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Intercomparison of the Charnock and CORE bulk wind stress formulations for coastal ocean modelling

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Abstract

The accurate parameterisation of momentum and heat transfer across the air-sea interface is vital for realistic simulation of the atmosphere-ocean system. In many modelling applications accurate representation of the wind stress is required to numerically reproduce surge, coastal ocean circulation, surface waves, turbulence and mixing. Different formulations can be implemented and impact the accuracy of: the instantaneous and long-term residual circulation; the surface mixed layer; and the generation of wave-surge conditions. This, in turn, affects predictions of storm impact, sediment pathways, and coastal resilience to climate change. The specific numerical formulation needs careful selection to ensure the accuracy of the simulation. Two wind stress formulae widely used in respectively the ocean circulation and the storm surge communities are studied with focus on an application to the NW region of the UK. Model-observation validation is performed at two nearshore and one estuarine ADCP stations in Liverpool Bay, a hypertidal region of freshwater influence with vast intertidal areas. The period of study covers both calm and extreme conditions to fully test the robustness of the 10 m wind stress component of the Common Ocean Reference Experiment (CORE) bulk formulae and the Charnock relation. In this coastal application a realistic barotropic-baroclinic simulation of the circulation and surge elevation is setup, demonstrating greater accuracy occurs when using the Charnock relation for surface wind stress.

1 Introduction

For realistic simulation of the atmosphere-ocean system an accurate parameterisation of momentum and heat transfer across the air-sea interface is required. Coupled modelling systems are often used to include interactions across this boundary (e.g. Liu et al., 2011). In oceanographic applications the parameterisation of the surface roughness is very important. The presence of waves can influence the coastal circulation and also sea surface temperatures through modification of the surface turbulence and

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mixed layer depth (Moon, 2005). The presence of ocean surface waves also modifies the wind profile itself (Large et al., 1995), requiring ocean-atmosphere model coupling to capture the feedback (Kukulka and Hara, 2008). Climate variability is also influenced by ocean-atmosphere interaction, model coupling is therefore essential to better understand the global climate and future change (Neelin et al., 1994). In barotropic storm surge models the wind stress is often represented by the Charnock (1955) relation, between the wind speed and the surface roughness. In coupled wave-circulation models this parameterisation is often replaced with a wave-related stress (Janssen, 1991) to properly account for the existence of the wave field (see Mastenbroek et al., 1992).

In non-coupled ocean models it is common to apply bulk formulae to atmospheric forcing fields to determine surface fluxes for baroclinic-barotropic circulation studies (e.g. Holt and Proctor, 2008). In the absence of ocean-atmosphere coupling the implementation of different formulations can impact the accuracy of: (i) the instantaneous and long-term residual circulation and (ii) the generation of coastal wave-surge conditions. This, in turn, affects predictions of storm impact, sediment pathways, and coastal resilience to climate change. To enable the best prediction of coastal circulation, we investigate two wind stress formulae widely used in the ocean circulation and the storm surge communities. We focus on an application to Liverpool Bay, which is in the NW region of the UK and a case study of specific interested for improving the understanding of sediment pathways around the UK. At this location both the Charnock (1955) relation and the CORE (Common Ocean Reference Experiment) bulk formulae (Fairall et al., 2003) have previously been used in separate studies of storm surge extremes (Brown and Wolf, 2009) and freshwater influence (O'Neill et al., 2012), but not compared.

Model comparisons against ADCP (Acoustic Doppler Current Profiler) data are employed at two nearshore and one estuarine location in Liverpool Bay, which is a hypertidal region of freshwater influence from 3 large estuary systems (Polton et al., 2011; Verspecht et al., 2009), and which is characterized by maximum tidal range O(10) m, maximum currents in excess of 1 $m\,s^{-1}$ and vast intertidal areas. The period of study (12 February–9 March 2008) coincides with a period of observations within the Dee

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Estuary (Bolaños and Souza, 2010), which are supplemented with nearshore measurements from the Irish Sea Observatory (ISO: http://cobs.noc.ac.uk/, Howarth and Palmer, 2011). Both calm and stormy conditions, including an extreme storm event (29 February 2008), occur during this period to fully test the robustness of:

1. The 10 m wind stress component of the CORE (Common Ocean Reference Experiment) bulk formulae used in operational barotropic-baroclinic deep ocean circulation modelling.

2. The Charnock relation used in operational barotropic surge modelling to capture increased surface roughness due to the presence of waves on the surface stress due to the 10 m wind components.

In this coastal application, a high-resolution (~ 180 m) Liverpool Bay model is nested within models of decreasing resolution. This enables the Liverpool Bay boundary forcing to include the tide-surge and baroclinic influence from the Northwest European Continental Shelf and more locally within the Irish Sea. The full CORE bulk formulae consist of methods to parameterise a set of atmospheric variables. These include: air temperature, relative humidity, cloud cover, atmospheric pressure and surface wind stress, to represent the transfer of heat and momentum fluxes across the atmosphere-ocean boundary in addition to the inverse barometer effect. This forcing along with riverine inputs allows a realistic barotropic-baroclinic simulation of the circulation within the study area. The full CORE bulk formulae are initially used to represent the complete atmospheric forcing. A second simulation then replaces the wind stress parameterisation within the CORE bulk formulae with that of the Charnock relation, using a Charnock constant of 0.0185 (consistent with the Irish Sea model setup as suggested Brown and Wolf, 2009, for fine resolution models).

In Sect. 2 the model setup is describe for Liverpool Bay along with the observed conditions during the period of study. Metrics to validate the model performance under different wind stress parameterisations are defined and used in Sect. 3 to present the

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results of the model accuracy. A short discussion of the results and concluding remarks are made in Sect. 4.

2 Model setup and observations

This study focuses on accurately simulating the coastal circulation, currents and surge elevation, within a hypertidal region or freshwater influence (Polton et al., 2011). We apply the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS, Holt and James, 2001) to simulate the coastal circulation within Liverpool Bay. POLCOMS is coupled to the General Ocean Turbulence model (GOTM, Holt and Umlauf, 2008) and we use the k-ε scheme with the stability functions derived from Canuto et al. (2001). The Liverpool Bay computational domain has a horizontal resolution of ~ 180 m with 10 vertical sigma-levels within the water column and is nested, in one-way, within a 1.8 km Irish Sea model (Fig. 1).

Both model domains are forced by ~ 12 km hindcast atmospheric data from the UK Met Office numerical weather prediction model, the wind speed and air pressure is provided hourly, while the air temperature, specific humidity and cloud cover are provided 3 hourly. External conditions to the Irish Sea are provided hourly for the barotropic fields and daily for the baroclinic fields from the hindcast outputs of the pre-operational ~ 12 km Atlantic Margin POLCOMS simulation, run at the NOC, Liverpool. Open boundary conditions for this model are provided by the Met Office Forecasting Ocean Assimilation Model (FOAM) system of the North Atlantic (Bell et al., 2000). Daily mean river flow are obtained from the UK river archive (maintained by the Centre for Ecology and Hydrology) of the Environment Agency gauging stations for the river systems in Liverpool Bay (Alyn, Bollin, Clwyd, Conwy, Dane, Dee, Douglas, Irwell, Lostock, Mersey, Ribble, Sankey Brook, Sinderland Brook, Weaver) and also provide the coastal freshwater source for the Irish Sea.

The Irish Sea model is run using the Charnock relation for wind stress, with a 0.0185 constant value and CORE bulk formulae to parameterise the other atmospheric drivers.

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This model provides hourly elevation and depth-averaged velocity components along with daily mean (25 h) depth-varying velocity, salinity and temperature components to force the boundaries of both local Liverpool Bay model experiments. The first experiment uses the full CORE bulk formulae and the second experiment replaces the wind stress parameterisation in the CORE bulk formulae with that of the Charnock relation.

Observations of the vertical velocity component profiles are available for this study period from three Acoustic Doppler Current profilers (ADCP) the locations of which are indicated in Fig. 1. Sites A and B are fixed nearshore moorings that were part of the Irish Sea Observatory (ISO, Howarth and Palmer, 2011), making measurements between 2002 and 2012. The Hilbre site was part of a series of Dee Estuary observational cruises (Bolaños and Souza, 2010) and was positioned in the Hilbre Channel, close to the estuary mouth, during the period 12 February–9 March 2008, which defines the period of this study. The velocity at the nearest ADCP bin to the surface (10 % of the depth below the surface) is used to validate the wind stress parameterisation within the model, the near surface being where the wind influence is the greatest. To do this the model data is extracted at a depth of 10 % below the surface (i.e., the −0.1 sigma-level). The surge elevation is obtained by applying harmonic tidal analysis to pressure sensor records and to the modelled total elevations at the same locations. The tidal analysis is performed using t-tide (Pawlowicz et al., 2002) with all the available shallow water constituents considered. The limited period (2 months of data) is likely to cause slight discrepancy between the analysed surge and that from the long-term tide gauge data (problems extracting the surge elevation are discussed further by Brown et al., 2012).

Wind observations are available from the ISO at Hilbre Island in the mouth of the Dee, a few hundred meters from the Hilbre Channel ADCP deployment, and show that the 10 m winds were initially SE and rarely in excess of 10 $\mathrm{m\,s^{-1}}$ (up to 21 February), before veering SW and reaching speeds up to 20 $\mathrm{m\,s^{-1}}$. On the 29 February, strong (< 23.6 $\mathrm{m\,s^{-1}}$) SSW winds veering W occurred over a 90 h period; such conditions are associated with extreme surge and wave generation in Liverpool Bay (Brown et al., 2011). The initial period is therefore considered calm and the later stormy. Waves within the estuary were below 0.61 m during the calm period, reaching 2.23 m during stormy period. Offshore, the WaveNet wave rider buoy, close to Site A recorded wave heights reaching 0.63 m and 4.83 m during these respective periods (available from the CEFAS WaveNet site, http://www.cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/wavenet.aspx). The maximum surge of 1.32 m occurred on the 29 February 22:24, recorded by the Liverpool Gladstone Dock tide gauge (available from the British Oceanographic Data Centre, www.bodc.ac.uk).

2.1 Validation method

Intercomparison between the two numerical experiments requires a quantitative assessment in order to determine which modelling approach is best. To that end, we introduce a time-varying comparative accuracy metric which is based on the absolute error of each model experiment. This metric is used to show the time variation in the comparison of the wind stress parameterisation performance. Using standard error metrics (*RMS error* and *mean of the time-varying Bias*) applied to the full study period allows the overall accuracy of each model experiment to be determined. For each mooring location we determine the time-varying differential accuracy (DA) as the difference between the absolute errors of each numerical experiment:

$$\mathrm{DA}_i = |O_i - C_i| - |O_i - B_i|, \tag{1}$$

where O represent observations, C model results using the Charnock approach and B model results using the CORE bulk formulae at each time instance, i. The time interval is hourly and the parameters considered are surge elevation, current speed and current direction. Here, the model error for the CORE bulk formulae setup is subtracted from that of the Charnock relation setup: a negative differential accuracy indicates better performance from the Charnock approach and a positive value indicates better performance of the CORE bulk formulae.

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3 Results

3.1 Time-varying accuracy

The time-varying results of the differential accuracy metric (described above) are shown in Figs. 2–4 for each study site, along with the model wind forcing at that location. It is clearly seen in panel a (Figs. 2–4) that the Hilbre location is slightly sheltered from the wind and experiences lower speeds than the offshore sites. Across the domain the wind direction is fairly constant. In response to the atmospheric forcing, the surge (panel b), current speed (panel c) and current direction (panel d) all experience similar range in the variability of the differential accuracy at the three sites analysed. The closer the differential accuracy metric is to zero the smaller the difference in the model experiment accuracy. It is seen that when one of the model setups performs better (i.e. if the line is negative or positive at that time) in one property, or at one location, it can still perform poorly (take the opposite sign) for another. At Site B the models perform with similar accuracy (small differential accuracy metric values) for surge. At all locations this property has the smoothest time-varying differential accuracy metric, showing the model experiments have a more consistent discrepancy in their accuracy for this property. The frequency of variability in the surge differential accuracy metric is greatest at the Hilbre location, suggesting very changeable agreement levels between the two experiments. The underlying trend at Hilbre is similar to that of Site A. This is most likely associated with the complexity of the surge elevation within the estuary system being generated locally while also being forced at the mouth by external (Site A) conditions (see Brown et al., 2012). For current speed and direction the time variation in the differential accuracy metric is much greater than for surge, due to the complex density-driven vertical structure in Liverpool Bay (Polton et al., 2011) and the Dee Estuary (Bolaños et al., 2013). The current speed and direction again show the wind stress parameterisations to be in closer agreement at Site B. This is due to the shallower depth and complex dynamics of Site A compared with Site B causing less accuracy in model simulation at this location. The current speed shows

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most disagreement in model accuracy at Hilbre and the current direction shows most disagreement at Site A. For current direction, differences in the model accuracy often occurs close to slack water, which is expected as the weak currents are changing direction and this is when models become least accurate. No correlation between the wind direction and the better performing wind stress parameterisation is identified for any of the properties studied.

3.2 Overall accuracy

By calculating standard error metrics (*RMS error* and *mean of the time-varying Bias*) the overall accuracy of the Charnock (Table 1) and Core bulk (Table 2) wind stress formulae can be identified for the study period. For both metrics a lower value indicates better performance, zero being perfect model agreement with observation. All parameters, with the exception of the current speed at Hilbre modelled using the Charnock approach, show a positive *mean Bias* indicating model over-prediction.

For the Charnock relation (Table 1) the current properties are always more accurately simulated at Site B, then Site A, and finally Hilbre. The metrics are more variable for surge. For the CORE Bulk formulae (Table 2) the same patterns in accuracy are seen, accept for the *mean Bias* in current speed. In most cases the current speed is the most accurately simulated property, followed by surge elevation, then current direction. The low values in all error metrics suggest either method is valid. However, in all cases the error over the time period is greater for the CORE bulk formulae than for the Charnock relation, suggesting in coastal fetch limited conditions the Charnock relation is the more accurate method for parameterising wind stress.

4 Discussion with concluding statements

Three locations within Liverpool Bay have been used to test the accuracy within a coastal model of two wind stress parameterisations: the CORE bulk formulae and

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the Charnock relation, with regionally tuned constant value for surge. The locations represent nearshore and estuarine environments. Under these fetch limited conditions error analysis confirms both methods of wind stress parameterisations give valid results compared with ADCP and pressure sensor observations. A differential accuracy metric is applied to identify which method performs with highest accuracy in coastal seas. Over the duration of the study period either formula can perform more accurately at an instance, but on average over the longer term the Charnock relation performs with higher accuracy. The Charnock relation has a constant which is tuned for coastal application, while the CORE bulk formulae were developed for open ocean conditions. In Liverpool Bay the largest fetches are from west to northwest directions, but are still more limited than open ocean conditions. No correlation between the wind direction (fetch) and which model performs more accurately has been found. The Charnock constant has been set here to a value that gives good surge simulation across the eastern Irish Sea region. The value of this parameter is thought to be related to the model grid resolution (0.0275 for ~ 12 km grid and 0.0185 for ~ 1.8 km grid, Brown and Wolf, 2009). Adjustment to the value (0.0185) used here in the 180 m Liverpool Bay model has very little influence, as the model fetches are short and the model boundary conditions determine the majority of surge accuracy. For clarification, this constant has only been tuned for surge elevation and not circulation so this study also validates the accuracy of the Charnock relation on wind-driven circulation. The same boundary conditions (Charnock parameter 0.0185) have been used for each local model setup in this case to test the two parameterisations at the local coastal scale.

In conclusion, it is found that the Charnock relation performs favourably for both surge and near surface velocity (current speed and direction) over the longer term. Although both model experiments give valid results, it is advised that the Charnock wind stress relation in conjunction with the CORE bulk formulae for heat fluxes will give the highest accuracy over a period of study in coastal applications.

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Table 1. The validation metrics (RMS error and the mean Bias) showing the overall accuracy of the Charnock relation at the three study sites.

Parameter	Error metric	Site A	Site B	Hilbre
Surge elevation, m	RMS	0.1608	0.1650	0.1915
	Bias	0.0334	0.0517	0.0137
Current speed, $m\,s^{-1}$	RMS	0.0991	0.0712	0.2100
	Bias	0.0073	0.0012	−0.0089
Current direction, degrees	RMS	0.4986	0.4665	0.7000
	Bias	0.2793	0.1988	0.3728

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Table 2. The validation metrics (RMS error and the mean Bias) showing the overall accuracy of the CORE bulk wind stress formula at the three study sites.

Parameter	Error metric	Site A	Site B	Hilbre
Surge elevation, m	RMS	0.1774	0.1823	0.2034
	Bias	0.0639	0.0781	0.0406
Current speed, $\mathrm{m\,s^{-1}}$	RMS	0.1220	0.1088	0.2301
	Bias	0.0253	0.0123	0.0222
Current direction, degrees	RMS	0.6825	0.5762	0.7867
	Bias	0.4575	0.2734	0.4229

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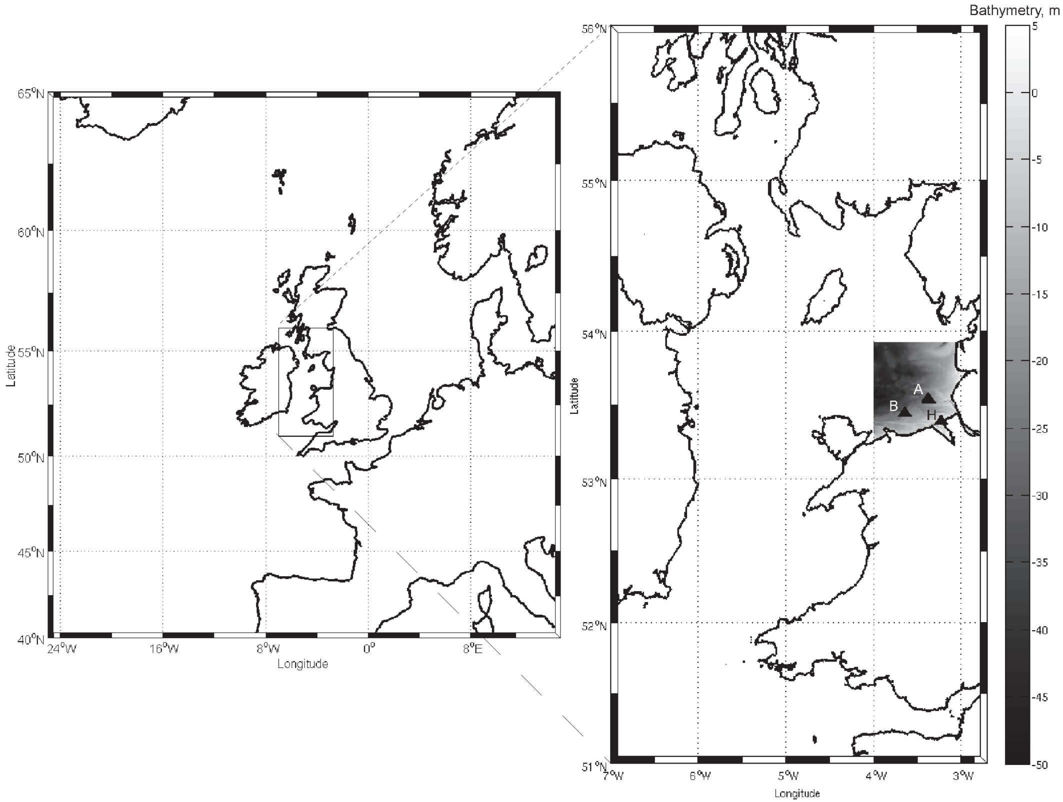

Fig. 1. The Atlantic Margin model domain (left) and the nested Irish Sea model domain (right), with the Liverpool Bay model bathymetry (in m below the mean tidal level) inserted as a map showing the locations of the moorings marked as triangles: Site A (A), Site B (B) and Hilbre (H).

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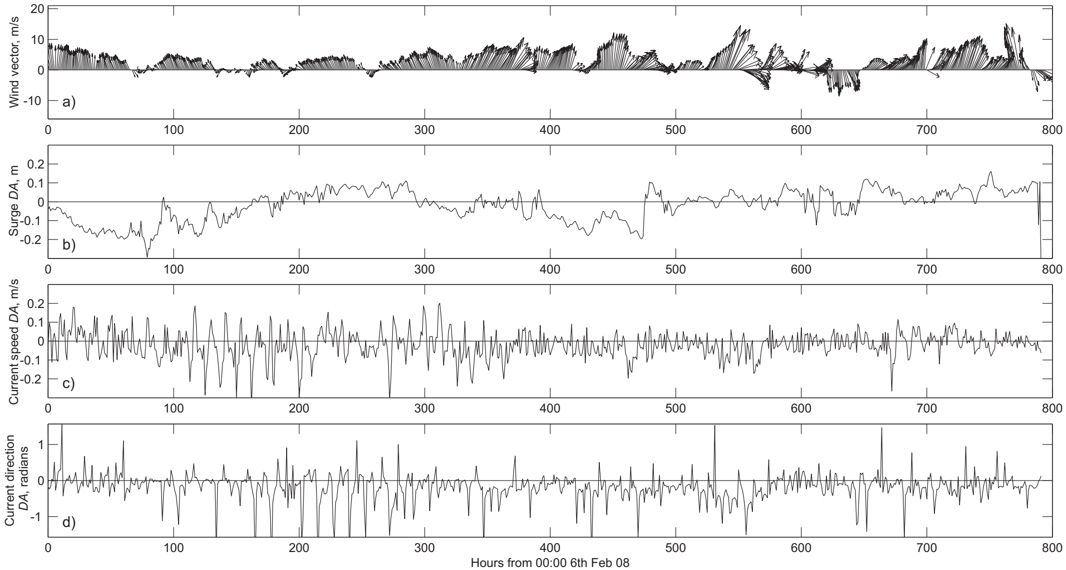

Fig. 2. Time-varying accuracy at Site A. **(a)** Wind vectors at this location and differential accuracy metric (DA) for **(b)** the surge, **(c)** the current speed and **(d)** the current direction. Negative values indicate the Charnock relation is performing with higher accuracy at this site than the CORE bulk wind stress formula and vice versa for positive values.

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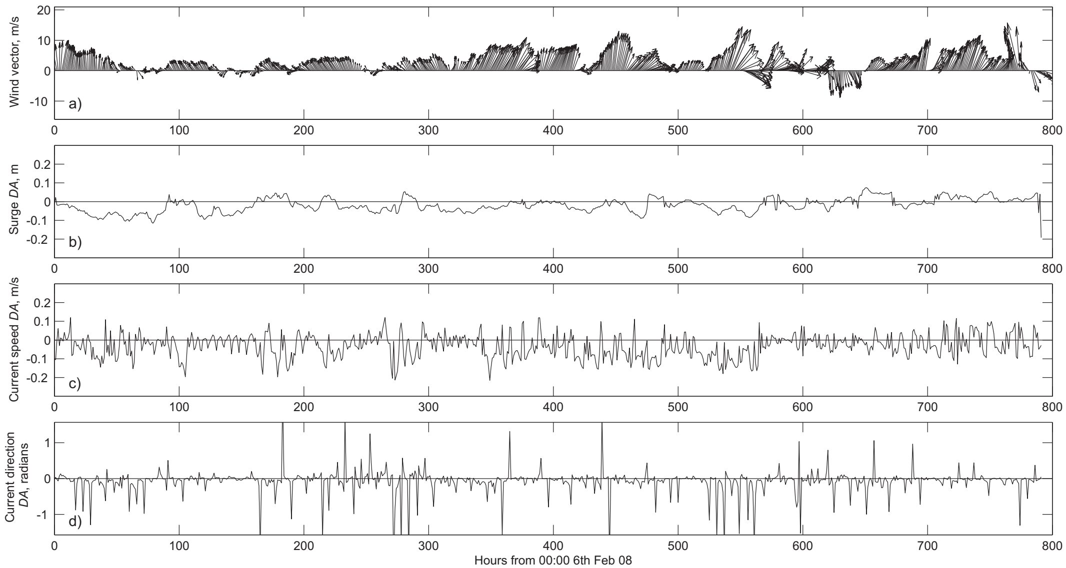

Fig. 3. Time-varying accuracy at Site B. **(a)** Wind vectors at this location and differential accuracy metric (DA) for **(b)** the surge, **(c)** the current speed and **(d)** the current direction. Negative values indicate the Charnock relation is performing with higher accuracy at this site than the CORE bulk wind stress formula and vice versa for positive values.

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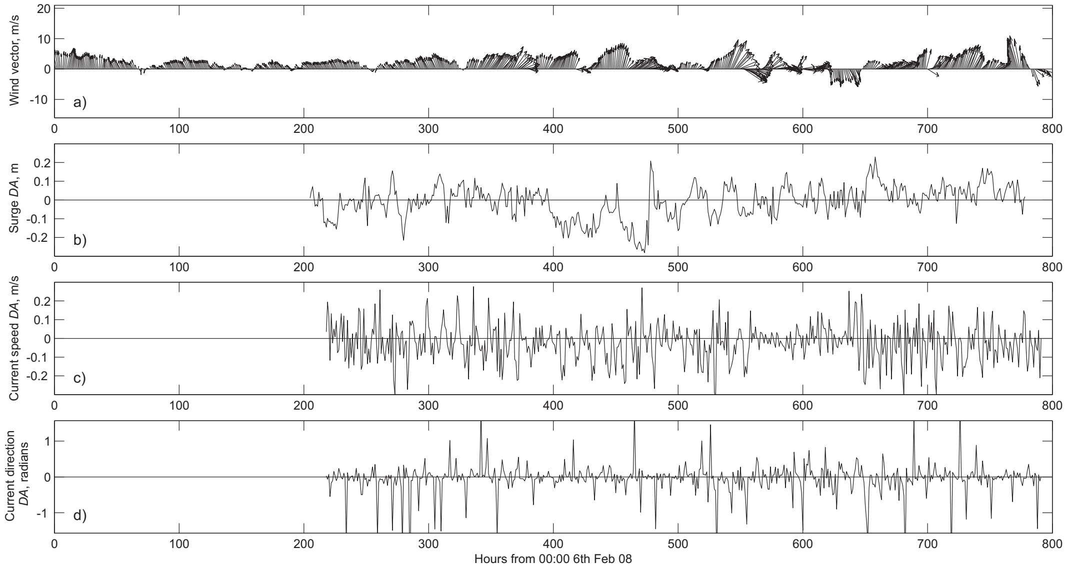

Fig. 4. Time-varying accuracy at the mooring location in the Hilbre Channel. **(a)** Wind vectors at this location and differential accuracy metric (DA) for **(b)** the surge, **(c)** the current speed and **(d)** the current direction. Negative values indicate the Charnock relation is performing with higher accuracy at this site than the CORE bulk wind stress formula and vice versa for positive values.