

## COMPARISONS OF OPEN BOUNDARY CONDITIONS IN A BAROTROPIC MODEL OF THE NORTHERN ARABIAN SEA

Tariq Masood Ali Khan, J.G. De Las Alas and Mariano A. Estoque

National Institute of Oceanography St-47, Clifton-1, Karachi-75600, Pakistan (TMAK);  
DMO, University of the Philippines, Diliman Quezon City, Philippines. (JGDLA);  
Remote Sensing Laboratory, University of Miami, Coral Gables,  
Florida 33124, USA. (MAE).

**ABSTRACT:** These simulations are focused on the sensitivity of the barotropic ocean non-linear model to the various open boundary conditions (OBCs). Different open boundary conditions from gradient to radiation condition are examined to determine the best result and help to choose the most appropriate OBCs. Since the interior points are changing with time both implicit and explicit forms are applied. The simulations showed that the interior flow is sensitive to changes in the open boundary conditions and the results are highly dependent on the bathymetry of the area. When a constant depth (100 m) is used, the circulation pattern with all open boundary conditions are same. The best boundary conditions are Orlanski Radiation and its modified form. These boundary conditions produce identical adjustment in velocity and are determined to be satisfactory for both constant depth and actual bathymetry.

**KEY WORDS:** Open boundary conditions - barotropic model - northern Arabian Sea.

### INTRODUCTION

The northern Arabian Sea is situated in the Indian Ocean and is located between the Indian subcontinent, the Arabian Peninsula and Iran. Being situated within the monsoon regime, it is therefore influenced by the regular seasonal reversal of winds i.e., the alternating cycle of the southwest monsoon in the northern summer, and the northeast monsoon in the northern winter. These periodical reversals in the wind, drive corresponding reversals in the currents of the upper ocean. The current system in the southwest monsoon is more intense than the northeast monsoon, because of the stronger winds.

In a series of Indian Ocean studies more attention has been paid to the southwest monsoon as compared to the northeast monsoon, more emphasis is given to the western boundary region particularly the Somali Current regime and very little attention is given to the area above 20°N (Luther and O'Brien 1985; Luther *et al.*, 1985; Dube *et al.* 1986).

The main purpose of this study is to develop a numerical circulation model of the northern part of the Arabian Sea (area above 20°N), and study the effect of different open boundary conditions on circulation pattern. A fundamental problem in the ocean modeling is the specification of the open boundaries. Better results can be expected when proper open boundary conditions are used. Therefore in this study different types of open boundary conditions are applied to improve results.

The area under study extends from 56.75°E - 73.0°E longitude and 20°N - 25.4°N latitude including some parts of the Gulf of Oman (Fig. 1). The southern boundary along 20°N is an open boundary. The closed boundary from 20°N to the 25.4°N is formed by India. The western side is bounded by the Arabian Peninsula, and the northern side by Pakistan and Iran. The entire area has a complex topography. The

depth increases very rapidly from north to south, and the southern part of the deep sea basin has a depth that exceeds 3000m (Fig. 2).

## MATERIALS AND METHODS

### FORMULATION OF THE MODEL

The momentum and continuity equations are simplified by integrating them vertically with the assumption of constant density (Ali Khan, *et al.*, 1993). Thus the depth integrated dynamical equations of motion and continuity of a homogeneous ocean are as follows:

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x} \left( \frac{U^2}{H} \right) + \frac{\partial}{\partial y} \left( \frac{UV}{H} \right) = fV - gH \frac{\partial \zeta}{\partial x} + \frac{1}{\rho_w} (\tau_{xw} - \tau_{xb}) + A_h \left[ \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right] \quad (1)$$

$$\frac{\partial V}{\partial t} + \frac{\partial}{\partial x} \left( \frac{UV}{H} \right) + \frac{\partial}{\partial y} \left( \frac{V^2}{H} \right) = -fU - gH \frac{\partial \zeta}{\partial y} + \frac{1}{\rho_w} (\tau_{yw} - \tau_{yb}) + A_h \left[ \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right] \quad (2)$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \quad (3)$$

where the  $U$  and  $V$  are the horizontal components of the vertically integrated equations in the  $x$  and  $y$  directions respectively,  $\zeta$  is the free upper surface (sea surface) elevation.  $H$  is the depth of the water,  $\rho_w$  is the density of water and  $\tau_{xw}$ ,  $\tau_{xb}$  and  $\tau_{yw}$ ,  $\tau_{yb}$  are the wind and bottom stress components in  $x$  and  $y$  directions respectively.

The quadratic drag law (bulk aerodynamic formula) is used for the computation of wind stress. The quadratic drag law in terms of  $x$  and  $y$  components are thus

$$\tau_{xw} = \rho_a C_d W_x |W| \quad (4)$$

$$\tau_{yw} = \rho_a C_d W_y |W| \quad (5)$$

where  $\rho_a$  is the air density and  $C_d$  is the drag coefficient.  $W$  is a wind vector and  $|W|$  is the magnitude of the wind vector in m/s.

In this study Wind pseudo-stress  $W |W|$  is the same which have been used by Luther *et al.* (1985) of their Arabian Sea model, and Somali current study. In all simulations, as a forcing function, the July wind stress is used.

The bottom stress is expressed as a linear function of the vertically integrated current (De las Alas and Sodusta, 1985; Jensen 1986).

$$\tau_{xb} = \rho_w C_b U \quad (6)$$

$$\tau_{yb} = \rho_w C_b V \quad (7)$$

where  $C_b$  is the bottom friction coefficient.

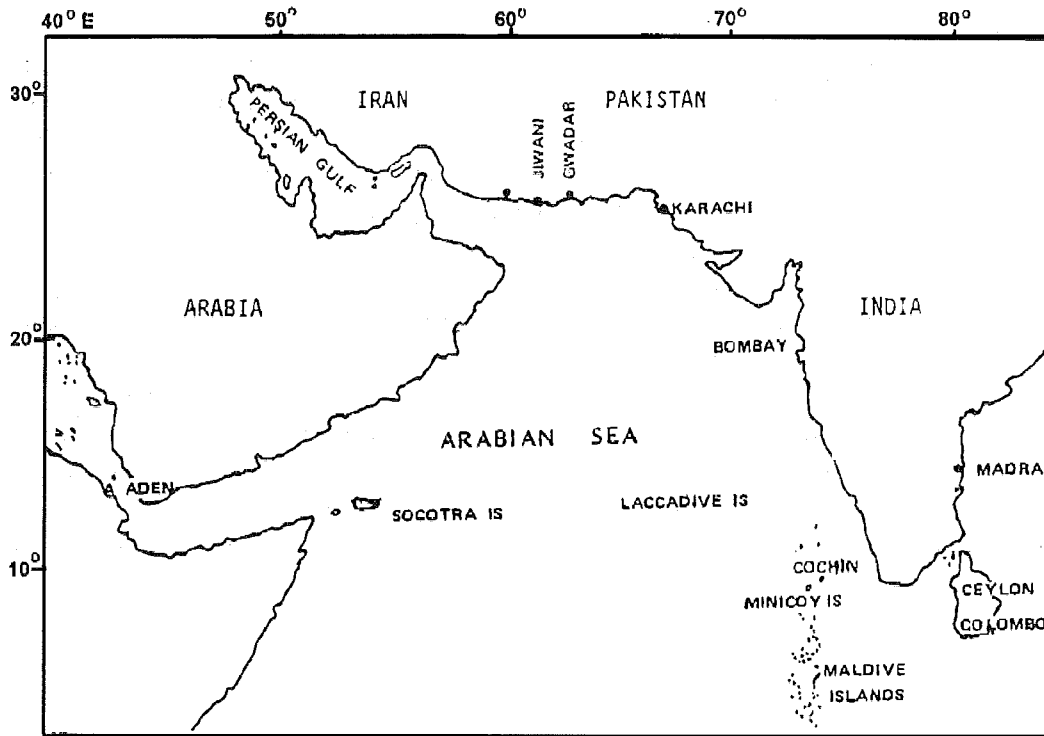


Fig.1. Map showing the area under study.

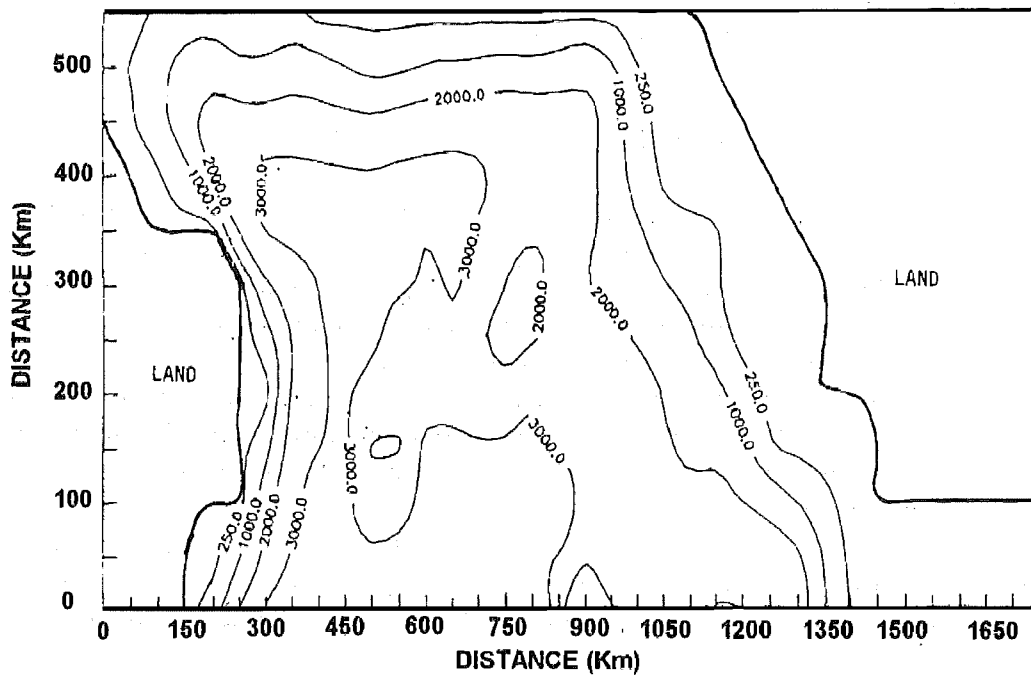


Fig.2. Bathymetry of the area in meters.

### BOUNDARY CONDITIONS

The transport components normal to the solid boundaries are set to zero. These conditions represent no flow across the boundaries. The southern boundary is open. The term "open" implies a sea boundary where the solution is unknown and must be extrapolated from the interior solution. Ideal open boundaries are transparent to motions which are generated within the area under study. Since no boundary formulation can give this ideal condition, it is necessary to experiment with various open lateral boundary conditions and choose the most effective one.

The general approach for this study is to test the response of the northern Arabian Sea circulation model to different open boundary conditions using actual bathymetry. The selection of open lateral boundary conditions (OBCs) are based on common usage, simplicity of implementation and the realistic features of the simulation results. The variety of boundary formulations vary from gradient to radiation boundary conditions (Orlanski, 1976; Camerlengo and O'Brien, 1980; Chapman, 1985). Most of the open boundaries considered here are basically Sommerfeld radiation conditions of the form

$$\varphi_t \pm c \varphi_x = 0 \quad (8)$$

where  $c$  is the phase speed and  $\varphi$  is any dependent variable such as the normal transport component.

Since the interior points has updated when the OBCs are applied, it is possible that Sommerfeld radiation condition can be implemented in explicit and implicit forms. The forms used in this model are Gradient (GRD), Gravity-Wave Radiation Explicit (GWE), Gravity-Wave Radiation Implicit (GWI), Orlanski Radiation Explicit (ORE), Orlanski Radiation Implicit (ORI), Modified Orlanski Explicit (MOE), and Modified Orlanski Implicit (MOI). The details of these boundary conditions can be found in Chapman (1985).

### RESULTS AND DISCUSSION

The results of various simulations which have been performed are presented here. The approach is to run the model for three days using each of the above defined different open boundary conditions. The results are subsequently compared. Results of numerical simulations with different open boundary conditions are presented in the form of computer plots (with or without bathymetry).

GRD is one of the most widely used open boundary conditions. GRD, the gradient boundary condition is good only when the domain is shallow, or for a relatively large area. The maximum current speed of 47.81 cm/s occurs at about 20°N near India with actual bathymetry, and this speed is about 5% of the wind speed (Fig. 3a).

In the unrealistic case of constant depth, the maximum current speed occurs at the western side of the domain near the open boundary. Two gyres have been observed: one is counter clockwise at the middle of the domain, and the other is clockwise near the southern boundary (Fig. 3b).

In cases of GWE and GWI the results with actual bathymetry are not consistent with the observed pattern and the noise produced contaminates the solution (Figs. 4a and 5a). Whereas, with constant depth the results show the same flow patterns and

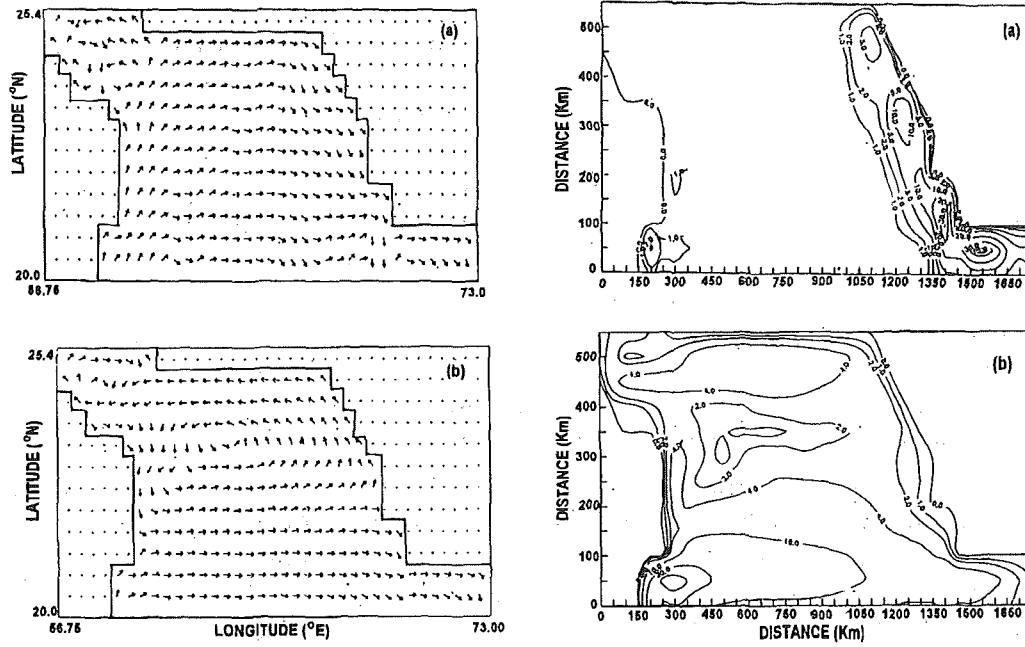


Fig.3. The predicted currents for July corresponding to the gradient boundary conditions: (a) with actual bathymetry and (b) with constant depth. Length of vectors are not proportional to speed. Dots indicate the land area (left). Isotachs in cm/sec.

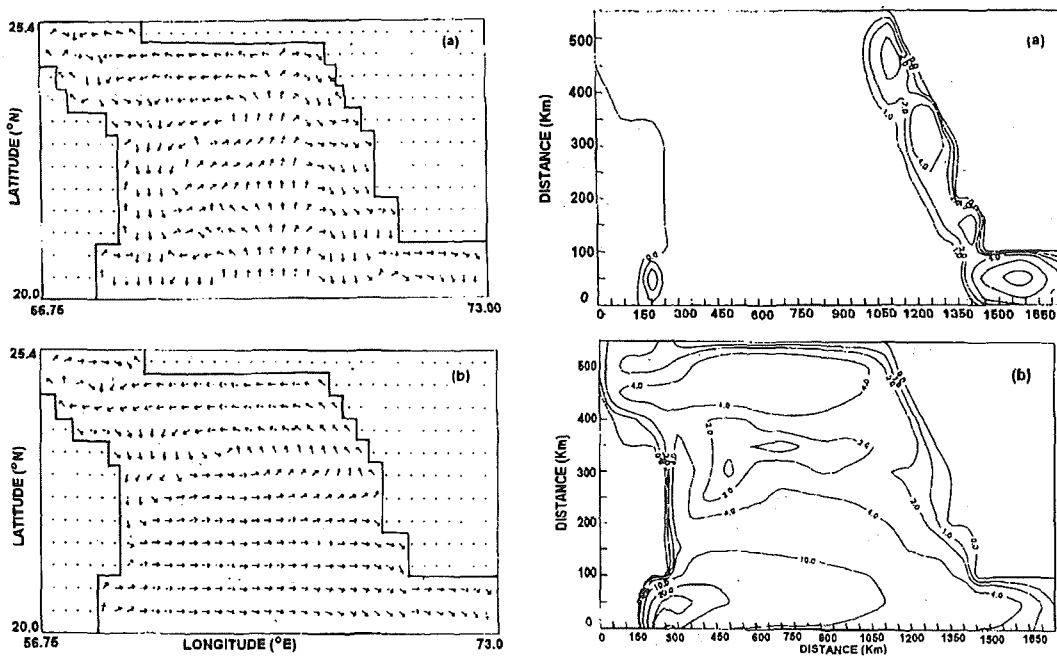


Fig.4. The predicted currents for July corresponding to the GWE boundary conditions: (a) with actual bathymetry and (b) with constant depth. Length of vectors are not proportional to speed. Dots indicate the land area (left). Isotachs in cm/sec.

speed as the other boundary conditions. The reason for that inconsistency in results is the phase speed. In GWE and GWI, the phase speed is for shallow water gravity wave on a flat bottom basin. Therefore it is suggested that these open boundary conditions are good only for shallow flat bottom case (Figs. 4b and 5b), which is not representative of the northern Arabian Sea system, hence not very appropriate.

The flow fields of ORE, ORI, MOE and MOI with actual bathymetry are shown in Figs. 6a - 9a. In all cases, the currents in the western and central part of the domain have a very low speed and maximum velocities up to 47.80 cm/sec occur at the eastern part of the domain about 21°N near India. Again, the maximum speed of the current is about 5% of the wind speed.

The predicted current velocities and the circulation pattern with constant depth are the same as in ORE, ORI, MOE and MOI open boundary conditions. The patterns of circulation is more or less similar as in the previously mentioned boundary conditions. Flow fields are shown in Figs. 6b- 9b. There are two gyres, one at about 23°N - 24°N having the anti-clockwise circulation and the other in the southern part of the domain having its circulation in the clockwise direction.

The GRD, ORE, ORI, MOE and MOI conditions produce virtually identical adjustments in velocity and reach almost the same steady state.

The more realistic conditions are the ones that allow the rapid removal of seiching and since the radiation boundary condition is good energy absorber, the use of this boundary condition reduces the noise from the false reflection of waves at the boundaries. For this reason we believe that the ORE, ORI, MOE and MOI conditions are most desirable for wind-driven models and acceptable in the wind stress simulations presented.

The GRD also gives good results in this case, most probably because of the large domain. However, GRD boundary conditions are not suggested for all wind-driven models.

The influence of bottom topography on the wind-driven circulation is quite dramatic. The maximum speed on the eastern side of the domain is most probably due to the very shallow water in this area. In the model simulation presented herein, the effects are more severe where the topographic slopes are quite steep. Currents in the subject region tend to follow the bottom contours. This behavior is well known at a large scale homogeneous ocean-circulation theory where the flow tends to follow the contours of  $f/h$ .

Probably, the most noticeable difference between the velocity fields of constant depth and actual bathymetry is that on the average the current strength in a constant depth simulation is about one and a half times the strength in the actual depth simulation. What is needed are in situ measurements to validate these simulations.

### CONCLUDING REMARKS

The GWE and GWI are found to be useful only for shallow water and flat bottom conditions.

The GRD, ORE, ORI, MOE and MOI produce identical adjustments in velocity and are determined to be satisfactory for both constant depth and actual bathymetry.

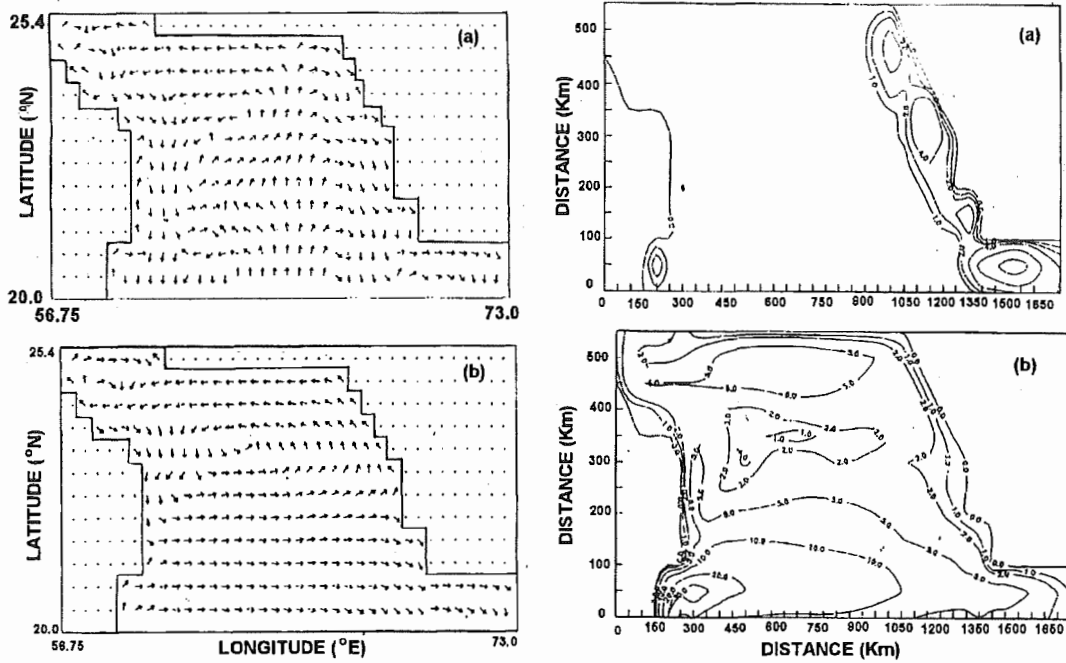


Fig.5. The predicted currents for July corresponding to the GWI boundary conditions: (a) with actual bathymetry and (b) with constant depth. Length of vectors are not proportional to speed. Dots indicate the land area (left). Isotachs in cm/sec.

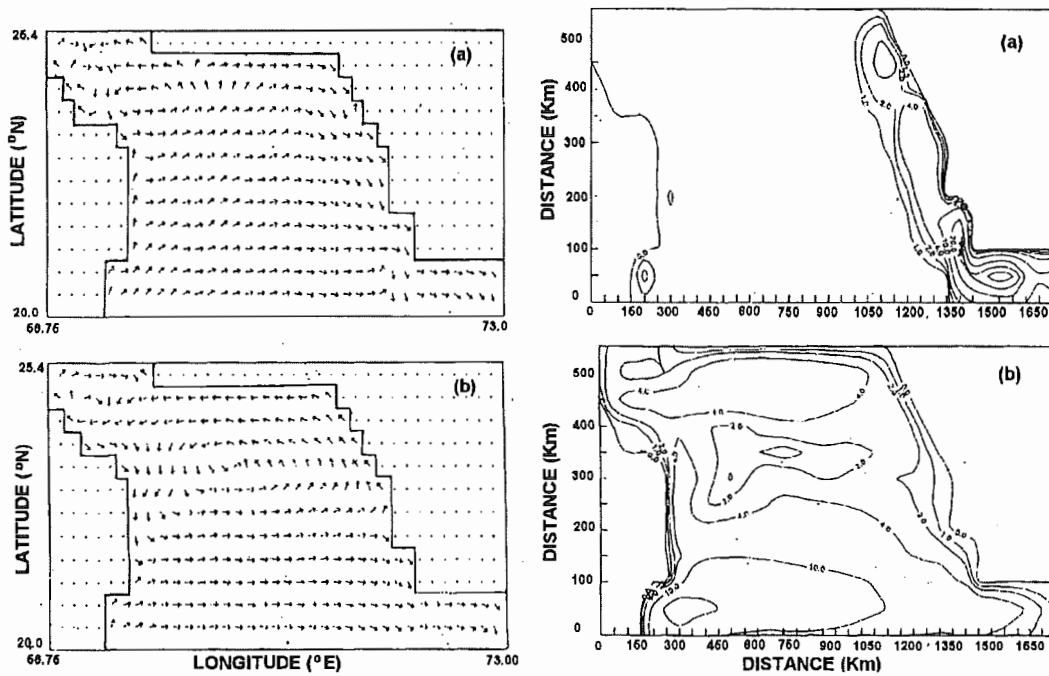


Fig.6. The predicted currents for July corresponding to the ORE boundary conditions: (a) with actual bathymetry and (b) with constant depth. Length of vectors are not proportional to speed. Dots indicate the land area (left). Isotachs in cm/sec.

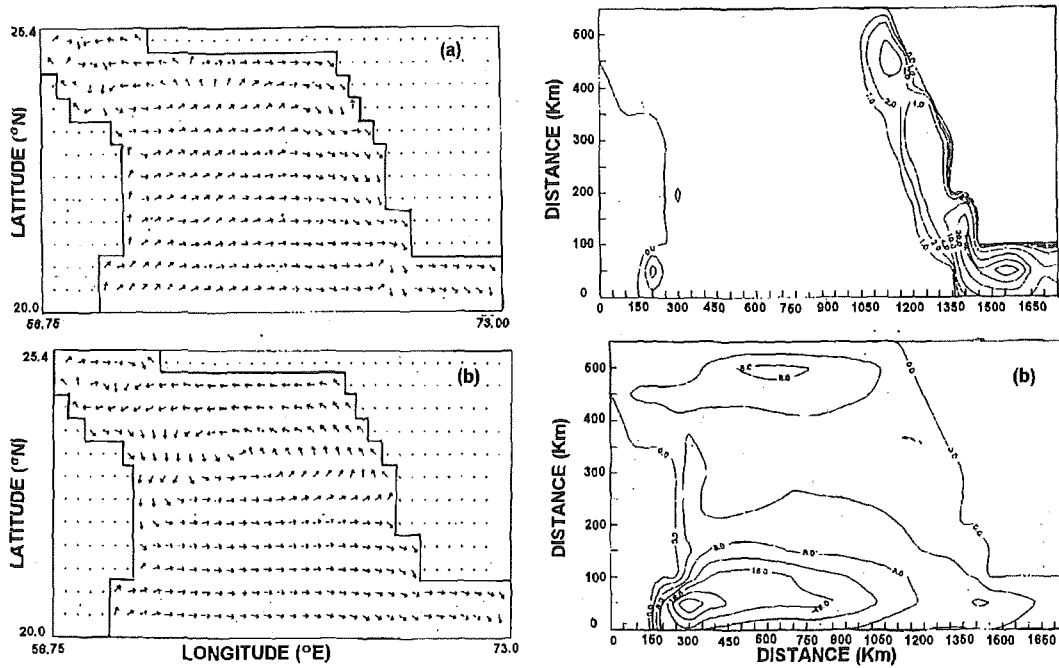


Fig. 7. The predicted currents for July corresponding to ORI boundary conditions: (a) with actual bathymetry and (b) with constant depth. Length of vectors are not proportional to speed. Dots indicate the land area (left). Isotachs in cm/sec.

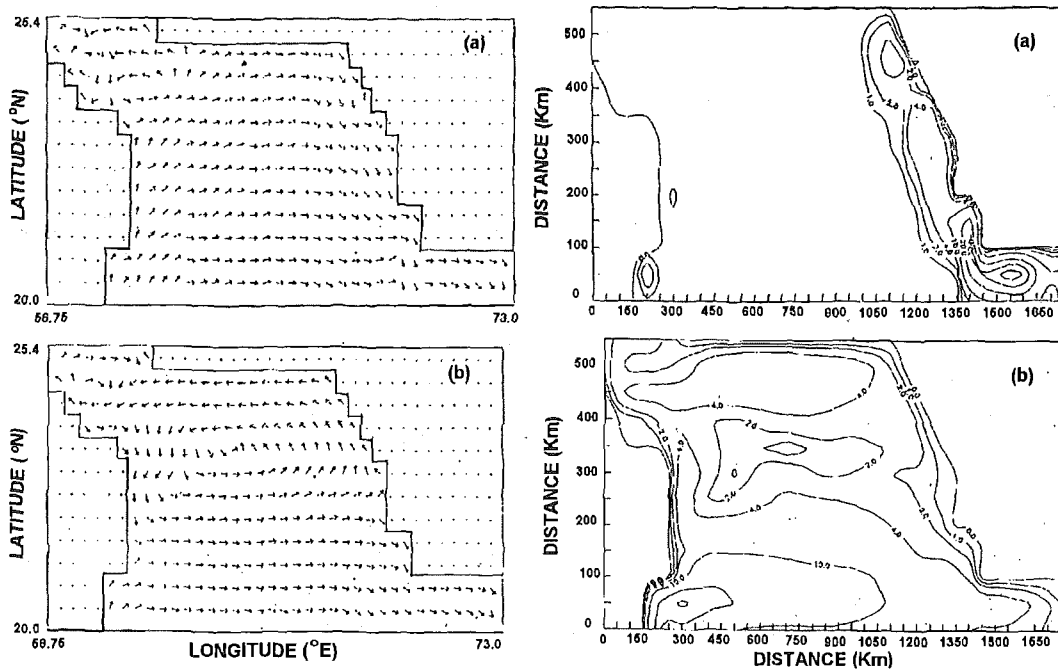


Fig. 8. The predicted currents for July corresponding to the MOE boundary conditions: (a) with actual bathymetry and (b) with constant depth. Length of the vectors are not proportional to speed. Dots indicate the land area (left). Isotachs in cm/sec.



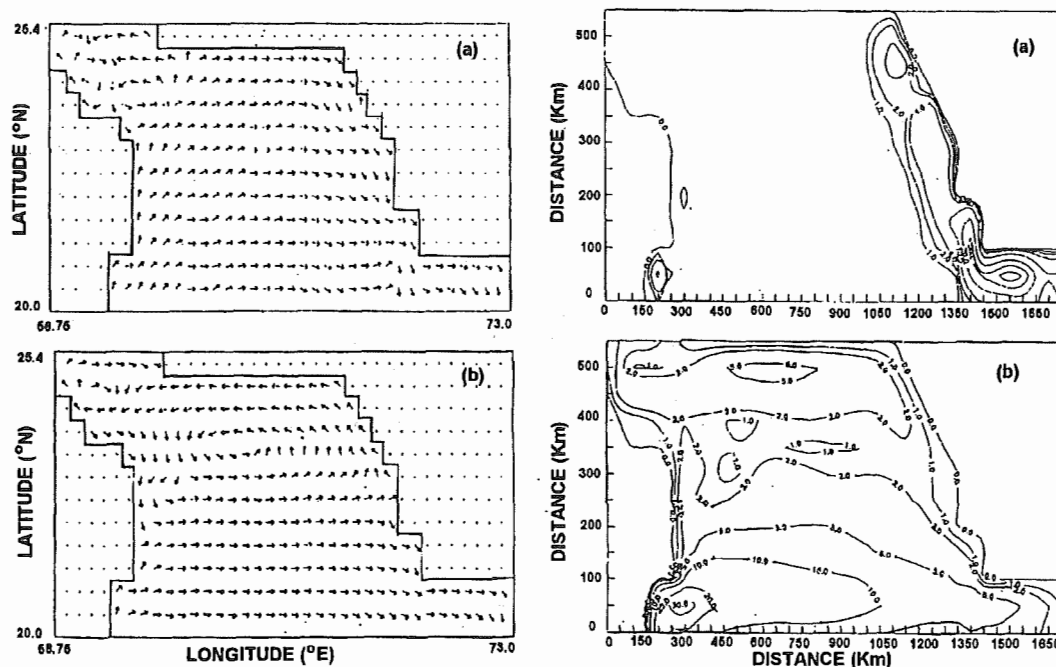


Fig. 9. The predicted currents for July corresponding to the MOI boundary conditions: (a) with actual bathymetry and (b) with constant depth. Length of vectors are not proportional to speed. Dots indicate the land area (left). Isotachs in cm/sec.

It can be concluded that the ORE, ORI, MOE and MOI are the better open boundary conditions. All are radiation conditions which reduce the noise from the false reflection of waves. These boundary conditions are, therefore, more desirable for wind-driven models.

Tests of the performances of different open boundary conditions for barotropic models must continue. Since their performance depends upon the bathymetry of the area, wind-forcing, grid size, time step, etc., the use of open boundary conditions and type of the wind stress considered here are very limited. It is suggested that appropriate open boundary conditions be tested and compared with in situ measurements over the annual cycle so as to understand their relative strength and weaknesses.

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