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太湖风生流的三维数值模拟

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提要 建立了太湖三维风生流数值模型，并用差分法求解；垂直方向上采用了坐标变换技术，把任一节点的水深转换成无量纲水深，从而有效地消除了因风力作用造成的自由水面波动和湖底不规则的影响；水平面上采用锯齿网格处理，对于四周以闭边界为主的湖泊水域，显得比较合理。计算结果表明，湖泊风生流沿垂直、水平方向都有较大变化，流向上下、水平也并不一致，这是湖泊水流区别于其它水域水流之所在。计算模拟显示所建模型的有效性和可操作性。

关键词 太湖 风生流 数值模拟 增减水 拟合变换

1 引 言

太湖南北长 68.5km，东西平均宽 34km，湖盆呈浅碟形(图1)，平均水深 1.89m。太湖地处北亚热带和中亚热带的过渡带，盛行东南风，加上湖陆风的影响，湖泊水面在风力作用下往往出现明显增减水现象，迎风面水位因增水而抬高，背风面水位则因减水而下降，因此，形成湖流流速、流向的变化[1]，对出入湖河道的水流也产生影响，甚至会改变原先的流场。正确地模拟太湖风生流，不仅对了解太湖本身的水文物理特征，而且对出入湖泊的河网地区的洪水预报、水质分析都具有重要意义[2]。

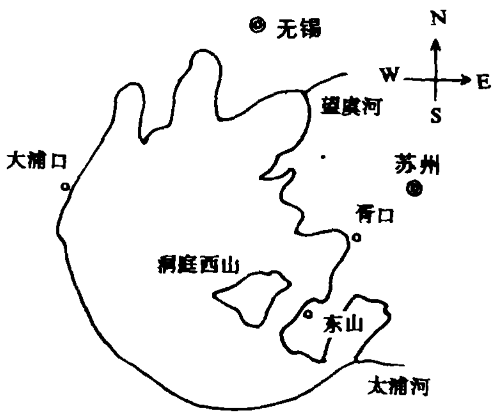

图1 太湖示意图
Fig. 1 Sketch map of Taihu Lake

2 数值模型

把太湖划分为 1750m×1750m 的正方形网格，平面边界取锯齿形；在垂向上把水深转换成无量纲水深，并均匀分成四层，再求其三维水流模型的差分解。

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2.1　基本方程

由于太湖为一浅水湖泊，温度上下的差异可以忽略。假定湖水等密度分布，并假定垂向服从静水压力分布，用笛卡尔坐标系下的三维水流方程来描述湖泊风生流的三维流动，略去相对较小项，方程可改写为：

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial u}{\partial z}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=f_0v-\frac{1}{\rho}\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}(N_x\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}(N_y\frac{\partial u}{\partial y})+\frac{1}{\rho}\frac{\partial \tau_{zx}}{\partial z} \tag{2}$$

$$\frac{\partial v}{\partial z}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-f_0u-\frac{1}{\rho}\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}(N_x\frac{\partial v}{\partial x})+\frac{\partial}{\partial y}(N_y\frac{\partial v}{\partial y})+\frac{1}{\rho}\frac{\partial \tau_{zy}}{\partial z} \tag{3}$$

$$\frac{\partial P}{\partial z}+\rho g=0 \tag{4}$$

式中：u、v、w 分别表示为 x、y、z 方向上的流速分量(m/s)；

g 为重力加速度(m/s^2)；

f_0 为柯氏系数($f_0=2\omega\sin\varphi$，ω 为地球自转速度，φ 为地理纬度)；

P 为水压强(kN/m^2)；

N_x、N_y 分别为 x、y 方向的涡动粘性系数(本文取 $100m^2/s$)；

ρ 为水密度(kg/m^3)；

τ_{zx}、τ_{zy}分别为 x、y 方向流速剪切变形引起的附加切应力(kN/m^2)。

2.2　差分求解

2.2.1　垂向坐标的拟合变换[4]

众所周知，天然水体中，自由表面的非恒定流动和床面地形的不规则变化对水流影响较大，必须精确模拟。本文采用一个新的坐标系(x，y，z^*，t)，以便使网格能连续跟踪自由表面的运动，精确地拟合自由表面和床面边界；对湖泊边界则采用锯齿边界。在(x，y，z^*，t)中定义无量纲 z^* 为：

$$z^*=(z+h)/H \tag{5}$$

式中，H 为整层水深($H=\xi+h$)，ξ 为湖面相对平均水面的高度，h 为平均水深(m)。

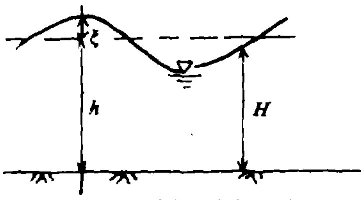

图 2　水深、水位示意图

Fig. 2　Coordinate system showing the depth and water level

借助于(5)式，可将(x，y，z，t)坐标系中随时间变化的流动区域变换到新坐标系(x，y，z^*，t)中限制在两个水平面之间的固定计算域(图 3)。

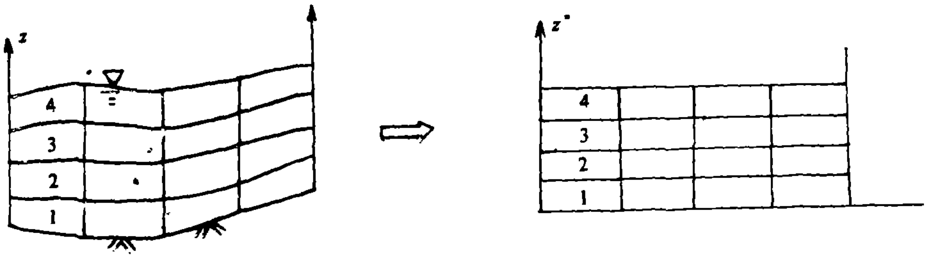

图 3　从(x，y，z，t)到(x，y，z^*，t)变换下的网格变化

Fig. 3　Grid regularization from (x，y，z，t) to (x，y，z^*，t)

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在新坐标下,定义一个新的流速分量:

$$w^* = \frac{\partial z^*}{\partial t} + u\frac{\partial z^*}{\partial x} + v\frac{\partial z^*}{\partial y} + w\frac{\partial z^*}{\partial z} \tag{6}$$

由(5)可得:

$$\frac{\partial z^*}{\partial z} = \frac{1}{H} \tag{7}$$

略去变换后由水平扩散项引出的派生项,则第 k 层水体在新坐标系下的运动方程为:

$$\frac{\partial \xi}{\partial t} + \sum_{k=1}^{4} H\left[\frac{\partial}{\partial x}(\Delta z^* u_k) + \frac{\partial}{\partial y}(\Delta z^* v_k)\right] = 0 \tag{8}$$

$$\frac{\partial u_k}{\partial t} + u_k\frac{\partial u_k}{\partial x} + v_k\frac{\partial u_k}{\partial y} + w_k^*\frac{\partial u_k}{\partial z^*} = f_0 v_k - g\frac{\partial \xi}{\partial x} + N_x\frac{\partial^2 u_k}{\partial x^2} + N_y\frac{\partial^2 u_k}{\partial y^2} + \frac{1}{\rho H\Delta z^*}\cdot(\tau_{x,k+1/2} - \tau_{x,k-1/2}) \tag{9}$$

$$\frac{\partial v_k}{\partial t} + u_k\frac{\partial v_k}{\partial x} + v_k\frac{\partial v_k}{\partial y} + w_k^*\frac{\partial v_k}{\partial z^*} = -f_0 u_k - g\frac{\partial \xi}{\partial y} + N_x\frac{\partial^2 v_k}{\partial x^2} + N_y\frac{\partial^2 v_k}{\partial y^2} + \frac{1}{\rho H\Delta z^*}\cdot(\tau_{y,k+1/2} - \tau_{y,k-1/2}) \tag{10}$$

$$w_{k+1/2}^* = w_{k-1/2}^* - \Delta z^*\cdot\left(\frac{\partial u_k}{\partial x} + \frac{\partial v_k}{\partial y}\right) \tag{11}$$

式中,Δz^*为垂向无量纲空间步长。

2.2.2 *差分格式* 模型采用交错网格,取横向和纵向等间距为 1750m,即 $\Delta x = \Delta y = 1750$m,并令 $\Delta s = \Delta x = \Delta y$,水平流速 u、v 和垂向流速都定义在网格边线的中点(图 4)。

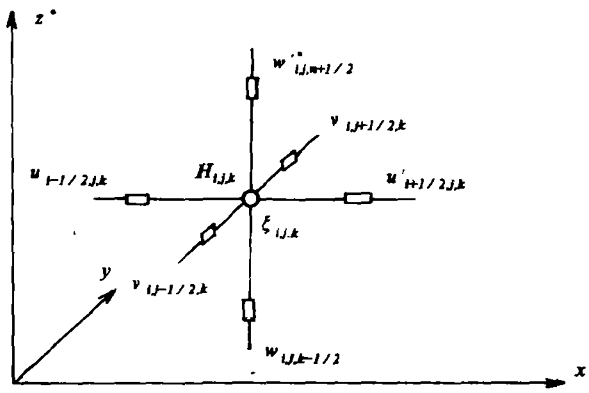

图4 网格与流速点布置图

Fig. 4 Diagram of grids and velocity discretization

在水流方程求解中,平面采用显式中心差分,垂向采用隐式中心差分,水面计算采用预测校正方法[5]。差分格式如下:

$$u_{i,j,k} = \frac{u_{i-1/2,j,k} + u_{i+1/2,j,k}}{2} \tag{12}$$

$$v_{i,j,k} = \frac{v_{i,j-1/2,k} + v_{i,j+1/2,k}}{2} \tag{13}$$

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$$w^*_{i,j,k} = \frac{w^*_{i,j,k-\frac{1}{2}} + w^*_{i,j,k+\frac{1}{2}}}{2} \tag{14}$$

$$\left.\frac{\partial u}{\partial t}\right|_{i,j,k} = \frac{u^{n+1}_{i,j,k} - u^n_{i,j,k}}{\Delta t} \tag{15}$$

$$\left.\frac{\partial v}{\partial t}\right|_{i,j,k} = \frac{v^{n+1}_{i,j,k} - v^n_{i,j,k}}{\Delta t} \tag{16}$$

$$\left.\frac{\partial u}{\partial x}\right|_{i,j,k} = \frac{u_{i+\frac{1}{2},j,k} - u_{i-\frac{1}{2},j,k}}{\Delta x} \tag{17}$$

$$\left.\frac{\partial v}{\partial x}\right|_{i,j,k} = \left(\frac{v_{i+1,j,k} + v_{i,j,k}}{2} - \frac{v_{i,j,k} + v_{i-1,j,k}}{2}\right)/\Delta x \tag{18}$$

$$\left.\frac{\partial u}{\partial y}\right|_{i,j,k} = \left(\frac{u_{i,j+1,k} + u_{i,j,k}}{2} - \frac{u_{i,j,k} + u_{i,j-1,k}}{2}\right)/\Delta y \tag{19}$$

$$\left.\frac{\partial v}{\partial y}\right|_{i,j,k} = \frac{v_{i,j+\frac{1}{2},k} - v_{i,j-\frac{1}{2},k}}{\Delta y} \tag{20}$$

$$\left.\frac{\partial u}{\partial z^*}\right|_{i,j,k} = \left(\frac{u_{i,j,k+1} + u_{i,j,k}}{2} - \frac{u_{i,j,k} + u_{i,j,k-1}}{2}\right)/\Delta z^* \tag{21}$$

$$\left.\frac{\partial v}{\partial z_*}\right|_{i,j,k} = \left(\frac{v_{i,j,k+1} + v_{i,j,k}}{2} - \frac{v_{i,j,k} + v_{i,j,k-1}}{2}\right)/\Delta z^* \tag{22}$$

$$\left.\frac{\partial \xi}{\partial x}\right|_{i,j,k} = \left(\frac{\xi_{i+1,j,k} + \xi_{i,j,k}}{2} - \frac{\xi_{i,j,k} + \xi_{i-1,j,k}}{2}\right)/\Delta x \tag{23}$$

$$\left.\frac{\partial \xi}{\partial y}\right|_{i,j,k} = \left(\frac{\xi_{i,j+1,k} + \xi_{i,j,k}}{2} - \frac{\xi_{i,j,k} + \xi_{i,j-1,k}}{2}\right)/\Delta y \tag{24}$$

$$\left.\frac{\partial^2 u}{\partial x^2}\right|_{i,j,k} = \frac{u_{i+1,j,k} + u_{i-1,j,k} - 2u_{i,j,k}}{\Delta x^2} \tag{25}$$

$$\left.\frac{\partial^2 u}{\partial y^2}\right|_{i,j,k} = \frac{u_{i,j+1,k} + u_{i,j-1,k} - 2u_{i,j,k}}{\Delta y^2} \tag{26}$$

$$\left.\frac{\partial^2 v}{\partial x^2}\right|_{i,j,k} = \frac{v_{i+1,j,k} + v_{i-1,j,k} - 2v_{i,j,k}}{\Delta x^2} \tag{27}$$

$$\left.\frac{\partial^2 v}{\partial y^2}\right|_{i,j,k} = \frac{v_{i,j+1,k} + v_{i,j-1,k} - 2v_{i,j,k}}{\Delta y^2} \tag{28}$$

$$\left.\frac{\partial w^*}{\partial z^*}\right|_{i,j,k} = \frac{w^*_{i,j,k+\frac{1}{2}} - w^*_{i,j,k-\frac{1}{2}}}{\Delta z^*} \tag{29}$$

方程(8)的预测差分方程为：

$$\hat{\xi}^{n+1} = \xi^n - \frac{\Delta t}{\Delta s}H\left[\sum_{k=1}^{4}\Delta z^*(u^n_{i+\frac{1}{2},j,k} - u^n_{i-\frac{1}{2},j,k}) - \sum_{k=1}^{4}\Delta z^*(v^n_{i,j+\frac{1}{2},k} - v^n_{i,j-\frac{1}{2},k})\right] \tag{30}$$

校正差分方程为：

$$\xi^{n+1} = \frac{1}{2}\hat{\xi}^{n+1} + \frac{1}{2}\left\{\xi^n - \frac{\Delta t}{\Delta s}H\left[\sum_{k=1}^{4}\Delta z^*(u^{n+1}_{i+\frac{1}{2},j,k} - u^n_{i-\frac{1}{2},j,k}) - \sum_{k=1}^{4}\Delta z^*(v^{n+1}_{i,j+\frac{1}{2},k} - v^n_{i,j-\frac{1}{2},k})\right]\right\} \tag{31}$$

把(12)—(19)式代人(9)、(10)、(11)式中各对应的项中，即可得到各自对应的差分方程，其

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中(11)式用隐式差分,其余各式用显式中心差分。

水面计算第一步采用时间前差,空间中心差,显式求出$(n+1)\Delta t$时刻的各点水深,以此作为$(n+1)\Delta t$时刻水深的预测值,并求出$(n+1)\Delta t$时刻的速度场,以新得到的$(n+1)\Delta t$时刻的速度场和$n\Delta t$时刻的速度场,再用校正方程(31)求出$(n+1)$时刻的水深,并再次计算速度场,通过误差控制,反复计算,然后再进行下一时间步长的计算,以消除不稳定性,并达到提高精度的目的。

2.3 **定解条件**[3]

2.3.1 *边界条件* 由于进、出入太湖的河道流量都不大[1],最大的望虞河、太浦河流量平均在200—300m³/s,相对太湖这一水体,它对短期风生流的模拟影响不大,因而本文不考虑所有进出入太湖的河道水流,x、y向边界都作为闭边界处理,即:

$$u=v=0,\quad \frac{\partial H}{\partial x}=\frac{\partial H}{\partial y}=0 \quad 或 \quad \frac{\partial \xi}{\partial x}=\frac{\partial \xi}{\partial y}=0$$

2.3.2 *床面切应力*

$$\tau_{x(i,j,1/2)}=\rho g u(u_{i,j,1}^2+v_{i,j,1}^2)^{1/2}/C^2$$
$$\tau_{y(i,j,1/2)}=\rho g v(u_{i,j,1}^2+v_{i,j,1}^2)^{1/2}/C^2$$

式中,C为谢才系数($C=\frac{1}{n}H_{i,j}^{1/6}$),$n$为糙率,本文取0.02。

2.3.3 *水面风切应力*

$$\tau_{x(i,j,k+1/2)}=\rho_a C_a w_x(w_x^2+w_y^2)^{1/2}$$
$$\tau_{y(i,j,k+1/2)}=\rho_a C_a w_y(w_x^2+w_y^2)^{1/2}$$

式中,ρ_a为空气密度($1.25\times10^{-3}g/cm^3$);C_a为风阻力系数,本文取2.56×10^{-6};w_x、w_y分别为10m高空x、y向的风速(m/s)。

2.3.4 *水体内部*

$$\tau_{x(i,j,k-1/2)}=\rho\gamma_i^2(u_{i,j,k}-u_{i,j,k-1})\cdot[(u_{i,j,k}-u_{i,j,k-1})^2+(v_{i,j,k}-v_{i,j,k-1})^2]^{1/2}$$
$$\tau_{y(i,j,k-1/2)}=\rho\gamma_i^2(v_{i,j,k}-v_{i,j,k-1})\cdot[(u_{i,j,k}-u_{i,j,k-1})^2+(v_{i,j,k}-v_{i,j,k-1})^2]^{1/2}$$

式中,γ_i^2为内部界面阻力系数,取0.0001。

2.3.5 *初始条件* 取水位变幅和初始流速为零,即:

$$\xi_{i,j}|_{t=0}=0$$
$$u_{i,j,k}|_{t=0}=0$$
$$v_{i,j,k}|_{t=0}=0$$
$$w_{i,j,k}^*|_{t=0}=0$$

3 计算与分析

用1988年太湖东山站7月20—21日以及1988年8月26—27日的风速、风向资料对胥口(湖东南)和大浦口(湖西北)两水位站水位进行了计算与实测对比(图5),其中,7月20—21日风向主体是W和SW,8月26—27日之间风向变化过程为S→SSW→WNW→W,风速绝对值在4.5m/s左右变化,实测风向在几小时内有时变化较大。由计算结果可知,计算

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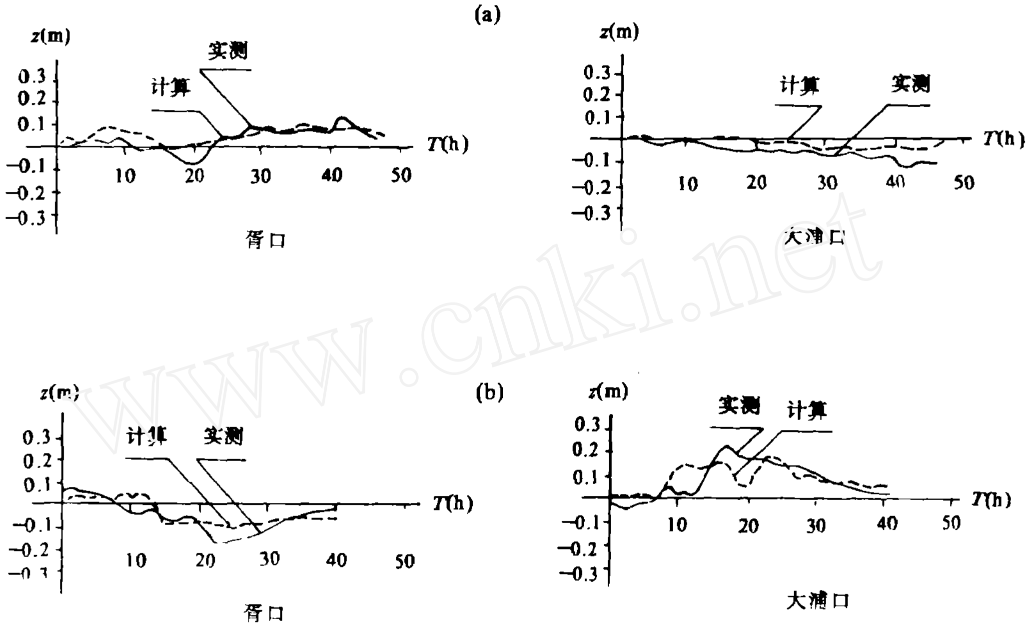

图5　1988年7月20—21日(a)、8月26—27日(b)计算与实测水位过程
Fig. 5　Comparison between calculated and observed water level in July 20—21(a), and Aug. 26—27 (b), 1988

与实测水位是比较吻合的(图5)。

计算与实测之间所以有一定的差异，其原因主要是东山站偏于太湖的东南处，西南方又有洞庭西山与它紧邻，因而用东山站的风速、风向来代表整个太湖的风速、风向还不太准确；另外，由于条件限制，本文中所选资料为一小时一次的瞬时风速、风向值，有一定的跳动性。当风向偏转22.5°时，由此会造成结果上的不正常的跳动。

本文模拟了太湖上空为14m/s的东南风持续20小时的情况，大浦口、胥口水位的计算结果如图6所示。20小时后即水位基本稳定条件下的不同层流场分布见图7，图中(a)、(b)、(c)、(d)分别是由上至下四个层面的流场图，可以看出表层水流流速较大，流向与风向一致；

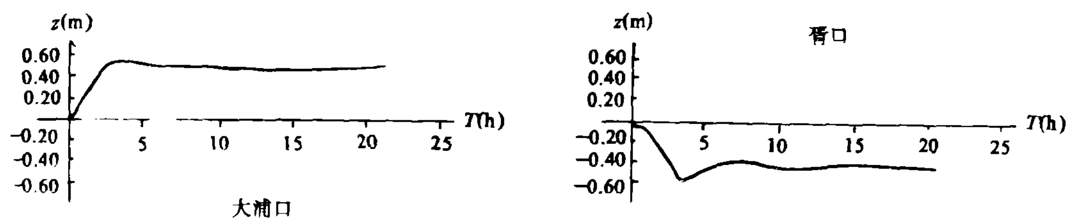

图6　$w=14$m/s(SE)时大浦口、胥口水位变化过程
Fig. 6　The calculated water level at Dapukou St. and Xukou St. under $w=14$ m/s, SE

第三、四层的流向与表层流向大致相反；第二层流向有较大变化。由于四个层面沿垂向均匀

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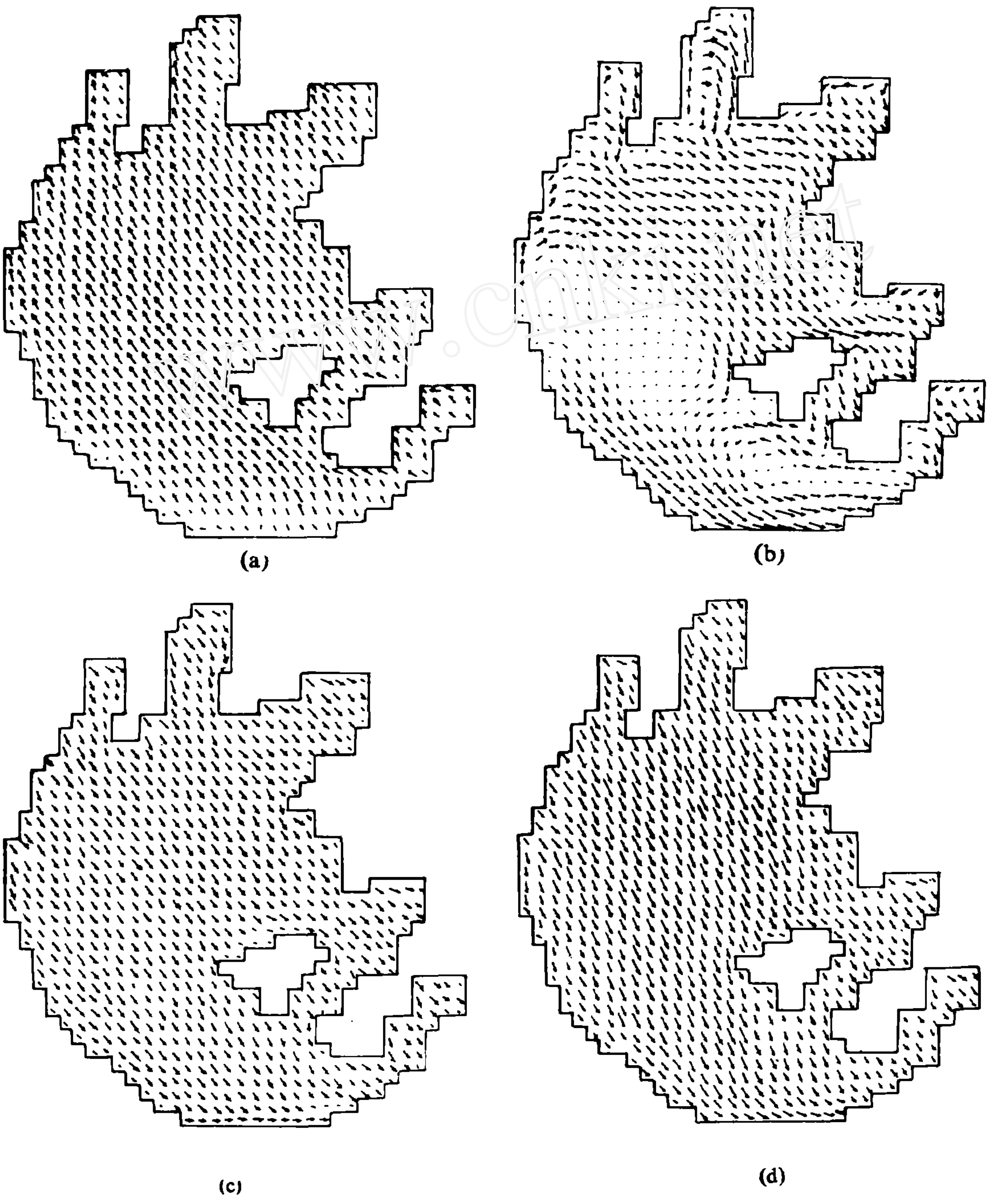

图 7　$w=14$m/s(SE)，$T=20$h 时流场图
(a)表层，网格单位：1.19m/s；(b)第二层，网格单位：0.31m/s；
(c)第三层，网格单位：0.95m/s；(d)底层，网格单位：0.31m/s
Fig. 7　Calculated velocity fields at the surface(a), second layer(b), third layer(c) and near bed(d) under $w=14$m/s(SE) for 20 hours

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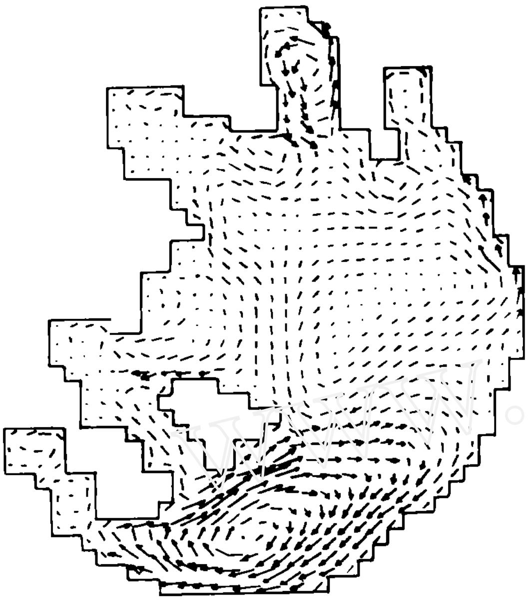

图8 u=11m/s(SE)，T=20h时
整层平均流场图(网格单位:0.21 m/s)
Fig.8 Depth-mean velocity field

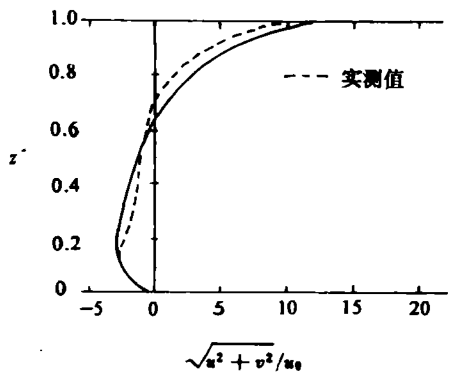

图9 文献[6]的实测结果
(u_0 为自由表面摩阻流速)
Fig.9 Vertical distribution of observed velocity from ref. [6]

分布，取对应垂线的四层流速的平均值作为其整层平均流速，流速场见图8。可以看出流速绝对值比表层和底层小，且流向不定，整个湖泊流场由多个环流组成。出现以上结果，主要原因是表层流向受风的作用而决定，因而表层水流主体方向必然与风向大体一致，水流稳定后，下层也就必然以补偿流而出现，这与文献[6]中的实测风生流垂向分布(图9)大体一致。由图9可以看出，表层与底层也呈相反趋势，这说明，本文结果大体是合理的。

4 结 语

(1) 由本文结果可以看出，湖泊风生流流态比较复杂，稳定后的湖流，表层流速较大，流向与风向一致；底层以补偿流为主，流速一般较小，且流向与表层湖流流向大体相反；水体中偏上层流向改变较大，这与国外的研究结果相比，是一致的。

(2) 大型湖泊风生流的模拟中，风的作用至关重要，因为它是湖流产生的主要动力，因而它的不稳定性会造成计算结果上的波状跳动；此外，风速、风向的代表性是模拟成功的关键，代表性的好坏直接影响到成果的精度，可能的话，用多点风速、风向来模拟风生流会更合理。

(3) 风生流造成湖泊增减水，湖泊周边水位的不断改变会导致湖泊周围河网中出入湖河道中水流的变化。由此也会影响到整个河网中流速、流向的改变，因此，平原河网模型中把湖泊看作一块水面水平的蓄水体不太准确[1]。

(4) 因条件限制，没有更准确详细的流速资料对模型验证，模型有待进一步验证。

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A THREE-DIMENSIONAL NUMERICAL SIMULATION OF WIND-DRIVEN WATER CURRENT IN TAIHU LAKE

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Abstract

A three-dimensional numerical simulation on wind-driven current in Tauhu Lake is developed in this paper, in which the finite difference method is used. A dimensionless vertical coordinate is applied for the vertical grid regulation so as to eliminate the impacts of the wind-induced water level fluctuation and the irregular lake bottom forms, whereas grids with saw-toothed boundaries is applied along the horizontal dimensions when supposing the boundaries of the lake are closed.

The wind data in July and August, 1988 are used in the numerical simulation of water level at Dapukou Station and Xukou Station. The comparison between the simulated and the observed results indicates certain consistancy. Further studies reveal that, when a constant 14 m/s SE wind dominates for 20 hours on the water surface, the water level at Dapukou St. increases 45 cm while the level at Xikou St. decreases 40 cm. The four-layer (surface, upper-middle, lower-middle, near bed) velocity fields obtained respectively show that the absolute velocity of the surface flow is about 1.2 m/s, while the bed flow is between 0.3—0.6 m/s but in the opposite direction. The simulation also reveals that the velocity field in the upper-middle layer change directions more frequently, which is in agreement with former researches done by foreigners.

In conclusion, the wind-driven currents in lakes are very complicated, the representativeness of wind data is an important factor that affects the accuracy of numerical simulation. That the wind-induced current directions are vertically inconsistent and the velocity fields along the horizontal dimensions not evenly distributed is the characteristics of lake flow differed from that of other water bodies.

Key Words Taihu Lake, wind-driven current, numerical simulation, increase and decrease of water level, finite difference method, simulation regulation

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