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1 Near-bed sediment transport during offshore bar 2 migration in large-scale experiments

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Abstract.

This paper presents novel insights into hydrodynamics and sediment fluxes in large-scale laboratory experiments with bichromatic wave groups on a relatively steep initial beach slope (1:15). An Acoustic Concentration and Velocity Profiler provided detailed information of velocity and sand concentration near the bed from shoaling up to the outer breaking zone including suspended sediment and sheet flow transport. The morphological evolution was characterized by offshore migration of the outer breaker bar. Decomposition of the total net transport revealed a balance of onshore-directed, short wave-related and offshore-directed, current-related net transport. The short wave-related transport mainly occurred as bedload over small vertical extents. It was linked to characteristic intrawave sheet flow layer expansions during short wave crests. The current-related transport rate featured lower maximum flux magnitudes but occurred over larger vertical extents. As a result, it was larger than the short wave-related transport rate in all but one cross-shore position, driving the bar's offshore migration. Net flux magnitudes of the infragravity component were comparatively low but played a non-negligible role for total net transport rate in certain cross-shore positions. Net infragravity flux profiles sometimes featured opposing directions over the vertical. The fluxes were linked to a standing infragravity wave pattern and to the correlation of the short wave envelope, controlling suspension, with the infragravity wave velocity.

Plain Language Summary

25 Nearshore sandbars are seabed features that protect coastal infrastructure behind many
26 sandy beaches around the world. In response to waves they change in shape and distance
27 to the beach. To improve understanding of their offshore movement, experiments repre-
28 senting natural conditions in a controlled laboratory setting were done. In this context,
29 the underwater transport of sand was measured. The experiments featured groups of
30 single short waves (less than 2.5 meters long), which transported sand in different ways.
31 Single short waves largely transported sand towards the beach, and in a very thin layer
32 close to the seabed. Currents, caused by the short waves and their breaking, largely trans-
33 ported sand away from the beach, and over a much wider layer. Interactions between the
34 single short waves in a group created longer waves. They transported sand partly towards
35 and partly away from the beach. The currents transported sand more effectively than
36 the single short waves which explains the sandbar's offshore movement. The long waves
37 transported less sand and only became important when transports from currents and
38 short waves canceled each other out. This study provides useful information for better
39 forecasting of sandbar movement, improving coastal protection.

1. Introduction

40 Beaches are natural barriers against the ocean wave action and inundation. Unlike
41 classic man made flood protection structures, they are very dynamic systems which cycle
42 through various states [*Wright and Short*, 1984]. Such morphological evolution must be
43 understood in detail to harness their protective capabilities and services. In this context,
44 bar offshore migration under erosive wave conditions is an important part of morphological

45 evolution, as bars are important for wave energy dissipation and their morphodynamics
46 must be considered in nourishment strategies for coastal protection.

47 Evidence from laboratory (e.g. *Eichentopf et al.* [2020]) and field experiments (e.g.
48 *Mariño-Tapia et al.* [2007a]) suggests that bar offshore migration under erosive wave
49 conditions is determined by wave breaking and the resultant hydrodynamics. In fact,
50 several studies have confirmed a morphodynamic link between bar and wave breaking
51 locations (e.g. *Plant et al.* [1999], *Pape et al.* [2010], *Alsina et al.* [2016] and *Eichentopf*
52 *et al.* [2020]). This link was shown to result from the convergence of cross-shore sediment
53 transport induced by wave breaking and from morphological feedback mechanisms (e.g.
54 *Gallagher et al.* [1998] and *Mariño-Tapia et al.* [2007b]).

55 More specifically, bar migration depends on the net result of various sediment transport
56 processes. *Gallagher et al.* [1998] highlighted the role of time-averaged offshore currents
57 near the bed which lead to net offshore transport. The time-averaged offshore currents,
58 on the other hand, originate from radiation stress gradients linked to wave breaking (e.g.
59 *Svendsen* [1984]). Net onshore transport on the seaward side of breaker bars has often
60 been linked to short wave asymmetry and skewness (e.g. *Hoefel and Elgar* [2003], *Hen-*
61 *derson et al.* [2004] and *Brinkkemper et al.* [2018]). However, net onshore transport was
62 calculated equally well with models that considered either process (e.g. *Hsu et al.* [2006]
63 and *Fernández-Mora et al.* [2015]) and the numerical modeling of net onshore transport
64 remains difficult [*van Rijn et al.*, 2011]. Another important factor may be infragravity
65 wave-related net transports. However, these can be either onshore or offshore-directed and
66 they importantly depend on the correlation of wave envelope and associated infragravity
67 wave (e.g. *de Bakker et al.* [2016]).

68 The numerical assessment of sediment transport processes is based on parametriza-
69 tion, because the processes themselves often cannot be resolved (lack of computational
70 capacity or physical understanding). Parametrization requires the use of calibration pa-
71 rameters and model performance was shown to heavily depend on them [*Dubarbier et*
72 *al.*, 2015]). High quality calibration data sets facilitate parameter choice. However, such
73 measurements are costly and difficult to obtain, especially under field conditions. In fact,
74 modeling studies often rely on beach profile measurements of morphological evolution to
75 gauge model performance (e.g. *Hoefel and Elgar* [2003], *Fernández-Mora et al.* [2015]
76 or *Dubarbier et al.* [2015]). But the morphological evolution itself is only a product of
77 sediment transport rates which depend on sediment concentration, flow velocity and their
78 underlying processes.

79 Detailed measurements of sediment concentration and flow velocity may help to obtain
80 a better understanding of processes. Optical Backscatter Sensors (OBS) are often used for
81 measuring sediment concentration (e.g. *Alsina et al.* [2016] and *Brinkkemper et al.* [2018]).
82 However, they only measure at one single location and they can only measure the relatively
83 low concentrations typical in suspended load, neglecting bedload even though it can be
84 highly important (e.g. *Fromant et al.* [2019] or *Mieras et al.* [2019]). Conductivity-based
85 systems (*Ribberink and Al-Salem* [1992] and later *Lanckriet et al.* [2013]) were developed
86 precisely for measuring high sediment concentrations very close to the undisturbed bed
87 (bedload transport). Because the technology is based on conductivity, it struggles to
88 capture suspended concentration and requires the combined use with other sensors, like
89 OBS, to capture a sufficient part of the water column (e.g. *Mieras et al.* [2019]). Fur-
90 thermore, both OBS and conductivity-based systems do not provide direct measurements

91 of flow velocity to calculate sediment fluxes. The Acoustic Concentration and Velocity
92 Profiler (ACVP; *Hurther et al.* [2011]), on the other hand, provides co-located profiles of
93 concentration and velocity while covering suspended load [*van der Zanden et al.*, 2017a]
94 and bedload at similar quality as conductivity-based systems [*Fromant et al.*, 2018]. In
95 general, the measurement of sediment concentration and fluxes remains a very complex
96 technological challenge subject to large uncertainties, especially in the evolving near-bed
97 region where there are large vertical gradients.

98 Most of the studies with detailed measurements of sediment transport were conducted
99 in the laboratory rather than the field (e.g. *O'Donoghue and Wright* [2004b], *van der*
100 *Zanden et al.* [2017a], *Fromant et al.* [2019] or *Mieras et al.* [2019]). This is because de-
101 tailed measurements often require very specific conditions in order to be successful (e.g.
102 specific distance between sensor and bed), which can hardly be guaranteed in the field
103 (e.g. changing water levels because of tides and bed evolution). However, laboratory
104 experiments often fail to represent field conditions appropriately. Certain studies only
105 consider monochromatic waves (e.g. *van der Zanden et al.* [2017a] and *Mieras et al.*
106 [2019]), neglecting sediment transport from infragravity waves and leading to a very lo-
107 calized breaking region. The latter may result in higher undertow magnitudes and higher
108 cross-shore gradients in sediment transport than expected under irregular waves. An-
109 other problem is the use of fixed, non-evolving beach profiles (e.g. *Mieras et al.* [2019]),
110 neglecting the feedback mechanisms between hydrodynamics and morphology. Addition-
111 ally, most studies fail to capture a sufficient number of cross-shore positions to observe
112 the cross-shore evolution of processes and quantities (e.g. *Mieras et al.* [2019]).

113 In the present study, bichromatic erosive wave conditions (i.e. causing net offshore
114 transport in most of the cross-shore beach profile) were used in a large-scale laboratory
115 experiment with evolving beach profiles and state of the art instrumentation [*Hurther*
116 *et al.*, 2011] in multiple cross-shore positions. This is expected to bridge the gap be-
117 tween the limited reproduction of field conditions in previous laboratory studies involving
118 monochromatic waves and the limited detail of measurements in previous field studies,
119 hence providing novel information on sediment transport processes and their relative im-
120 portance for total net transport rate and morphologic evolution. Bichromatic waves are
121 based on two primary frequency components and on their interaction during wave prop-
122 agation (e.g. *Alsina et al.* [2016]). This produces realizations similar to random waves,
123 while maintaining clear frequency signatures that facilitate spectral analysis and ensemble-
124 averaging. They were shown to provide similar sediment transport rate and beach response
125 as random waves, in contrast to monochromatic waves [*Baldock et al.*, 2011].

126 The paper is structured as follows: Sections 2 and 3 cover the experimental setup and
127 data treatment. Section 4 summarizes results on morphological evolution and sediment
128 transport within the sheet flow layer and above. Subsequently, the results are discussed
129 and put into context with similar studies in section 5, followed by the main conclusions
130 in section 6.

2. Experimental setup

2.1. Facility and test conditions

131 The present data were acquired within the HYDRALAB+ transnational access project
132 "Influence of storm sequencing and beach recovery on sediment transport and beach re-
133 silience" (RESIST). The experiments were conducted in the large-scale CIEM wave flume

134 at the Universitat Politcnica de Catalunya (UPC) in Barcelona. The flume is 100m long,
135 3m wide and 4.5m deep, and is equipped with a wedge-type wave paddle. The cross-shore
136 coordinate x was defined as 0 at the wave paddle, increasing towards the beach (Figure
137 1a) and the still water depth was 2.5m. The vertical coordinate z was defined as pointing
138 upwards from the still water level (SWL). The bed-referenced vertical coordinate ζ (Fig-
139 ure 1b) is the vertical elevation with respect to the time-dependent bed position (z_{bed}) –
140 time dependent as erosion or accretion occurs during the experiments. The computation
141 of ζ and z_{bed} will be explained in more detail in section 3.5.

142 The flume contained medium-grained sand with a median sediment diameter (D_{50}) of
143 0.25mm and a measured settling velocity w_s of 0.034m/s. A handmade slope of 1:15 was
144 constructed as the initial profile before the start of the waves. Subsequently, a benchmark
145 condition (B) of random waves with root-mean-square wave height $H_{rms}=0.3\text{m}$ and peak
146 period $T_p=4\text{s}$ was applied over 30 minutes to homogenize and compact the manually
147 shaped profile before the start of the actual experiments. The benchmark condition is
148 performed to allow the experiments to start from the same initial profile ("benchmark")
149 compacted by random waves. They were followed by erosive (E1 and E2) and accretive
150 (A1, A2 and A3) wave conditions in three different sequences (Table 1). At intervals (30
151 minutes for some tests, including all featured E2 tests, and 60 minutes for other tests)
152 the waves were paused to measure the beach profile, resulting in 4 to 6 tests per erosive
153 wave condition and sequence (with a larger number of accretive tests because of the longer
154 duration required for beach recovery). For additional details on the wave conditions, refer
155 to *Eichentopf et al.* [2020].

156 The bichromatic erosive and accretive wave conditions consisted of two primary fre-
 157 quency components, yielding repeatable wave groups. This article focuses on the erosive
 158 wave condition E2, where $f_1 = 0.3041\text{Hz}$ and $f_2 = 0.2365\text{Hz}$, because the complexity
 159 of processes under the accretive wave conditions merits separate analysis. Their wave
 160 group period (T_g) is defined as $T_g = \frac{1}{f_1 - f_2} = 14.79\text{s}$ and there were 3-4 short waves per
 161 group. Each one of the short waves is subject to a peak period of $T_p = 1/f_p = 3.7\text{s}$
 162 where $f_p = \frac{f_1 + f_2}{2}$. The repetition period (T_r), i.e. the period after which a wave phase
 163 repeats exactly, was $T_r = 2 * T_g = 29.58\text{s}$. This resulted in time series composed of con-
 164 secutive repeats of two slightly differing, alternating wave groups with seven short waves
 165 per T_r (a typical water surface elevation realization is sketched in blue in Figure 1a).
 166 In this study, T_r is of central importance because it determines the exact repetition of
 167 processes and the period for ensemble-averaging. At $H_1 = H_2 = 0.245\text{m}$ the waves were
 168 fully modulated. They are classified "erosive" because their dimensionless sediment fall
 169 velocity $\Omega = \frac{H_{rms}}{T_p * w_s} = 2.54$ [Wright and Short, 1984]. The waves were generated based
 170 on first-order theory without active wave absorption. Previous studies described a minor
 171 influence of basin seiching when using, as was done in the present experiments, bichro-
 172 matic waves with combination of primary frequencies far from the seiching modes and
 173 super-/subharmonics of the seiching modes (e.g. Alsina et al. [2016]). E2 produced the
 174 development of a breaker bar with successive offshore migration [Eichentopf et al., 2020].
 175 Not all of the tests with wave condition E2 are analyzed in depth in this study but only
 176 tests 36, 37, 39, 53, 54 and 105. In these tests measurements were taken on the offshore
 177 side of the outer bar. Data quality in concentration measurements on the onshore side of
 178 the outer bar crest was affected by wave breaking which induced undesired measurement

179 gaps at specific phases within the periodically repeated wave sequence due to air bubble
180 entrainment (see explanation in section 3.4).

2.2. Instrumentation

181 The experiments featured measurements of near-bed and outer flow velocities, sediment
182 concentrations, water surface elevations and beach profiles. The primary measurements
183 were taken from instruments deployed from a custom-built mobile frame (Figure 1b/c).
184 The frame consisted of 30mm stainless steel tubing and was designed to minimize flow
185 perturbations while withstanding wave impacts. It can be vertically adjusted with sub-
186 mm accuracy and was re-positioned in between tests to measure hydrodynamics and
187 sediment concentration in various locations surrounding the outer breaker bar. Additional
188 measurements, mainly of water surface elevation, were taken in fixed locations all along
189 the flume (Figure 1a).

190 The Acoustic Concentration and Velocity Profiler (ACVP; *Hurther et al.* [2011]) mea-
191 sured sediment concentrations, velocities and instantaneous bed elevations (because the
192 seabed erodes and accretes during tests) below the mobile frame. The co-located sedi-
193 ment concentration and velocity measurements (cross-shore and vertical) are provided as
194 vertical profiles of up to 20cm above the non-moving bed. Previous studies have shown
195 the high precision of its measurements for bottom wave boundary layer studies (cf. *Chas-*
196 *sagneux and Hurther* [2014]; *Fromant et al.* [2018]; *Fromant et al.* [2019]). In the current
197 study, it was set to measure with a bin resolution of 1.5mm, a sampling frequency of
198 50Hz, horizontal radius of the sampling volume of about 3mm and an acoustic carrier
199 frequency of 1MHz. While measuring, the ACVP tracks the instantaneous bed. In this

200 way, it is possible to reference sediment concentration and velocity measurements to their
201 instantaneous bed position.

202 Additional concentration measurements inside the ACVP measuring domain were ob-
203 tained from a three-nozzle Transverse Suction System (TSS) on the mobile frame. It
204 consisted of three vertically spread stainless-steel nozzles connected through plastic tub-
205 ing to a peristaltic pump on top of the wave flume. Following *Bosman et al.* [1987],
206 intake velocities amounted to 2.3m/s, exceeding the maximum orbital velocities measured
207 by more than 1.5 to guarantee a constant sediment trapping efficiency. The nozzle in-
208 take diameter was 3mm (same as *Bosman et al.* [1987]) and the pump discharge was
209 1L/min. The 30mm long nozzles were oriented parallel to the bed and perpendicular to
210 the wave direction. The nozzles were located in the lowermost 20cm above the bed at
211 distances of 4cm, coinciding with the ACVP measurement domain (Figure 1b/c). The
212 collected sediment-water mixture was treated following *van der Zanden et al.* [2017a] to
213 obtain time-averaged concentrations. Above the ACVP measuring domain (approximately
214 25–30cm and 39–44cm above the instantaneous bed elevation), two Optical Backscatter
215 Sensors (OBSs) were used to measure sediment concentrations at 40Hz. They were cali-
216 brated with sand samples from the wave flume in a replica of the apparatus explained by
217 *Downing and Beach* [1989].

218 Outer flow velocities (i.e. higher than 10cm from the bed) were measured using a vertical
219 array of three Nortek Vectrino Acoustic Doppler Velocimeters (ADV; Figure 1b/c) on the
220 mobile frame. The ADVs operated at an acoustic frequency of 10MHz and provided three
221 component (cross-shore, longshore and vertical denoted u , v and w respectively) velocity
222 measurements at 100Hz. The sampling volume is cylinder-shaped with 3mm radius and

223 2.8mm height. The lowermost ADV was located within the ACVP measuring domain,
224 approximately 10–15cm above the instantaneous bed elevation. The other two mobile
225 frame ADVs were located approximately 20–25cm and 30–35cm above the instantaneous
226 bed elevation respectively.

227 Water surface elevations were measured at 40Hz using Resistive (wire) Wave Gauges
228 (RWGs), Acoustic Wave Gauges (AWGs) and Pressure Transducers (PTs) in fixed lo-
229 cations along the flume (Figure 1). Additionally, one PT was attached to the mobile
230 frame. PTs were deployed in the surf zone instead of RWGs because, especially in large-
231 scale experiments, splashing water from breaking waves is known to affect data quality of
232 RWG measurements negatively. The dynamic pressure measurements of PTs were con-
233 verted to surface elevations via linear wave theory. The facility is equipped with a data
234 acquisition system that combines steering of the wave paddle and time synchronization
235 of instruments. ACVP and ADVs were recorded in separate computers and synchronized
236 via trigger impulses from the facility’s data acquisition system.

237 The active beach profile was measured in intervals of 30 minutes with a mechanical
238 profiler. The measurements were conducted along the center line of the flume with a
239 cross-shore resolution of 0.02m and a vertical measuring accuracy of 0.01m. During the
240 experiments, the ACVP was continuously tracking the instantaneous bed elevation under
241 the mobile frame.

3. Data analysis

3.1. Data cleaning

242 For each of the 30-minute tests, the first 5 minutes of data were discarded to remove po-
243 tential transient hydrodynamic effects. In ADV measurements, a despiking routine based

244 on *Goring and Nikora* [2002] was applied and spikes were not interpolated. Additionally,
 245 quality control measures were applied. Data with Signal to Noise Ratio (SNR) lower than
 246 75% or the amplitude of the signal lower than 15dB were discarded. This led to removal
 247 of less than 5% of data. Custom-built data cleaning routines were applied to ACVP ve-
 248 locity measurements but did not affect output considerably. In the most onshore position
 249 considered (test 105), air bubbles were observed to penetrate into the ACVP measuring
 250 domain from above, affecting the measurements. The affected parts of the domain were
 251 not considered for analysis.

3.2. Data averaging

252 Continuous time series were separated into T_r ensembles based on water surface elevation
 253 measurements from offshore of the beach slope (at $x = 28.5\text{m}$). For the separation, the
 254 repetition period which produced the lowest standard deviation over all ensembles of the
 255 test, was applied consecutively throughout the measured time series to obtain ensembles.
 256 Subsequently, ensemble-averaging (indicated by angle brackets) at individual time steps
 257 t of a variable Ψ over N ensembles according to:

$$\langle \Psi \rangle(t) = \frac{1}{N} \sum_{n=1}^N \Psi(t + (n-1)T_r) \quad (1)$$

258 was conducted. 46 ensembles were used for each test. For brevity the angle brackets
 259 and dependency on t will be omitted in most references to time-dependent, ensemble-
 260 averaged quantities. To obtain a higher resolution and to increase robustness, sediment
 261 concentrations and velocities were ensemble-averaged before applying detailed analyses to
 262 them (e.g. multiplying them to obtain sediment flux or time-averaging). Furthermore,

ensemble-averaging isolates periodically-repeating processes from the stochastic variability inherent to concentrations and flow velocities, and allows more detailed study of the processes.

Time-averaging was conducted at wave group and short wave time scales. For the former, the whole repetition period T_r was considered as the averaging period T_{av} ; for the latter, the repetition period was divided into single short waves, based on upcrossings of ensemble-averaged horizontal free stream velocity u_∞ , taken at 5cm above the instantaneous bed elevation. Then, every intrawave time step during the repetition period was associated with one of the short waves and the averaging period T_{av} spanned from the first time step of a short wave to the last. Quantities like horizontal velocity u , for example, were then time-averaged according to:

$$\bar{u} = \frac{1}{T_{av}} \int_0^{T_{av}} \langle u(t) \rangle dt. \quad (2)$$

3.3. Exner transport calculations

To obtain net sediment transport rates from beach profile transect measurements, the beach profiles before and after each test were input into the Exner equation:

$$Q_p = Q(x_i) = Q(x_{i-1}) - (1 - p) \int_{x_{i-1}}^{x_i} \frac{\Delta z}{\Delta t} dx \quad (3)$$

where $Q(x_i)$ is net sediment transport rate in the current cross-shore grid point, $Q(x_{i-1})$ is net sediment transport rate in the previous grid point, p is porosity of the sediment (measured to be 0.36), Δz is the elevation change calculated from beach profiles before and after the test and Δt is the duration of the test. To obtain output at every cross-shore grid

280 point, a step-wise iteration starting from a known boundary condition is necessary. Very
281 far offshore and on the emerged section of the beach only negligible transport rates are
282 expected. This provides the necessary boundary conditions of zero net sediment transport
283 rate. However, small measurement inaccuracies accumulate during the step-wise iteration
284 over the beach profile. Therefore, the second boundary condition on the opposite end of
285 the profile is commonly not satisfied and a residual remains. To account for the residual, it
286 was evenly distributed over the whole cross-shore domain. In the process, the assumption
287 that inaccuracies occur evenly over the whole profile, and not in single points, was made.
288 For more details see *Baldock et al.* [2011].

3.4. Acoustic signal inversion to sediment concentration

289 The ACVP supplies profiles of acoustic backscatter intensity. Sediment concentration
290 information can be derived from the ACVP backscatter intensities following the method-
291 ology of *Hurther et al.* [2011]. This inversion from intensity to concentration is done by
292 iterating downwards from the emitter while accounting for the signal attenuation occurring
293 along the way, as described in detail by *Fromant et al.* [2018]. The interpretation requires
294 calibration of system-dependent, particle backscattering and attenuation constants.

295 In the present study two types of data were used for calibration and the same calibration
296 constants were used in all tests. On the one hand, TSS measurements of time-averaged
297 concentration were used to assess agreement in all considered tests. Here, a complicating
298 factor was the time-varying elevation of TSS concentration measurements taken at a
299 fixed vertical position over an eroding/accreting bed. In most tests the time-averaged
300 concentration profile from the ACVP was within one order of magnitude of the single
301 data points given by the TSS (comparative figures are not shown for brevity). On the

302 other hand, volumetric net transport rates Q_p from beach profile transect measurements
303 were used for calibration.

304 The ACVP domain is limited to 20cm above the bed with potential reductions due to
305 bed elevation changes (as explained in detail in section 3.5). In offshore locations, the vast
306 majority of sediment flux is found near the bed and within the ACVP domain. In onshore
307 locations, however, fluxes occur at higher elevations above the bed as well. Therefore,
308 additional net sediment transport rates at higher elevations from OBS and ADV mea-
309 surements (explained in detail in section 3.6) were considered during the calibration. The
310 results on net sediment transport rate (shown later in section 4.5) feature a comparison of
311 the net transport rates obtained from the different methods to outline calibration agree-
312 ment. Considering the fundamentally different methods of obtaining net transport rates
313 and the uncertainties of the methods, the agreement is accepted as good enough.

314 During the calibration stage, dissatisfying net transport rate agreement became visible
315 in tests on the onshore side of the bar crest. On the one hand, this may result from
316 the limited vertical extent of ACVP and OBS/ADV measurements in combination with
317 sediment suspension to higher elevations under breaking waves. On the other hand,
318 detailed analysis of acoustic backscatter intensity profiles in the respective tests revealed
319 signal drop-outs at crest phases of the largest short waves. The drop-outs are suspected to
320 be caused by air bubbles which were entrained into the water column by breaking waves
321 (see Cáceres *et al.* [2020]). The bubbles are suspected to block the signal entirely at
322 those phases. Tests with drop-outs in more than 5% of the ensemble-averaged repetition
323 period were discarded. In tests with successful concentration measurements, the upper

324 limit of the sheet flow layer was obtained from the 8%-volumetric concentration criterion
325 [*Dohmen-Janssen et al.*, 2001] applied to ensemble-averaged concentrations.

3.5. Bed elevation changes

326 The instantaneous bed elevation below the mobile frame was measured via the ACVP
327 at every time step based on the methodology given in *Hurther and Thorne* [2011]. When
328 considering bed evolution, two time-scales are important. On the one hand, there was
329 gradual erosion and/or accretion over the duration of the whole test (blue line in Figure
330 2a). To ensure that measurements in different ensembles (e.g. from the start and end
331 of a test) are comparable, the gradual trend of bed evolution over the test was obtained
332 by lowpass-filtering the bed evolution (shown in red). Subsequently, every ensemble of
333 instantaneous bed elevation, sediment concentration and velocity measurements was cor-
334 rected for the gradual bed evolution, z_{filtered} , by shifting the ensembles' measurement bins
335 vertically under the use of $\zeta_0(t) = z - z_{\text{filtered}}(t)$. In this way, all ensembles refer to the
336 same intrawave coordinates instead of absolute coordinates and ensemble-averaging only
337 occurs after the coordinate shift. Note, however, that referencing with the gradual trend
338 of bed evolution limits the vertical extent of ensemble-averaged outputs to the smallest
339 vertical extent over all ensembles (the ensemble-average at a specific elevation cannot be
340 calculated when some of the ensembles do not feature output at this elevation). As a
341 result, tests with large bed accretion under the ACVP only provide profiles with a very
342 limited vertical extent.

343 On the other hand, there were instantaneous bed changes during the repetition period.
344 Those were preserved and ensemble-averaged (after conversion to the vertically-shifted
345 coordinate system) to obtain a detailed understanding of the intrawave bed evolution

(Figure 2b). In flow tunnel experiments (e.g. *O'Donoghue and Wright [2004a]*) the vertical coordinate system typically refers to the stillwater bed level. In the present study, the profile is evolving so that a different vertical reference is necessary. The bed level during the u_∞ upcrossing of the first short wave in the group, ζ_{cross} , was chosen for this purpose and the bed-referenced ζ -coordinate system (pointing upwards) is given by $\zeta(t) = \langle \zeta_0(t) \rangle - \zeta_{\text{cross}}$. Whereas single instantaneous bed ensembles are limited to the ACVP's vertical resolution of 1.5mm (note the edginess in Figure 2a), their ensemble-average provides the bed elevation at sub-bin accuracy (Figure 2b). Yet, this ensemble-averaging makes the assumption that a large number of ensembles provides a more reliable output than the single bed elevation ensembles. An assumption justified by the fact that bed interfaces normally have a smaller extent than the available resolution of 1.5mm.

ACVP velocity and concentration filtering (explained in more detail in the following section), and time-averaging to obtain sediment flux profiles, was conducted under use of the ζ' -coordinate system to ensure that the signal is not interrupted by the evolving bed. The origin of the ζ' -coordinate system is the instantaneous erosion depth according to $\zeta'(t) = \zeta(t) - \zeta_{\text{bed}}(t)$, where $\zeta_{\text{bed}}(t)$ is the black line in Figure 2c/d, and the necessary additional coordinate shift was applied to already ensemble-averaged data. To illustrate why there is a need for the ζ -coordinate system, the Figures 2c/d feature an example of near-bed sediment concentration. The example shows considerable intrawave bed evolution during T_r (Figures 2c). In bins below the maximum intrawave bed elevation, the intrawave time series is intercepted by phases of no-flow boundary condition. This causes problems in filtering and phases of no-flow boundary condition should not influence the value of outputs over the whole time series – neither outputs from filtering

369 nor from time-averaging. Use of the ζ' -coordinate system ensures that time-averaging over
 370 T_r does not consider values from no-flow boundary conditions and that reliable outputs
 371 are obtained from filtering. Nevertheless, to appreciate bed elevation changes during T_r ,
 372 filtered intrawave time series will be shifted back to the ζ -coordinate system for graphical
 373 representation.

3.6. Sediment transport calculations

374 Sediment fluxes, q , from ACVP measurements were calculated as the product of co-
 375 located horizontal velocity and sediment concentration. To obtain a better understand-
 376 ing of sediment transport processes, a Reynolds decomposition was applied to ensemble-
 377 averaged concentrations and velocities:

$$q_{tot} = \langle u \rangle \langle C \rangle = \bar{u} \bar{C} + u_{ig} C_{ig} + u_{sw} C_{sw} \quad (4)$$

378 where subscript "ig" indicates infragravity components and subscript "sw" indicates
 379 short wave components. In data treatment, the fluctuating contributions are separated
 380 into frequency bands via filtering. Note that in the present study the short wave compo-
 381 nent does not contain fluctuations at turbulence frequencies because of prior ensemble-
 382 averaging. In the multiplication of decomposed concentrations and velocities only the
 383 highly correlated terms are considered, assuming that the other terms are negligibly low
 384 (e.g. *Ruessink et al.* [1998] or *Brinkkemper et al.* [2018]). In fact, the net transport
 385 rates from those terms were verified to be multiple orders of magnitude lower than the
 386 considered ones (not shown for brevity).

387 Fourier-based filtering techniques require a certain length of the time series in order to
388 capture all harmonic components correctly. Therefore, the ensemble-averages of concen-
389 tration and velocity were artificially repeated a number of times (>50) before applying
390 a 6th order Butterworth filter with cut-off frequency 0.117Hz. Note that the cut-off fre-
391 quency was optimized via spectral analysis to ensure the clean separation of frequency
392 bands. The high-passed outputs were multiplied to obtain short wave sediment fluxes,
393 q_{sw} . In the low-passed outputs, the time-average was subtracted and they were then
394 multiplied to obtain infragravity sediment fluxes, q_{ig} . Net fluxes were then obtained by
395 time-averaging the time dependent fluxes as explained previously (section 3.2).

396 The net current-related (mean) flux, q_c , was obtained by time-averaging total concen-
397 tration and velocity and multiplying them. Net sediment transport rates from ACVP
398 measurements, Q_{ACVP} , were obtained by depth-integrating ensemble-averaged sediment
399 fluxes at every time step of T_r and averaging over time at wave group and short wave
400 scales. In offshore positions, the ACVP measuring domain is expected to encompass all
401 notable sediment flux. Closer to the outer bar crest, sediment is suspended to higher
402 elevations so that sediment fluxes also occur outside the ACVP domain.

403 Therefore, additional net fluxes and transport rates were calculated from OBS and ADV
404 measurements. Due to bed elevation changes over the test (Figure 2a), the instruments
405 measured at different elevations over the bed. At the used ADV vertical elevations,
406 small vertical gradients in the velocity profile are expected. The concentration profiles,
407 on the other hand, may feature large vertical gradients. Therefore, every concentration
408 measurement from OBS was first associated with its elevation over the instantaneous
409 bed in the ζ' -coordinate system. Second, the measurements were grouped in bins of 5cm

410 vertical elevation. Finally, at every intrawave phase the ensemble-average was taken over
411 the measurements within each group, outputting a single data point for every 5cm vertical
412 bin. Spline and logarithmic functions were then fitted to the data points from OBS and
413 ADV measurements respectively. Subsequently, the fitted functions were evaluated in
414 elevations below the highest ADV data point. As the highest ADV data point was always
415 located below the highest OBS data point (Figure 1), there was no extrapolation of data.
416 Subsequently, decomposition and calculation of sediment fluxes from OBS and ADV were
417 done in the same way as described previously for fluxes from the ACVP.

418 For total net sediment transport rates, depth-integrals were calculated at every time
419 step of T_r over the total vertical domain available from ACVP, OBS and ADV. For bedload
420 net transport rates, instantaneous erosion depths and upper sheet flow limits were used
421 as integration boundaries (within the ACVP measuring domain). For suspended load net
422 transport rates, upper sheet flow limits and the upper ends of the domain available from
423 ACVP, OBS and ADV were used as integration boundaries.

3.7. Cross-shore data aggregation

424 In most analysis steps, results from different tests and different E2 sequences will be
425 aggregated to obtain a cross-shore resolution of measurements around the migrating outer
426 breaker bar. To do so, the cross-shore positions of measurements were normalized with
427 the breaker bar cross-shore position based on visually-identified bar crests, as exemplified
428 in Figure 3 via the dashed vertical lines. The validity of this normalization for the study of
429 morphodynamic processes was shown in earlier studies (e.g. *Mariño-Tapia et al.* [2007a]
430 and *Eichentopf et al.* [2018]). To confirm this for the present data, Figure 4a shows
431 that relative, rather than absolute, cross-shore coordinates determined bed evolution (cf.

432 *Eichentopf et al.* [2018], Figure 9 and following their calculation procedure). Additionally,
433 Figure 4b shows that profiles in the considered tests had a very similar shape in the
434 vicinity of the outer bar crest (3.5m offshore and onshore of it; note the relative cross-
435 shore coordinate $x' = x - x_{bar}$) and that bars had similar heights.

4. Results

4.1. Morphological evolution

436 Figure 3 exemplifies the morphological changes occurring over successive E2 tests within
437 sequence 2. Application of wave condition B already led to formation of a small outer
438 bar, as can be observed from the differences between the initial, handmade profile and
439 the profile before test 53. Under erosive wave condition E2, the outer bar is observed to
440 take a distinct shape and migrate offshore while slightly changing in shape and distance
441 to SWL ($65\text{m} < x < 67.5\text{m}$). Similarly, an inner bar grows and migrates offshore (67.5m
442 $< x < 70\text{m}$). There are bar troughs onshore of both bars. The inner surf zone and the
443 shoreline erode and retreat. The described morphological evolution was observed in all
444 tests with wave condition E2, see [*Eichentopf et al.*, 2019] for a detailed description of
445 profile evolution.

4.2. Hydrodynamics

446 Figure 3 displays the cross-shore evolution of water surface elevation quantities. To
447 obtain the wave heights of short waves, $H_{rms,sw}$, and infragravity (long) waves, $H_{rms,ig}$, the
448 power spectrum of water surface elevation was integrated over their respective frequency
449 bands using the cut-off frequency 0.117Hz (same frequency as used for separation of
450 concentration and velocity (section 3.6)). The cross-shore evolution of $H_{rms,sw}$ indicates

451 the dissipation of energy at short wave frequencies through wave breaking, which also
452 affects the size of the short wave orbits and, therefore, η_{max} and η_{min} . The cross-shore
453 evolution of $H_{rms,ig}$ shows distinct minima and maxima. In experiments with similar
454 bichromatic waves in the same wave flume, *Alsina et al.* [2016] attributed such a distinct
455 $H_{rms,ig}$ cross-shore structure to infragravity wave reflection at the beach and breakpoint-
456 generation of infragravity waves (see *Moura and Baldock* [2017] and *Padilla and Alsina*
457 [2018]). Furthermore, $H_{rms,ig}$ is larger than $H_{rms,sw}$ close to the shoreline, consistent
458 with short wave breaking and energy dissipation. In agreement with expectations under
459 breaking waves, time-averaged water surface elevations, $\bar{\eta}$, indicate a set-down offshore of
460 the visually-identified breakpoints and a set-up onshore of them.

461 Figure 5 shows measurements from the mobile frame of time-averaged (mean) velocities
462 in their cross-shore positions relative to the bar crest. Note that the figure aggregates data
463 from all E2 tests with successful sediment concentration measurements and, therefore,
464 features an ensemble-averaged beach profile centered at the bar crest, as illustrated in
465 Figure 4b. In contrast to the mechanical profiler, the ACVP considers instantaneous
466 bed evolution. The length of its ensemble-averaged measuring domain is limited by the
467 smallest distance between emitter and bed which occurred over the whole test (section
468 3.5) and more accretion was observed in the tests on the seaward face of the bar crests
469 (seaward bar migration). This led to the shorter ACVP domain visible.

470 Good agreement between ACVP and ADV time-averaged velocity measurements be-
471 comes visible (Figure 5a). Only at cross-shore locations close to the bar crest there are
472 small discrepancies. Those may result either from differential appreciation of breaking
473 processes due to the different configuration of the instruments or from the fact that time-

474 averaging of ACVP measurements is always done at the same elevation relative to the bed,
 475 whereas time-averaging of ADV measurements is always done at the same absolute ele-
 476 vation. The largest depth-dependent magnitudes of time-averaged velocity are observed
 477 just offshore of the bar crest (Figure 5b). In the furthest offshore location (test 36, 2.4m
 478 offshore of bar crest), time-averaged onshore velocity becomes visible close to the bed.
 479 This may result from short wave streaming [*Longuet-Higgins*, 1953]. Closer to the bar
 480 crest, the wave breaking influence and return current, or undertow, is more evident.

4.3. Intrawave hydrodynamics and sediment dynamics

481 4.3.1. Shoaling region

482 Figure 6 presents ensemble-averaged measurements resolving T_r in a single test 2.4m
 483 offshore of the bar crest. During T_r , seven short waves (numbered in Figure 6b) occur.
 484 As mentioned previously (section 3.2) and visible in Figure 6, the delimitation into short
 485 waves was based on upcrossings of $\langle u_\infty \rangle$. T_r is made up of two wave groups with period
 486 14.79s so that $T_r = 2 * T_g = 29.58$ s. Ensemble-averaged intrawave η -measurements over
 487 T_r (Figure 6a) show larger amplitudes of the short waves compared to the associated
 488 infragravity wave (shown in light blue). As expected under two wave groups, two crests
 489 ($t/T_r = 0.01$ and 0.51) and two troughs ($t/T_r = 0.28$ and 0.78) of the infragravity wave
 490 become visible.

491 Ensemble-averaged, co-located measurements of u_∞ show good agreement between
 492 ACVP and ADV (Figure 6b) and u_∞ is in phase with the η -measurements shown pre-
 493 viously (Figure 6a). There are large time-dependent gradients (accelerations) of u_∞ at
 494 phases of upcrossings and magnitudes of u_∞ are higher at velocity crest phases compared
 495 to velocity trough phases. In general, the short waves are visibly skewed and asymmet-

496 ric, with the larger waves in the groups being more asymmetric (as reported for different
497 experiments with bichromatic wave groups by *Padilla and Alsina* [2017]).

498 When observing the whole ACVP measuring domain from bed to emitter (Figure 6c),
499 strong near-bed gradients in contrast to approximately depth-uniform velocities at higher
500 elevations become visible. At phases of $u(z)$ crests, near-bed onshore velocities were higher
501 than the free stream ones (e.g. compare $\zeta = 0.01$ to $\zeta = 0.045$ at $t/T_r = 0.16$).

502 In Figure 6a-c a variety of phase leads become visible. In water surface elevation mea-
503 surements (Figure 6a), infragravity wave troughs would be expected to coincide with the
504 largest short waves and infragravity wave crests with the smallest short waves. However,
505 a phase shift between short waves and the associated infragravity wave becomes visible
506 (e.g. *Battjes et al.* [2004] and *Padilla and Alsina* [2017]). When comparing the water
507 surface elevations with free stream velocity measurements (Figure 6b), the short wave
508 fluctuations of u_∞ and η are in phase but there is a phase shift between u_{ig} and η_{ig} . Addi-
509 tionally, phase leads between free stream and near-bed velocity are visible (e.g. Figure 6c
510 at $t/T_r = 0.28$), with flow reversal close to the bed occurring earlier than at free-stream
511 elevations. Such phase leads are typical for oscillatory boundary layers (e.g. *Sleath* [1987],
512 *Jensen et al.* [1989] or *van der A et al.* [2011]).

513 The measurements of near-bed sediment concentration (Figure 6d) show double peaks
514 (at $\zeta < 0.005\text{m}$, visible in expansion of yellow contours) before and after the upcrossings
515 of the largest short waves (e.g. $t/T_r = 0.1$ and 0.155). They coincide with peaks in
516 offshore and onshore velocity although often the double peaks look as one merged single
517 peak especially up in the water column in comparison to elevations close to the bed. The
518 concentration peaks during the velocity crests are larger than the ones during the troughs.

519 Moreover, high concentrations during the crests extend further up into the water column,
520 resulting in expansion of the sheet flow layer. The higher peaks during the crests may
521 be linked to the rapid accelerations under velocity upcrossings and the positive vertical
522 velocity w at those phases. The sediment does not settle down fully during the time
523 span between the velocity troughs and the following crests, indicating “phase lag effects”
524 due to large sediment diffusivity (as defined in *Ribberink et al.* [2008]). This potentially
525 indicates the influence of sediment advection from adjacent cross-shore locations and that
526 sediment mobilized during the offshore wave phase is subsequently mobilized during the
527 onshore phase. This partly results from the short duration between largest offshore and
528 onshore velocity magnitudes in asymmetric waves and the relatively low settling velocity
529 associated to a relatively fine sediment size. The sheet flow layer (delimited by the 8%
530 volumetric concentration criterion [*Dohmen-Janssen et al.*, 2001]) is observed to expand
531 at phases of largest short wave crests, in line with calculations from semi-empirical models
532 (e.g. *Nielsen and Callaghan* [2003]).

533 At higher elevations ($\zeta > 0.01\text{m}$), plumes of suspended sediment are observed during
534 upcrossings of the largest short waves. Their concentrations build up slowly before the
535 upcrossings and, after their maxima, which are in phase with the upcrossings, decrease
536 more rapidly. Furthermore, during the largest short waves the sediment does not settle
537 down fully and it is mobilized importantly by the following wave even though the wave’s
538 velocity is not very large, e.g. waves 6 and 7 at $t/Tr = 0.8$. The origin of the sediment
539 suspension plumes will be investigated in depth in section 5.5.

540 4.3.2. Outer surfzone

541 Similar figures to Figure 6 are now presented in shallower water depth and very close
542 to the bar crest (0.1m offshore of it). This position is slightly onshore from the visually
543 observed position of outer wave breaking (defined as the breaking location of the highest
544 waves in the groups). The ensemble-averaged water surface elevations of the largest short
545 waves (Figure 7a) show smaller crests and shallower troughs compared to positions further
546 offshore, indicating breaking or initiation of breaking of the largest waves in the groups.
547 In wave groups, wave breaking typically starts at the largest short waves in the group
548 expanding to the adjacent waves and reducing the wave groups' modulation [*Padilla and*
549 *Alsina, 2017*]. The previously-observed phase shift between short waves and associated
550 infragravity wave is still visible, but less substantial than further offshore.

551 In comparison with the results further offshore, Figure 7b shows slightly worse agree-
552 ment between ACVP and ADV, potentially because of higher breaking intensity. Due to
553 reduced water depths, velocity magnitudes are higher and the signal is more saw tooth-
554 shaped with higher horizontal velocity gradients at upcrossings than in Figure 6b.

555 Indications of a transition from large vertical gradient in velocity close to the bed
556 to depth-constant velocity towards the upper end of the measuring domain are visible
557 (Figure 7c, note the changing vector lengths). Again, phase leads between free stream
558 and near-bed velocity and shorter onshore than offshore phases become visible.

559 Additionally, higher concentrations are observed throughout the whole repetition pe-
560 riod (Figure 7d). Concentration plumes contain larger concentrations and have longer
561 duration. In fact, suspended concentration does not have enough time to settle down
562 throughout most of T_r and the distinction between the sediment peaks during the neg-
563 ative and positive velocity phases is even less clear than in Figure 6d. This indicates

564 a larger impact of sediment advection and sediment diffusivity. These may be of spe-
565 cial importance between the wave groups ($t/T_r = 0.3$ to 0.45 and 0.85 to 0.95), where
566 suspended concentrations remain large at high vertical elevations (suspension) during con-
567 secutive waves (see also *Villard et al.* [2000], *O'Hara et al.* [2012] and *van der Zanden et*
568 *al.* [2019b]). The increased suspension might be partly induced by larger velocity magni-
569 tudes and, most likely, by larger turbulent kinetic energy (*van der Zanden et al.* [2019a]
570 and *Larsen et al.* [2020]).

571 In contrast to the other position, the intrawave bed elevation changes are more signif-
572 icant. A larger thickness of the sheet flow layer at phases of expansion, partly because
573 of their coincidence with bed erosion, becomes visible. Additionally, more short waves
574 now generate sheet flow expansions. This likely relates to the overall higher maximum in-
575 stantaneous velocities and resulting bed shear, compared to the position further offshore.
576 Furthermore, increasing velocity accelerations and the resulting increase in near-bed pres-
577 sure gradients (e.g. *Anderson et al.* [2017] or [*Ruessink et al.*, 2011]) might play an
578 important role as well.

4.4. Intrawave sediment transport

579 4.4.1. Shoaling region

580 Horizontal sediment flux over the repetition period (Figure 8) was obtained as the
581 product of ensemble-averaged, co-located horizontal velocity and sediment concentration
582 (shown in Figure 6c/d). The measured quantities were decomposed and integrated over
583 depth as previously described (section 3.6). Figure 8 presents the measured fluxes in the
584 shoaling region and includes the depth-integrated transport rates from the summation of
585 ACVP and OBS/ADV data as dotted lines.

586 Total fluxes and transport rates (Figure 8a) fluctuate in phase with u_{sw} (not shown for
587 brevity but evident from u_{∞}) and the largest fluxes and transport rates are associated
588 with the largest short waves. Offshore transport occurs over longer durations than onshore
589 transport. This may be related to the longer troughs and steeper crests of skewed waves
590 but also to the time-averaged offshore current (Figure 5). Onshore flux at crest phases
591 features higher magnitudes and notable flux magnitudes extend further up into the water
592 column than during offshore fluxes.

593 The concentration signal, which is positive at all time instants, is decomposed based
594 on the frequencies present while ensuring that the sum of decomposed components equals
595 the input signal. At certain phases this requires that c_{sw} takes negative values. However,
596 this does not mean “physically” negative, because the only physical measurement was
597 taken of non-decomposed concentrations. Rather, the negative c_{sw} values should be in-
598 terpreted in relation to the total, directly-measured concentration. Multiplication of such
599 “negative” concentrations with velocities, however, may lead to confusion over the defini-
600 tion of onshore and offshore transports. Therefore, it was chosen to refer to decomposed
601 sediment transports as either “positive” or “negative” instead of onshore or offshore and
602 to interpret them with respect to a mean, decomposed value.

603 In the short wave component (Figure 8b), positive fluxes and transport rates are domi-
604 nant, consistent with the asymmetry of the waves. Whereas positive flux extends further
605 up into the water column, negative flux is confined to regions very close to the bed. Sur-
606 prisingly, two crests and troughs can be observed over the phase of a single short wave
607 (e.g. short wave 2). This results from the decomposition of velocity and concentration,
608 as mentioned in the previous paragraph.

609 In the infragravity component (Figure 8c), negative transport is higher than positive
610 transport and its duration is longer. Highest flux magnitudes are observed in the near-bed
611 region ($\zeta < 0.01\text{m}$) and there are larger negative transport rates during the second wave
612 group, which is consistent with its larger η_{ig} amplitude (Figure 6a). Surprisingly, four
613 crests and troughs can be observed over T_r .

614 T_r contains two wave groups so that two crests and troughs of infragravity compo-
615 nents should be expected. However, crests and troughs of infragravity velocity u_{ig} and
616 concentration c_{ig} are phase shifted. In fact, calculations via cross-correlation indicate an
617 approximately depth-uniform phase shift of roughly 90 degrees between u_{ig} and c_{ig} . Thus,
618 two of the observed q_{ig} troughs (crests) result from multiplication of positive (negative)
619 u_{ig} with negative c_{ig} and two from the multiplication of negative (positive) u_{ig} with pos-
620 itive c_{ig} . As explained in more detail in section 5.6, the phase shift between u_{ig} and c_{ig}
621 originates from a phase shift between short wave envelope and infragravity wave, which
622 affects sediment transport in two ways. On the one hand, infragravity waves transport
623 the sediment stirred up by short waves and the phase shift affects their relative timing.
624 On the other hand, short waves occurring at phases of infragravity wave troughs, rather
625 than crests, are more effective in stirring sediment (smaller water depth).

626 Note that there is an additional decomposed transport component which is not shown
627 as a separate panel in Figure 8. The current-related (mean) component of sediment
628 transport results from time-averaging velocity and concentration separately before multi-
629 plying them. Therefore, it does not have an intrawave time series. Nevertheless, the total
630 transport (Figure 8a) contains the influence of this component, which is mainly negative
631 (offshore-directed; as shown in a detailed analysis in section 4.5). This leads to the off-

shore transports which are visible at certain phases in the total transport (e.g. Figure 8a
 $t/Tr = 0.25$) but not in the short wave-related transport (Figure 8b).

4.4.2. Outer surfzone

When observing sediment transports in a cross-shore position closer to the bar crest, the non-decomposed transport (Figure 9a) shows similar intrawave characteristics as mentioned previously for the shoaling zone. However, fluxes and transport rates are a factor 2-3 higher. The figure further shows that the crests and troughs of transport rate become more peaked, consistent with the more asymmetric wave shape. Furthermore, the vertical and temporal extents of onshore (offshore) flux during crest (trough) phases of the single short waves are larger.

In the decomposed fluxes (Figure 9b/c) data gaps at the upper end of the measuring domain become visible. As mentioned in section 3.5, decomposed quantities were calculated in the ζ' -coordinate system (Figure 2d) to ensure the continuity of time series in single bins. In the process, the phase with shortest vertical extent over T_r determines the vertical extent of measurements in the ζ' -coordinate system for all phases of T_r . This is because only bins with continuous information throughout T_r are accepted for decomposition. When shifting measurements back to the ζ -coordinate system for graphical representation, the data gaps become visible at phases of intrawave erosion. The position further offshore (Figure 8) did not feature the gaps in the shown vertical domain because the available vertical extent of measurements was much larger.

Similar to the total transport, the short wave fluxes and transport rates (Figure 9b) feature larger transport magnitudes (factor 2-3) as well as larger vertical and temporal

654 extent of notable fluxes than further offshore. The double crests and troughs during single
655 short waves have the same cause as described previously for the position further offshore.

656 The infragravity flux and transport rate (Figure 9c) show four troughs of near-bed
657 negative transport, similar to the ones observed further offshore. They result from the
658 same phase shift between u_{ig} and c_{ig} that was mentioned previously. Flux and transport
659 rate magnitudes are much higher than further offshore (factor 5), but are of considerably
660 lower magnitude than the short wave contributions (note the different scales). There are
661 indications of opposing flux directions during the same phase at different elevations.

662 For brevity, only the intrawave plots of the most offshore and onshore test were pre-
663 sented. In the other tests substantial flux magnitudes were observed at higher elevations
664 above the bed as well (even at $\zeta = 0.05\text{m}$ and higher) and sheet flow thicknesses up to
665 1.5cm were measured. Nevertheless, their intrawave time series of fluxes and transport
666 rates are conceptually very similar to the ones shown. Only in the infragravity compo-
667 nent there was a notable difference. Whereas Figure 9c only slightly indicates a vertical
668 separation of transport directions, this becomes much more evident in tests 53 and 54 and
669 will be explained in detail in section 5.6.

4.5. Net sediment transport

670 4.5.1. Linking net transport rates and morphological evolution

671 Figure 10 serves to connect the previously observed morphological evolution to net sed-
672 iment transport rates. As explained in section 3.3, the net transport rate which occurred
673 during a single test in each cross-shore location can be calculated by inputting beach
674 profile transect measurements into the Exner equation. Ensemble-averaging over all con-
675 sidered tests provides the red solid line shown in Figure 10a. To quantify the influence

676 of error accumulation in residuals and measurement inaccuracies, the calculations were
677 repeated without correction for residuals and with a shift of profile transect measurements
678 by their inaccuracy (up and down 1cm). This provides the error bounds (red dashed lines)
679 shown in Figure 10a. By depth-integrating and time-averaging ACVP and OBS/ADV in-
680 stantaneous sediment transport measurements, net transport rate in single cross-shore
681 locations (star and square markers respectively) can be obtained. When comparing their
682 summation (circle markers) to the net transport rate from profile transect measurements,
683 good agreement well within error bounds is observed.

684 Net offshore transport rate becomes visible over most of the region surrounding the
685 outer bar crest (Figure 10a). Only on the offshore edge of the shown domain there is
686 net onshore transport rate ($x' < -2\text{m}$ in Figure 10a). The net offshore transport rate
687 increases on the offshore side of the crest and decreases on its onshore side. The maximum
688 in net offshore transport rate obtained from the Exner equation is located slightly onshore
689 of the bar crest. The ACVP and OBS/ADV net transport rates follow a similar cross-
690 shore evolution starting from onshore transport rate in offshore positions to increasing
691 offshore transport rate in positions closer to the bar crest. However, their maximum in
692 total (sum of ACVP and OBS/ADV contributions) net offshore transport rate is observed
693 further offshore than from the Exner equation. In the breaking region, sediment might be
694 suspended up to elevations above wave trough level, forming a notable onshore-directed
695 transport contribution [*van der Zanden et al., 2017a*]. This contribution is disregarded in
696 the present approach, which might explain why the total transport rate by the combined
697 ACVP and OBS/ADV measurements (circles) tends towards more negative values than
698 the total transport rate obtained from the profile transect measurements.

699 The present variations in net transport rate indicate a distinct pattern of morphological
700 evolution over the outer bar. Increase of net offshore transport rate on the offshore side
701 of the bar ($x' < 0.5\text{m}$) results in erosion; decrease of net offshore transport rate on the
702 onshore side of the bar ($x' > 0.5\text{m}$) results in accretion. At the same time, there is larger
703 net offshore transport rate on the onshore side of the bar ($x' = 2\text{m}$) than on its offshore
704 side ($x' = -2\text{m}$). In combination this leads to offshore migration of the bar, maintaining
705 its general shape.

706 Resolving the vertical dimension of ACVP and OBS/ADV measurements (Figure 10b)
707 provides additional detail on the net transport rates. In the most offshore position (test 36)
708 the only substantial flux is observed close to the bed ($\zeta' < 2\text{cm}$) and it is onshore directed.
709 At locations closer to the bar crest, the vertical extent and magnitude of near-bed onshore
710 flux increases. At the same time, an increase in net offshore flux at higher elevations is
711 observed in locations closer to the bar crest. In the shoaling region ($x' < -0.5\text{m}$), the
712 available vertical domain of ACVP and OBS/ADV measurements captures all substantial
713 net flux, as net flux magnitudes decrease towards its upper end. On the bar crest, however,
714 offshore flux remains at the upper end of the vertical measurement domain (which is
715 also slightly shorter than in other tests because of the significant bed evolution in the
716 considered tests (53 and 105)). In general, net flux profiles are characterized by large
717 magnitudes of net onshore flux over small vertical extents close to the bed and smaller
718 magnitudes of net offshore flux over larger vertical extents at higher elevation above the
719 bed.

720 4.5.2. Depth-resolving, decomposed net fluxes

721 To explain how different time scale-related processes contributed to the observed net
722 transport rates, sediment fluxes were Reynolds-decomposed (Figure 11). Essentially, Fig-
723 ure 11 results from time-averaging of the intrawave time series shown in Figures 8 and 9.
724 Summation of the decomposed net flux profiles (Figure 11b-d) results in the total net flux
725 profile (Figure 11a).

726 The short wave-related component (Figure 11b) is characterized by large net onshore
727 flux over a small vertical extent in the near-bed region. Maximum magnitudes are ob-
728 served offshore of the bar crest ($-1 < x' < -0.5\text{m}$). The current-related component
729 (Figure 11c) is characterized by large net offshore flux near the bed and smaller net off-
730 shore flux at higher elevations. Again, maximum magnitudes are observed offshore of
731 the bar crest ($-1 < x' < -0.5\text{m}$). The infragravity-related component (Figure 11d) fea-
732 tures much lower magnitudes than the other two components. It is characterized by net
733 offshore flux near the bed and, in some cross-shore positions, net onshore flux at higher el-
734 evations ($0.03 < \zeta' < 0.1\text{m}$). In most cross-shore positions the short wave-related onshore
735 flux is counteracted by the current-related offshore flux. Whereas the short wave-related
736 onshore flux dominates near the bed, the current-related offshore flux does at higher el-
737 evations. The infragravity-related flux features both onshore and offshore contributions
738 but has lower magnitudes than the other two components. A detailed explanation of the
739 underlying sediment transport processes follows in section 5.1.

740 4.5.3. Depth-integrated, decomposed net transports rates

741 Figure 12 illustrates the cross-shore evolution of depth-integrated net transport rates as-
742 sociated with different transport components. Initially, the total transport rate is onshore-
743 directed but it becomes more offshore-directed in positions closer to the bar crest (star

744 markers in Figure 12a). The maximum of total net offshore transport rate is observed
745 around 0.4m offshore of the bar crest. Short wave- and current-related transport rates
746 have opposing directions but follow a similar cross-shore evolution. It is characterized
747 by increasing transport rate magnitudes up to the maxima at $-1 < x' < -0.5$ m fol-
748 lowed by decrease further shoreward. Infragravity-related net transport rate is initially
749 offshore-directed but, in contrast to short wave- and current-related components, changes
750 sign further onshore. Bedload and suspended load follow a similar cross-shore evolution
751 as short wave- and current-related transport components (Figure 12b). Similarly, they do
752 not change sign and their magnitudes increase initially, followed by a decrease.

753 During the morphological evolution towards equilibrium, certain components are more
754 important than others. When comparing different frequency ranges, infragravity net
755 transport rate has the smallest magnitude. Large short wave- and current-related net
756 transport rates determine the total net transport rate but cancel each other out. There-
757 fore, the resulting total net transport rate was, in certain cross-shore positions, of similar
758 magnitude as the infragravity net transport rate. When comparing the modes of trans-
759 port, in most locations larger suspended net transport rates are observed, resulting in net
760 offshore transport rate. Short wave-related net transport rate and bedload follow similar
761 evolutions but the former has larger net magnitudes. The same applies to current-related
762 net transport rate and suspended load.

5. Discussion

5.1. Sediment transport processes

763 The near-bed onshore flux (Figure 11a) results from short wave-related processes, which
764 depend on short wave orbital motion, asymmetry and skewness (Figure 11b). Time series

765 of c_{sw} close to the bed (not shown for brevity) show gradual increases of concentration
766 during the velocity trough phases, but rapid concentration spikes of higher magnitude were
767 observed at velocity crest phases. The mentioned correlations occur, more or less, during
768 all short waves and have consequences for net transport. Even though u_{sw} trough phases
769 are longer than u_{sw} crest phases, crest magnitudes are higher than trough magnitudes
770 and c_{sw} is higher during crest phases. Additionally, near-bed velocity is observed to be
771 phase-shifted ahead of u_{∞} (flow reversals inside the wave bottom boundary layer lead
772 the free-stream elevations, e.g. Figure 7) which is consistent with expectations under
773 asymmetric waves (e.g. *Sleath* [1987], *Jensen et al.* [1989] or *van der A et al.* [2011]). This
774 limits the duration over which high concentrations are correlated with negative velocities
775 and further contributes to positive transport. So that, overall, positive net flux occurs
776 near the bed.

777 At higher elevations, c_{sw} concentration peaks occur closer to the upcrossings and are
778 more evenly distributed on both sides of them (e.g. Figure 6). Furthermore, the change
779 from offshore to onshore velocity occurs more precisely at the upcrossing. Therefore, the
780 amounts of positive and negative q_{sw} are more similar at higher elevations. In combination
781 with the low sediment concentrations at high elevations this leads to very low net flux at
782 high elevations.

783 The cross-shore evolution of q_{sw} is associated to the cross-shore evolution of the short
784 waves within the groups and the resulting sediment dynamics. Through shoaling during
785 onshore propagation the orbital amplitude, skewness and asymmetry of short waves is
786 known to increase. Once the waves start breaking, their orbital amplitude, skewness and
787 asymmetry usually decrease again. Furthermore, the single short waves of a group become

788 more similar through breaking – the group is demodulating. In the present study, the short
789 waves were predominantly governed by shoaling in between $x' = -2.4\text{m}$ (test 36) and
790 $x' = -0.6\text{m}$ (test 54) and predominantly governed by breaking onshore of $x' = -0.4\text{m}$.
791 Therefore, it is not surprising that near-bed onshore flux magnitude and the vertical
792 extent of onshore flux increased from $x' = -2.4\text{m}$ to $x' = -0.6\text{m}$ and decreased again
793 after (Figure 11b).

794 For the current-related component (Figure 11c), the vertical distributions of time-
795 averaged sediment concentrations and velocities are important. The former depends on
796 many different factors including velocity shear stress (e.g. *Nielsen* [1992]), turbulence
797 injection into the water column (e.g. *Deigaard et al.* [1986]) and advection-diffusion of
798 concentration over the vertical and horizontal (e.g. *van der Zanden et al.* [2017a]). The
799 latter depends on radiation stress gradients [*Longuet-Higgins and Stewart*, 1964], which,
800 in turn, depend on wave breaking and profile slope, time-averaged onshore transport (e.g.
801 *Svendsen* [1984]) and turbulent Reynolds stresses (e.g. *Larsen et al.* [2020]). Certainly,
802 both time-averaged sediment concentration and velocity heavily depend on water depth
803 and cross-shore position relative to the bar crest. In general, the time-averaged velocity
804 profiles decreased in the near-bed region. The time-averaged concentration profiles, on
805 the other hand, increased significantly in the near-bed region. This results in the high
806 near-bed current-related flux peaks visible in Figure 11c.

807 Offshore of the bar crest (Figure 6d), continuously large concentrations were only ob-
808 served very close to the bed ($\zeta' < 0.005\text{m}$). Closer to the bar crest, suspended sediment
809 concentrations increased, resulting in constantly high concentrations at higher elevations,
810 too (e.g. Figure 7d). At the same time, there was a cross-shore evolution of time-averaged

811 velocities (Figure 5). Far offshore of the bar crest the influence of wave breaking and un-
812 dertow is low so that nonlinear streaming [*Longuet-Higgins, 1953*] and onshore transport
813 dominates (Figure 11c, test 36). Closer to the bar crest the influence of undertow becomes
814 stronger and all current-related sediment flux is offshore-directed. The largest current-
815 related offshore flux magnitude is observed at $x' = -0.6\text{m}$ (Figure 11c, test 54), consistent
816 with the position of largest time-averaged offshore velocity magnitude (Figure 5b, test 54).
817 Net flux contributions from the infragravity component (Figure 11d) are much lower
818 than the ones from the short wave- and current-related components. As discussed in detail
819 previously, magnitude and direction of its net flux depend on the correlation of c_{ig} and
820 u_{ig} . They, in turn, depend on correlation of the wave group envelope and the infragravity
821 wave, as explained in detail in section 5.6. At $-1.5 < x' < -0.5\text{m}$ the correlations were
822 such that a significant net transport rate from the infragravity component was measured
823 (Figure 12a).

824 To explain how different elevation-related processes contributed to the observed net
825 transport rates, sediment fluxes were integrated over different vertical layers associated
826 with transport as bedload and suspended load. Bedload sediment transport rate may
827 reach very high magnitudes because it occurs just above the seabed, where sediment
828 concentrations are highest. A common way to define it, is that it occurs under the
829 influence of intergranular forces [*Bagnold, 1956*]. In the absence of methods to measure
830 those forces directly, a volumetric concentration threshold of 8% [*Dohmen-Janssen et al.,*
831 2001] is usually taken to delimit the sheet flow layer and, thus, the bedload transport.
832 All transport below the corresponding intrawave varying elevation is considered bedload.

833 Thus, the net transport rate from bedload depends heavily on the magnitude and phasing
834 of sheet flow layer thickness.

835 The T_r -resolving contour plots shown previously (Figures 6c/d and 7c/d) indicate larger
836 sheet flow layer thicknesses at phases of short wave crests. At those phases the horizontal
837 velocity is directed onshore and large onshore sediment fluxes and transport rates are
838 visible. As this process clearly operates at the time scale of the short waves, a large
839 proportion of the net onshore flux by the short wave component visible in Figure 11b is
840 probably associated with bedload. At most of the other phases of T_r , the sheet flow layer
841 limit is located just above the bed. Time-averaged offshore currents were shown to operate
842 throughout T_r . In the near-bed region, their magnitude decreases rapidly (Figure 5a).
843 Nevertheless, the remaining time-averaged currents act on large sediment concentrations,
844 especially below the upper sheet flow layer limit. Therefore, part of the near-bed peak
845 in net offshore flux by the current component (Figure 11c) is probably associated with
846 bedload. Yet, the onshore bedload transport at short wave crest phases occurs over a
847 large vertical extent and at high concentrations and velocity magnitudes. Thus, bedload
848 transport rate is onshore-directed in all observed cross-shore positions (Figure 12b).

849 Suspended transport occurs whenever sediment particles in suspension are transported
850 by instantaneous or time-averaged currents. Note that the present study considers parti-
851 cles inside the sheet flow layer as not in suspension (because of the intergranular forces, as
852 mentioned previously). In suspended sediment transport the concentration magnitudes
853 and, in consequence, flux magnitudes are lower than in bedload. However, it potentially
854 occurs over larger parts of the water column, influencing net transport rates substantially.

855 At short wave timescale, there was no substantial suspended net flux (Figure 11b), as
856 explained at the top of this subsection. On a time-averaged scale, suspended concentra-
857 tions become more significant. Here, the transport direction was mainly offshore, leading
858 to large net offshore fluxes in suspension (Figure 11c). At infragravity time-scale, there
859 was some transport in suspension (Figure 11d). Interestingly, suspended transport at in-
860 fragravity time-scale can be onshore- or offshore-directed. Ultimately, the total suspended
861 transport rate is offshore-directed (Figure 12b).

5.2. Comparison to transport processes in other studies

862 The present data agree well with other large-scale experiments (*van der Zanden et*
863 *al.* [2017a] and *Mieras et al.* [2019]) when considering the mode of sediment transport,
864 either bedload or suspended load. Total net transport rate resulted from a balance of
865 net offshore transport in suspension, mainly from the current-related component, and net
866 onshore transport occurred as bedload, mainly from the short wave-related component.
867 When net bedload was larger than net suspended load, net onshore transport rate resulted.
868 In the present study and in the experiments of *van der Zanden et al.* [2017a] this occurred
869 only offshore of the outer breaker bar crest ($x' < -2\text{m}$). In the experiments of *Mieras*
870 *et al.* [2019], which focused on one cross-shore position (breaker bar crest), it occurred
871 under the waves with larger wave height. Under the previously-mentioned conditions
872 (offshore positions and large wave heights at the bar crest with wave breaking onshore
873 of the crest), time-averaged offshore currents were relatively low and wave asymmetry,
874 resulting in considerable onshore transport under short wave crests, takes an important
875 role in sediment transport processes.

876 In contrast to the other experiments (*van der Zanden et al.* [2017a] and *Mieras et al.*
877 [2019]), there was an infragravity-wave related transport component in the present study.
878 Its net transport rate was much lower than the short wave- and current-related rates, but
879 they opposed each other. As a result, in certain cross-shore position the magnitude of
880 the net infragravity-related transport was considerable when compared to the total net
881 transport magnitude and shows potential for influencing the total net transport direction
882 ($-1.5 < x' < -0.5\text{m}$ Figure 12a). In field experiments on the seaward side of bars,
883 *Ruessink et al.* [1998] identified a similar importance of infragravity wave-related transport
884 relative to short wave- and current-related transports which opposed each other.

5.3. Limitations

885 In contrast to other sediment transport studies with ensemble-averaging (e.g. *Mieras*
886 *et al.* [2019]), the present experiments featured fully-evolving beach profiles. Thus, there
887 may be doubt about the quasi-steadiness of hydro-morphodynamic conditions, which is
888 required for ensemble-averaging. To assess this, the time-averaged free stream velocities in
889 all ensembles of single tests were compared (not shown for brevity). No organized trends
890 over the course of the tests became visible and the standard deviations of each population
891 of 46 ensembles varied between 0.011 and 0.035m/s. Considering other complicating influ-
892 ences on the measurements of each ensemble, like turbulence, this variability is assumed
893 low enough for ensemble-averaging to be applicable.

894 The present experiments only featured one type of sand ($D_{50} = 0.25\text{mm}$). Repetition
895 of the experiments with coarser sand is expected to show reduced offshore bar migration.
896 This is because grains would react more quasi-instantaneously to hydrodynamic forcing
897 with less sediment suspension and less net offshore suspended transport, reducing total

988 net offshore transport rate. Repetition with finer sand, on the other hand, might show
989 increased offshore bar migration because of a less quasi-instantaneous reaction of grains.
990 However, there is the complicating factor that the net short wave-related transport rate
991 has been argued to reduce in very fine sands because of time lags [*Dohmen-Janssen et*
992 *al.*, 2002]. Indeed, calculation of their phase lag parameter with values from the present
993 experiments (not shown for brevity; use of measured sheet flow thicknesses and T_p) in-
994 dicates no phase lag effects. But for a finer sand, like the fine one ($D_{50} = 0.13\text{mm}$) in
995 *Dohmen-Janssen et al.* [2002], phase lag effects and net transport rate reduction would
996 be expected in the short-wave related transport component (assuming the same or larger
997 sheet flow layer thickness).

998 Furthermore, the present study is limited by the lack of detailed measurements on the
999 shoreward side of the bar due to air bubble intrusion from breaking waves (section 3.4).

910 To avoid such problems in the future, it is recommended to ensure that air bubbles do not
911 penetrate into the measuring domain of acoustic instruments (e.g. through larger water
912 depth or less violent breaking).

5.4. Transport processes onshore of the bar

913 In the absence of detailed ACVP measurements onshore of the bar, judgments on the
914 local sediment transport processes will be based on less-detailed measurements and results
915 from literature. Overall, it seems likely that net transport rates were still controlled by the
916 balance of offshore-directed suspended transport and onshore-directed bedload transport
917 (e.g. *van der Zanden et al.* [2017b]), which, on the seaward side of the bar, were linked
918 to current- and short wave-related transport.

919 In regards to current-related, suspended net offshore transport, undertow magnitude
920 was measured (in the excluded E2 tests) to stay constant on the bar's shoreward side
921 ($0 < x' < 1\text{m}$) and to decrease further onshore ($x' > 1\text{m}$). This is consistent with
922 expectations from experiments and numerical modeling (e.g. *Garcez-Faria et al.* [2000]
923 or *Boers* [2005], Fig. 2.17). The other factor determining current-related net transport,
924 time-averaged concentration, was not measured at sufficient detail.

925 Related measurement problems originated from air bubbles which indicate increased
926 levels of turbulence in the water column. As turbulence and sediment suspension are
927 inherently linked, see *Aagaard et al.* [2021] for example, this indicates that sediment
928 suspension at $0 < x' < 1.5\text{m}$ was either similar or larger than further onshore ($-0.5 <$
929 $x' < 0\text{m}$) – which is supported by various studies that linked turbulence from wave
930 breaking to increased sediment suspension (e.g. *Yu et al.* [1993] or *Zhou et al.* [2017]).

931 Thus, one might expect current-related, suspended net offshore transport to stay constant
932 or increase on the bar's onshore side ($0 < x' < 1.5\text{m}$).

933 In regards to short wave-related, bedload net onshore transport, hydrodynamics on the
934 shoreward side of the bar ($0 < x' < 1.5\text{m}$; in the excluded E2 tests), show reduced short
935 wave velocity amplitudes and very asymmetric short wave velocity time series. Bedload
936 is generally accepted (and often modeled) to depend on free stream velocity to a certain
937 power (e.g. *Ribberink* [1998]), so that a decreased velocity amplitude should decrease net
938 onshore transport rate. Short wave asymmetry has been linked to net onshore transport
939 rate in various experiments (e.g. *Ruessink et al.* [2009] or *Kim et al.* [2019]) and increased
940 asymmetry would be expected to increase net onshore transport rate [*van der A et al.*,

2010]. Thus, the changes in short wave-related, bedload net onshore transport would
depend on the balance of these two competing processes.

Calculations with the Exner equation indicate a decrease in net offshore transport rates
(Figure 10a, $0.4 < x' < 1.5\text{m}$). This is consistent with the balance between the previously-
mentioned processes shifting more towards asymmetry-related net onshore transports
rather than undertow-related net offshore transports. Note that there may be additional
complicating factors like transport due to steep local bed slopes (e.g. *van der Zanden et al.* [2017b]), a process often considered in numerical modeling as well (e.g. *Bailard* [1981]
or *Fernández-Mora et al.* [2015]).

5.5. Suspended sediment concentration plumes

In the sheet flow layer the present experiments show a rapid response of sediment
concentration to flow velocity, without evidence of significant phase lags. Above the sheet
flow layer, however, plumes of suspended sediment concentration not directly correlated
with velocity were observed. *van der Zanden et al.* [2017a] observed similar suspended
sediment plumes as shown in Figures 6d and 7d. They linked them to the horizontal
(by advection) instead of vertical exchange of sediment. As visible in Figure 5, the time-
averaged current is offshore-directed in the present experiments. Therefore, suspended
sediments were, in general, advected offshore. Furthermore, the time-averaged offshore
current under wave groups fluctuates in magnitude, which makes horizontal transports
from cross-shore gradients in velocity more likely.

5.6. Details of infragravity sediment transport

960 The cross-shore evolution of H_{ig} in Figure 3 indicates a quasi-standing wave pattern,
961 which is reaffirmed by the surfbeat similarity parameter, $\xi_{surfbeat}$ [Baldock, 2012], amount-
962 ing to 0.306. A similar pattern was observed in the same wave flume by *Alsina et al.*
963 [2016] and a similar result to their Figure 13a was obtained during data analysis in the
964 present study (Figure 13). At cross-shore positions around the outer breaker bar, phase
965 shifts between η_{ig} and η_{sw} of 45 to 90 degrees were measured. On dissipative beaches
966 ($\xi_{surfbeat} < 0.02$) up to the start of short wave breaking, infragravity waves are dominated
967 by second order energy transfers from short waves. As a result, they are 180 degrees out
968 of phase with the short wave envelope (e.g. *Battjes et al.* [2004]). On intermediate or
969 steep beach slopes, however, breakpoint infragravity wave generation (e.g. *Symonds et al.*
970 [1982] or *Baldock et al.* [2000]) and reflection of the ingoing infragravity wave (e.g. *Padilla*
971 *and Alsina* [2018]) become important as well and influence the phase shift. Therefore, the
972 influence of phase shifts between η_{ig} and η_{sw} changes with cross-shore location because
973 of the distance to breakpoint and shoreline [*Padilla and Alsina*, 2018]. The phase shift
974 between η_{ig} and η_{sw} causes, in turn, a phase shift between u_{ig} and c_{ig} as mentioned earlier
975 (section 4.4.1). This resulted in four crests and troughs of infragravity sediment fluxes
976 and transport rates (Figures 8c and 9c).

977 Opposing flux directions over the vertical became visible in the infragravity component
978 in positions close to the bar crest (Figure 9c and Figure 11d, tests 53, 54 and 105). These
979 are related to differences in sediment suspension. Near the bed, c_{ig} (not shown for brevity)
980 is heavily influenced by sediment suspension at short wave time scale and maxima occur at
981 times of largest short waves. This applies in all the observed relative cross-shore positions.
982 Higher in the water column ($\zeta' > 0.015\text{m}$), there is no considerable c_{ig} in offshore positions

983 (e.g. tests 36 or 39). Closer to the bar crest (tests 53, 54 and 105), however, there is
984 more suspension to higher elevations and sediment stays in suspension during the smaller
985 short waves that mark the transition from one wave group to the next (e.g. Figure 7d,
986 $t/T_r = 0.3 - 0.4$). As a result, the maxima of c_{ig} are found at times of the smallest short
987 waves. This leads to the opposing infragravity net flux direction at higher elevation.

988 Different studies have reported both onshore and offshore net transport rates from the
989 infragravity component (e.g. *Osborne and Greenwood* [1992], *Alsina and Cáceres* [2011],
990 *Cáceres et al.* [2016] and *de Bakker et al.* [2016]). The presence of free and bound in-
991 fragravity waves and the correlation of the infragravity velocity with the wave group
992 structure, which in turn dominates the infragravity sediment concentration, is the main
993 factor explaining the infragravity sediment transport direction – see for example *de Bakker*
994 *et al.* [2016] for a resumed conceptual model. When considering the present results, the
995 question arises whether infragravity sediment fluxes measured with OBSs have been ob-
996 tained in the net onshore or the net offshore part of the infragravity net flux profile as
997 it is very difficult to track the bed elevation during field experiments. The present mea-
998 surements show the importance of measuring infragravity sediment flux profiles instead
999 of single elevations to obtain a reliable depth-integrated result (sediment transport rate).
1000 Nevertheless, the presented results agree well with previous works obtained in similar con-
1001 ditions, i.e. a moderate beach slope and relatively small infragravity frequency showing a
1002 dependence between infragravity sediment flux and cross-shore infragravity wave pattern
1003 (e.g. *Alsina and Cáceres* [2011]; *Cáceres et al.* [2016] and *de Bakker et al.* [2016]). A
1004 quasi-standing wave pattern was observed to influence the phase shift between u_{ig} and

1005 c_{ig} , which determines the direction of net flux. Furthermore, phase shifts might change
1006 after wave breaking as the group loses modulation (see *Padilla and Alsina* [2017]).

6. Conclusion

1007 Sediment transport processes near the seabed were investigated through a large-
1008 scale wave flume experiment with erosive ($\Omega = 2.54$), bichromatic wave groups over a
1009 morphologically-evolving beach of medium sand. Apart from standard instrumentation
1010 in various cross-shore positions, tests featured detailed near-bed measurements of co-
1011 located velocity, sediment concentration and sediment flux profiles in single cross-shore
1012 positions. Normalization of cross-shore and vertical positions relative to the outer breaker
1013 bar position and elevation allowed the analysis of near-bed hydrodynamics and sediment
1014 transport processes during erosive beach profile evolution (offshore bar migration) in a
1015 quasi-steady equilibrium state. Aggregation over 6 tests ranging from shoaling to breaking
1016 zone provided insights into the processes' cross-shore evolution. To investigate processes
1017 further, measurements were frequency-filtered and divided into transport modes (bedload
1018 and suspended load). Based on the results we conclude the following:

1019 1. Total net transport rate mainly resulted from a balance of onshore-directed short
1020 wave-related transport near the bed and offshore-directed current-related transport. The
1021 short wave-related transport occurred mainly as bedload whereas the current-related
1022 transport occurred both as bedload and suspended load.

1023 2. Infragravity wave-related fluxes were of much lower magnitude than short wave- and
1024 current-related fluxes. However, when short wave- and current-related net fluxes canceled
1025 out in certain cross-shore positions, the infragravity wave-related net fluxes formed a dis-
1026 tinct contribution to the total net transport rate. Interestingly, some infragravity net flux

1027 profiles featured opposing directions between near-bed offshore-directed and suspended
1028 onshore-directed sediment flux.

1029 3. The outer bar offshore migration resulted from a cross-shore gradient in net offshore
1030 transport rate on the bar's offshore slope. This increase in net offshore transport rate,
1031 in turn, resulted from a stronger increase in current-related (mostly suspended) offshore
1032 transport than short wave-related (mostly bedload) onshore transport on the bar slope.
1033 The stronger increase in current-related transport only partly results from net flux mag-
1034 nitudes because the vertical extent of fluxes is a very important factor as well. Onshore
1035 flux was confined to the near-bed region whereas offshore flux occurred over large parts
1036 of the water column.

1037 4. Closer to the outer bar crest, (instantaneous and time-averaged) suspended sediment
1038 concentrations were higher and sheet flow layer thicknesses were larger, compared to
1039 locations further offshore. Sediment suspension plumes above sheet flow layer elevations
1040 indicated that not only vertical but also horizontal exchange of sediment was important.

1041 5. The main sediment suspension events were linked to short wave crests. Yet, net
1042 suspended transport by short waves was very low because fluxes under crests and troughs
1043 balanced each other. The net suspended transport by currents was considerable, be-
1044 cause time-averaged currents were always directed offshore. The net suspended transport
1045 by infragravity waves was affected by concentration processes not only related quasi-
1046 instantaneously to short wave crests but also to the complicated phase relationship with
1047 infragravity wave velocities.

1048 The present experimental data feature a combination of realistic representation of nat-
1049 ural conditions (e.g. large-scale experiments, bichromatic waves and fully-evolving beach

1050 profiles) with the high detail of measurements (e.g. multiple cross-shore locations, very
1051 high vertical resolution in lowest 20cm and continuous bed tracking for referencing of
1052 measurements) only possible in the laboratory. Therefore, they represent a further step
1053 in providing detailed hydrodynamic and sediment transport information needed for a
1054 better understanding of bar morphodynamics and related sediment transport processes.
1055 As such, they may contribute to the further development of (process-based) numerical
1056 models. The complete set of data presented in this article can be consulted online (see
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Table 1. Wave sequences in RESIST with measured wave conditions. Highlighted rows contain the tests for detailed analysis in this study.

Sequence	Test Number	Wave Condition	H_{rms}	T_p	T_g	Duration [min]	Ω [-]
1	16	B	0.3	4	n/a	30	2.21
	17–23	E1	0.42	3.7	14.79	240	3.34
	24–35	A1	0.23	4.7	33.68	600	1.44
	36–39	E2	0.32	3.7	14.79	120	2.54
	40–51	A1	0.23	4.7	33.68	600	1.44
2	52	B	0.3	4	n/a	30	2.21
	53–56	E2	0.32	3.7	14.79	120	2.54
	57–68	A1	0.23	4.7	33.68	600	1.44
	69–74	E1	0.42	3.7	14.79	240	3.34
	75–86	A1	0.23	4.7	33.68	600	1.44
3	87	B	0.3	4	n/a	30	2.21
	88–91	E1	0.42	3.7	14.79	240	3.34
	92–104	A2	0.19	5.3	37.98	780	1.05
	105–108	E2	0.32	3.7	14.79	120	2.54
	109–132	A3	0.14	5.7	40.85	1440	0.72

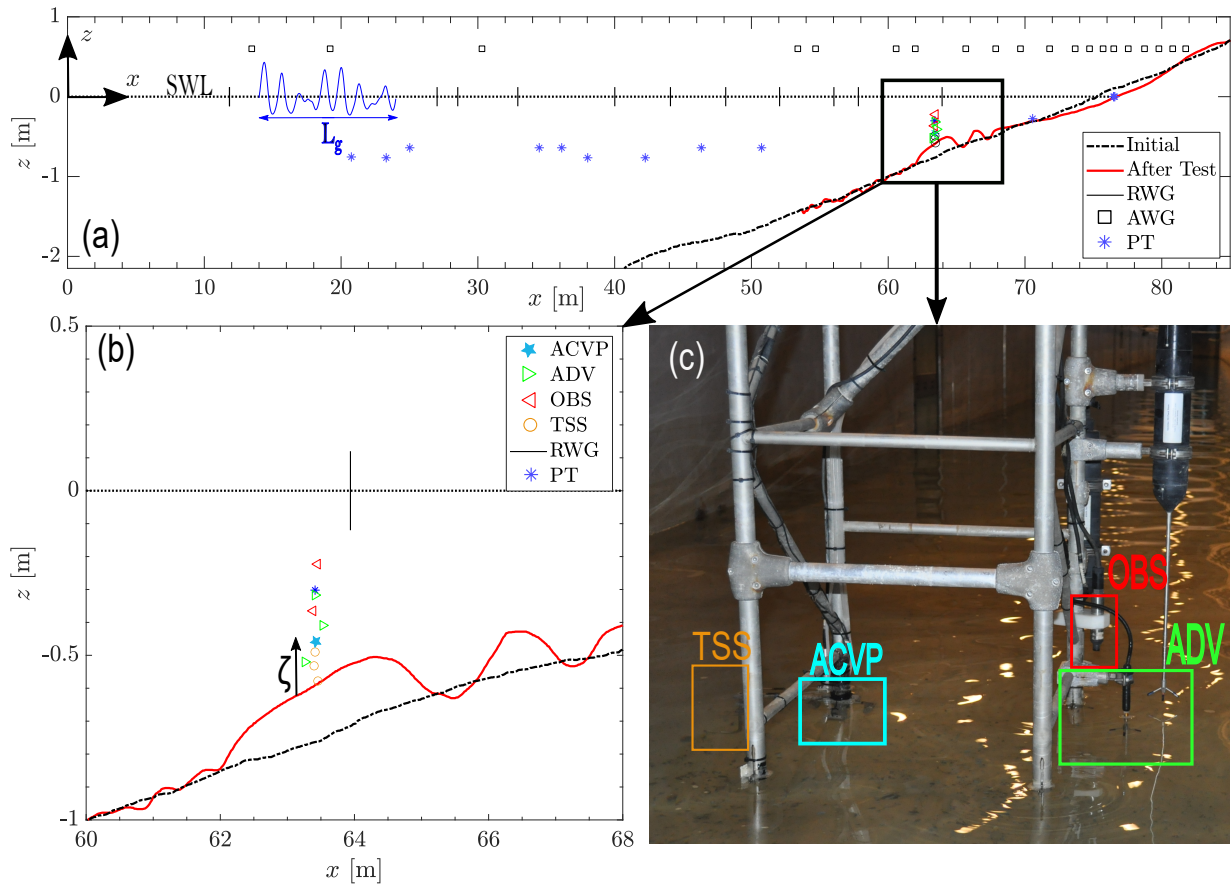


Figure 1. Layout of wave flume, experimental setup and instrumentation. (a) Entire wave flume with instruments and beach profile at the start of waves (black) and after 120 minutes of testing (red); (b) Schematic representation of instruments on mobile frame; (c) Photo of instruments on mobile frame; note that one OBS is located on the non-visible side of the frame.

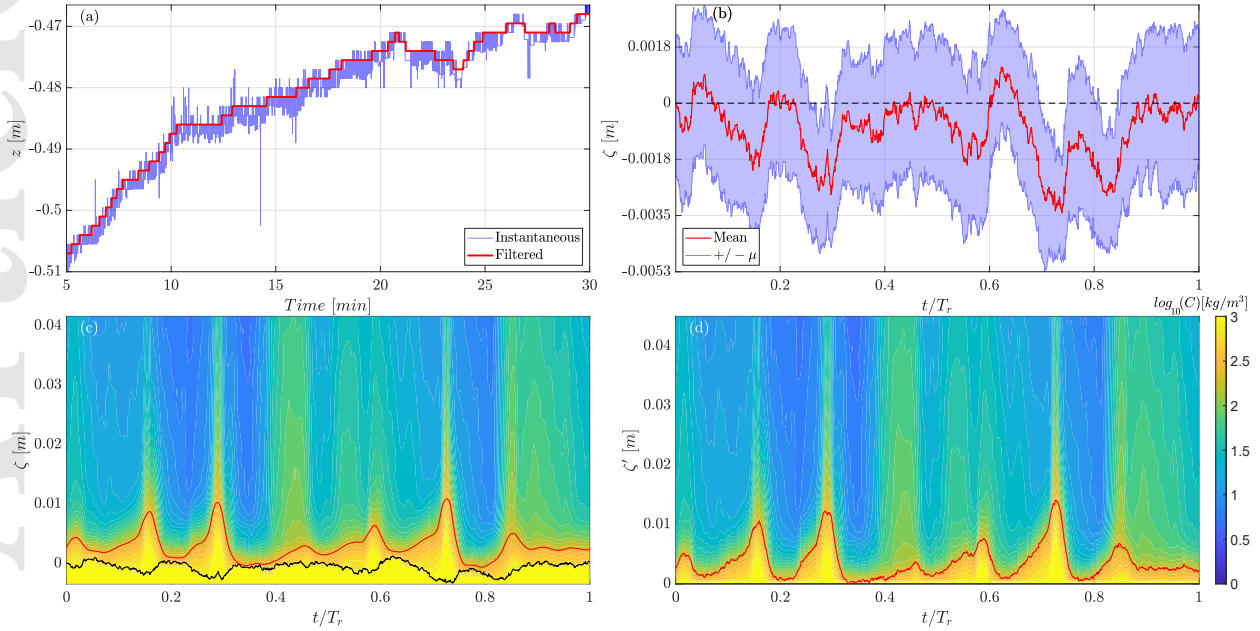


Figure 2. Differences in vertical coordinate systems, exemplified via test 54. (a) Measured and filtered bed evolution over the whole test. They are shown in the absolute flume coordinate z , which refers to SWL; (b) Ensemble-averaged intrawave bed evolution (including one standard deviation envelope) over T_r , which refers to the bed elevation during the velocity upcrossing of the first short wave in the group; (c) and (d) Near-bed intrawave concentration field with upper sheet flow limit (red line) shown in two different coordinate systems as explained in the accompanying text (section 3.5). The intrawave bed elevation (black line) in (c) corresponds to the red line in (b). In (d) the intrawave bed elevation is used for additional referencing of measurements so that its value is constantly 0.

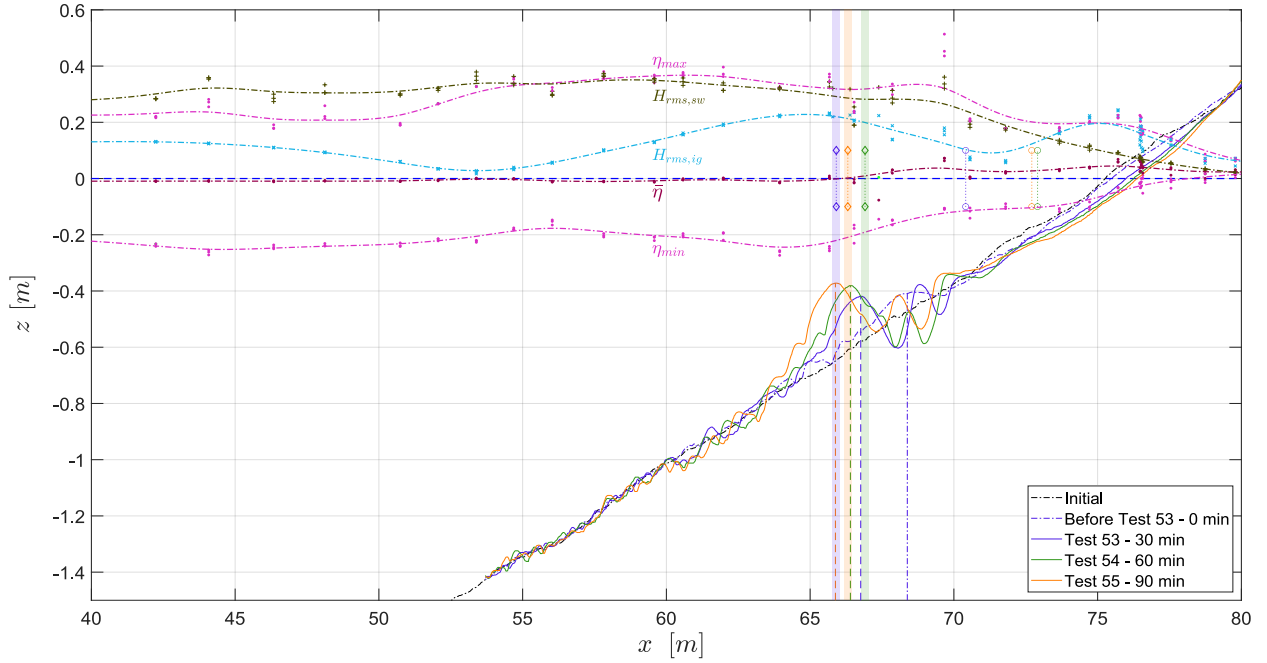


Figure 3. Example of profile evolution during application of benchmark (B) wave condition followed by three consecutive tests with erosive wave condition E2. SWL in dark blue dashed and profiles as indicated in legend (measured after the respective tests). Time-averaged water levels and short wave and infragravity wave wave heights with measured points plotted as markers and smoothing spline interpolation to obtain line. Visually observed outer breaking location (dashed vertical line with diamonds and transparent patch) and inner breaking location (dashed vertical line with circles). Identified bar maxima as dashed vertical lines.

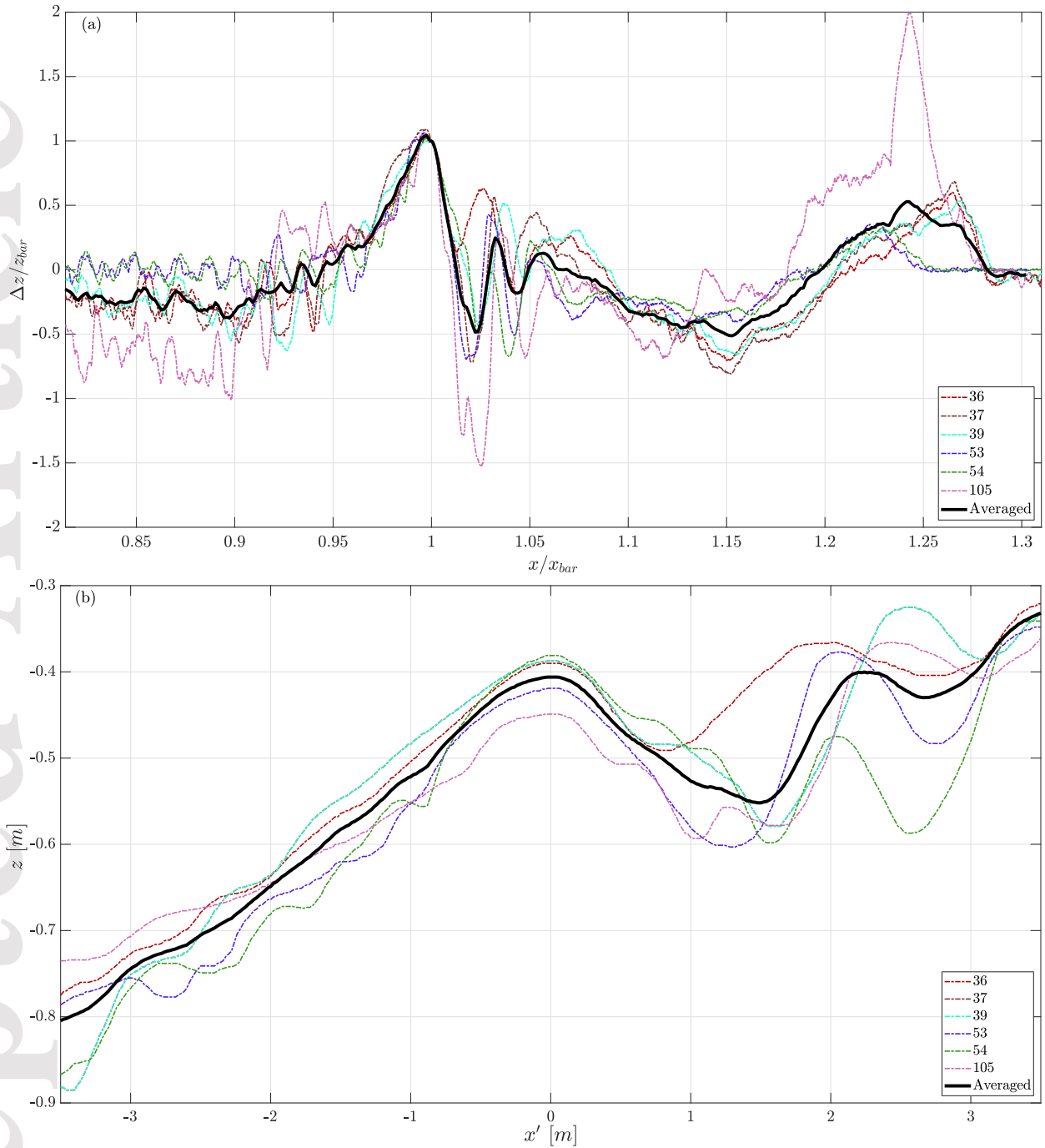


Figure 4. Generalization of morphological evolution in considered tests. (a) Bar coordinate-normalized bed evolutions (multiple colors) and their ensemble-average (black); (b) Beach profiles in vicinity of bar crest (multiple colors) and their ensemble-average (black). Note that $x/x_{bar} = 1$ in (a) refers to the same location as $x' = 0$ in (b).

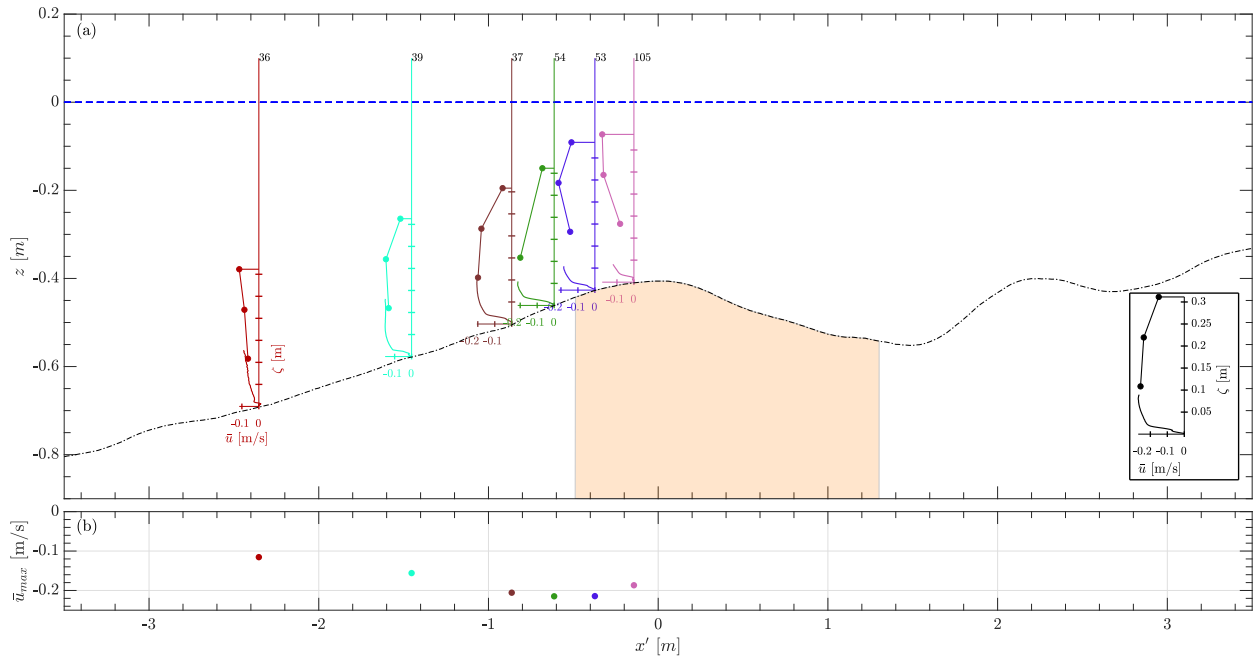


Figure 5. Time-averaged velocities in cross-shore positions relative to bar crest. (a) Horizontal velocity profiles from ACVP (near-bed solid lines) and ADVs (circles connected by solid lines) over ensemble-averaged beach profile (dashed-dotted black line) with SWL (dashed dark blue line) and test-averaged outer breaking location \pm one standard deviation (shaded area); black sketch in the bottom right corner explains inset axes; (b) Maximum time-averaged, depth-dependent offshore velocity measured by ACVP and ADVs.

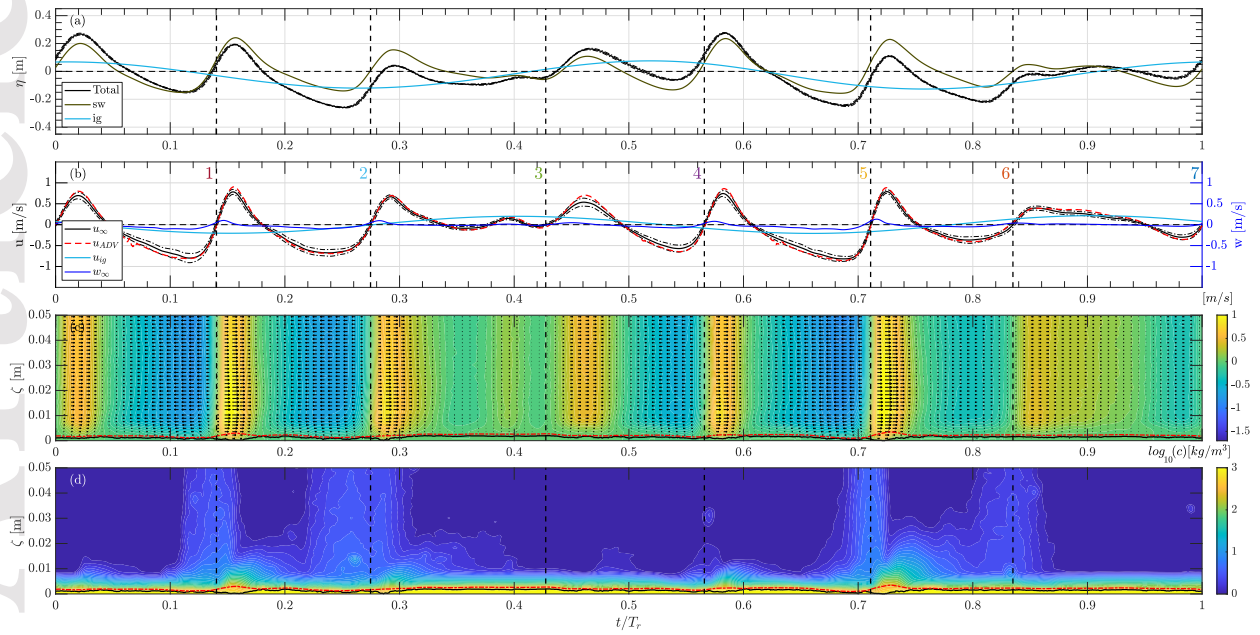


Figure 6. Hydrodynamic and sediment dynamics data in test 36 at 2.4m offshore of the bar crest in the shoaling region. Vertical dashed lines indicate separation into short waves, as numbered in (b). (a) Water surface elevations from PT shown before (black line with \pm one standard deviation as black dashed-dotted line) and after separation into short wave (dark green) and infragravity contributions (light blue); (b) Free stream velocities from ACVP (featuring \pm one standard deviation as black dashed-dotted line in u_∞) and lowest ADV, horizontal velocities referring to left y-axis and vertical velocity referring to right y-axis; (c) Near-bed velocity field from ACVP; (d) Near-bed concentration field from ACVP. Fields (c and d) referring to colorbars on their right and including instantaneous bed level (black) and upper limit of sheet flow layer (red dashed-dotted). Limited vertical extent of fields for focus on near-bed region.

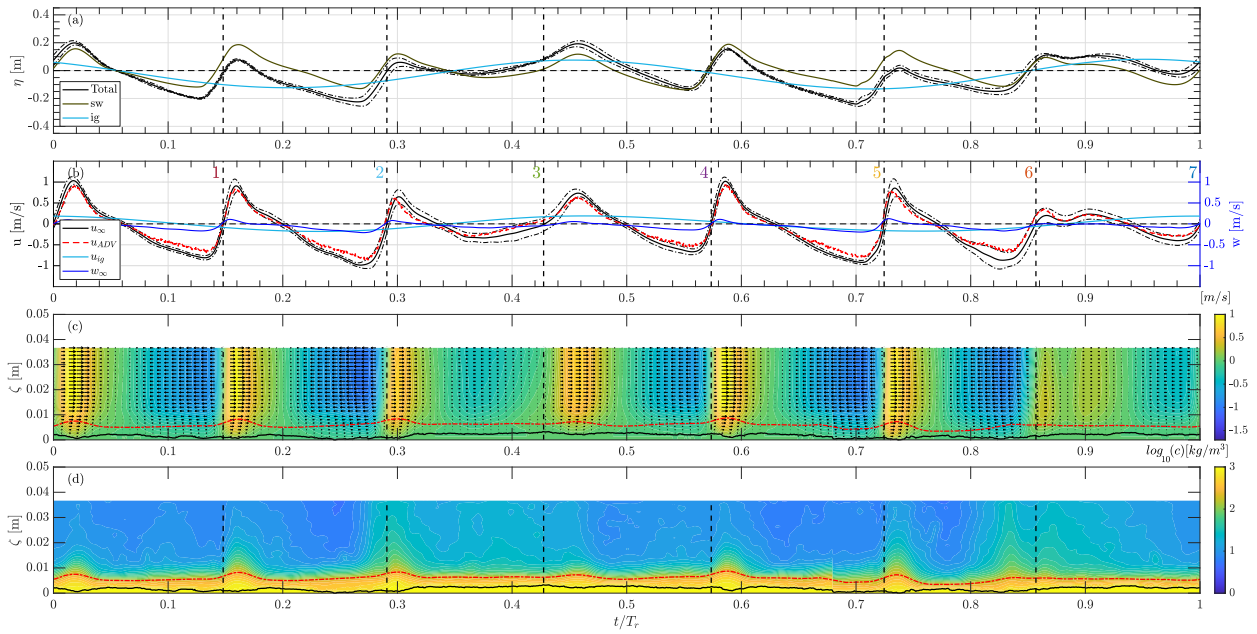


Figure 7. Hydrodynamic and sediment dynamics data in test 105 at 0.1m offshore of the bar crest in the outer breaking zone. Same definitions and color codes as previous figure. Discontinuity at $T_r = 0.685$ resulting from gateshifting on the basis of gradual bed erosion, as explained in detail in section 3.5.

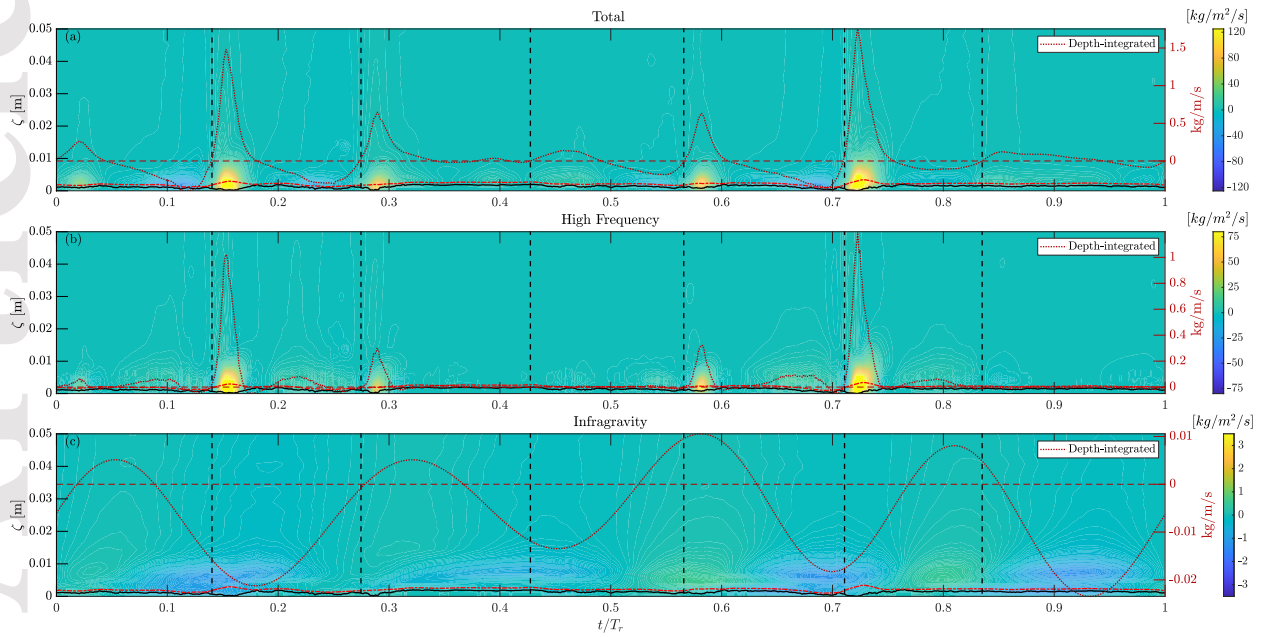


Figure 8. Decomposed sediment transport fields from ACVP with the depth-integrated transport rate (dotted line) combined from ACVP and OBS/ADV in test 36 at 2.4m offshore of the bar crest in the shoaling region. (a) Total, non-decomposed transport; (b) Short wave transport; (c) Infragravity transport. Note the different scales of the color contours and right y-axes. Instantaneous bed level (black solid line) and upper limit of the sheet flow layer (red dashed-dotted line). Furthermore, the shown onshore flux magnitudes in (a) and (b) were clipped at 125 and 80kg/m²/s for representation purposes. The highest onshore transport magnitudes were 273 and 192kg/m²/s, respectively in (a) and (b), and the limits were exceeded in 0.1% of the available data points (bright yellow patches). There is no intrawave time series for current-related transport rate but it amounted to -0.021kg/m/s.

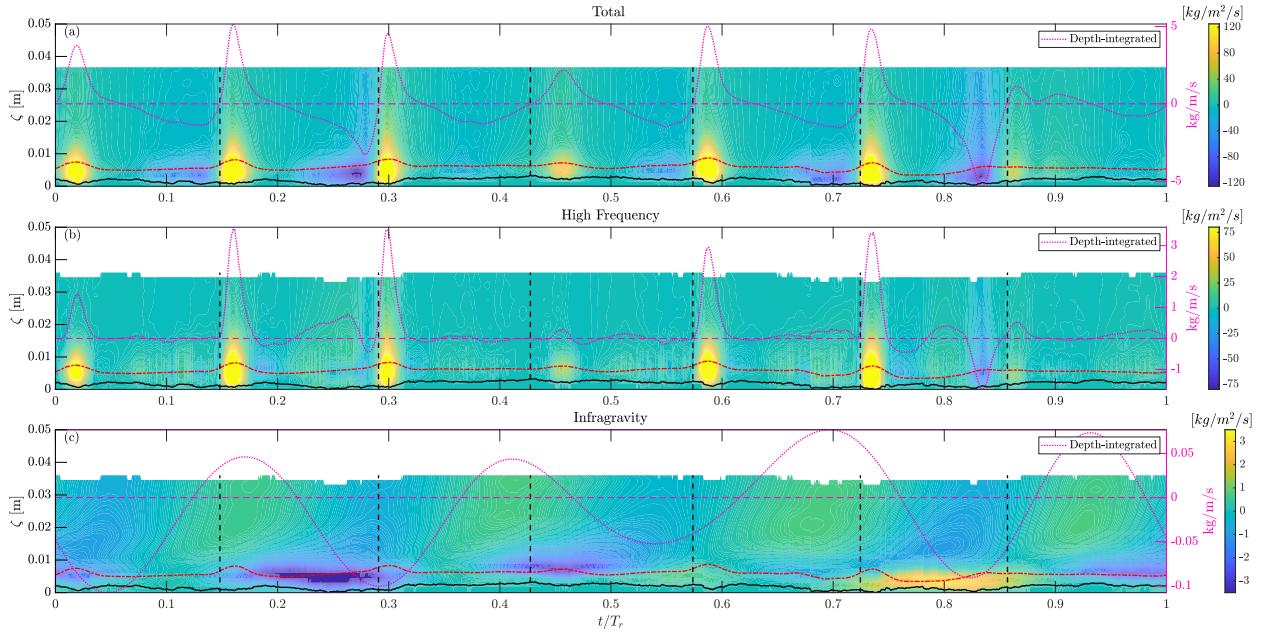


Figure 9. Decomposed sediment transport fields from ACVP with the depth-integrated transport (dotted line) combined from ACVP and OBS/ADV in test 105 at 0.1m offshore of the bar crest in the outer breaking zone. (a) Total, non-decomposed transport; (b) Short wave transport; (c) Infragravity transport. Note the different scales of the color contours and right y-axes. Instantaneous bed level (black solid line) and upper limit of the sheet flow layer (red dashed-dotted line). Again, the shown onshore flux magnitudes in (a) and (b) were clipped at 125 and 80kg/m²/s for representation purposes. Here, the highest onshore transport magnitudes were 338 and 186kg/m²/s, exceeding the limits in 1.5% and 1% of the available data points (bright yellow patches), respectively in (a) and (b). The chunky data gaps in (b) and (c) at $\zeta \approx 0.032\text{m}$ originate from the fact that calculations were conducted in the ζ' -coordinate system, as described in section 3.6. There is no intrawave time series for current-related transport rate but it amounted to -0.313kg/m/s.

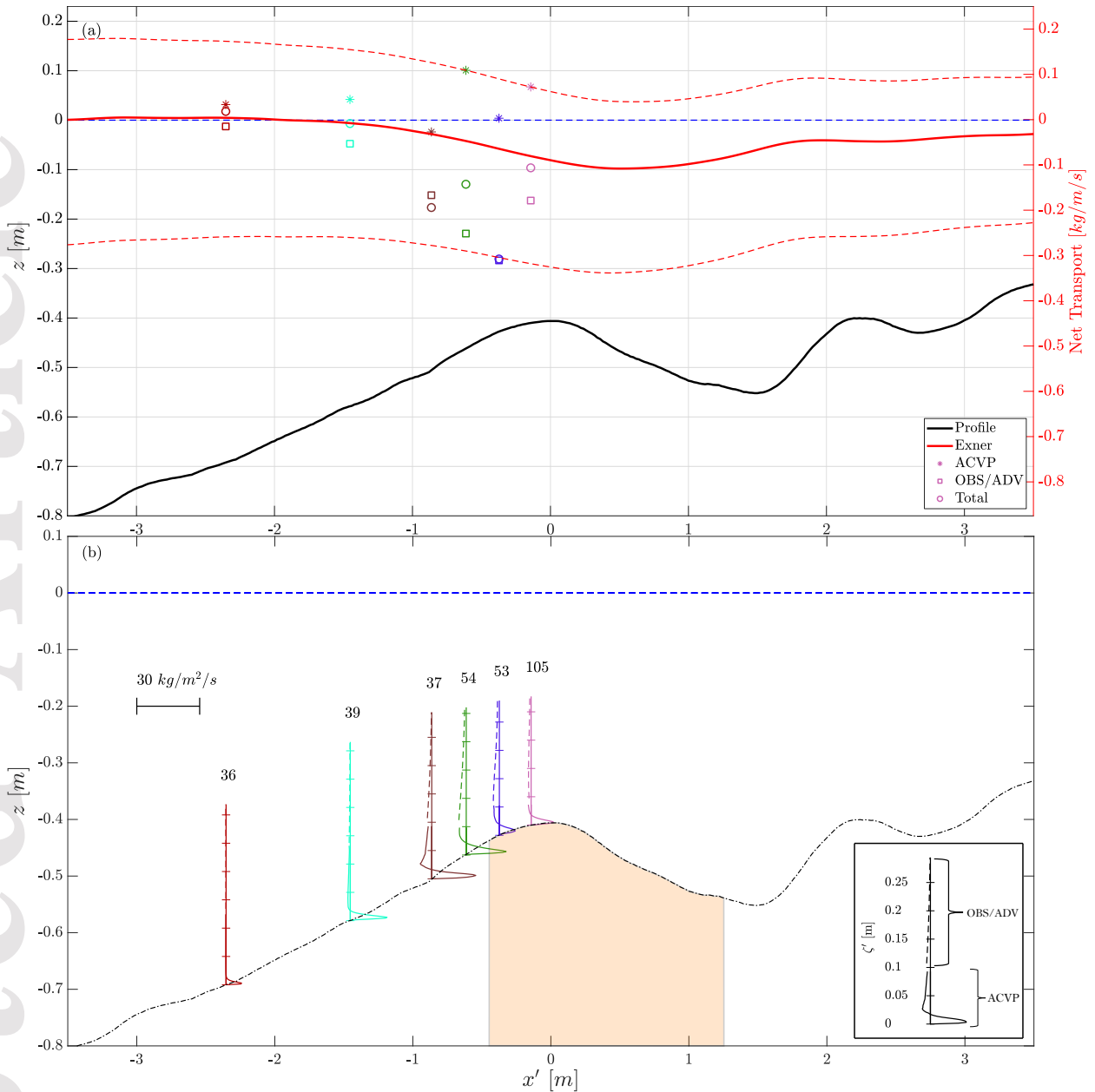


Figure 10. Net transport from mechanical profiler, ACVP and OBS/ADV. (a) Cross-shore evolution of net transport and comparison of net transport from the different methods. Profile transect measurements (red line referring to right y-axis) based on ensemble-averaging of Exner equation calculations in single tests with error bounds (red dashed lines) calculated as explained in accompanying text (section 4.5). ACVP and OBS/ADV measurements (markers of different shape with color indicating respective tests), on the other hand, are based on time-averaging and depth-integration of instantaneous measurements of horizontal velocity and sediment concentration in the ζ' -coordinate system. They are shown separately and as their summation ("Total");

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(b) Net flux profiles from ACVP (solid lines) and OBS/ADV (dashed lines) in their respective cross-shore positions and test-averaged outer breaking location \pm one standard deviation (shaded area).

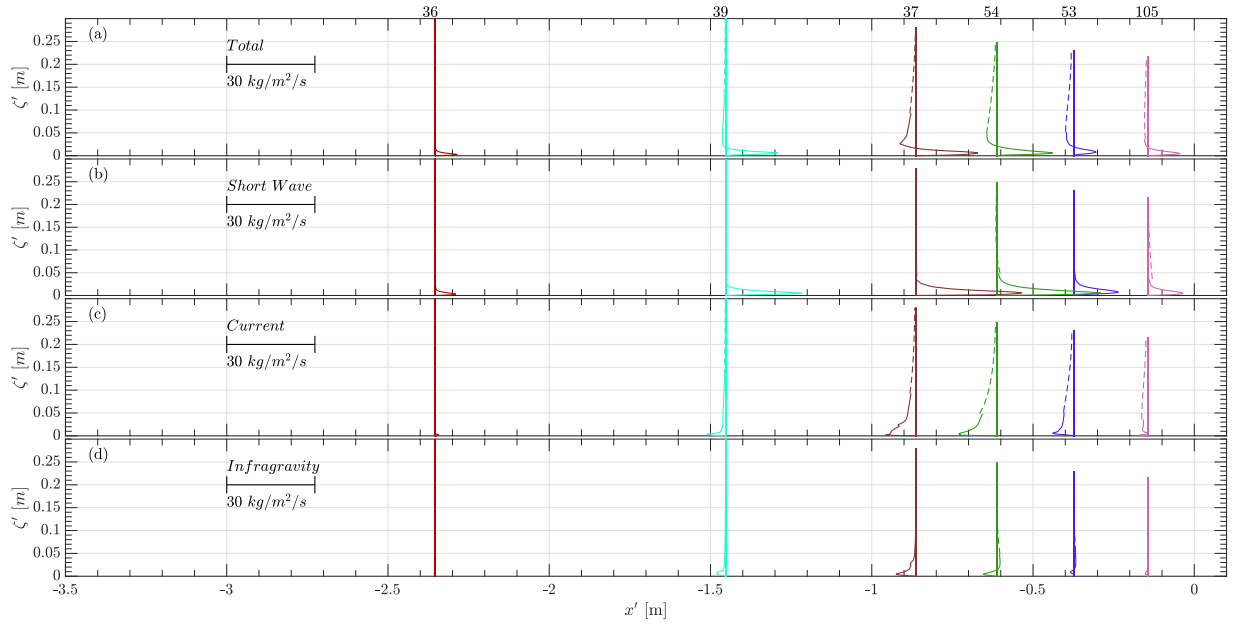


Figure 11. Decomposed net flux profiles (vertical extent of some profiles shortened for consistency) in their relative cross-shore positions. (a) Total; (b) Short wave component; (c) Current-related (mean) component; (d) Infragravity component. Combination of measurements from ACVP (solid line) and OBS/ADV (dashed line).

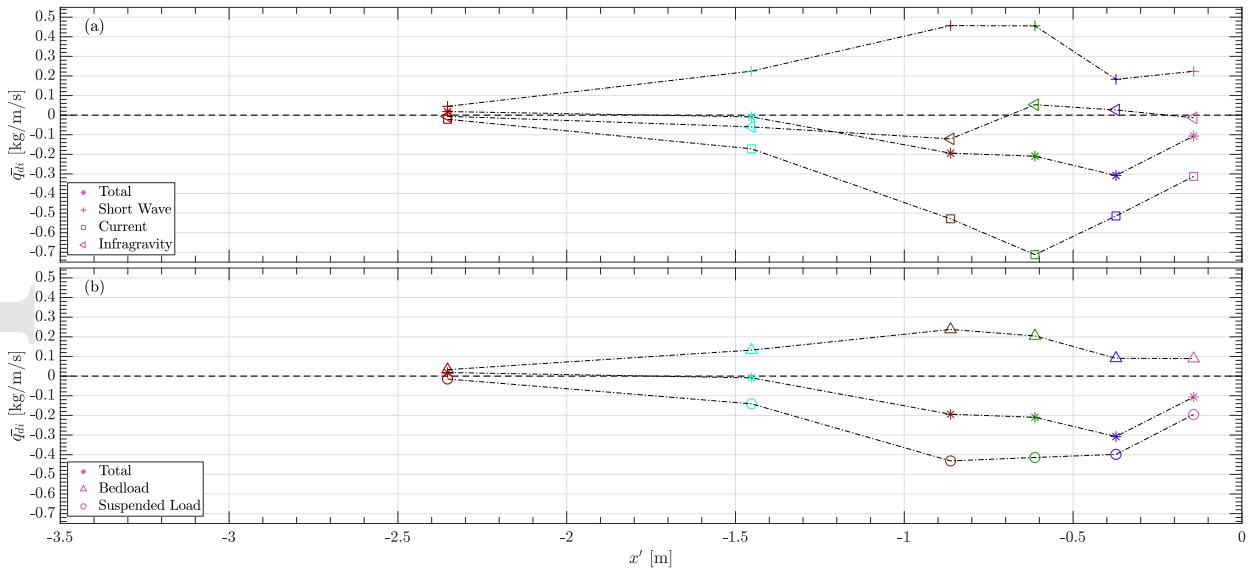


Figure 12. Depth-integrated (over entire available vertical extent as shown in Figure 10b), time-averaged sediment transports. (a) Frequency-decomposed; (b) Vertically-decomposed.

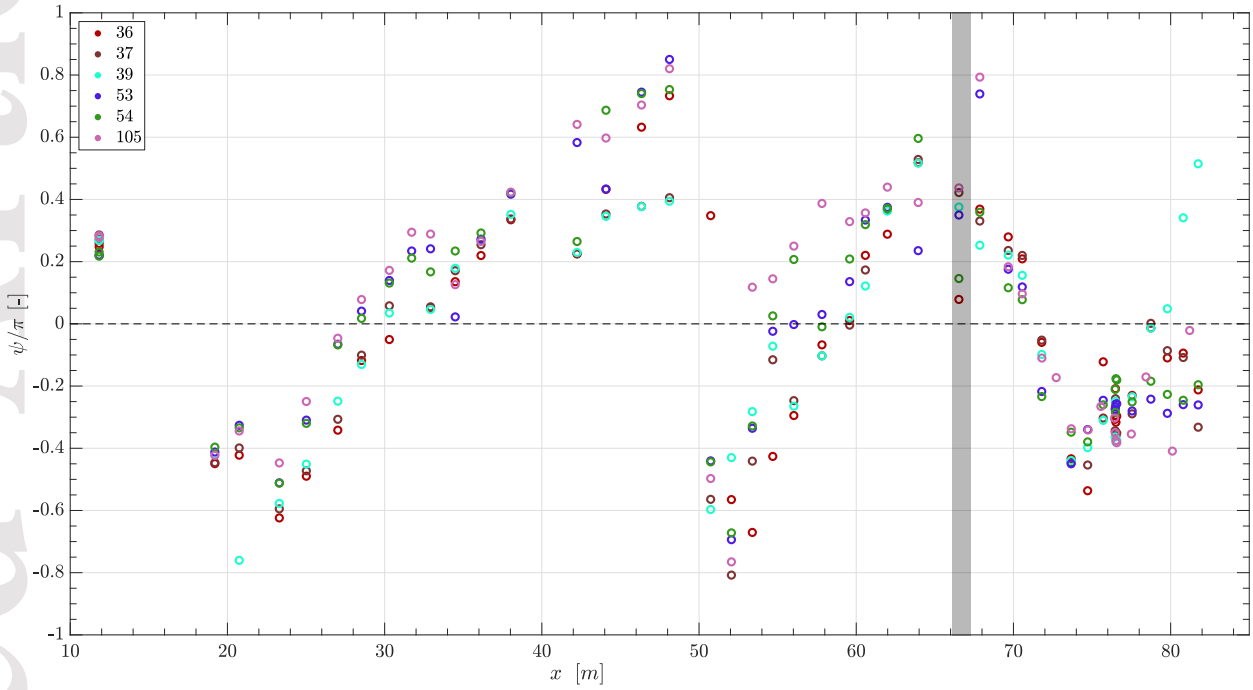


Figure 13. Phase lags ψ between infragravity waves and short wave envelopes (calculated from Hilbert transform). Different colors according to test number as shown in the legend. Horizontal axis referring to absolute cross-shore positions. Outer bar crest positions over all considered tests indicated by shaded area.