LONG WAVES OVER THE GREAT BARRIER REEF

by

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ABSTRACT

Low-frequency forcing of water currents over the continental shelf of Australia is quite strong and should be taken into account when the flow for durations greater than 1 day is important. In the case of the Queensland coast, the longshore wind generates barotropic continental shelf waves, raising or lowering the mean sea level by as much as 30 cm and generating longshore currents over the continental shelf, even very close to the coast, that are often larger than the tidal currents. These wind-driven currents can reverse sign, flowing alternately northward and southward, although the longshore wind stress, though fluctuating, does not change direction. To reproduce such phenomena in an analytical or computer model of wind-driven currents, it is necessary to extend the offshore boundaries of the model offshore from the continental shelf break.

1. INTRODUCTION

In 1966, Hamon digitized sea level observations at various ports around Australia, removed the tidal component from the time series and discovered that the "mean sea level" is not a constant. Shelf waves were thus discovered and have since been intensively studied by physical oceanographers (see a review by Allen (1980) and Winant (1980)). In their simplest mode, the continental shelf waves are disturbances of the sea level, highest near the coast and negligible in the deep ocean, with a longshore wave length often exceeding 1500 km, of duration typically one to two weeks, raising or lowering the mean sea level by as much as 50 cm.

Until recently, coastal engineers in Australia have often ignored these waves in many applications where currents were a design parameter, presumably because the sea level disturbance (say, 30 cm) is small compared to the tidal range (say, 2 m). Yet, as will be shown, the currents introduced by shelf waves can be stronger than the tidal currents. Further, the shelf-wave-driven currents can reverse sign, though the wind direction does not change, typically in one to two weeks, so that water current investigations of duration less than two weeks will likely lead to aliased data if the mean flow has to be determined, such as for estimating the dispersion of contaminants from outfalls.

2. FIELD STUDIES IN AUSTRALIA

As part of the research program in physical oceanography by the Australian Institute of Marine Science, I have run a long-term study of water currents over the continental shelf of the Great Barrier Reef.

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The initial study site was the central region (16 to 20°S lat.) from 1980 to 1981, and more recently the northern region (9 to 15°S) from 1981 to 1982. The study in the central region, which is reviewed here, involved the deployment and maintenance for more than one year of self-recording current meters, water level recorders and weather stations. The location of some of the instruments is shown in Fig. 1.

Wind

It was found (Wolanski, 1982) that, in the trade wind season, the dominant wind direction changed from westward over the Coral Sea to northwestward over the continental shelf. The dominant wind component was found to be highly coherent over distances of at least 1500 km, with negligible time lags from site to site, so that the wind-field over the continental shelf can be treated as time-dependent but stationary. The wind is energetic at all periods greater than a few

Figure 1 Location map, with depth in m, showing the mooring sites of some of the current meters (▲), water level recorders(■), and weather stations (●).
days, with a suggestion of a peak in the wind autospectrum at about 10 and 30 days duration.

**Currents**

Because the shelf is fairly flat (Fig. 2), the current meters were all in comparable depth. Baroclinic effects on the shelf are not very important, except near the shelf break (Wolanski and Pickard, 1983), because the shelf waters are well-mixed, the thermocline being located at 100 m depth or so, i.e. offshore from the continental shelf break. In Fig. 3 are shown the low-frequency (after removing the tidal signal) current time series at several locations, over roughly 4 months. At the Green Island mooring site, the tidal component of the currents is so weak that the longshore currents do not reverse sign with the tides, though a spring tidal range of about 3 m is experienced. Instead, as can be seen from Fig. 3, the currents are alternately northward and southward, reversing sign in typically one to two weeks. Such low-frequency forcing is apparent at all sites (Wolanski and Bennett, 1983). At Green Island and Euston Reef, the longshore currents are nearly equal and no residual 'mean flow' is found after several months, although, for practical purposes, the longshore wind component did not reverse sign (Fig. 3).

**Sea levels**

The variance of the sea level signal is primarily (90%) due to diurnal and semi-diurnal tides. The spring tidal range exceeds 3 m, the neap tide range is about 40 cm. The low-frequency signal is typically 30 cm from peak to trough (Fig. 3) and is found to be highly coherent at all stations.

**Propagation of the disturbances**

Using lagged correlation techniques or coherence and phase calculations, it was shown (Wolanski and Bennett, 1983) that the low-frequency longshore current and sea level disturbances are travelling
Figure 3

Time series of the low-frequency longshore wind component (positive if northward), of the low-frequency sea level and longshore currents (positive if northward) at various locations. The letters A to D identify some wind-driven events. Note that the longshore wind component is nearly always positive, but that the currents reverse sign.
longshore northward at a speed of roughly 650 km day$^{-1}$, although the wind field is stationary and the longshore wind component is highly correlated with both the low-frequency longshore currents and the low-frequency sea levels.

3. MATHEMATICAL FORMULATION

The $f$-plane shallow water wave equations are

\[ u_t + uu_x + vu_y - fv = -gh_x + \eta^x/(H+h) - P^x/(H+h) \]  
\[ v_t + uv_x + vv_y + fu = -gh_y + \eta^y/(H+h) - P^y/(H+h) \]  
\[ h_t + ((H+h)u)_x + ((H+h)v)_y = 0 \]

where $t$ is the time, $x$ and $y$ the horizontal Cartesian coordinates ($x$ is oriented cross-shelf pointing offshore, $y$ longshore pointing northward, the origin being at the coast), $u$ and $v$ the corresponding velocity components, $T^x$ and $T^y$ the wind stress components, and $F^x$ and $F^y$ the bottom friction components. A subscript indicates a partial derivative, $g$ is the acceleration due to gravity, $H$ is the undisturbed water depth, $h$ the sea level disturbance, and $f$ the Coriolis parameter.

Equations (1)-(3) are non-linear but can be greatly simplified without losing the important physical processes controlling the dynamics of water currents over the Great Barrier Reef continental shelf. Using the array of current meter and tide gauge data centered around Brook Island, it was possible (Wolanski and Bennett, 1983) to estimate a number of terms in equations (1)-(3). For example, as is shown in Fig. 4, the sea level vertical velocity, $h_y$, can be neglected in equation (3). This approximation is called the "rigid-lid assumption" (e.g., see Allen, 1980), and averages out the seiching which occurs during wind set-up. This seiching has a time scale appropriate to the time taken for a long surface gravity wave to traverse the shelf and that is about typically 1-2 hours. The cross-shelf momentum equation (1) is simplified in practice (Fig. 5) to a simple geostrophic balance between the longshore current, $v$, and the cross-shelf slope of the water surface, $h_y$. The non-linear terms can be neglected and the total depth $(H+h)$ in equations (1) to (3) can be approximated by the undisturbed water depth, $H$.

With these approximations, originating from the field data, the equations of motion become

\[ fv = -gh_x \]  
\[ v_t + fu = -gh_y + \eta^y/H - P^y/H \]  
\[ (hu)_x + (hv)_y = 0 \]

To model the wind-driven currents, we assume a simple topography, shown in Fig. 6, namely a shelf of uniform depth $H$ and extending
Figure 4  Term balance in the continuity equation (3)

Figure 5  Time series of various terms in the cross-shelf momentum equation (1)
from the shore \(x=0\) to the shelf break \(x=L\), the ocean of depth \(H_0\) extending from \(x=L\) to infinity.

The boundary conditions are continuity of sea level \(h\) and of cross-shelf fluxes \(uH\) at \(x=L\), the disturbance \(h\) vanishing as \(x\) goes to infinity (the data showing that the mean sea level perturbations are much smaller over the Coral Sea than over the shelf), and \(u=0\) at \(x=0\).

The forcing is provided by the longshore wind stress (from which the time-averaged mean wind has been substracted as the mean flow is very small)

\[
T^y = \begin{cases} 
0, & \text{for } y < 0 \\
T_0 \exp(iwt), & \text{for } 0 < y < A \\
0, & \text{for } y > A
\end{cases} \tag{7}
\]

where \(T_0\) is a constant, \(w\) the frequency, \(A\) the size of the wind-field, and \(i=(2l)^{-1}\).

The solution, to order \(H_s/H_0\), is

\[
u = -xv_y 
\tag{8}
\]

\[
h = (x-L) fv/y 
\tag{9}
\]

\[
v = B \exp(iwt) \left(1 - \exp(-iyw/c) \exp(-by/c)\right) \tag{10}
\]

where

\[
B = \left(\frac{T_0}{H_s}\right)/(i(w-ib)) \tag{11}
\]

\[
b = \frac{r}{H_s} \tag{12}
\]

\[
c = -\frac{fL}{g} \tag{13}
\]

Figure 6 Sketch of the model geometry
where \( r \) is the friction coefficient, assuming a linear law

\[
p^y = rv
\]

which turns out, from the field data, to be of the order of

\[
2 \times 10^{-4} = \text{m}^{-1}
\]

c is the phase speed of free shelf waves, about 200-230 km day\(^{-1}\) in this region.

A number of features of equations (8) to (10) are in good agreement with observations, namely that \( v \) is independent of \( x \), that \( h \) is largest at the coast, and that \( v \) and \( h \) are in phase. Further, the correlation field of sea level and current disturbances propagate northward longshore at a phase speed of \( 2c \), i.e. about 450 km day\(^{-1}\), in good agreement with the observations. From equation (10), it is apparent also that the longshore current, \( v \), can be alternately northward and southward, resulting in a net zero total displacement after one period (wind event).

Near the shelf break, the ocean stratification introduces important baroclinic effects. These are compounded by the effects of the Great Barrier Reef which, as it turns out, result in only a small enhancement of the friction over the shelf by damping the exchange of water between the continental shelf and the Coral Sea. The link between the shelf and the ocean effectively traps the disturbance over the shelf and implies that a mathematical or computer model of wind-driven currents over the shelf must cover an area extending offshore from the continental shelf break.

The low-frequency modulation of sea levels controls the frequency of inundation, hence the flushing of coastal wetlands in Queensland. This modulation of sea level can also be important in harbours where depth is limiting, and in shallow shipping lanes such as Torres Strait (Wolanski and Gardiner, 1981, Wolanski and Thomson, 1983).

4. REFERENCES


Wolanski, E. and G.L. Pickard (1983), "Upwelling by internal tides and Kelvin waves at the continental shelf break on the Great Barrier Reef"
