Evaluation and correction of noise related to physical processes in estimates of estuary metabolism

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Acknowledgments

Abstract

Reliable estimates of ecosystem metabolism depend on measures of dissolved oxygen (DO) flux that are dominated by biological processes. Long-term time series of DO measurements may include variation related to both biological and physical processses such that the use of observed data may be insufficient or even misleading in some examples. Statistical modelling techniques that dynamically quantify variation in DO over time and tidal changes have the potential to isolate biological signals in DO variation to more accurately estimate metabolism. A weighted regression method that estimates DO as a function of time and tidal height was developed to normalize, or detide, the predicted DO signal to remove the influence of physical advection on metabolism estimates. First, a simulation approach was used to create multiple DO time series with known additive components of biological and physical variation on different periods. Comparisons of detided estimates with the known, simulated biological component of the DO signal suggested the method accurately and precisely removed varation attributed to tidal advection. Extension of the method to four case studies provided a proof of concept illustrating the method could be useful for real-world applications. We provide a detailed discussion on use of the method for improving certainty in evaluation of DO measurements from sites with strong tidal influences. Moreover, we propose that the method could expand use of the open-water method for estimating ecosystem metaoblism in estuaries given that the approach can produce robust estimates of DO values that are independent of tidal advection. In particular, this could facilitate the use of shorter deployment periods for water quality monitors or incomplete time series given that known biases related to water movement could be removed with weighted regression. {acro:DO}

Key words:

Introduction

{intro}

Metabolism estimates from time series of dissolved oxygen provide integrated evaluations of trophic state in aquatic ecosystems (Kemp and Testa 2012, Needoba et al. 2012). Autotrophic or productive systems are characterized by high rates of energy transfer between trophic levels leading to accumulation organic matter, whereas heterotrophic systems are sinks of organic matter that are supported by allochthonous sources of energy input. Integrated measures of metabolism describe the balance between production and respiration that accounts for varying rates in processes that create and consume organic matter. Although metabolic rates vary naturally at multiple spatiotemporal scales (Ziegler and Benner 1998, Caffrey 2004, Russell and Montagna 2007), anthropogenic stressors are generally accepted as contributing factors that increase rates of production (Diaz 2008). Inputs of limiting nutrients beyond background concentrations may decrease the resilience of an ecosystem such that higher rates of production are coupled with higher biological oxygen demand (Yin et al. 2004, Kemp et al. 2009). Cultural eutrophication is frequently linked to declines in water quality through lower levels of dissolved oxygen, degradation in aquatic vegetation habitat, and increased frequency of harmful algal blooms (Cloern 1996, Short and Wyllie-Echeverria 1996, Rabalais et al. 2002). Reliables estimates of ecosystem metabolism are critical for measuring both background rates of production and potential impacts of human activities on ecosytem condition.

Ecosystem metabolism can be estimated using two basic techniques, each of which is appropriate under different conditions or assumptions (Kemp and Testa 2012). Bottle-based techniques rely on rate measurements from discrete water quality samples, whereas open-water techniques infer metabolic rates using *in situ* measurements from continuous monitoring data.

Bottle-based techniques are useful for direct partitioning of metabolic contributions into discrete habitats, such as planktonic production rates during specific time periods (Kemp and Testa 2012). However, such measurements may be inappropriate for evaluating whole ecosystem metabolism if significant production occurs in habitats that are not sampled, such as benthic or seagrass production. As such, the open-water technique provides an integrative measure of metabolism by inferring process rates from *in situ*, continuous monitoring data. Originally for use in streams (Odum 1956), the method has been used with varying success in lakes (Staehr et al. 2010, Coloso et al. 2011, Batt and Carpenter 2012) and estuaries (Caffrey 2004, Hopkinson and Smith 2005, Caffrey et al. 2013). As with any method, the ability of the open-water technique to accurately estimate whole system metabolism depends on whether the assumptions for its use are met. Such assumptions are are often only implicity verified in practice, leading to potential biases. The increasing availability of high resolution monitoring data further necessitates more quantitative assessments of the open-water technique.

The open-water method uses the diel fluctuation of dissolved oxygen to infer rates of ecosytem metabolism, after correcting for losses or gains through air-water exchange (Kemp and Testa 2012). Daily integrated measurements of metabolism are based on the balance between daytime estimates of gross production and nighttime estimates of respiration extrapolated to a 24 hour period. The fundamental assumption of the open-water method is that measurements come from a water mass that has the same recent history (Needoba et al. 2012). Estimates of metabolism from a single location may be inaccurate if substantial variation in water column mixing occurs throughout the period of observation (Russell and Montagna 2007). As such, the original technique designed for use in streams requires the comparison of data from an upstream and downstream station (Odum 1956). Application of the method to systems without continuous flow, such as lakes or estuaries, have often assumed that a single sampling station provides sufficient data for estimating metabolism Staehr et al. (2010). While single stations may be valid under specific conditions, numerous studies have shown that the open-water method may be inappropriate given the effects of physical mixing (Ziegler and Benner 1998, Caffrey 2003, Coloso et al. 2011, Batt and Carpenter 2012, Nidzieko et al. 2014).

The open-water method has been applied to coastal ecosystems with mixed success. An exhaustive analysis by Caffrey (2003) applied the method to estimate metabolim at 28 continuous monitoring stations at 14 US estuaries. Data from two of the reserves were used to evaluate the assumption of homogeneity of water masses measured by each sensor. Although significant differences were not observed for metabolism estimates between adjacent stations, the analysis was based on a comparison of means using conventional significance tests rather than a systematic comparison of time series. Moreover, a portion of metabolism estimates from all stations were negative for production during the day and positive for respiration during the night. These values were opposite in sign than expected since production increases oxygen during the day (i.e., positive effect on metabolism) and respiration consumes oxygen at night (i.e., negative effect on metabolism). These 'anamolous' values were attributed to violations in the assumption of water-column heterogeneity, particularly in relation to tidal advection.

The effects of tidal advection on estimates of ecosystem metabolism have been a point of concern in numerous studies (Monbet 1992, Ziegler and Benner 1998, Caffrey 2003, Collins et al. 2013, Howarth et al. 2014), although systematic estimates of its effects in tidal systems have been minimal. An exception is Nidzieko et al. (2014) that described quantitative assessment of the effects of fortnightly tidal modulations on metabolism estimates. Using a control volume approach to measure fluxes into and out of a shallow tidal creek, significant biases in metabolism estimates were observed. Net heterotrophy was observed during spring tides, whereas metabolism was balanced during neap tides. The timing of irradiance relative to the tidal cycle was a primary factor contributing to heterotrophy during summer months such that maximum tides occurred during the night, increasing total area for respiration. The results of the analysis, although specific to the study location, suggest that the effects of tidal advection on dissolved oxygen (DO) {acro:DO} measurements are of primary concern when selecting locations and length of time for sonde deployment in estuaries. In many cases, the relative magnitude of these effects may be a significant source of bias. Analytical techniques to evaluate and correct for tidal advection could improve certainty in metabolism estimates and increase the use of data from shorter deployment periods if sources of bias are quantified and removed.

This article describes the theory and application of a novel method for detiding an observed DO time series to more accurately quantify estimates of ecosystem metabolim for estuaries. Specifically, the method characterizes the effects of tidal advection on DO observations to improve estimates of open-water metabolism with multi-year time series of high frequency (< one hour) water quality data. The focus of our analysis is the use of a weighted regression method previously developed for trend analysis of pollutant concentrations in streams and rivers (Hirsch et al. 2010) and recently adapted for trend evaluation of water quality in estuaries (Beck and Hagy, In review). The weighted regression approach creates dynamic predictions of DO as a function of time and tidal height change, which are then used to normalize, or detide, the DO signal. First, we use a simulation approach to create time series of DO observations with known characteristics to evaluate ability of the weighted regression to remove the effects of tidal advection. Second, four case studies from the National Estuarine Research Reserve System (NERRS, Wenner et al. 2004) are used to validate the method for improving estimates of ecosystem metabolism. Overall, the analysis is meant to improve the certainty of information obtained from monitoring data by evaluating the relative roles of biological and physical processes in estuarine systems. Applications are expected to have implications for ecosystem management by outlining strategies for interpreting water quality data with more accuracy.

Materials and Procedures

Weighted regression for modelling and detiding DO time series

The weighted regression model for detiding DO time series was adapted from the {acro:WRTI weighted regression on time, discharge, and season (WRTDS) method developed by Hirsch et al. (2010). The WRTDS method was developed to model pollutant concentration in streams and normalize predictions to changes in discharge. The functional form of our model is as follows:

$$DO_{obs} = \beta_0 + \beta_1 t + \beta_2 H \tag{1}$$ {funform}

where observed DO is a linear function of decimal time t and astronomical tidal height H. Decimal time is a continuous variable for the day and time of each observation with time as a proportion of the number of total observations added to each day. The beginning of each day was considered the nearest thirty minute observation (i.e., on the hour and half hour) at which sunrise was expected for a given location and time of year. Days were centered on the diel cycle rather than conventional times given that the objective was to develop a predictive model relevant for biological DO variation that follows solar and seasonal cycles. The functional form also differed from the original WRTDS method that included parameters to estimate variation of the response variable on a sinuisoidal period. DO variation was not modeled using this approach because rates of change may be abrupt following diurnal variation in irradiance or daily DO variation may be muted given the weather, as on cloudy days.

Weighted regression is implemented as a moving window that allows for estimation of DO throughout the time series by adapting to variation through time as a function of tide. Regression models are estimated sequentially for each observation in the time series using dynamic weight vectors that change with the center of the window. Weight vectors quantify the relevance of observations to the center of the window in respect to decimal time, hour of the day, and tidal height. Specifically, weights are assigned using a tri-cube weighting function (Hirsch et al. 2010):

$$w = \begin{cases} \left(1 - (d/h)^3\right)^3 & \text{if } |d| \leq h \\ 0 & \text{if } |d| > h \end{cases} \tag{2}$$

where the weight w of each observation is inversely proportional to the distance d from the center of the window such that observations more similar to the point of reference are given higher importance in the regression. Weights exceeding the maximum width of the window h are equal to zero. The tri-cube weighting function is similar to a normal distribution such that weights decrease gradually from the center until the maximum window width is reached. Observations that are half the distance from the center of the window to the maximum window width are weighted one third less than values at the center. Regressions that use simpler windows (e.g., boxcar approach) are more sensitive to influential observations as they enter or leave the window, whereas the tri-cube function minimizes their effect through gradual weighting of observations from the center (Hirsch et al. 2010). The weight vector for each observation is the product of three separate weight vectors for decimal time, hour, and tidal height. A low weight is given to an observation if any of the three weighting values were not similar to the center of the window since the final weight vector is the product of three weight vectors for each variable (see the link in the multimedia section for graphical display of different weights).

A nontrivial issue with weighted regression is the choice of window width for calculating weights. Excessively large or small window widths may respectively under- or over-fit the data. Additionally, optimal window widths may depend on the objective for using the model. The weighted regression approach can be used for both predicting DO and normalizing to remove the variance in the DO signal from tidal changes. Optimal window widths that minimize prediction error or fit to the observed data are typically smaller than the optimum window widths for normalizing the time series. Similarly, window widths that more effectively detide the DO signal may produce predictions for the observed data that are not optimal. Evaluations of the weighted regression method with simulated DO time series, described below, used different window widths to identify an approximate optimal window width for detiding the DO signal. As such, the ability of the models to predict observed DO was not a primary concern given that the optimal window width for detiding likely corresponds to a model that predicts DO as a function of tide rather than observed DO as a function of both tide and biological variation.

Detiding the DO signal using weighted regression

The primary objective of the analysis was to evaluate ability of the weighted regression method to detide a DO signal to obtain more accurate estimates of metabolism. Hirsch et al. (2010) developed the normalization approach for the WRTDS method using a two-dimensional interpolation grid that contains predicted values of pollutant concentrations across the time series and the range of stream discharge values observed in the study system (Hirsch et al. 2010).

Normalized values for pollutant concentration are obtained by averaging the model predictions across the discharge values that are likely to occur on a given day to provide an estimate that is independent of flow variation.

Predicted values of DO concentration were normalized to remove variation from tidal height changes, although the approach herein differs slightly from Hirsch et al. (2010). Our approach uses weighted regression to isolate sources of variation in the observed DO signal that are related to unique effects of tidal height and biological process (Fig. 1). Two sets of values are predicted for the observed time series DO_{obs}, rather than creating an interpolation grid. The first set of values uses the tidal height of an observation and second set uses the mean tidal height across the time series, DO_{tid} and DO_{nrm} respectively. In other words, the first set of predictions represent DO as a function of time and tide, where the second set represents DO conditional on time and mean tidal height:

$$DO_{tid} = f(DO_{obs}|H, t) \quad (3) \quad \{\texttt{do\_tid}\}$$

$$DO_{nrm} = f(DO_{obs}|\bar{H}, t) \quad (4) \quad \{\texttt{do\_nrm}\}$$

Assessment

Simulation of DO time series

The ability of the weighted regression to detide the DO signal was evaluated first using a simulation approach. Observed DO time series were created to represent the sum of variation from biological processes and physical effects related to tidal advection:

$$DO_{obs} = DO_{bio} + DO_{adv} \quad (5) \quad \{\texttt{do\_obs}\}$$

Biological DO signals are inherently noisy (Batt and Carpenter 2012) and can be further described as:

$$DO_{bio} = DO_{die} + DO_{unc} \tag{6}$$ {do_bio}

$$DO_{unc} = \epsilon_{obs} + \epsilon_{proc} \tag{7}$$ {do_unc}

where the biological DO signal is the sum of diel variation on a 24 hour scale plus uncertainty or noise. Total uncertainty in the biological DO signal is described as variation from observation and process uncertainty (Hilborn and Mangel 1997). Multiple time series at 30 minute observations over 30 days were created following eqs. (5) to (7) such that observed DO is generalized as the additive combination of four time series (Fig. 2):

$$DO_{obs} = DO_{adv} + DO_{die} + \epsilon_{obs} + \epsilon_{pro} \tag{8}$$ {do_obs_a

Time series were created by varying the relative magnitudes of each of the four components of observed DO to test the effectiveness of weighted regression under different scenarios. The effects of air-sea gas exchange were not considered in the simulation given that methods are available for *in situ* data to correct observed DO for diffusion (i.e., Thébault et al. 2008).

Each parameter of the simulated time series was created as follows. First, biological DO time series in eq. (6) were created by adding noise or variance to a diel component (Fig. 2). The diel component, DO_{die}, was estimated using a sine/cosine function (Cryer and Chan 2008):

$$DO_{die} = \alpha + \beta \cos\left(2\pi f t + \Phi\right) \tag{9}$$ {do_sin}

such that the mean DO α was 8, amplitude β was 1, f was 1/48 to repeat on a 24 hour period every 30 minutes, t was the time series vector and Φ was the x-axis origin set for an arbitrary sunrise at 630am. The diel signal was increasing during the day and decreasing during the night for each 24 hour period and ranged from 7 to 9 mg L^{-1}. Noise or uncertainty was added to the diel DO signal to simulate natural variation in DO throughout the time series (Fig. 2). Total uncertainty was the sum of observation and process uncertainty for $n = 1440$ (30 minutes by 30 days) observations (Hilborn and Mangel 1997), such that:

$$DO_{unc,n} = \epsilon_{obs,n} + \int_{t=1}^{n} \epsilon_{pro,t} \qquad (10)$$

{do_unc_n}

where observation and process uncertainty (ϵ_{obs}, ϵ_{pro}) were simulated as normally distributed random variables with mean zero and standard deviation varying from zero to an upper limit, described below. To induce auto-correlation, process uncertainty was estimated as the cumulative sum of n observations where the noise at time $t + 1$ was equal to the noise at time t plus additional variation drawn from the normal distribution. The noise vector for process uncertainty was rescaled to constrain the variation within the bounds for standard deviation defined by the random variable. The total uncertainty, DO_{unc}, was added to the diel DO time series to create the biological DO time series (Fig. 2).

A semidiurnal tidal series was simulated as a sine wave with a period of 12.5 hours to approximate the principal lunar component (Foreman and Henry 1989). The amplitude was set to 1 meter and centered at 4 meters. Initial assessments indicated that tide type (i.e., diurnal, semidiurnal, mixed) did not signifcantly affect the outcome of the results and a semidiurnal time series was used to reduce the total number of simulations. The tidal time series was added to the biological DO series to simulate DO changes with advection, DO_{adv} (Fig. 2). Conceptually, this vector represents the rate of change in DO as a function of horizontal water movement from tidal advection such that:

$$\frac{\delta DO_{adv}}{\delta t} = \frac{\delta DO}{\delta x} \cdot \frac{\delta x}{\delta t} \qquad (11) \quad \{\texttt{deltdo}\}$$

$$\frac{\delta x}{\delta t} = k \cdot \frac{\delta H}{\delta t} \qquad (12) \quad \{\texttt{deltx}\}$$

where the first derivative of the tidal time series, as change in height over time $\delta H/\delta t$, is multiplied by a constant k, to estimate horizontal tidal excursion over time, $\delta x/\delta t$. The horizontal excursion is assumed to be associated with a horizontal DO change, $\delta DO/\delta x$, such that the product of the two estimates the DO change at each time step from advection, DO_{adv}. In practice, the simulated tidal signal was used to estimate DO_{adv}:

$$DO_{adv} \propto H \qquad (13) \quad \{\texttt{do\_advp}\}$$

$$DO_{adv} = 2 \cdot a + a \cdot \frac{H - \min H}{\max H - \min H} \qquad (14) \quad \{\texttt{do\_adv}\}$$

where a is analogous to k in eq. (12) and is chosen as the transformation parameter to standardize change in DO from tidal height change to desired units. For example, $a = 1$ will convert H to a scale that simulates changes in DO from tidal advection that range from +/- 1 mg L^{-1}. The final time series for observed DO was the sum of biological DO and advection DO (Fig. 2).

Evaluation of weighted regression with simulated DO time series

Multiple time series were simulated by varying the conditions in eqs. (5) to (14). Specifically, the simulated data varied in the relative amount of noise in the measurement, relative amplitude of the diel DO component, and degree of association of the tide with the DO signal. Three levels were evaluated for each variable: relative noise as 0, 1, and 2 standard deviations for both process and observation uncertainty, amplitude of diel biological DO as 0, 1, and 2 mg L^{-1}, and DO change from tidal advection as 0, 1, and 2 mg L^{-1}. A total of 81 time series were created based on the unique combinations of parameters (Fig. 3). Three half window widths for each variable (day, hour of day, and tide height) were evaluated: decimal time as 1, 3, and 6 days, time of day as 1, 3, and 6 hours, and tidal height as 0.25, 0.5, and 1 as a proportion of the observed value at the center of the window. The window widths were chosen based on preliminary assessments that suggested variation in model performance was adequately captured by these values. In total, 27 window width combinations were evaluated for each of 81 simulated time series, producing results for 2187 weighted regressions.

The detided or normalized values for each regression were compared to the simulated data to evaluate the ability of weighted regression to reproduce the biological DO signals. Results were summarized using Pearson correlation coefficients and the root mean square error (RMSE) {acro:RMSE between the detided time series and the biological DO time series as a known component of the observed. Overall, the weighted regressions provided accurate results for the detided time series compared to the 'true' biological time series regardless of the simulation parameters (Table 1) or window widths (Table 2). Results for each simulation can be viewed using the link in the multimedia section. Mean correlation for all time series and window widths between the detided and biological values was 0.60, with values ranging from -0.78 to 1.00. Mean error was 1.21, with values ranging from 0.00 to 2.40. Simulations with very poor performance (e.g., negative correlations) were those that had minimum widths for day windows and maximum widths for hour windows, or were those with the DO signal composed entirely of noise from observation uncertainty. Conversely, simulations with detided time series that were identical to the true time series (e.g., correlation of one, RMSE of zero) were those for which there was no biological or tidal influence. While the latter examples do not represent real-world scenarios, they were included in the simulations to provide verification that the weighted regression provided reasonable results given extremes.

Characteristics of DO time series that contributed to improved model performance were increasing amplitude of the diel DO component (DO_{die}) and increasing process uncertainty (e_{pro}), whereas increasing observation uncertainty contributed to decreasing performance (Table 1 and Fig. 4). Model performance was minimally influenced by magnitude of the tidal advection component (DO_{adv}), although performance decreased slightly with increasing tidal effects. Increasing widths for day and tidal proportion windows contributed to increasing model performance, whereas the opposite was true for increasing hour windows (Table 2 and **??**). Graphical summaries of model performance by simulation parameters (Fig. 4) and half window widths (Fig. 5) support the general trends described by Tables 1 and 2. Scale differences between Fig. 4 and Fig. 5 emphasize that model performance was more affected by characteristics of the DO time series rather than the selected window widths. For example, the range of correlation values comparing the effects of half window widths (averaged across all simulation parameters, Fig. 5) were approximately half the range of correlations for comparing the effects of simulation parameters (averaged across all half window widths, Fig. 4).

Validation of weighted regression with case studies

NERRS is a federally-funded network of 28 protected estuaries established for long-term research, water-quality monitoring, education, and coastal stewardship (Wenner et al. 2004).

Continuous water quality data have been collected at NERRS sites since 1994 through the System {acro:SWM

Wide Monitoring Program (SWMP). In addition to providing a basis for trend evaluation, data from SWMP provides an ideal opportunity to evaluate long-term variation in water quality parameters attributed to both biological and physical processes. Continuous SWMP data can be used to describe DO variation at sites with different characteristics, including variation from ranges in tidal regime (Sanger et al. 2002) and rates of ecosystem production (Caffrey 2003, 2004).

Continuous DO time series and tidal height measurements at four sites from the SWMP database (CDMO 2014) were used to validate the detiding model with real data. Monitoring data from January 1st to December 31st 2012 were obtained from a range of geographic locations (Fig. 6 and Table 3). Astronomical tidal heights were predicted for each site using harmonic regression applied to the sonde depth data (`oce` package in R, Foreman and Henry 1989, RDCT 2014). Although, the depth data represent tidal height variation from both astronomical (i.e., gravitational effects) and meteorological (e.g., wind, precipitation inflows) sources, we isolated the former given that daily metabolism estimates were more likely to be affected by repeated diel cycling from normal tidal changes. Each station was also chosen based on high correlations between DO and tidal changes. The four sites included the Vierra Mouth station at Elkhorn Slough (California, 36.81°N, 121.78°W), Bayview Channel at Padilla Bay (Washington, 48.50°N 122.50°W), Middle Blackwater River station at Rookery Bay (Florida, 25.93°N 81.60°W), and Dean Creek station at Sapelo Island (Georgia, 31.39°N 81.28°W). The stations are generally macrotidal semidiurnal or mixed semidiurnal and net heterotrophic on an annual basis. Net heterotrophy (i.e., respiration exceeding production) is typical for shallow water systems at temperate latitudes (Caffrey 2003), although values in Table 3 are from observed DO time series that are strongly influenced by tidal advection.

Estimates of ecosystem metabolism before and after detiding

{met_sec}

The weighted regression method was applied to the time series for each station to obtain a detided DO time series for estimating metabolism. Half window widths of six days, one hour, and a tidal proportion of one half were chosen based on a balance between large and small window widths, although we recognize that the chosen widths are somewhat arbitrary and a more exhaustive evaluation should be conducted prior to using the results to inform management actions. Unlike the simulated data, the true biological DO signal was unknown for the case studies. Accordingly, results were evaluated using correlations of DO and metabolism estimates with tidal height before and after application of the model. Results were also evaluated based on the occurrence of 'anomalous' daily production or respiration estimates, where anomalous was defined as negative production during the day and positive respiration estimates during the night. Anomalous values have been previously attributed to the effects of physical processes on DO time series (Caffrey 2003). We hypothesized that metabolism esimates using the detided signal would contain less 'anomalous' values than those from the observed DO time series. Although anomalies could be caused by processes other than tidal advection, e.g., abiotic dark oxygen production (Pamatmat 1997), we assume that physical processes are the dominant sources of these values.

Ecosystem metabolism was estimated from the DO time series using the open-water technique (Odum 1956) as described in Caffrey et al. (2013). The method is used to infer net ecosystem metabolism using the mass balance equation:

$$\frac{\delta DO}{\delta t} = P - R + D \qquad (15) \quad \{\texttt{metrate}\}$$

where the change in DO concentration (δDO, g O_2 m^{-3}) over time (δt, hours) is equal to photosynthetic rate (P, g O_2 m^{-3} hr^{-1}) minus respiration rate (R, g O_2 m^{-3} hr^{-1}), corrected for air-sea gas exchange at the interface (D, g O_2 m^{-3} hr^{-1}) (Caffrey et al. 2013). D is estimated as the difference between the DO saturation concentration and observed DO, multiplied by a volumetric reaeration coefficient, k_a (Thébault et al. 2008). The diffusion-corrected DO flux estimates were averaged during day and night for each 24 hour period in the time series, where flux is an hourly rate of DO change as the difference between observations at time t and $t + 1$. Areal respiration rates were assumed constant during the night and substracted from daily gross production estimates to yield net ecosystem metabolism (Table 3).

Detiding had significant effects on the correlations between tidal height changes, DO time series, and metabolism estimates (Table 4). Correlations of observed DO time series with predicted tidal height were highly significant, with all sites indicating positive relationships, except Padilla Bay where tidal increases were associated with declines in DO concentration. This suggests that seaward water masses were less anoxic than landward masses, with the opposite being true for Padilla Bay. The detided DO time series had greatly reduced correlations with tidal height, although relationships were still significant after detiding likely because of the large sample size for each site (n $\approx$ 17500). Metabolism estimates before and after detiding were compared to the mean rate of tidal height change (i.e., first derivative of the predicted tidal height) for each day during separate solar periods. Production rates were compared to mean rates of tidal height change during the day, respiration rates were compared to mean rates of change during the night, and net metabolism rates were compared to mean rates of change for the total 24 hour period each day. Comparison of metabolic rates to tidal changes before and after detiding produced inconsistent results (Table 4). Correlations for Elkhorn Slough and Sapelo Island showed consistent reductions in all three metabolims estimates after detiding. Correlations for Padilla Bay and Rookery Bay were of opposite sign and greater magnitude after detiding for production and respiration, although net metabolism estimates had reduced correlations.

The percent of daily integrated metabolism estimates that were anomalous (negative production, positive respiration) were significantly reduced for most sites after detiding (Table 5). Before detiding, anomalous values ranged from 0.09 (Rookery Bay) to 0.22 (Padilla Bay) for production and 0.08 (Rookery Bay) to 0.21 (Elkhorn Slough) for respiration as proportions of the daily estimates. Anomalous values were reduced to near zero for Rookery Bay and Sapelo Island, by approximately half for Padilla Bay (0.13 for production, 0.13 for respiration), and only slightly reduced for Elkhorn Slough (0.17 for production, 0.17 for respiration). Metabolism estimates using detided DO time series had decreased mean production and respiration for Elkhorn Slough, increased mean production and respiration for Padilla Bay, and generally unchanged mean production and respiration for Rookery Bay and Sapelo Island (Table 5). Mean net ecosystem metabolism was unchanged for all sites. Decreases in the standard erorr for all metabolism estimates (production, respiration, and net) were observed for all cases after detiding. Graphical results for each case study can be viewed using the link in the multimedia section.

An example from Sapelo Island illustrates the effects of weighted regression on DO and metabolism estimates (Figs. 7 to 9). A two-week period in February shows when the tidal changes were both in and out of phase with the diel cycling. The first week illustrates a period of observation when maximum tide heights are generally out of phase with the diel cycle such that low tides are observed during the middle of the night and the middle of the day (Fig. 8). The second week illustrates when the maximum tide height occurs during the day and night (Fig. 8). The effects of tidal height change on the observed DO time series are visually apparent in the plots. Maximum or minimum tidal heights also occur when the contributions of respiration and production are largest (i.e., mid-day or mid-night). The first example illustrates a strong negative bias (less respiration, less production) in the observed DO signal from low tides, whereas the second example illustrates a strong positive bias (more respiraiton, more production) in the observed DO from high tides. These biases are apparent in the metabolism estimates based on the observed data (Fig. 9). Anomalous estimates occur when low tides are in phase with the solar cycle, whereas metabolism estimates are likely over-estimated when high tides are in phase with the solar cycle. The detided time series shows noticeable changes given the direction of bias associated with tidal height and diel period. DO values were higher after detiding when low tides occurred during night and day periods, whereas DO values were lower after detiding when high tides occurred during day and night periods. Changes in metabolism estimates after detiding were also apparent, such that the anomalous values were removed during the first week and the positive bias in the second week is decreased. Detiding had similar effects for the remaining sites, particularly when tidal changes were in or out of phase with diel periods.

Effects of aggregation and importance of detiding

A final point of concern is the period of observation within which observed DO is affected by tidal height changes and the extent to which this affects the interpretation of ecosystem metabolism. From a management or ecological perspective, the effects of tidal variatoin on daily estimates may not be a primary concern given that seasonal or annual rates may be more relevant for evaluating ecosystem dynamics with continuous monitoring data. The example from Sapelo Island in the previous section further highlights this point given that mean production and respiration estimates before and after detidng were generally unchanged for the two-week period. Table 5 also indicated that mean annual estimates of production and respiration were unchanged for Rookery Bay and Sapelo Island, whereas production and respiration estimates were significantly different at both mean annual and daily time scales for Elkhorn Slough and Padilla Bay. Although we acknowledge that the specific results may be related to the window widths, this suggests that detiding may contribute to changes in metabolic estimates that are aggregated on longer time periods. Therefore, an evaluation of the effects of tidal variation on ecosystem metabolism for different periods of observation is critical for understanding practical implications of weighted regression. Specifically, when should detiding be applied if aggregation of observed data on longer time periods removes potential bias? A comparison of observed and detided estimates that are aggregated over different periods of observation (e.g., annual, seasonal, monthly) could help address this question.

The observed and detided daily estimates were averaged by month and season (Fall, Spring, Summer, and Winter) for each case study to evaluate effects of aggregation on mean production and respiration estimates (Figs. 10 and 11). Mean annual estimates in Table 5 also provided a basis of comparison with monthly and seasonal aggregation. Significant variation in aggregated production and respiration estimates for month and season was observed for each case study. Detided production and respiration estimates for Padilla Bay and Rookery Bay exhibited seasonal and monthly variation that was more characteristic of expected trends with increases in metabolism during warmer months. Specifically, production estimates based on observed DO were substantially muted for both Padilla Bay (Fig. 10) and Rookery Bay (Fig. 11) during summer months, whereas values were significantly higher based on the detided data. Results for Sapelo Island suggested that winter and summer months were under- and over-estimated, respectively, based on the observed data. Results for Elkhorn Slough varied significantly such that production and respiration were significantly reduced after detiding regardless of the aggregation period. Overall, these trends emphasize the importance of considering different aggregation periods for interpreting metabolism estimates. Each case study showed differences in observed and detided values at monthly and seasonal aggregations, whereas only two of the four case studies had mean aggregated estimates that were substantially different (Elkhorn Slough and Padilla Bay, Table 5). Periods of observation as long as one year may include significant sources of bias from tidal advection, suggesting the need for applying weighted regression.

Discussion

The primary objective for development and application of the weighted regression technique was to provide a method for more accurately estimating ecosystem metabolism by removing bias associated with tidal change in observed DO time series. The application of weighted regression to simulated DO time series with known characteristics and extension to continuous monitoring data from selected NERRS sites provided a proof-of-concept that the method can isolate and remove variation in observed DO from tidal change. Further, aggregation of metabolism estimates using the detided DO time series were significantly different than those using the observed data, particularly for relatively long periods of observation. These results suggest that previous estimates of annual means may not accurately reflect true metabolic signals if the effects of tidal variation confound biological signals in observed DO time series.

Additionally, variation of mean estimates was substantially reduced for estimates based on detided DO time series, suggesting that the certainty of conclusions from detided estimates can be improved even if the mean annual estimates do not change. Monitoring data for periods of observation less than one year may also produce biased metabolism estimates if observed data are not detided. Results for each case study showed that significant differences were observed for the detided data at seasonal and monthly aggregations, particularly during summer months for Padilla Bay and Rookery Bay.

Comparisons between detided and biological DO time series from the simulations indicated that adequate results can be obtained from the weighted regression for a range of characteristics of DO time series, as well as half window widths used in the regression. An examination of scenarios that produced abnormal results can provide additional insight into factors that affect the performance of weighted regression. For example, poor performance was observed when the observation uncertainty (ϵ_{obs}) was high and both process uncertainty (ϵ_{pro}) and tidal advection (DO_{adv}) were low. These examples represent time series with excessive random variation, no auto-correlation, and no tidal influence. Poor performance is expected because the weighted regression models a non-existent tidal signal in a very noisy DO time series. These results were observed even for time series with a large diel component of the biological DO signal, suggesting that the model will produce unreliable results in microtidal systems with high noise and no serial correlation. From a practical perspective, weighted regression should not be applied to noisy time series if there is not sufficient evidence to suggest the variation is related to tidal changes. Similarly, results with perfect or near-perfect correlations between detided and biological DO time series were observed when observation uncertainy and tidal advection effects were not in the simulated time series. Although there is no logical basis for applying weighted regression to time series with no apparent tidal influences, the results will be as expected, as was true for cases with low tidal advection, high observation uncertainty, and low process uncertainty. We emphasize that the weighted regression should only be applied to time series for which specific conditions apply, as described below.

The performance metrics used to evaluate weighted regression with the case studies suggested that detiding provided more accuate estimates of ecosystem metabolism. Correlations of metabolism estimates with tidal height changes after detiding were generally reduced, although trends were not always consistent as correlations were reduced in some cases (Sapelo Island) or reversed in others (Padilla Bay). However, correlations of net metabolism estimates were reduced in all cases. Tidal height change provides a proxy measure for horizontal advection that directly affects the measured rate of change of oxygen. Further, changes in DO concentration represent integrated measures of both production and respiration (eq. (15)). The inconsistent results in Table 4 are potentially related to the effects of horizontal advection on the integrated DO signal, given that production and respiration each represent a unique component of the diel DO variation that is directly affected by tidal variation. Regardless, the proportion of anomalous metabolism estimates was reduced by detiding for all case studies, although this measure may also be an incomplete indication of the combined effects of tidal variation. Negative production and positive respiration estimates suggest assumptions of the open-water method are violated (Needoba et al. 2012), whereas 'normal' estimates (positive production and negative respiration) may still include a significant source of bias from physical advection by providing over-estimates of true values. For example, Nidzieko et al. (2014) observed that net metabolism at Elkhorn Slough was more often heterotrophic during maximum spring tides that occurred at nighttime, as a substantially larger area of salt marsh was inundated leading to higher respiration estimates. Although this result supports our general conclusions, a broader discussion regarding whether or not this represents a bias in metabolism from physical advection may be needed.

A strength of the weighted regression approach is the lack of assumptions for describing the relationships between DO and tidal variation over time. Although the functional form of the model is a simple linear regression with two explanatory variables (eq. (1)), the moving window approach combined with the adaptive weighting scheme allows for quantification of complex tidal effects that may not be possible using alternative approaches. For example, Batt and Carpenter (2012) described the use of a moving window or Kalman filter to improve estimates of ecosystem metabolism in lakes. The approach minimizes the influences of process and observation uncertainty on observed DO time series, which is attributed to the effects of water movement on metabolic signals. Although a similar approach may be useful for estuaries if process and observation uncertainty are the only sources of variation in the DO series, the weighted regression approach is more appropriate if tidal advection is the primary confounding factor. Additionally, results from the case studies illustrated the ability of the weighted regression approach to model changes over time in the relationships between tidal change and DO. Results for Padilla Bay and Rookery Bay suggested that detiding had the largest effect during the summer, whereas the results for cooler months were not significantly different from the observed. The weighted regression method produced detided time series that accommodated seasonal variation in DO conditional on tidal height change, whereas moving window filters or standard regression techniques would likely not have characterized these dynamic relationships.

Comments and recommendations

Results from the simulations and case studies suggested that weighted regression can be a practical approach for detiding DO time series to remove the effects of physical advection on estimates of ecosystem metabolism. However, application of the method may only be appropriate under specific situations. The case studies were chosen based on the expected influence of tidal variaiton given the relatively high proportion of metabolism estimates that were anomalous and the strength of correlation between the observed DO time series and tidal height. Despite these similarites among the case studies, detiding had variable effects on metabolism estimates. The results for Elkhorn Slough and Padilla Bay are particular cause for concern given that mean annual estimates were substantially different compared to those from the observed DO time series. Although the correlation of DO and tidal height was reduced for both cases, in addition to a reduction of anomalous estimates, the relative change in mean metabolism before and after detiding suggests a more careful evaluation of the method is needed. In particular, optimal window widths should be chosen based on the ability to remove tidal effects while preserving the biological signal.

The case studies emphasize a critical challenge in evaluating the effects of physical advection: the true biological signal is not known, or more appropriately, the relative contribution of horizontal advection to bias is not accuratley quantified. Comparative analyses between systems with varying tidal influence or within-system evaluations of multiple sites at fixed distances are necessary to further validate performance of weighted regression. Regardless, the current analysis suggests the method is potentially useful and we propose a precautionary approach for its application pending further validation. Weighted regression should only be applied at macrotidal sites with strong evidence of the confounding effects of tidal advection on biological signals. A weight-of-evidence approach should be used such that the occurrence of anomalous metabolism estimates, strong correlations between observed DO and tide height, and clear visual patterns of tide change on DO would suggest detiding is appropriate. The choice of window widths may also produce varying results. Optimal widths may be those that indicate a reduction of anomalous estimates, reduction in daily variation of production and respiration, and a reduction of the correlation between DO and tide. Results from window widths that produce large changes in the mean annual estimates should interpreted with caution. In general, a pragmatic approach is emphasized such that results should be evaluated based on the preservation of diel variation related to production while exhibiting minimal changes with the tide. Such an approach, combined with further validation, will support informed management decisions through more accurate estimates of ecosystem metabolism.

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Figures

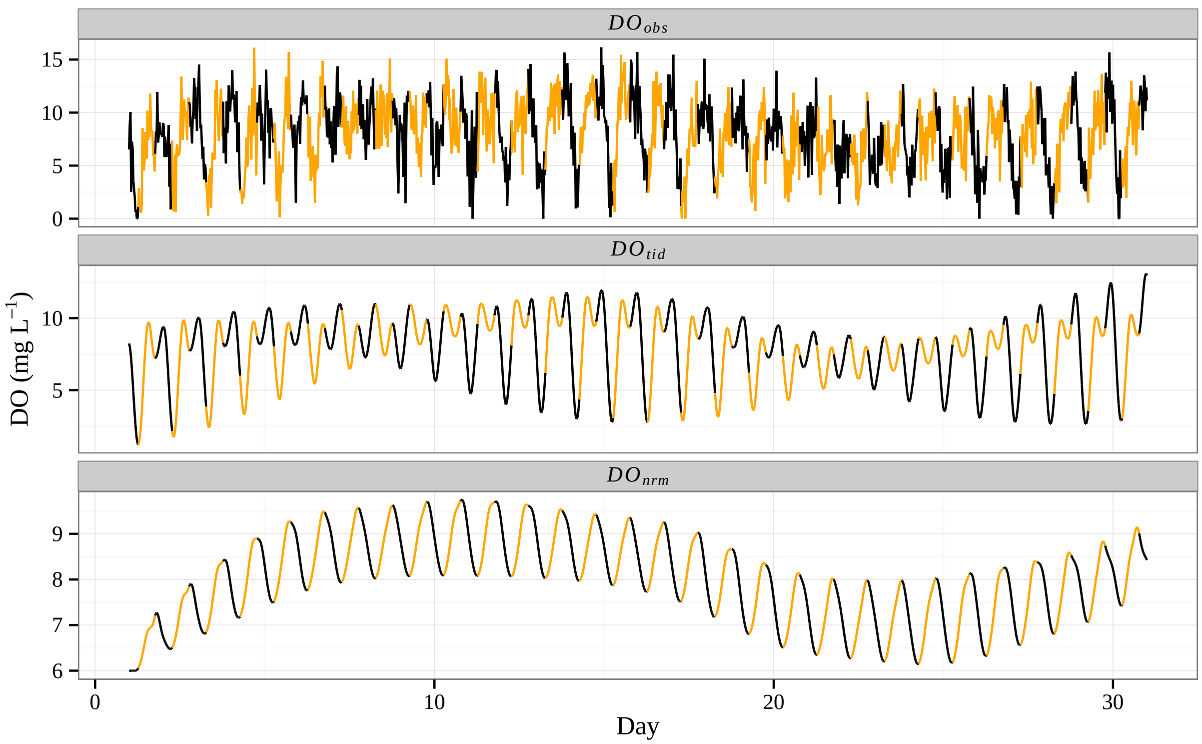

Fig. 1: Example of detiding a simulated DO time series. Simulated values are those in Fig. 2. Yellow indicates daylight periods. fig:do_dtd

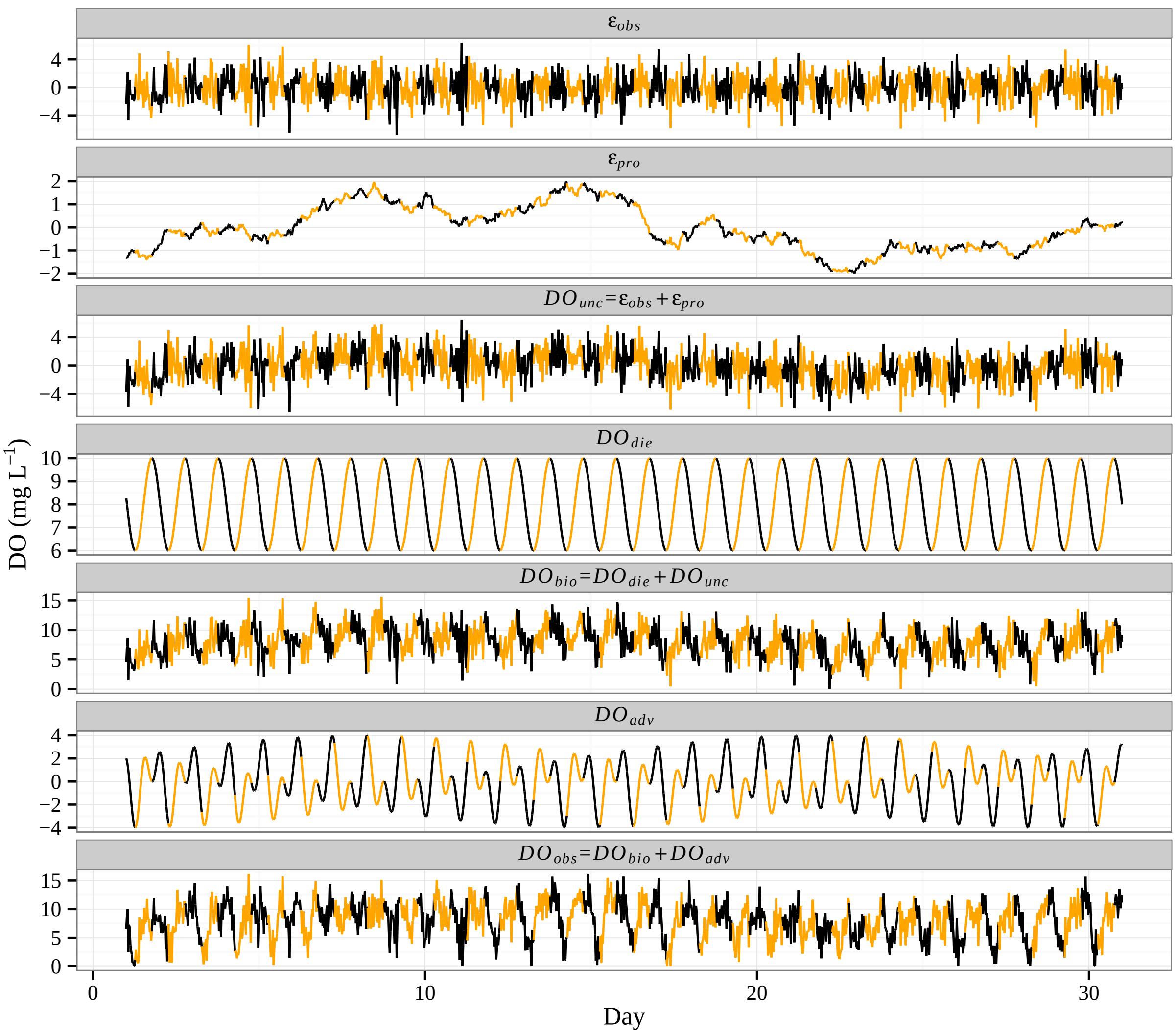

Fig. 2: Example of creating a simulated DO time series. Values were simulated every 30 minutes for 30 days. Yellow indicates daylight periods. fig:do_sim

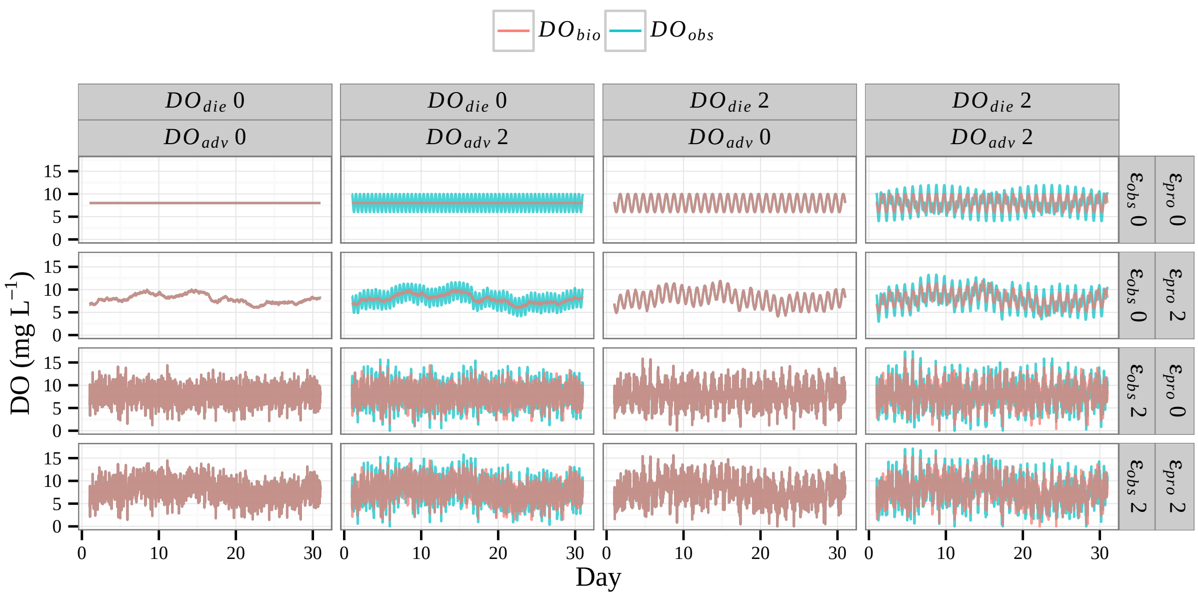

Fig. 3: Representative examples of simulated observed DO (DO_{obs}) and biological DO (DO_{bio}) as a component of observed) time series created by varying each of four parameters: tidal strength of tidal association with DO signal using DO_{adv}, amount of process uncertainty ϵ_{pro}, amount of observation observation uncertainty ϵ_{obs}, and strength of diel DO component DO_{die}. Parameter values represent the minimum and maximum used in the simulations.fig:sim_ex

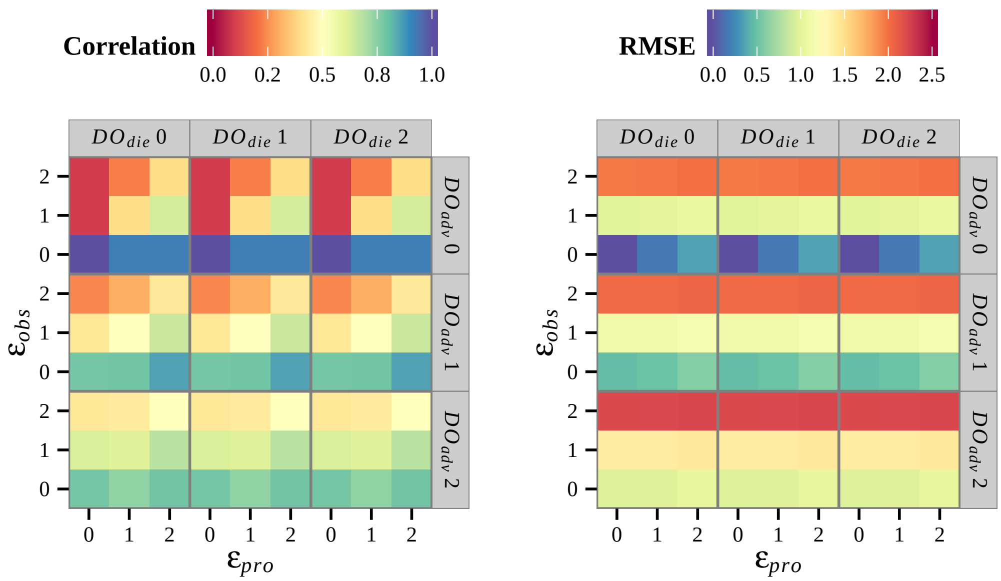

Fig. 4: Correlations and errors (RMSE) for detided DO time series, DO_{dtd}, from weighted regression with 'true' biological DO, DO_{bio}, for varying simulation parameters: strength of tidal association with DO signal DO_{adv}, amount of process uncertainty ϵ_{pro}, amount of observation observation uncertainty ϵ_{obs}, and strength of diel DO component DO_{die}. Each tile represents the correlation or error between detided and biological DO time series from results for a given combination of simulation parameters. Results are averaged for all window widths used to evaluate the regressions (Fig. 5). fig:err_surf1

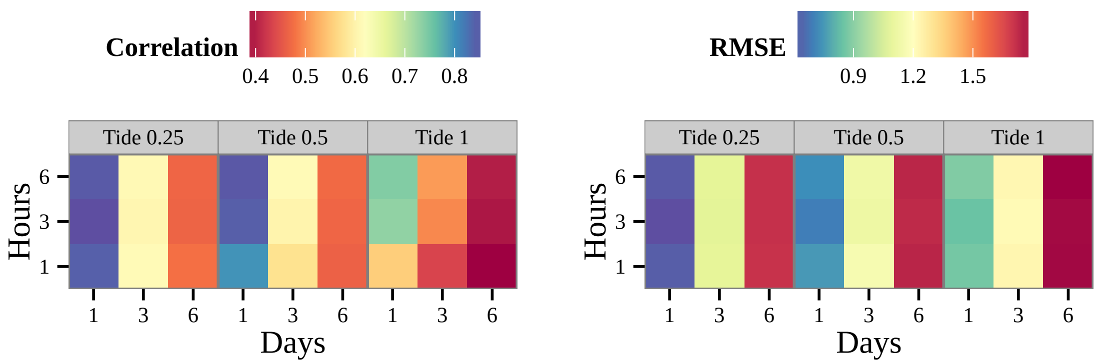

Fig. 5: Correlations and errors (RMSE) for detided DO time series, DO_{dtd}, from weighted regression with 'true' biological DO, DO_{bio}, for varying half window widths: days, hour of day, and proportion of tidal range. Each tile represents the correlation or error between detided and biological DO time series from results for a given combination of window widths. Results are averaged for all simulation parameters used to evaluate the regressions (Fig. 5). fig:err_surf2

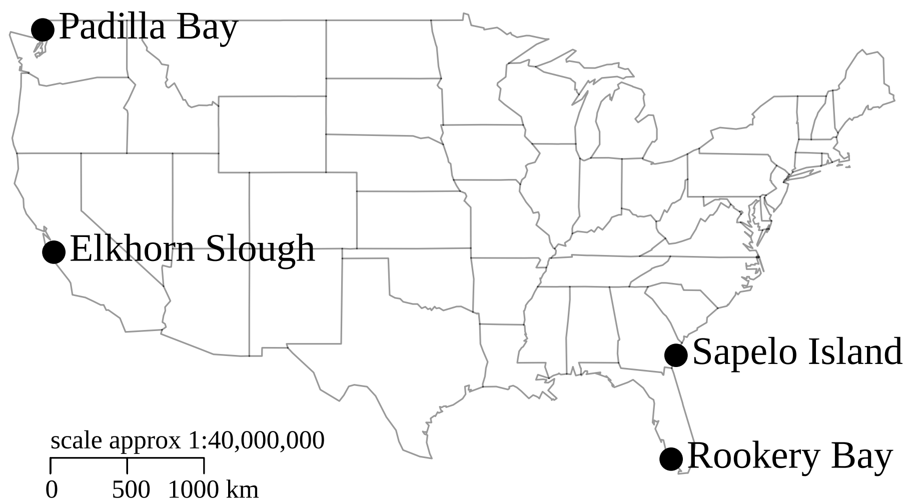

Fig. 6: Locations of NERRS sites used as case studies to evaluate of weighted regression. Individual stations at each reserve are PDBJE (Joe Leary Estuary at Padilla Bay), RKBMB (Middle Blackwater River at Rookery Bay), SAPDC (Dean Creek at Sapelo Island), and TJRBR (Boca Rio at Tijuana River). fig:case_map

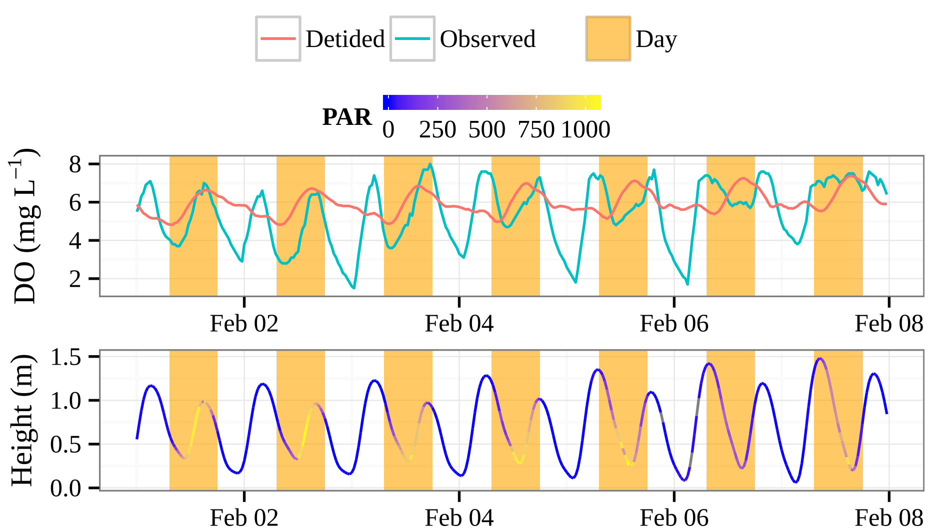

Fig. 7: Continuous DO time series before (observed) and after (detided) detiding with weighted regression and tidal height colored by total photosynthetically active radiation (mmol m^{-2}). Results are for the Sapelo Island station for a seven day period when high tide events were out of phase with diel periods, creating lower than expected observed DO during night and day periods. Detided values are based on a weighted regression with half windows of six days, one hour within each day, and tidal height proportion of one half. fig:phase_out

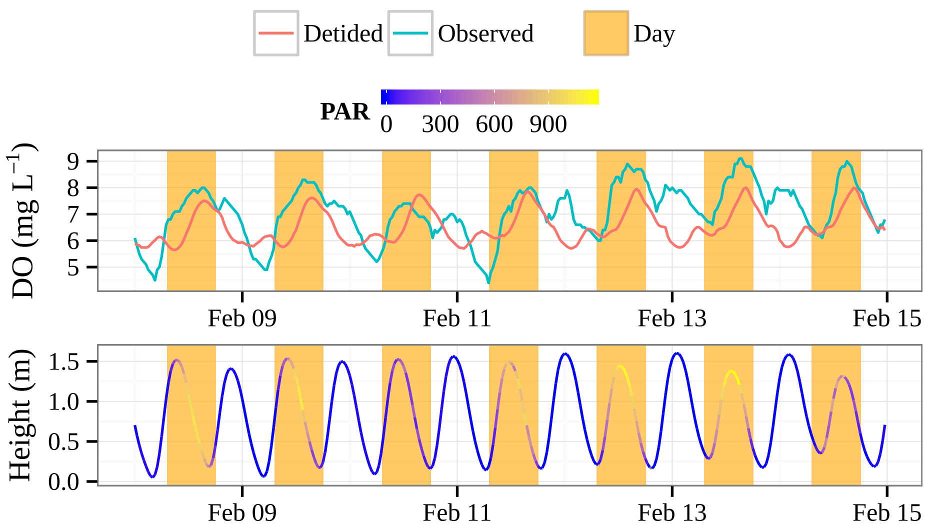

Fig. 8: Continuous DO time series before (observed) and after (detided) detiding with weighted regression and tidal height colored by total photosynthetically active radiation (mmol m^{-2}). Results are for the Sapelo Island station for a seven day period when high tide events were in phase with diel periods, creating higher than expected observed DO during night and day periods. Detided values are based on a weighted regression with half windows of six days, one hour within each day, and tidal height proportion of one half.fig:phase_in

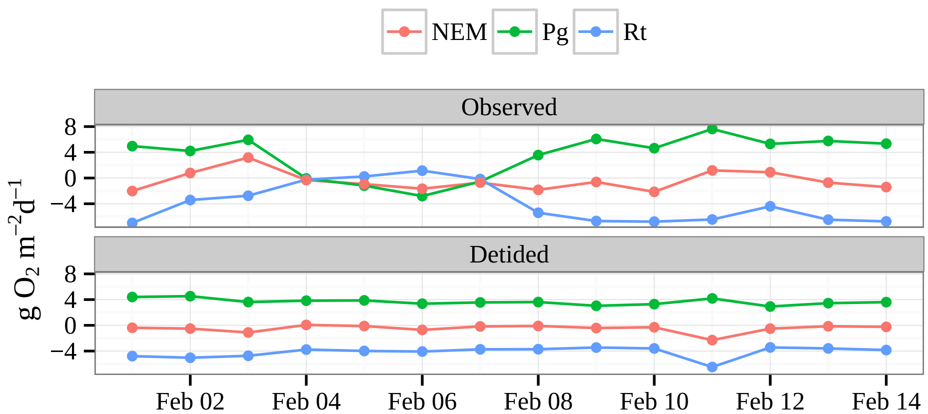

Fig. 9: Example of daily mean metabolism (net ecosystem metabolism, gross production, and total respiration) before (observed) and after (detided) detiding with weighted regression. Results are for the Sapelo Island station for a two week period in February, 2012 when high tide was out of phase with the diel cycle during the first week (Fig. 7) and in phase during the second week (Fig. 8). fig:case_ex

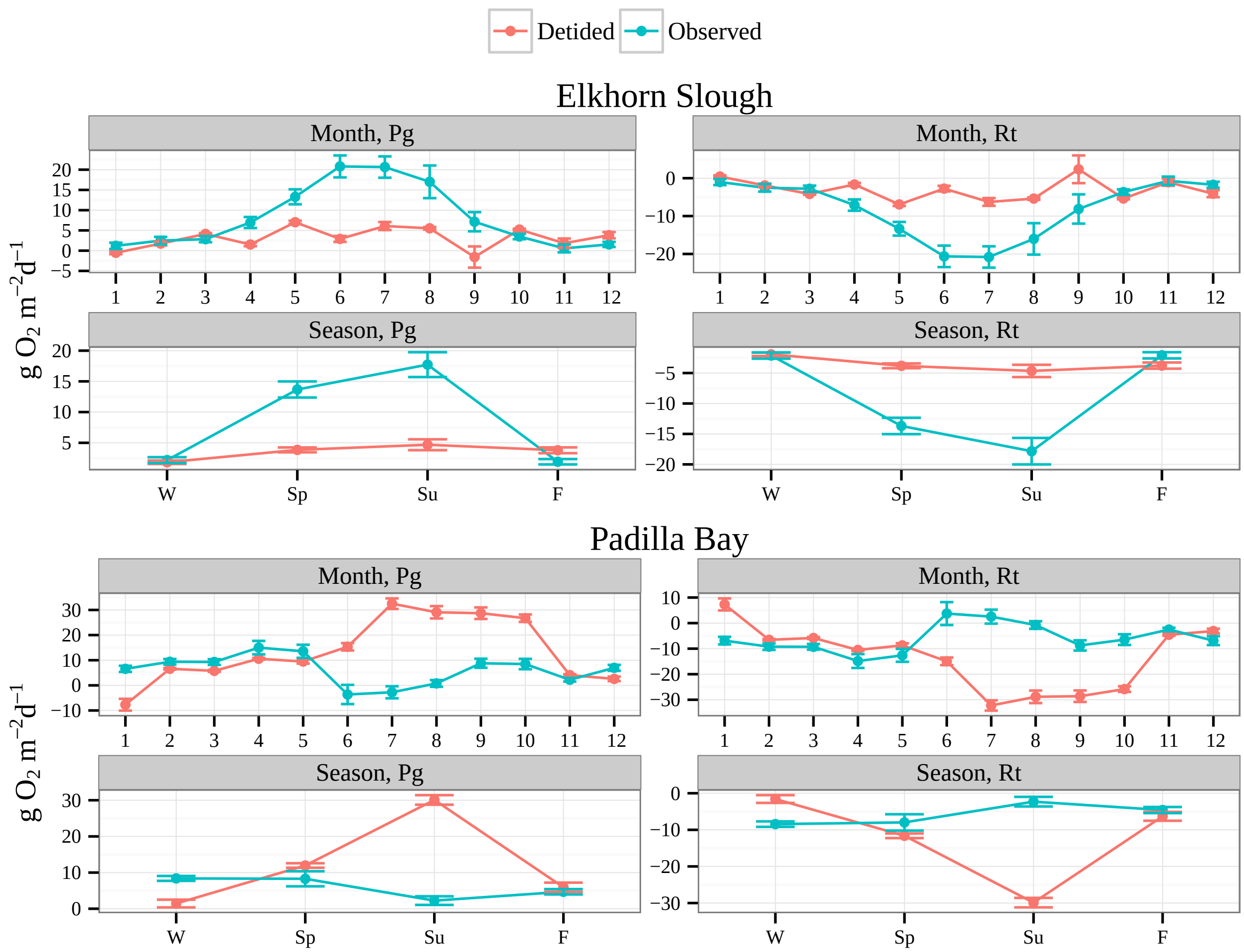

Fig. 10: Means and standard errors of daily metabolism estimates (gross production, total respiration, net ecosystem metabolism) aggregated by month and season. Aggregated estimates are for Elkhorn Slough and Padilla Bay from observed and detided DO time series. fig:metab_sum1

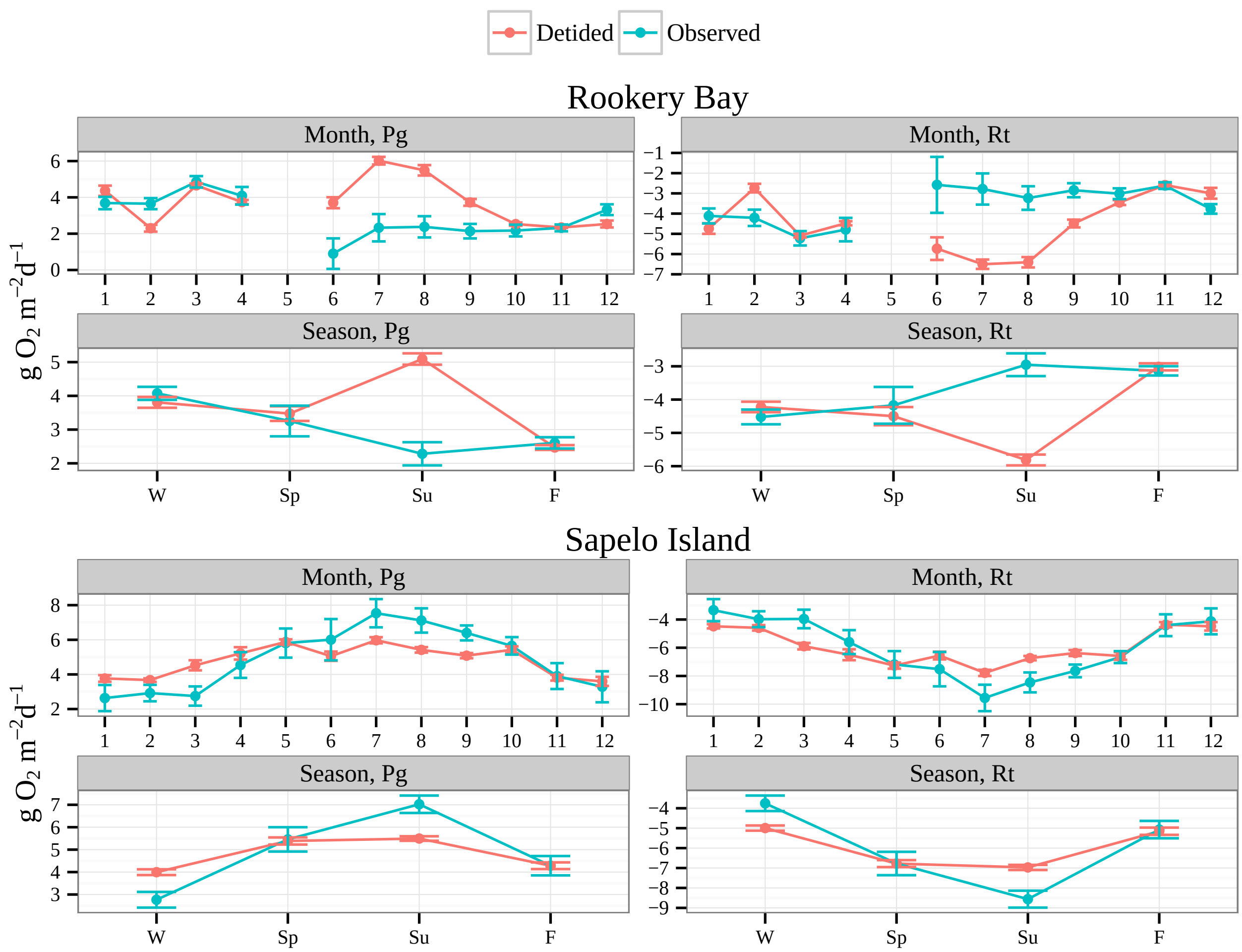

Fig. 11: Means and standard errors of daily metabolism estimates (gross production, total respiration, net ecosystem metabolism) aggregated by month and season. Aggregated estimates are for Rookery Bay and Sapelo Island from observed and detided DO time series. May was removed from Rookery Bay because of incomplete data. fig:metab_sum2

Tables

Table 1: Summary (range, mean, percentiles) of correlations and error estimates comparing detided and biological DO time series for different simulation parameters (tidal category, DO_{die}, DO_{adv}, ϵ_{pro}, ϵ_{obs}). Values represent a combination of results from multiple simulations with the parameter value held constant for each row (e.g., row one is a summary of all simulations for which the tidal category was diurnal).tab:dtd_perf1

Parameter	**Correlation**					**RMSE**				
	Min	25th	Mean	75th	Max	Min	25th	Mean	75th	Max
$\boldsymbol{DO_{die}}$										
0	-0.78	0.30	0.53	0.82	1.00	0.00	0.68	1.22	1.97	2.39
1	-0.28	0.38	0.61	0.88	1.00	0.00	0.59	1.20	1.96	2.40
2	-0.39	0.46	0.65	0.90	1.00	0.00	0.62	1.22	1.97	2.40
$\boldsymbol{DO_{adv}}$										
0	0.00	0.27	0.57	0.93	1.00	0.00	0.34	1.07	1.96	2.12
1	-0.78	0.37	0.59	0.83	1.00	0.00	0.63	1.18	1.98	2.12
2	-0.78	0.47	0.63	0.82	1.00	0.00	0.98	1.38	1.99	2.40
$\boldsymbol{\epsilon_{pro}}$										
0	-0.78	0.34	0.58	0.86	1.00	0.00	0.63	1.19	1.96	2.40
1	-0.78	0.37	0.59	0.85	1.00	0.00	0.63	1.21	1.97	2.40
2	-0.78	0.41	0.61	0.85	1.00	0.00	0.63	1.24	1.98	2.40
$\boldsymbol{\epsilon_{obs}}$										
0	-0.78	0.31	0.65	0.98	1.00	0.00	0.29	0.92	1.50	2.40
1	0.05	0.37	0.57	0.81	0.99	0.07	0.98	1.18	1.49	2.39
2	0.05	0.40	0.57	0.70	0.99	0.15	1.06	1.54	2.01	2.40

Table 2: Summary (range, mean, percentiles) of correlations and error estimates comparing detided and biological DO time series for simulations using different half window widths in the weighted regressions (days, hours, and proportion of tidal range). Values represent a combination of results from multiple simulations with the window value held constant for each row (e.g., row one is a summary of all simulations for which the half window width was one day). tab:dtd_perf2

Window	Correlation					RMSE				
	Min	25th	Mean	75th	Max	Min	25th	Mean	75th	Max
Days										
1	-0.78	0.63	0.78	0.97	1.00	0.00	0.28	0.74	1.04	2.12
3	-0.07	0.40	0.56	0.75	1.00	0.00	0.99	1.15	1.28	2.08
6	0.00	0.26	0.45	0.58	1.00	0.00	1.95	1.75	2.05	2.40
Hours										
1	-0.78	0.36	0.57	0.82	1.00	0.00	0.63	1.22	1.96	2.40
3	0.00	0.40	0.61	0.87	1.00	0.00	0.58	1.20	1.97	2.36
6	0.03	0.37	0.61	0.85	1.00	0.00	0.64	1.22	1.98	2.40
Tide										
0.25	0.00	0.42	0.64	0.91	1.00	0.00	0.51	1.14	1.97	2.21
0.5	0.06	0.43	0.63	0.88	1.00	0.00	0.61	1.20	1.97	2.27
1	-0.78	0.30	0.52	0.79	1.00	0.00	0.73	1.30	1.97	2.40

Table 3: Summary statistics of tidal component amplitudes (m), selected water quality parameters (DO mg L^{-1}, chlorophyll-a μg L^{-1}, salinity psu, water temperature °C) and metabolism estimates (gross production, respiration, and net ecosystem metabolism as g m^{-2} d^{-1}) for each case study. Tidal components are principal lunar semidiurnal (O1, frequency 25.82 hours), solar diurnal (P1, 24.07 hours), lunar semidiurnal (M2, 12.42 hours), and solar semidiurnal (S2, 12 hours), estimated from harmonic regressions of tidal height (`oce` package in R, Foreman and Henry 1989, RDCT 2014). Water quality data are averages for the entire period of record (30 minute observations) for each site. Metabolism estimates are means of daily integrated values. tab:case_att

Site	Tidal amplitude				Water quality				Metabolism[a]		
	O1	P1	M2	S2	DO	Chl	Sal	Temp	Pg	Rt	NEM
ELKVM	0.24	0.12	0.48	0.13	7.87	3.87	32.43	13.78	8.14	-8.19	-0.05
PDBBY	0.46	0.23	0.63	0.15	8.97	2.24	29.17	10.44	5.95	-5.90	0.05
RKBMB	0.13	0.04	0.36	0.10	4.48	4.50	30.53	25.85	3.02	-3.62	-0.60
SAPDC	0.10	0.02	0.54	0.07	4.96	5.98	27.30	21.77	4.89	-6.04	-1.16

[a]Pg: gross production, Rt: respiration, NEM: net ecosystem metabolism

Table 4: Correlations of tidal changes at each site with continuous DO observations and metabolism estimates (gross production, respiration, and net metabolism) before (observed) and after (detided) detiding from weighted regression. DO values are correlated with predicted tidal height at each observation, whereas metabolism estimates are correlated with mean tidal height change between observations during day, night, or total day periods for production, respiration, and net metabolism, respectively. tab:cor_res

Site	DO	Pg[a]	Rt	NEM
ELKVM				
Observed	0.47***	0.60***	0.73***	0.35***
Detided	0.02*	0.19***	0.13*	0.06
PDBBY				
Observed	-0.45***	-0.33***	-0.46***	-0.25***
Detided	0.07***	0.48***	0.47***	-0.21***
RKBMB				
Observed	0.28***	0.34***	0.39***	0.24***
Detided	-0.02**	-0.31***	-0.36***	0.12*
SAPDC				
Observed	0.48***	0.54***	0.71***	0.41***
Detided	-0.03***	0.16**	0.18***	-0.05

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$
[a]Pg: gross production, Rt: respiration, NEM: net ecosystem metabolism

Table 5: Summary of metabolism estimates (gross production, respiration, and net metabolism) for case studies using DO time series before (observed) and after (detided) application of weighted regression. Means and standard errors are based on daily integrated metabolism estimates. Anomalous values are the proportion of metabolism estimates that were negative for gross production and positive for respiration. Results are for weighted regression with half windows of six days, one hour around the time of observation for each day, and a tidal height proportion of one. tab:case_res

Site	**Pg**[a]			**Rt**			**NEM**	
	Mean	Std. Err.	Anom	Mean	Std. Err.	Anom	Mean	Std. Err.
ELKVM								
Observed	8.14	0.67	0.19	-8.19	0.69	0.21	-0.05	0.16
Detided	3.63	0.23	0.17	-3.67	0.24	0.17	-0.04	0.05
PDBBY								
Observed	5.95	0.69	0.22	-5.90	0.74	0.19	0.05	0.22
Detided	10.36	0.63	0.13	-10.32	0.63	0.13	0.04	0.08
RKBMB								
Observed	3.02	0.14	0.09	-3.62	0.15	0.08	-0.60	0.06
Detided	3.73	0.09	0.01	-4.35	0.10	0.00	-0.62	0.04
SAPDC								
Observed	4.89	0.23	0.13	-6.04	0.25	0.11	-1.16	0.09
Detided	4.85	0.08	0.00	-6.04	0.10	0.00	-1.19	0.05

[a]Pg: gross production, Rt: respiration, NEM: net ecosystem metabolism

Multimedia

{multi}

The supporting information for this manuscript includes a graphical illustration of the weighting scheme described in the material and procedures section (http://spark.rstudio.com/beckmw/weights_widget), results for each simulation (http://spark.rstudio.com/beckmw/detiding_sims), and results for each case study (http://spark.rstudio.com/beckmw/detiding_cases). Each link is a graphical summary of data based on interactive inputs to support the results in the manuscript.