LONG WAVES OVER THE GREAT BARRIER REEF

by

Eric Wolanski *

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 contin-
ental 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.

* Principal Research Scientist, Australian Institute of Marine
   Science, P.M.B. No.3, Townsville, Q.4810, Australia.

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
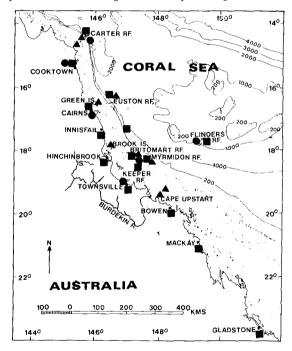
Figure 1 Location map, with depth in m, showing the mooring sites of
          some of the current meters (▲), water level recorders(■),
          and weather stations (●).

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
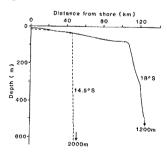

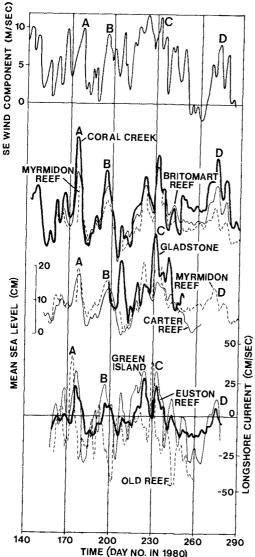Figure 2   Offshore bathymetry at two locations.

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 450 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

$$u_t + uu_x + vu_y - fv = -gh_x + T^x/(H+h) - F^x/(H+h) \qquad (1)$$

$$v_t + uv_x + vv_y + fu = -gh_y + T^y/(H+h) - F^y/(H+h) \qquad (2)$$

$$h_t + ((H+h)u)_x + ((H+h)v)_y = 0 \qquad (3)$$

where t is the time, x and y the horizontal Cartesian coordinates (x is oriented cross-shelf pointing offshore, y longshore poiting 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_t, 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_x. The non-linear terms can be neglected and the total depth (H+h) in equations (1) to (3) can be approximated by the undisturbed depth, H.
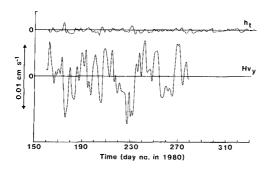
   With these approximations, originating from the field data, the equations of motion become

$$- fv = - gh_x \qquad (4)$$

$$v_t + fu = - gh_y + T^y/H - F^y/H \qquad (5)$$

$$(Hu)_x + (Hv)_y = 0 \qquad (6)$$

To model the wind-driven currents, we assume a simple topography, shown in Fig. 6 , namely a shelf of uniform depth H_s and extending

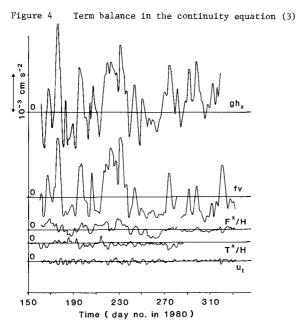Figure 4   Term balance in the continuity equation (3)

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_o 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)

$$T^y \begin{cases} =0, \text{ for } y < 0 \\ =T_o \exp(iwt), \text{ for } 0 < y < A \qquad (7) \\ =0, \text{ for } y > A \end{cases}$$

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

The solution, to order H_s/H_o, is

$$u = - xv_y \qquad (8)$$

$$h = (x-L) \ fv/g \qquad (9)$$

$$v= B \exp(iwt) \ (1 - \exp(-iwy/c) \exp(-by/c)) \qquad (10)$$

where

$$B = (T_o/H_s)/(i(w-ib)) \qquad (11)$$

$$b = r/H_s \qquad (12)$$

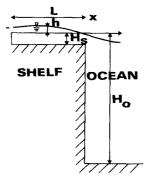$$c = - fL \qquad (13)$$

Figure 6   Sketch of the model geometry

where r is the friction coefficient, assuming a linear law

$$F^y = rv \qquad\qquad (14)$$

which turns out, from the field data, to be of the order of
2. x 10^{-4} m s^{-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).

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