AARMS IPSW 2018

Halifax, Canada, July3-6, 2018

Atlantic Association for Research in the Mathematical Sciences

CHARACTERIZATION OF AN ISLAND WAKE AT A TIDAL TURBINE SITE USING MARINE RADAR AND NUMERICAL MODELLING

KEWORDS: island wake; numerical model; Minas Passage; radar measurements; tidal channel.

1 INTRODUCTION

There is increasing use of remote sensing technologies in the marine renewable energy sector to mitigate against the technical challenges and costs of operating at sea. One such technology, land-based X-band radar, has been implemented at the Fundy Ocean Research Center for Energy (FORCE) in-stream tidal energy demonstration site in Minas Passage, Nova Scotia, to provide spatial maps of surface velocities, eddies and wakes. Using this data in addition to texture analysis methodology and model data, this problem will focus on a developing a methodology for wake characterization. The wakes behind topographic/bathymetric features will serve as the "test cases", but with an eye towards applying this methodology to turbine wakes, the characterization of which is critical to array planning and environmental impact assessment.

Most of the description below is from an extended abstract that has been submitted to Marine Renewables Canada 2018 Research Form in Halifax, November 21-22. The work will be also be published as a research paper. More importantly for the workshop, FORCE wants to establish that the radar observations can be combined with numerical simulations and other measurements techniques into a data product that can be used to accurately predict the characteristics of the tidal currents, especially the wakes created by islands, bathymetric features and tidal turbines. The specific issues to address in the workshop are covered at the end in section 6.

2 BACKGROUND

In-stream tidal turbines are typically located nearshore (within 3 km of shore) and in shallow waters (less than 75 m), to minimize costs and complexity associated with infrastructure and marine operations, and in high-velocity flows, to maximize energy yield (for example, see Figure 1). All these conditions contribute (on average, through the larger region) to increased eddy activity and higher turbulence levels. Moreover, the bi-directional flow at tidal sites can result in highly asymmetric eddy fields between ebb and flood tide. Furthermore, the turbines themselves generate eddy/wake fields, which interact in complex ways with the ambient surroundings and with adjacent turbine wakes. Clearly, there is a need to map eddy fields to support turbine placement, deployment and operation and to quantify the environmental impact of turbines.

Ground-truth measurements of the flow field are derived from bottom-mounted acoustic Doppler current profilers (BMADCPs), but individual units provide these measurements at only one location in horizontal space. Typically, spatial maps of a tidal flow field are derived from numerical models. With modern computing power, hydrostatic models can be used to generate several months of 3-D velocity data (Karsten et al., 2017), but cannot simulate eddies with a significant vertical scale of motion, such as those that might be generated by sharp bathymetric features and tidal turbines. Non-hydrostatic/CFD models can generate these types of eddies (Wilcox et al., 2017), but they remain prohibitively expensive to run for full tidal cycles and, regardless, require validation against ground-truth observations.

A promising tool for the mapping of eddy fields is remote sensing by land-based radar. The radar of relevance to in-stream tidal sites is X-band marine radar, which has less range but higher resolution than radio-band radar (e.g., CODAR) – both appropriate specifications for a tidal site – and is significantly less expensive. In broad terms, the 2-D surface velocity is inferred from radar backscatter images, which are a proxy of the surface gravity wave field, using a single equation – the current-shifted linear wave dispersion relation. Complementary to this approach, the amplitude of raw radar backscatter, which is a measure of sea surface roughness, can be used to infer high-resolution characteristics of the eddy field through texture analysis methodologies.

In this paper, we use marine radar and numerical modelling to characterize an island wake at a tidal site. This wake, on ebb tide, is a key constraint on development within and proximate to the Fundy Ocean Research Center for Energy (FORCE) in-stream tidal demonstration site in Minas Passage, Bay of Fundy.

3 RADAR AND MODEL: DESCRIPTION AND VERIFICATION

For this study, we use the Finite Volume Community Ocean Model (FVCOM) (Chen et al. 2003) to solve the ‘Acadia-FORCE model’, which consists of model input files co-developed by Acadia University and FORCE (Karsten et al. 2017). This model has an unstructured grid, with highest resolution ($O(20\ m)$) in the FORCE region and a domain that covers all the Bay of Fundy and extends into the Gulf of Maine. Model bathymetry through Minas Passage and adjacent waters is derived from (sub) two metre resolution multibeam bathymetry and lidar data (see Figure 1 and 2). The model is strictly forced by tidal constituents, inferred from satellite measurements, along the ‘open boundary’ in the Gulf of Maine (hence, all other possible forcings, including wind and freshwater input, are set to zero. For the Minas Passage, the absence of freshwater input is justified by observations, but wind forcing will be added in the near future). FVCOM is set to hydrostatic, barotropic and depth-resolving (10 sigma layers) modes to solve the Acadia-FORCE model.

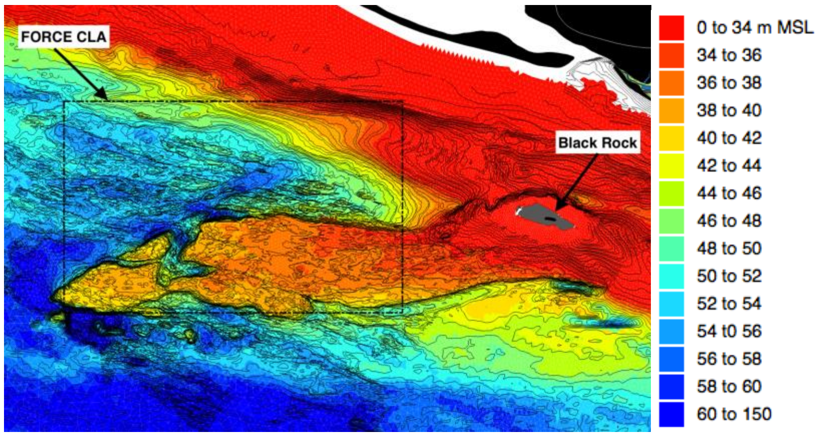

Figure 1: The near-coast bathyemtry near the FORCE CLA, showing the island Black Rock. The black contours are from the orginal from high resolution bathymetry. The coloured triangles is the bathymetry used in the Acadia-FORCE numerical model.

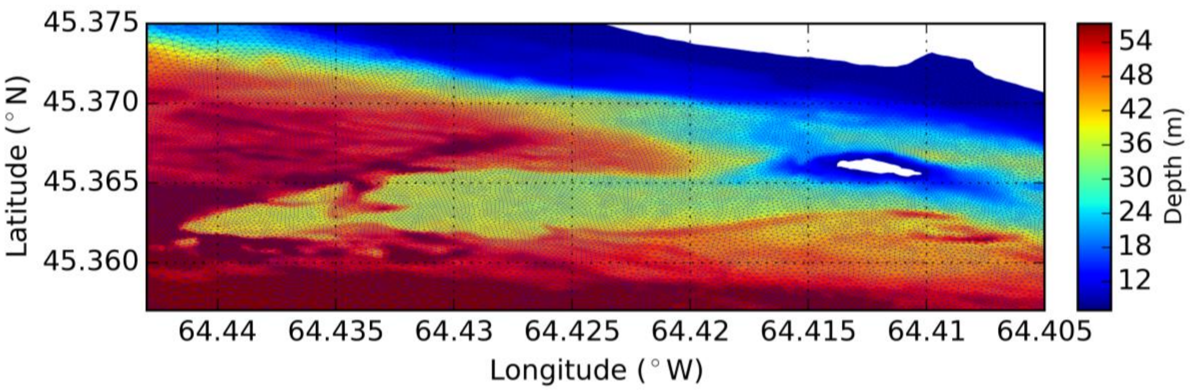

Figure 2: The near-coast bathymetry used in the Acadia-FORCE numerical model. The faint lines show the unstructured triangular mesh and the white island is Black Rock.

Since 2015, a non-coherent, horizontally polarized, X-band marine radar has been continuously operating atop the FORCE Visitor Centre, overlooking western Minas Passage, including the rectangular Crown Lease Area (CLA) for turbine deployment, which lies within 3 km of the radar. Raw amplitude data are saved at the radar’s rotation period of 2.2 seconds and projected onto a mesh with a grid-point spacing of 4.8 m and whose domain reaches 9 km from the radar. Due to data storage and transfer constraints, only the data from the first 5 minutes of every 15 minutes are saved. Using algorithms developed by Paul Bell of the National Oceanography Centre, U.K. (e.g., Bell and Osler, 2011), raw backscatter is converted into surface velocity data on a regular grid with a spatial resolution of 75 m and a temporal resolution of 5 minutes (given the resolution at which raw data are saved, the ‘effective’ temporal resolution of the radar-derived velocity is 15 minutes). However, the temporal coverage of ‘good’ radar-derived velocities – which relies on a sufficiently defined surface gravity wave field – is somewhat sparse because of the relatively benign sea state in the Minas Passage, where swell is largely absent and fetch is limited.

Radar-derived and modelled velocities have been verified (not shown) against a BMADCP (a Nortek Signature 500) deployed through December 2017 and January 2018 in the CLA at (-64.4277, 45.3630). Previous model validation work (e.g., Karsten et al. 2017) against several BMADCPs through the FORCE region and beyond showed the model’s ability to capture the spatial variability of the flow field. Hence, the good agreement between radar-derived and modelled tidal current ellipses (not shown) gives confidence in the radar's velocity mapping capabilities, setting the stage for the present task of analyzing an island wake in the FORCE region using marine radar and numerical modelling.

4 METHODOLOGY AND RESULTS

For turbine placement and operation, key characteristics of a wake include the locations of its lateral boundaries, the length scales of the near-wake region of high vorticity/turbulence, and velocity distributions in the far wake. In practice, these characteristics determine geographical boundaries for turbines, separating where they can and cannot operate safely and profitably. As our results will show, these boundaries are dynamic – they are dependent on the tidal phase/strength.

Visual inspection of raw radar data, and modelled velocity data (Figure 2), shows that the Black Rock wake on ebb tide (hereafter, the Black Rock wake) has a coherent structure, resembling the Karman vortex street from the classical case of homogeneous, non-rotational flow behind a circular cylinder (for a review, see Williamson 1996). Its distinguishing feature, of a train of counter-rotating vortices, has been observed in atmospheric (Schar and Smith 1993) and oceanic (Ingram and Chu 1987) settings. The following analysis is guided by the evidently low-dimensional quality of the observed wake and analysis appropriate to the study of Karman vortex streets.

4.1 Time-averaged characteristics of the Black Rock wake

Black Rock has a transverse/cross-stream length of $L = 50\ m$. From cylinder wake theory, the Strouhal number, L/λ, for an obstacle with length scale L in high Reynolds number flow implies a wake eddy length scale λ of $O(250\ m)$ (e.g., Neill and Elliott 2004), which far exceeds the depth $D = 40\ m$ at the site. Hence, the wake is expected to be effectively horizontally planar, for which the wake's centreline is a key dimension. In dynamic coastal ocean flows, an island wake's centreline is difficult to establish. In characterizing a wake behind a (rotating) vertical axis turbine, Araya et al. (2017) defined a 'centreline' as those points, in the along-stream direction, where steady state velocity was at a minimum in the cross-stream direction. This approach will be implemented in the full paper, but for this abstract, a centreline was manually chosen, at each time, that approximately bisects the wake.

Figure 3 shows the along-stream component of velocity normalized by the upstream speed ('normalized velocity') and the difference between the upstream speed and along-stream component of velocity normalized by upstream speed ('normalized velocity deficit'). The upstream speed was approximated as the convergent speed in the upstream direction, along the centreline extended a short distance upstream (eastward) of Black Rock. For model data, individual plots largely 'collapse' onto a single plot, as expected from wake theory. In particular, the normalized velocity plot is consistent with a near-wake recirculation of length $X/D = 8$, where velocity is at a minimum, followed by a sharp increase in velocity and recovery towards the free-stream value at $X/D = 50$. The radar plots of normalized velocity are not as well defined, particularly in the near wake region. A more careful calculation of radar-derived velocities along the centreline is expected to significantly improve results.

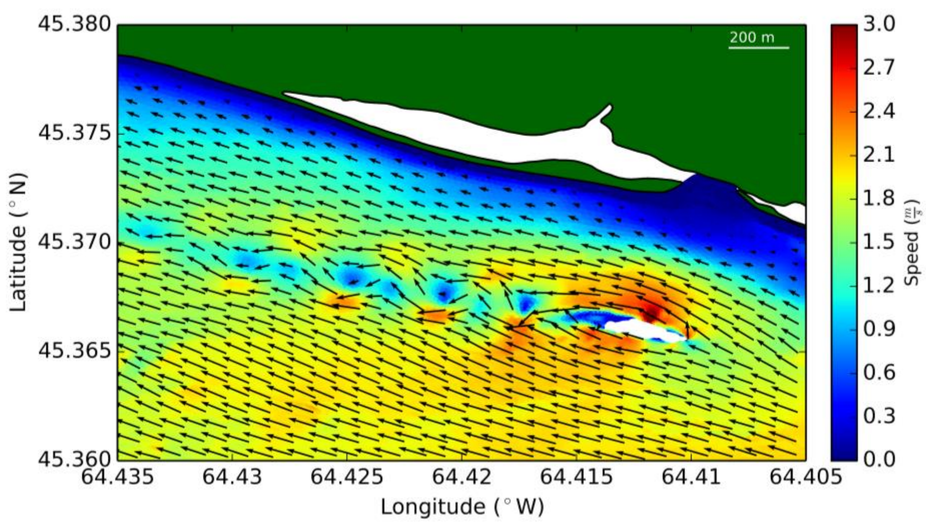

Figure 3: Modelled velocity at an instant, demonstrating the presence of a vortex train behind Black Rock island.

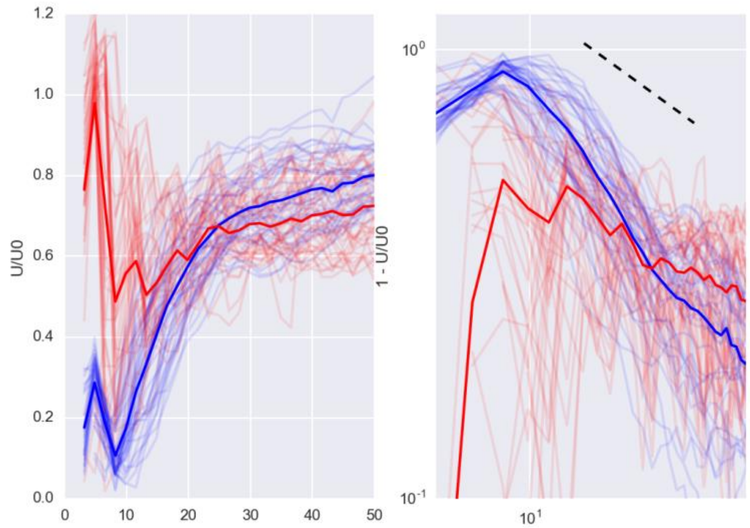

Figure 4: Left: Normalized velocity against normalized along-stream distance. Right: Normalized velocity deficit against normalized along-stream distance (in a log-log scale, the dashed line has slope ?). Blue is model and red radar, with bolder lines indicating time-averages of the individual plots.

4.2 Time-varying characteristics of Black Rock wake

Velocity deficit distributions were found for velocities averaged over five-minute intervals. We now examine variability within these intervals, to elucidate coherent structures within the wake and establish key wake parameters such as the locations of lateral boundaries and the length scales of the region of high vorticity.

First, we apply 'classical' linear principal component analysis (PCA) to extract the most energetic/highest variance modes of the wake. PCA is applied to a series of successive 'snapshots' of spatial data to derive orthogonal spatial patterns (i.e., empirical orthogonal functions (EOFs)) and a corresponding time series of principal components (PCs) (e.g., Kutzbach 1967). By construction, the leading modes (i.e., PC-EOF combinations) account for the highest variability in the data set. To minimize variability from sources other than Black Rock wake, we choose a spatial region that is focused on the wake and a time period of calm winds, when the Black Rock wake is the dominant feature of the sea state. Although this latter criterion precludes deriving a coherent radar-derived velocity field, our focus, regardless, is on the $O(5\ m)$ radar backscatter amplitude, complemented by the modelled velocity and vorticity fields, as well as wake theory.

We restrict our present analysis to a single ebb tide on March 2, 2018, 1700-2300 UTC. Figure 4 shows EOF-1 of modelled velocity and of radar backscatter amplitude at two times: 1930 h and 2100 h. Each EOF has a well-defined, oscillating, anti-symmetric patterns downstream of Black Rock island, with the anti-symmetric quality persisting further in the radar output. The leading two modes, accounting for ca. 20% and 70% of the total variability in radar and model data, respectively, are in quadrature (not shown), the combination of which yields a propagating, wave-like pattern. These properties are consistent with leading modes of the wake behind a circular cylinder (e.g., Araya et al. 2017).

This pattern first emerges at 1845 h and 1930 h in the model and radar EOF-1, respectively, and persists for over two hours (the pattern appears to emerge quickly, but dissipates slowly). Although the modelled pattern is more linear and anti-symmetric about its centreline, both show a stronger signal on the south side of the centreline as the ebb tide diminishes. Of particular importance to turbine developers in the FORCE region, the observed, radar-derived wake is wider than the modelled wake, limiting potential turbine deployment sites.

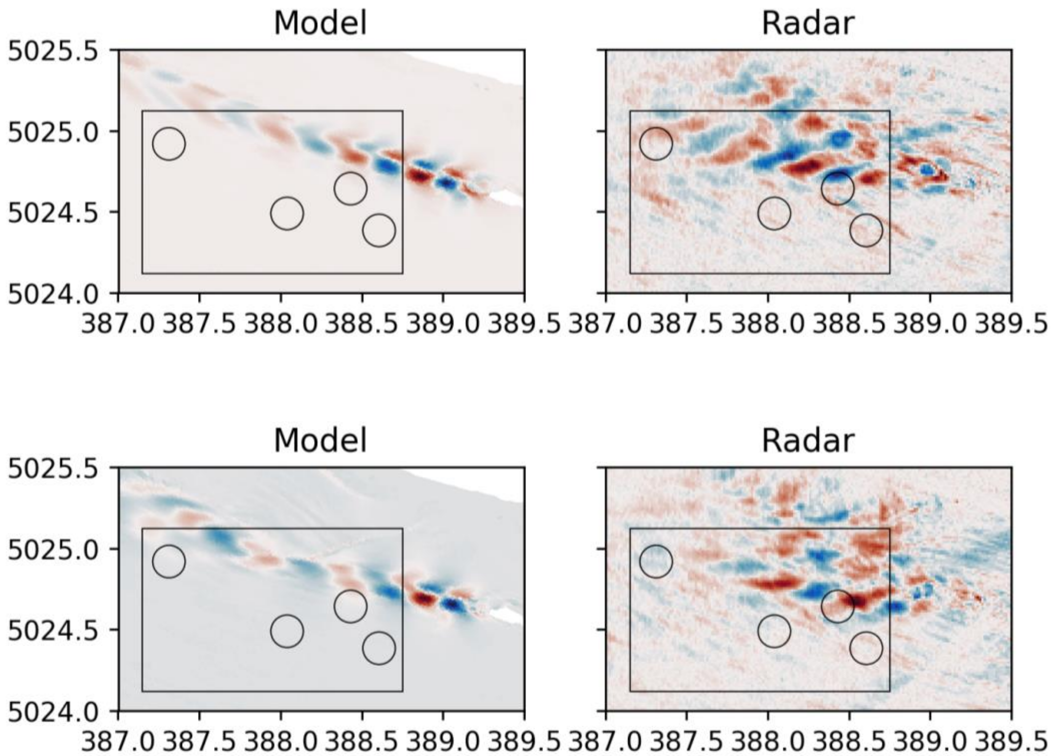

Figure 5: EOF-1 of modelled velocity and radar backscatter amplitude at 1930 h (top) and 2100 (bottom).

5 CONCLUSIONS

Land-based marine radar and numerical modelling were used to demarcate an island wake, impinging on the FORCE in-stream tidal turbine demonstration site, by defining its lateral boundaries, the region of high vorticity and the mean velocity distribution in the along-stream direction. Model and radar results were consistent with the presence of a Karman vortex street, which emerges 2.5 hours after the beginning of ebb tide and persists for over 2 hours, but which dynamically evolves, with implications for turbine placement.

6 PROBLEMS FOR THE WORKSHOP

For the workshop, we want to improve the analysis in several ways and eventually combine all the tools into an data analysis tool box that could be run autonomously on new radar data . All analysis of the data is calculated using python scripts. Here are a list of outstanding issues we can address:

1. Determine the best quantities that permit a better comparison of the radar observations and numerical simulations. In the above analysis we compared i) the velocity/velocity deficit of the wakes and (ii) the EOFs of the radar backscatter to the EOFs of the model speed, Calculate a flow speed from radar data is somewhat challenging, and usually done on a course grid (75m x 75m), making it difficult to calculate detailed wake quantities. Possible strategies:
   a. Adjust radar velocity calculations to calculate velocities at the numerical simulation grid points, allowing for a detailed comparison
   b. Further examine the EOF analysis, to examine the variability on longer time scales and compare the results.
   c. Compare tidal ellipses for radar and model, use utide.
2. Automatically detecting the centreline and extent of the wake region. One of the challenge is that the wakes shifts position as the flow changes. For the analysis above the centreline of the wake was determined manually using images of the mean speed. We need a method to do this numerically. Possible strategies:
   a. Detect the cross-stream minimum in the mean wake velocity
   b. Detect the cross-stream maximum in eddy velocity
   c. Use statistical methods/image analysis to determine the along stream axis in images of EOFs, vorticity etc.

3. In the analysis above, we only examined the along stream structure of the wake. We also need to examine the cross stream structure of the wake. Possible strategies:
    a. Once we have an accurate centreline, we can generate a regular rectangular mesh oriented to coincide with this centreline. The radar-derived velocity and numerical velocity can be calculated at these grid ponts. The perpendicular gird lines will be used to estimate the wake width as a function of the cross-stream velocity distribution.
    b. The methods in 2, may be able to determine the cross-stream structure without generating such a grid
4. We need to further analyse the more theoretical properties of the wake, using the tools of classical fluid dynamics. This includes calculating the length scales of the eddies, the frequency/period of the wake oscillations, etc. Such quantities can be used to calculate non-dimensional numbers like the Strouhal number and island wake parameter ((Wolanksi and Imberger, 1984). Possible strategies:
    a. Compute the power spectra of the EOFs or other quantities to determine the frequency of eddy production
    b. Use results of 2 and 3, to examine the length scale of the variations in wake.
5. A final question is how the wakes vary over long time scales as the tide varies, and whether these variations can be easily determined as functions of the upstream flow speed or tidal range. Possible strategies:
    a. Use the methods above to examine the long-time numerical simulation data
    b. Apply some simple regression models for wake characteristics (length, width, frequency) vs flow speed/tidal range
    c. Relate back to wake theory

REFERENCES

Araya, D.B., Colonius T., Dabri, J.O., 2017. Transition to bluff-body dynamics in the wake of vertical-axis wind turbines. *Journal of Fluid Mechanics*, 813, 346-381.

Bell, P.B., Osler, J., 2011. Mapping bathymetry using X-band marine radar data recorded from a moving vessel, *Ocean Dynamics*, 61(12):2141-2156.

Chen, C., Liu, H., Beardsley, R.C., 2003. An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: Application to coastal ocean and estuaries. J. Atmos. Ocean. Tech., 20:159-185.

Ingram R.G., Chu, V.H., 1987. Flow around islands in Rupert Bay: An investigation of the bottom friction effect, *Journal of Geophysical Research*, 92(C13):14521-14533.

R. Karsten, T. Roc, J. Culina, G. Trowse, M. O'Flaherty-Sproul, 2017, High-Resolution Numerical Model Resource Assessment of Minas Passage, Bay of Fundy, Proceedings of the 12th European Wave and Tidal Energy Conference.

Kutzbach, J.E., 1967. Empirical eigenvectors of sea-level pressure, surface temperature and precipitation complexes over North America, J. Applied Meteor. and Climatology, 6:791-802.

Neill, S., Elliott, A.J., 2004. Observations and simulations of an unsteady island wake in the Firth of Forth, Scotland, *Ocean Dynamics*, 54:324-332.

Schar, C., Smith, R.B., 1993. Shallow-water flow past isolated topography. Part II: Transition to vortex shedding, Journal of the Atmospheric Sciences, 50(10):1401-1412.

Wilcox, K.W., Zhang, J.T., McLeod, I.M., Gerber, A.G., Jeans, T.L., McMillan, J., Hay, A., Karsten, R., Culina, J., 2017. Simulation of device-scale unsteady turbulent flow in the Fundy Tidal Region, Ocean Engineering, 145:59-76.

Williamson, C.H.K., 1996. Vortex dynamics in the cylinder wake, *Annu. Rev. Fluid. Mech.*, 28:477-539.

Wolanski, E., Imberger, J., 1984. Island Wakes in Shallow Coastal Waters, *Journal of Geophysical Research*, 89(6):10553-10569.