Supplementary Information - Multi-sensor observations and modeling of wave swash on a low-tide terrace beach

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ABSTRACT

This study presents the first application of the non-hydrostatic CROCO model to simulate surf- and swash-zone hydrodynamics over a continuous, week-long field experiment. Combining LiDAR, camera, and ADCP observations with fully non-hydrostatic modeling enabled detailed validation of cross-shore wave transformation and run-up dynamics. CROCO successfully reproduces dominant swash components and extreme run-up events, highlighting the influence of total incident energy (H_s and T_p), still water level, and spectral characteristics, particularly in the infragravity band.

Sensitivity analyses demonstrate the interdependence of H_s and T_p: small changes in wave period ($\approx$ 1 s) strongly influence swash response at changes in H_s, while doubling H_s amplifies sensitivity to period in a nonlinear manner. Runup increases with tide under low-energy conditions but decreases under high-energy conditions, reflecting complex interactions between incident and infragravity waves over low-tide terrace (LTT) beaches. Frequency spreading has limited effect at low energy but becomes significant at higher energy levels, further linking total incident energy and spectral properties.

Model limitations include underestimation of infragravity tidal modulation, incomplete representation of bottom friction at the swash active slope, and the absence of directional spreading for a 2DV configuration. While these factors introduce biases, adjustments to H_s and comparisons at consistent cross-shore locations confirm that key findings remain robust.

Overall, results emphasize the hydrodynamic triad of wave energy, spectral spread, and water level, and the importance of depth-controlled morphological parameters (e.g. surf-zone slope) for run-up prediction, . The study demonstrates CROCO's potential for near–real-time operational applications and supports the development of locally calibrated, site-specific run-up parameterizations, offering a foundation for, data-driven scenario analyses, and machine-learning–based coastal hazard assessment.

Supplementary figures

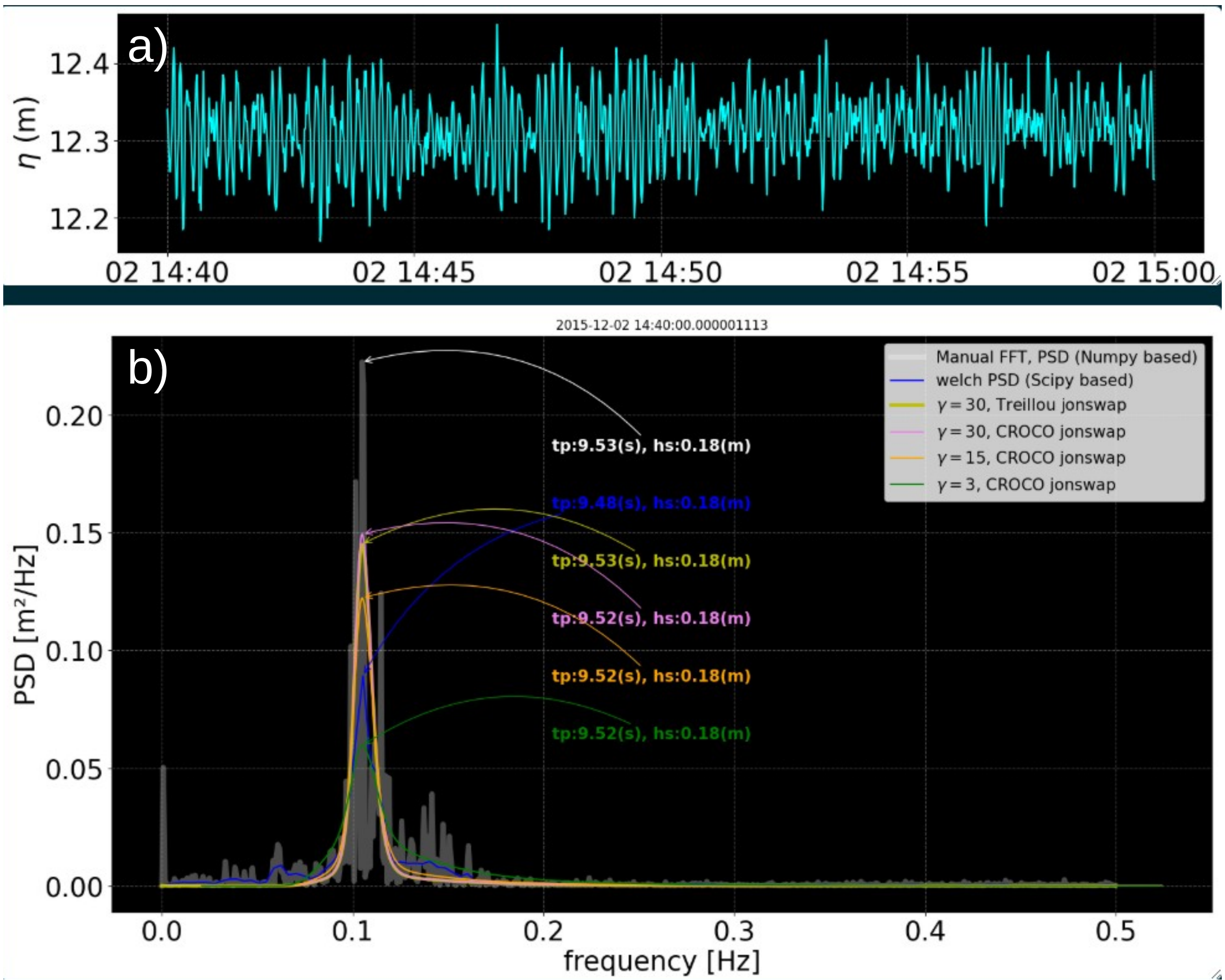

Figure 1. Spectrum comparison with actual ADCP data. Panel (a) displays a 20-minute free surface time series for a specific moment during the experiment. Panel (b) presents a comparison of the signal's power spectral density (PSD) obtained using three approaches: a direct FFT analysis, a smoothed version via the Welch method (NumPy implementation), and various JONSWAP spectra defined with different gamma values.

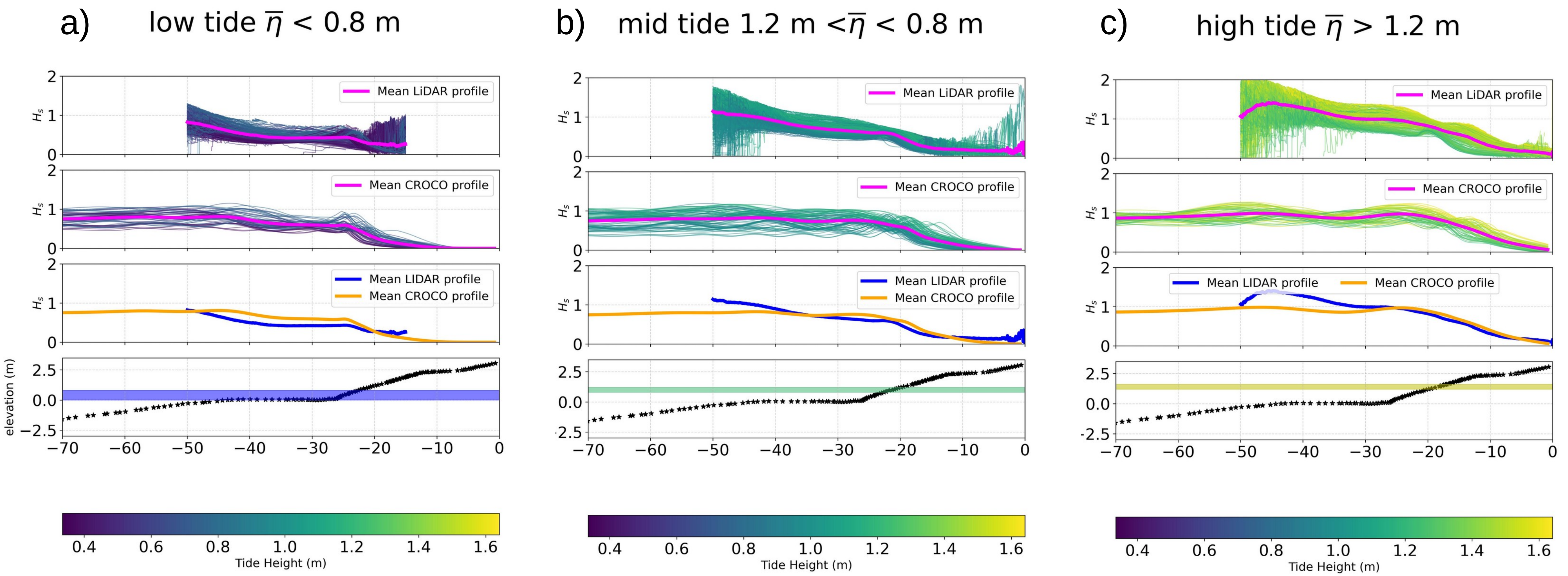

Figure 2. Comparison of LiDAR measurements and CROCO simulation of H_s profiles across low, mid, and high tide ranges (a, b, c). In each column, the first and second rows display the H_s profiles from LiDAR and CROCO, respectively. The third row presents a comparison of the mean H_s profiles, while the bottom row shows the corresponding water level elevations relative to the mean bathymetry profile.

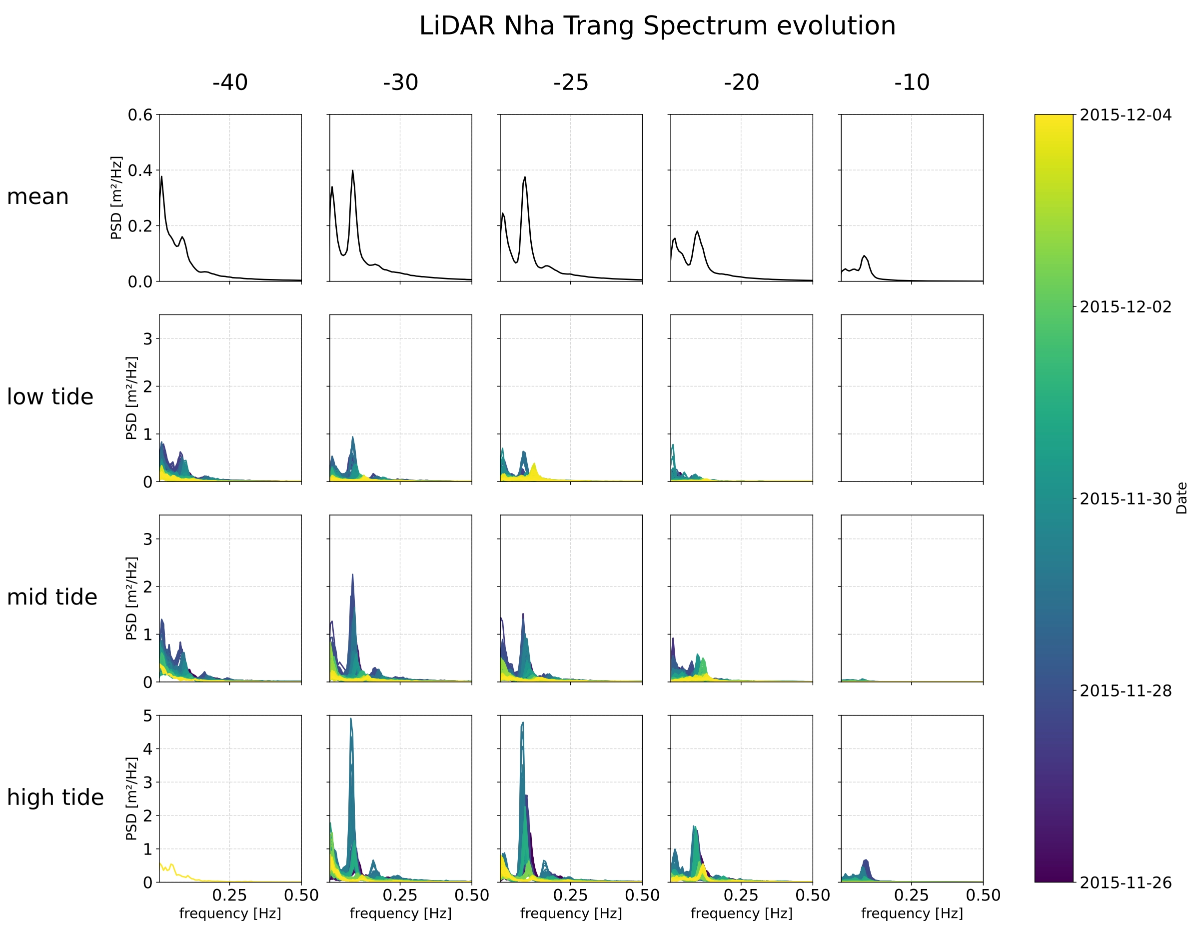

Figure 3. Spectral evolution of the water free surface at different cross-shore positions (columns) and tidal stages (rows: mean over the experiment, low: $\overline{\eta} < 0.8$; mid: $1.2 < \overline{\eta} < 0.8$, high:$\overline{\eta} > 1.2$) derived from LiDAR data.

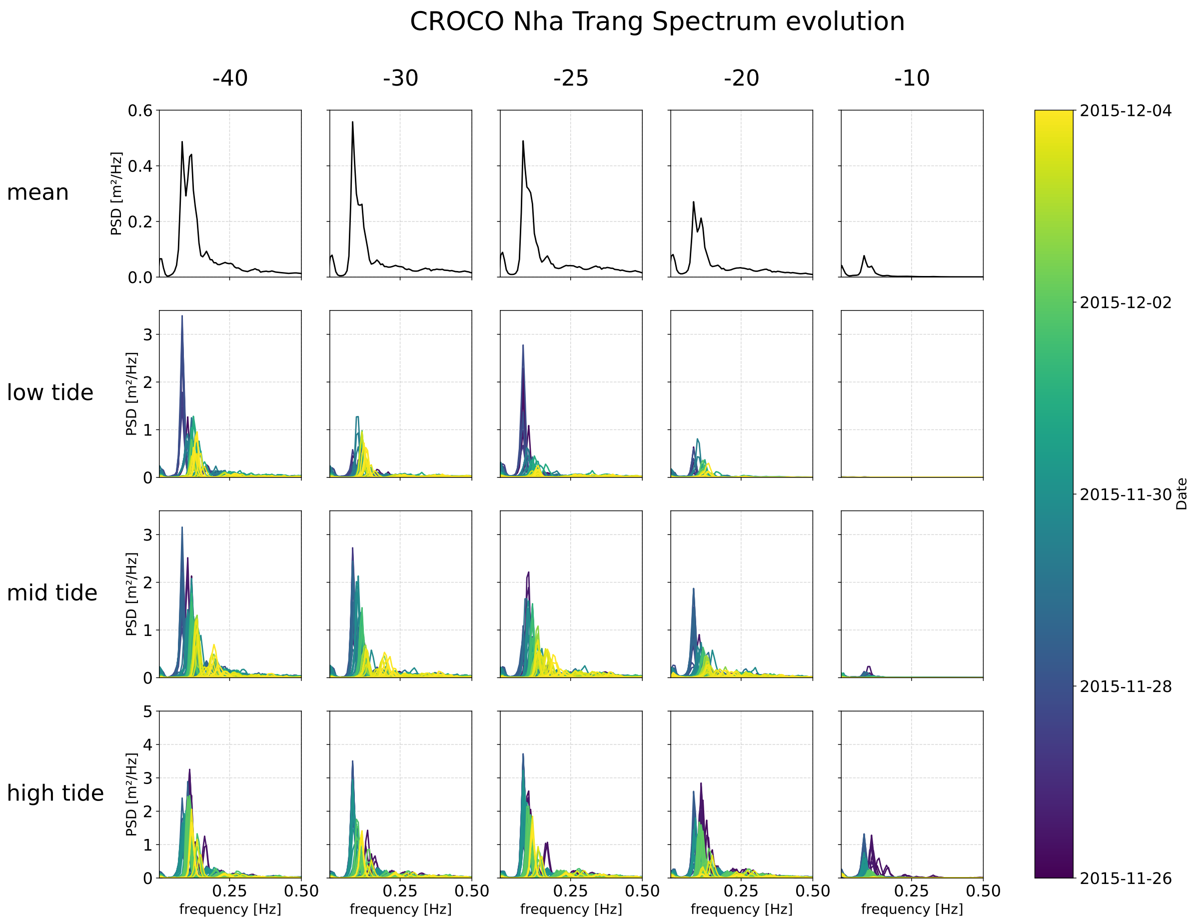

Figure 4. Spectral evolution of the water free surface at different cross-shore positions (columns) and tidal stages (rows: mean over the experiment, low: $\overline{\eta} < 0.8$; mid: $1.2 < \overline{\eta} < 0.8$, high:$\overline{\eta} > 1.2$), derived from CROCO simulations.

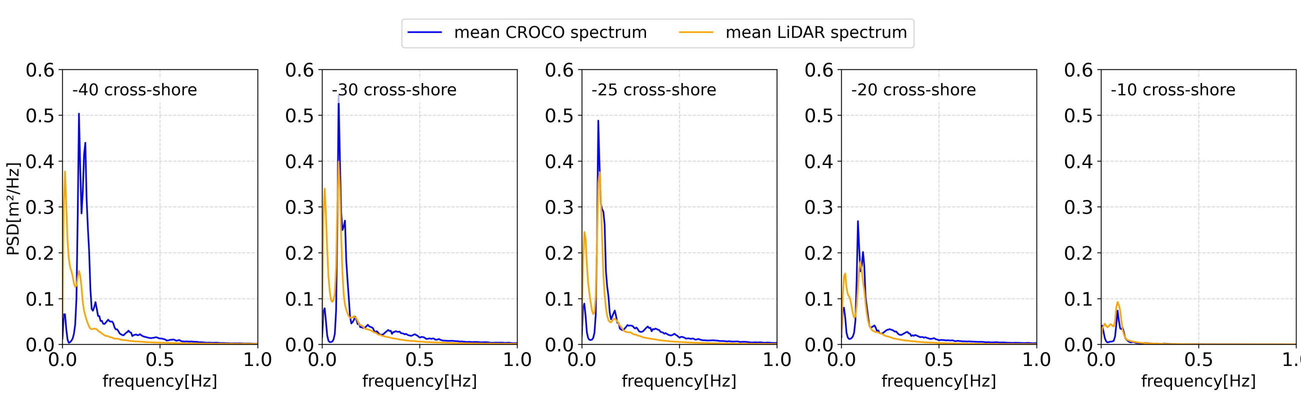

Figure 5. Comparison of LiDAR-observed free-surface spectra and CROCO simulations at different cross-shore positions, averaged over the duration of the experiment.

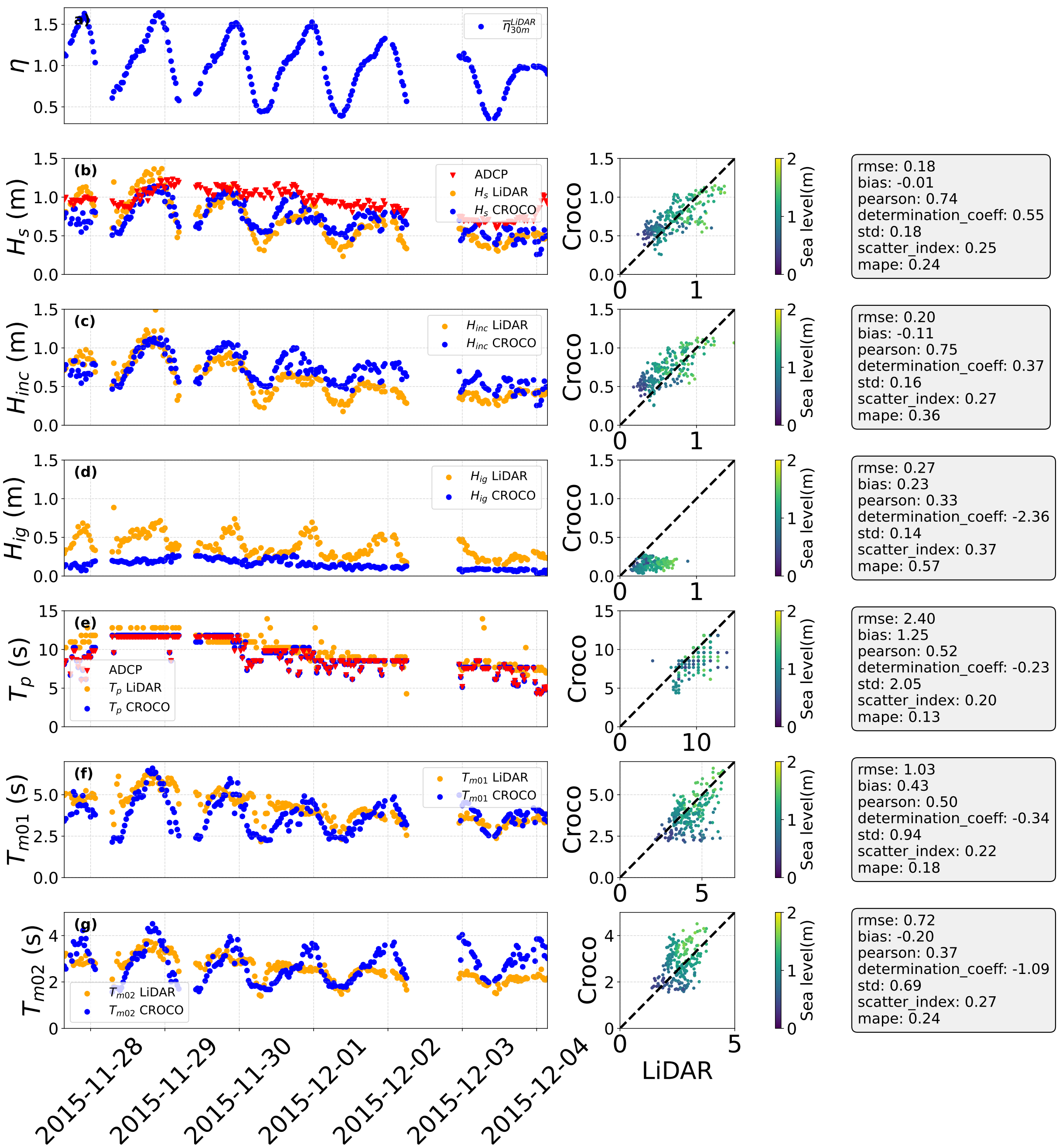

Figure 6. Offshore and surf-zone hydrodynamic conditions during the experience. Panel (a) presents the still water level measured by the LiDAR at a location 30 m seaward of the instrument. Panels (b) and (g), from left to right, show: (i) time series of H_s, H_{inc}, H_{ig}, T_p, T_{m01}, T_{m02} derived from the offshore ADCP (red downward triangles), the surf-zone LiDAR (orange dots), and the CROCO model (blue dots); (ii) scatter plots comparing CROCO and LiDAR estimates; and (iii) a summary of the main statistics.

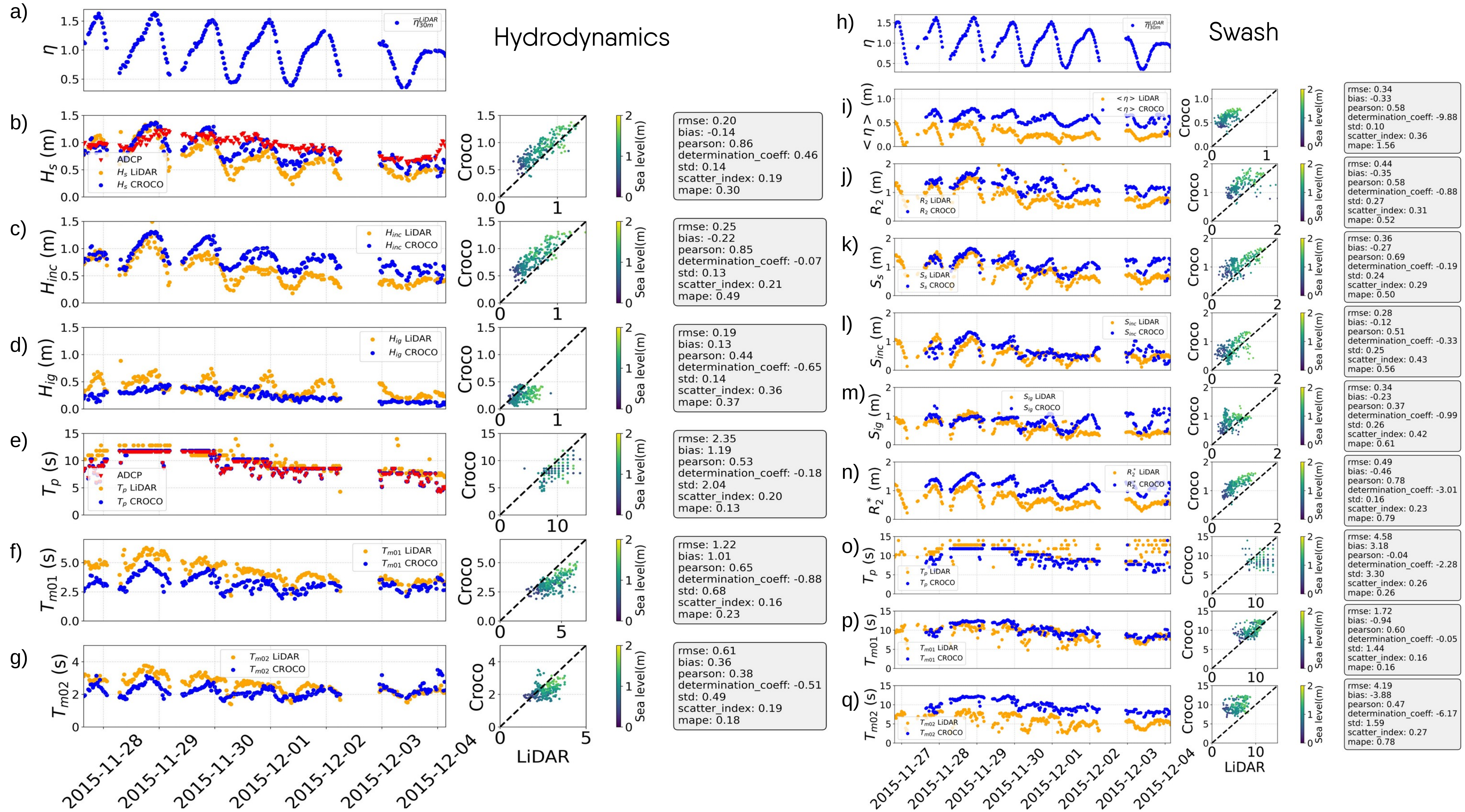

Figure 7. LiDAR and CROCO hydrodynamics and swash comparisons, with CROCO forced by 100% of Hs. Right column set, Offshore and surf-zone hydrodynamic conditions during the experience. Panel (a) presents the still water level measured by the LiDAR at a location 30 m seaward of the instrument. Panels (b) and (g), from left to right, show: (i) time series of H_s, H_{inc}, H_{ig}, T_p, T_{m01}, T_{m02} derived from the offshore ADCP (red downward triangles), the surf-zone LiDAR (orange dots), and the CROCO model (blue dots); (ii) scatter plots comparing CROCO and LiDAR estimates; and (iii) a summary of the main statistics. Left colmumn set, Swash representatives values during the experience, from observation (LiDAR orange dots) and CROCO (blue dots). All rows left panel, timeseries, central panel scatter plots between observation and models, right panels, main comparison stats between CROCO and LiDAR. from h) to q): Wave-setup $< \eta >$;Measured and modeled discrete R_2 ;Total variance of Swash S_s; Swash incident (high frequency) variance S_{inc}; Swash infra-gravity variance S_{ig};Extreme run-up estimated by its components R_2^* (see Methods); Swash peak period T_p^{Swash}: first and second momentum wave period from swash signal (T_{m01}^{Swash};T_{m02}^{Swash}).

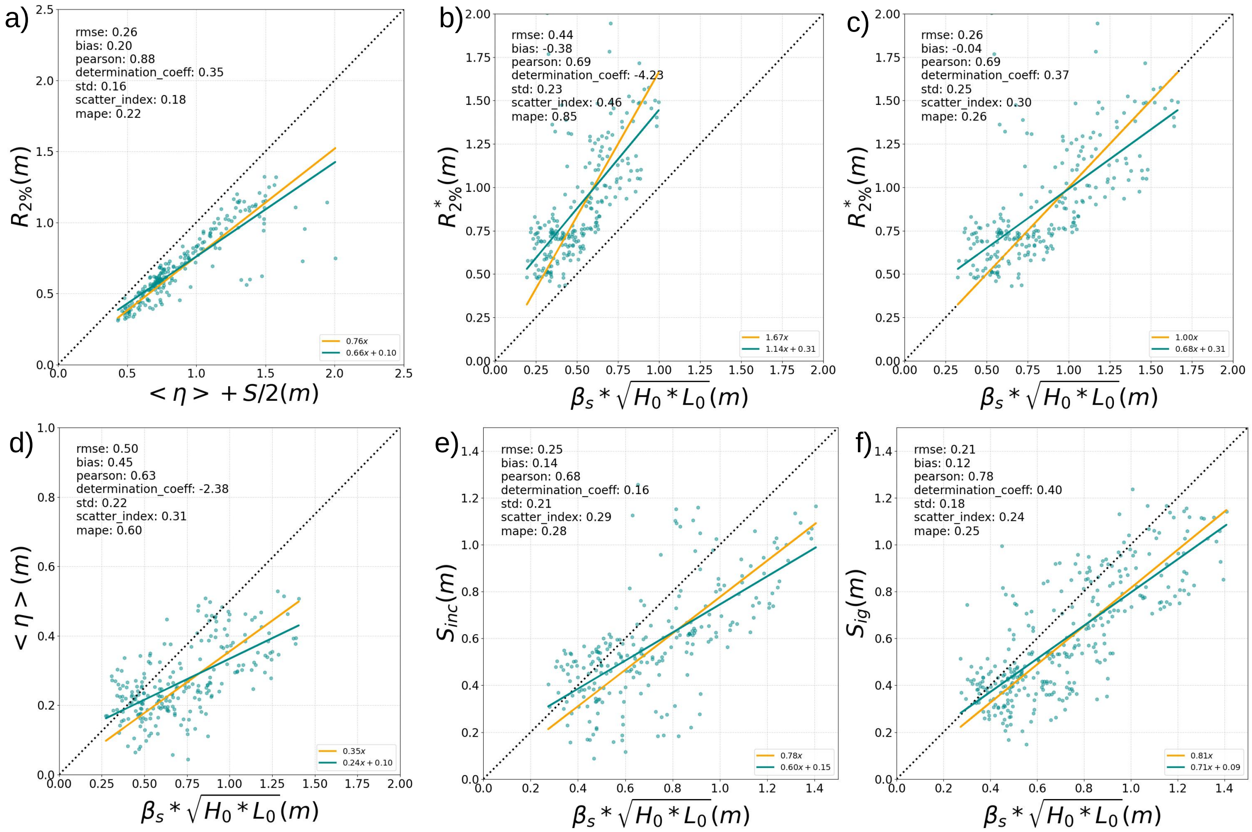

Figure 8. Dispersion plots of runup and swash components versus morphological and offshore hydrodynamic conditions. Panel (a) shows the dispersion between discrete run-up ($R_{2\%}$) plus wave setup ($\langle\eta\rangle$) and total swash variability (S). Panels (b) and (c) depict the dispersion of the first and adjusted run-up parameterizations against morphological (β_s) and offshore wave conditions (H_0 and T_p). Panels (d), (e), and (f) present dispersion plots of wave setup ($\langle\eta\rangle$), incident swash variability (S_{inc}), and infragravity swash (S_{ig}), respectively.

1 CROCO forcing conditions

Table 1. Wave conditions time series

date	$\overline{\eta}$	H_s	T_p
2015-11-27 15:28:13	1.14	0.96	8.00
2015-11-27 15:54:30	1.12	1.00	8.50
2015-11-27 17:40:27	1.27	0.93	6.80
2015-11-27 18:00:31	1.30	0.96	8.83
2015-11-27 18:30:37	1.37	0.89	9.80
2015-11-27 19:00:41	1.41	0.94	9.80
2015-11-27 19:30:46	1.45	0.96	8.65
2015-11-27 20:00:53	1.47	0.95	7.75
2015-11-27 20:30:58	1.57	0.94	8.50
2015-11-27 21:01:02	1.55	0.93	5.95

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date	$\overline{\eta}$	H_s	T_p
2015-11-27 21:31:06	1.58	0.96	7.45
2015-11-27 22:01:10	1.63	0.99	8.87
2015-11-27 22:31:34	1.57	1.00	6.10
2015-11-27 23:01:44	1.55	0.98	8.88
2015-11-27 23:31:55	1.47	0.97	9.15
2015-11-28 00:02:04	1.39	0.97	8.83
2015-11-28 00:32:14	1.29	0.97	9.80
2015-11-28 01:02:27	1.17	0.98	9.80
2015-11-28 01:32:36	1.04	0.96	9.80
2015-11-28 07:03:03	0.61	0.95	11.60
2015-11-28 07:34:08	0.68	0.91	9.55
2015-11-28 08:33:47	0.74	0.89	11.60
2015-11-28 08:57:11	0.73	0.87	11.60
2015-11-28 09:29:57	0.71	0.90	11.60
2015-11-28 10:04:43	0.79	0.92	11.60
2015-11-28 10:28:20	0.79	0.88	11.60
2015-11-28 10:58:25	0.88	0.87	11.60
2015-11-28 11:28:31	0.90	0.88	11.60
2015-11-28 12:00:10	0.98	0.87	11.60
2015-11-28 12:32:28	1.00	0.85	11.60
2015-11-28 13:02:35	1.05	0.87	11.60
2015-11-28 13:33:28	1.10	0.90	11.60
2015-11-28 14:03:33	1.10	0.94	11.60
2015-11-28 14:24:06	1.14	0.97	11.60
2015-11-28 14:59:56	1.18	1.08	11.60
2015-11-28 15:31:58	1.17	1.02	11.60
2015-11-28 16:02:03	1.18	0.95	11.60
2015-11-28 16:34:13	1.22	1.01	11.60
2015-11-28 17:04:33	1.19	1.09	11.60
2015-11-28 17:34:41	1.30	1.10	11.60
2015-11-28 18:01:14	1.30	1.05	11.60
2015-11-28 18:31:57	1.36	0.95	11.60
2015-11-28 19:03:41	1.45	1.05	11.60
2015-11-28 19:33:51	1.43	1.05	11.60
2015-11-28 20:03:59	1.53	1.04	11.60
2015-11-28 20:34:08	1.53	1.11	11.60
2015-11-28 21:04:14	1.60	1.11	11.60
2015-11-28 22:00:44	1.64	1.14	11.60
2015-11-28 22:30:51	1.59	1.21	11.60
2015-11-28 23:00:59	1.61	1.20	11.60
2015-11-28 23:31:05	1.51	1.13	11.60
2015-11-29 00:01:14	1.46	1.11	11.60
2015-11-29 00:32:11	1.44	1.22	11.60
2015-11-29 00:52:44	1.34	1.22	11.60
2015-11-29 01:29:52	1.18	1.17	9.55
2015-11-29 02:01:26	1.05	1.15	8.53
2015-11-29 02:31:39	0.94	1.23	11.60
2015-11-29 03:03:57	0.85	1.13	11.60
2015-11-29 03:27:04	0.79	1.16	11.60
2015-11-29 03:59:17	0.60	1.21	11.60
2015-11-29 04:35:09	0.55	1.19	11.60
2015-11-29 10:07:12	0.66	1.13	11.60

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date	$\overline{\eta}$	H_s	T_p
2015-11-29 10:27:22	0.68	1.15	11.60
2015-11-29 10:59:03	0.70	1.16	11.60
2015-11-29 11:32:23	0.78	1.12	11.60
2015-11-29 13:01:14	0.92	1.10	11.60
2015-11-29 13:31:25	0.97	1.06	11.60
2015-11-29 14:01:36	1.00	1.04	11.60
2015-11-29 14:31:43	1.00	1.08	11.60
2015-11-29 15:31:37	1.11	1.01	11.60
2015-11-29 16:01:47	1.05	1.03	11.60
2015-11-29 16:22:11	1.05	1.16	11.60
2015-11-29 17:04:14	1.13	1.14	11.60
2015-11-29 17:34:25	1.14	1.14	11.60
2015-11-29 18:04:35	1.15	1.13	11.60
2015-11-29 18:34:42	1.20	1.11	11.60
2015-11-29 19:04:48	1.25	1.16	11.60
2015-11-29 19:34:53	1.31	1.12	11.60
2015-11-29 20:04:59	1.35	1.09	11.60
2015-11-29 20:33:37	1.42	1.11	11.60
2015-11-29 21:03:48	1.44	1.06	11.60
2015-11-29 21:33:54	1.50	1.10	11.60
2015-11-29 22:04:00	1.47	1.16	11.15
2015-11-29 22:34:09	1.50	1.17	9.80
2015-11-29 22:56:47	1.52	1.13	11.15
2015-11-29 23:26:56	1.50	1.11	11.60
2015-11-29 23:57:02	1.47	1.08	11.15
2015-11-30 00:27:34	1.44	1.00	9.80
2015-11-30 00:57:42	1.37	0.99	8.82
2015-11-30 01:27:48	1.28	1.05	10.05
2015-11-30 02:00:03	1.16	1.07	10.57
2015-11-30 02:30:11	1.10	0.98	7.50
2015-11-30 03:00:18	0.96	1.03	8.25
2015-11-30 03:30:24	0.86	1.04	8.00
2015-11-30 03:58:20	0.77	1.03	7.75
2015-11-30 04:28:27	0.68	1.03	8.50
2015-11-30 04:58:34	0.57	1.08	8.50
2015-11-30 05:28:41	0.52	1.09	8.50
2015-11-30 06:28:55	0.45	1.03	8.50
2015-11-30 06:59:02	0.44	1.02	8.50
2015-11-30 07:59:13	0.45	0.99	9.80
2015-11-30 08:35:01	0.46	1.09	9.80
2015-11-30 09:00:10	0.45	1.06	9.80
2015-11-30 09:30:25	0.48	1.06	9.80
2015-11-30 10:02:02	0.51	1.04	9.80
2015-11-30 10:34:36	0.56	0.98	9.80
2015-11-30 11:34:15	0.72	1.14	9.80
2015-11-30 11:57:08	0.77	1.16	9.80
2015-11-30 12:28:00	0.86	1.17	9.80
2015-11-30 12:59:17	0.91	1.09	8.82
2015-11-30 13:29:25	0.95	1.03	9.15
2015-11-30 14:03:12	0.96	1.03	9.80
2015-11-30 14:33:21	1.04	1.10	9.80
2015-11-30 15:03:29	1.02	1.06	9.80

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date	$\overline{\eta}$	H_s	T_p
2015-11-30 15:33:36	1.07	1.07	8.25
2015-11-30 15:58:17	1.10	1.07	7.15
2015-11-30 16:28:24	1.08	1.03	8.50
2015-11-30 16:58:30	1.11	1.14	9.48
2015-11-30 17:28:37	1.13	1.16	9.80
2015-11-30 17:58:45	1.16	1.14	9.80
2015-11-30 18:28:53	1.16	1.12	9.80
2015-11-30 18:58:59	1.21	1.06	6.65
2015-11-30 19:26:05	1.26	1.06	7.05
2015-11-30 19:56:11	1.28	1.05	8.83
2015-11-30 20:26:18	1.30	0.98	9.80
2015-11-30 20:56:26	1.38	0.93	9.80
2015-11-30 21:26:32	1.41	0.92	9.15
2015-11-30 21:56:39	1.46	0.95	8.83
2015-11-30 22:26:45	1.47	1.00	9.80
2015-11-30 22:56:52	1.48	1.02	8.82
2015-11-30 23:27:37	1.53	0.96	9.15
2015-11-30 23:59:05	1.46	0.91	9.47
2015-12-01 00:30:50	1.47	0.92	8.50
2015-12-01 01:03:09	1.41	0.95	7.15
2015-12-01 01:35:10	1.34	0.99	7.60
2015-12-01 01:58:42	1.27	1.02	8.50
2015-12-01 02:33:00	1.15	1.01	8.50
2015-12-01 03:29:27	0.97	0.96	8.00
2015-12-01 03:59:48	0.86	0.95	7.50
2015-12-01 04:30:40	0.78	0.92	7.50
2015-12-01 05:01:34	0.68	0.94	6.90
2015-12-01 05:31:40	0.61	0.93	7.60
2015-12-01 06:01:45	0.52	0.93	8.50
2015-12-01 06:31:50	0.48	0.94	8.50
2015-12-01 06:57:10	0.44	0.94	7.75
2015-12-01 08:27:26	0.40	0.88	8.50
2015-12-01 08:57:31	0.39	0.93	8.50
2015-12-01 09:27:36	0.40	0.91	8.50
2015-12-01 10:01:31	0.45	0.88	8.05
2015-12-01 10:31:37	0.48	0.87	6.70
2015-12-01 11:01:42	0.51	0.89	8.05
2015-12-01 11:31:48	0.58	0.89	8.50
2015-12-01 12:02:25	0.64	0.87	7.90
2015-12-01 12:32:29	0.69	0.80	6.10
2015-12-01 13:02:34	0.78	0.88	7.90
2015-12-01 13:33:06	0.83	0.90	8.50
2015-12-01 14:03:55	0.89	0.91	8.50
2015-12-01 14:24:23	0.91	0.94	8.50
2015-12-01 15:00:43	0.96	0.87	7.15
2015-12-01 15:31:43	1.01	0.85	7.60
2015-12-01 16:02:25	1.01	0.86	8.50
2015-12-01 16:28:58	1.05	0.89	8.50
2015-12-01 17:33:49	1.07	0.96	8.50
2015-12-01 17:56:20	1.09	0.94	8.50
2015-12-01 18:30:22	1.10	0.86	8.50
2015-12-01 19:37:25	1.11	0.90	8.50

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date	$\overline{\eta}$	H_s	T_p
2015-12-01 19:58:50	1.14	0.84	8.50
2015-12-01 20:29:30	1.19	0.85	8.50
2015-12-01 20:59:38	1.24	0.83	8.50
2015-12-01 21:29:45	1.26	0.83	7.30
2015-12-01 21:59:51	1.30	0.86	6.70
2015-12-01 22:29:57	1.31	0.95	8.50
2015-12-01 23:00:05	1.33	0.90	8.50
2015-12-02 01:28:27	1.25	0.87	8.50
2015-12-02 01:58:35	1.21	0.81	8.50
2015-12-02 02:28:44	1.15	0.88	8.50
2015-12-02 02:58:50	1.07	0.87	8.50
2015-12-02 03:28:56	1.01	0.85	8.50
2015-12-02 03:59:09	0.91	0.82	8.25
2015-12-02 04:29:16	0.80	0.79	7.50
2015-12-02 04:59:22	0.76	0.76	8.25
2015-12-02 05:29:28	0.65	0.80	8.50
2015-12-02 05:59:35	0.57	0.82	8.50
2015-12-02 23:05:33	1.12	0.74	8.05
2015-12-02 23:25:37	1.09	0.75	6.45
2015-12-02 23:56:07	1.10	0.74	5.18
2015-12-03 00:26:15	1.15	0.69	7.50
2015-12-03 00:56:22	1.08	0.71	7.50
2015-12-03 01:26:28	1.08	0.70	7.50
2015-12-03 01:56:35	1.07	0.69	7.50
2015-12-03 02:56:48	0.98	0.70	7.50
2015-12-03 03:31:44	0.94	0.70	7.50
2015-12-03 04:01:52	0.86	0.69	7.75
2015-12-03 04:34:07	0.79	0.70	8.50
2015-12-03 04:54:36	0.75	0.66	8.50
2015-12-03 05:26:42	0.69	0.63	8.50
2015-12-03 06:35:01	0.53	0.72	7.50
2015-12-03 07:03:09	0.47	0.67	7.50
2015-12-03 07:34:42	0.43	0.68	7.50
2015-12-03 07:56:26	0.40	0.70	7.50
2015-12-03 08:30:04	0.36	0.71	7.50
2015-12-03 10:34:57	0.36	0.65	6.10
2015-12-03 10:55:20	0.40	0.60	6.10
2015-12-03 11:25:59	0.42	0.62	6.80
2015-12-03 12:04:59	0.46	0.66	7.50
2015-12-03 13:30:48	0.60	0.66	8.00
2015-12-03 14:01:54	0.67	0.66	7.50
2015-12-03 14:32:04	0.72	0.66	7.50
2015-12-03 15:02:13	0.79	0.68	7.50
2015-12-03 15:31:36	0.82	0.68	7.50
2015-12-03 16:01:45	0.85	0.68	7.02
2015-12-03 16:31:52	0.87	0.67	5.60
2015-12-03 17:01:58	0.93	0.67	5.98
2015-12-03 17:32:05	0.94	0.71	5.40
2015-12-03 18:02:11	0.95	0.73	5.40
2015-12-03 18:32:17	0.99	0.71	7.50
2015-12-03 19:02:26	0.98	0.74	7.50
2015-12-03 19:27:51	0.97	0.71	6.55

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date	$\overline{\eta}$	H_s	T_p
2015-12-03 19:58:00	0.98	0.70	6.08
2015-12-03 20:28:07	0.97	0.74	7.50
2015-12-03 20:58:14	0.97	0.69	7.50
2015-12-03 23:01:46	0.99	0.69	7.50
2015-12-03 23:33:07	0.98	0.76	5.80
2015-12-04 00:04:35	0.98	0.83	4.25
2015-12-04 00:25:57	0.99	0.83	4.70
2015-12-04 00:57:39	0.99	0.86	4.25
2015-12-04 01:30:15	0.98	0.95	4.25
2015-12-04 02:01:37	0.97	1.02	4.58
2015-12-04 02:33:31	0.96	1.01	5.10
2015-12-04 03:05:11	0.94	0.95	4.80
2015-12-04 03:25:19	0.90	0.91	5.15