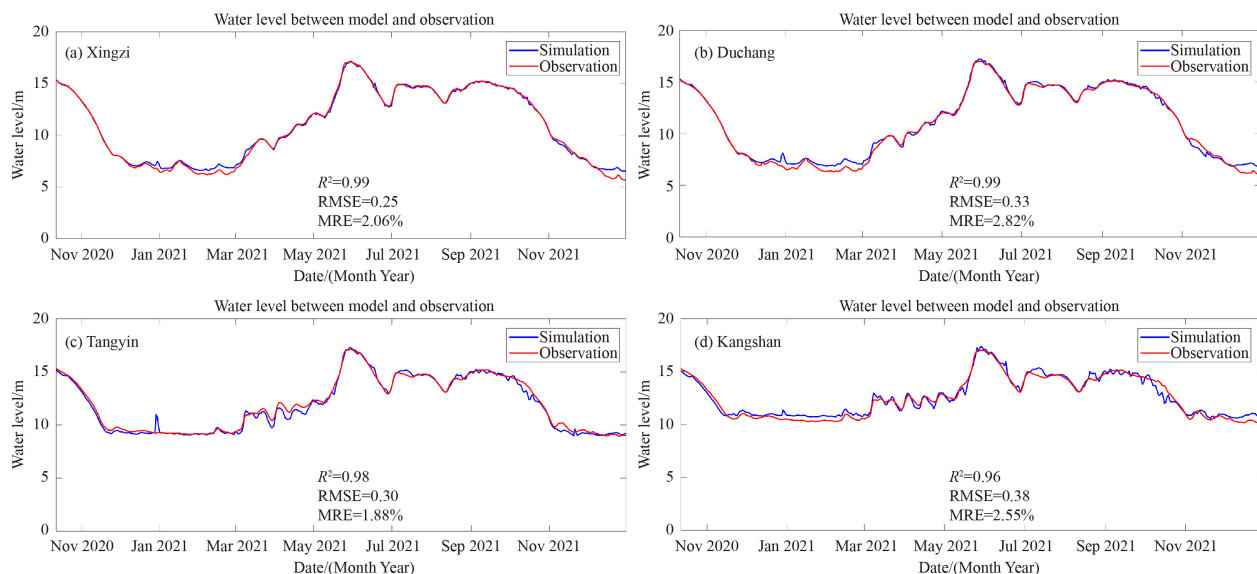


Fig. 3 Comparison of the time series of simulated and observed water levels at four lake area stations in Poyang Lake.

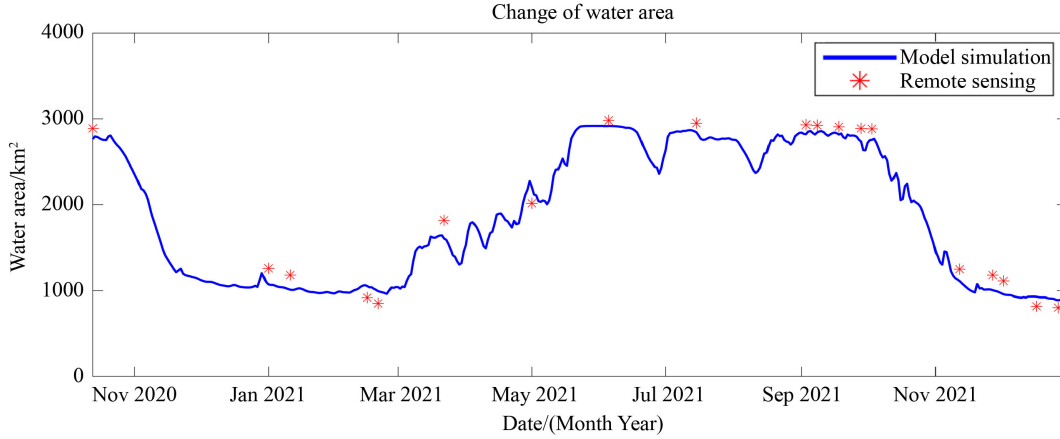


Fig. 4 Comparison of time series between water area calculations from the model and remote sensing imagery.

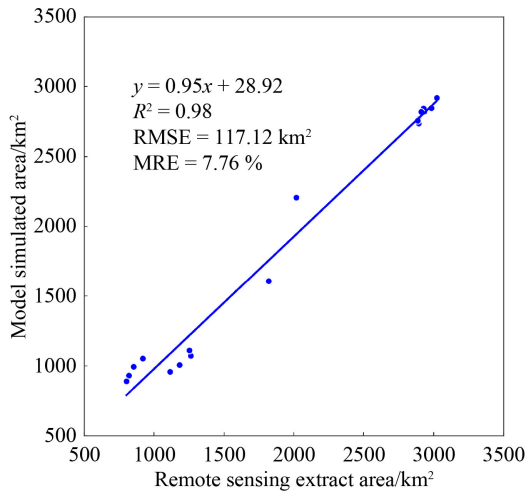


Fig. 5 The correlation between the water body areas calculated by the model and those determined from remote sensing imagery.

area coverage, and velocity (Zhang et al., 2018). The primary factors influencing these variations are the inflows from five major upstream rivers and the water levels at Hukou, the lake's outlet to the Yangtze River (Lai et al., 2014; Li et al., 2022b). Figure 7 presents the monthly flow rates at six stations across these rivers, highlighting the impact of water discharge on the lake. The data indicates strong river flows at Waizhou, Meigang, and Lijiadu, in contrast to relatively weaker flows at Dufengkeng, Hushan, Wanjiabu, and Qiuji. This demonstrates the varied impact of the five rivers on the lake's hydrodynamics. Table 2 lists the annual river discharges into Poyang Lake from these rivers in 2021. It reveals that the Ganjiang and Xinjiang Rivers, located to the west and south of the lake, respectively, are the most significant hydrological forces.

For Poyang Lake, momentum analysis indicates that the pressure gradient force is the dominant driving term in the motion equations (Eqs. (2) and (3), as identified in Xu et al. (2023). From the modeling outputs, we calculate the water elevation gradient, which corresponds to the

pressure gradient force, differing only by a constant factor of gravitational acceleration. The negative gradient of water elevation can be described as follows:

$$-\frac{\partial \eta}{\partial x} = -\frac{1}{g} \frac{\partial P}{\partial x}, \quad (4)$$

$$-\frac{\partial \eta}{\partial y} = -\frac{1}{g} \frac{\partial P}{\partial y}, \quad (5)$$

where P represents the water pressure, g is a constant representing gravitational acceleration, and η denotes the water elevation. Figure 8 illustrates the bi-monthly negative water elevation gradient for 2021, demonstrating the variations in pressure gradient forcing over the course of the year. The left panel of the figure displays the negative elevation gradient in the x -direction, while the right panel presents the gradient in the y -direction.

In January and February, the pressure gradient force exhibits positive values in the x -direction, indicating an eastward force in Poyang Lake, except in the main channel on the east side of the lake (Fig. 8(a)). In the y -direction, the pressure gradient is mostly negative across the lake, with positive values downstream of the Ganjiang River (Fig. 8(b)). During these months, the flow rate gradually increases, particularly in the Ganjiang River (as indicated by the Waizhou station, Fig. 7(e)), leading to a rising water elevation on the west side of Poyang Lake. This rise might be causing the eastward pressure gradient force and the corresponding eastward velocity pattern (not shown).

In March and April, the eastward pressure gradient force strengthens on the west side of Poyang Lake, responding to the continued increase in river flow and water elevation of the Ganjiang River. Negative pressure gradient forces appear north-east of the lake between north of Duchang and Tangying (Fig. 8(c), Fig. 1). Figure 8(c) shows a clear boundary separating eastward and westward pressure gradient forces in the central area of Poyang Lake. East of the lake, the eastward pressure

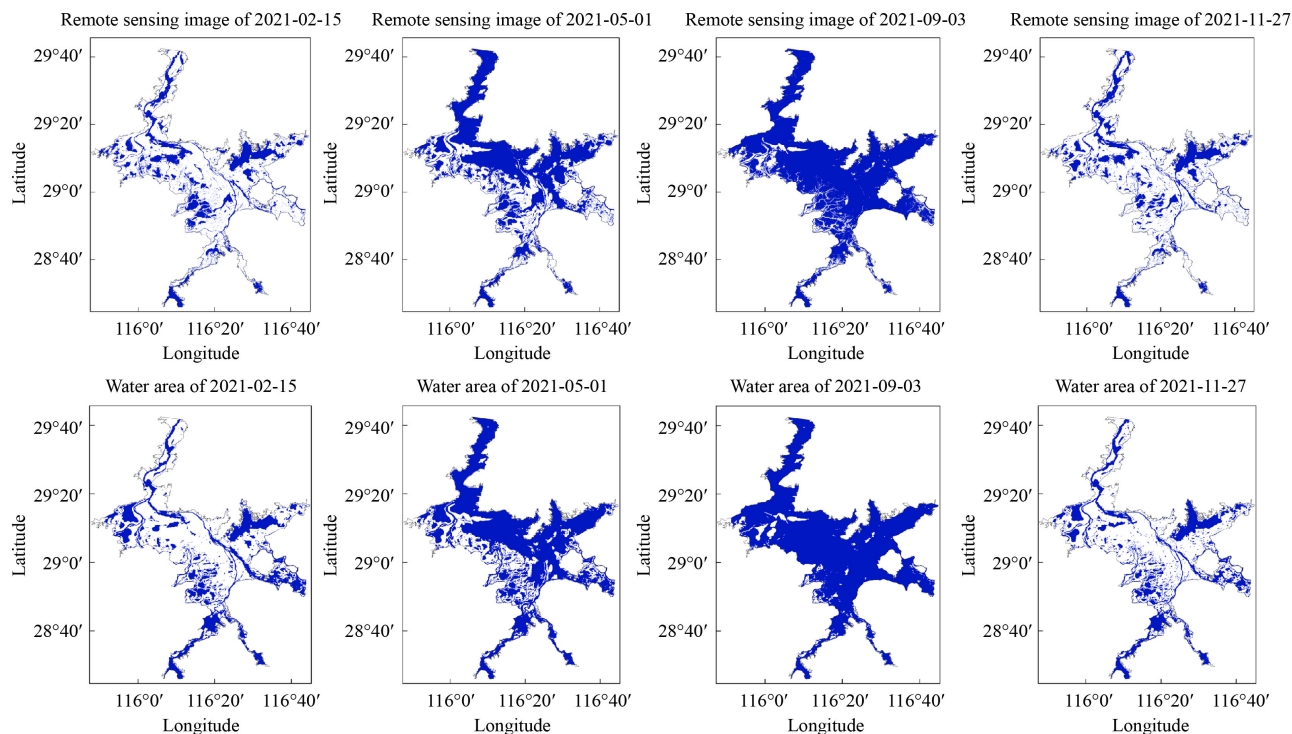


Fig. 6 Spatial distribution and comparison of water bodies as simulated by the model and water areas extracted from remote sensing.

gradient corresponds to increased flow from the Ganjiang River on the west side. In the y -direction, most of the central lake area exhibits positive, northward forcing (Fig. 8(d)), while the east side still shows negative, southward pressure gradients. This suggests that water dynamics in this area are mainly influenced by the Ganjiang River, with lesser impact from the Xinjiang River on the south side.

In May and June, as the flow rates of both the Ganjiang and Xinjiang Rivers decline, the x -direction pressure gradient force becomes negative, indicating a westward direction in most of the lake area (Fig. 8(e)). The boundary between positive and negative pressure gradients shifts toward the inlets of the Ganjiang River on the west side. The y -direction shows a similar pattern with a predominant southward pressure gradient, except in some small regions along the river channel (Fig. 8(f)).

In July and August, the patterns of pressure gradient forcing are similar to those in May and June in both x and y directions (Figs. 8(g) and 8(h)). During these months, the inflows from the Ganjiang and Xinjiang Rivers remain relatively stable compared to May and June, with a slight decrease in the intensity of the negative pressure gradient. Correspondingly, the north-eastward velocity in the lake also declines (not shown).

In September and October, the pressure gradient force is positive in the x -direction (Fig. 8(i)), reflecting an increase in flow rate from October to November. In the y -direction, the pressure gradient is negative, indicating a southward direction (Fig. 8(j)). This suggests that the

flow increase in the Ganjiang River might be dominating the hydrodynamics in Poyang Lake, while the flow in the Xinjiang River remains weak, and the southward pressure gradient predominates over most of the lake area.

In November and December, the pressure gradient force in the x -direction is positive and eastward, except in the main river channel of the lake. In the y -direction, the predominant force is southward in most of the lake area, turning northward in the river channel. This pattern is similar to that observed in January and February.

Based on the forcing analysis, it's evident that the hydrodynamic properties of Poyang Lake are predominantly influenced by water inflow from the Ganjiang River in most of the lake area. In contrast, the southward inflow from the Xinjiang River primarily controls the hydrodynamics along the lake main channel. This characteristic becomes more pronounced in the winter season when the water is largely confined to the main channel.

The hydrodynamic forcing intensifies during the spring months of March and April, coinciding with substantial increases in river discharges. During this period, there is a distinct boundary between eastward and westward forcing, corresponding to the increasing flow from the Ganjiang River. This may suggest the presence of a water elevation trough along the pressure gradient boundary, leading to the formation of a front between two water masses. One of these masses is the fresh river inflow from the Ganjiang River, while the other comprises the older river waters from the Xinjiang River and the Raohe

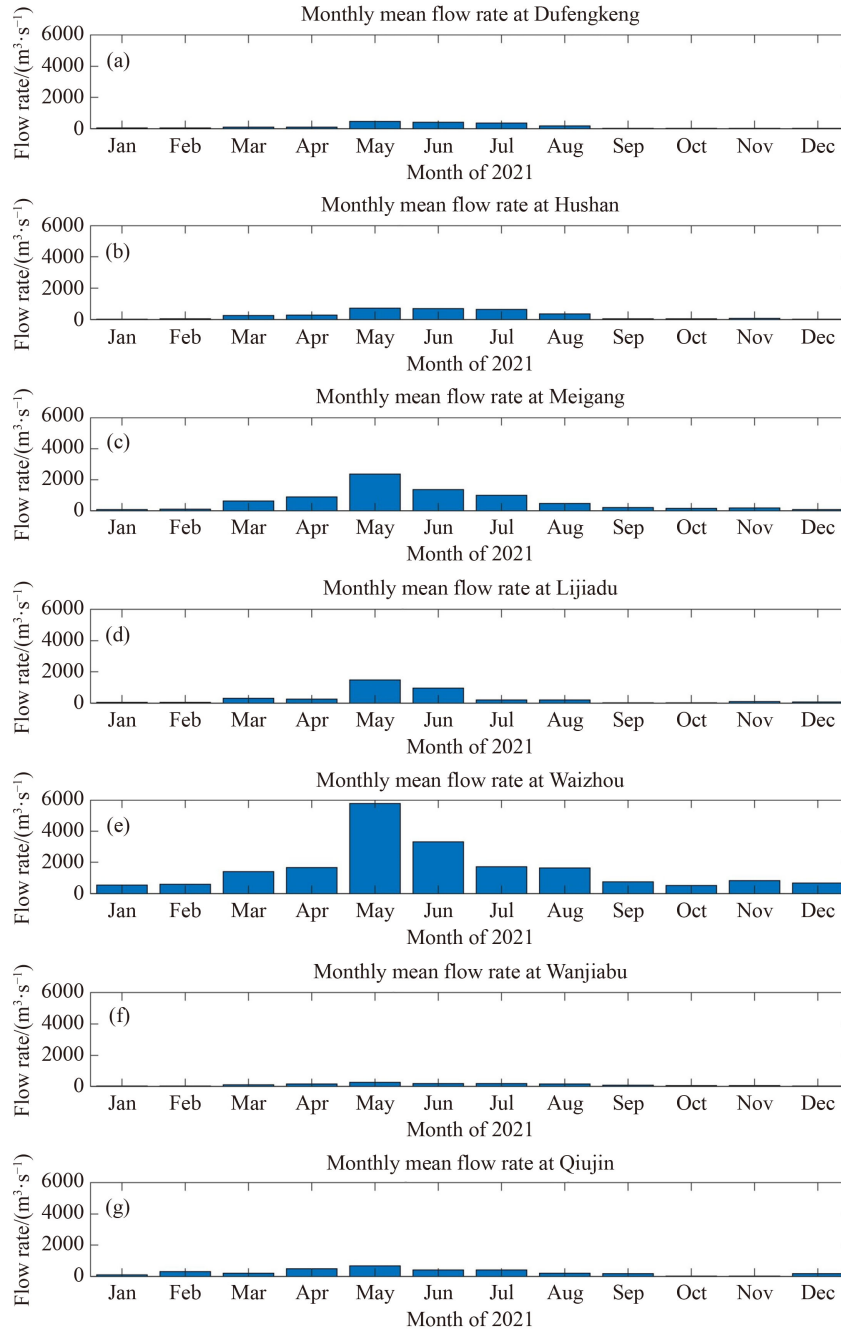


Fig. 7 Monthly flow rate at the 7 hydrological stations.

River. This interaction between different water masses and their respective forces plays a critical role in shaping

the hydrodynamic behavior of Poyang Lake, particularly during seasons of significant flow variation.

Table 2 Annual river discharges from the five major rivers into Poyang Lake

River	Annual river discharge/($\times 10^{10} \text{ m}^3$)
Ganjiang River (Wanzhou)	5.08
Xinjiang River (Meigang)	2.00
Fuhe River (Lijiadu)	0.98
Raohe River (Dufengkang, Hushan)	1.32
Xiushui River (Qiujin, Wanjiabu)	1.22

5.2 Eddy kinetic energy

Compared to other major lakes in China, Poyang Lake displays a high level of energy, characterized by abundant hydrodynamic features such as eddies (Li et al., 2022a). These eddies, with their substantial kinetic energy, can transport water masses and various materials, distributing them throughout the lake area, beyond the confines of the main channel (Meunier et al., 2018). This results in a

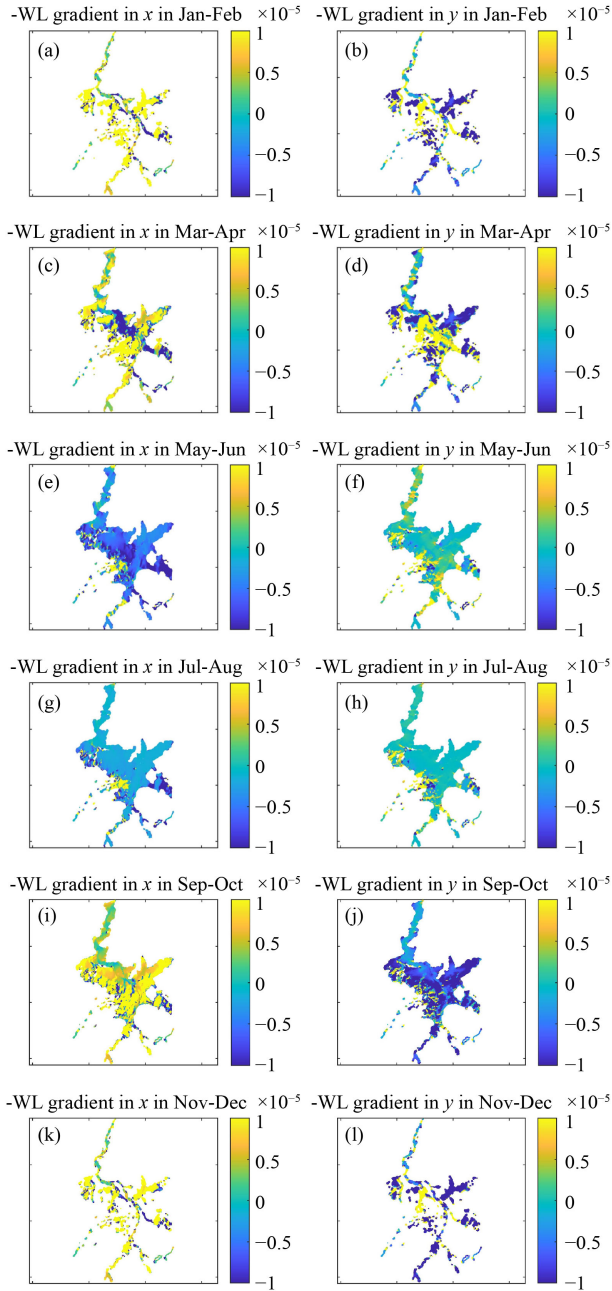


Fig. 8 The negative elevation gradient in x (left panel) and y directions (right panel) in January–February (a, b), March–April (c, d), May–June (e, f), July–August (g, h), September–October (i, j), November–December (k, l).

notable variability in the water mass and material composition within the lake. In this study, we broaden the definition of an eddy to encompass variations in water velocity, which are indicative of general variability in kinetic energy. To analyze this aspect, we define the kinetic energy of the eddies as follows:

$$Ke = \frac{1}{2} \rho [(u - \bar{u})^2 + (v - \bar{v})^2], \quad (6)$$

where Ke represents the kinetic energy of an eddy per

unit volume at the water surface. The variables, \bar{u} and \bar{v} signify the average velocities in the x - and y -directions, respectively, over a specific period. In this case, a 7-day interval is used for the calculations. Additionally, when computing velocity anomalies using Eq. (6), the overall trend in velocity is removed to isolate the fluctuations due to eddies. The bimonthly analysis of eddy energy for the year 2021 has been carried out using this methodology and the results are presented in Fig. 9. This figure illustrates the spatial and temporal variations in eddy kinetic energy within Poyang Lake, providing insights into how these dynamic features contribute to the distribution of water masses and materials within the lake over different periods of the year.

Figure 9 illustrates the seasonal variations in eddy kinetic energy within Poyang Lake throughout the year 2021. In January and February, the eddy field is relatively less energetic, displaying low kinetic energy. This suggests a period of relative hydrodynamic calm in the lake during these months. During May and June, there is a noticeable increase in the eddy kinetic energy, covering larger areas of the lake. This heightened activity is particularly evident on the west side of the lake near the Ganjiang River inlet and on the south side at the Xinjiang River inlet, indicating more dynamic water movement due to increased river inflows. In July and August, the overall kinetic energy of eddies decreases compared to May and June. However, there is a concentration of high

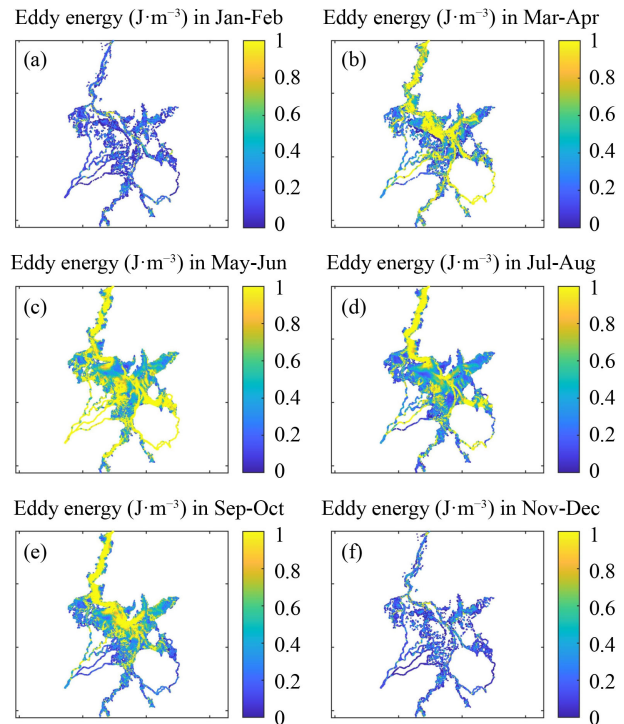


Fig. 9 The eddy kinetic energy in January–February (a), March–April (b), May–June (c), July–August (d), September–October (e), and November–December (f).

eddy kinetic energy in the water channel stretching from north of Duchang to Hukou, the outlet to the Yangtze River. This could be due to the changing flow patterns in the lake during these months. September and October see another increase in the eddy kinetic energy, with the area of high energy expanding around the middle of the lake, particularly near Duchang. This suggests a resurgence of hydrodynamic activity in the autumn months. Finally, in November and December, the eddy kinetic energy substantially decreases, reaching levels comparable to those observed in January and February. This marks a return to a less energetic state in the lake's hydrodynamics as the year closes. These observations highlight the significant seasonal fluctuations in hydrodynamic energy within Poyang Lake, influenced by various factors such as river inflows and the lake's connection to the Yangtze River.

The spatial analysis of eddy kinetic energy in Poyang Lake suggests distinct seasonal patterns in its distribution and intensity. In May and June, the kinetic energy reaches its maximum, with high values covering the largest area within the lake. This extensive distribution of kinetic energy indicates a period of heightened hydrodynamic activity. During these months, the increased kinetic energy facilitates the widespread dispersion of water masses and materials throughout the lake, contributing to dynamic changes in the lake's hydrology and ecology. Another peak in kinetic energy is observed in September and October. This increase aligns with the rise in flow rates typically seen in September. The elevated kinetic energy during these months again leads to more pronounced movement and mixing of water and materials within the lake. This could be due to seasonal variations in river inflows or other climatic factors influencing the lake's hydrodynamics (Zhan et al., 2019). These findings highlight the significant role of kinetic energy in shaping the hydrodynamic behavior of Poyang Lake, particularly in terms of material transport and distribution across different seasons.

To further elucidate the variation of eddy kinetic energy in Poyang Lake, five specific locations representing different parts of the lake were selected for analysis, as depicted in Fig. 10. The kinetic energy variations at these locations are illustrated in Fig. 11. At Location 1, close to the Ganjiang River inlet, high kinetic energy is observed primarily between May and July, and again around September, as per Fig. 11(a). This indicates the significant impact of the Ganjiang River inflow on eddy activity in this area. Location 2, positioned in the central part of the lake between Duchang and Tangyin, shows large eddy kinetic energy early in the year, between March and May. However, it doesn't display a notable increase in eddy kinetic energy during September, as seen in Fig. 11(b). This suggests different hydrodynamic influences compared to Location 1. Location 3, situated in the eastern part of the lake, displays its maximum eddy

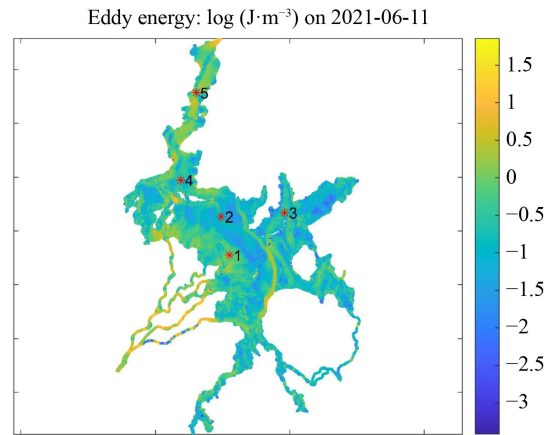


Fig. 10 Locations 1-5 represent different areas of Poyang Lake.

kinetic energy values in May, with elevated levels also in October and November, according to Fig. 11(c). This pattern indicates a varied temporal distribution of eddy activity in this region. Location 4, in the upper part of the central lake, reveals multiple peaks of high eddy kinetic energy in May, October, August, and November, as shown in Fig. 11(d). This area appears to be particularly active in terms of eddy movements. Finally, Location 5, in the north channel of the lake, experiences high eddy kinetic energy from August to November, while the kinetic energy in the spring months is comparatively low, as depicted in Fig. 11(e). This area has a distinct seasonal pattern, with more active eddy dynamics in the latter half of the year.

These observations from different locations within Poyang Lake highlight the complex and varied nature of eddy activities across the lake, influenced by factors such as river inflow, lake morphology, and seasonal changes (Du et al., 2018; Huang et al., 2021). Generally, Poyang Lake experiences two distinct periods of high eddy kinetic energy: one during the spring months and the other in the autumn. In the southern part of the lake, the spring months are predominant in terms of eddy activity throughout the year. In contrast, the northern channel, particularly near Hukou, witnesses its peak activity in the autumn. This pattern suggests that in the central area of the lake, the transport of mass and materials by eddies is more likely to occur in the spring. Conversely, in the northern channel of the lake, such transport is most pronounced in the autumn. This spatial and temporal variation in eddy activity reflects the complex interplay of hydrodynamic forces within different regions of Poyang Lake, influenced by seasonal changes in water inflow and other environmental factors.

The variance spectra of eddy kinetic energy at five locations in Poyang Lake, as shown in Fig. 12, exhibit distinct frequency patterns unique to each location. At Location 1, the peak cycle of eddy kinetic energy occurs in the low-frequency range of approximately 5 cycles per year, corresponding to a period of 2.4 months, with a

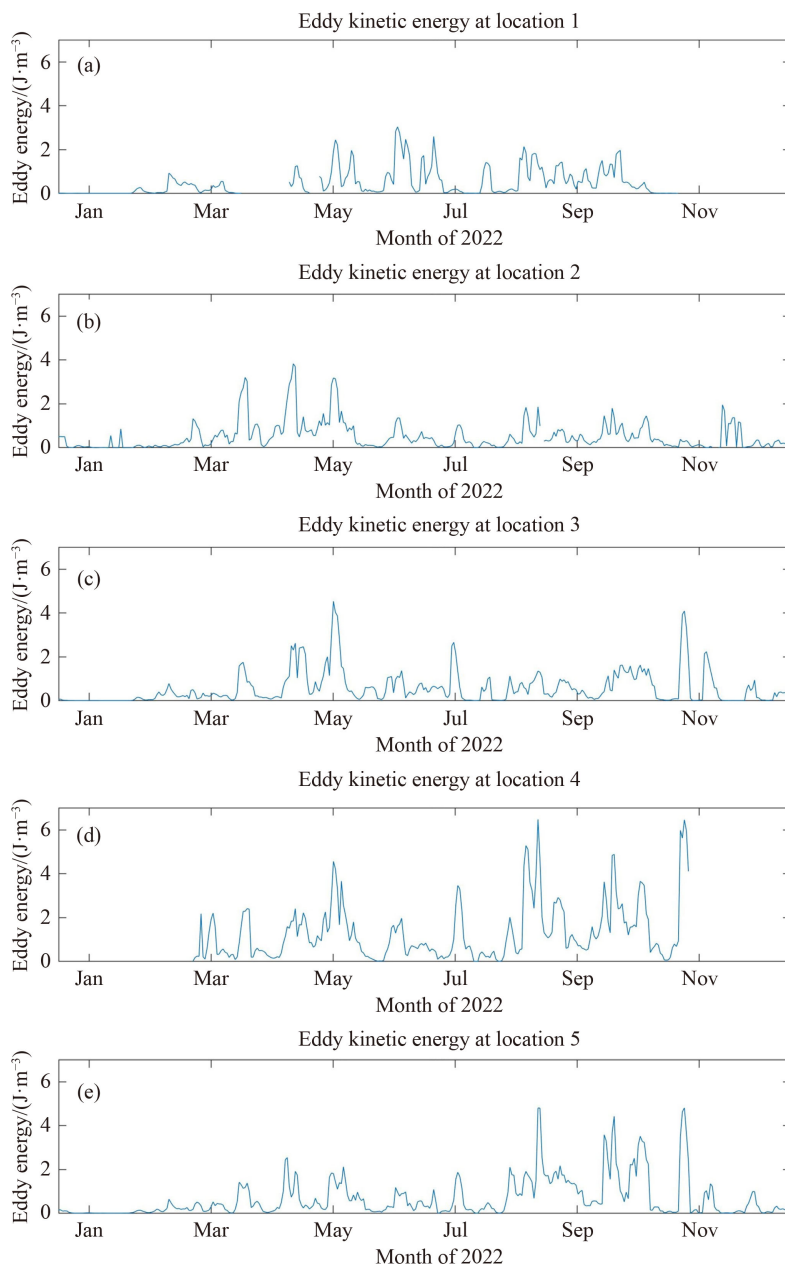


Fig. 11 Eddy kinetic energy in 2021 in Poyang Lake at Locations 1 (a), 2 (b), 3 (c), 4 (d), and 5 (e).

secondary peak at 16.4 cycles per year or a 3-week period. This suggests a strong influence of the Ganjiang River's water flow, leading to more frequent eddy activities. Location 2 displays a lower peak frequency than Location 1, with a frequency of 2.6 cycles per year and a period of 4.6 months. The next notable peak occurs at 6.5 cycles per year, indicating a period of 1.9 months. This pattern suggests less frequent but more prolonged eddy activity compared to Location 1. At Location 3, the dominant frequency appears at 1.3 cycles per year with a longer period of 9.0 months, followed by a peak at 6.6 cycles per year with a 1.8-month period. This indicates even less frequent but more sustained eddy activity. Location 4 shows an increased peak frequency of 3.2

cycles per year, with a secondary peak at 11.2 cycles per year. The respective periods are 3.8 months and 1.0 month, suggesting more varied eddy activity. Finally, at Location 5, the first and second peaks are observed at 2.9 and 7.2 cycles per year, with periods of 4.1 and 1.7 months, respectively. This pattern reflects a balance between the frequency and duration of eddy activity, similar to Location 4.

6 Discussions

The dynamics of Poyang Lake, including its forcing and eddy kinetic energy, play a crucial role in shaping the

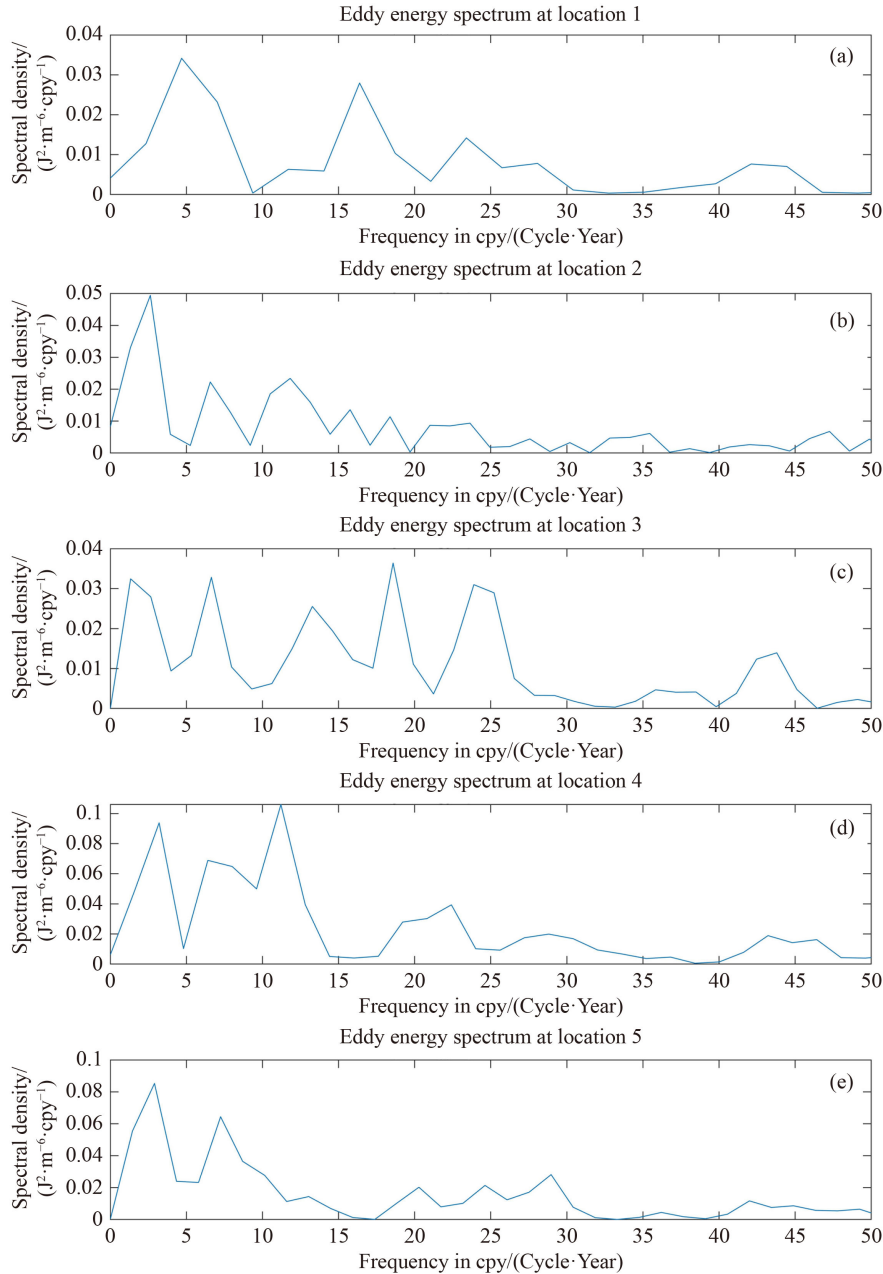


Fig. 12 The variance spectra of the eddy energy at Locations 1 (a), 2 (b), 3 (c), 4 (d), and 5 (e).

spatial distribution of materials within the lake (Razmi et al., 2013; Xu et al., 2023). This is particularly evident in the distribution of lake turbidity, which serves as an indicator of suspended sediments (van Wijk et al., 2023). Figure 13 provides insights into the turbidity distribution in Poyang Lake for the months of May and July, as derived from satellite imagery. In May, the turbidity of Poyang Lake is widely dispersed across a large area, with high values observed in the central and eastern parts of the lake, as well as in the western part near the inlet of the Ganjiang River. This widespread distribution of turbidity reflects the dynamic nature of the lake during this period, influenced by the energetic eddy kinetic energy patterns. By July, the distribution of turbidity becomes more

concentrated, particularly in the northern channel of the lake and in the north-west central part, between Duchang and Tangyin. This change in turbidity distribution aligns with the eddy kinetic energy patterns observed in May–June and July–August. During these months, areas with high turbidity correspond to regions of energetic kinetic energy. The correlation between the turbidity distribution and the eddy kinetic energy patterns in Poyang Lake suggests that eddy activities are instrumental in the transport of suspended sediments. Eddies, with their dynamic movements, can effectively redistribute sediments across different areas of the lake, influencing the overall turbidity and thus impacting the lake’s ecological and hydrological characteristics.

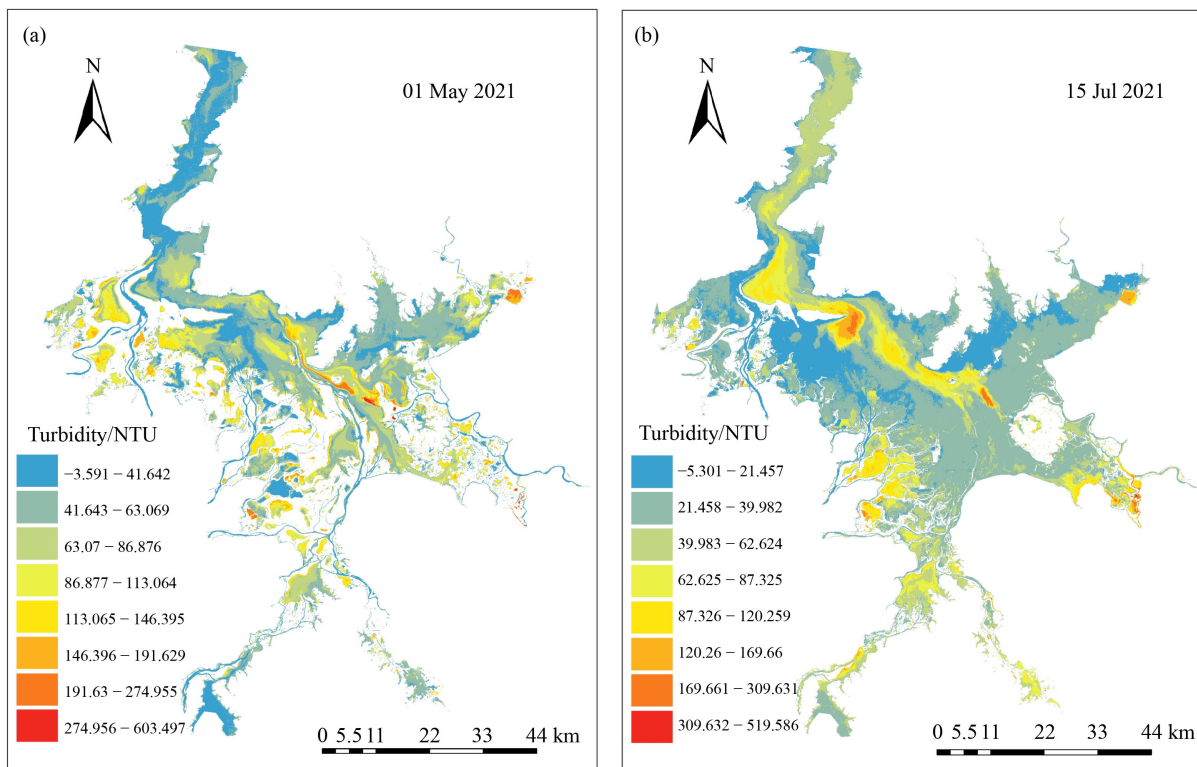


Fig. 13 Turbidity patterns in Poyang Lake on 1 May 2021 (a) and 15 July 2021 (b).

The analysis of eddy kinetic energy in Poyang Lake reveals that it reaches its maximum values in May and June. Interestingly, the spatial pattern of this kinetic energy correlates with the magnitude of the pressure gradient during the same months (though this is not shown in the provided figures). This correlation suggests that the heightened eddy activities in May and June could be driven by pressure gradient forcing. However, it's noteworthy that while the pressure gradient forcing peaks in March and April, the maximum eddy kinetic energy is observed one or two months later. This delay indicates a sequence where the pressure gradient initially enhances the lake's velocities. Subsequently, as the water levels and water area in Poyang Lake increase, the eddy activities intensify. In the northern channel of the lake, particularly north of Xingzi, the eddy kinetic energy is consistently high. Yet, the pressure gradient forcing in this area is relatively low. This discrepancy suggests that the strong eddy activities in the northern channel are not directly related to the pressure gradient forcing. Instead, the high velocities in this part of the lake are likely the primary contributors to the elevated kinetic energy observed there. Therefore, different mechanisms appear to influence eddy activity in various parts of Poyang Lake. In some areas, pressure gradients play a significant role, while in others, such as the northern channel, local velocity patterns are more influential. This complexity highlights the dynamic nature of the lake's hydrodynamics and the factors influencing material transport and

distribution within it.

7 Conclusions

In this study, the hydrodynamic properties of Poyang Lake were simulated using the three-dimensional MIKE model, covering the period from October 2020 to December 2021. The model's results were validated against observed water level data and satellite-derived measurements of the lake's water area. The high R^2 values, greater than 0.96 for water level comparisons and 0.98 for water area comparisons, demonstrate the model's accuracy in replicating the hydrodynamics of Poyang Lake.

The hydrodynamic forcing in the model is determined from the gradient of water elevations. A key finding is that the maximum pressure gradient forcing occurs in March and April, coinciding with significant increases in flowrate in the Ganjiang River. This pressure gradient is influenced by the influx of river water from the Ganjiang River on the east side of Poyang Lake. During March and April, a pressure gradient forcing front is observed along the deep channel in the central lake area between Duchang and Tangyin, potentially trapping lake material compositions along this front.

Additionally, the eddy kinetic energy was calculated using velocity data from the model outputs. The highest levels of eddy kinetic energy are found in May and June, facilitating the widespread distribution of water mass and

materials across the lake. Another peak in kinetic energy occurs in September and October, likely in response to the increased flow rates in September. Frequency analysis indicates that the eddy kinetic energy in the central area of the lake is predominantly influenced by local dynamic properties characterized by low frequencies and extended periods. This contrasts with other lake areas where different factors might be at play. Moreover, the consistency between the turbidity patterns observed in satellite images for May and July and the distributions of eddy kinetic energy underlines the impact of eddy activities on the spatial distribution of water materials in Poyang Lake. This suggests a strong correlation between hydrodynamic activities, specifically eddy movements, and the distribution of suspended materials within the lake.

Acknowledgments This study was supported by National Key R&D Program of China (No. 2021YFB3900400).

Competing interests The authors declare that they have no competing interests.

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