CHAPTER 81

Wind-induced Cross-shore Water Flows

J B Crowley* and D H Swart**

1. Abstract

To cater for the effect of wind-driven nearshore processes on the prediction of nearshore onshore/offshore sediment transport a series of field experiments were carried out to establish a reference framework to be used as basis for the modelling of wind-driven cross-shore currents. The results indicate a clear relationship between bottom return current, wind speed and the water depth. This implies that a mathematical framework can be established using the conservation of mass and momentum and the similarity criterion.

2. Background

Nearshore sediment transport takes place as the combined action of wind, waves and tides. The processes are characterised by extreme turbulence under the action of breaking or near-breaking waves. Predictive techniques for the magnitude of the resulting nearshore transport rate, whether it be in the alongshore or the cross-shore direction, proliferate but they have all got but one commonality - the extreme simplifications and assumptions that have to be made. Typically what is done is that both wind and tide effects are neglected and only wave effects are considered. If we concentrate on cross-shore sediment transport, the best and/or most-used techniques today are those of Baillard (1981), Nairn (1988), Larson (1989), Stive (1987) and Swart (1974, 1986). Apart from the last technique, which has a broad theoretical basis with empirical coefficients which has proved extremely robust and accurate over a

---

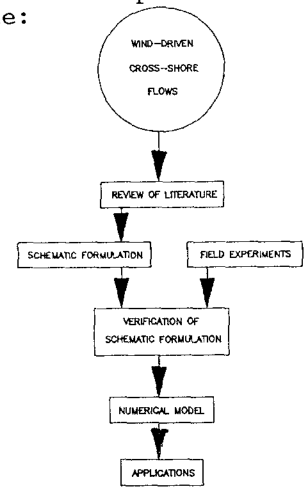
* CSIR, P O Box 320, Stellenbosch, 7600, South Africa.

** CSIR, P O Box 395, Pretoria, 0001, South Africa.

wide range of conditions, the other methods all utilise a momentum approach and are more theoretical of nature.

Experience has shown that these techniques are reasonably reliable (Seymour *et al.*, 1988, Möller *et al.*, 1988) but that specifically wind effects can totally upset the predicted results. Swart (1987) showed, e.g. that whereas all known predictors of the direction of cross-shore wave-driven transport would indicate offshore-directed sediment movement (beach erosion), the beach in the centre of a large bay of the south coast of South Africa accreted heavily whilst being attacked by normally-incident storm waves with a significant incident height of about 7 m and a deep-water steepness of 0,05. At the time a 20 m/s offshore wind was blowing, with presumably onshore return flow at the bed to compensate for water blown seawards.

This inspired the present study, which has the following outline:



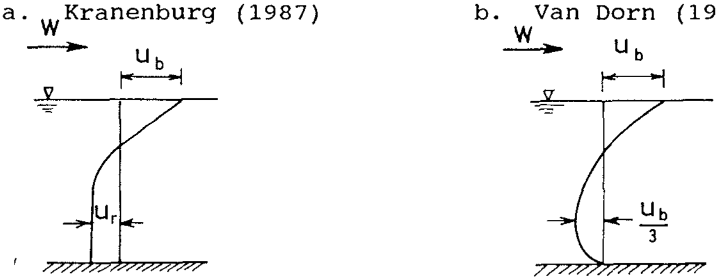
The present paper concentrates on the field work and covers all aspects but the last two, namely, the numerical model and potential applications.

2. Review of Literature

A scan of the literature reveals a wide selection of papers dealing with the prediction of wind-driven water flow, e.g. Kranenburg (1987), Hubertz (1987), Kullenberg (1976), Winant (1980), Komen and Riepma (1981), Thomas (1975), Eidnes (1986), Bennett (1974, 1979), Birchfield (1972), Grant (1979), Madsen (1976), Kuzmic (1989) and Van Dorn (1953). However, although these papers contain valuable insights into the theoretical treatment of wind-driven flows in general, they contain virtually nothing on cross-shore flows.

The only two papers with an applicable treatment of cross-shore flows are those by Kranenburg (1987) and Van Dorn (1953). In these two cases the following representation of the vertical flow profile was postulated on the basis of data:

a. Kranenburg (1987) b. Van Dorn (1953)



a.
- Laboratory data
- Theoretical framework sketchy

b.
- Theoretical framework
- Sketchy data in pond

Figure 1. Postulated Wind-driven Flow Profile

Theoretical treatment. If one considers the various theoretical treatments in the whole body of the literature referred to above, it can be concluded that these are both numerous and varied. A short summary is included below.

The **basic equations** typically are

- the conservation of mass; and
- the equations of motion.

The **boundary conditions** used to solve these are then:

- the mean vertical surface flow is equal to zero; and/or
- the bottom shear stress is specified; and/or
- the surface shear stress is specified; and/or
- the surface drift velocity is related to the wind speed at some elevation above the water surface.

If one looks at the assumptions made by the various investigators, one sees the following spread:

- Direction of wind - on/offshore
  - longshore

•	Water surface slope	- horizontal - sloping
•	Homogeneous wind stress	- all
•	Coastal alignment	- straight - curved - arbitrary
•	Wave effects	- included - excluded
•	Temporal variability	- yes - no
•	Vertical averaging	- yes - no
•	Hydrostatic pressure	- yes - no
•	Dynamic pressure terms	- included - excluded
•	Return flow	- yes - no
•	Bed friction	- neglected - linear - quadratic
•	Geometry of water body	- arbitrary - rectangular - two-dimensional

3. Schematic Formulation

On the basis of an analysis of the literature, the following first approximate approach is formulated.

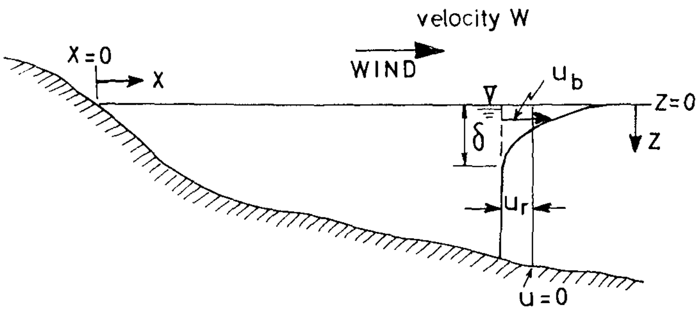


Figure 2. Definition Sketch

The following assumptions are made:

- the rigid-lid approximation is used;

- wave effects are neglected;
- the water surface slope is horizontal;
- the pressure distribution is hydrostatic;
- turbulent pressures are neglected;
- shear stresses in the return flow area are disregarded;
- the velocity profiles in the boundary layer agree to similarity, that is, the surface drift is proportional to the shear velocity U_*.

With these assumptions as basis, the following formulation is found:

Equation of motion

$$U_r \frac{dU_r}{dx} + \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x} = 0 \qquad \ldots (1)$$

Conservation of mass

$$- U_r d + \int_0^{\delta} U_b(x,z)\, dz = 0 \qquad \ldots (2)$$

Integral conservation of momentum

$$d \frac{\partial \bar{p}}{\partial x} + \frac{d}{dx}\left[\rho \int_0^{\delta}\left\{-U_r + U_b\left(x,z\right)\right\}^2 dz\right] = \rho\, U_*^2 \qquad \ldots (3)$$

Similarity criterion

$$u_b(x,z) = U_* f(\zeta) \qquad \text{where } \zeta = z/\delta \qquad \ldots (4)$$

The function $f(\zeta)$ determines the shape of the velocity profile inside the boundary layer. Kranenburg (1987) manipulated his data into a form where an expression could be found for $f(\zeta)$.

For the case where the bed slope is constant and with the surface shear velocity u_* proportional to the wind velocity W, it can be show that

$$\frac{U_r}{W} \propto d^{-1} \qquad \ldots (5)$$

This relationship will be used later as framework to plot the field data.

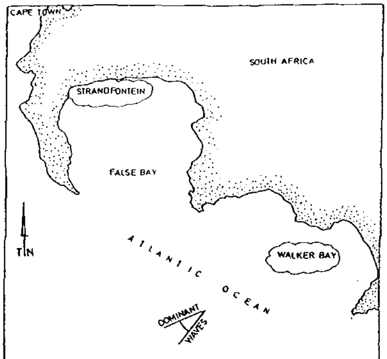


FIGURE 3: FIELD MEASUREMENT SITES

4. Field Experiments

The field measurements to quantify bottom return current as a result of a cross-shore wind were done at two sites on the south-western coast of South Africa. As can be seen on Figure 3, both of these bays face the predominant south-westerly swells although False Bay due to its dimensions is more protected than Walker Bay. Storm waves arrive at the latter nearly unabated.

In all three experiments were done, namely, in September 1986 and February 1990 in Walker Bay and in March 1990 in False Bay. The Walker Bay exercises were part of much bigger field measurement campaigns into nearshore coastal processes but the False Bay exercise was done solely for the purpose of determining wind-driven currents.

At Walker Bay the strongest wind events are from the north-west (May to August) and from the south-east during the rest of the year. Cross-shore wind events are therefore less prevalent. Nevertheless, a few useful blows in roughly the cross-shore direction did occur during the two exercises. The strongest wind events at False Bay occur from the same directions but due to the orientation of the bay and more specifically the prominent mountain ranges around it, the strong winds are nearly always roughly aligned in the cross-shore direction.

In doing the experiments during the three field programmes it was generally strived to deploy the equipment in the bottom 20 % of the water column and seaward of the dominant breaker line. Deployment water depth varied from 4 m to 20 m and in some of the shallower cases the current meters were at times inside the surf zone or very close to it, thus measuring wave-driven currents. It is easily visible on the plots of current velocity when this occurred.

As a result of the manner of deployment (location, depth, etc.) the results represent a breadth of varying influences, e.g. in incident waves (surface roughness), wave effects (rip currents, orbital velocity) and the bottom roughness (False Bay generally has a smoother bottom than Walker Bay).

Walker Bay : September 1986 Figure 4 gives an overview of the type of data gathered during this exercise. Figure 4c summarises all the available data points obtained with a vector-averaging current meter in 20 m water depth every 15 min. between 21 and 26 September 1986.

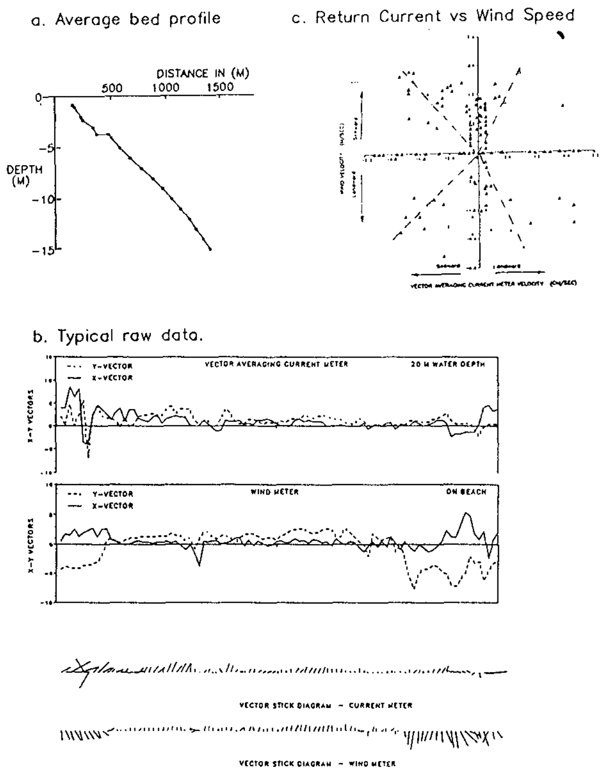


FIGURE 4: WALKER BAY DATA : September 1986

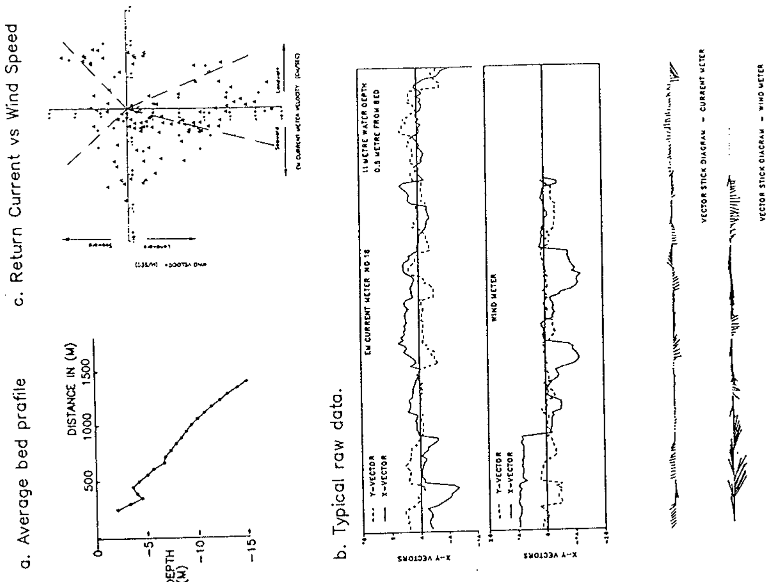


FIGURE 5 : WALKER BAY : February 1990

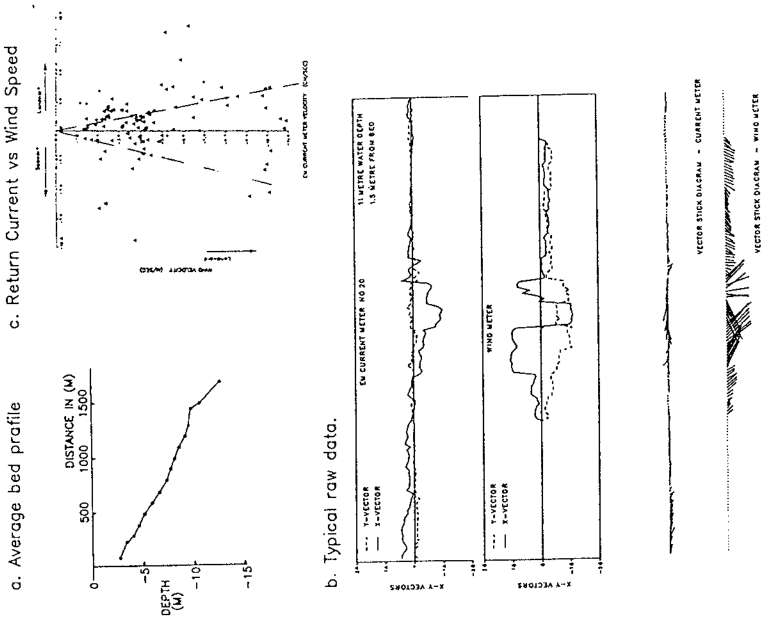


FIGURE 6 : STRANDFONTEIN : March 1990

During this period the incident, offshore wave climate varied as follows:

	Maximum	Mean	Minimum
* Significant height (m)	4,1	2,9	2,1
* Peak period (s)	15,5	12,3	7,5

The beachline was characterised by prominent cusps at 300 m centres, but the nearshore contours were nearly straight. As a result of the cuspate shoreline rip currents occurred along the beach at 300 m intervals leading to breaches in the main breaker bar at 5 m water depth, also at 300 m centres. At the position of the meter, well outside the breaker line, the contours were nearly parallel.

Walker Bay : February 1990. During this exercise 'bottom' current meters were deployed in 4 m and 11 m water depth, in each case at 0,5 m and 1,5 m above the bed. Figure 5 gives an overview of the data for the 11 m depth, 1,5 m above the bed case. The duration of the measurement campaign was from 9 to 22 February 1990, for a period of 2 hours around each day time high and low tide. Electromagnetic current meters were used for all four deployments.

During this period the incident, offshore wave climate varied as follows:

	Maximum	Mean	Minimum
* Significant height (m)	3,8	2,1	1,2
* Peak period (s)	13,5	10,3	6,6

The nearshore topography was fairly complex with no clear, well-developed breaker bar. Thus the contours were also complex, characterised by rapidly changing bars, troughs and gullies in 4 m depth but with a reasonably stable, straight set of contours in 11 m depth. The location of the breaker bar in Figure 5a in relation to the measuring stand also shows the potential for variability.

False Bay : March 1990. During this exercise the configuration of the February 1990 Walker Bay experiment was repeated, except that the deeper stand now had current meters at 0,5 m, 1,5 m and 2,5 m above the bed. Unfortunately, the meter closest to the bed at this deep stand malfunctioned and no data was obtained for that elevation above the bed.

Measurements were obtained for 2 hours around each day time high and low tide for the period 11 March to

21 March 1990. During this period the incident wave climate varied as follows:

	Maximum	Mean	Minimum
* Significant height (m)	3,0	1,8	1,0
* Peak period (s)	13,5	10,3	5,5

Figure 6 shows an overview of the data for the meter at 2,5 m above the bed in 11 m water depth. Figure 6c clearly shows some predominant wave effects, associated with a macro-rip current occurrence in the area.

This site is characterised by a very much flatter bottom profile than at Walker Bay, a very straight beach with fine sand, a smooth calcretous surface offshore and nearly straight contours at both deployment stands.

5. Verification of Schematic Representation

It was shown earlier that for a constant bed slope, which is a realistic assumption for all cases as can be seen, in Figures 4 to 6, the ratio U_r/W is proportional to the inverse of the water depth. To test this hypothesis the data in figures like Figures 4 to 6, but for all instruments, were fitted with a best-fit straight line through the origin. It is important to note that the wind condition varied between onshore and offshore, thus giving two possible data points per graph. The data, given in Figure 7a, show clearly that the correct tendency is prevalent in the plot. The scatter is to be expected, since the experiments were done under very different wave conditions and with varying seabed configurations. It is interesting that ratios between approximately 0,01 and 0,02 are found for the return current, whereas earlier studies have shown that the **surface** drift velocity varies between 3 % and 7 % of the wind speed (Kullenberg, 1976).

What is interesting, however, is that not only do those cases conform where the bottom current is a return current when compared to the wind direction, but this is also the case for those situations when the bottom current is in the same direction as the wind direction (Figure 7b). Presumably this represents cases where the whole water column is moved by wind action and continuity is achieved through horizontal water circulation.

The problem with field observations of wind-induced drift, or for that matter with laboratory observations, is that the drift takes place in a part of the nearshore area characterised by fairly vigorous currents, to mention but nearshore circulation with frequently stormy rip currents, orbital velocities and mass transport. All but the last are up to an order of magnitude higher than the wind-induced drift. Separation of the wind drift from the complex composite of currents in the nearshore area is at best a guestimate. However, the analysis done herein is not intending to provide absolute values for the drift, but rather to indicate qualitative final estimates of what appears to be the wind drift. As was shown, some clear guidelines emerged, obviously keeping the above comments in mind.

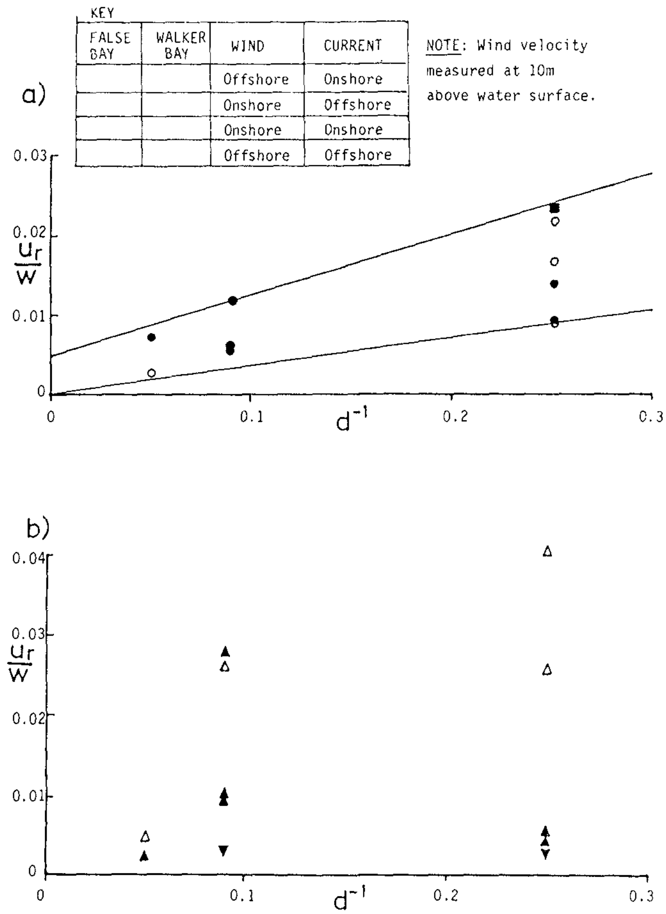


Figure 7. Schematic Framework for Prediction of Return Velocity U_r as a Function of Wind Velocity W and Water Depth d.

6. Conclusions and Recommendations

The main conclusions reached to date in this study on wind-induced cross-shore water flows are the following:

(1) The theoretical framework represented by Equations (1) to (4) is promising.

(2) The bottom 'return' layer concept seems reasonable, although the field data show that there are also cases where the return flow does not take place in the same cross-section. Presumably this latter case is strongly related to irregularities in the sea bottom and the obliqueness of the incident waves.

(3) The effect of bed slope on the results in Figure 7a and 7b appears to be fairly minimal.

(4) At present it is not sure to what extent waves will influence the results.

Therefore, with this as basis, we are taking the following approach:

- We are developing a numerical model for an arbitrary bottom profile; and

- We are further investigating the effect of varying surface roughness caused by variations in wave height.

Having made these advances, we hope to in time be in a position to predict the wind-driven cross-shore flows in a situation such as depicted below.

References

Bailard, J A (1981). An energetics bedload model for a plane sloping beach: local transport. *Journal of Geophysical Research*. Vol. 86, No. C3.

Bennett, J R (1974). On the dynamics of wind-driven lake currents. *Journal of Physical Oceanography*, Vol. 4, pp 400-414.

Bennett, J R and Magnell, B A (1979). A dynamical analysis of currents near the New Jersey Coast. *Journal of Geophysical Research*, Vol. 84, pp 1165-1175.

Nirchfield, G E)1072). Theoretical aspects of wind-driven currents in a sea or lake of variable depth with no horizontal mixing. *Journal of Physical Oceanography,* Vol. 2, pp 355-362.

Eidnes, G, Utnes, T and McClimans, T A (1986). Wind mixing a stratified shear flow. *Continental Shelf Research,* Vol. 6, pp 597-613.

Hubertz, J M (1987). A wind- and wave-driven nearshore current model. Department of the Army, US Army Corps of Engineers, Washington. *Final Report* February 1987.

Komen, G J and Riepma, H W (1981). The generation of residual vorticity by wind and bottom topography in a shallow sea. *Oceanological Acta,* Vol. 4, pp 267-277.

Kranenburg, C (1987). Turbulent surface boundary-layer induced by an offshore wind. *Journal of Hydraulic Research,* Vol. 25, pp 53-65.

Kullenberg, G E B (1976). On vertical mixing and the energy transfer form the wind to the water. *Tellus XXVIII,* Vol. 2, pp 159-165.

Kuzmic, M (1989). A numerical study of wind-induced motions in shallow coastal seas: model and basic experiment. *Appl. Math. Modelling,* Vol. 13, pp 178-191.

Larsen, M (1989). S beach: numerical model for simulating storm-induced beach change. Department of the Army, US Army Corps of Engineers, Washington. *Report* 1.

Madsen, O S (1976). A realistic model of the wind-induced Ekman boundary layer. *Journal of Physical Oceanography,* Vol. 7, pp 248-255.

Möller, J P and Swart, D H (1988). Extreme erosion event on an artificially nourished beach. *Proc. 21th International Conference on Coastal Engineering.* Malaga, Spain.

Nairn, R B (1988). Prediction of wave height and mean return flow in cross-shore sediment transport modelling. *IAHR Symposium in Mathematical Modelling of Sediment Transport in the Coastal Zone.* Copenhagen.

Seymour, R J, Castel, D (1988). Validation of cross-shore transport formulations. *21st International Conference on coastal Engineering*. Malaga.

Stive, M J F (1987). A model for cross-shore sediment transport. *Proc. 20th International Conference on Coastal Engineering*. Taipei.

Swart, D H (1974a). Offshore sediment transport and equilibrium beach profiles. Doctoral thesis, Technische Hogeschool. Delft.

Swart, D H (1974b). A schematisation of on/offshore transport. *Proc. 14th International Conference on Coastal Engineering*.

Swart, D H (1976). Predictive equations regarding coastal transports. *Proc. 15th International Conference on Coastal Engineering.* Honolulu, Hawaii.

Swart, D H (1986). Prediction of beach changes and equilibrium beach profiles. Lecture notes for short course on: *Dynamics of sand beaches*. Taipei, Taiwan.

Thomas, J H (1975). A theory of steady wind-driven currents in shallow water with variable eddy viscosity. *Journal of Physical Oceanography*, Vol. 5, pp 136-142.

Winant, C D (1980). Coastal circulation and wind-induced currents. *Ann. Rev. Fluid Mech.*, Vol. 12, pp 271-301.