

中国科学院海洋研究所编辑

海洋科学集刊

STUDIA MARINA SINICA

Institute of Oceanology, Chinese Academy of Sciences

38

科学出版社

1997年10月

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海洋科学集刊

第 38 集

中国科学院海洋研究所 编辑

青岛市南海路 7 号

邮政编码: 266071

科学出版社出版

北京东黄城根北街 16 号

邮政编码: 100717

中国科学院印刷厂印刷

新华书店北京发行所发行 各地新华书店经售

*

1997 年 10 月第 一 版 开本: 787×1092 1/16

1997 年 10 月第一次印刷 印张: 16 插页: 2

印数: 1—800

字数: 335 000

ISBN 7-03-005840-2/P·969

定价: 32.00 元

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内潮的一种分层三维数值模式*

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在中国近海的不少海域曾经发现相当强的内潮现象,例如赵俊生(1992)报道了渤海海峡的内潮现象,Yamashiro(1988)在东海陆坡处亦发现内潮的存在。特别是 Amoco 石油公司在南海陆坡处进行了一年多的海流测量,测得最大的全日潮流振幅可超过 60 cm/s,这里正压潮流小于 10cm/s,故观测到的潮流主要与内潮有关。迄今关于内潮的数值模式大多将表面潮作为已知输入条件,从而使模式的应用受到较多限制(Jiang and Fang, 1992)。Heaps(1983)曾发展了一种自由海面多层模式,但他们忽略了非线性平流项,这无疑也会损失许多有用信息。本文将叙述一种自由海面的多层模式,它能够同时模拟表面潮和内潮,并包含了非线性平流项。

一、基本方程

我们把海洋分成 K 层,用 $k=1,2,\dots,K$ 记之。每层具有相同的海水密度 ρ_k ,即 ρ_k 与

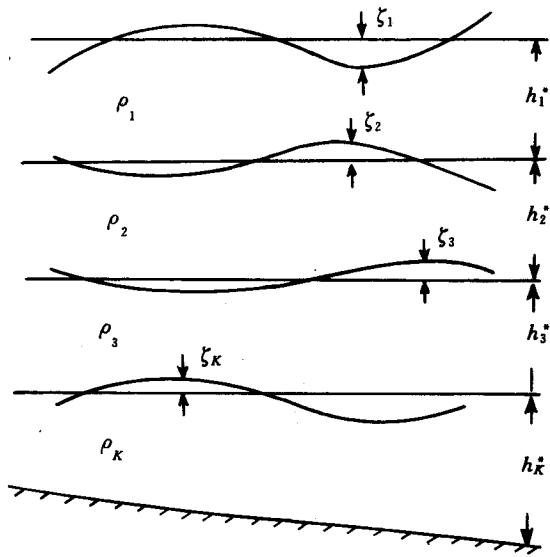


图 1 垂向分层

*中国科学院海洋研究所调查研究报告第 2878 号。本工作得到国家重点科技专项资助。
收稿日期:1996 年 3 月 7 日。

层号 k 有关,与水平位置 (x, y) 无关。各层静止时的厚度除底层外也只与 k 有关,与 (x, y) 无关,记为 $h_1^*, h_2^*, \dots$, 各层上界面的扰动高度记为 ζ_k (如图 1)。以 u_k 和 v_k 记各层水平流速的 x 和 y 方向分量; τ_{kx} 和 τ_{ky} 记第 k 层与第 $k+1$ 层之间摩擦力的 x 和 y 方向分量,特别地, τ_{1x}, τ_{1y} 和 τ_{Kx}, τ_{Ky} 分别为海面风应力和海底处摩擦力; h 为未扰动总水深, f 和 g 分别为 Coriolis 参量和重力加速度, P_a 为海面大气压, A 为水平湍粘系数,则基本方程可写为:

$$\begin{cases} \frac{\partial u_1}{\partial t} = -L_1(u_1) + fv_1 - g \frac{\partial \zeta_1}{\partial x} - \frac{1}{\rho_1} \frac{\partial p_a}{\partial x} + \frac{\tau_{1x} - \tau_{1x}}{h_1 + \zeta_1 - \zeta_2} + A\Delta u_1 \\ \frac{\partial v_1}{\partial t} = -L_1(v_1) - fu_1 - g \frac{\partial \zeta_1}{\partial y} - \frac{1}{\rho_1} \frac{\partial p_a}{\partial y} + \frac{\tau_{1y} - \tau_{1y}}{h_1 + \zeta_1 - \zeta_2} + A\Delta v_1 \\ \frac{\partial \zeta_1}{\partial t} = \frac{\partial \zeta_2}{\partial t} - \frac{\partial[(h_1 + \zeta_1 - \zeta_2)u_1]}{\partial x} - \frac{\partial[(h_1 + \zeta_1 - \zeta_2)v_1]}{\partial y} \end{cases} \quad (1.1)$$

$$\begin{cases} \frac{\partial u_2}{\partial t} = -L_2(u_2) + fv_2 - g \frac{\rho_1}{\rho_2} \frac{\partial \zeta_1}{\partial x} - g \frac{\rho_2 - \rho_1}{\rho_2} \frac{\partial \zeta_2}{\partial x} - \frac{1}{\rho_2} \frac{\partial p_a}{\partial x} + \frac{\tau_{1x} - \tau_{2x}}{h_2 + \zeta_2 - \zeta_3} + A\Delta u_2 \\ \frac{\partial v_2}{\partial t} = -L_2(v_2) - fu_2 - g \frac{\rho_1}{\rho_2} \frac{\partial \zeta_1}{\partial y} - g \frac{\rho_2 - \rho_1}{\rho_2} \frac{\partial \zeta_2}{\partial y} - \frac{1}{\rho_2} \frac{\partial p_a}{\partial y} + \frac{\tau_{1y} - \tau_{2y}}{h_2 + \zeta_2 - \zeta_3} + A\Delta v_2 \\ \frac{\partial \zeta_2}{\partial t} = \frac{\partial \zeta_3}{\partial t} - \frac{\partial[(h_2 + \zeta_2 - \zeta_3)u_2]}{\partial x} - \frac{\partial[(h_2 + \zeta_2 - \zeta_3)v_2]}{\partial y} \end{cases} \quad (1.2)$$

.....

$$\begin{cases} \frac{\partial u_K}{\partial t} = -L_K(u_K) + fv_K - g \frac{\rho_1}{\rho_K} \frac{\partial \zeta_1}{\partial x} - g \frac{\rho_2 - \rho_1}{\rho_K} \frac{\partial \zeta_2}{\partial x} - \dots \\ \quad - g \frac{\rho_{K-1} - \rho_{K-2}}{\rho_K} \frac{\partial \zeta_{K-1}}{\partial x} - g \frac{\rho_K - \rho_{K-1}}{\rho_K} \frac{\partial \zeta_K}{\partial x} \\ \quad - \frac{1}{\rho_K} \frac{\partial p_a}{\partial x} + \frac{\tau_{K-1x} - \tau_{Kx}}{h_K + \zeta_K} + A\Delta u_K \\ \frac{\partial v_K}{\partial t} = -L_K(v_K) - fu_K - g \frac{\rho_1}{\rho_K} \frac{\partial \zeta_1}{\partial y} - g \frac{\rho_2 - \rho_1}{\rho_K} \frac{\partial \zeta_2}{\partial y} - \dots \\ \quad - g \frac{\rho_{K-1} - \rho_{K-2}}{\rho_K} \frac{\partial \zeta_{K-1}}{\partial y} - g \frac{\rho_K - \rho_{K-1}}{\rho_K} \frac{\partial \zeta_K}{\partial y} \\ \quad - \frac{1}{\rho_K} \frac{\partial p_a}{\partial y} + \frac{\tau_{K-1y} - \tau_{Ky}}{h_K + \zeta_K} + A\Delta v_K \\ \frac{\partial \zeta_K}{\partial t} = - \frac{\partial[(h_K + \zeta_K)u_K]}{\partial x} - \frac{\partial[(h_K + \zeta_K)v_K]}{\partial y} \end{cases} \quad (1.3)$$

其中,

$$L_k(a) = \frac{\partial}{\partial x}(u_k a) + \frac{\partial}{\partial y}(v_k a), \quad \Delta a = \frac{\partial^2 a}{\partial x^2} + \frac{\partial^2 a}{\partial y^2} \quad (1.4)$$

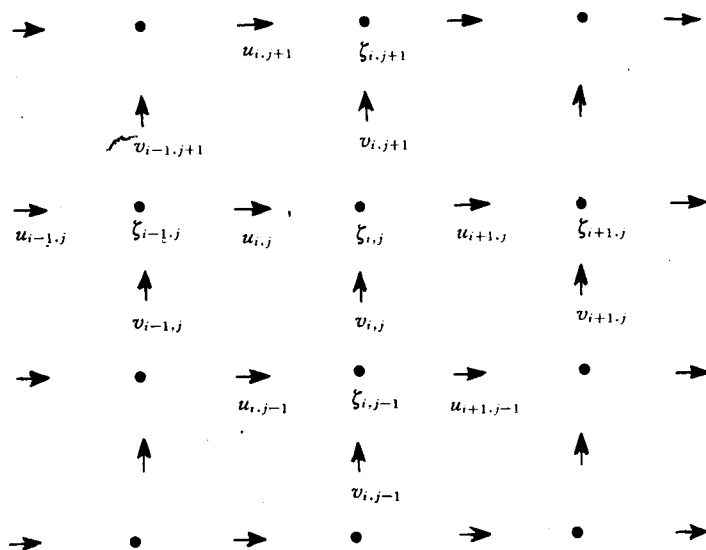


图2 水平网格点配置图

u 点: $h'(i, j), K'(i, j), h'_1(i, j), h'_2(i, j), h'_3(i, j), \beta'(i, j), g'_2(i, j), g'_3(i, j), \tau_{xx}(i, j),$
 $u(i, j), u_1(i, j), u_2(i, j), u_3(i, j), Q_x(i, j)$

v 点: $h''(i, j), K''(i, j), h''_1(i, j), h''_2(i, j), h''_3(i, j), \beta''(i, j), g''_2(i, j), g''_3(i, j), \tau_{yy}(i, j),$
 $v(i, j), v_1(i, j), v_2(i, j), v_3(i, j), Q_y(i, j)$

此外,在模式中包含有下列参数:

$\rho_1, \rho_2, \rho_3, h_1^*, h_2^*, g, f, A, C, \Delta x, \Delta y, \Delta t, T_x (= \Delta t / (2\Delta x)), T_y (= \Delta t / (2\Delta y)), C_r (= f\Delta t / 2), v_2, v_3$

其中 v_2 和 v_3 为第一、二层之间及第二、三层之间的垂直湍粘系数。上列变量和参数的计算方法如下:

1. $\tilde{p} \equiv p_a / \rho_1$, 若 p_a 单位取 mb (即 hPa), 则 $\tilde{p} = p_a \div 102.5$, 单位: m.

2. 如水深 $h_{i,j}$ 在水平网格空格处 (即 $v_{i-1,j}$ 和 $v_{i,j}$ 之间, 亦即 $u_{i,j-1}$ 和 $u_{i,j}$ 之间) 给出, 则可事先算出 $h'_{i,j}$ 和 $h''_{i,j}$, 算完后 $h_{i,j}$ 即可不必保留。计算公式为

$$h'_{i,j} = (h_{i,j} + h_{i,j+1}) / 2, \quad h''_{i,j} = (h_{i,j} + h_{i+1,j}) / 2$$

3. K', h'_1, h'_2, h'_3 的确定方法如下:

若 $h''_{i,j} \leq h_1^*$, 则 $K'_{i,j} = 1, h'_{1i,j} = h'_{i,j}$

若 $h_1^* < h'_{i,j} \leq h_1^* + h_2^*$, 则 $K'_{i,j} = 2, h'_{1i,j} = h_1^*, h'_{2i,j} = h'_{i,j} - h_1^*$

若 $h_1^* + h_2^* < h'_{i,j}$, 则 $K'_{i,j} = 3, h'_{1i,j} = h_1^*, h'_{2i,j} = h_2^*, h'_{3i,j} = h'_{i,j} - h_1^* - h_2^*$

K'', h''_1, h''_2, h''_3 确定方法一样。

4. $g'_{2i,j} = g[h'_{2i,j}(\rho_2 - \rho_1)/\rho_2 + h'_{3i,j}(\rho_2 - \rho_1)/\rho_3]/h'_{i,j}$
 $g'_{3i,j} = g[h'_{3i,j}(\rho_3 - \rho_1)/\rho_3]/h'_{i,j}$
 $\beta'_{i,j} = [h'_{1i,j} + h'_{2i,j}(\rho_1/\rho_2) + h'_{3i,j}(\rho_1/\rho_3)]/h'_{i,j}$
 g''_2, g''_3, β'' 算法一样, 仅将 h', h'_k 换成 h'', h''_k 。

三、有限差分方程

设 $n\Delta t$ 时刻 ζ_1, u, v 已知, $n\Delta t$ 时刻 $u_k, v_k (k=1, 2, 3)$ 已知, $(n+1/2)\Delta t$ 时刻 $\zeta_k (k=2, 3)$ 已知, $(n+1/2)\Delta t$ 时刻 $\tilde{p}, \tau_{xx}, \tau_{xy}$ 已算出, 则下一个 Δt 时刻内的计算过程如下:

1. ζ_1, u, v 的计算

ζ_1, u, v 为与表面潮有关的量, 我们采用 Leendertse (1967) 的交替方向隐格式, 具体计算步骤如下:

(1) 第一个半步

(a) ζ_1, u , 用隐式计算, 方程组为

$$\begin{cases} A'_{i,j}\zeta_{1i-1,j}^{n+1/2} + B'_{i,j}u_{i,j}^{n+1/2} + C'_{i,j}\zeta_{1i,j}^{n+1/2} = F'_{i,j} \\ A_{i,j}u_{i,j}^{n+1/2} + B_{i,j}\zeta_{1i,j}^{n+1/2} + C_{i,j}u_{i+1,j}^{n+1/2} = F_{i,j} \end{cases} \quad (3.1)$$

其中

$$\begin{cases} A'_{i,j} = -T_x g \beta'_{i,j} \\ B'_{i,j} = 1 \\ C'_{i,j} = -A'_{i,j} \\ F'_{i,j} = u_{i,j}^n + (\Delta t/2) \{ f \bar{v}_{i,j} - Q_{xi,j} + A[(u_{i+1,j}^n + u_{i+1,j}^n - 2u_{i,j}^n)/\Delta x^2 \\ + (u_{i,j-1}^n + u_{i,j+1}^n - 2u_{i,j}^n)/\Delta y^2] \} \end{cases} \quad (3.2)$$

$$\begin{cases} A_{i,j} = -T_x h'_{i,j} \\ B_{i,j} = 1 \\ C_{i,j} = T_x h'_{i+1,j} \\ F_{i,j} = \zeta_{1i,j}^n - T_y (h''_{i,j+1} v_{i,j+1}^n - h''_{i,j} v_{i,j}^n) \end{cases} \quad (3.3)$$

式(3.2)中

$$\begin{aligned} Q_{xi,j} = & [g'_{2i,j}(\zeta_{2i,j}^{n+1/2} - \zeta_{2i-1,j}^{n+1/2}) + g'_{3i,j}(\zeta_{3i,j}^{n+1/2} - \zeta_{3i-1,j}^{n+1/2}) \\ & + \beta'_{i,j}(\tilde{p})_{i,j}^{n+1/2} - \tilde{p}_{i-1,j}^{n+1/2}]/\Delta x \\ & - \{ \tau_{xx,j}^{n+1/2} - C[(u_{K'i,j}^n)^2 + (\bar{v}_{K'i,j}^n)^2]^{1/2} u_{K'i,j}^n \}/h'_{i,j} \end{aligned} \quad (3.4)$$

(b) v 用显式计算, 公式为

$$\begin{aligned} v_{i,j}^{n+1/2} = & v_{i,j}^n - (\Delta t/2) \{ Q_{y,i,j} + g\beta''_{i,j}(\zeta_{1,i,j}^n - \zeta_{1,i,j-1}^n)/\Delta y \\ & + A[(v_{i-1,j}^n + v_{i+1,j}^n - 2v_{i,j}^n)/\Delta x^2 \\ & + (v_{i,j-1}^n + v_{i,j+1}^n - 2v_{i,j}^n)/\Delta y^2] \} \end{aligned} \quad (3.5)$$

式中

$$\begin{aligned} Q_{y,i,j} = & f\bar{u}_{i,j}^{n+1/2} + [g''_{2i,j}(\zeta_{2i,j}^{n+1/2} - \zeta_{2i,j-1}^{n+1/2}) + g''_{3i,j}(\zeta_{3i,j}^{n+1/2} - \zeta_{3i,j-1}^{n+1/2}) + \beta''_{i,j}(\tilde{p}_{i,j}^{n+1/2} - \tilde{p}_{i,j-1}^{n+1/2})]/\Delta y \\ & - \{ \tau_{syn,i,j}^{n+1/2} - C[(\bar{u}_{K^u,i,j}^n)^2 + (v_{K^u,i,j}^n)^2]^{1/2} v_{K^u,i,j}^n \} / h''_{i,j} \end{aligned} \quad (3.6)$$

(2) 第二半步

(a) ζ_1, v 用隐式计算, 方程组为

$$\begin{cases} A'_{i,j}\zeta_{i,j-1}^{n+1} + B'_{i,j}v_{i,j}^{n+1} + C'_{i,j}\zeta_{i,j}^{n+1} = F'_{i,j} \\ A_{i,j}v_{i,j}^{n+1} + B_{i,j}\zeta_{i,j}^{n+1} + C_{i,j}v_{i,j+1}^{n+1} = F_{i,j} \end{cases} \quad (3.7)$$

其中

$$\begin{cases} A'_{i,j} = -T_y g\beta''_{i,j} \\ B'_{i,j} = 1 \\ C'_{i,j} = -A'_{i,j} \\ F'_{i,j} = v_{i,j}^{n+1/2} - (\Delta t/2) \{ Q_{y,i,j} - A[(v_{i-1,j}^{n+1/2} + v_{i+1,j}^{n+1/2} - 2v_{i,j}^{n+1/2})/\Delta x^2 \\ + (v_{i,j-1}^{n+1/2} + v_{i,j+1}^{n+1/2} - 2v_{i,j}^{n+1/2})/\Delta y^2] \} \end{cases} \quad (3.8)$$

$$\begin{cases} A_{i,j} = -T_y h''_{i,j} \\ B_{i,j} = 1 \\ C_{i,j} = T_y h''_{i,j+1} \\ F_{i,j} = \zeta_{1,i,j}^{n+1/2} - T_x (h'_{i+1,j} u_{i+1,j}^{n+1/2} - h'_{i,j} u_{i,j}^{n+1/2}) \end{cases} \quad (3.9)$$

式(3.8)中 $Q_{y,i,j}$ 见式(3.6)。

(b) u 用显式计算, 公式为

$$\begin{aligned} u_{i,j}^{n+1} = & u_{i,j}^{n+1/2} + (\Delta t/2) \{ f\bar{v}_{i,j}^{n+1} - g\beta'_{i,j}(\zeta_{1,i,j}^{n+1/2} - \zeta_{1,i-1,j}^{n+1/2}) - Q_{x,i,j} \\ & + A[(u_{i-1,j}^{n+1/2} + u_{i+1,j}^{n+1/2} - 2u_{i,j}^{n+1/2})/\Delta x^2 + (u_{i,j-1}^{n+1/2} + u_{i,j+1}^{n+1/2} - 2u_{i,j}^{n+1/2})/\Delta y^2] \} \end{aligned} \quad (3.10)$$

上面各式中 $\bar{u}, \bar{v}$ 定义如下:

$$\bar{u}_{i,j} = (u_{i,j} + u_{i+1,j} + u_{i+1,j-1} + u_{i,j-1})/4, \bar{v}_{i,j} = (v_{i,j} + v_{i-1,j} + v_{i-1,j+1} + v_{i,j+1})/4 \quad (3.11)$$

2. $u_k, v_k (k=1, 2, 3), \zeta_k (k=2, 3)$ 的计算

(1) u_k, v_k 的计算

(a) u_k 的计算

若第 (i, j) 个 u 点的 $K'_{i,j} = 1$, 可直接取

$$u_{1i,j}^{n+1} = u_{1i,j}^n \quad (3.12)$$

若 $K'_{i,j} = 2$, 则

$$\begin{cases} \hat{u}_{1i,j}^{n+1} = (B_2 F_1 - C_1 F_2) / (1 - A_2 - C_1) \\ \hat{u}_{2i,j}^{n+1} = (B_2 F_2 - A_2 F_1) / (1 - A_2 - C_1) \end{cases} \quad (3.13)$$

式中

$$\begin{cases} C_1 = -2v_2 \Delta t / [h'_{1i,j} (h'_{1i,j} + h'_{2i,j})] \\ B_1 = 1 - C_1 \\ A_2 = C_1 h'_{1i,j} / h'_{2i,j} \\ B_2 = 1 - A_2 \\ F_1 = u_{1i,j}^n + \Delta t \{ f \bar{v}_{1i,j}^n - G_1 + \tau_{ixi,j}^{n+1/2} / h'_{1i,j} + A [(u_{1i-1,j}^n + u_{1i+1,j}^n - 2u_{1i,j}^n) / \Delta x^2 \\ + (u_{1i,j-1}^n + u_{1i,j+1}^n - 2u_{1i,j}^n) / \Delta y^2] \} \\ F_2 = u_{2i,j}^n + \Delta t \{ f \bar{v}_{2i,j}^n - G_2 - C [(u_{2i,j}^n)^2 + (\bar{v}_{2i,j}^n)^2]^{1/2} u_{2i,j}^n / h'_{2i,j} \\ + A [(u_{2i-1,j}^n + u_{2i+1,j}^n - 2u_{2i,j}^n) / \Delta x^2 + (u_{2i,j-1}^n + u_{2i,j+1}^n - 2u_{2i,j}^n) / \Delta y^2] \} \end{cases} \quad (3.14)$$

其中

$$\begin{cases} G_1 = [g(\zeta_{1i,j}^{n+1/2} - \zeta_{1i-1,j}^{n+1/2}) + (\tilde{p}_{i,j}^{n+1/2} - \tilde{p}_{i-1,j}^{n+1/2})] / \Delta x \\ G_2 = (\rho_1 / \rho_2) G_1 + g(1 - \rho_1 / \rho_2) (\zeta_{2i,j}^{n+1/2} - \zeta_{2i-1,j}^{n+1/2}) / \Delta x \end{cases} \quad (3.15)$$

最后取

$$u_{1i,j}^{n+1} = \hat{u}_{1i,j}^{n+1} + \Delta u, \quad u_{2i,j}^{n+1} = \hat{u}_{2i,j}^{n+1} + \Delta u \quad (3.16)$$

其中

$$\Delta u = u_{1i,j}^{n+1} - (\hat{u}_{1i,j}^{n+1} h'_{1i,j} + \hat{u}_{2i,j}^{n+1} h'_{2i,j}) / h'_{i,j} \quad (3.17)$$

应注意的是,在计算 u_k, v_k 时用到 $\zeta_1^{n+1/2}$, 故对 $\zeta_{1(i,j)}$ 需两个数组。在计算出 $u^{n+1/2}$ 和 $\zeta_1^{n+1/2}$ 后, ζ_1 仍要保留, 用于计算 $v^{n+1/2}$ [见式(3.5)]; 在计算出 $v^{n+1/2}$ 和 ζ_1^{n+1} 后 ζ_1^n 可不要, 但 ζ_1^{n+1} 仍要保留, 用于计算 u_k, v_k 。

若 $K'_{i,j}=3$, 则需解下列三对角系数矩阵的方程组:

$$\begin{cases} B_1 \hat{u}_{1i,j}^{n+1} + C_1 \hat{u}_{2i,j}^{n+1} & = F_1 \\ A_2 \hat{u}_{1i,j}^{n+1} + B_2 \hat{u}_{2i,j}^{n+1} + C_2 \hat{u}_{3i,j}^{n+1} & = F_2 \\ A_3 \hat{u}_{2i,j}^{n+1} + B_3 \hat{u}_{3i,j}^{n+1} & = F_3 \end{cases} \quad (3.18)$$

其中

$$\begin{cases} C_1 = -2v_2 \Delta t / [h'_{1i,j}(h'_{1i,j} + h'_{2i,j})] \\ B_1 = 1 - C_1 \\ A_2 = C_1 h'_{1i,j} / h'_{2i,j} \\ C_2 = -2v_3 \Delta t / [h'_{2i,j}(h'_{2i,j} + h'_{3i,j})] \\ B_2 = 1 - A_2 - C_2 \\ A_3 = C_2 h'_{2i,j} / h'_{3i,j} \\ B_3 = 1 - A_3 \\ F_1 = u_{1i,j}^n + \Delta t \{ f \bar{v}_{1i,j}^n - G_1 + \tau_{1i,j}^{n+1/2} / h'_{1i,j} + A[(u_{1i-1,j}^n + u_{1i+1,j}^n - 2u_{1i,j}^n) / \Delta x^2 \\ + (u_{1i,j}^n + u_{1i,j+1}^n - 2u_{1i,j}^n) / \Delta y^2] \} \\ F_2 = u_{2i,j}^n + \Delta t \{ f \bar{v}_{2i,j}^n - G_2 + A[(u_{2i-1,j}^n + u_{2i+1,j}^n - 2u_{2i,j}^n) / \Delta x^2 \\ + (u_{2i,j}^n + u_{2i,j+1}^n - 2u_{2i,j}^n) / \Delta y^2] \} \\ F_3 = u_{3i,j}^n + \Delta t \{ f \bar{v}_{3i,j}^n - G_3 - C[(u_{3i,j}^n)^2 + (\bar{v}_{3i,j}^n)^2]^{1/2} u_{3i,j}' / h'_{3i,j} \\ + A[(u_{3i-1,j}^n + u_{3i+1,j}^n - 2u_{3i,j}^n) / \Delta x^2 + (u_{3i,j-1}^n + u_{3i,j+1}^n - 2u_{3i,j}^n) / \Delta y^2] \} \end{cases} \quad (3.19)$$

其中

$$\begin{cases} G_1 = [g(\zeta_{1i,j}^{n+1/2} - \zeta_{1i-1,j}^{n+1/2}) + (\tilde{p}_{i,j}^{n+1/2} - \tilde{p}_{i-1,j}^{n+1/2})] / \Delta x \\ G_2 = (\rho_1 / \rho_2) G_1 + g(1 - \rho_1 / \rho_2)(\zeta_{2i,j}^{n+1/2} - \zeta_{2i-1,j}^{n+1/2}) / \Delta x \\ G_3 = (\rho_2 / \rho_3) G_2 + g(1 - \rho_2 / \rho_3)(\zeta_{3i,j}^{n+1/2} - \zeta_{3i-1,j}^{n+1/2}) / \Delta x \end{cases} \quad (3.20)$$

最后取

$$u_{1i,j}^{n+1} = \hat{u}_{1i,j}^{n+1} + \Delta u, \quad u_{2i,j}^{n+1} = \hat{u}_{2i,j}^{n+1} + \Delta u, \quad u_{3i,j}^{n+1} = \hat{u}_{3i,j}^{n+1} + \Delta u \quad (3.21)$$

其中

$$\Delta u = u_{i,j}^{n+1} - (\hat{u}_{1i,j}^{n+1} h'_{1i,j} + \hat{u}_{2i,j}^{n+1} h'_{2i,j} + \hat{u}_{3i,j}^{n+1} h'_{3i,j}) / h'_{i,j} \quad (3.22)$$

(b) v_k 的计算

若 $K''_{i,j}=1$, 可直接取

$$v_{1i,j}^{n+1} = v_{i,j}^{n+1} \quad (3.23)$$

若 $K''_{i,j}=2$, 则

$$\begin{cases} \hat{v}_{1i,j}^{n+1} = (B_2 F_1 - C_1 F_2) / (1 - A_2 - C_1) \\ \hat{v}_{2i,j}^{n+1} = (B_1 F_2 - A_2 F_1) / (1 - A_2 - C_1) \end{cases} \quad (3.24)$$

其中

$$\begin{cases} C_1 = -2v_2 \Delta t / [h''_{1i,j} (h''_{1i,j} + h''_{2i,j})] \\ B_1 = 1 - C_1 \\ A_2 = C_1 h''_{1i,j} / h''_{2i,j} \\ B_2 = 1 - A_2 \\ F_1 = v_{1i,j}^n + \Delta t \{ -f \bar{u}_{1i,j}^n - G_1 + \tau_{sy}^{n+1/2} / h''_{1i,j} + A [(v_{1i-1,j}^n + v_{1i+1,j}^n - 2v_{1i,j}^n) / \Delta x^2 \\ + (v_{1i,j-1}^n + v_{1i,j+1}^n - 2v_{1i,j}^n) / \Delta y^2] \} \\ F_2 = v_{2i,j}^n + \Delta t \{ -f \bar{u}_{2i,j}^n - G_2 - C [(\bar{u}_{2i,j}^n)^2 + (v_{2i,j}^n)^2]^{1/2} v_{2i,j}^n / h''_{2i,j} \\ + A [(v_{2i-1,j}^n + v_{2i+1,j}^n - 2v_{2i,j}^n) / \Delta x^2 + (v_{2i,j-1}^n + v_{2i,j+1}^n - 2v_{2i,j}^n) / \Delta y^2] \} \end{cases} \quad (3.25)$$

式中

$$\begin{cases} G_1 = [g(\zeta_{1i,j}^{n+1/2} - \zeta_{1i,j-1}^{n+1/2}) + (\tilde{p}_{i,j}^{n+1/2} - \tilde{p}_{i,j-1}^{n+1/2})] / \Delta y \\ G_2 = (\rho_1 / \rho_2) G_1 + g(1 - \rho_1 / \rho_2) (\zeta_{2i,j}^{n+1/2} - \zeta_{2i,j-1}^{n+1/2}) \Delta y \end{cases} \quad (3.26)$$

最后取

$$v_{1i,j}^{n+1} = \hat{v}_{1i,j}^{n+1} + \Delta v, \quad v_{2i,j}^{n+1} = \hat{v}_{2i,j}^{n+1} + \Delta v \quad (3.27)$$

其中

$$\Delta v = v_{i,j}^{n+1} - (\hat{v}_{1i,j}^{n+1} h''_{1i,j} + \hat{v}_{2i,j}^{n+1} h''_{2i,j}) / h''_{i,j} \quad (3.28)$$

若 $K''_{i,j}=3$, 则 $\hat{v}_k^{n+1}$ 由下列方程解出

$$\begin{cases} B_1 \hat{v}_{1i,j}^{n+1} + C_1 \hat{v}_{2i,j}^{n+1} & = F_1 \\ A_2 \hat{v}_{1i,j}^{n+1} + B_2 \hat{v}_{2i,j}^{n+1} + C_2 \hat{v}_{3i,j}^{n+1} & = F_2 \\ A_3 \hat{v}_{2i,j}^{n+1} + B_3 \hat{v}_{3i,j}^{n+1} & = F_3 \end{cases} \quad (3.29)$$

其中

$$\begin{cases} C_1 = -2v_2 \Delta t / [h''_{1i,j} (h''_{1i,j} + h''_{2i,j})] \\ B_1 = 1 - C_1 \\ A_2 = C_1 h''_{1i,j} / h''_{2i,j} \\ C_2 = -2v_3 \Delta t / [h''_{2i,j} (h''_{2i,j} + h''_{3i,j})] \\ B_2 = 1 - A_2 - C_2 \\ A_3 = C_2 h''_{2i,j} / h''_{3i,j} \\ B_3 = 1 - A_3 \\ F_1 = v_{1i,j}^n + \Delta t \{ -f \bar{u}_{1i,j}^n - G_1 + \tau_{xy}^{n+1/2} / h''_{1i,j} + A[(v_{1i-1,j}^n + v_{1i+1,j}^n - 2v_{1i,j}^n) / \Delta x^2 \\ \quad + (v_{1i,j-1}^n + v_{1i,j+1}^n - 2v_{1i,j}^n) / \Delta y^2] \} \\ F_2 = v_{2i,j}^n + \Delta t \{ -f \bar{u}_{2i,j}^n - G_2 + A[(v_{2i-1,j}^n + v_{2i+1,j}^n - 2v_{2i,j}^n) / \Delta x^2 \\ \quad + (v_{2i,j-1}^n + v_{2i,j+1}^n - 2v_{2i,j}^n) / \Delta y^2] \} \\ F_3 = v_{3i,j}^n + \Delta t \{ -f \bar{u}_{3i,j}^n - G_3 - C[(\bar{u}_{3i,j}^n)^2 + (v_{3i,j}^n)^2]^{1/2} v_{3i,j}^n / h''_{3i,j} \\ \quad + A[(v_{3i-1,j}^n + v_{3i+1,j}^n - 2v_{3i,j}^n) / \Delta x^2 + (v_{3i,j-1}^n + v_{3i,j+1}^n - 2v_{3i,j}^n) / \Delta y^2] \} \end{cases} \quad (3.30)$$

式中

$$\begin{cases} G_1 = [g(\zeta_{1i,j}^{n+1/2} - \zeta_{1i,j-1}^{n+1/2}) + (\tilde{p}_{i,j}^{n+1/2} - \tilde{p}_{i,j-1}^{n+1/2})] / \Delta y \\ G_2 = (\rho_1 / \rho_2) G_1 + g(1 - \rho_1 / \rho_2) (\zeta_{2i,j}^{n+1/2} - \zeta_{2i,j-1}^{n+1/2}) / \Delta y \\ G_3 = (\rho_2 / \rho_3) G_2 + g(1 - \rho_2 / \rho_3) (\zeta_{3i,j}^{n+1/2} - \zeta_{3i,j-1}^{n+1/2}) / \Delta y \end{cases} \quad (3.31)$$

解出 $\hat{v}_k$ 后, v_k 值由 $\hat{v}_k$ 加上一个订正得到:

$$v_{1i,j}^{n+1} = \hat{v}_{1i,j}^{n+1} + \Delta v, \quad v_{2i,j}^{n+1} = \hat{v}_{2i,j}^{n+1} + \Delta v, \quad v_{3i,j}^{n+1} = \hat{v}_{3i,j}^{n+1} + \Delta v \quad (3.32)$$

其中

$$\Delta v = v_{i,j}^{n+1} - (\hat{v}_{1i,j}^{n+1} h''_{1i,j} + \hat{v}_{2i,j}^{n+1} h''_{2i,j} + \hat{v}_{3i,j}^{n+1} h''_{3i,j}) / h''_{i,j} \quad (3.33)$$

从式(3.30)可知, $u_1(i, j), u_2(i, j), u_3(i, j), v_1(i, j), v_2(i, j), v_3(i, j)$ 在计算过程中需使用两个数组。

(2) ζ_k 的计算

ζ_2 和 ζ_3 可用简单的显式计算:

$$\begin{cases} \zeta_{3i,j}^{n+3/2} = \zeta_{3i,j}^{n+1/2} - \Delta t \{ (h'_{3i+1,j} u_{3i+1,j}^{n+1} - h'_{3i,j} u_{3i,j}^{n+1}) / \Delta x \\ \quad + (h''_{3i,j+1} v_{3i,j+1}^{n+1} - h''_{3i,j} v_{3i,j}^{n+1}) / \Delta y \} \\ \zeta_{2i,j}^{n+3/2} = \zeta_{2i,j}^{n+1/2} + \zeta_{3i,j}^{n+3/2} - \zeta_{3i,j}^{n+1/2} - \Delta t \{ (h'_{2i+1,j} u_{2i+1,j}^{n+1} - h'_{2i,j} u_{2i,j}^{n+1}) / \Delta x \\ \quad + (h''_{3i,j+1} v_{3i,j+1}^{n+1} - h''_{3i,j} v_{3i,j}^{n+1}) / \Delta y \} \end{cases} \quad (3.34)$$

由上式知 $\zeta_k (k=2,3)$ 只要一个数组,其中第二式用到 $\zeta_{3i,j}^{n+3/2}$,可用一个单元暂存。

四、初步应用结果

作为对模式可用性的一次检验,我们选取了南海西北部潮波进行试算。计算区域包括 15°N 以北, 115°E 以西的海域,网格距离大约 $1/8$ 度,即取 $\Delta x = 13.132\text{km}$, $\Delta y = 13.889\text{km}$, $\Delta t = 89.4283\text{s}$ 。其他参数为: $h_1 = 200\text{m}$, $h_2 = 200\text{m}$, $\rho_1 = 1021\text{kg/m}^3$, $\rho_2 = 1024\text{kg/m}^3$, $\rho_3 = 1027\text{kg/m}^3$, $A = 100\text{m}^2/\text{s}$, $v_2 = v_3 = 0.05\text{m}^2/\text{s}$, $C = 0.0025$ 。由于只模拟潮波,海面风应力忽略,因而开边界以 m_1 和 M_2 分潮潮汐高度输入, m_1 的定义为 K_1 和 O_1 的平均值。

模拟得到的 m_1 和 M_2 见图 3 和图 4,将这些图与由观测得到的同潮图(Fang, 1986)相

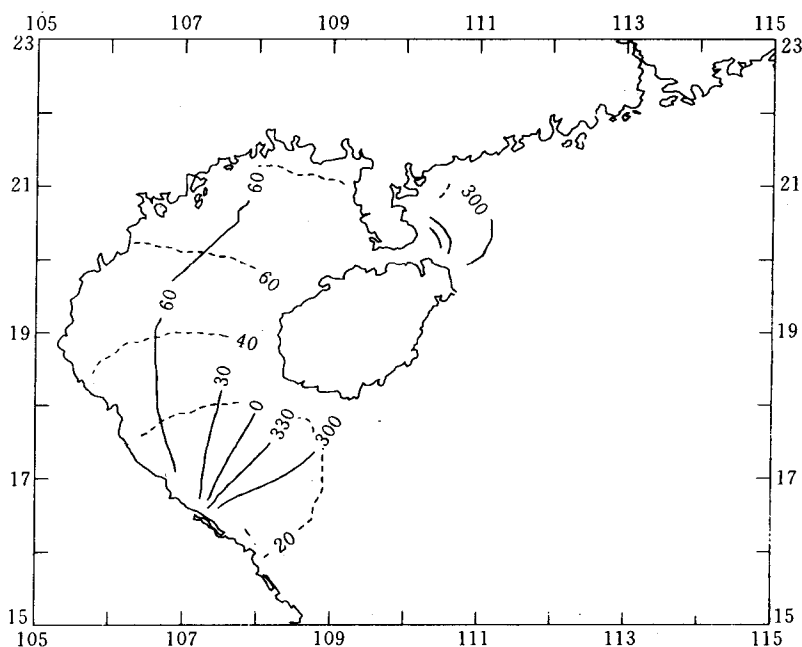


图 3 模拟得到的 m_1 表面同潮图

----振幅(单位为 cm); ——迟角(单位为度)

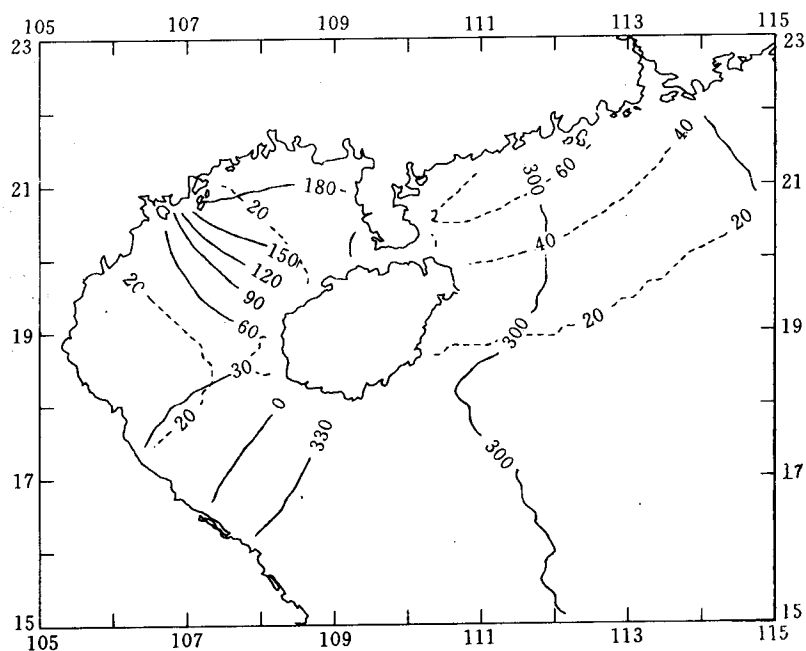


图4 模拟得到的 M_2 表面同潮图

---振幅(单位为 cm); —迟角(单位为度)

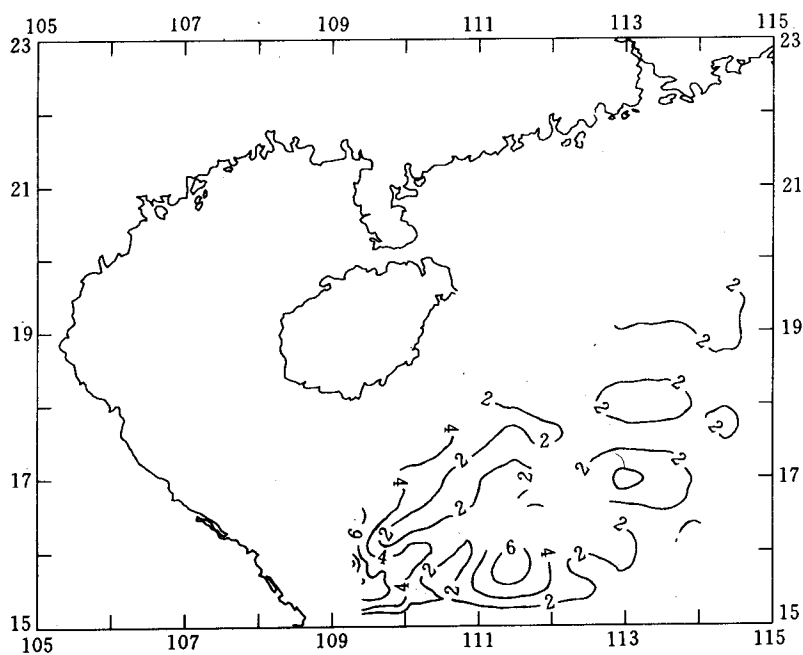


图5 第一与第二界面处的 m_1 内潮振幅分布(m)