Wind-Induced Circulation in Semiclosed Homogeneous, Rotating Basins

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ABSTRACT

The wind-induced circulation over laterally varying bathymetry was investigated in homogeneous systems using the three-dimensional Regional Ocean Model System (ROMS). The investigation focused on the influence of the earth’s rotation on the lateral distribution of the flow, with particular emphasis on the transverse circulation. Along-basin wind stress with no rotation caused a circulation dominated by an axially symmetric transverse structure consisting of downwind flow over the shoals and upwind flow in the channel along the whole domain. Transverse circulation was important only at the head of the system where the water sank and reversed direction to move toward the mouth. The wind-induced flow pattern under the effects of the earth’s rotation depended on the ratio of the maximum basin’s depth $h$ to the Ekman depth $d$. The solution tended to that described in a nonrotating system as $h/d$ remained equal to or below 1. For higher values of $h/d$, the longitudinal flow was axially asymmetric. Maximum downwind flow was located over the right shoal (in the Northern Hemisphere, looking downwind). The transverse component of velocity described three gyres. The main gyre was clockwise (looking downwind) and occupied the entire basin cross section, as expected from the earth’s rotation and the presence of channel walls. The other two gyres were small and localized and were linked to the lateral distribution of the along-channel velocity component, which in turn was dictated by bathymetry. These results compared favorably with a limited set of observations and are expected to motivate future measurements.

1. Introduction

The wind-induced exchange between an estuary and the adjacent continental shelf is recognized as one of the most important mechanisms in determining the long-term transport and distribution of dissolved and suspended matter that leaves or enters an estuary. Analytical models (Csanady 1982; Hunter and Hearn 1987; Wong 1994; Friedrichs and Hamrick 1996; Winant 2004) and numerical models (Hearn et al. 1987; Signell et al. 1990; Glorioso and Davies 1995) on this topic have shown the importance of laterally varying bathymetry on the lateral distribution of the along-channel flow driven by local winds. For example, in flat-bottom systems the velocity vertical profile is the same at each point of the cross section. The structure of the response is downwind at the surface and upwind at depth as required by continuity. In contrast, over laterally varying bathymetry the flow is strongly dependent on lateral position. The local wind forcing response is downwind at all depths in shallow regions and upwind mainly concentrated in the deep channel.

There have been several studies that feature analytical solutions in homogeneous systems. Csanady (1982) described the lateral variability of the vertically integrated transport driven by wind over laterally varying bathymetry in the absence of rotational effects and bottom stress. The solution (valid away from the closed ends) showed that the vertically integrated transport was downwind over the shoals and upwind in deeper water. In shallow water the accelerations produced by wind stress are greater than those from the barotropic pressure gradient. In deep water the pressure gradient dominates, because of the depth-dependent nature of wind-induced accelerations, and a return flow develops. Hunter and Hearn (1987) solved the lateral and vertical variations of wind-driven circulation in a nonrotating system and showed that the relative importance of the horizontal to vertical transport was sensitive to the bot-
bottom roughness and the cross-sectional depth distribution, parameterized as $\delta h/h$ (where $\delta h$ are the variations of the depth $h$). They found that the along-channel transport showed lateral distribution for bathymetries where $\delta h/h > 0.1$, independent of the shape of the bottom. They also used three different eddy viscosity parameterizations and found no relevant differences in the results. Wong (1994) proposed an analytical solution for the lateral structure of the flow driven by local winds, remote forcing, and buoyancy forcing for non-rotating systems using a constant eddy viscosity in the cross section. Results for local winds were consistent with those of Csanady (1982). Winant (2004) presented a three-dimensional, linear, barotropic model to describe the wind-induced flow over laterally varying bathymetry on an $f$ plane. The influence of the earth’s rotation was characterized by the $\bar{h}/d$ ratio, where $h$ is the maximum depth of the basin and $d$ is the Ekman depth. For large $\bar{h}/d$ values (>4), the along-channel flow showed that axial asymmetries and transverse circulations played an important role. As $\bar{h}/d$ approached 1, the circulation pattern induced by the wind approached that described by Wong (1994) in a nonrotating system.

Similar to analytical solutions, there have been several numerical solutions in homogeneous systems. Hearn et al. (1987) found, through observations and numerical simulations, that the wind-induced circulation in a shallow bay was significantly modified by bottom topography. They found that the water exchange between a shallow system and the adjacent water can be intensified by a deep channel dredged along the prevailing wind direction. They mentioned that, even though the vertical spiraling expected from Ekman dynamics was not evident in shallow systems, Coriolis accelerations affect the direction of the current vectors. Also, the water exchange between the systems could be strongly modified by the earth’s rotation under certain wind directions. Signell et al. (1990) found that the wind-driven circulation in shallow embayments, and in turn the flushing time, were sensitive to both the shape of the cross section and the effects of surface waves. Flushing time increased by increasing the slope of the cross-channel bathymetric profile but decreased through inclusion of surface waves, which in turn increased the bottom drag and in consequence the strength of the circulation. Glorioso and Davies (1995) extended Signell et al.’s (1990) work by analyzing the influence of changes of bottom topography, eddy viscosity parameterization, and wave–current interaction on the wind-driven circulation in shallow homogeneous systems. Using a full three-dimensional numerical model, they found that for flat-bottom embayments the wind-driven flow was sensitive to the eddy viscosity formulation (i.e., to the turbulence closure). In contrast, laterally varying embayments were insensitive to the turbulence closure used. In basins with V-shaped cross sections, horizontal variability rather than vertical variability dominated the circulation pattern. The local vertical profile of the flow was more uniform than that over flat bottoms, and the circulation pattern was no longer sensitive to the eddy viscosity formulation.

From observational data on the lateral distribution of the along-channel flow in semienclosed shallow basins, Valle-Levinson et al. (2001) reported one of the few examples of the transverse structure of the wind-induced circulation in homogeneous systems with laterally varying bathymetry. The set of observations consisted of hydrographic and horizontal velocity profiles obtained at the entrance to the Bay of Guaymas, Mexico, in February 2000. Guaymas Bay is about 10.4 km long and 8.5 km wide and has an average depth of 2 m. Communication to the adjacent Gulf of California is through a channel 3 km long and 1.6 km wide. The transverse bathymetric profile of the communication channel featured a V shape with minimum depth of 4 m and maximum depth of 14 m. The observational periods were influenced by moderate sea breeze that was reflected in the residual circulation. Subtidal flow was mainly driven by the wind such that the flow over the shoals followed the direction of the wind, and flow in the deep channel was upwind, in agreement with the analytical solution of Wong (1994). Valle-Levinson et al. (2001) also pointed out the possible influence of the earth’s rotation on the lateral distribution of the along-channel flow, as the core of maximum upwind flow appeared on the right side of the channel. The apparent influence of the earth’s rotation in these observations motivated the numerical experiments in homogeneous systems presented here. Most of the published work on local wind-induced circulation refers to nonrotating systems and mainly concentrates on the lateral distribution of the along-channel flow. Winant (2004) published a semianalytical solution of the linear problem of the wind-induced circulation on a homogeneous and rotating system with a V-shaped cross section.

This work reports advances in the understanding of the flow pattern driven by local winds in homogeneous estuaries with laterally varying bathymetry. The study focuses on two main topics: 1) the influence of the earth’s rotation on the circulation pattern induced by local winds and 2) the influence of bathymetric changes on the lateral distribution of the flow, with emphasis on the transverse flow. The first topic is similar to that addressed by Winant (2004) but this work complements it with the use of a numerical model that considers all
nonlinear terms, that is, advective and frictional, which are usually important in shallow systems. These numerical simulations allow the eddy viscosity to vary in space and time. Also, an important advance with respect to previous work is the analysis of the distribution of the flow in multiple-channel cross sections that include a channel shallower than the mean depth. The Regional Ocean Model System (ROMS) was used to address these issues.

2. Numerical experiments

A total of 10 numerical experiments were carried out to illustrate the wind-induced circulation in homogeneous systems with and without rotation over arbitrary bathymetric cross sections (Table 1). The nonrotating homogeneous experiment illustrated a baseline case that could be compared with analytical solutions (e.g., Wong 1994). The rotating homogeneous cases focused on the influence of the earth’s rotation on the lateral distribution of the three velocity components and on bathymetric effects on wind-induced flow.

The numerical domain consisted of a longitudinally uniform basin 100 km long and 10 km wide with laterally varying bathymetry. The x axis coincided with the southern lateral wall of the basin and pointed toward the head of the system. The y axis is laid along the open boundary at \( x = 0 \) (Fig. 1). Grid size was 2 km along the x direction and 200 m in the y direction. The number of vertical levels ranged from 10 to 30 depending on the maximum depth of the bathymetric profile employed. The vertical levels were spread out between the local bottom and the free surface, allowing more vertical resolution near the surface and near the bottom than in the interior.

Every numerical experiment included all terms of the primitive equations except the horizontal diffusive terms. The advection scheme used in ROMS was third order and upstream biased, so no explicit horizontal viscosity or diffusivity was needed, according to Haidvogel et al. (2000). The turbulence-closure scheme proposed by Large et al. [(1994); the \( K \)-profile parameterization (KPP)] is used throughout, which has been used successfully in estuarine numerical application of ROMS (MacCready and Geyer 2001). Other experiments with the Mellor and Yamada level-2.5 turbulence closure scheme yielded essentially the same results. Salinity and temperature surface fluxes were turned off in all experiments, while a constant surface wind stress was prescribed. Bottom boundary conditions for the normal derivatives of salinity and temperature were set to zero. The quadratic drag law was used to parameterize bottom friction with a nondimensional bottom drag coefficient of 0.0025. The free-slip condition was established for all closed boundaries and the no-gradient condition was used at the open boundary for all variables. The basin was open at the seaward boundary only. The fluid in the channel started from rest and a wind stress increased linearly during the first six hours of simulation. After those six hours, the wind was constant. The wind stress acted toward the head of the system aligned with the x axis and blew uniformly throughout the domain.

<table>
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<th>( \tau ) (Pa)</th>
<th>( f ) (s(^{-1}))</th>
<th>( h_0 ) (m)</th>
<th>( h ) (m)</th>
<th>( h/d )</th>
<th>( D ) (km)</th>
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* Gaussian profiles are defined in (1) and (2).
The first six numerical experiments (to analyze the effect of the earth’s rotation) were run over triangular cross sections to compare with analytical and semianalytical solutions (e.g., Wong 1994; Winant 2004). The earth’s rotation influence was characterized as in Winant (2004), as a function of $h/d$ [where $h$ is the maximum depth and $d$ is the Ekman layer depth ($d = \sqrt{2A \tau f}$), with $A_\lambda$ being the eddy viscosity coefficient and $f$ the Coriolis parameter]. This is equivalent to the inverse of the Ekman number. Any given value of this ratio can be obtained through modification of the wind stress value (which modifies $d$) or of the maximum water depth ($h$).

The last four experiments (from 7 to 10 to analyze bathymetric effects) were run over four different cross-sectional shapes. Emphasis was placed on the effects of channel–shoal configurations and on the bottom slope. The bottom configurations consisted of Gaussian functions that tend to emulate coastal plain estuarine topographies (e.g., Li and Valle-Levinson 1999; Reyes-Hernández 2001). The Gaussian functions adopted in the numerical experiments were

$$h(y) = 8 + 12 \exp \left[ - \left( \frac{y - D/2}{C} \right)^2 \right]$$

(1)

and

$$h(y) = a_0 + a_1 \exp \left[ - \left( \frac{y - D/2}{2000} \right)^2 \right] + a_2 \exp \left[ - \left( \frac{y - 4D/5}{2000} \right)^2 \right].$$

(2)

Equation (1) describes a cross section of width $D$, 20 m deep at the channel, and edges with minimum depth of 8 m. The values of $C$ dictate the width of the channel. The values of $C$ and $D$ are listed in Table 1. Equation (2) describes a bottom profile with two channels of depths $(a + b_1)$ and $(a + b_2)$ and a middle shoal with minimum depth equal to $a_0$. The values chosen for $a_0$, $a_1$, and $a_2$ are listed in Table 1. The depth profiles with two channels were chosen such that, in one, the shallow channel was deeper than the mean cross-sectional depth and, in the second, the shallow channel was shallower than the mean cross-sectional depth. The cross-sectional areas of the double-channel profiles were the same.

3. Results

This section presents results obtained in nonrotating and rotating systems. In contrast to Winant’s approach, where he examines the exclusive effects of $h$ on $h/d$, this work also looks at the influence of the wind stress $\tau$ on $d$ and on $h/d$. So, for any $h/d$ the magnitude of the response may be different if $\tau$ decreases or if $h$ increases. The results are mainly analyzed at two lateral sections: midway between the basin ends and at the head of the system. The results show the quasi-steady-state solution, and all figures of this section portray views toward the head of a rotating system in the Northern Hemisphere.

a. Rotation effects

To analyze the earth’s rotation effects in terms of the separate influences of wind stress and maximum water depth, five numerical experiments were performed and compared to the first experiment that excluded rotation. In three of the examples with rotation, the maximum depth was the same and wind stress was prescribed to yield values of $h/d \approx 1$, 2, and 4. The other two experiments, with rotation and triangular cross section, were forced with a given wind stress but changing the maximum depth. The wind stress was the same as in the case of $h/d \approx 2$ but the maximum depths were chosen such that $h/d$ took values of $\sim 1$ and 4. In all these experiments, cross-sectional averages of the eddy viscosity were used to evaluate the corresponding Ekman depths.

1) Experiment 1: Nonrotating case (baseline)

The first experiment represents the baseline case in which the $u$-velocity component of the flow shows lateral variability related to the bathymetry. The bathymetric profile was triangular, with minimum depth of 3 m, maximum depth $h$ of 20 m, and the wind stress was 0.08 Pa toward the head. Over shallow water (shallower than the average depth), the wind drove downwind circulation throughout the water column (Fig. 2). Maximum values of the downwind flow (0.24 m s$^{-1}$) were located at the surface and decreased with depth as expected from bottom friction. In the channel (area deeper than the average depth), the flow was upwind over much of the water column, with maximum magnitudes of 0.15 m s$^{-1}$ appearing below midwater in the channel. The lateral structure of the flow associated with the laterally varying bathymetry showed strongest lateral shears around the zero isothach, which intersects the bottom at the mean depth. Over shallow water, the main momentum balance was purely frictional between wind stress and internal stress divergence. In the channel, the pressure gradient given by the sea level slope also influenced the momentum balance. This was consistent with previous work (e.g., Csanady 1982; Signell et al. 1990; Wong 1994; Friedrichs and Hamrick 1996).
and provided confidence in the model performance to this forcing. Most of the velocity field was dominated by the $u$-velocity component as the other two components, $v$ and $w$, were very small. The lateral flow $v$ was $O(10^{-4} \text{ m s}^{-1})$ and $w$ was $O(10^{-6} \text{ m s}^{-1})$. This was true for all $x$ locations except near the closed end.

Owing to the presence of the closed boundary, streamlines must close near the head, showing an area of flow return. In this area, the lateral velocity component had magnitudes of up to $0.08 \text{ m s}^{-1}$ and converged toward the center of the cross section. The vertical component was downward with magnitudes up to $2.6 \times 10^{-4} \text{ m s}^{-1}$. Away from this recirculation area (about 6 km wide), the transverse circulation decreased rapidly. At a distance 10 km away from the closed end, the maximum magnitude of $v$ was only $\sim 0.001 \text{ m s}^{-1}$. These distributions were also consistent with Winant’s (2004) solutions. An important feature of this nonrotating response (Fig. 2) was that horizontal and vertical velocity components were axially symmetric in the numerical domain.

2) Experiment 2: Rotating case, $h/d \approx 2$

To compare the results between nonrotating and rotating systems, the effect of the earth’s rotation was added to the nonrotating baseline case. Under these conditions, the thickness of the surface Ekman layer occupied about one-half of $h$ (i.e., $h/d \approx 2$).

Inclusion of the earth’s rotation into the dynamics caused significant differences in all velocity components relative to the nonrotating case. Although the $u$ zero isotachs still intersected the bathymetric profile around the mean depth and downwind flow appeared only over the shoals, the lateral distribution of the $u$-velocity component featured axial asymmetries (Fig. 3). Stronger downwind flow was found over the right shoal.
than over the left shoal (looking into the system and downwind, in the Northern Hemisphere). The asymmetries of the $u$-velocity component became most evident near the head of the system, around 10 km away from the closed end, where the downwind flow began to converge. The core of maximum upwind flow near the head of the system moved toward the left (again looking downwind) as expected from differential transport of along-channel flow. Differential transport meant that more water moved downwind over the right shoal than over the left shoal because of rotation. This differential transport induced a lateral pressure gradient at the head of the system that pushed the upwind flow core toward the left. The asymmetries resulting from this experiment suggested that, under the condition of $h/d \approx 2$, the Coriolis term played an important role in the dynamics.

More noticeable differences relative to the nonrotating baseline case appeared in the other two velocity components, that is, in the lateral and vertical flow. Midway along the domain, the lateral flow showed two distinct layers with the upper layer moving toward the right of the wind (as expected from Ekman dynamics) and a compensatory lower layer flowing in the opposite direction. Maximum $u$ values on the surface Ekman layer were located at the transition between downwind and upwind flows, while relatively weak $u$ values where found near the lateral walls of the basin and in the middle of the cross section (Fig. 3). The latter response occurred because downwind flow over the shoals induced lateral circulation toward the right of the wind due to the earth’s rotation. In the channel, Coriolis deflection on the upwind flow acted in the opposite direction (toward the left of the wind). At the head of the system, the lateral distribution of the $v$ component showed convergence toward the center of the channel as in the nonrotating case, but was not axially symmetric. Owing to the axially asymmetric distribution of the $u$-velocity component, the water over the left shoal (where the flow was weaker) started to reverse toward the mouth at a greater distance from the head than the water over the right shoal (where the flow was stronger).

Away from the area influenced by the closed end, the vertical velocity component showed two upwelling and two downwelling cells related to divergence and convergence of lateral flow. As mentioned before, the convergence and divergence of the $u$-velocity component was relatively small (except near the head), while the transverse component showed convergence and divergence near the lateral walls and on both sides of the upwind flow. Along the basin left wall (looking toward the head) lateral flow caused upwelling while on the right wall it caused downwelling. The other convergence and divergence regions related to the upwind flow induced relatively weak upwelling and downwelling cells (Fig. 3). As in the nonrotating case, the vertical flow near the head was almost everywhere toward the bottom except in the middle of the cross section, but in the rotating case it was axially asymmetric (Fig. 3). Maximum downward flows ($3.7 \times 10^{-4}$ m s$^{-1}$) were located over the right bathymetric slope as expected from the asymmetries of the lateral distribution of the $u$ component. Relatively weak (up to $10^{-5}$ m s$^{-1}$) upward flow was found in the middle of the cross section at the head, associated with the divergence of the upwind flow.

Another important feature of the solution caused by the inclusion of the earth’s rotation was the free surface elevation distribution in the domain (Fig. 4). In the nonrotating baseline case, the surface elevation distribution was only a function of along-channel direction. According to Glorioso and Davies (1995), the across-channel barotropic pressure gradient expected in wind-induced flow over flat-bottom rotating systems is nearly a linear function of y location. The combination of both
Coriolis effects and laterally varying bathymetry produced a more complicated lateral barotropic pressure gradient distribution (Fig. 4). Surface elevation contours showed stronger lateral variability compared to the nonrotating case, due to the spatial variability in the longitudinal flow and vertical mixing dictated by the laterally varying bathymetry. The spatial distribution of the modeled surface elevation was consistent with that obtained by Glorioso and Davies (1995).

In general, the magnitude of the $u$-velocity component was about the same for both nonrotating and rotating baseline cases. But the magnitude of the lateral and vertical velocity component of the rotating cases was larger than for the nonrotating case in areas away from the closed ends. The $|\overline{v}|/|\overline{u}|$ ratio evaluated midway along the basin, where $|\overline{v}|$ is the absolute value of the cross-sectional average of the lateral flow, was 0.005 for the nonrotating baseline case and 0.03 for the rotating case ($h/d = 2$).

3) DIFFERENT $h/d$ BY CHANGING $h$

To analyze rotation influences in terms of different maximum water depth, two different numerical experiments were run with the same wind stress as in experiment 2 (0.08 Pa toward the head) but the maximum depth was chosen such that $h/d$ took values around 1 and 4.

(i) Experiment 3: $h/d \approx 4$

In the $h/d \approx 4$ case, the bathymetric profile was triangular, with minimum depth of 3 m and maximum depth of 60 m. Increasing the maximum depth of the channel ($h$) caused an increase in the magnitude of the $u$-velocity component compared with the baseline rotating case, as expected from the reduction of bottom stress effects throughout the water column. On the other hand, the ratio of the magnitude of the horizontal velocity components $|\overline{v}|/|\overline{u}|$ increased with respect to experiment 2. The $|\overline{v}|/|\overline{u}|$ value for the $h/d \approx 4$ case was $\sim 0.06$ while for the $h/d \approx 2$ case it was $\sim 0.03$. Increasing $h/d$ through an increment of the maximum depth of the channel ($h$) causes the lateral distribution of the $u$-velocity component to become more asymmetric (Fig. 5) compared to the $h/d \approx 2$ case. The small gyres formed around the upwind core were intensified.

(ii) Experiment 4: $h/d \sim 1$

In experiment 4, the reduction of the maximum depth of the channel to 8 m caused the lateral distribution of the $u$-velocity component to become symmetric (Fig. 6) as in the nonrotating case (Fig. 2). The lateral velocity component still showed a two-layer structure. The magnitude of the $u$ component was reduced slightly compared with experiment 2 as expected from increased bottom stress effects. The $v$ component was reduced such that the $|\overline{v}|/|\overline{u}|$ ratio for this rotating case was 0.02. As the system became shallower, the vertical shear stress became more important in the dynamics such that the main balance became that described in the nonrotating condition. This indicated that in the along-channel balance the Coriolis term became less important as the ratio $h/d$ approached 1, which was consistent with the semianalytical solution of Winant (2004). The noticeable reduction of the magnitude of the other two velocity components ($v$ and $w$) was also consistent with decreased rotation influences.

4) DIFFERENT $h/d$ BY CHANGING $d$

Two different numerical experiments were run with the same bathymetry as in experiment 2 but with wind stresses such that $h/d$ adopted values of 1 and 4. The cross section was triangular with minimum depth of 3 m and maximum depth of 20 m. To better analyze the effects of changing $h/d$ by changing $d$ through using
different wind stresses, the results from experiments 2, 5, and 6 were plotted as $u/u_*$ instead of only $u$ (Fig. 7), where $u_*$ is the frictional velocity due to the wind ($u_*^2 = \tau/\rho$, where $\tau$ is the wind stress and $\rho$ is the water density).

\( (i) \) Experiment 5: $h/d \approx 4$

By forcing the system with a weak wind stress of $\tau = 0.008$ Pa the ratio $h/d$ took values of $\sim 4$; that is, the Ekman surface layer was limited to one-quarter of the water column (Fig. 7a). The magnitude of all velocity components decreased (relative to experiment 2) as expected from the reduction of the wind stress. Although the $|\bar{v}|/|\bar{u}|$ ratio midway along the channel was similar to the other $h/d \approx 4$ case (0.07), the axial asymmetries of the $u$-velocity component were not as evident because of weaker Coriolis accelerations from weaker wind stress. Asymmetries were only evident near the head of the system (Fig. 7b).

\( (ii) \) Experiment 6: $h/d \approx 1$

In the other experiment that changed $d$, in order to approach the value of $h/d$ of 1, the system was forced with a strong wind of 0.5 Pa. The Ekman surface layer occupied the entire water column at all $y$ locations (Fig. 7e). The magnitude of all velocity components increased as expected from the increment of the wind stress, but the horizontal velocity ratio $|\bar{v}|/|\bar{u}|$ decreased to $\sim 0.014$. Lateral distribution of the $u$-velocity component (or $u/u_*$) became symmetric. This was also true near the head of the system (Fig. 7f), as in the previous $h/d \approx 1$ case. Under these strong wind conditions, the lateral change of the $u$-velocity component became more important than in previous cases as shown by the $u/u_*$ isolines separation.

Wind-induced circulation in the triangular cross section showed lateral distribution of the along-channel velocity component for low and high Ekman numbers. Lateral gradients of the $u$-velocity component depended on the strength of the wind (experiments 2, 5, and 6) and/or on the lateral slope of the channel (experiments 2–4). Although the lateral gradient of the $u$-velocity component suggested that lateral mixing might be important (for strong wind cases and/or abrupt lateral slopes) in the $u$-momentum balance, lateral mixing was not included explicitly in the numerical model: first of all, because the selection of an appropriate value and/or function of the horizontal eddy viscosity is nontrivial and, second, because weak lateral mixing was included implicitly through the advection scheme used (Haidvogel et al. 2000).

b. Bathymetric effects

To study the effects of arbitrary transverse depth variations on the wind-driven circulation, numerical experiments similar to experiment 2 were run over four different Gaussian bathymetric profiles given by (1) and (2). Two experiments (7 and 8) analyzed the effect of the bottom slope and the width of the channel. The wind stress used in these experiments was such that $h/d$ remained invariant (0.03 Pa in experiment 7 and 0.025 Pa in experiment 8). The last two experiments (9 and 10) emphasized the role played by the value of mean cross-sectional depth on the lateral structure of the wind-induced flow. These experiments were forced with a constant and uniform wind stress of 0.03 Pa.

1) EXPERIMENTS 7 AND 8: ARBITRARY TRANSVERSE DEPTH VARIATIONS

The channel–shoal combination in the Gaussian profile resulted in essentially the same overall wind-induced exchange flows (Fig. 8a). These exchange patterns only differed in a few features compared with the triangular cross section. In Fig. 8a, downwind flow over the flat areas showed well-defined vertical gradients in
contrast to the pattern in the channel, which showed well-defined horizontal gradients. The velocity vertical profiles over the shoals were independent of lateral position. They showed maximum downwind flow at the surface and minimum flow at the bottom as expected from wind forcing and bottom friction, respectively. In the channel, the magnitude of the flow was strongly dependent of the local position. The rapid changes in slopes of the along-channel isotachs were associated with the edges of the channel.

It is clear that the lateral shear of the $u$-velocity component decreased as bathymetry became smoother (Figs. 8a and 8b). This was illustrated by the separation of the $u$-velocity isotachs. The magnitude of the upwind flow decreased and maximum upwind flow tended to concentrate near the bottom as bathymetric changes became smoother. In other words, as the slope of the bottom decreased, the maximum upwind flow spread out across the bottom such that the solution approached that for flat-bottom systems (i.e., Wong 1994; Signell et al. 1990). These results were consistent with Hunter and Hearn (1987), who found the cross-sectional bottom slope to be proportional to the lateral gradient in $u$. The lateral convergence of the $v$-velocity component associated with the $u$-zero isotachs tended to disappear as the slope of the bottom decreased, such
that the transverse circulation described one gyre that occupied the entire cross section (Fig. 8a).

2) EXPERIMENTS 9 AND 10: DOUBLE-CHANNEL PROFILES

To emphasize the role played by the shape of the bathymetry and the value of mean depth on the lateral structure of the wind-induced flow, two additional numerical experiments with a double-channel profile [given by (2)] were analyzed. For the case in which both channels were deeper than the cross-sectional mean depth, the $x$ component of the flow was upwind in both channels and downwind elsewhere. Maximum upwind flow was found in the deepest channel (Fig. 8a), as was expected from bottom friction acting more noticeably in the shallow channel. Both cores of maximum upwind flow were centered with respect to each channel. For the case where only one of the two channels was deeper than the mean depth (Fig. 9b), both channels showed lateral structure of the along-channel flow, but upwind flow developed only in the channel that was deeper than the mean depth. Downwind flow in the middle flat shoal exhibited vertical shears in contrast with the shallow channel that showed lateral shears. Transverse circulation showed a gyre that occupied the entire cross section and small gyres located around the $u$-zero isolat, similar to the one-channel cross section.

Double-channel bathymetric profiles showed that lateral variations of depth induced lateral shears in the along-channel velocity component, but upwind flow developed only in channels deeper than the cross-sectional mean depth (Fig. 9). This was because the lateral partition of the $u$-velocity component into upwind flow and downwind flow occurred around the average depth of the bathymetric profile, in agreement with the vertically integrated transports of Csanady (1982). Also noteworthy was the rapid change of the slope of the $u$ isolats associated with the bathymetric change. Over the middle shoal the isolats became horizontal but in the channels they bent upward to reflect lateral variability of the flow.

Fig. 8. Velocity field for the midway transverse section in the rotating cases for Gaussian cross sections given by (1): (a) with $C = 2000$, $h/d = 2.47$, $\tau = 0.03$ Pa, and $h = 20$ m (max $|v| = 0.014$ m s$^{-1}$; max $|w| = 6.5 \times 10^{-3}$ m s$^{-1}$) and (b) with $C = 5500$, $h/d = 2.5$, $\tau = 0.025$ Pa, and $h = 20$ m (max $|v| = 0.014$ m s$^{-1}$; max $|w| = 9.0 \times 10^{-3}$ m s$^{-1}$). Experiments 7 and 8.

Fig. 9. As in Fig. 8, but for Gaussian cross sections given by (2): (a) with $a_0 = 8, a_1 = 8, and a_2 = 12$ (max $|v| = 0.016$ m s$^{-1}$; max $|w| = 9.2 \times 10^{-3}$ m s$^{-1}$) and (b) with $a_0 = 9, a_1 = 2.5, and a_2 = 12.5$ (max $|v| = 0.015$ m s$^{-1}$; max $|w| = 1.4 \times 10^{-4}$ m s$^{-1}$). Experiments 9 and 10.
4. Summary

A three-dimensional primitive equation model has been used over idealized bathymetry with lateral depth variation to examine the lateral distribution of the wind-driven flow. In all cases a turbulence closure model was used to examine the nonlinear interaction between current and vertical mixing. The choice of the turbulence closure did not affect the essence of the results.

The wind stress induced a circulation pattern consisting of downwind flow over the shoals and upwind flow in the channel along the entire domain. This pattern was consistent with other studies. For rotating cases, the details of the wind-induced pattern depended on the ratio of the maximum depth $h$ to the Ekman layer depth $d$. In cases where $h/d \geq 2$, the longitudinal flow was axially asymmetric in such a way that maximum downwind flow was located over the right shoal (looking downwind) in the Northern Hemisphere. The rotating solution approached that described in a nonrotating case as $h/d$ remained equal to or below 1. The earth’s rotation effects were most evident in the transverse circulation. In nonrotating cases, the transverse circulation was very weak and became relevant only at the head of the system, where the water sank and reversed direction to move toward the mouth. In rotating systems, the relative importance of the transverse circulation to the longitudinal circulation increased as $h/d$ increased.

In general, the transverse circulation in rotating systems described three gyres. The main gyre was clockwise (looking downwind) and occupied the entire basin cross section. Looking downwind, upwelling developed at the left boundary and downwelling appeared at the right boundary. The surface flow moved from left to right (to the right of the wind in the Northern Hemisphere) and bottom flow moved from right to left. The other two gyres were small and localized and were linked to the channel edges, at the transition between upwind and downwind flow.

The numerical results described above showed similarities and differences with the linear semianalytical solution presented by Winant (2004). The similarities were as follows. In both semianalytical (Winant 2004) and numerical solutions, the transverse component of velocity described a clockwise gyre (looking downwind) that showed upwelling on the left wall and downwelling on the right wall. This gyre occupied the entire cross section and resulted from rotation effects on wind-induced flow constrained by basin walls. Also in both numerical and analytical solutions, the lateral distribution of the rotating $u$-velocity component approached the nonrotating solution when the ratio $h/d$ approached 1 and became axially asymmetric as $h/d$ increased.

The differences between these results and those of Winant (2004) are as follows. The inclusion of all terms in the momentum equations with the eddy viscosity varying in time and space yielded a few more features in the numerical solution. The numerical solution resolved two small-scale gyres in the $y-z$ plane linked to the lateral distribution of the along-channel velocity component, which in turn was dictated by bathymetry. This was true for all the rotating experiments. The earth’s rotation effects, manifested by enlarged asymmetries or increased $|\mathbf{v}|/|\mathbf{w}|$ ratios, were noticeable for the cases with $h/d > 2$. In cases in which $h/d \sim 1$ over relatively deep channels (e.g., $\sim 20$ m; Figs. 7e,f), the wind stress was such that it drove $u$ velocities with large lateral shears. The largest lateral shears were localized along the partition between upwind and downwind flows.

These results are expected to motivate future measurements that verify the numerical results in terms of (a) axial asymmetries produced by rotation and the associated transverse circulation and (b) the inverse estuarine circulation induced by upestuarial winds.

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