Adjusting for measurement lag in the estimation of rapid marine tidal current flow with sparse spatiotemporal boat survey data

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***Abstract*—Accurate determination of marine tidal current flow is a crucial component in assessing offshore site suitability for marine renewable energy devices. The use of real time boat surveys to provide field data of estimated current speeds and directions can help identify potential sites for development. However, in a rapidly changing tidal flow system the time lag between measurements at different points in space and time may induce significant error into estimates of current speeds and directions. This in turn implies substantial inaccuracies from spatiotemporal computations which attempt to extrapolate tidal flow patterns over a wider regional scale. Whereas hydrodynamic models can provide flow parameter estimates at any position and time, they cannot be relied on to be accurate without verification or correction from such field measurements.**

Here, we introduce a statistical approach which adjusts for measurement lags inherent in measured flows, by combining boat survey data with hydrodynamic model output. The approach exploits a regression model which is fitted to observed differences between survey data and output from the hydrodynamic model. It is exemplified with the POLPRED® (POLPRED, 2007) hydrodynamic model for the Pentland Firth in the north of Scotland, a key region designated for development of tidal stream technology. The regression model is used to estimate currents with associated uncertainties over a spatiotemporal range within the domain of the survey region. Our results indicate that correction for measurement lag is likely to be a major factor in achieving accurate estimation of currents in such dynamic marine environments.

Keywords: regression; current profile; hydrodynamic model; ADCP; POLPRED

I. INTRODUCTION

Discrete time field data of current flow measurements from a boat survey can be helpful in assessing tidal dynamics at both a local and regional scale. Such surveys typically record current speed and direction with an onboard underway Acoustic Current Doppler Profiler (ADCP) recorder at discrete points of a boat track as exemplified in the 30 minute survey exhibited in Fig. 1A.

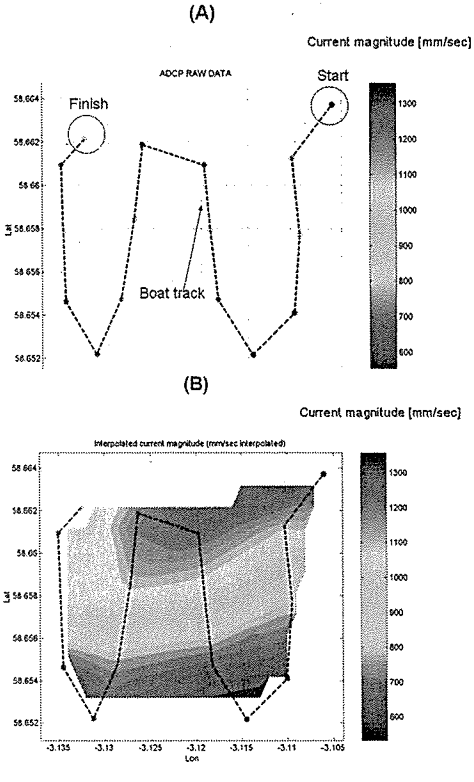

Figure 1. (A) Current magnitude [mms-1] data (circles) recorded at a fixed depth over 30 minutes at 15 points in the Stroma Channel separated by 2 minute intervals, during a single boat survey using ADCP equipment, (B) current magnitude [mms-1] profile estimated by spatial interpolation (with Delaunay triangulation) of the data points for the convex hull of the boat track in (A).

These field survey data can be incorporated into a spatial interpolative model to provide a tidal current profile estimated over a wider spatial domain. An example is shown in Fig. 1B, where current magnitude is estimated by spatial interpolation over the convex hull of the boat survey track of Fig. 1A. An implicit assumption in this approach is that tidal current is unchanging during the time course of the boat journey. However, in a locality such as the Pentland Firth (where the survey of Fig. 1 was performed) changes in tidal currents, within periods of under an hour may be sufficient to ensure that such an estimated profile is inaccurate.

This is demonstrated by comparing the current magnitude profile of Fig. 1B with those generated by the POLPRED (2007) hydrodynamic model for the identical convex hull and real time interval at the start (Fig. 2A) and finish (Fig. 2B) of the survey. These snapshots strikingly show the extent of current magnitude change estimated by POLPRED during the period of the survey. So how can such sparse boat survey data be utilized to enhance estimation accuracy of tidal currents in these circumstances?

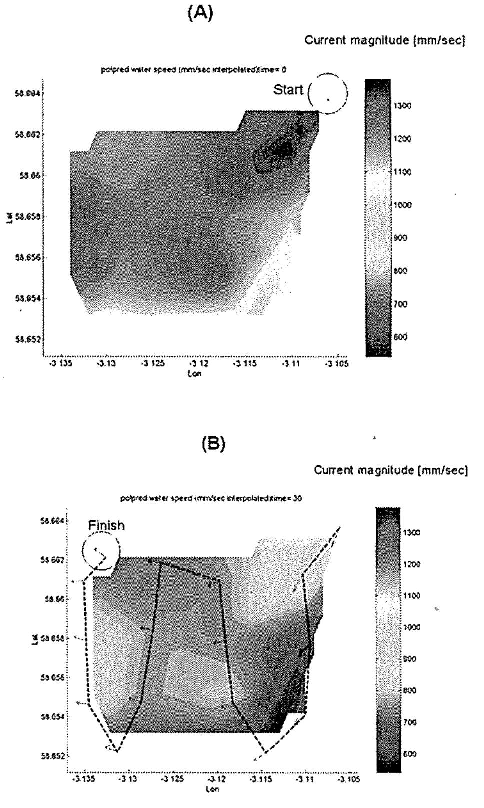

Figure 2. Current magnitude profiles generated by POLPRED (2007) for the convex hull of the boat track in Fig. 1 at (A) the start of the survey when $t = 0$, (B) the finish when $t = 30$, with current direction arrows superimposed at each of the 15 points on the boat track.

We show how this may be achieved by fitting a regression model to differences in tidal current between survey measurements and hydrodynamic model output. The approach adjusts for inaccuracies resulting from the inherent time lag between field data taken at different locations during a boat survey.

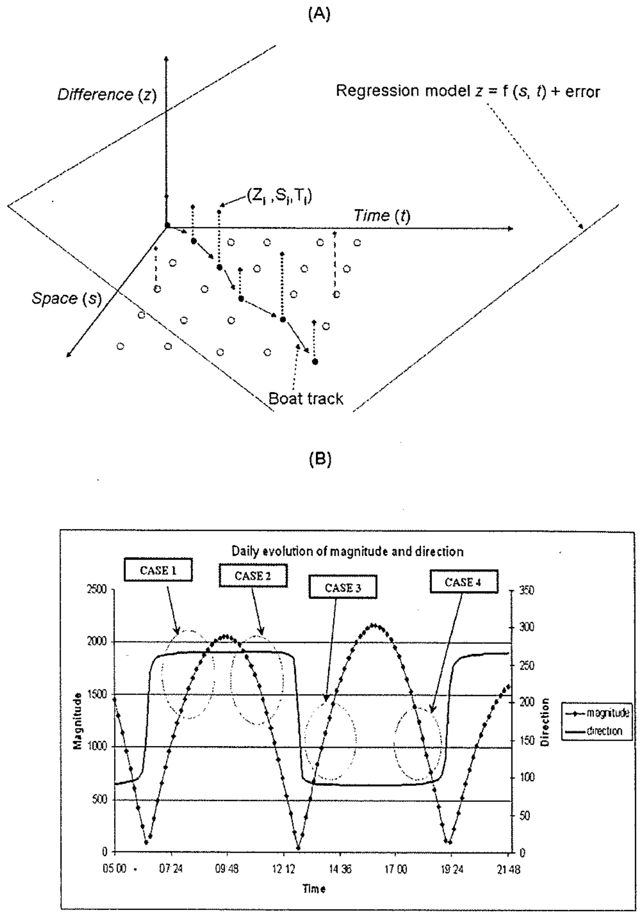

Figure 3. (A) Schematic diagram showing a regression surface $f(s, t)$ fitted to the set of $\{Z_i, S_i, T_i\}$ where z represents the current magnitude difference between POLPRED (2007) and field survey data, s is space and t is time, (B) typical plots of current magnitude (dot-dash) and direction (solid) in the Stroma Channel illustrating the temporal partitioning into four separate Cases (encircled).

II. MODEL FORMULATION

We consider the tidal current difference $Z_i = B_i - H_i$ between boat survey data (B_i) and hydrodynamic model output (H_i) at each survey point i at location S_i and time T_i along the boat track. At each survey point, we assume the boat survey data correctly reflect the true current magnitude and direction at the time of measurement. We assume also that the distribution of the set of differences $\{Z_i\}$ is representative of the true distribution of differences between actual current (magnitude or direction) and hydrodynamic model over the entire space (s) and time (t) domains of interest.

We model the $\{Z_i, S_i, T_i\}$ data as $z = f(s, t)$ + error, where $f(s, t)$ is a regression model function and the 'error' term consists of the residuals $\{Z_i - z\}$, shown schematically in Fig. 3A. The fitted model surface $f(s, t)$ has the key property that it can be extrapolated anywhere within the spatiotemporal domain of interest. It represents the estimated adjustment to the hydrodynamic model output $h(s, t)$ at location s and time t required to obtain an estimate of the true current $c(s, t)$, where

$$c(s, t) = h(s, t) + f(s, t) \qquad (1)$$

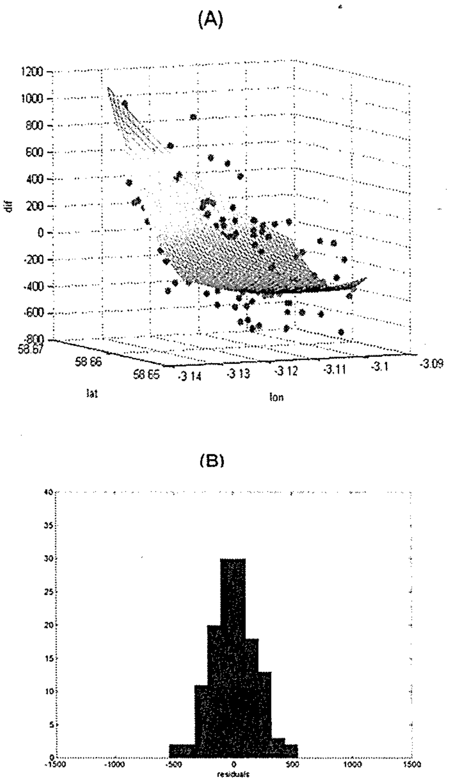

Figure 4. (A) Regression model surface $f(lon, lat)$ as defined in (2) fitted to $\{Z_i, S_i\}$ obtained from six Case 2 boat surveys (solid circles), $n = 131$, (B) the corresponding distribution of the $\{Z_i - z\}$ residuals 'error' term in Fig. 4A.

The general form of $f(s, t)$ has dependence on both space and time. However, depending on the spatial or temporal scales and locality over which survey data are collected, there may be a dependence upon only one entity. This was found to be the situation for a collated data set obtained from several boat surveys performed in the narrow Stroma Channel within the Pentland Firth. Exploratory analysis of these data indicated a broad temporal partitioning within the main tidal cycle into four separate Cases (numbered 1 to 4), each with dependence only upon space (Fig. 3B). Within each of these Cases, the $\{Z_i, S_i, T_i\}$ could therefore be treated as $\{Z_i, S_i\}$.

III. EXAMPLE OF APPLICATION

We demonstrate an application of the model (1) to a Case 2 data set ($n = 131$) consisting of current magnitudes recorded in 6 surveys (including that of Figure1) performed in the Stroma Channel. We model $\{Z_i, S_i\}$ as a linear function $z = f(s)$ + error, with s specified by longitude (lon) and latitude (lat). Keeping all interaction terms to second order, the chosen regression function is

$$f(s) = a_0 + a_1\,lon + a_2\,lat + a_3\,lon\,lat + a_4\,lon^2 + a_5\,lat^2 \qquad (2)$$

where a_i are constants. Fig. 4A shows the fitted model surface $z = f(lon, lat)$ obtained by maximum likelihood regression to the Case 2 data set. The distribution of the residuals $\{Z_i - z\}$ is shown in Fig. 4B and clearly follows a normal distribution, thus indicating a reasonable fit of this regression model to these data. A standard confidence interval for $f(lon, lat)$ to a desired level of significance could be similarly derived as lower and upper surfaces to $f(lon, lat)$, to reflect the uncertainty associated with model extrapolations.

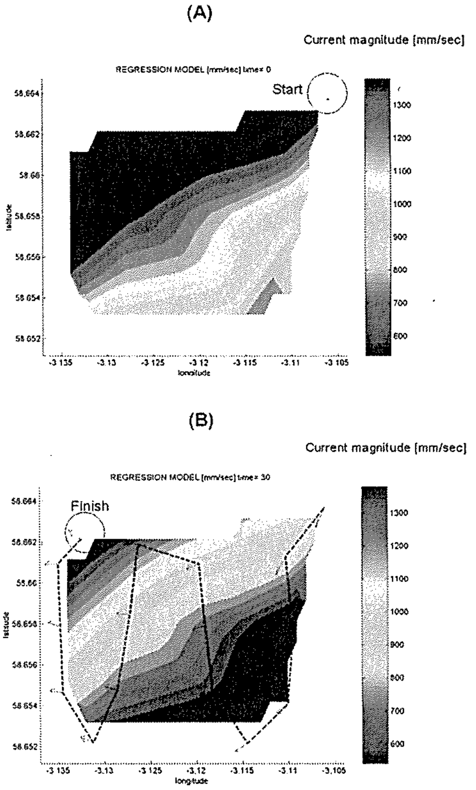

Figure 5. Temporally adjusted current magnitude profiles for the convex hull of the boat track in Fig. 1 and 2 determined from model (1) with $f(s) = f(lon, lat)$ as defined in (2), at (A) the start of the boat journey when $t = 0$, (B) the finish of the survey when $t = 30$, with current direction arrows superimposed at each of the 15 points on the boat track.

The adjusted profiles of current magnitude at the start ($t = 0$) and finish ($t = 30$) of the survey as estimated by (1) after inserting $f(s, t) = f(s) = f(lon, lat)$ from (2) and interpolating for the identical convex hull of the survey are shown in Fig. 5(A) and 5(B) respectively. Visual comparison of these with the respective profiles of Fig. 2A and Fig. 2B suggest an enhancement of the POLPRED (2007) current estimates when the boat survey data are incorporated, as revealed by flow stratification and a north westerly 'drift' of the current structure during the time interval between the profiles of Fig. 5A and Fig. 5B.

IV. DISCUSSION

In this paper we demonstrate a statistical method by which measurement time lag can be adjusted in sparse field data sets obtained from tidal current boat surveys performed in highly dynamic tidal environments such as the Pentland Firth. Our results suggest the approach can be used to enhance current flow profiles estimated from local or regional scale hydrodynamic models. It is hoped the methodology will enable real time currents to be estimated to greater accuracy in a variety of different marine localities and regions.

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