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Observations of Time Dependent Bedform Transformation in Combined Wave-Current Flows

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Key Points:

- Bedform building is a time dependent process, especially important in combined wave current flows.
- The sediment continuity equation or Exner equation can be used to estimate bedform volume change.
- Contribution of unique dataset of combined waves and current influence on bottom roughness.

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Abstract

Although combined wave-current flows in the nearshore coastal zone are common, there are few observations of bedform response and inherent geometric scaling in combined flows. Our effort presents observations of bedform dynamics that were strongly influenced by waves, currents, and combined wave-current flow at two sampling locations separated by 60 m in the cross shore. Observations were collected in 2014 at the Sand Engine mega-nourishment on the Delfland coast of The Netherlands. The bedforms had wavelengths ranging from 14 cm to over 2 m and transformed shape and orientation within, at times, as little as 20 minutes and up to 6 hours. The dynamic set of observations was used to evaluate a fully unsteady description of changes in the bedform growth with the sediment transport continuity equation (Exner equation), relating changes in bedform volume to bedload sediment transport. Analysis shows that bedform volume was a function of the integrated transport rate over the bedform development time period. The bedform development time period (time lag of bedform growth/adjustment) is important for estimating changes in bedform volume. Results show that this continuity principle held for wave, current, and combined wave-current generated bedforms.

1 Introduction

Time varying wave, current, and combined wave-current flows are characteristic of most nearshore regions (e.g. *Grant and Madsen* [1979]; *Passchier and Kleinhans* [2005]; *Soulsby and Clarke* [2005]). These complex hydrodynamic environments are complicated with small scale bed roughness (e.g. sand ripples and megaripples) that have a two way feedback with the local hydrodynamics, apparent within nearshore modeling [*Wikramanayake and Madsen*, 1994; *Lesser et al.*, 2004; *Ganju and Sherwood*, 2010]. Previous research demonstrates that characteristic bedform roughness lengths (bedform wavelength and height) scale with the hydrodynamic forcing applied to the seabed under waves or currents (e.g. *Fredsøe* [1984]; *Clifton and Dingler* [1984]; *Wiberg and Harris* [1994]; *Traykovski et al.* [1999]; *Hay and Mudge* [2005]). However, there have been very few studies of bedform scaling and orientation in response to dynamically changing forcing that includes combined wave-current flows [*Li and Amos*, 1998; *Hay and Mudge*, 2005; *Lacy et al.*, 2007; *Soulsby et al.*, 2012; *Nelson and Voulgaris*, 2015].

For combined wave-current flows, most of the literature addresses the transition of bedforms between flow states with observations of relatively small bedforms with wavelengths of less than 0.5 m under relatively low energy wave conditions or with waves plus weak mean flow (e.g. *Grant and Madsen* [1979]; *Li and Amos* [1998]; *Soulsby and Clarke* [2005]; *Lacy et al.* [2007]; *Soulsby et al.* [2012]). Results of these efforts show that combined flow bedforms are less steep than wave dominant bedforms, and generally orient in a pattern influenced by the maximum gross bedform normal transport direction [*Gallagher et al.*, 1998; *Lacy et al.*, 2007]. There are a limited number efforts that observe larger scale bedforms, like megaripples, in wave dominant or combined flows (*Gallagher et al.* [1998]; *Gallagher* [2003]; *Larsen et al.* [2015]), but these efforts do not address characteristics of bedform response to transition periods.

Observations of bedforms under wave dominant or current dominant flows suggests that bedform building is a time dependent process (e.g. *Davis et al.* [2004]; *Testik et al.* [2005]; *Doucette and O'Donoghue* [2006]; *Austin et al.* [2007]; *Traykovski* [2007]; *Soulsby et al.* [2012]; *Nelson and Voulgaris* [2015]). The bedform shape and volume is dependent on present hydrodynamic conditions, as well as past forcing. Time-dependent bedform models that estimate roughness length scales use a departure from equilibrium approach (e.g. *Traykovski* [2007]; *Soulsby et al.* [2012]) that assumes bedform length scales are being driven toward equilibrium with the present hydrodynamic conditions. The assumption is generally valid for waves [*Davis et al.*, 2004; *Testik et al.*, 2005; *Doucette and O'Donoghue*, 2006; *Traykovski*, 2007]; however, present equilibrium theory may not capture the physics of bedform adjustment in combined wave-current flows because the time constants associated with current models may not be appropriate to represent dynamics in combined flows [*Austin et al.*, 2007].

In our effort, we present observations of ripple and megaripple formation in response to high energy combined flows with, at times, the addition of a strong current. Forcing conditions ranged from wave dominant flow, to combined wave-current flow, to mean current flow. Bedform transition periods and growth cycles were observed in response to the variable flow conditions. Additionally, the results demonstrate that the sediment continuity equation, or Exner equation, captures bedform building as a time dependent process, suggesting that the sediment continuity equation may be used to model dynamic roughness in the nearshore, especially relevant when considering combined wave-current flows.

2 Methods

2.1 Experiment and Instrumentation

Data were collected during a field campaign at the Sand Engine mega-nourishment as a part of the MEGA-Perturbation EXperiment (MEGAPEX) in the fall of 2014 on the Delfland Coast of the Netherlands [*Radermacher et al.*, 2017]. Since the installment of the 21.5 million cubic meters of sand in 2011, the Sand Engine has dramatically changed shape [*Stive et al.*, 2013]; in 2011 it stretched 2 km in the alongshore and 1 km into the North Sea, and in 2014 it stretched 4 km alongshore and 800 m in the cross shore [*Radermacher et al.*, 2017]. The large scale morphology is considered very dynamic with observable bathymetric changes over periods of days to months. Our effort investigates the dynamic nature of the small scale morphology at the seaward tip of the Sand Engine.

Local small scale morphology and hydrodynamics were observed between the shoreline and the shore-parallel sandbar that were 136 m apart at two cross shore stations, S1 and S2, at the tip of the Sand Engine (Figure 1a). S1 was located 20 m seaward of the low tide shoreline and S2 was located 66 m further offshore and 50 m shoreward of the subtidal sandbar. Morphology was sampled at each location with a stationary sweeping and rotating 1 MHz Imagenex 881a pencil beam sonar with a 3 m diameter footprint. S1 was sampled every 20 minutes with a 1.4° sweep step and a 2.4° rotation step from 26 Sept. to 23 Oct. 2014 (day of year 269-296), and S2 was sampled every 2 hours with a 1.4° sweep step and a 1.4° rotation step from 2 Oct. to 18 Oct. (day of year 275 to 291). Hydrodynamic forcing was measured at S1 using a downward looking high resolution acoustic Doppler current profiler (ADCP) positioned 0.4 m above the seabed and burst sampled for 20 minutes every hour at 4 Hz, and at S2 using an acoustic Doppler velocimeter (ADV) positioned 1 m above the seabed and burst sampled for 20 minutes every hour at 64 Hz (Figure 1b). The mean lower low water depth at S1 was -1.0 m NAP (Normaal Amsterdam Peil, approximately mean sea level) and at S2 was -1.7 m NAP and the median sediment grain size of the quartz sediment at both sites was 350 μm. The tidal range was approximately 1.5 m. Large scale bathymetry was measured with an echo sounder during regular jet ski surveys. The large scale coordinate system used throughout this paper is with respect to degrees from shore-normal, with 0° being onshore (-x), +90° rotating counterclockwise from shore normal, and -90° rotating clockwise from shore normal.

2.2 Hydrodynamics

The local flow at each monitoring station was decomposed into current velocities, with magnitude U and direction ϕ_c, and wave orbital velocities, with magnitude u_o and direction ϕ_w, over 10 minute averaged time intervals. The current velocity is defined by the resultant of the temporal mean of the horizontal (u, v) velocities with ,

$$U = |\overline{u}|, \tag{1}$$

and the overbar represents a tempral average over 10 minutes. The magnitude of the orbital velocity assumes a siusoidal velocity with,

$$u_o = \sqrt{2} u_{std}, \tag{2}$$

where $u_{std} = \overline{[(u - U)^2]^{0.5}}$ [*Traykovski et al.*, 1999]. The wave period is defined with,

$$T = \frac{2\pi}{S_{m_2}/S_{m_1}}, \tag{3}$$

where S is the spectra of the pressure signal, and the subscripts m_1 and m_2 refer to the first (mean) and second (variance) moments of the spectra [*Madsen et al.*, 1988]. The wave orbital diameter was defined with

$$d_o = 2\frac{u_o}{2\pi/T}. \tag{4}$$

The combined wave current velocity [*Lacy et al.*, 2007] relates the wave orbital and current velocities with a third term representing the combined effect depending on the angle between the orbital and current velocities, where

$$u_{wc} = [u_o^2 + U^2 + 2u_o U \cos|\phi_w - \phi_c|]^{0.5}. \tag{5}$$

Finally, the maximum kinetic energy in the combined wave-current flows is defined as

$$E_{k_{wc}} = \frac{1}{2}u_{wc}^2. \tag{6}$$

In our observations we distinguish between wave dominant, current dominant and combined flow conditions using a fraction-of-energy approach to assess the contribution of waves and/or currents to sediment flux. $E_{k_{wc}}$ is defined as the maximum kinetic energy in the flow field including both waves and currents. $E_{k_w}/E_{k_{wc}}$ is defined as the fraction of kinetic energy due to waves. A value of 1 would be purely wave driven flow, and a value of 0 would be purely current driven flow. Previous literature has distinguished wave dominant flows from combined flows based on a ratio of wave induced to current induced friction velocity, where purely wave ripples occur at a friction velocity ratio of 0.5 or greater [*Li and Amos*, 1998; *Lacy et al.*, 2007]. The estimate of friction velocity can vary based upon the method used to estimate the bed shear stress, where $u_* = (\tau_b/\rho)^{1/2}$. Due to the wide variability in friction velocity estimates, friction velocity was not used to evaluate the relative strength of the waves and currents. The ratio of wave and current dominant flow is highly dependent upon the method(s) chosen for the estimates of the wave and current friction velocity. Rather, we choose to express the relative strength of waves and currents as a function of the total kinetic energy. To put this limit from [*Lacy et al.*, 2007] in terms of energy, the threshold of 0.5 is squared. Therefore we define, $E_{k_w}/E_{k_{wc}}$ >0.75 to be wave dominant, 0.75≥ $E_{k_w}/E_{k_{wc}}$ ≥0.25 for combined wave-current flow, and 0.25> $E_{k_w}/E_{k_{wc}}$ to be current dominant. An energy approach is used instead of the friction velocity due to the high uncertainties associated with estimating the friction velocity in combined flow conditions (particularly when the bedform field is highly dynamic). The kinetic energy was either measured or calculated using linear wave theory for the wave contribution and a log layer approximation for the mean flow contribution. Calculated values were attenuated through the water column to approximately 10 cm above the crest of the bedforms.

2.3 Measured Bedform Statistics

Statistics of bedform wavelength (λ), bedform height (η), and bedform orientation (ϕ_r) are determined through analysis of sonar return data. Bottom position within each sonar dataset was found by identifying the high intensity return region for each sonar ping using two methods. The first is a weighted mean sum (WMS) method and the second is a bearing direction indicator (BDI) method [*SeaBeam*, 2000]. WMS applies a weighted mean sum to each sonar ping, where the location of the highest WMS for each beam is the location of the bed. The WMS method works well for return data with high grazing angles (data within 30° of the sonar nadir). The BDI applies a parabolic fit to the high intensity return for all the beams intersecting the same section of bed within one sweep over multiple pings. The BDI method is suited to intensity returns at low grazing angles since the multiple ping fit gives higher confidence in bed location. WMS was used to detect the bed within the inner 1 m diameter at bed level and BDI was used to detect the bed from the 1 m diameter range to the sonar sampling extent at bed level (see *Wengrove et al.* [2017] for more detail).

With a time series of 2D local bathymetries (Figures 2f-h and 3f-h), the dominant ripple wavelengths, heights, and orientations were determined with normalized 2D spatial wavenumber spectral analysis [*Maier and Hay*, 2009; *Becker et al.*, 2007]. The 2D spatial spectra, S (m^3), have axes of wavenumber, k_x (cross shore) and k_y (alongshore) (1/m). The spectra were normalized by premultiplying S by the wavenumber k_x and k_y, where $\hat{S} = S k_x k_y$ [*Alamo and Jimenez*, 2003]. The benefit of a normalized spectra is that the multiplication by wavenumber emphasizes higher wavenumbers and enhances the energy peaks of interest for analysis. The energy distribution in the spectra indicate the dominant bedform wave number and orientation. The bedform wavelength is defined as the bedform-normal distance from crest to crest, and the bedform height is defined as the vertical distance between bedform trough and crest. Estimates of bedform height are found by integrating the spectrum, analogous to a significant ocean wave height calculation from temporal spectral analysis [*Traykovski*, 2007; *Penko et al.*, 2017] (see [*Wengrove et al.*, 2017] for more detail).

The uncertainties associated with the spatial resolution of the pencil beam sonar measurements were related to range resolution, beam width, and sweep and rotation step angles. During the course of the experiment the water temperature stayed relatively constant with time, and a sound speed of 1502 m/s was used to convert sonar time returns into range estimates. The range resolution of the pencil beam is 2 mm for a sampling range of 1 m to 4 m. The conical beam width operating at 1 MHz is 1.4°, so 1 m away from the transducer (within 30° of the sonar nadir) the resolution limit is 2.5 cm, while at the profiling extent or approximately 2 m way from the transducer, the resolution limit becomes 5.0 cm. Finally, with respect to spatial sampling step angle, for S1, directly under the sonar the spatial resolution was 2 cm x 4 cm and at the radial edge of the swath the spatial resolution was 5 cm x 8 cm. For S2, directly under the sonar the spatial resolution was 2 cm x 2 cm and at the profiling extent the spatial resolution was 5 cm x 5 cm. With these limitations, the smallest bedform wavelength that could be resolved within the inner 30° of the sonar nadir was approximately 12 cm, and at the profiling extent was approximately 25 cm. Bedform height could be resolved within 2 cm.

Uncertainties associated with the temporal resolution of the bedform migration involve the timescale for the sonar sensor rotations. Bedload sediment transport processes with a time scale less than a full sweep-rotation time window were not resolved; for S1 this was 10 minutes and for S2 this was 15 minutes. Additionally, processes that occurred with a time scale of less than the time between subsequent sonar scans, dt, were not resolved; dt was 20 minutes for S1 and 2 hours for S2. However, the low noise floor of the spectra of the time series of observed bedform wavelengths over the month long deployment at S1 showed that there were no sign of aliasing with a dt of 20 minutes for estimating migration rates (not shown), so a dt of 15 minutes to estimate migration rates at S2 is considered sufficient as well.

2.4 Sediment Continuity Equation

Assuming a sinusoidal function for transport,

$$\mathbf{q_b} = q_b \cos\left[\frac{2\pi}{\lambda}\left(V_{mig.}t - x_b - \delta_{x_b}\right)\right], \tag{7}$$

where $\mathbf{q_b}$ is the bedload sediment flux [m^3/m/s], q_b is the scalar transport, $V_{mig.}$ is the migration rate, t is time, λ is the wave length, δ_{x_b} is the phase offset between the bedform shape and the function for transport, x_b is the position along the bedform wavelength, and t is time. Using $\cos(\alpha - \beta) = \cos(\alpha)\cos(\beta) + \sin(\alpha)\sin(\beta)$,

$$q_b = q_1 \cos\left[\frac{2\pi}{\lambda}\left(V_{mig.}t - x_b\right)\right] + q_2 \sin\left[\frac{2\pi}{\lambda}\left(V_{mig.}t - x_b\right)\right], \tag{8}$$

$$q_1 = q_b \cos\left(\frac{2\pi}{\lambda}\delta_{x_b}\right), q_2 = q_b \sin\left(\frac{2\pi}{\lambda}\delta_{x_b}\right), \tag{9}$$

and $q_2/q_1 = \tan(\frac{2\pi}{\lambda}\delta_{x_b})$.

We assume the bed level, z_b, as

$$z_b(x,t) = \eta \cos\left[\frac{2\pi}{\lambda}\left(V_{mig.}t - x_b\right)\right]. \tag{10}$$

where η is the amplitude of the bedform. The bedform height, wavelength, and migration rate are allowed to be fully unsteady.

The sediment continuity equation, or the Exner equation, relates the sediment flux gradient per unit width to the rate of bed level change [*Nielsen*, 1992], and is commonly expressed with

$$\frac{\partial q_b}{\partial x} \equiv -n\frac{\partial z_b}{\partial t}. \tag{11}$$

where n is the sediment packing (~ 0.7 for sand). For the case of bedform migration or transformation with no local accretion or erosion, the bed elevation, z_b, can be expressed by the local bedform geometry ($z_b = \eta$). By taking the spatial derivative of the expression for q_b and the temporal derivative of the expression for z_b, and assuming that η, λ, and $V_{mig.}$ are a function of t, but q_1 and q_2 are not a function of x, then,

$$\frac{\partial q_b}{\partial x} = q_1\frac{2\pi}{\lambda}\sin\left[\frac{2\pi}{\lambda}\left(V_{mig.}t - x_b\right)\right] - q_2\frac{2\pi}{\lambda}\cos\left[\frac{2\pi}{\lambda}\left(V_{mig.}t - x_b\right)\right] \tag{12}$$

and

$$\frac{\partial z_b}{\partial t} = \frac{\partial \eta}{\partial t}\cos\left[\frac{2\pi}{\lambda}\left(V_{mig.}t - x\right)\right] - \eta\left[2\pi\left(\frac{t}{\lambda}\frac{\partial V_{mig.}}{\partial t} + V_{mig.}t\frac{\partial}{\partial t}\frac{1}{\lambda} + \frac{V_{mig.}}{\lambda} - x_b\frac{\partial}{\partial t}\frac{1}{\lambda}\right)\right]\sin\left[\frac{2\pi}{\lambda}\left(V_{mig.}t - x\right)\right]. \tag{13}$$

Now, using (12) and (13) in (11) and the definition if $ax + by = mx + ny$ then $a = m$ and $b = n$, shows that

$$n\eta\left[2\pi\left(\frac{t}{\lambda}\frac{\partial V_{mig.}}{\partial t} + V_{mig.}t\frac{\partial}{\partial t}\frac{1}{\lambda} + \frac{V_{mig.}}{\lambda} - x_b\frac{\partial}{\partial t}\frac{1}{\lambda}\right)\right] = \frac{2\pi}{\lambda}q_1, \tag{14}$$

and

$$n\frac{\partial \eta}{\partial t} = \frac{2\pi}{\lambda}q_2 \tag{15}$$

where (14) represents the unsteady sediment flux from the migrating bedform, and (15) represents the unsteady sediment flux from a growing or decaying bedform. Expressions for the bedform migration and growth with a semi-steady assumption for the bedform λ and $V_{mig.}$ can be found in *Nielsen* [1992] and *Roelvink and Reniers* [2011]. Both (14) and (15) are theoretically equivalent, by substituting (9) into (14) and (15), and equating the result by means of q_b gives,

$$\frac{\partial \eta}{\partial t} = 2\pi\eta\left(\frac{t}{\lambda}\frac{\partial V_{mig.}}{\partial t} + V_{mig.}t\frac{\partial}{\partial t}\frac{1}{\lambda} + \frac{V_{mig.}}{\lambda} - x_b\frac{\partial}{\partial t}\frac{1}{\lambda}\right)\tan\left(\frac{2\pi}{\lambda}\delta_{x_b}\right). \tag{16}$$

An expression for δ_{x_b}/λ as a function of $\partial\eta/\partial t$ and $V_{mig.}$ follows,

$$\delta_{x_b}/\lambda = \frac{1}{2\pi}\tan^{-1}\left[\frac{\partial\eta}{\partial t}\Big/\left(2\pi\eta\left(\frac{t}{\lambda}\frac{\partial V_{mig.}}{\partial t} + V_{mig.}t\frac{\partial}{\partial t}\frac{1}{\lambda} + \frac{V_{mig.}}{\lambda} - x_b\frac{\partial}{\partial t}\frac{1}{\lambda}\right)\right)\right]. \quad (17)$$

The bedform volumetric change as a function of the sediment flux is found beginning with (15) and expanding the time rate of change in bedform height with the product rule,

$$\frac{n\lambda}{2\pi}\frac{\partial\eta}{\partial t} = \frac{n}{2\pi}\frac{\partial\eta\lambda}{\partial t} - \frac{n}{2\pi}\frac{\eta\partial\lambda}{\partial t}. \quad (18)$$

By substituting the expression for q_2 and integrating the manipulation from $t-\tau$ to τ, an expression for the bedform volumetric change is given as

$$\Delta\Lambda_b = \Delta\frac{n}{2}\eta\lambda = \int_{t-\tau}^{t}\pi q_b\sin(2\pi\delta_{x_b}/\lambda)dt + \int_{t-\tau}^{t}\frac{n}{2}\frac{\eta\partial\lambda}{\partial t}dt. \quad (19)$$

where $\Delta\frac{n}{2}\eta\lambda$ is the change in volume of the bedform, $\Delta\Lambda_b$, over some time since it started to grow or decay, $\tau - t$, to the present time, t. The first term on the right hand side is the portion of the time integrated sediment flux related to bedform growth or decay. The second term on the right hand side of (19) is related to the bedform stretching over time. The expression represents a fully unsteady derivation of bedform transformation and translation with respect to bedform height, wavelength, and migration.

2.5 Existing Time-Dependent Bedform Geometry Models

In laboratory settings *Davis et al.* [2004], *Smith and Sleath* [2005], *Testik et al.* [2005], and *Doucette and O'Donoghue* [2006] explored the time dependent nature of bedforms between equilibrium conditions, as well as the associated time scale for bedforms to reach an asymptotic equilibrium state with imposed wave forcing conditions. These studies give estimates for bedform temporal adjustment to equilibrium based on sediment transport rates, with each showing that it takes time for bedforms to evolve and grow between equilibrium states. In field settings, *Traykovski* [2007], *Soulsby et al.* [2012], and *Nelson and Voulgaris* [2015] also take a departure from equilibrium approach by relating a change in geometry over a period of time to a departure from equilibrium geometry model that imposes a parameterized time scale of change. Our effort further considers the wave-only spectral time dependent model of *Traykovski* [2007], and the wave or current dominant time dependent model of *Soulsby et al.* [2012]; each summarized in the following.

Bedform evolution can be characterized with a time varying spectrum of bedform geometries defined by [*Traykovski*, 2007],

$$\frac{d\eta_{T07}(k)}{dt} = \frac{\eta_{eq}(k) - \eta_{T07}(k)}{T_{adj}(k)}, \tag{20}$$

where k is the associated bedform wavenumber ($2\pi/\lambda$), η_{eq} is the equilibrium ripple spectra modeled by a Gaussian distribution with inputs of a proposed equilibrium ripple height and ripple wavelength, and $T_{adj}(k)$ is an adjustment timescale for each wavenumber based on the wavenumber dependent cross sectional area of the bedform and the total bedform sediment flux, q [*Meyer-Peter and Muller*, 1948]. A numerical integration scheme results in a time series of wavenumber dependent ripple heights, where modeled $\eta_{m_{T07}}$ is found by integrating with respect to wavenumber (analogous to a significant wave height calculation) as discussed previously, and modeled $\lambda_{m_{T07}}$ is defined by $2\pi/k$ of the peak spectral energy band for each time step. The model gives high skill predictions of ripple geometry in a predominantly wave environment, where the model skill is the correlation coefficient squared.

Soulsby et al. [2012] proposed a time-dependent bedform evolution model that uses a Shields parameter criterion to decide whether ripples are wave- or current- generated. A departure from equilibrium approach allows ripples to evolve based on an adjustment time scale. For a given bedform variable (either ripple wavelength or height) the model is defined by

$$\frac{dx_{SWM12}}{dt} = a(t) - b(t)x_{SWM12}(t), \tag{21}$$

where x_{SWM12} is either the modeled $\eta_{m_{SWM12}}$ or $\lambda_{m_{SWM12}}$, and are found through numerical integration. Additionally, $a(t) = x_{eq}\beta/T_r$ and $b(t) = \beta/T_r + bio/T_b$, where x_{eq} is an equilibrium length and β is a rate of change parameter based on waves or current dominant forcing. T_r is a rate of change characteristic time scale that is equal to the wave period for wave forcing conditions and the time taken for an equilibrium ripple to be changed by the total bedload transport rate for current forcing. bio and T_b are a free parameter and a time scale related to biological degradation of the bedforms, respectively. The model has been shown to have high skill in prediction of wave dominant flow or current dominant flow bedforms of less than 0.5 m in wavelength; however it does not predict megaripples and does not account for combined wave-current flows.

3 Results

3.1 Observations of Bedform Geometry

Time series of hydrodynamic and bedform geometry observations are shown in Figures 2 and 3 for S1 and S2, respectively. S1 was deployed for a spring-neap-spring-neap-spring tidal cycle, including 4 storm events (day of year 278, 280, 287, 294). S2 was deployed for a neap-spring-neap tidal cycle with 3 storm events (day of year 278, 280, 287). At both locations the currents were strongly tidally influenced with stronger currents during flood tide, as the tidal flow runs parallel to the Delfland coast. Additionally, wave orbital velocities were tidally modulated due to waves breaking on an shore-parallel sandbar during low water, and more shoreward during high water (see Figure 1).

Bedform geometry was observed to vary substantially at each station over the period of investigation with a clear dependence on the type of hydrodynamic forcing (Figures 2 and 3). The hydrodynamic kinetic energy shaded by the fraction of energy due to waves ($E_{k_w}/E_{k_{wc}}$) highlights occurrences of current dominated flows (low $E_{k_w}/E_{k_{wc}}$), and wave dominated flows (high $E_{k_w}/E_{k_{wc}}$). During non-storm conditions semidiurnal peaks in the energy were associated with the tide as evident with low $E_{k_w}/E_{k_{wc}}$. At S2 larger wavelength bedforms corresponded with instances of increased flow, and occurred generally under current or combined flow dominant kinetic energy. However, observations at S1 showed that relatively large wavelength bedforms ($\lambda > 1$ m) can correspond with instances of large kinetic energy that was either current dominated or high wave energy dominated conditions (i.e. storms). Additionally, bedform steepness was generally characteristic of wave orbital ripple steepness ($\eta/\lambda \approx 0.16$) during wave energy dominated conditions, and dune steepness ($\eta/\lambda \approx 0.06$) during current energy dominated conditions [*Wiberg and Harris*, 1994; *Fredsøe and Deigaard*, 1992]. Figure 4 shows a truncated time series from Figure 2 to highlight the growth of one bedform over time with corresponding sonar images to show bed change.

3.2 Bedform Characterization

The distribution of the relative frequency of occurrence during each deployment of λ, η, and η/λ (Figure 5a-c for each site S1 and S2) shows that smaller wavelength bedforms occurred more often, and generally bedforms were in the range of the steepness of wave orbital ripples ($\eta/\lambda \approx 0.16$). However, the histogram of λ also shows that at each site bedforms of wavelengths longer than 0.5 m occurred between 29-33% of the time, and bedforms with a steepness of less than that of wave orbital ripples occur approximately 29-35% of the time. The observed bedforms were predominantly 2D, but during transition periods, bedforms could become 3D; the degree of three dimensionality is shown through the observed spread of dominant bedform orientation, as indicated with a shaded grey band (Figure 4).

Ripples observed in wave dominated environments are often characterized as either orbital ripples, suborbital ripples, and anorbital ripples [*Clifton and Dingler*, 1984; *Wiberg and Harris*, 1994]. The wavelength of orbital ripples scales with the orbital excursion of the waves. Anorbital ripples have a wavelength independent of orbital excursion and are thought to scale with the grain size. Suborbital ripples are some combination of the two regimes [*Clifton and Dingler*, 1984; *Wiberg and Harris*, 1994]. The *Clifton and Dingler* [1984] classification diagram is shown in Figure 6a overlaid with observations from S1 and S2. The wave dominated bedforms, with large $E_{k_w}/E_{k_{wc}}$, generally were classified as orbital or slightly suborbital (falling on the dark grey bar in Figure 6a and are consistent with *Clifton and Dingler* [1984]). However, ripples with larger wavelengths correspond to periods with smaller $E_{k_w}/E_{k_{wc}}$ (Figure 6a blue shading) and fall in an unclassified region in *Clifton and Dingler* [1984]. The unclassified bedforms did not show evidence of being relic (Figure 6a). Considering such attributes, we consider the bedforms that fall into this unclassified region by *Clifton and Dingler* [1984] as either combined wave-current or current dominant bedforms and were formed by the onset of strong currents.

Figure 6b shows the distribution of observed bedform wavelength as a function of $E_{k_w}/E_{k_{wc}}$, u_o, and U for both S1 and S2 sites. S1 and S2 were influenced strongly by tidal currents particularly with the occurrence of large U at relatively small u_o, that is, when wave-driven alongshore currents were weak (see *Hay and Mudge* [2005] Figure 11 for a reference case with small tidal currents). Additionally, larger wavelength bedforms were shown to occur with large u_o and/or large U, indicating that bedforms may have been formed by waves, currents, and with combined wave-current forcing contributions, shown by the shading of $E_{k_w}/E_{k_{wc}}$.

3.3 Observations of Bedform Orientation

The bedforms at S1 and S2 were very dynamic. During transitional periods they were not aligned and instead were oriented over a range of directions between 5° and 90°. The bandwidth range was determined by the spacing between peaks in 2D spatial spectra and is indicated by a shaded grey band in Figure 7 and a shaded grey band on each 2D bathymetry plot (Figures 2-4). The bedforms generally did not align with the current or the wave direction, but rather a combination of both depending on flow dominance. The bedforms sometimes align with the wave direction when $E_{k_w}/E_{k_{wc}}$ was large, notably during low tide, and with the current direction when $E_{k_w}/E_{k_{wc}}$ was small (Figure 7b, c). However, the bedforms did not always align with the dominant flow direction (e.g. Figure 7b and c day of year 281.2).

Figure 8 shows the bedform orientation in relation to the current magnitude and direction, the wave orbital magnitude and direction, the bedform wavelength, and $E_{k_w}/E_{k_{wc}}$. The strongest correlation between the four metrics displayed is the bedform orientation in relation to the current magnitude (panel a). As bedforms became more current influenced (low $E_{k_w}/E_{k_{wc}}$) they not only increased in wavelength, but also tended to orient between 30° and 70°, approaching the direction of the prevailing flood tidal currents oriented toward the northeast (90° counterclockwise from shore-normal in Figure 1). However, the bedform orientation in relation to the orbital velocity magnitude did not show a clear trend (panel c), indicating that the magnitude of the waves did not have a large effect on bedform orientation.

When considering the bedform orientation in relation to the current and wave directions (Figure 8b, d), the bedforms generally did not align with either the current or wave direction. A root-mean-square-error range ($rmse_{range}$) analysis is used to determine how well the bedform orientation observations fit the wave and current directions. The metric is a modified $rmse$ calculation, where the difference between the measured and modeled orientations are set to zero if the wave or current direction falls anywhere within the bedform orientation bandwidth range, and the differences are calculated at the center of the range if the wave or current direction falls outside. Circular statistics were used to calculate the root-mean-square-error range. The bedform orientation root-mean-square-error range statistics (given in the caption of Figure 8) show that the bedform orientation was neither predominantly influenced by waves or currents. However, with respect to the root-mean-square-error range analysis, the bedforms were more closely aligned with the wave direction than the current direction. Overall, the generally large root-mean-square-error range values indicate that the bedform orientation was not a function of the independent wave and current directions alone, but rather a concurrent combination [*Gallagher et al.*, 1998; *Lacy et al.*, 2007].

4 Discussion

4.1 Time-evolving Bedform Geometry and the Sediment Continuity Equation

The relationship between hydrodynamic forcing and bedform wavelength over one tidal cycle is shown in Figure 4. In combined wave-current flows, the bedform wavelength increased with increasing duration of forcing demonstrating that λ at any instance in time was not only dependent on the present hydrodynamic forcing, but also on past hydrodynamic conditions over some lag time, τ. In wave dominant flows, the bedforms also grew in volume with increased duration of forcing; however, they generally reached an equilibrium wavelength, scaling with the wave statistics, where the combined flow bedforms never reached an equilibrium condition.

The bedform will grow/decay and/or migrate based on the position of peak transport with respect to the bedform crest. When the non-dimensional phase shift, δ_{x_b}/λ, is ± 0.25 the bedform will only grow (+) or decay (-) in volume, when δ_{x_b}/λ is 0 the bedform will only migrate [*Nielsen*, 1992]. δ_{x_b}/λ was estimated by taking $t = dt$ and $x = 0$ since the non-dimensional phase shift is estimated with every measurement of bedform growth or decay and is estimated in position with respect to the bedform crest at $x = 0$. The bedform wavelength begins to increase with the onset of increases in $E_{k_{wc}}$. During this period the bedform grows and migrates, but when the bedform growth dominates δ_{x_b}/λ will be large, and when bedform migration dominates δ_{x_b}/λ will be close to zero (Figure 9 and Figure 10). Generally, the largest periods of bedform growth or decay have small migrations, and the largest periods of migration have small growth or decay (Figure 10). The sediment transport increases with either increased migration or increased growth, and decays with decreased migration or decay in bedform volume. Additionally, q_b can be estimated from either (14) and (15), with each estimating similar magnitudes (Figure 9e).

The results of the continuity analysis given by (19) are shown as Figure 11 and 12. Figure 11 shows the observed change in bedform volume and the integral of the sediment flux term calculated using (14) with three different methods (described below) to estimate the lag time for bedform growth, τ. The bedform volume was calculated by taking the average cross section of the ripple profile in the direction of the bedform orientation, and then used with the measured ripple wavelength from the 2D spectra to find the mean bedform volume for each time step.

To find the bedform adjustment time, τ, the first method sets $\tau = dt$, one sample time step (for S1 dt = 20 min. and for S2 dt = 2 hr.; denoted τ dt in Figures 11 and 12). The second method sets $\tau = \tau_{zc}$, or the adjustment time found with observations of bedform growth or decay by the time between subsequent upward and downward zero-crossings in $d\Lambda_b/dt$. An upward zero-crossing indicates the initiation of bedform growth, and a downward zero-crossing indicates the start of bedform decay. The time between upward to downward zero-crossings represents the adjustment time that the bedform underwent to reach its largest volume before it started to decay. The time between downward to upward zero-crossings represents the adjustment time for bedform decay. Depending upon the flow forcing condition, τ_{zc} will change. If the bedform reaches an equilibrium condition with the flow, and stops growing or decaying, the lag time was set to dt. An example of an individual bedform growing over time at S1 is shown in Figure 4. In this case the bedform adjusted to the flow field for approximately 2.4 hours (0.1 days) before its volume began to decay; thus for this case τ_{zc} = 2.4 hours. The observed bedform adjustment time using the zero-crossing method showed that within wave dominant conditions, the bedform adjustment time was fairly quick. Within 20 minutes to 1 hour the bedforms began to come into equilibrium with the flow field; however, with the addition of currents, the adjustment time became much longer, approximately 2.5 hours to 6 hours and the bedforms may have never adjusted into equilibrium with the flow forcing. The third method to find τ uses $\tau = \frac{n\eta\lambda}{2q_b}$ [*Traykovski*, 2007]. The method assumes that the sediment flux during bedform growth is uniform with respect to time. Since (19) estimates the change in bedform volume as a function of the sediment transport, it is viable even through quiescent conditions. However, with the dynamic qualities of this assumption has not been evaluated in such a dynamic enviornment.

Observations captured many instances of bedform building and decay over time (e.g. Figure 4). When $\tau = dt$, (19) greatly underestimates the change in bedform volume, especially for S1 where dt is much shorter (Figure 11 and 12). The under estimation is especially apparent during instances of increased changes in bedform volume, suggesting that bedform building or decay is a time dependent process. Additionally, at S1, τ was estimated using the bedform zero-crossing method. However, at S2, the bedform zero-crossing method could not be used because the sampling rate between subsequent sonar images was too slow to capture bedform building. The method to estimate the bedform adjustment time from *Traykovski* [2007] was applied at both S1 and S2.

At both S1 and S2, it is clearly evident that (19) has higher skill using a variable τ. Figure 11b and Figure 12 demonstrates that τ estimated directly from the bedform zero-crossing method ($rmse$ = 0.019 m^3/m, r^2 = 0.86 for S1) or calculated using $\tau = \frac{n\eta\lambda}{2q_b}$ ($rmse$ = 0.021 m^3/m, r^2 = 0.64 for S1 and S2) represents the range of measured bedform volumes much better than $\tau = dt$ ($rmse$ = 0.029 m^3/m, r^2 = 0.22 for S1 and S2).

4.2 Existing Time-Dependent Bedform Geometry Model Comparisons

Previous bedform geometry work primarily focuses on approximating bedform geometry (λ and η) from the overlying flow field. In our effort instead of bedform volume (Λ_b) as was predicted with the sediment continuity equation in the previous section. The leading time dependent bedform geometry models for prediction of bedform wavelength and height are *Traykovski* [2007] and *Soulsby et al.* [2012]. Each model was evaluated using the data collected at S1 and S2 for both the entire dataset as well as a subset of the data that represents data from which the model was developed (Figure 13).

The *Traykovski* [2007] model is formulated for waves only, and with smaller orbital ripples it performed with twice the r^2. Their model $rmse$ decreased by 2/3 or better for both λ and η when compared with the full dataset, which includes combined flow and current generated bedforms (Figure 13a, c). However, the concept behind the adjustment timescale, T_{adj}, in the *Traykovski* [2007] model is valid for both wave and current generated bedforms (as shown in Figure 12).

The *Soulsby et al.* [2012] model is applicable to either wave or current generated bedforms, but it generally fails to predict megaripple scale bedforms. If the model is used to predict bedforms with wavelengths less than 0.5 m (regardless of flow dominance), the model r^2 stays the same, but the model $rmse$ decreases by 2/3 or better, suggesting a model bias. The *Soulsby et al.* [2012] model may poorly predict larger volume bedforms partially because it excludes the effects of combined flows that are prevalent at S1 and S2. Additionally, the estimated equilibrium bedform geometry model used by *Soulsby et al.*

[2012] considerably under-predicts (λ_{eq} ~ 0.3 m) the observed bedform wavelengths (λ = 1-2.5 m) during combined flows. Finally, in *Soulsby et al.* [2012] the criterion distinguishing between wave or current generated bedforms is based on the Shields parameter, and depending on the approximation used for bed stress, under predicts mobility during combined flow conditions at the S1 and S2 sites.

The adjustment characteristic to an equilibrium length scale in *Traykovski* [2007] and *Soulsby et al.* [2012] seems reasonable; however, in practice may hinder the model skill (especially during combined flow conditions). The equilibrium geometry parameterizations may not be appropriate to all bedform generation conditions, especially combined wave-current bedforms. Additionally, the transition from wave generated to current generated is abrupt in the *Soulsby et al.* [2012] model, and does not allow for combined flow bedform generation.

Although these models have some limitations, their incorporation of time dependent growth is relevant to bedform building, even in combined wave-current flows. In our dataset, although wave dominated bedforms at times come into equlibrium with the wave conditions, the combined flow bedforms, never actually came into equilibrium with the flow forcing. The departure from equilibrium theory could be an explanation for the inability for bedform geometry models such as *Traykovski* [2007] and *Soulsby et al.* [2012] to predict bedform wavelength and height in combined flows. Although both of these models are time dependent, they also are based on an equilibrium approach. Equilibrium theory may not be representative of the physics of combined flow bedform growth, or at least, present equilibrium theory may not be consistent with the stability condition of combined wave-current bedforms.

5 Conclusions

Observations of bedform response to wave, current, and high energy combined wave-current dominant flows are presented. The observations capture both ripple and megaripple response to hydrodynamic conditions consisting of wave forcing plus strong currents (>0.5 m/s) collected within and near the surf zone. Dynamic bedform geometry transitions in response to shifts in flow conditions are resolved. Observations show that bedform volume - when exposed to current and combined wave-current forcing - continuously build until the flow changes.

Bedform transformation and growth are shown to be a highly time dependent sediment transport process. With hydrodynamic transitions, the bedform scaling did not respond immediately; instead, the bedform adjustment lagged behind in response to new forcing condition. Within wave dominant conditions, the bedform adjustment time was fairly quick; within 20 minutes to 1 hour the bedforms began to come into equilibrium with the flow field. However, when strong currents were present, the adjustment time became much longer, ranging between 2.5 hours to 6 hours and the bedforms never actually came into complete equilibrium with the flow forcing. The departure from equilibrium conditions captured in this dataset may be responsible for the inability of existing bedform geometry models to predict bedform wavelength and height in the measured combined flows. Demonstrating that current equilibrium theory may not be representative of combined flow bedform growth or, at least not consistent with the stability condition for combined wave-current bedforms.

Aside from our dynamic set of observations of bedform response to combined wave-current flows, our effort demonstrates that bedform volume at any given time was dependent on both the sediment transport rate and the time duration that the bedform was exposed to the flow field. Measured changes in bedform volume were additionally shown to be characterized with the sediment continuity equation, or Exner equation, integrated over the bedform adjustment time of growth, which to our knowledge is a new contribution that builds upon past efforts. In addition, our effort contributes expressions for the fully unsteady bedform migration rate, growth rate, sediment transport phase shift, and change in volume. The sediment continuity equation while accounting for bedform adjustment/growth times may be a viable method for temporal and spacial morphologic change predictions of bedforms, especially in combined wave-current flows and with bedforms of a larger scale.

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Figure 1. a) September 2014 bathymetry of Sand Engine mega-nourishment, Delfland, The Netherlands. b) Inset marked on panel a shows the sampling locations S1 and S2 indicated with white circles. Site S1 is close to the shoreline, and site S2 is close to the shore-parallel sandbar. The coordinate system used in this research is defined relative to the low tide shoreline, where shore parallel (alongshore) is y with +y being toward the Northeast, and shore normal (cross shore) is x with +x directed offshore. c) and d) Instrument array. Station S1 included an Imagenex 881a pencil beam sonar located 0.7 m from the bed and an ADCP located 0.4 m from the bed, and station S2 included an Imagenex 881a pencil beam sonar 1 m from the bed and an ADV 1 m from the bed.

Figure 2. Time series of observations at S1, where panel a) shows depth (h), b) shows amplitude of wave orbital velocity, u_o, in grey and mean velocity, U, in black, c) shows maximum kinetic energy, $E_{k_{wc}}$ shaded by fraction of kinetic energy due to waves, d) shows ripple wavelength, λ, e) and shows ripple steepness, η/λ. The vertical dashed lines in panels d and e indicate occurrences of local bathymetries shown as panels f-h. Panels f-h) show 2D bathymetries, where y is shore parallel, and x is shore-normal, with -x directed onshore, and is shaded by bedform height. Finally, dashed lines and shaded overlay in panels f-h indicate bedform orientation and orientation uncertainty, respectively.

Figure 3. Time series of observations at S2, where panel a) shows depth (h), b) shows amplitude of wave orbital velocity, u_o, in grey and mean velocity, U, in black, c) shows maximum kinetic energy, $E_{k_{wc}}$ shaded by fraction of kinetic energy due to waves, d) shows ripple wavelength, λ, e) and shows ripple steepness, η/λ. The vertical dashed lines in panels d and e indicate occurrences of local bathymetries shown as panels f-h. Panels f-h) show 2D bathymetries, where y is shore parallel, and x is shore-normal, with -x directed onshore, and is shaded by bedform height. Finally, dashed lines and shaded overlay in panels f-h indicate bedform orientation and orientation uncertainty, respectively.

Figure 4. Time series of observations at S1 for one tidal cycle, where panel a) shows depth (h), b) shows amplitude of wave orbital velocity, u_o, in grey and mean velocity, U, in black, c) shows maximum kinetic energy, $E_{k_{wc}}$ shaded by fraction of kinetic energy due to waves, and d) shows ripple wavelength, λ. The vertical dashed lines in panel d indicate occurrences of local bathymetries shown as panels e-j. Panels e-j) show 2D bathymetries, where y is shore parallel, and x is shore-normal, with -x directed onshore, and is shaded by bedform height. Finally, dashed lines and shaded overlay in e-j indicate bedform orientation and orientation uncertainty, respectively.

Figure 5. Histograms of bedform a) wavelength (λ), b) amplitude (η), and c) steepness (η/λ) at both stations, where S1 is in black and S2 is in grey.

Figure 6. Bedform classification scatter plot diagrams. Panel a) shows the *Clifton and Dingler* [1984] classification diagram (dark gray are classified as orbital ripples and white as anorbital ripples, with the region in-between classified as suborbital ripples) overlaid with observations from S1 and S2, shaded by fraction of kinetic energy due to waves. Panel b) shows the distribution of observed bedform wavelengths based on orbital velocity and current velocity flow contributions, shaded by fraction of energy due to waves, where the marker size indicates bedform wavelength (with larger markers indicating larger λ as shown at the top of the panel).

Figure 7. Observed bedform direction and concurrent flow directions. Panel a) shows a time series of depth at S1. Panel b) S1 and c) S2, show time series of range of observed bedform orientation colored by fraction of kinetic energy due to waves (circles with range bars), observed current direction (black dots), and observed wave direction (thin black line).

Figure 8. Observed bedform directions plotted against a) current magnitude, b) current direction [$rmse_{range}$ = 40°, c) wave orbital magnitude, d) wave orbital direction [$rmse_{range}$ = 23°. $rmse$ is calculated between the observed bedform range and the model as described in the text. Markers are colored by the fraction kinetic of energy due to waves and the size of the marker scales with the bedform wavelength as indicated in the bottom of panel d.

Figure 9. Time series of indicators for bedform growth, decay, and migration. Panel a) shows the wave-current energy time series colored by fraction of kinetic energy due to waves at S1. Panel b) shows a short time series of bedform wave length (o) and height (•). Panel c) shows the bedform growth/decay rate in red and the bedform migration rate in blue. Panel c) shows the non-dimensional phase offset between the sediment transport and bed shape, when δ_{x_b}/λ is positive the bedform will grow, negative will decay, and 0 will migrate. Panel e) shows the bedload sediment transport estimated with equations (14) (blue) and (15) (red).

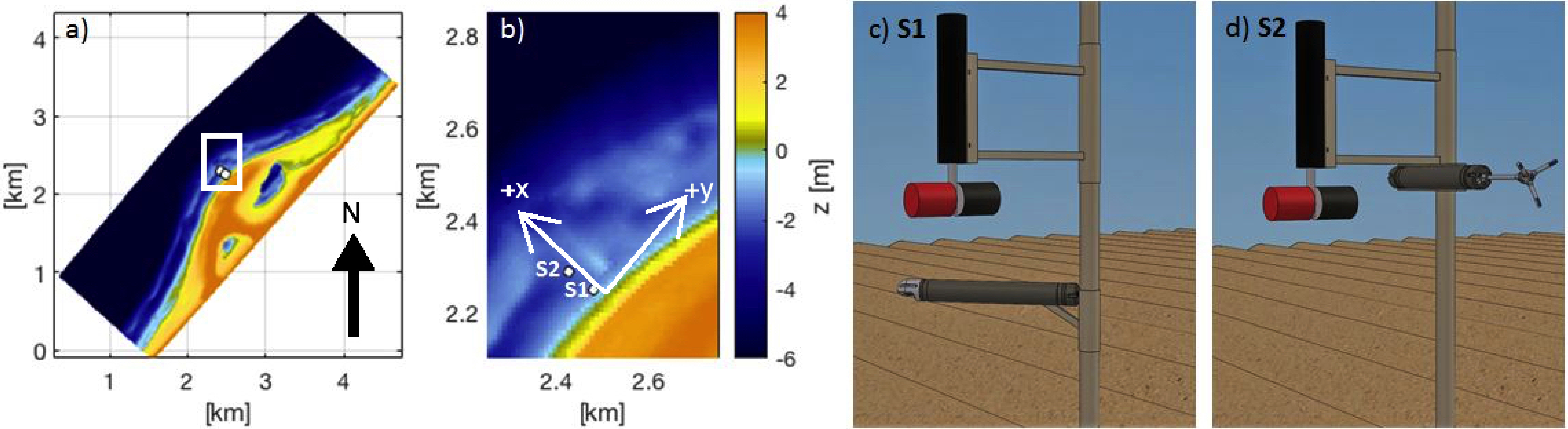
Figure 10. Scatter plot of bedform growth/decay and migration rate, colored by the non-dimensional phase offset between the sediment transport and bed shape, δ_{x_b}/λ is estimated with (17). When δ_{x_b}/λ is positive the bedform will grow, negative will decay, and 0 will migrate.

Figure 11. Time series of bedform volume represented by the sediment continuity equation. Panel a) shows the wave-current energy time series colored by fraction of kinetic energy due to waves at S1. Panel b) shows a short time series of $\Delta\Lambda_b$, where the thick grey line is the RHS of (19) and the markers represent the LHS of (19) using various approximations of the bedform lag time, τ, estimated as follows. The black $\times$ use a $\tau = dt$, the blue $\circ$ use a τ directly estimated from the bedform zero-crossing method, and the red $\bullet$ use a τ estimated from ($\tau = \frac{n\eta\lambda}{2q_b}$).

Figure 12. Scatter plot of the change in bedform unit volume vs. the time integrated transport (LHS vs. RHS of (19)) for the full data set collected at a) S1, and b) S2. The change in bedform volume (x axis) is plotted against the time integrated sediment flux using different approximations of the bedform lag time, τ (y axis). The black $\times$ use a $\tau = dt$, the blue $\circ$ use a τ directly estimated from the bedform zero-crossing method, and the red $\bullet$ use a τ estimated from ($\tau = \frac{n\eta\lambda}{2q_b}$). The solid black line is a 1 to 1 line. For the bedform zero-crossing method, $rmse$ = 0.019 m^3/m, r^2 = 0.86 for S1. For $\tau = \frac{n\eta\lambda}{2q_b}$, $rmse$ = 0.021 m^3/m, r^2 = 0.64. For $\tau = dt$, $rmse$ = 0.029 m^3/m, r^2 = 0.22.

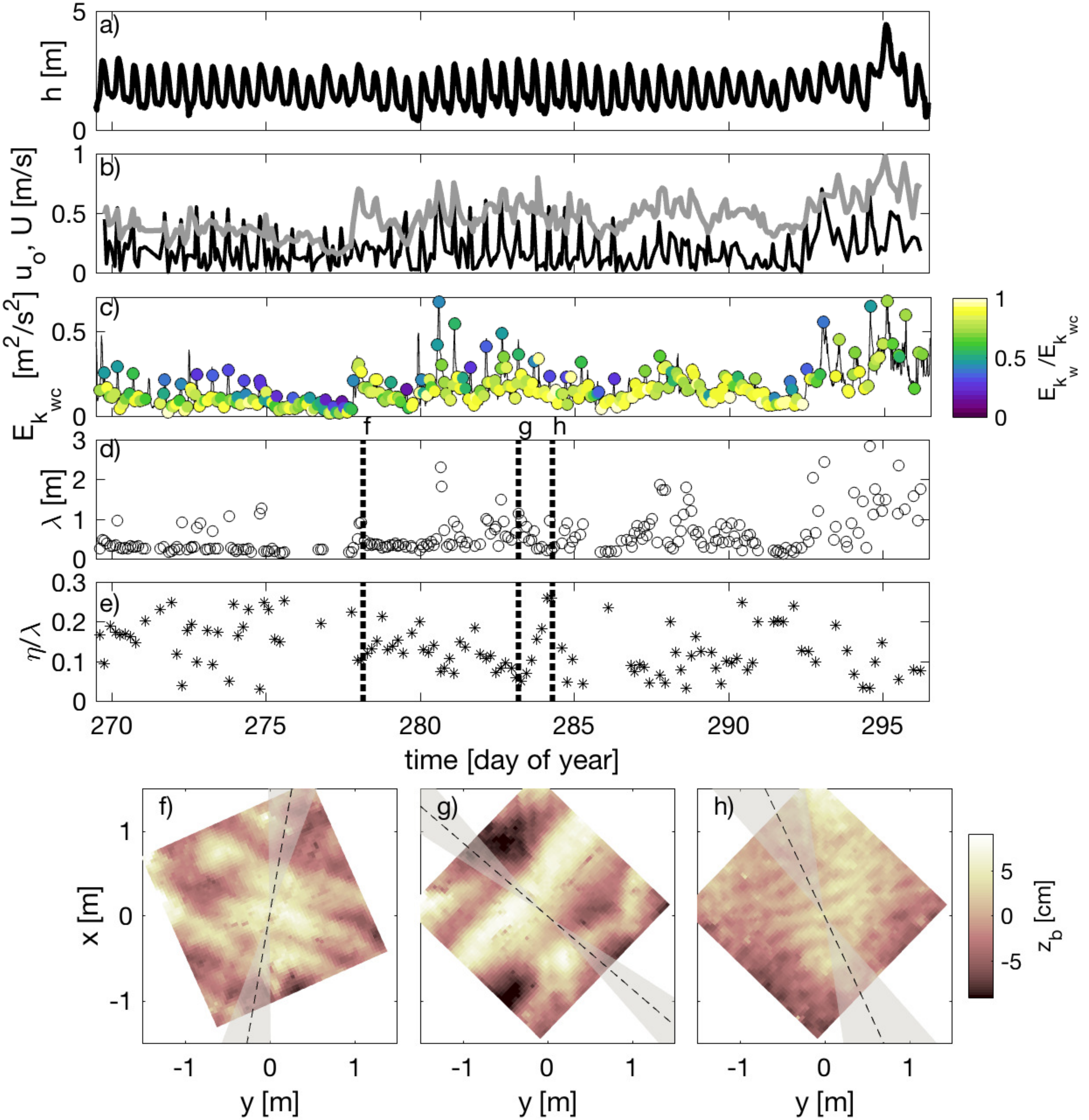
Figure 13. Observed vs. modeled bedform λ (panels a) and b)) and η (panels c) and d)) for site S1 in $\times$ and S2 in o. The grey markers show all data, and the black markers show the subset of data that the model was designed and tested on. a,c) plot the *Traykovski* [2007] model from (20), where the data in black are for wave dominant flows only, b,d) plot the *Soulsby et al.* [2012] model from (21), where the data in black are for bedforms less than 0.5 m in wavelength only. The model $rmse$ and r^2 are indicted in the lower right corner of each panel.

Figure 1.



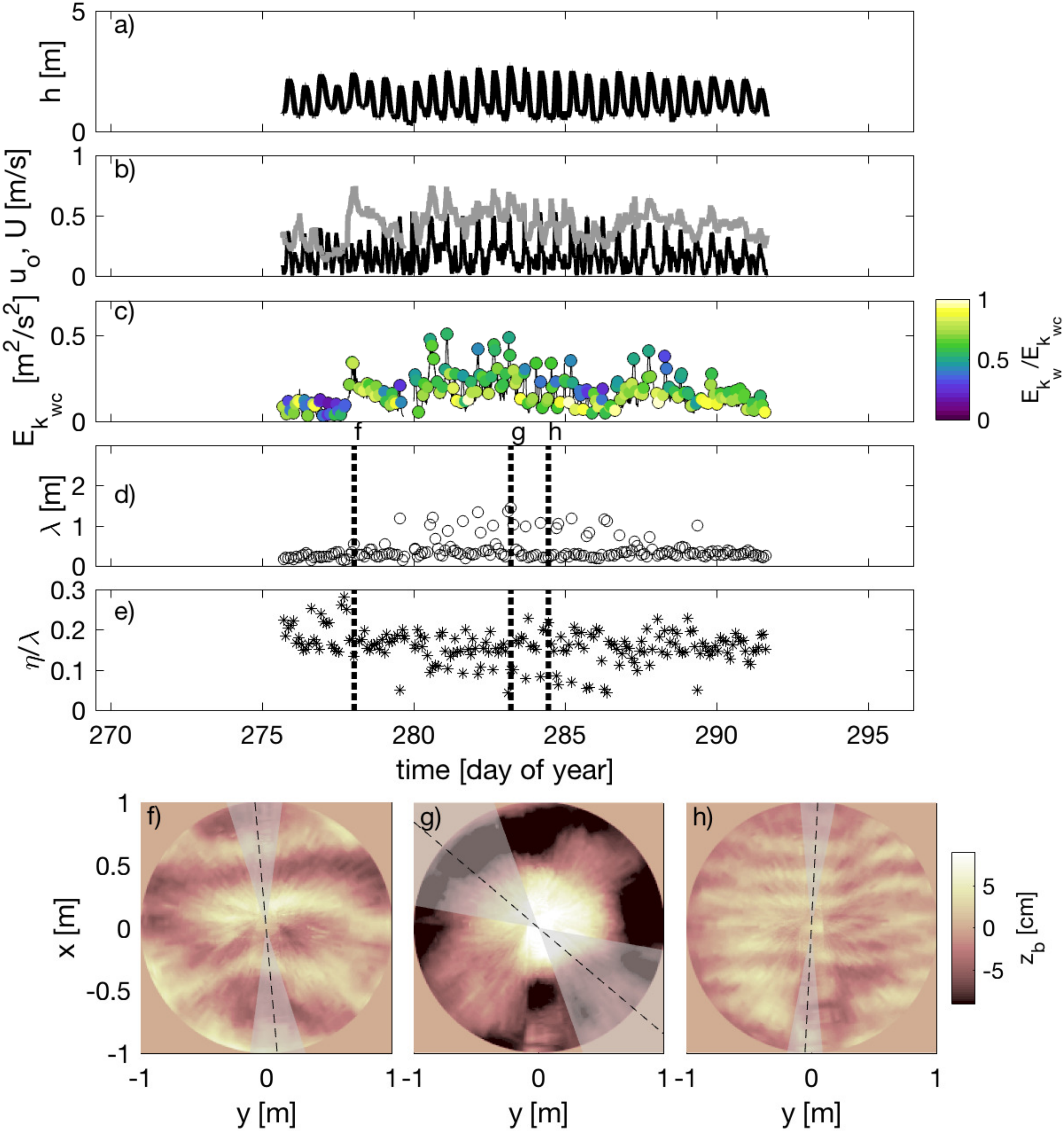
a)
[km]
[km]
N
b)
+x
+y
S2
S1
[km]
[km]
z [m]
c) S1
d) S2

Figure 2.



a)
h [m]
b)
u_o, U [m/s]
c)
$E_{k_{wc}}$ [m^2/s^2]
$E_{k_w}/E_{k_{wc}}$
d)
λ [m]
e)
η/λ
f
g
h
time [day of year]
f)
g)
h)
x [m]
y [m]
z_b [cm]

Figure 3.



a)
h [m]
b)
u_o, U [m/s]
c)
$E_{k_{wc}}$ [m^2/s^2]
$E_{k_w}/E_{k_{wc}}$
d)
λ [m]
e)
η/λ
f
g
h
time [day of year]
f)
g)
h)
x [m]
y [m]
z_b [cm]

Figure 4.

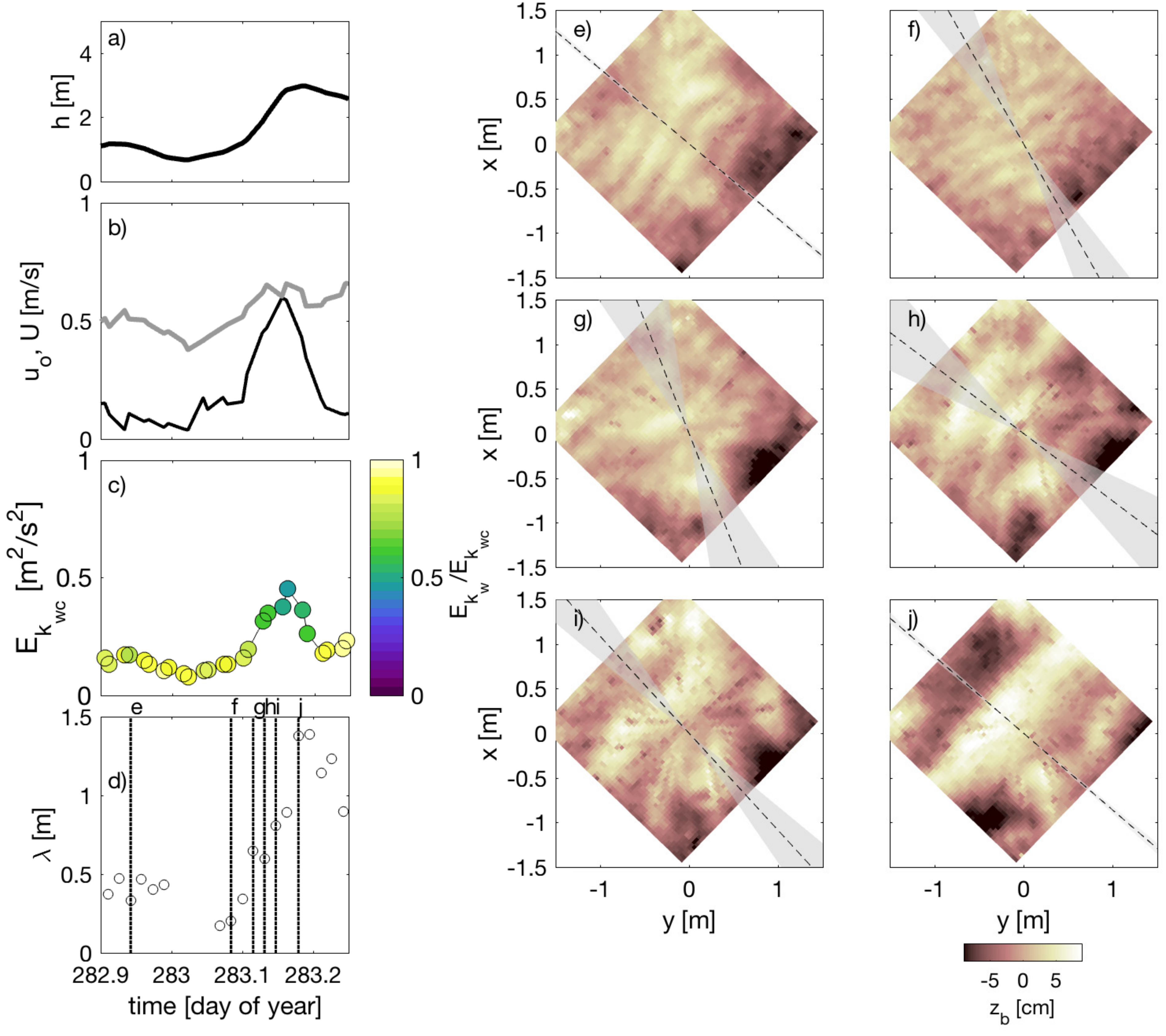
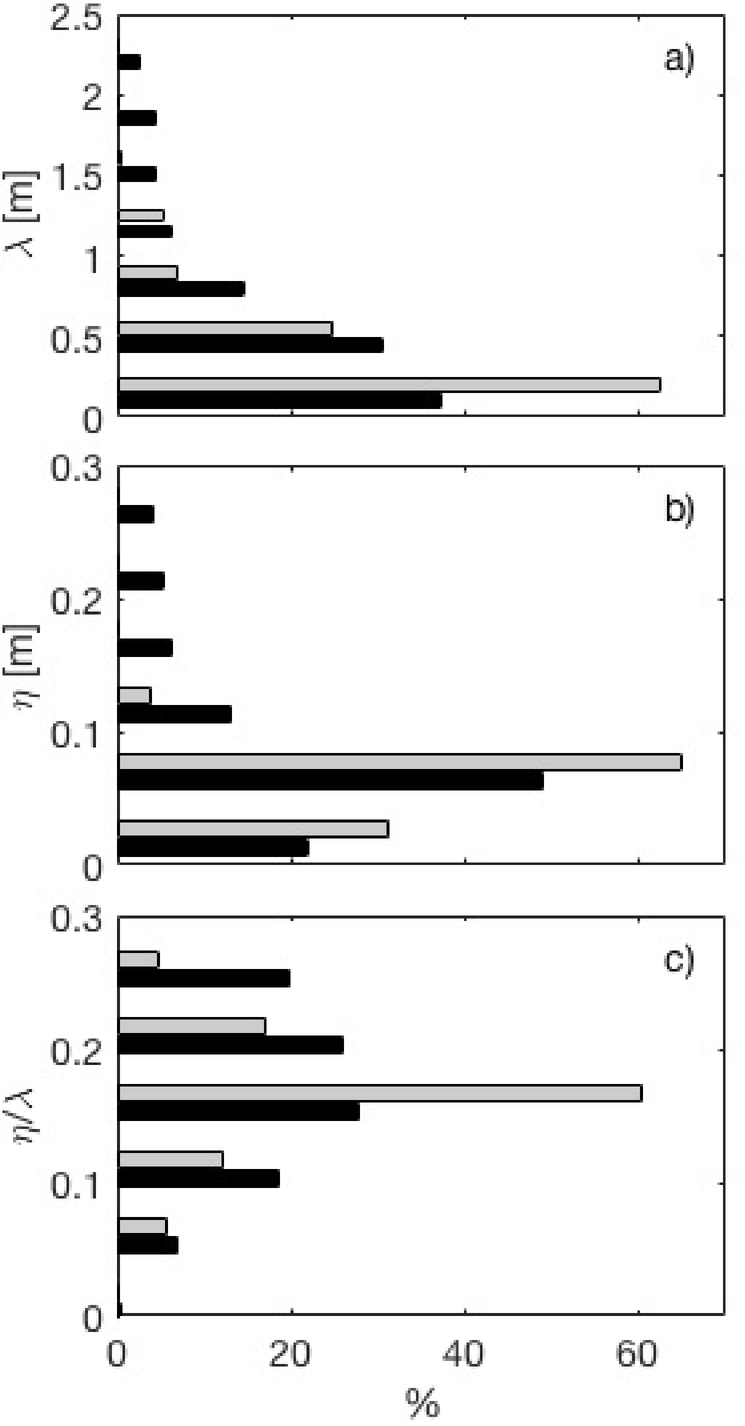

a)
h [m]
b)
u_o, U [m/s]
c)
$E_{k_{wc}}$ [m^2/s^2]
$E_{k_w}/E_{k_{wc}}$
d)
λ [m]
e
f
ghi
j
time [day of year]
e)
f)
g)
h)
i)
j)
x [m]
y [m]
z_b [cm]

Figure 5.



a)
b)
c)
λ [m]
η [m]
η/λ
%
2.5
2
1.5
1
0.5
0
0.3
0.2
0.1
0
0.3
0.2
0.1
0
0
20
40
60

Figure 6.

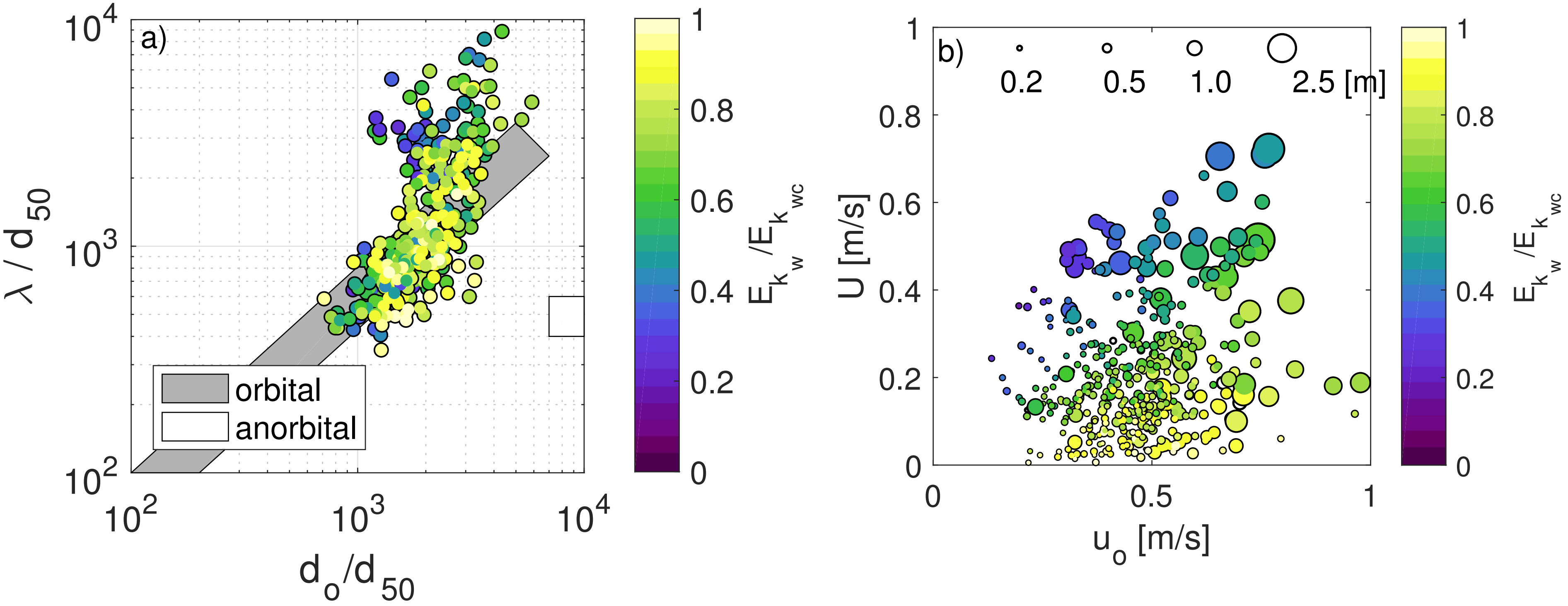
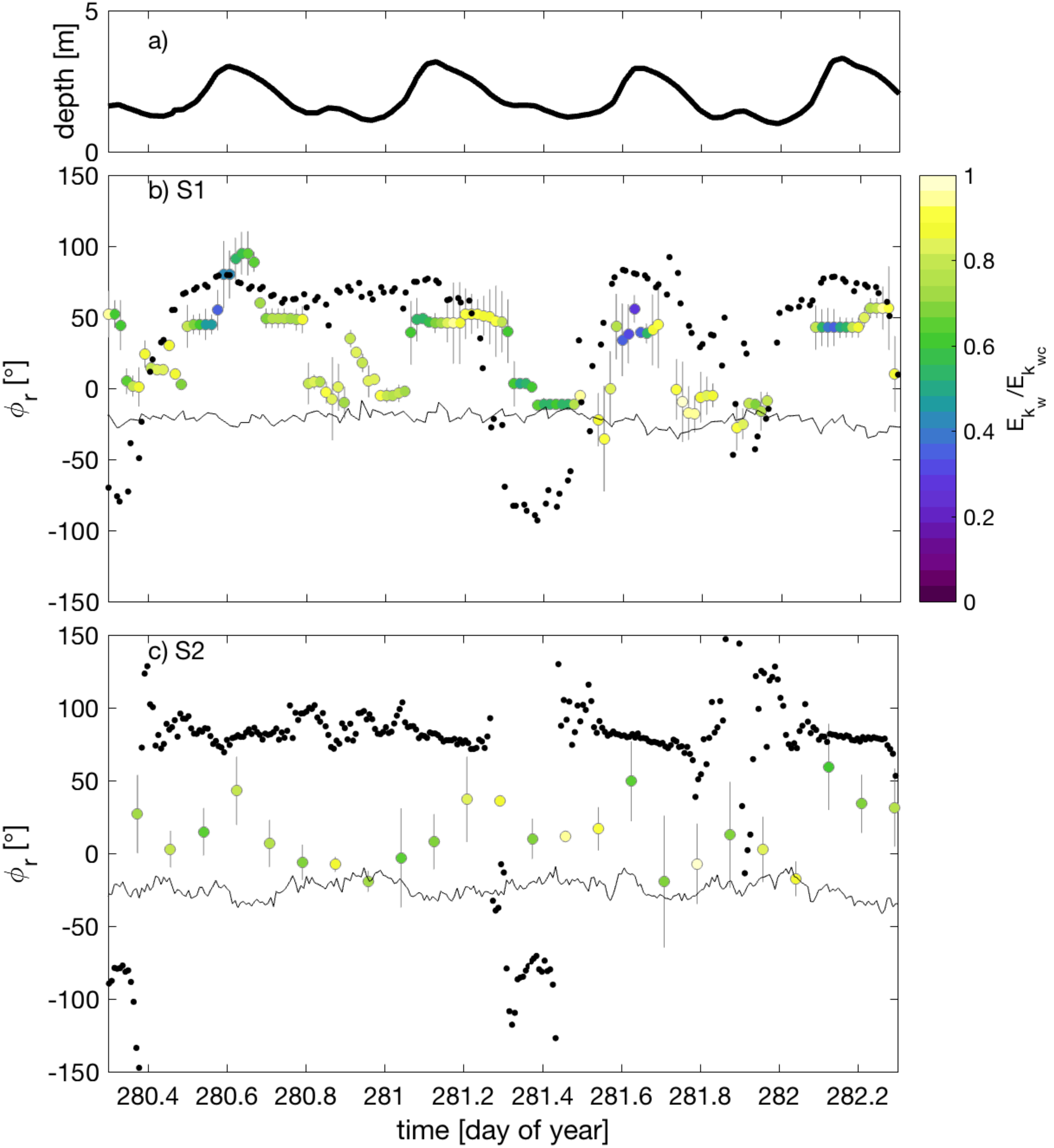
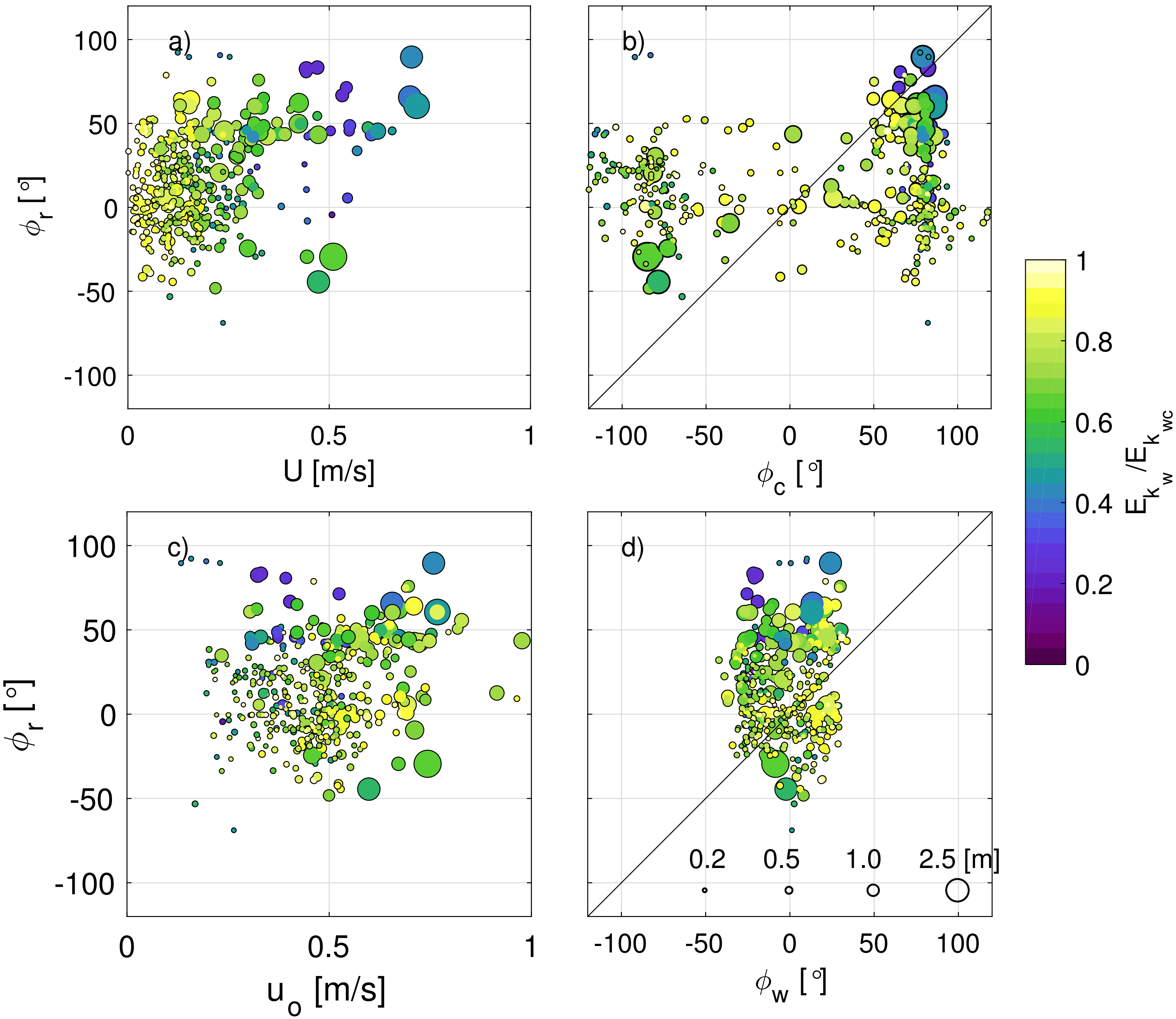

a)
λ / d_{50}
d_o/d_{50}
10^2
10^3
10^4
orbital
anorbital
$E_{k_w}/E_{k_{wc}}$
0
0.2
0.4
0.6
0.8
1
b)
0.2
0.5
1.0
2.5 [m]
U [m/s]
u_o [m/s]
0
0.5
1

Figure 7.



a)
depth [m]
5
0
b) S1
150
100
50
0
-50
-100
-150
ϕ_r [°]
1
0.8
0.6
0.4
0.2
0
$E_{k_w}/E_{k_{wc}}$
c) S2
150
100
50
0
-50
-100
-150
ϕ_r [°]
280.4
280.6
280.8
281
281.2
281.4
281.6
281.8
282
282.2
time [day of year]

Figure 8.



a)
b)
c)
d)
ϕ_r [°]
U [m/s]
ϕ_c [°]
u_o [m/s]
ϕ_w [°]
$E_{k_w}/E_{k_{wc}}$
0.2
0.5
1.0
2.5 [m]

Figure 9.

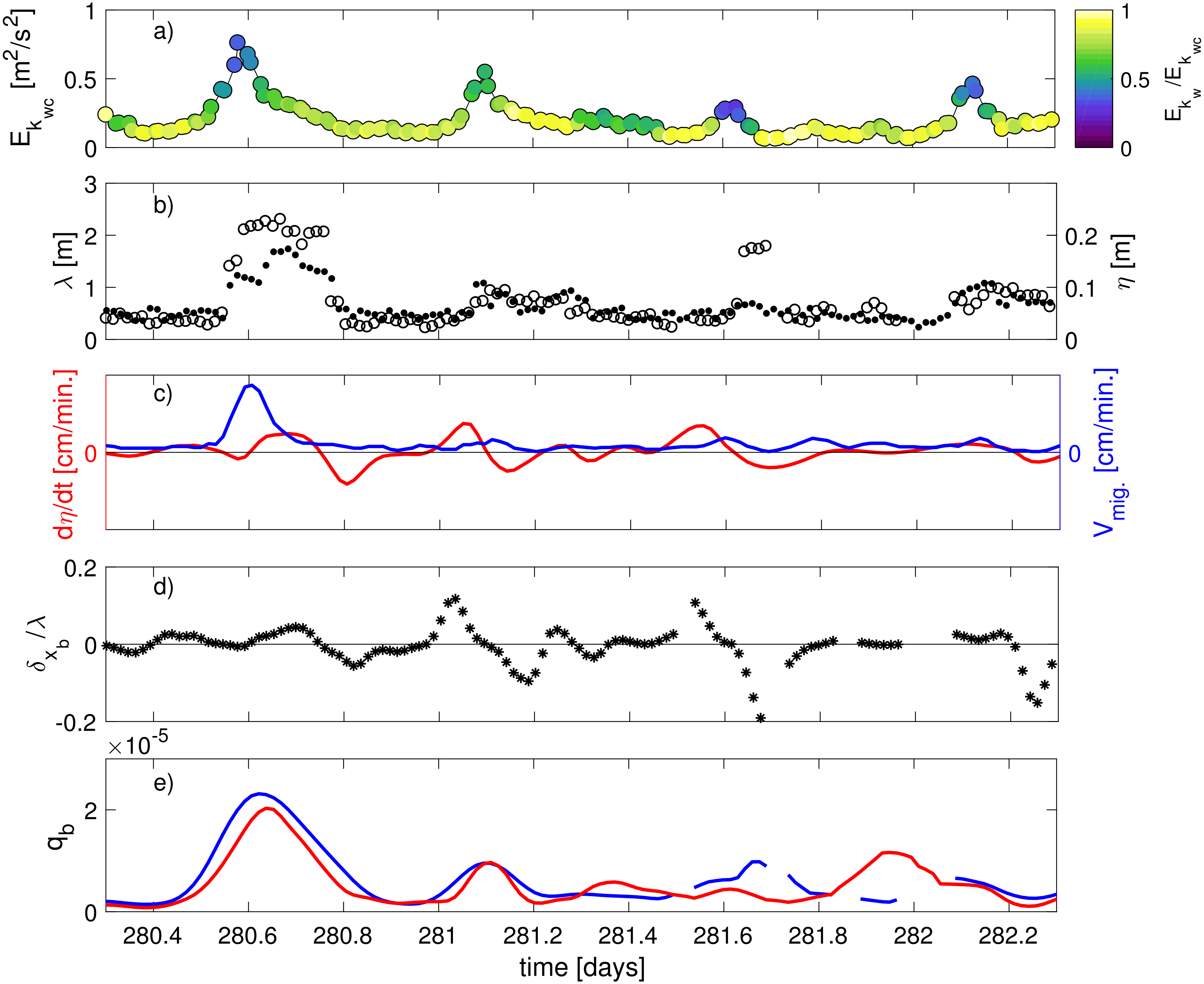
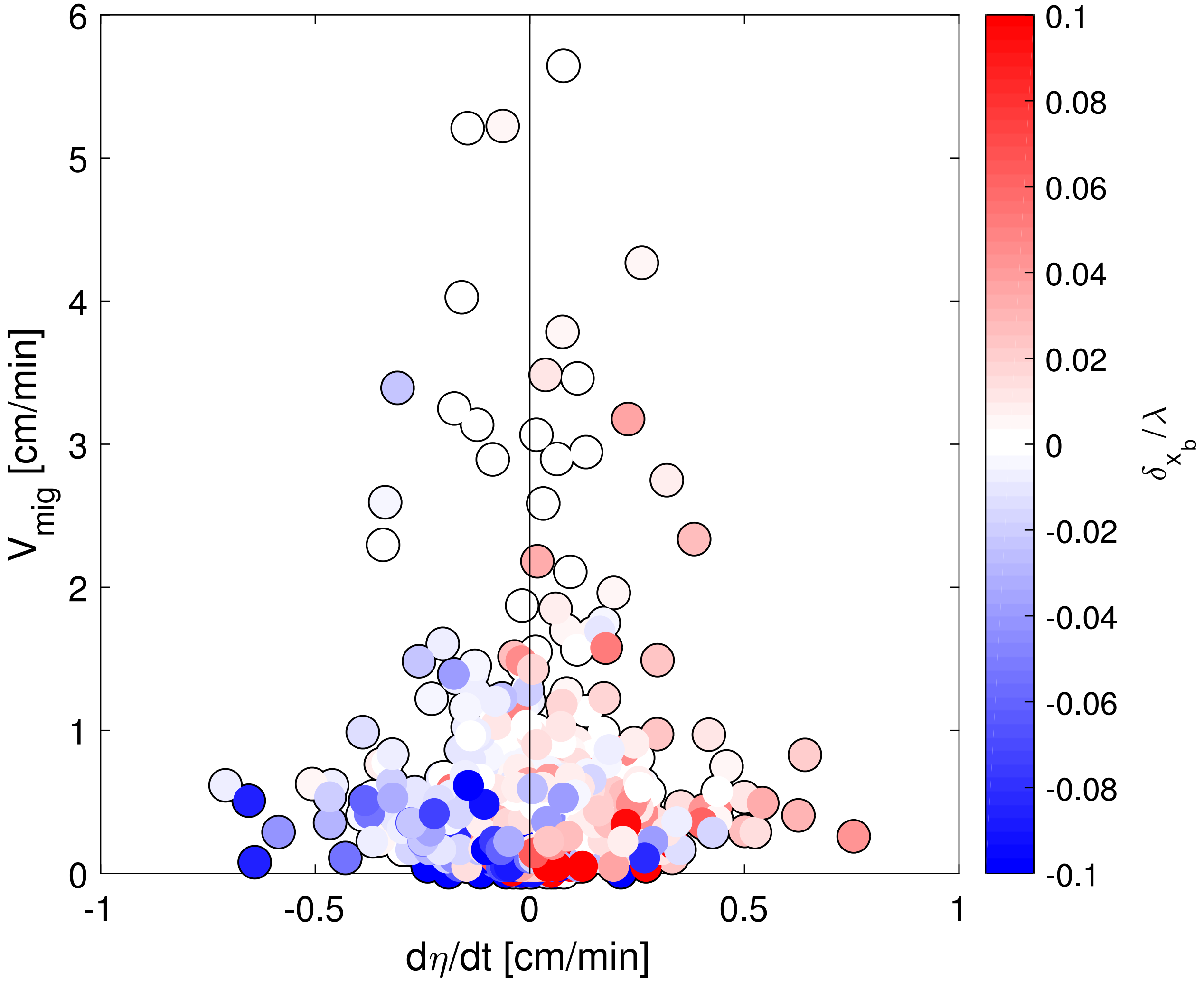

a)
b)
c)
d)
e)
$E_{k_{wc}}$ [m^2/s^2]
$E_{k_w}/E_{k_{wc}}$
λ [m]
η [m]
dη/dt [cm/min.]
$V_{mig.}$ [cm/min.]
δ_{x_b}/λ
q_b
×10^-5
time [days]

Figure 10.



6
5
4
3
2
1
0
V_mig [cm/min]
-1
-0.5
0
0.5
1
dη/dt [cm/min]
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
δ_xb / λ

Figure 11.

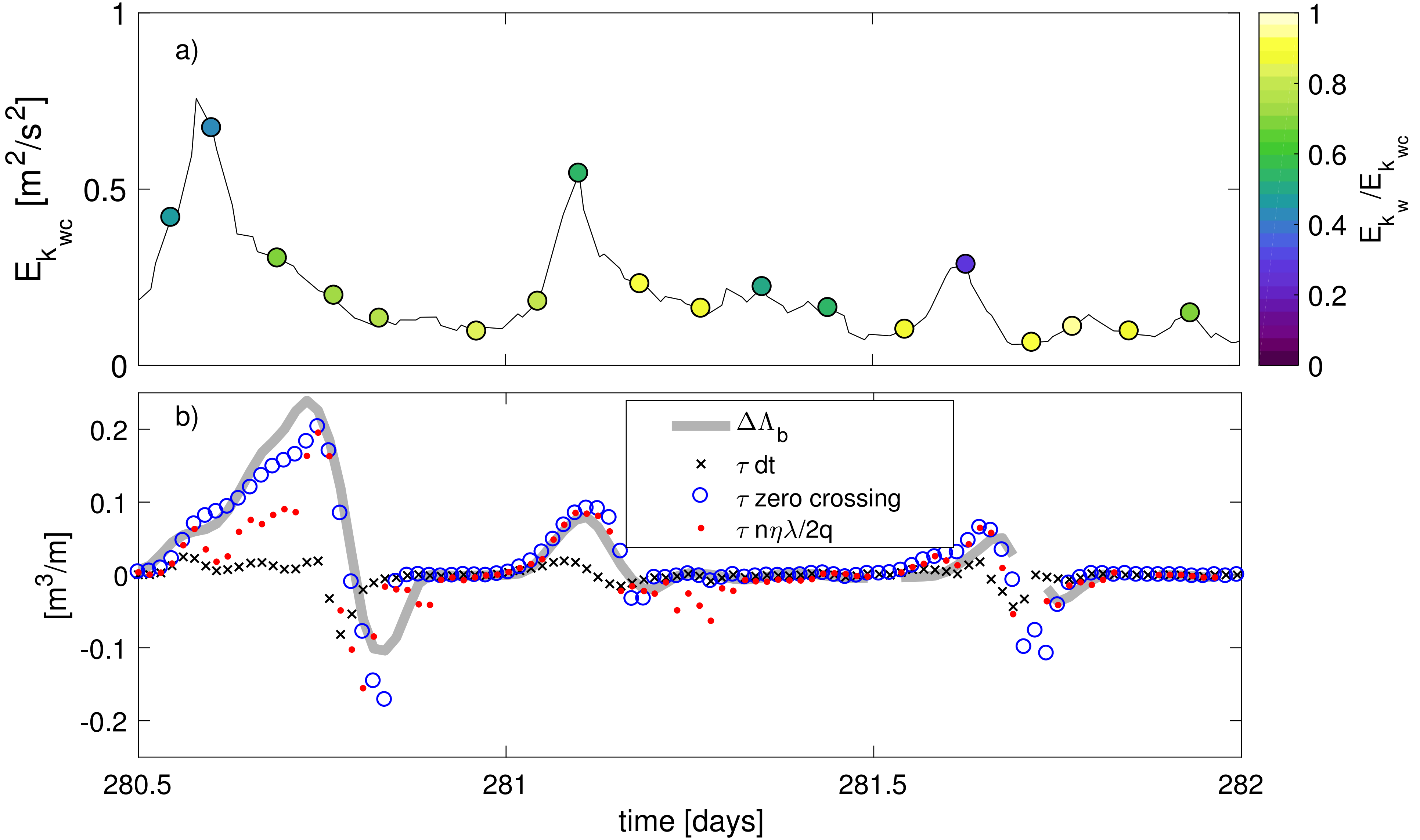
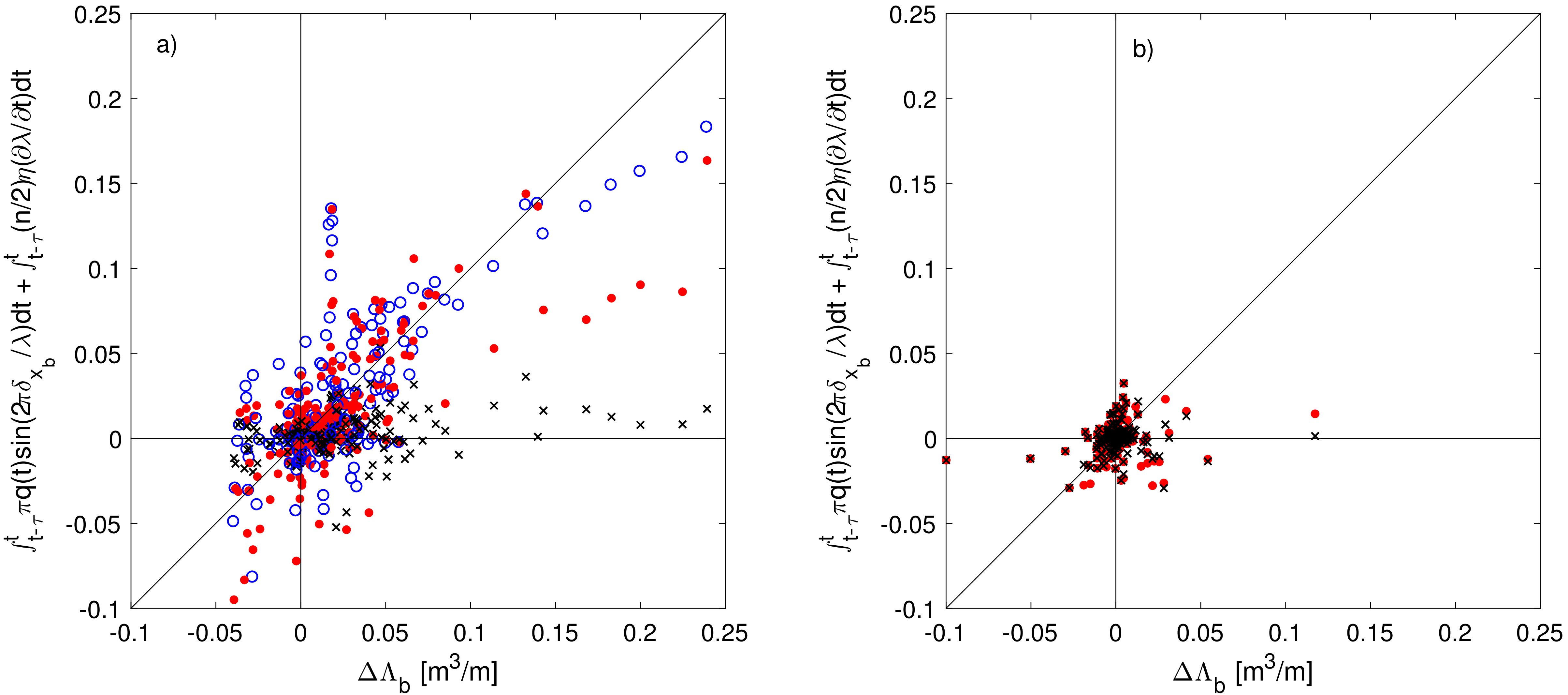
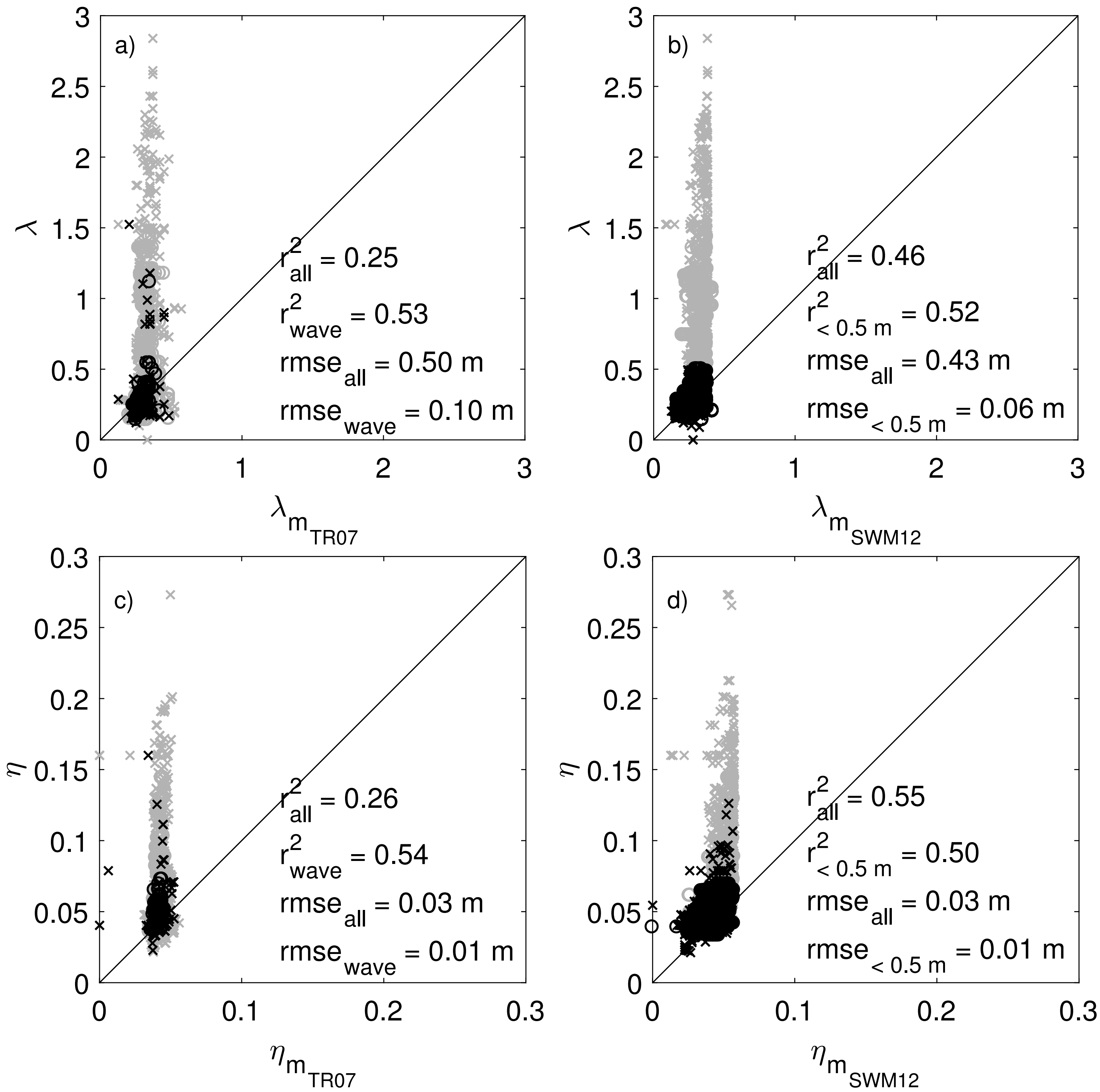

a)
b)
$E_{k_{wc}}$ [m^2/s^2]
$E_{k_w}/E_{k_{wc}}$
[m^3/m]
$\Delta\Lambda_b$
τ dt
τ zero crossing
τ $n\eta\lambda/2q$
time [days]
280.5
281
281.5
282
0
0.5
1
0.2
0.4
0.6
0.8
0.1
-0.1
-0.2

Figure 12.



a)
b)
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
ΔΛb [m3/m]
∫t t-τ πq(t)sin(2πδxb/λ)dt + ∫t t-τ (n/2)η(∂λ/∂t)dt

Figure 13.


a)
b)
c)
d)
λ
$\lambda_{m_{TR07}}$
$\lambda_{m_{SWM12}}$
η
$\eta_{m_{TR07}}$
$\eta_{m_{SWM12}}$
r^2_{all} = 0.25
r^2_{wave} = 0.53
$rmse_{all}$ = 0.50 m
$rmse_{wave}$ = 0.10 m
r^2_{all} = 0.46
$r^2_{< 0.5\ m}$ = 0.52
$rmse_{all}$ = 0.43 m
$rmse_{< 0.5\ m}$ = 0.06 m
r^2_{all} = 0.26
r^2_{wave} = 0.54
$rmse_{all}$ = 0.03 m
$rmse_{wave}$ = 0.01 m
r^2_{all} = 0.55
$r^2_{< 0.5\ m}$ = 0.50
$rmse_{all}$ = 0.03 m
$rmse_{< 0.5\ m}$ = 0.01 m