IMPLICATIONS OF CLIMATIC VARIATIONS IN THE FRESH WATER OUTFLOW ON THE WIND-INDUCED CIRCULATION OF THE BAY OF BENGAL

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Abstract—A barotropic model is applied to simulate the large-scale ocean circulation in the Bay of Bengal. The driving mechanisms consist, in general, of wind-stress forcing representative of that applying during the southwest monsoon season (July), and a forced southward transport of water across a northern open boundary that models the fresh water discharge from the northern river system. The model simulations (both with and without northern boundary forcing) are compared with the observed circulation pattern. The simulations provide definitive evidence that, with the simultaneous presence of both a forced fresh water flow and upwelling favourable winds along the east coast of India during the monsoon season, there is formation of a cyclonic gyre at the head Bay and occurrence of downwelling to the north of Machilipatnam along the east coast of India.

Key word index: Fresh water outflow, barotropic model, Bay of Bengal, climatological circulation.

INTRODUCTION

One of the anticipated consequences of the global warming is the change in the fresh water input into the coastal oceans. Close to land, variations in the inputs of fresh water largely determine the nature of physical environment, affecting the circulation pattern. Climate change will influence extreme as well as mean climatic conditions leading to anomalous conditions of wind direction and strength, fresh water input and thus the ocean dynamics. Coastal and oceanic current circulation may substantially change due to the abrupt variations in the fresh water input from the major river systems.

It is now well recognised that the large-scale circulation of the Bay of Bengal is greatly influenced because of the presence of large quantities of fresh water discharge from one of the greatest river systems of the world, i.e. Ganga–Brahmaputra–Meghana. The fresh water discharge from these rivers is highly variable from season to season. The greatest change in the surface circulation and salinity occur during the period of maximum river drainage towards the end of southwest monsoon season. The distribution of low-salinity waters at the head of Bay of Bengal varies with the direction of the currents. The counterclockwise circulation of the southwest monsoon season transports this low-salinity water westward towards the east coast of India as far as Visakhapatnam coast. It may therefore be expected that any variation of the water transport by these rivers will affect the circulation pattern and the distribution of the physical oceanographic parameters in the Bay of Bengal. These variations in the surface water may have important dynamic and climatic influences on the heat content of the oceanic surface layer. In this way, heat flow from the ocean to atmosphere may also change, resulting in changes of convective processes in the overlying atmosphere. Because the Bay of Bengal is a breeding ground for cyclonic atmospheric disturbances, these anticipatory changes may affect their frequency and strength.

Keeping this in view, an attempt has been made towards the development of a climatological ocean circulation model for the Bay of Bengal which includes the fresh water discharge in the head of Bay from the northern river systems. The model is fully nonlinear and vertically integrated with realistic basin geometry. The treatment of coastal boundaries involve a procedure leading to a realistic curvilinear representation of the western and eastern sides of the Bay of Bengal. This coastal representation has the advantage of taking into account the finer resolution in the northern Bay where the river systems join the sea.

The driving mechanisms of the model consist, in general, of wind stress forcing representative of the southwest monsoon season (July), and a forced southward transport of water across a northern open boundary that models the fresh water discharge from
the Ganga–Brahmaputra–Meghana rivers. Sensitivity experiments have been performed with varying fresh water inputs and a comparative study of the results have been made. The simulations provide definitive evidence that the variations in the discharge of fresh water during monsoon season has a modifying effect on the wind-induced circulation pattern of the Bay of Bengal.

**BASIC EQUATIONS**

The formulation of the model is the same as that used by Dube et al. (1993). This was used for the simulation of climatological circulation in the Bay of Bengal. In this formulation, the curvature of the earth's surface is ignored. A system of rectangular Cartesian coordinates is used in which the origin, O, is in the equilibrium level of the sea surface. Ox points towards the east, Oy points towards the north and Oz directed vertically upwards. The displaced position of the free surface is \( z = \zeta(x, y, t) \) and the position of the sea floor is \( z = -h(x, y) \).

The basic equations of continuity and momentum are

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \tag{1}
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} - \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_x}{\partial z} = - \frac{f}{\rho} \left( \frac{\partial^2 \zeta}{\partial y^2} - \frac{\partial^2 \zeta}{\partial x^2} \right), \tag{2}
\]

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} + f u = - \frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{1}{\rho} \frac{\partial \tau_y}{\partial z}, \tag{3}
\]

\[
\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = - \frac{1}{\rho} \frac{\partial p}{\partial z} - g, \tag{4}
\]

where \( u, v, w \) are the averaged components of velocity in the direction of \( x, y \) and \( z \), respectively, \( t \) is the time, \( p \) is the pressure, \( \rho \) is the density of the sea water assumed to be homogeneous (i.e. the thermohaline effects are neglected) and incompressible, \( f \) is the Coriolis parameter, \( g \) is the acceleration due to gravity and \( \tau_x, \tau_y \) are the \( x \) and \( y \) components, respectively, of the frictional stress (Reynolds stress).

It is well known that the thermohaline effects are more important in deep waters and as our main concern is to simulate the wind-induced surface circulation in the Bay of Bengal, these effects have therefore been neglected.

Molecular viscosity has been neglected in these equations. The terms in \( \tau_x \) and \( \tau_y \) are included to model vertical turbulent diffusion. The variation of the surface pressure \( (p_s) \) has negligible effect on the wind-induced circulation and hence it is assumed constant.

Denoting the wind-stress and bottom-stress components as \((\tau_x^w, \tau_y^w)\) and \((\tau_x^b, \tau_y^b)\), respectively. The relevant boundary conditions are

\[
(\tau_x, \tau_y) = (\tau_x^w, \tau_y^w) \quad \text{at} \quad z = \zeta, \tag{5}
\]

\[
\frac{\partial \zeta}{\partial t} + u \frac{\partial \zeta}{\partial x} + v \frac{\partial \zeta}{\partial y} = w \quad \text{at} \quad z = -h, \tag{6}
\]

The last condition in equation (5) is the kinematic surface condition and expresses the fact that the free surface is materially following the fluid.

Equation (4) reduces to the hydrostatic pressure approximation

\[
\frac{\partial p}{\partial z} = - \rho g. \tag{7}
\]

The principal equations (1)–(3) and (7) can be solved, in their present form but the procedure would be laborious because of the presence of a vertical coordinate. Unlike the atmosphere, a boundary layer would be needed at the top and the bottom of the domain of integration. There is insufficient knowledge about the flow in these boundary layers. To get over this difficulty, a simplification is introduced by vertical integration. The unknown dependent variables are then (a) the water transport (or mean current) and (b) the sea-surface elevation. After integrating equations (1)–(3) from \( z = -h \) to \( z = \zeta \), we write the prognostic equations in the flux form (Dube et al., 1993)

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \tag{8}
\]

\[
\frac{\partial u}{\partial t} + \frac{\partial (u^2)}{\partial x} + \frac{\partial (uv)}{\partial y} + \frac{\partial w^2}{\partial z} + fu = - \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_x}{\partial z} \tag{9},
\]

\[
\frac{\partial v}{\partial t} + \frac{\partial (uv)}{\partial x} + \frac{\partial (v^2)}{\partial y} + \frac{\partial w^2}{\partial z} + fu = - \frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{1}{\rho} \frac{\partial \tau_y}{\partial z}, \tag{10}
\]

where \( \tau_x = (\zeta + h)u \) and \( \tau_y = (\zeta + h)v \) are new prognostic variables and \( (\zeta + h) \) gives the total depth of the basin. The value of bottom friction coefficient, \( c_f \), is taken as \( 2.6 \times 10^{-3} \). The validity of this numerical value of \( c_f \) has been demonstrated by Johns et al. (1983). By considering a multilevel model of the Bay of Bengal, they parameterised internal Reynolds stress in terms of vertical velocity gradients and the turbulent energy density. The authors concluded that a depth-averaged model yields extremely satisfactory results with \( c_f = 2.6 \times 10^{-3} \).

**BOUNDARY CONDITIONS**

In addition to the fulfillment of the surface and bottom conditions (5) and (6), appropriate conditions
have to be satisfied along the lateral boundaries of the area under consideration for all time. Theoretically, the only boundary condition needed in the vertically integrated system is that the normal transport vanish at the coast. At the open-sea boundary, the normal current across the boundary may be prescribed.

The boundary conditions to be invoked at the southern and northern open boundaries are of crucial importance. In the southern boundary, the Sommerfeld radiation condition is used. It is of the form (Chapman, 1985)

$$\frac{\partial \phi}{\partial t} + c \frac{\partial \phi}{\partial x} = 0. \quad (11)$$

From the formulation, the phase speed $c$ is computed for each variable $\phi$ at each time step. The variable $\phi$ represents either the sea-surface elevation or the cross shelf velocity. On the implementation of the above condition, the value of $\phi_{b+1}$ at the southern boundary is given by

$$\phi_{b+1} = \phi_{b+2}$$

for outgoing flow ($c < 0$)

$$\phi_{b} = \phi_{b, b}$$

for incoming flow ($c > 0$). \quad (12)

On the northern boundary another radiation type of boundary condition is used (Johns et al., 1992). This is of the form

$$\nu - \left( \frac{h}{g} \right)^{1/2} \zeta = -2v_0 \quad \text{at} \quad y = L. \quad (13)$$

Here $v_0$ is a velocity, generally a function of $x$, the value of which determines the southward directed barotropic transport of water across the northern boundary and into the analysis domain. This form of specification is a crucial part of the formulation as it models the fresh water discharge from the major river systems at the head Bay.

**NUMERICAL EXPERIMENTS**

Numerical experiments are performed using the analysis area north of $6^\circ N$ of the Bay of Bengal. The two open boundaries of the analysis area lie along $6^\circ N$ and $22.4^\circ N$. A smoothed model bathymetry is derived utilising spot depths from the relevant hydrographic chart and applying an interpolation scheme based on distance weighing to determine the depth at the computational points. The model is forced from its initial state of rest by July monthly mean climatological winds derived from 30 years (1950–1979) data of Comprehensive Ocean–Atmosphere Data Set (COADS). After approximately 8 days of integration, a steady state is reached.

Two basic experiments are described in this paper. The first corresponds to the case of pure wind-stress forcing, the second to a combination of wind-stress and northern boundary forcing. The applied surface wind stress is determined from a bulk quadratic law in which the wind speed and direction are specified. In the case of northern boundary forcing, we prescribe different values of $v_0$ in equation for evaluating the effect of forced southward transport of water across the open boundary that models the fresh water discharge from the northern major river systems. The implied southward along shore transport of estuarial water will be evaluated in the model calculation in order to appraise the realism of the applied boundary forcing. Thus the value of the inward flux will depend on the value assigned to $v_0$. This implies that if the value of $v_0$ is increased the implied volume flux of water across the boundary may be prescribed.

Figure 1 shows the observed large-scale surface circulation in the Bay of Bengal for July (La Violette, 1967). The currents along the coast do not completely follow the coastline and they have the tendency to move eastward. At the head of the Bay there is a clear formation of a cyclonic gyre. As there is huge fresh water discharge during July from northern rivers, the presence of the counterclockwise circulation brings low-salinity waters to the coastal region up to the latitudes of Visakhapatnam.

Using the mean wind-stress forcing for July (Fig. 2), we depict the computed sea-surface current vectors in Fig. 3. Here we use $v_0 = 0$ in the northern open-boundary condition implying that there is no fresh water inflow. In the absence of estuarially controlled southward flow, the agreement of computed currents with the observations is only confined to the latitudes of Pur along the east coast of India. To the north of this latitude, the model is unable to simulate the cyclonic vortex in the sole presence of wind-stress forcing. As an anticipation the circulation in the monsoon season at the head Bay could be the combined dynamic effect of wind-stress and local fresh water discharge. In order to study the combined effect, the experiments are carried out using various values for $v_0$ along the northern open boundary. For each $v_0$, we compute the implied volume flux of water across the boundary. For $v_0 = 0.3 \text{ m s}^{-1}$, this flow is found to be $75,000 \text{ m}^3 \text{s}^{-1}$ and this should be identified with the combined flux of fresh water out of Ganga–Brahmaputra–Meghna river system. This value is consistent with the data published in the United Nations Report (1966). By prescribing the value $0.3 \text{ m s}^{-1}$ for $v_0$, we delineate in Fig. 4 the computed surface currents with July wind stress forcing. From the figure, it may be noted that the circulation in the latitudes north of Visakhapatnam (VSK) is completely dominated by the estuarial flow. A predominant cyclonic gyre is very well produced in the northern sector of the Bay of Bengal. The flow to the south of the latitude is unchanged and thereby limiting the local effect of the northern fresh water discharge. Finally, it may be interesting to see the sea-surface elevations for July corresponding to the simulated currents with (Fig. 5b) and without (Fig. 5a) inclusion of the fresh water discharge. In the case of pure wind forcing, Fig. 5a shows the negative elevations all along the coast up to Pur as a result of off-shore Ekman transport. This confirms the occurrence of upwelling processes along
Fig. 2. Mean monthly wind-stress for July.

Fig. 3. Computed sea-surface currents for July in the case of pure wind-stress forcing.
Fig. 4. As in Fig. 3 except in the case of combined wind-stress and boundary forcing.

Fig. 5a
the east coast of India as a consequence of favourable winds. This result is contrary to the observed feature reported by Gopal Krishna and Sastry (1985). They have observed that southward flow of fresh water suppresses the off-shore Ekman transport as a consequence of which no upwelling processes take place along the coast north of Visakhapatnam (VSK). This observation is confirmed with our model results when the fresh water flow is taken into account (Fig. 5b). From Fig. 5b, it is very clear that negative elevations are confined to a very limited zone in comparison to that simulated in Fig. 5a.

CONCLUSIONS

A numerical model has been applied to simulate the circulation for July in the Bay of Bengal. The model also incorporates the effect of an estuarial discharge of relatively fresh water across a northern open boundary. It has been shown that the fresh water discharge plays an important role in the circulation of Bay of Bengal. So, it is essential to include the effect in the modelling studies in order to simulate realistic observed features. To the north of Machilipatnam, it is shown that the local effect of the northern fresh water discharge sufficiently weakens the occurrence of anticipated purely wind-induced upwelling. The conclusion supports the observations reported by Gopal Krishna and Sastry (1985) in this respect.

REFERENCES