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Verification of DMI wave forecasts 3rd quarter of 2002

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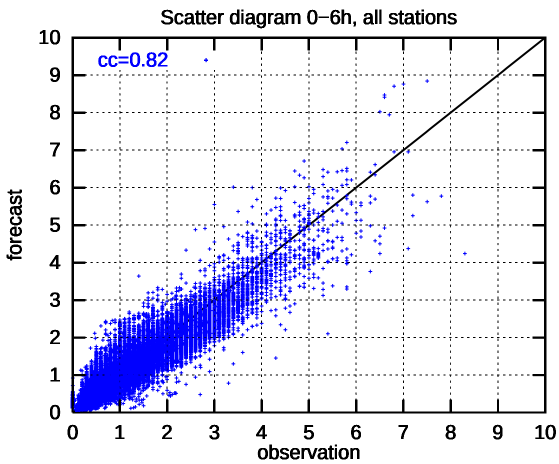

Contents

1 Introduction with Key Numbers

We analyse the quality of wave forecasts valid for the 3rd quarter of 2002, produced by *DMI-WAM* - DMI's operational set-up of the 3rd generation wave model *WAM Cycle4*.

The significant wave height H_s is of primary interest, but other wave parameters (period, direction, swell) are examined where the data material is adequate.

Standard error measures (bias, rms error, ..) are calculated both as a function of forecast range and of wave height. Special statistics are done for the highest waves. Grand averages are calculated as mean values over all stations, over all ranges, and for separate geographical regions.

All model results are forecasts. This means that errors in the parameters do not necessarily imply a wave model error, but may reflect errors in the wind forecast.

DMI has produced short-range operational wave forecasts since 1999. A pre-operational validation study was carried out in 1999 [8], a combined wave-wind validation study in 2000 [7], and a verification pilot study in 2002 [6]. Previous quarterly report(s) are [4],[5].

Outline: Ch. 2 describes the DMI wave model set-up, ch. 3 lines out the data material, and in ch. 4 we define the statistical error measures used to describe the forecast quality. Ch. 5 presents and discusses the results. Ch. 6 concludes the work. Comprehensive results for each station are found in the Appendix. References and lists of figures/tables are found at the end of the report.

For convenience, the Table below shows *Key Numbers* pertaining to the full model system. Please refer to the Results section (ch. 5) for a detailed explanation and discussion.

Parameter	H_s	T_{02}	T_p	θ_w
bias	-8cm	0.9s	1.2s	6^o
relative bias	-4%	24%	22%	
rms error	35cm	1.1s	2.5s	
st.dev				49^o
scatter index	0.36	0.32	0.45	
corr.coeff.	0.82	0.55	0.45	0.86
peak bias	-48cm			
rel. peak bias	-15%			

Table 1. Key numbers

2 DMI-WAM

DMI has run an operational wave forecasting service for Danish waters since 1999, using the 3rd generation wave model *WAM Cycle4* (described in [1], [3]) forced by DMI's numerical weather prediction model *HIRLAM*. In 2002, the geographical model domain includes a large part of the North Atlantic, the North Sea and Baltic Sea, and the Mediterranean. The DMI-WAM model set-up is described in detail below.

2.1 Physical model

WAM Cycle4 solves the spectral wave equation

$$\frac{\partial F}{\partial t} + \vec{c} \cdot \vec{\nabla} F \quad = \quad S_{in} + S_{nl} + S_{ds} + S_{cu} + S_{bf}$$

where $F(f, \theta; \vec{x}, t)$ is spectral wave energy density, depending on wave frequency, wave direction, position and time; $c(f, d)$ is the depth-dependent wave group speed; S_{in} is wind energy input; S_{nl} is non-linear wave-wave interaction; S_{ds} is wave energy dissipation through wave breaking (white capping); S_{cu} is wave-current interaction; S_{bf} is interaction with the sea bed through friction and wave refraction. DMI-WAM still lacks current data (S_{cu}=0) and information about sea ice (acts to dampen waves).

2.2 Model set-up

DMI provides wave forecasts in three geographical domains as shown below:

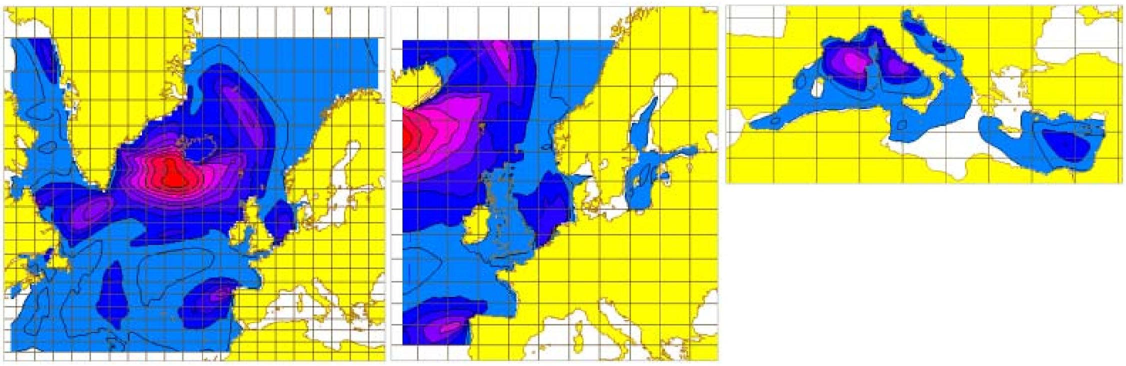

Figure 1. DMI wave models. North Atlantic, North Sea-Baltic, and Mediterranean model

The model open boundaries are chosen as follows. The coarse grid North Atlantic model uses the JONSWAP wind-sea spectrum (see [1], [2]). The fine grid North Sea - Baltic model is nested into the North Atlantic model, and uses time/space interpolated boundary wave spectra calculated by that model. The Mediterranean is treated as a closed basin, assuming no wave energy exchange with the Atlantic or the Black Sea. Please refer to Table 2 for a model set-up summary.

The wave forecasting system was coldstarted using developed sea. Subsequent model runs are initialised using the sea state at analysis time, calculated by the previous run.

Model	North Atlantic	North Sea - Baltic	Mediterranean
Space res.	$1/2^o$	$1/6^o$	$1/6^o$
Time step	4 min	4 min	2 min
Frequencies	25	25	25
Direction resol.	30^o	30^o	30^o
Forcing model(s)	Hirlam G	Hirlam E	Hirlam E+G
- resolution of	0.45^o	0.15^o	$0.15^o/0.45^o$
Longitudes	69^oW-30^oE	20^oW-30^oE	6^oW-46^oE
Latitudes	30^oN-75^oN	36^oN-68^oN	30.5^oN-46^oN
Open boundaries	JONSWAP	Nested	Closed basin
Forecast range	54 h	54 h	54 h
Output time step	1 h	1 h	1 h
Schedule	4x daily	4x daily	4x daily

Table 2. DMI-WAM set-up. The wave model frequencies range from 0.04177 Hz to 0.41145 Hz in 10% steps. The Mediterranean model patches Hirlam E+G to get maximum resolution. Changes to the model set-up usually require a new coldstart.

2.3 Weather model

The forcing models are the DMI limited area numerical weather prediction models Hirlam-E and Hirlam-G. Both are currently being used in the DMI weather forecasting service. The G model embeds the E model, but in coarser spatial resolution (45km vs. 15km on a rotated latitude-longitude grid). The wind vector at 10m height is interpolated linearly in time and space to match the spherical wave model grids.

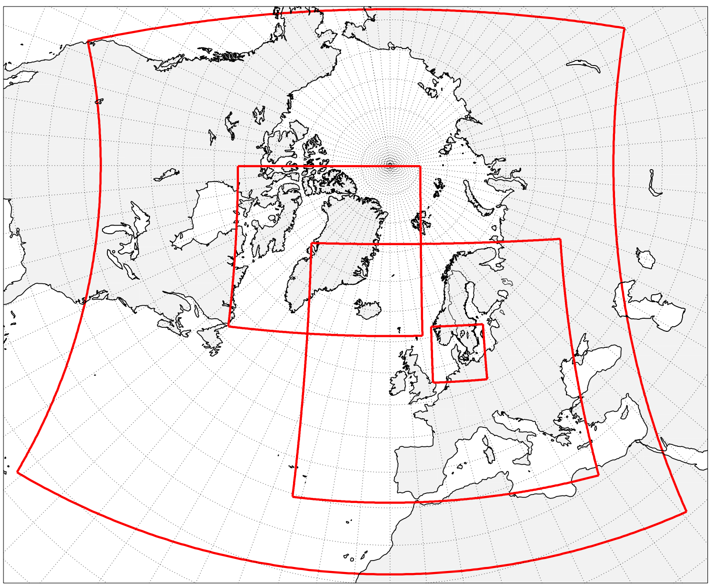

Figure 2. DMI Hirlam. The outermost box is the G model, the box covering most of Europe is the E model.

3 Wave data

The verification data consists of operational DMI-WAM wave forecasts, and wave observations from a number of fixed positions (buoys and platforms).

3.1 Forecasts

Wave parameters output from DMI-WAM are shown in Table 3.

DMI-WAM output	
H_s	Significant wave height
H_{sw}	Height of swell
T_{02}	Mean wave period
T_p	Dominant wave period
T_{sw}	Swell mean period
θ_w	Mean wave direction
θ_{sw}	Swell direction

Table 3. DMI-WAM wave parameters, obtained by a suitable integral of the wave energy spectrum. T_p is the discretized model frequency (inverse) containing the highest energy, picked from a set of predefined values.

The forecasts are stored as hourly maps in model resolution. Time series for each station are sampled using nearest model grid point. This is done for each analysis and each parameter. During the 3rd quarter of 2002, 363 out of 368 scheduled forecasts were produced.

3.2 Observations

The wave recorder positions are shown in Fig. 3 below. A total of 31 stations that record more or less regularly are selected for verification. The mean data coverage is 86% (see Fig. 4 for missing data). Comprehensive station information is found in Appendix 7.1. Observed wave statistics and wave height/period diagrams are shown in Appendices 7.2 and 7.3.

Wave data is obtained from a number of sources, as indicated in table 4. SMHI, KDI, BSH and NCMR data are kindly provided by each agency in question. NDBC data is retrieved via the GTS. Table 5 shows the number of stations for each wave parameter, and for each of 8 geographical domains.

Wave Data providers	
NDBC	National Data Buoy Center (UK)
SMHI	Swedish Meteorological Institute
KDI	Danish Coastal Authority
NCMR	National Center for Marine Research (Greece)
BSH	Bundesamt für Seeschiffahrt in Hamburg

Table 4. Wave data providers.

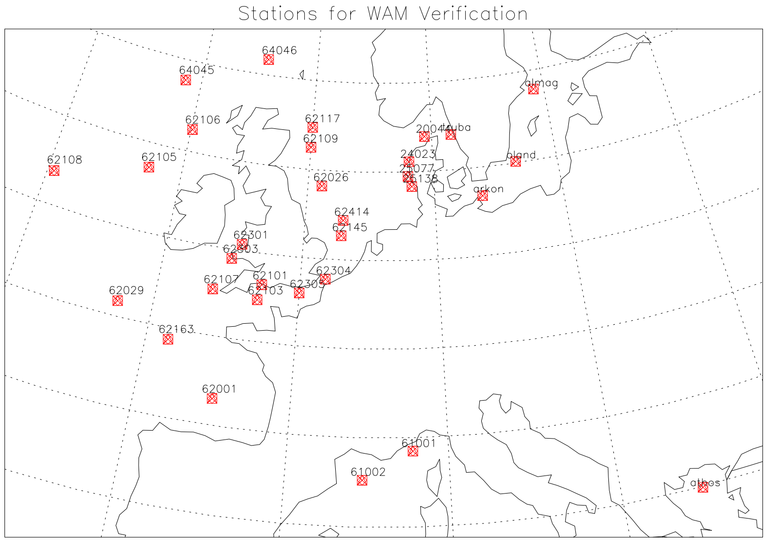

Figure 3. Wave recorder locations.

Parameter	H_s	T_{02}	T_p	θ_w	H_m
Atlantic	8	-	8	-	-
Scotland-Faroe	1	-	1	-	-
Irish Sea	2	-	2	-	-
Br. Channel	4	-	4	-	-
North Sea	5	-	4	-	-
Danish West Coast	4	4	4	4	4
Kattegat - Baltic Sea	4	4	-	1	4
Mediterranean	3	1	3	1	-
Total	31	9	26	6	8

Table 5. Number of wave stations in each domain, and for each wave parameter. Maximum wave height H_m is not output by the wave model, and none of the fixed stations record swell.

Standard sampling rate is 1 hour. 9 stations (cf. Table 11) sample only every 3 hours.

Standard sampling accuracy is H_s:0.1m, T_{02}:0.01s, T_p:1s, θ_w:1^o. A number of buoys use higher accuracy for some parameters. Two buoys (62101, 62301) use low 0.5m H_s accuracy.

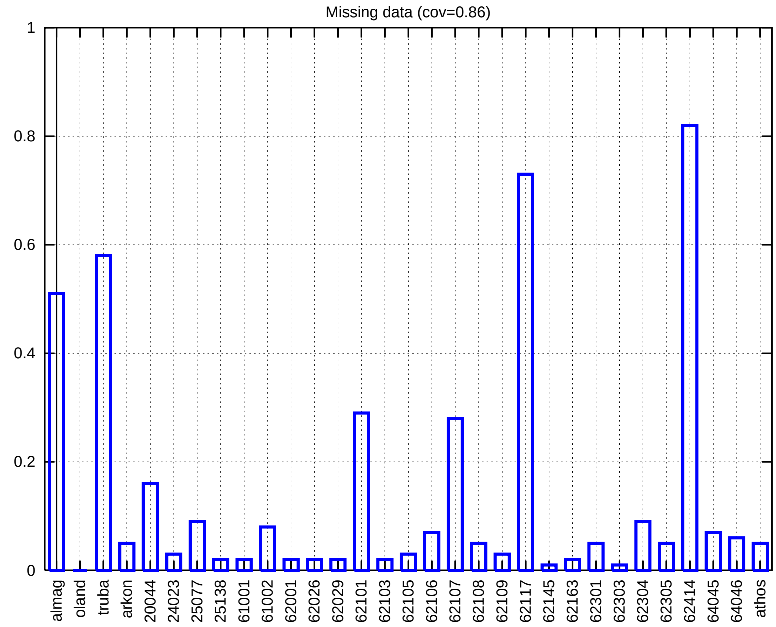

Figure 4. Missing data. St. 20044, 24023, 25077 and 25138 sample every 3 hours, but every hour in storm situations. St. 61001, 61002, 62117, 62414 and Athos sample every 3 hours. At these stations, the data coverage is based on 3 hour sampling.

4 Error measures

Model errors are calculated using a 3-d residual matrix, built from all available observations and forecasts. With the general formula $residual = forecast - observation$ the matrix reads (brackets indicate a dependency)

$residual(station, analysis, range)$

with the number of stations depending on the parameter in question (cf. Table 5), analysis every 6 hours, and forecasts ranging from 1-54 hours in 1 hour steps. With 31 stations, the size of the residual matrix is about 0.6*10^6. By averaging the residual over all analyses, we get the model bias or mean error:

$bias(station, range)$

Further linear averaging gives the bias for each forecast range (averaged over all stations), for each station (averaged over the full forecast range), and as a grand average.

$bias1(range)$
$bias2(station)$
$BIAS$

In the same way, the root mean square error $rms(station, range)$ is calculated and averaged using the residual squared.

For the wave height only, the bias and rms error are also calculated as a function of wave height. The residual is sorted into observation bins 0.5m wide and averaged for each bin.

$bias(station, obsbin)$
$rms(station, obsbin)$

Averaging over all stations gives the model error dependency on wave height, calculated both as an absolute value and as a relative error in %.

The scatter index $si = \frac{rms}{<obs>}$ is obtained by normalising rms with the observed mean value. si may be used to intercompare rms errors at stations with large differences in wave climate. Averaging is done as above.

Correlation coefficients $cc(station, block)$ are calculated using forecast pseudo time series, established by concatenating forecasts in 6 hour range blocks. This gives coefficients valid for each of the 9 range blocks 1-6, 7-12, .. , 49-54 hours. Range block and station-dependent values ($cc1, cc2$), and a grand average (CC), are calculated.

A special peak bias $pbias(station, block)$ is calculated using the 5 most extreme events at each station, allowing for a forecast phase error of a few hours. Peak biases are calculated both as absolute and relative values.

5 Results

This section describes wave verification results for the 3rd quarter of 2002, for significant wave height (H_s), mean and dominant wave period (T_{02}, T_p), and mean wave direction (θ_w). In the sections below, we discuss grand averages and regional averages for each wave parameter in turn. Detailed results for each station are found in the Appendix at the end of the report.

5.1 Significant wave height

Table 6 shows bias and relative bias, rms error, scatter index and correlation coefficient, averaged over the full forecast range. Fig. 5 shows the short range (1-6h) scatter diagram. The error estimates are sorted out on 8 geographical regions.

Parameter	#st	bias		rms	si	cc
Region		cm	%	cm		
Atlantic	8	−16	−7	44	0.25	0.86
Scotland−Faroe	1	−21	−11	44	0.23	0.89
Irish Sea	2	−11	−14	28	0.35	0.81
Br.Channel	4	17	27	34	0.57	0.76
North Sea	5	−16	−13	38	0.33	0.80
Danish West Coast	4	−6	−8	26	0.31	0.89
Kattegat−Baltic	4	−1	0	26	0.43	0.79
Mediterranean	3	−14	−16	35	0.44	0.80
All Waters	31	−8	−4	35	0.36	0.82

Table 6. Significant wave height results

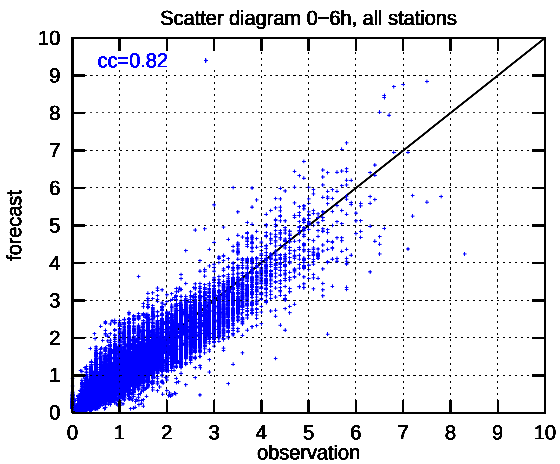

Figure 5. Significant wave height: short range (1-6h) scatter diagram

There is a small negative bias and an rms error of 0.35 m. Scatter index is low (0.36) and correlation coefficient high (0.82). There is some regional spread. Waves are underestimated on average (negative bias) at the Atlantic, Irish Sea, Shetland, North Sea and Mediterranean stations, and overestimated (positive bias) in the British Channel. RMS errors range roughly from a quarter to half a metre. The scatter index (see Fig. 6) is well below an acceptance level of 0.4 in most regions, but exceeds at some stations in the British Channel, in the Baltic and in the Mediterranean.

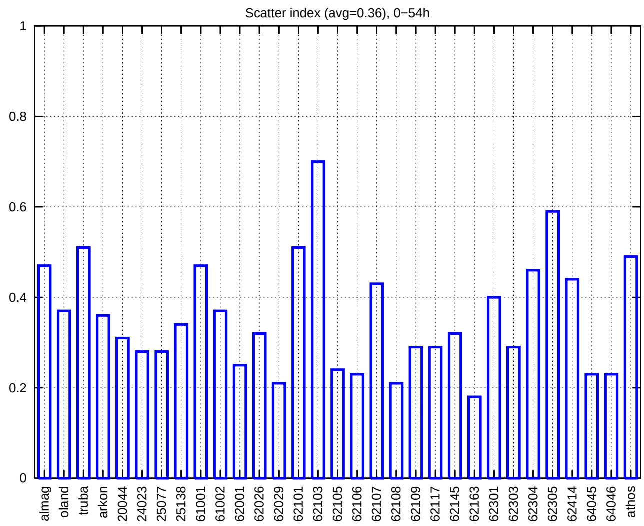

Figure 6. Significant wave height: scatter index. A scatter index of 0.15-0.20 may be considered as a lower limit due to stochastic processes.

The error dependency on forecast range and on wave height is shown in Fig. 7.

The bias is independent of forecast range, while rms error, scatter index and correlation coefficient get slightly worse as forecast range increases. The rms error is significant already at analysis time since the model is initialised without any use of the observed sea state.

Errors depend strongly on wave height. Small waves have small bias, while higher waves (3-6m) are underestimated by 0.5m on average. For waves higher than that the data material gets very sparse, please refer to section 5.2 on peak errors. The rms error increases with wave height. The relative rms error is 20-30% except for very high or very small waves.

Results on significant wave height for each single station is shown in Table 15, Appendix 7.4. Data sheets are presented in Appendix 7.5.

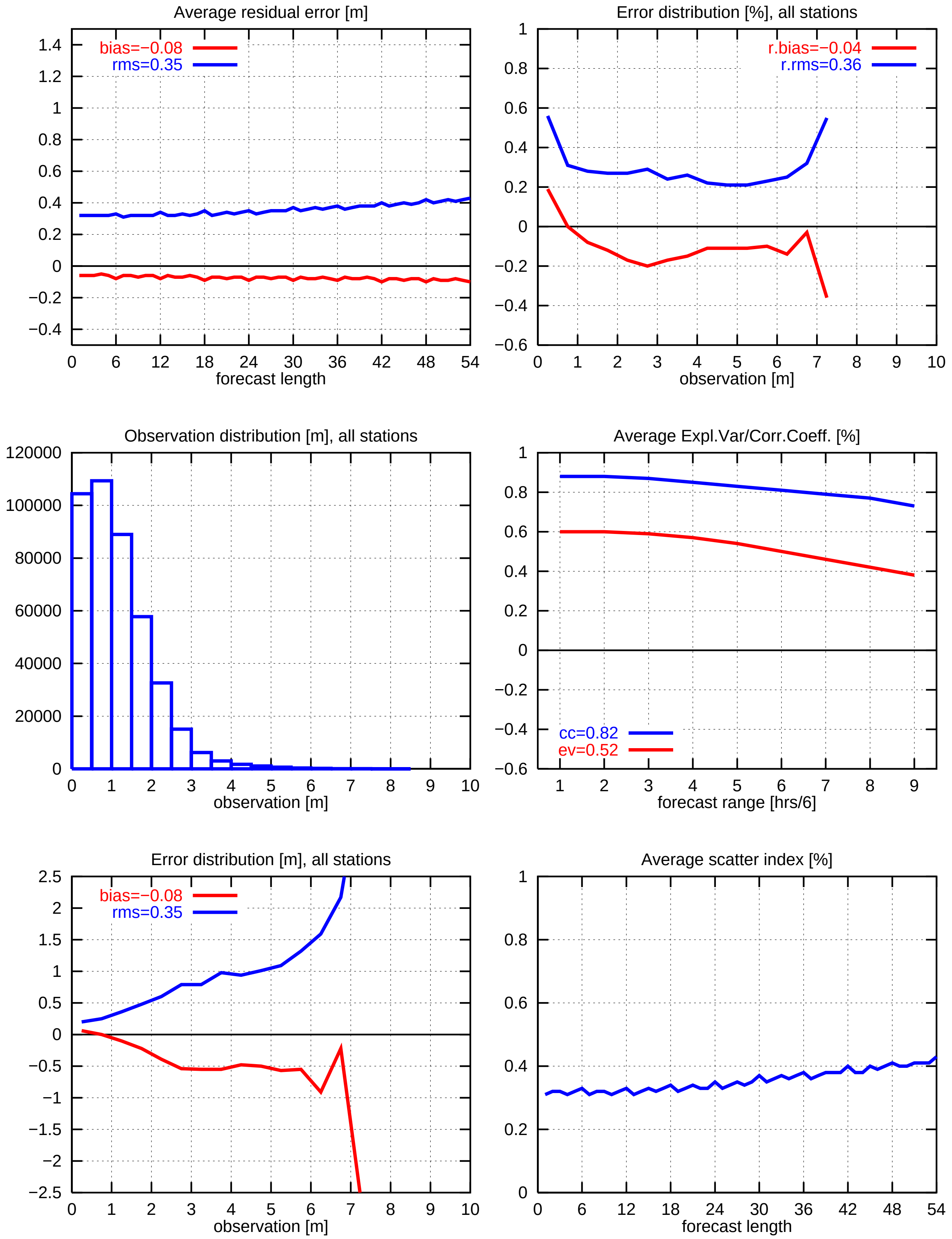

Figure 7. Significant wave height

5.2 Extreme wave height

The error on the highest waves observed is calculated for the 5 highest events at each station, using the forecast error allowing for a few hours' phase displacement. Table 7 shows peak biases for each of the 8 geographical domains, averaged over all forecast ranges.

Parameter Region	#st	peak bias cm	peak bias %
Atlantic	8	−83	−17
Scotland−Faroe	1	11	2
Irish Sea	2	−45	−20
Br.Channel	4	−8	−2
North Sea	5	−60	−21
Danish West Coast	4	−38	−16
Kattegat−Baltic	4	−39	−17
Mediterranean	3	−33	−14
All Waters	31	−48	−15

Table 7. Extreme wave height results

There is a negative peak bias in most regions. On average, the system has a negative peak bias of -48cm or -15%.

The dependency of the peak bias on forecast range is shown in Fig. 8. The peak bias doubles from -0.4m at short range to -0.8m beyond day 2.

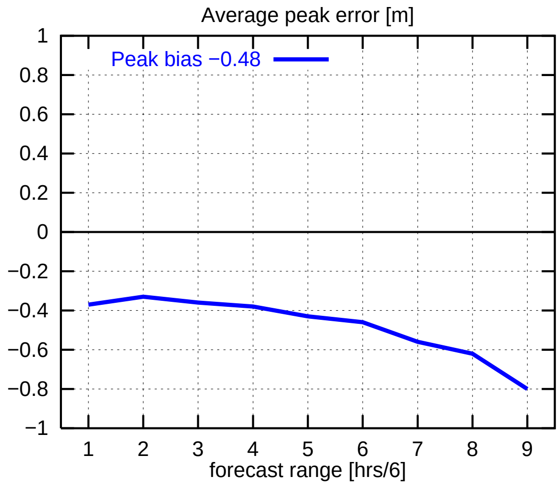

Figure 8. Peak wave height errors.

Table 16 in Appendix 7.4 shows peak biases for each single station.

5.3 Mean wave period

The mean wave period T_{02} is recorded at 9 stations. Grand averages are shown in Table 8, and a short-range scatter diagram in Fig. 9.

Parameter Region	#st	bias sec.	 %	rms sec.	si	cc
Danish West Coast	4	1.4	38	1.7	0.46	0.51
Kattegat–Baltic	4	0.4	12	0.7	0.20	0.60
Mediterranean	1	0.6	19	0.9	0.26	0.49
All Waters	9	0.9	24	1.1	0.32	0.55

Table 8. Mean wave period results

At the Danish West Coast stations T_{02} is overestimated by almost 40%. The reason for this is unresolved. At Baltic and Meditteranean stations T_{02} is slightly overestimated. The scatter index at these stations is well below the acceptancy level of 0.4.

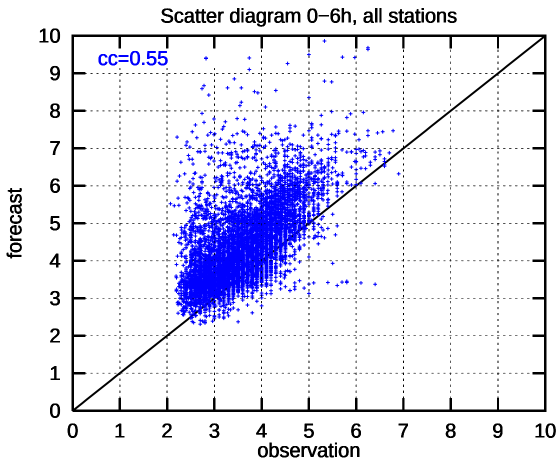

Figure 9. Mean wave period, 1-6h range.

Results on mean wave period for each station are shown i Table 17, Appendix 7.4. Data sheets are presented in Appendix 7.6.

5.4 Dominant wave period

The dominant (or *peak*) wave period T_p is recorded at 26 stations. Grand averages are shown in Table 9, short-range scatter diagrams in Fig. 10.

Parameter Region	#st	bias sec.	 %	rms sec.	si	cc
Atlantic	8	2.2	34	2.8	0.42	0.56
Scotland–Faroe	1	2.3	34	2.8	0.42	0.64
Irish Sea	2	1.9	38	2.9	0.59	0.44
Br.Channel	4	−0.2	4	2.6	0.46	0.25
North Sea	4	1.7	37	2.6	0.57	0.26
Danish West Coast	4	0.5	9	2.2	0.39	0.56
Mediterranean	3	0.0	1	1.4	0.31	0.48
All Waters	26	1.2	22	2.5	0.45	0.45

Table 9. Dominant wave period results

T_p errors are large, due partly to low recording and forecasting accuracy, and partly to the non-smoothness of the series, with T_p shifting abruptly between a high and a low period peak. Even when the wave spectrum is rather well predicted, a small error in the shape of the spectrum may lead to very large T_p errors in situations with a two-peaked spectrum (swell and wind sea). Two examples are found in Figs. 50 and 51, when a low-frequent swell suddenly dominates a very calm sea.

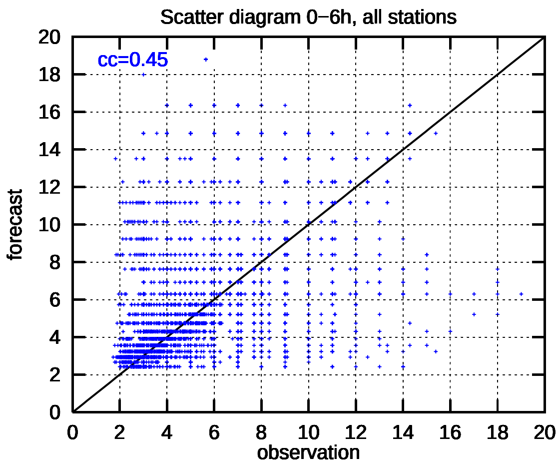

Figure 10. Dominant wave period, 1-6h range.

Results on dominant wave period for each stations is found in Table 18, Appendix 7.4. Data sheets for Mediterranean stations only in Appendix 7.7.

5.5 Mean wave direction

The mean wave direction θ_w is recorded at 6 stations. The results are presented in Table 10 and the scatter diagram in Fig. 11.

Parameter Region	#st	bias deg.	std deg.	cc
Danish West Coast	4	1	45	0.83
Kattegat–Baltic	1	9	43	0.94
Mediterranean	1	24	69	0.87
All Waters	6	6	49	0.86

Table 10. Mean wave direction results

The mean wave direction predictions fit the observations well, with almost no bias and a high correlation coefficient. The Athos buoy is an exception in this season, with a rather high directional error.

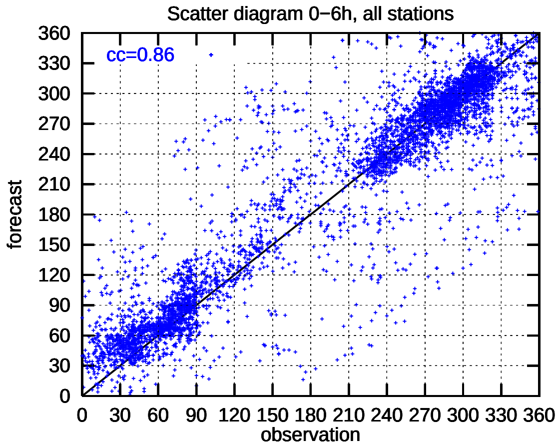

Figure 11. Mean wave direction, 1-6h range.

Results on the mean wave direction for each station is found in Table 19, Appendix 7.4. Data sheets are not shown.

6 Conclusion

DMI wave forecasts valid for the 3rd quarter of 2002 are verified, using wave data from 31 buoys. A Key Number Table is found in Introduction section (Table 1).

Main conclusions are:

- Significant wave height H_s and mean wave direction θ_w are well predicted
- We have some problems predicting wave period T_{02} and T_p
- There is a large regional spread in forecast quality
- The H_s error depends on wave height
- Very high waves are usually underestimated on average
- The forecast quality decreases slightly with increasing forecast range

The *significant wave height* is recorded at all stations. The error distribution is examined in terms of forecast range, as a function of observed wave height, and for separate geographical regions.

The observation-forecast correlation is high, 0.82 on average. This falls off a bit as the prediction range increases.

The average bias is small, independent of forecast range, There is some geographical spread, and a pronounced dependency on wave height. Low waves are overpredicted, while the highest waves are underestimated by about 10%.

The average rms error is 0.35m, increasing gradually with forecast range. For medium-sized waves (3-6m) the rms error is roughly 20%; larger and smaller waves have larger relative error. The average scatter index SI=0.36. 11 stations have si$>$0.4 (sometimes used as an acceptance level), mostly due to low recording accuracy or small average wave height.

The highest waves are usually underestimated, with an average -15% peak bias. The peak error doubles beyond day two.

Two types of wave period are recorded; mean and dominant (peak) wave period.

The *mean wave period* is recorded at 9 locations, half of which have a data interpretation problem. At the remaining 5 stations the model overestimates the mean wave period by roughly 0.5s, with a low scatter index, and a correlation coefficient of about 0.5.

Dominant wave period predictions are not good. Bias and rms errors range up to several seconds. This could be a data problem; a well predicted wave spectrum does not guarantee a correct dominant wave period in situations with two spectral maxima. Also, most stations sample only with 1s accuracy and so does the model; this in itself leads to large error measures.

Mean wave direction predictions have insignificant bias, a standard deviation of about 50^o, and a high correlation coefficient.

Swell parameters are not recorded at any of the fixed positions. A few record *maximum wave height* but this is not predicted by the wave model.

7 Appendix

This Appendix contains a wave recorder station table (below), observation statistics tables, forecast statistics tables, wave height/period plots, and a plot sheet for each station and each parameter ($H_s, T_{02}, T_p, \theta_w$), arranged sequentially according to the station table.

7.1 Wave recorder information

Station ID	Agency	Region	lat.	lon.	δt	parameters
almag	SMHI	Baltic	59.15N	19.13E	1h	H_s, H_m, T_{02}
oland	SMHI	Baltic	56.07N	16.68E	1h	H_s, H_m, T_{02}
truba	SMHI	Baltic	57.60N	11.63E	1h	H_s, H_m, T_{02}
arkona	BSH	Baltic	54.72N	13.74E	1h	$H_s, H_m, T_{02}, \theta_w$
20044	KDI	D. West Coast	57.58N	9.41E	3h	$H_s, H_m, T_{02}, T_p, \theta_w$
24023	KDI	D. West Coast	56.47N	8.06E	3h	$H_s, H_m, T_{02}, T_p, \theta_w$
25077	KDI	D. West Coast	55.81N	7.94E	3h	$H_s, H_m, T_{02}, T_p, \theta_w$
25138	KDI	D. West Coast	55.35N	8.23E	3h	$H_s, H_m, T_{02}, T_p, \theta_w$
61001	NDBC	Mediterranean	43.4N	7.8W	3h	H_s, T_p
61002	NDBC	Mediterranean	42.1N	4.7W	3h	H_s, T_p
62001	NDBC	Atlantic	45.2N	5.0W	1h	H_s, T_p
62026	NDBC	North Sea	55.3N	1.1E	1h	H_s, T_p
62029	NDBC	Atlantic	48.7N	12.4W	1h	H_s, T_p
62101	NDBC	B.Channel	50.6N	2.7W	1h	H_s, T_p
62103	NDBC	B.Channel	49.9N	2.9W	1h	H_s, T_p
62105	NDBC	Atlantic	54.9N	12.6W	1h	H_s, T_p
62106	NDBC	Atlantic	57.0N	9.9W	1h	H_s, T_p
62107	NDBC	Atlantic	50.1N	6.1W	1h	H_s, T_p
62108	NDBC	Atlantic	53.5N	19.5W	1h	H_s, T_p
62109	NDBC	North Sea	57.0N	0.0	1h	H_s, T_p
62117	NDBC	North Sea	57.9N	0.0	3h	H_s, T_p
62145	NDBC	North Sea	53.1N	2.8E	1h	H_s, T_p
62163	NDBC	Atlantic	47.5N	8.5W	1h	H_s, T_p
62301	NDBC	Irish Sea	52.3N	4.5W	1h	H_s, T_p
62303	NDBC	Irish Sea	51.6N	5.1W	1h	H_s, T_p
62304	NDBC	B.Channel	51.1N	1.8E	1h	H_s, T_p
62305	NDBC	B.Channel	50.4N	0.0	1h	H_s, T_p
62414	NDBC	North Sea	53.8N	2.9E	3h	H_s
64045	NDBC	Atlantic	59.1N	11.4W	1h	H_s, T_p
64046	NDBC	Scotland	60.7N	4.5W	1h	H_s, T_p
athos	NCMR	Mediterranean	39.96N	24.72E	3h	$H_s, T_{02}, T_p, \theta_w$

Table 11. Wave stations. Station name/number, driving agency, position, and wave parameters. SMHI=Swedish Meteorological Institute, BSH=Bundesamt für Seeschiffahrt in Hamburg, KDI=Coastal Authorities (Denmark), NDBC=National Data Buoy Center (UK), NCMR=National Center for Marine Research (Greece). H_s=significant wave height, H_m=maximum wave height, T_{02}=mean wave period, T_p=peak or dominant wave period, θ_w=mean wave direction. δt is the sampling rate in hours.

7.2 Observed wave statistics tables

Station	min	mean	max	stdev
almag	0.1	0.6	1.8	0.3
oland	0.1	0.8	3.6	0.4
truba	0.1	0.4	1.8	0.3
arkon	0.1	0.8	3.0	0.4
20044	0.1	0.8	3.1	0.6
24023	0.2	0.9	2.7	0.6
25077	0.2	0.9	3.6	0.6
25138	0.1	0.7	2.4	0.4
61001	0.2	0.8	2.7	0.4
61002	0.2	1.1	4.6	0.9
62001	0.7	1.6	5.1	0.6
62026	0.3	1.2	3.4	0.6
62029	0.6	2.0	5.6	0.8
62101	0.0	0.6	2.0	0.3
62103	0.2	0.7	2.0	0.3
62105	0.8	2.1	8.3	1.0
62106	0.7	2.0	7.8	0.9
62107	0.3	1.1	3.6	0.5
62108	0.8	2.2	5.8	0.8
62109	0.4	1.2	3.4	0.5
62117	0.3	1.1	2.5	0.5
62145	0.2	1.0	3.5	0.5
62163	0.7	1.6	4.2	0.6
62301	0.0	0.6	2.0	0.4
62303	0.2	1.0	3.2	0.5
62304	0.1	0.5	2.5	0.4
62305	0.1	0.6	2.8	0.4
62414	0.2	1.2	4.5	0.7
64045	0.8	2.2	7.5	0.9
64046	0.7	2.0	6.3	0.9
athos	0.1	0.6	1.9	0.4

Table 12. Observed wave height. The fraction of missing data is shown in Fig 4.

Station	min	mean	max	stdev
almag	2.5	3.6	5.2	0.6
oland	2.4	3.8	6.9	0.7
truba	2.3	3.3	5.1	0.5
arkon	2.0	3.3	5.6	0.6
20044	2.2	3.6	5.6	0.8
24023	2.3	4.0	6.2	0.7
25077	2.5	4.0	6.8	0.8
25138	2.1	3.4	5.3	0.7
athos	2.3	3.2	5.4	0.5

Table 13. Observed mean wave period

Station	min	mean	max	stdev
20044	1.9	5.7	13.3	2.3
24023	1.8	6.5	14.3	2.1
25077	2.3	6.2	15.4	2.4
25138	1.7	4.7	15.4	1.9
61001	3.0	5.0	9.0	1.2
61002	3.0	5.1	11.0	1.2
62001	4.0	6.3	11.0	1.2
62026	4.0	4.9	7.0	0.8
62029	4.0	6.5	10.0	1.0
62101	3.0	3.8	7.0	0.7
62103	4.0	7.0	15.0	1.5
62105	4.0	6.6	12.0	1.1
62106	4.0	6.8	11.0	1.1
62107	5.0	7.6	12.0	1.2
62108	5.0	6.9	11.0	1.0
62109	4.0	5.0	8.0	0.7
62117	3.0	4.4	8.0	0.9
62145	3.0	4.2	7.0	0.8
62163	4.0	6.2	11.0	1.0
62301	3.0	4.4	12.0	1.2
62303	4.0	5.7	11.0	1.0
62304	5.0	6.0	9.0	0.6
62305	5.0	7.7	26.0	2.0
64045	5.0	6.7	10.0	1.1
64046	4.0	6.6	11.0	1.1
athos	2.0	4.0	8.1	1.1

Table 14. Observed dominant wave period

7.3 Wave height vs. wave period plots

The relation between significant wave height H_s and mean wave period T_{02} is shown on the diagrams, below, for those stations that record both quantities. At each station, there is a fair linear correlation between H_s and T_{02}, superimposed by a weak swell component.

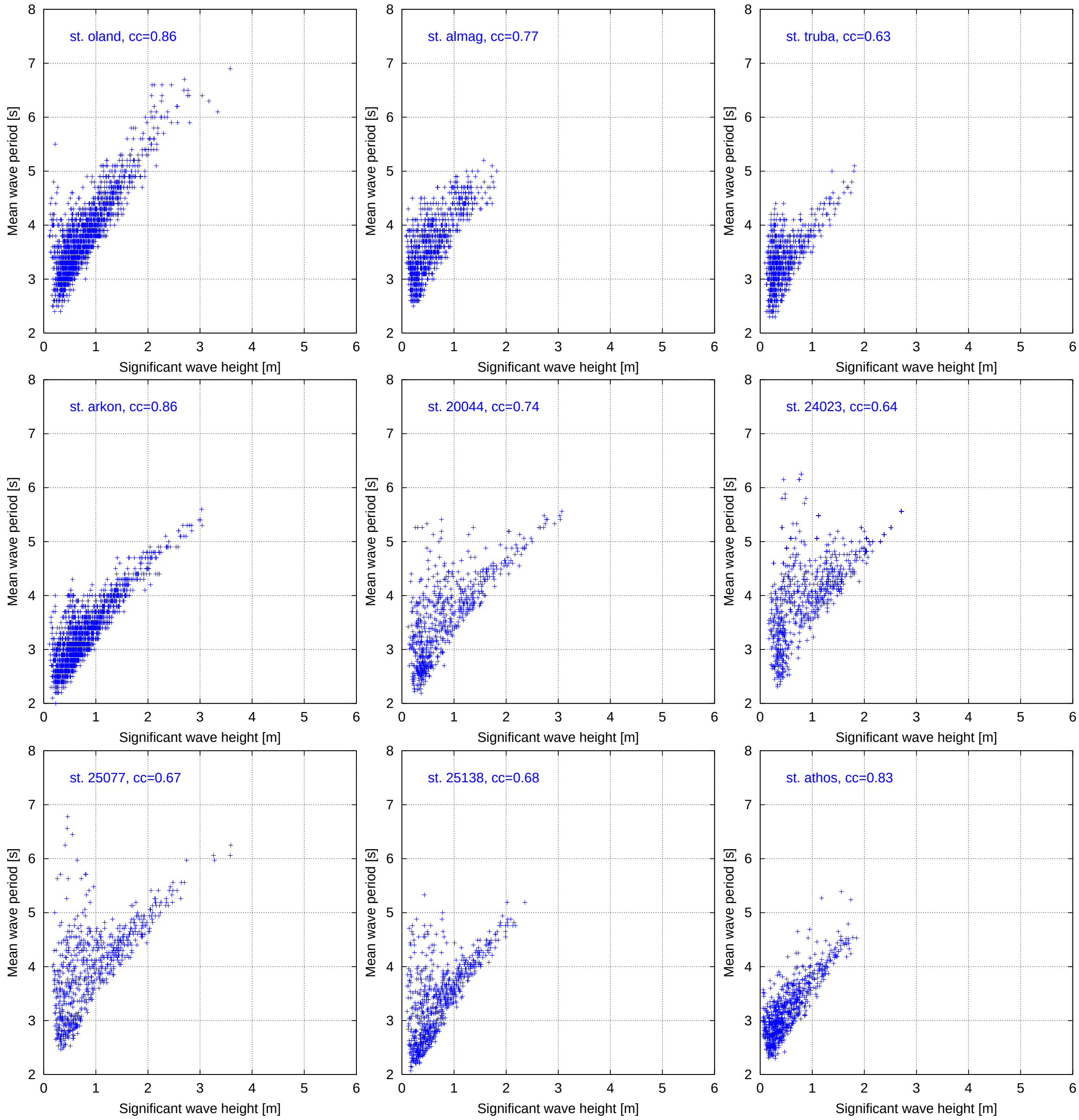

Figure 12. Significant wave height vs. mean wave period

7.4 Wave forecast statistics tables

Parameter	bias		rms	si	cc
Station	cm	%	cm		
almag	5	9	26	0.47	0.78
oland	−1	−1	29	0.37	0.81
truba	4	8	23	0.51	0.76
arkon	−12	−16	28	0.36	0.83
20044	−7	−9	26	0.31	0.90
24023	−2	−2	26	0.28	0.88
25077	−4	−4	26	0.28	0.90
25138	−13	−18	25	0.34	0.88
61001	−19	−25	35	0.47	0.72
61002	−18	−16	42	0.37	0.91
62001	−23	−15	40	0.25	0.84
62026	−25	−21	39	0.32	0.83
62029	−25	−13	42	0.21	0.89
62101	11	18	32	0.51	0.67
62103	39	57	48	0.70	0.82
62105	−25	−12	50	0.24	0.89
62106	−20	−10	46	0.23	0.90
62107	27	24	48	0.43	0.71
62108	−23	−11	45	0.21	0.88
62109	−21	−17	36	0.29	0.82
62117	4	3	32	0.29	0.77
62145	−12	−12	32	0.32	0.83
62163	−10	−6	30	0.18	0.89
62301	−11	−17	26	0.40	0.77
62303	−12	−12	29	0.29	0.84
62304	2	4	25	0.46	0.75
62305	17	31	32	0.59	0.80
62414	−25	−21	53	0.44	0.74
64045	−24	−11	49	0.23	0.88
64046	−21	−11	44	0.23	0.89
athos	−4	−8	27	0.49	0.77

Table 15. Predicted significant wave height

Parameter	Obs	peak	
Station	m	m	%
almag	1.6	−0.1	−4
oland	2.9	−0.6	−24
truba	1.6	−0.2	−13
arkon	2.7	−0.7	−26
20044	2.7	−0.3	−12
24023	2.2	−0.3	−14
25077	2.7	−0.5	−17
25138	2.0	−0.4	−22
61001	2.4	−0.6	−23
61002	3.7	−0.2	−5
62001	3.8	−1.2	−31
62026	3.0	−0.8	−27
62029	4.4	−0.5	−11
62101	1.8	0.0	5
62103	1.9	0.5	25
62105	6.3	−1.6	−22
62106	6.3	−0.7	−9
62107	3.1	−0.8	−25
62108	5.4	−0.9	−17
62109	3.0	−0.8	−26
62117	1.8	−0.2	−9
62145	2.9	−0.9	−28
62163	3.6	−0.3	−9
62301	1.8	−0.3	−18
62303	2.7	−0.6	−21
62304	2.0	−0.4	−19
62305	2.5	−0.4	−16
62414	2.2	−0.3	−13
64045	6.4	−0.7	−10
64046	5.4	0.1	2
athos	1.8	−0.2	−13

Table 16. Average of top 5 wave events (peaks) and corresponding mean peak error (peak bias)

Parameter Station	bias sec	 %	rms sec	si	cc
almag	0.3	9	0.6	0.17	0.58
oland	0.3	7	0.6	0.15	0.74
truba	0.5	15	0.8	0.24	0.37
arkon	0.6	19	0.8	0.24	0.69
20044	1.2	35	1.5	0.43	0.57
24023	1.6	40	1.9	0.48	0.49
25077	1.3	34	1.6	0.40	0.59
25138	1.4	42	1.7	0.52	0.40
athos	0.6	19	0.9	0.26	0.49

Table 17. Predicted mean wave period

Parameter Station	bias sec	 %	rms sec	si	cc
20044	0.2	3	2.3	0.40	0.53
24023	0.3	4	2.0	0.30	0.63
25077	0.2	3	2.0	0.32	0.65
25138	1.3	27	2.6	0.55	0.45
61001	0.0	−1	1.4	0.29	0.57
61002	0.1	1	1.3	0.25	0.50
62001	2.6	42	3.4	0.54	0.47
62026	1.2	26	2.4	0.48	0.22
62029	2.4	36	2.9	0.45	0.53
62101	2.0	54	2.9	0.77	0.27
62103	0.9	13	2.4	0.35	0.29
62105	2.5	38	2.9	0.43	0.62
62106	2.4	35	2.8	0.42	0.60
62107	1.1	15	2.4	0.31	0.47
62108	1.9	28	2.3	0.33	0.62
62109	1.8	36	2.9	0.58	0.14
62117	2.5	56	3.4	0.77	0.17
62145	1.3	31	1.8	0.43	0.51
62163	2.6	42	3.3	0.53	0.54
62301	2.1	48	3.2	0.73	0.38
62303	1.6	28	2.6	0.45	0.50
62304	−1.1	−18	1.6	0.26	0.36
62305	−2.6	−33	3.5	0.46	0.08
64045	2.2	33	2.6	0.39	0.65
64046	2.3	34	2.8	0.42	0.64
athos	0.1	2	1.5	0.38	0.36

Table 18. Predicted dominant wave period

Parameter Station	bias deg	std deg	cc
arkon	9	43	0.94
20044	6	48	0.92
24023	-7	37	0.73
25077	-1	42	0.84
25138	6	52	0.84
athos	24	69	0.87

Table 19. Predicted mean wave direction

7.5 Significant wave height plots

The following pages show significant wave height error statistics for each station.

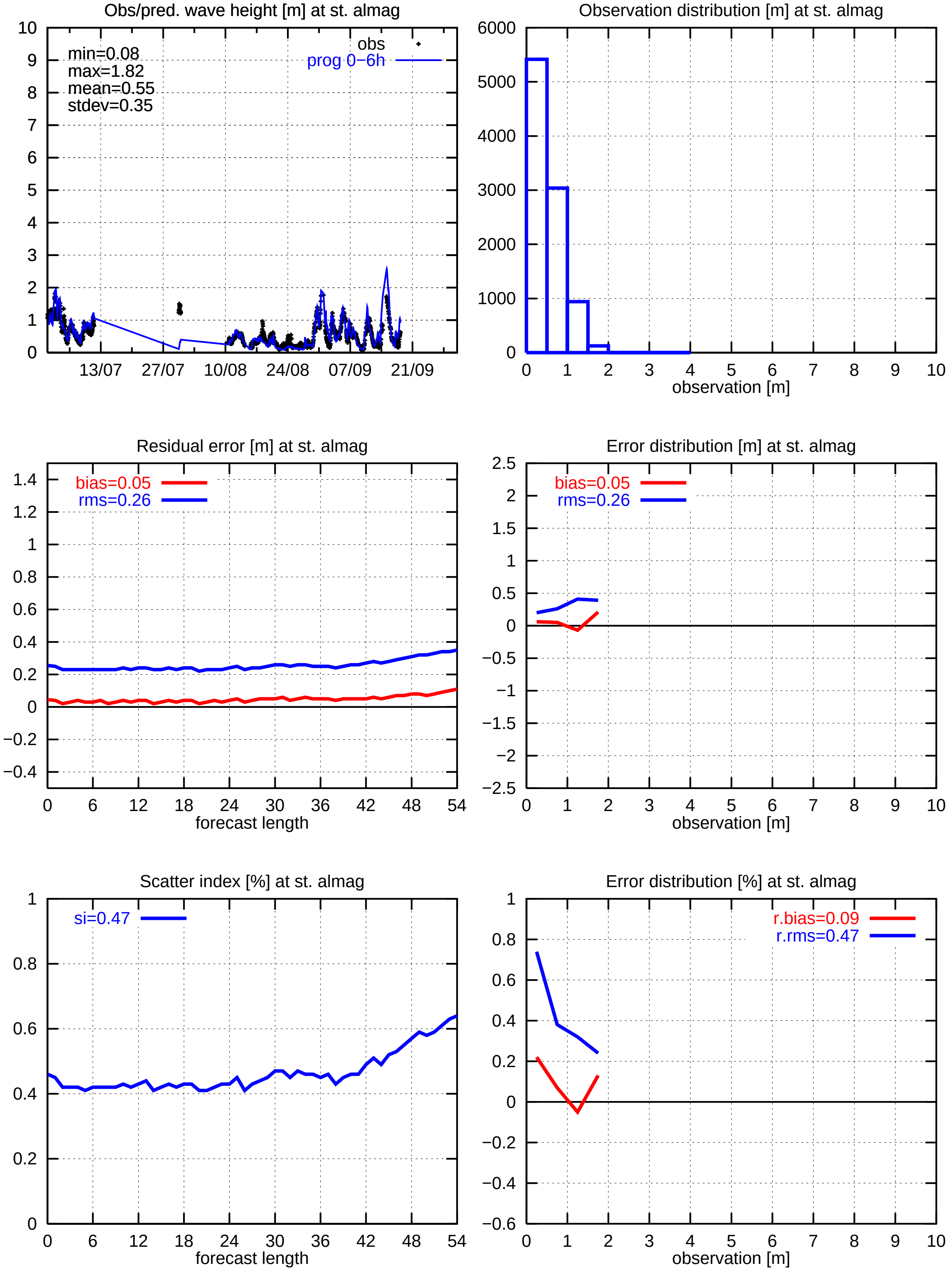

Figure 13. Significant wave height: Almagrundet

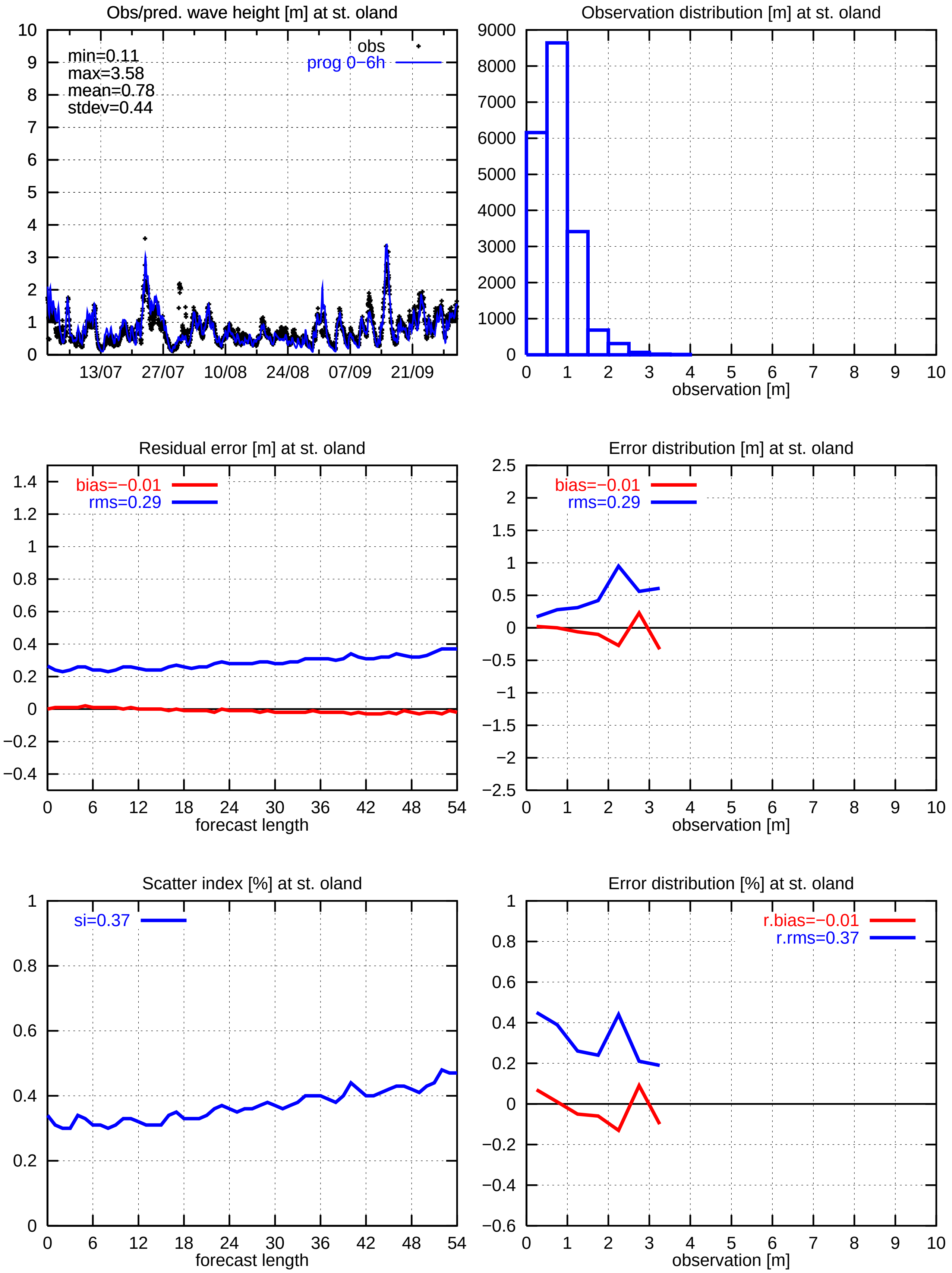

Figure 14. Significant wave height: Øland

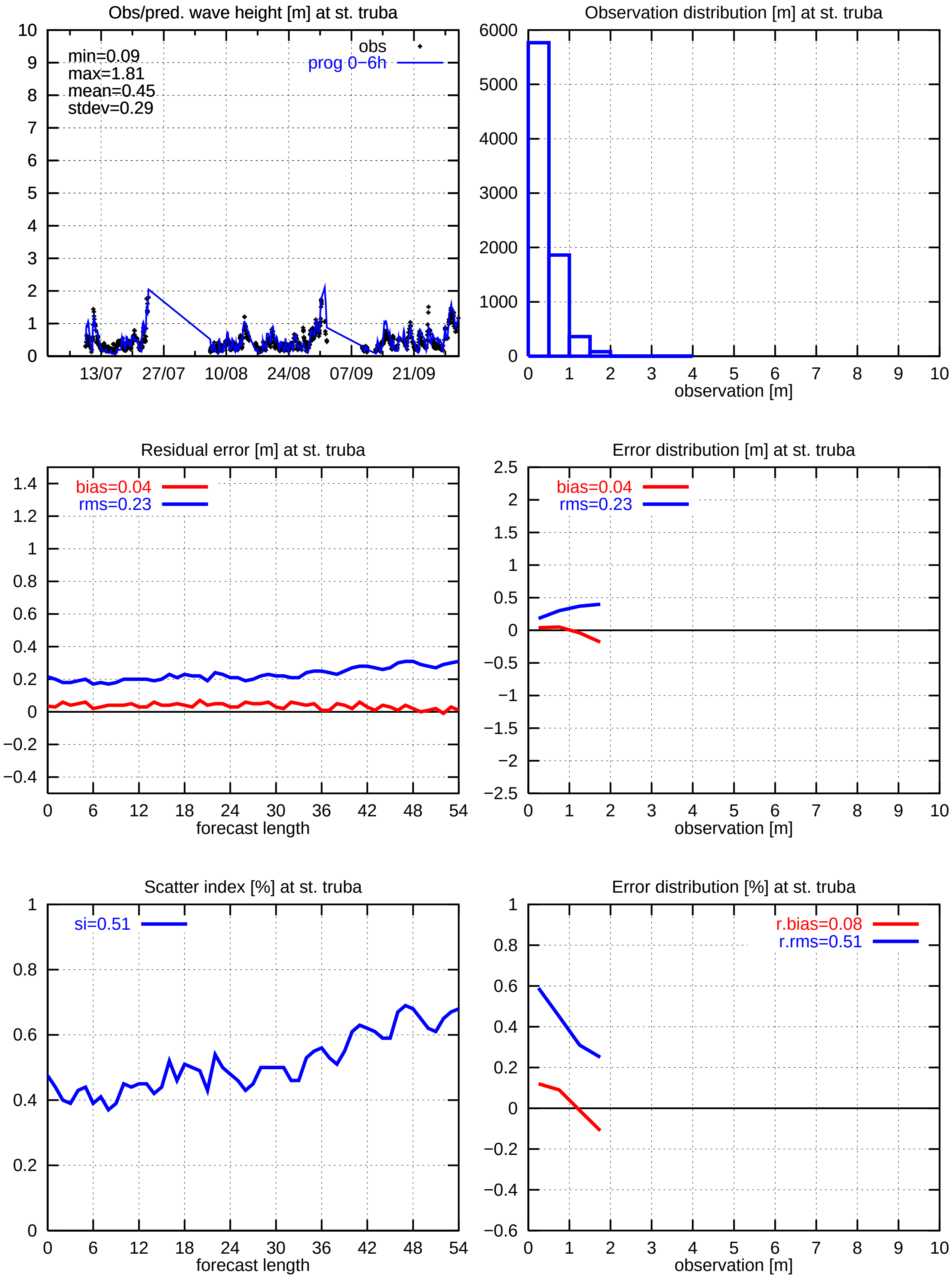

Figure 15. Significant wave height: Trubaduren

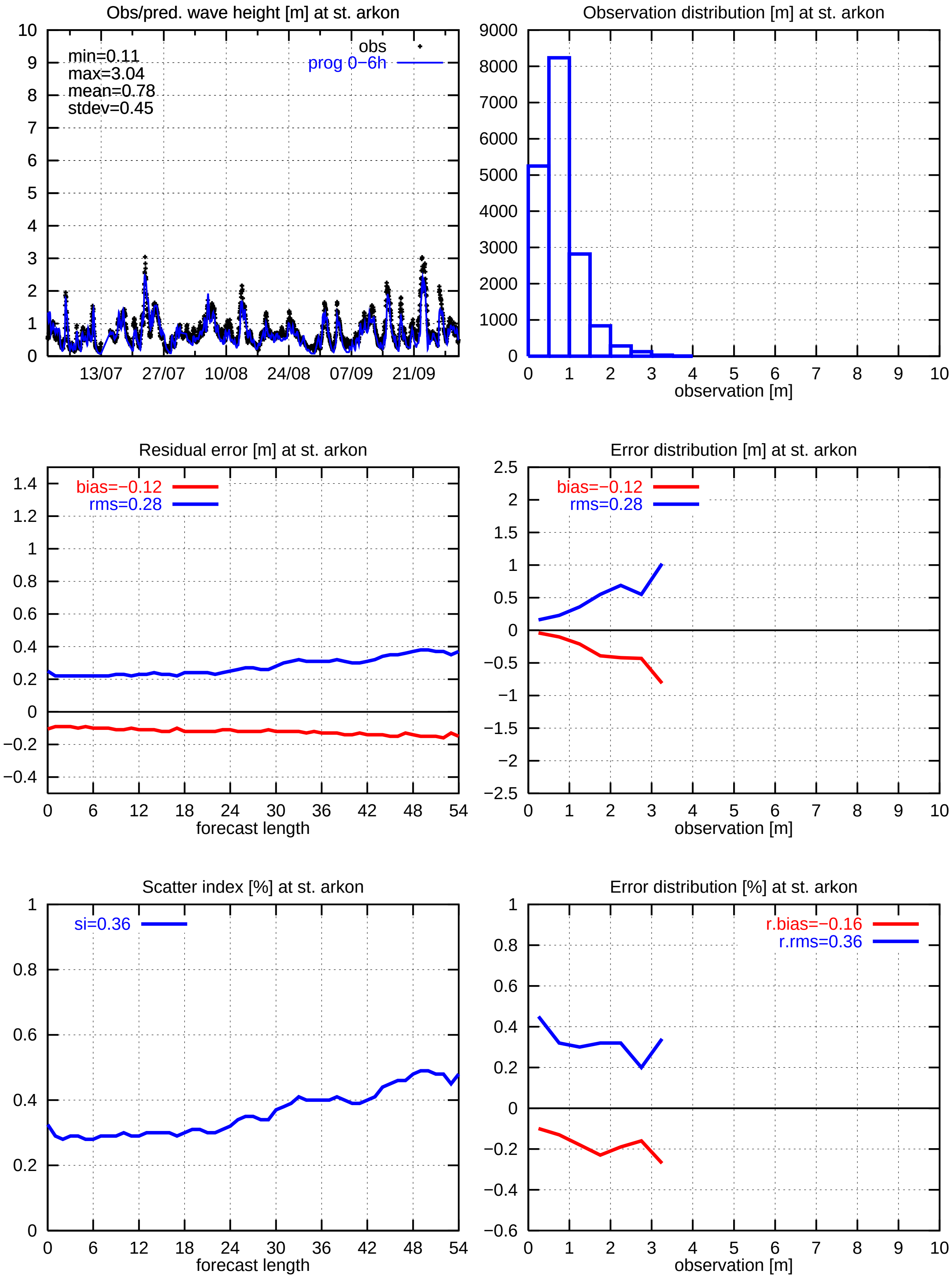

Figure 16. Significant wave height: Arkona

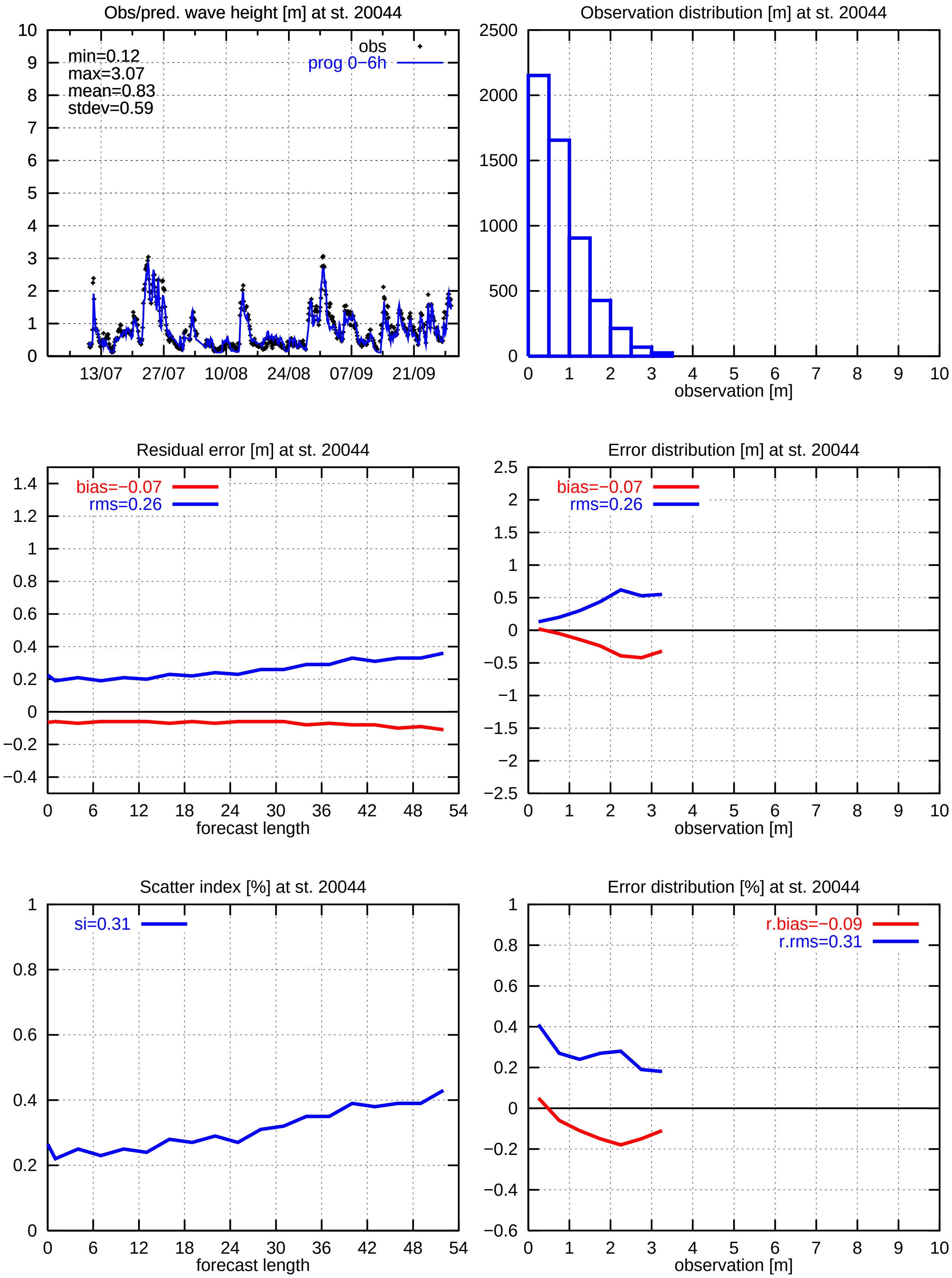

Figure 17. Significant wave height: 20044

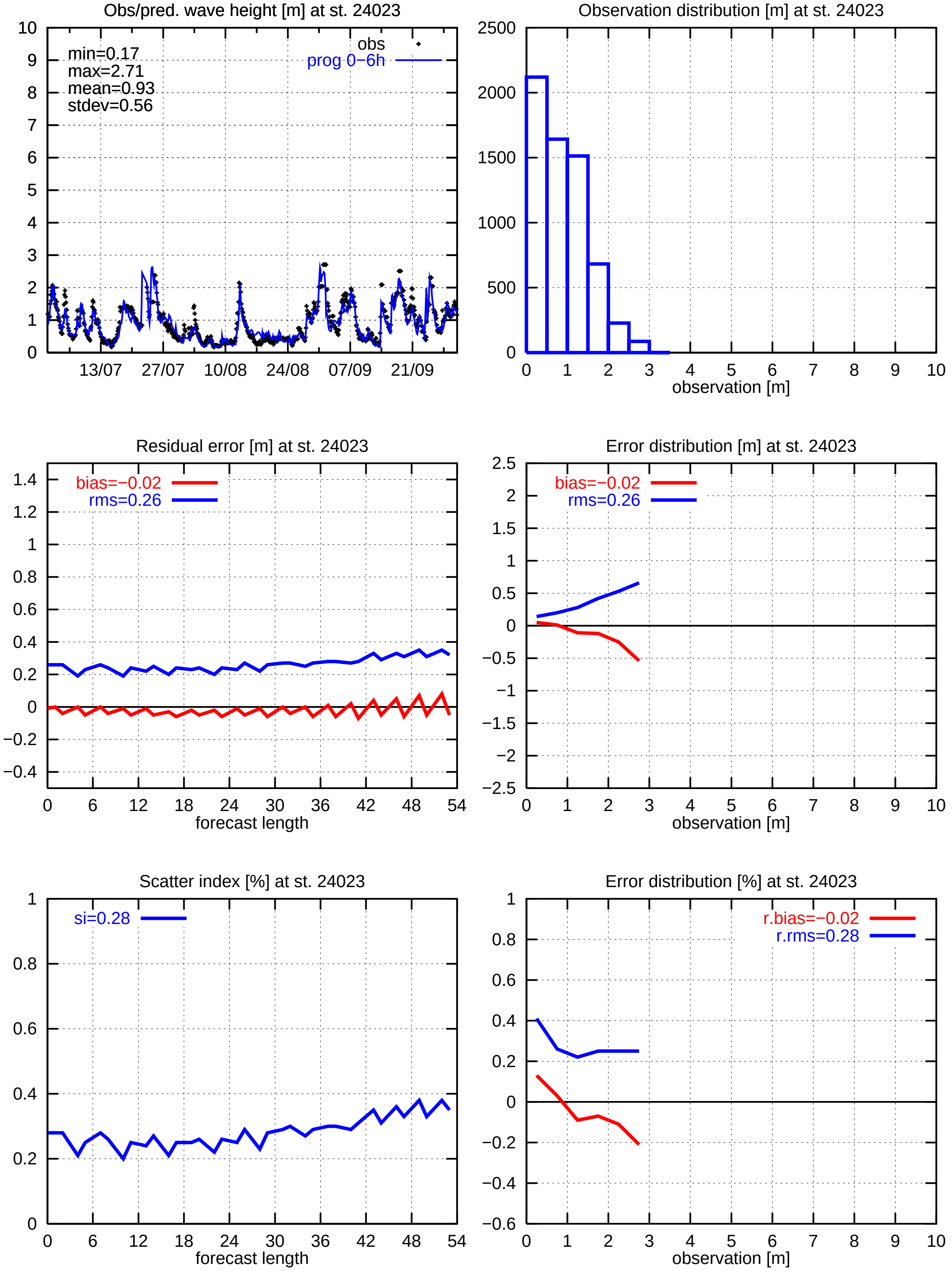

Figure 18. Significant wave height: 24023. The zig-zag curves are caused by irregular 3h sampling.

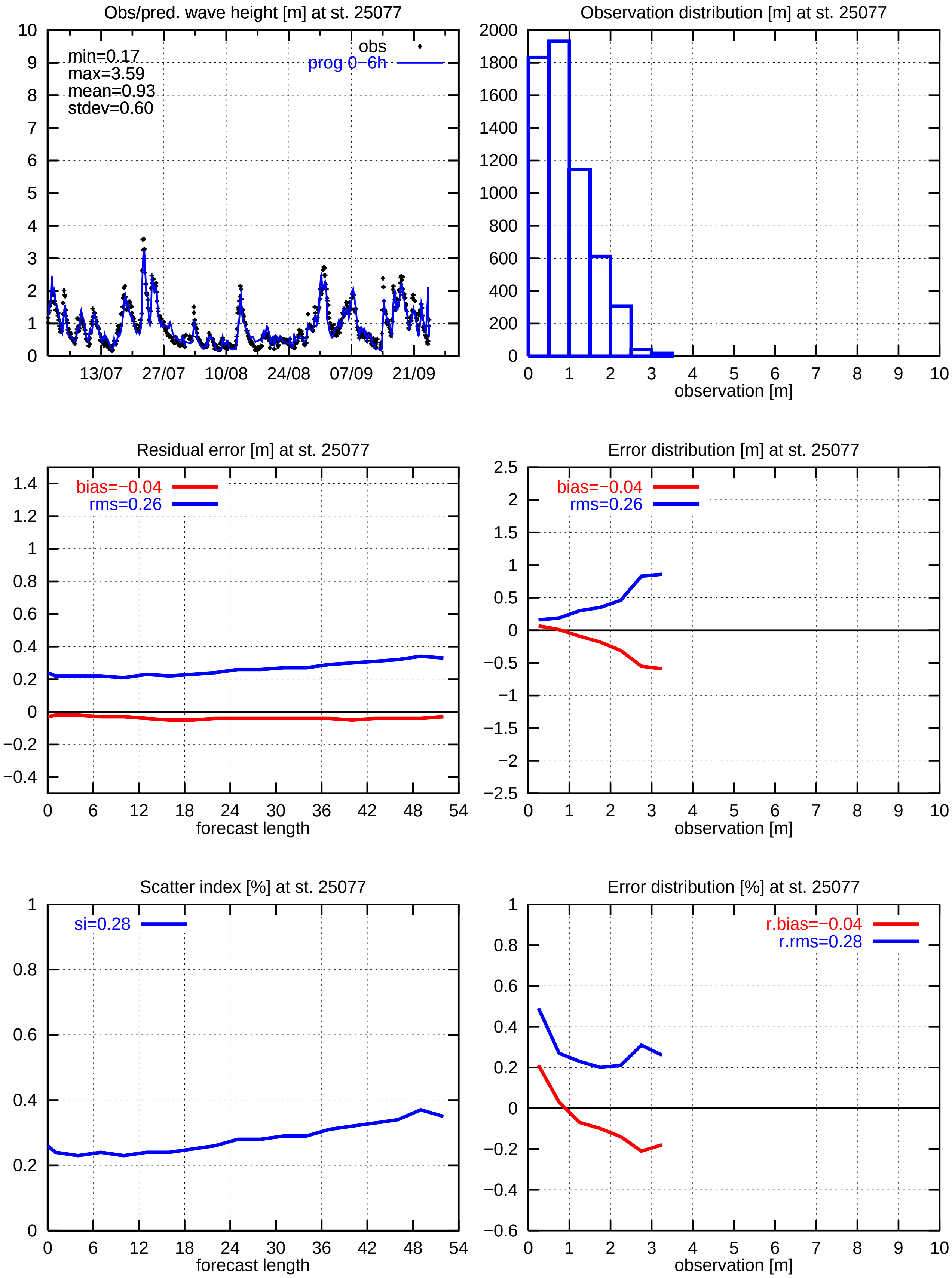

Figure 19. Significant wave height: 25077.

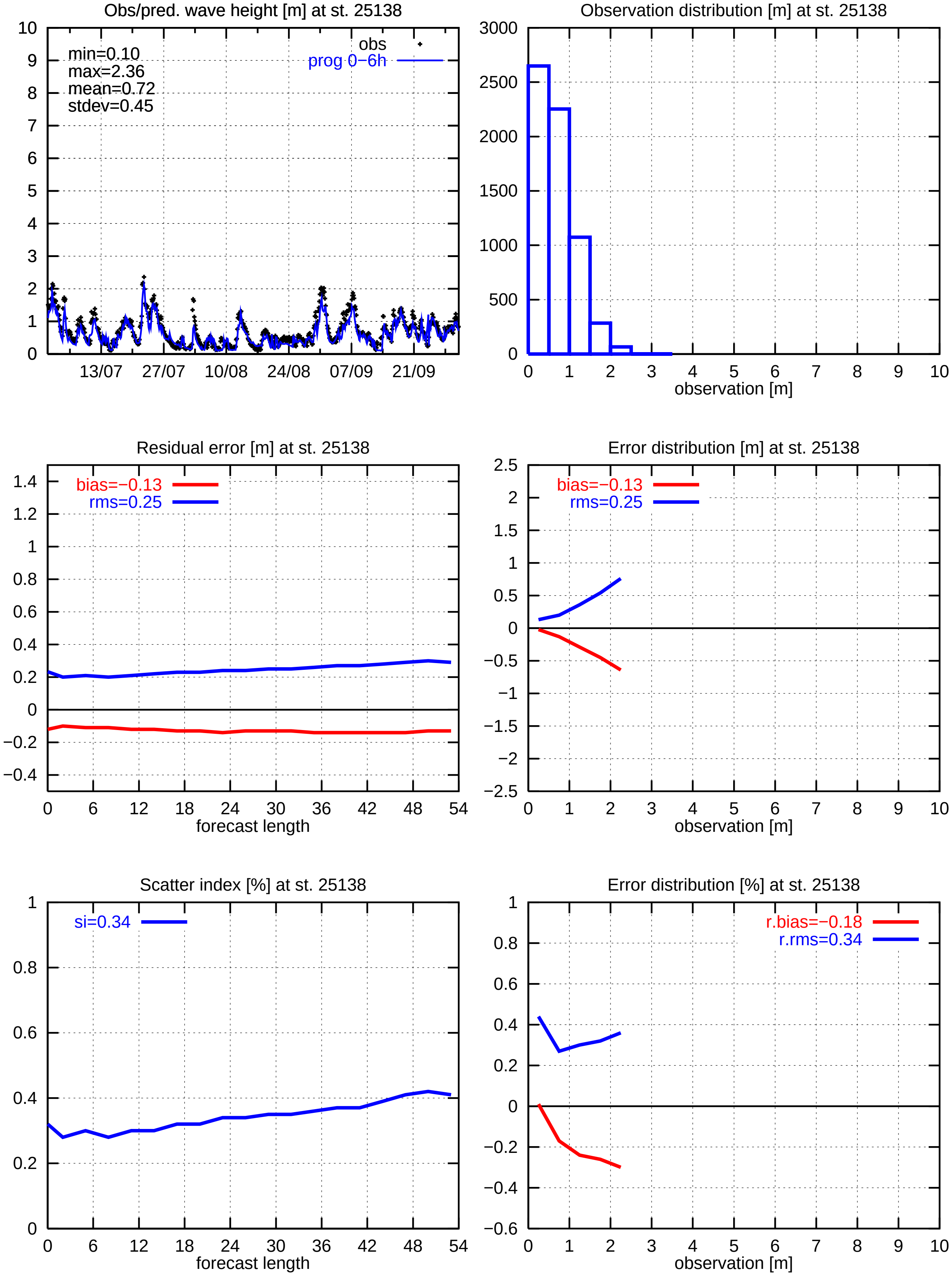

Figure 20. Significant wave height: 25138

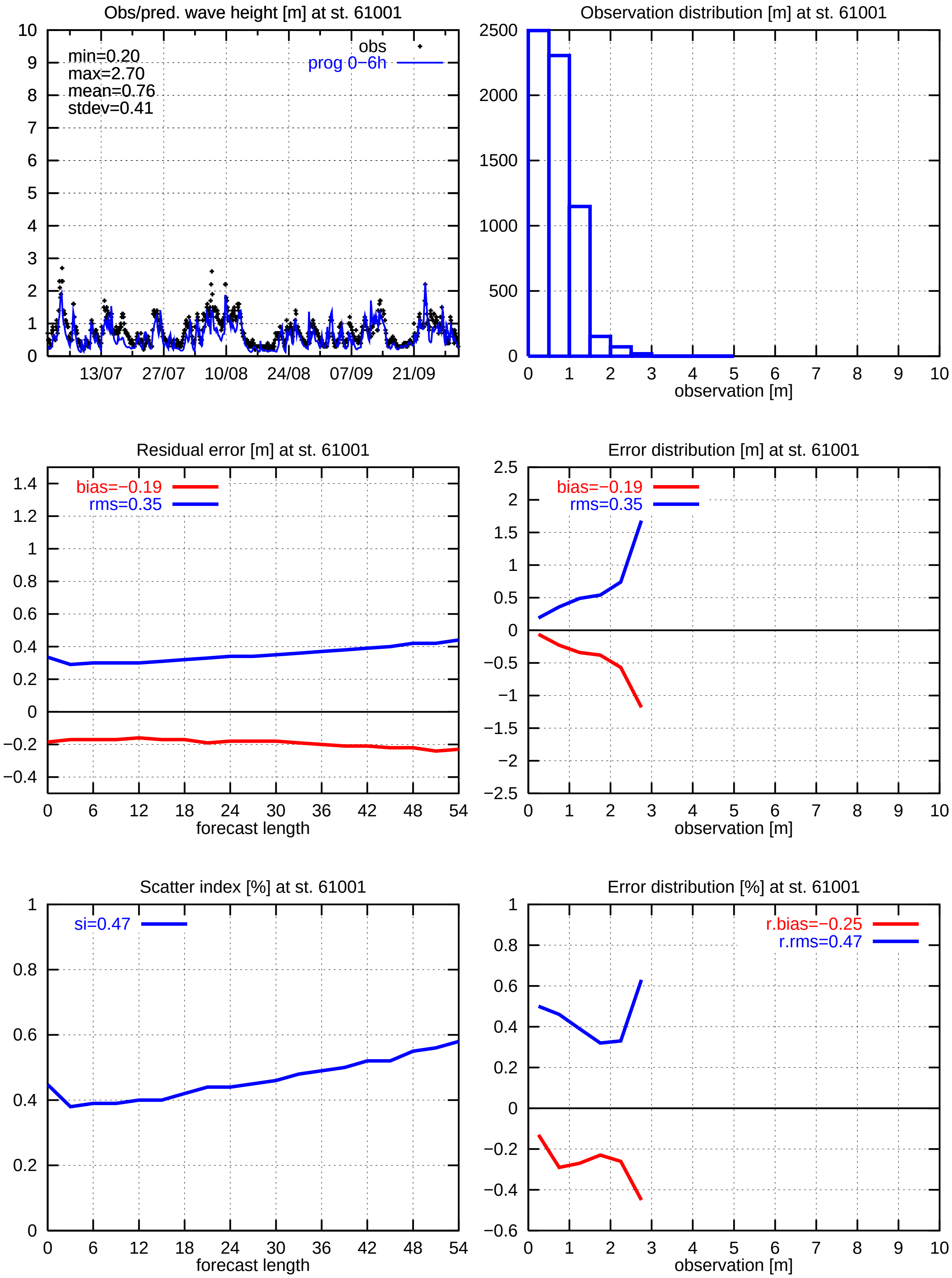

Figure 21. Significant wave height: 61001

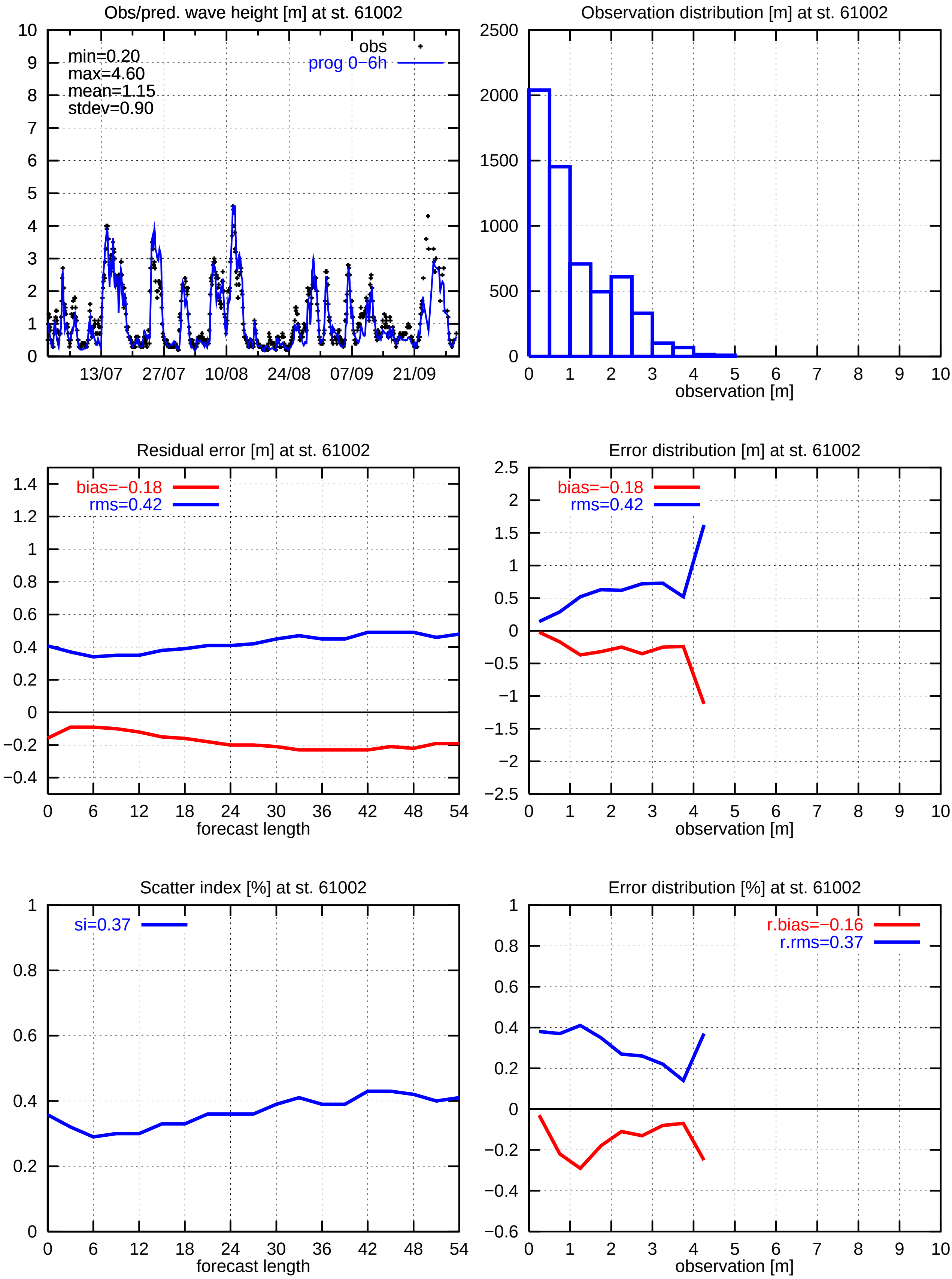

Figure 22. Significant wave height: 61002

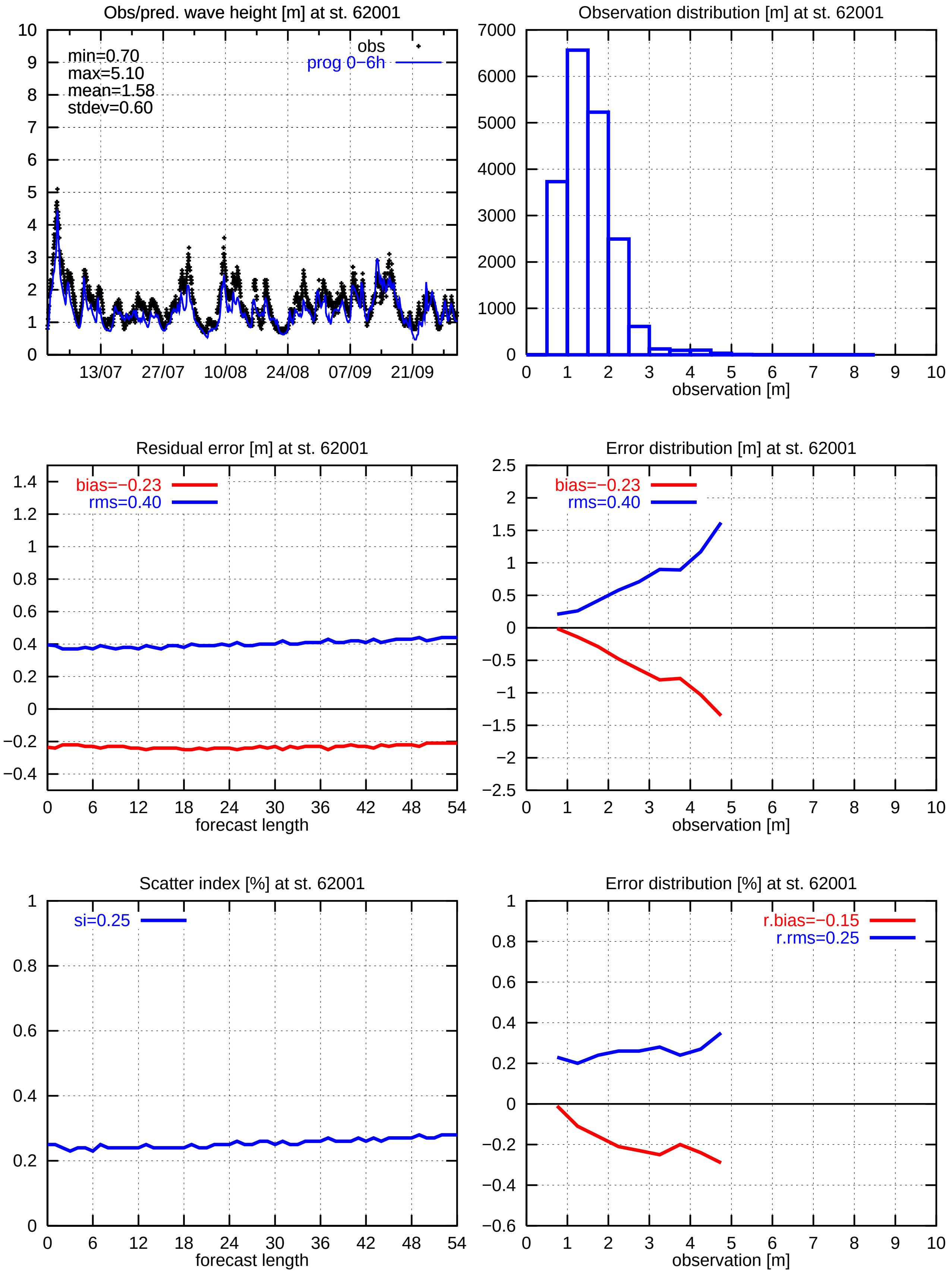

Figure 23. Significant wave height: 62001

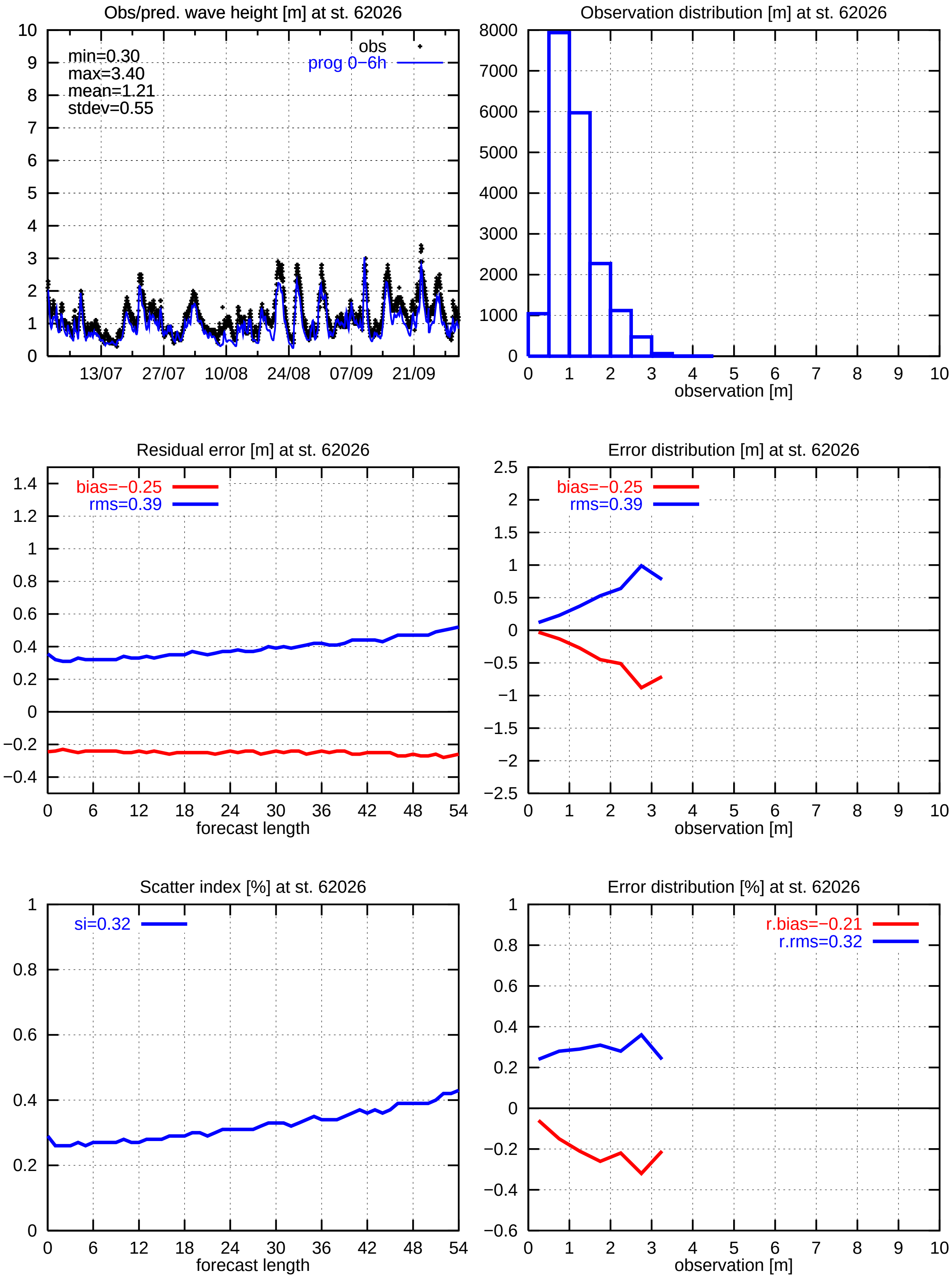

Figure 24. Significant wave height: 62026

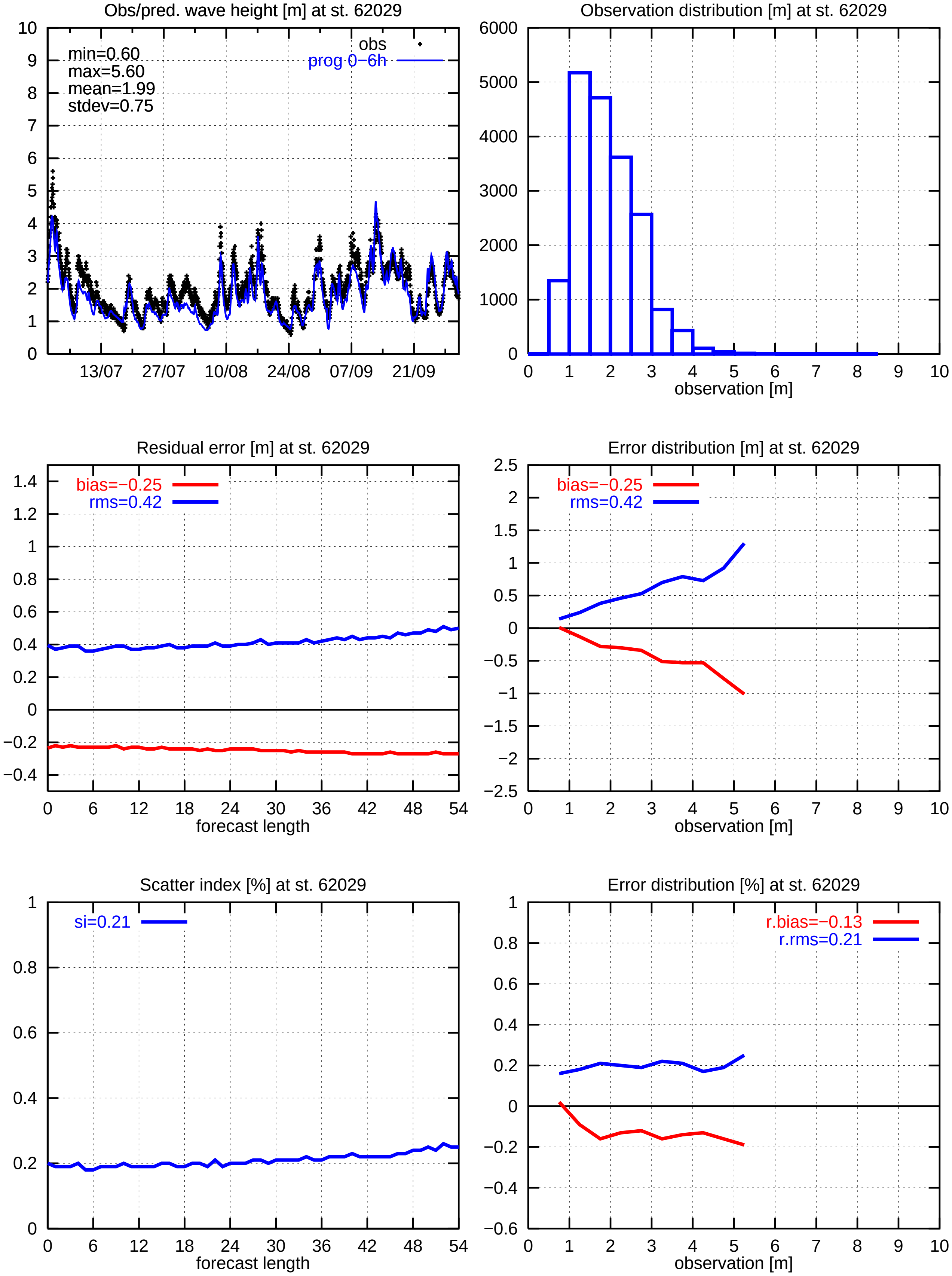

Figure 25. Significant wave height: 62029

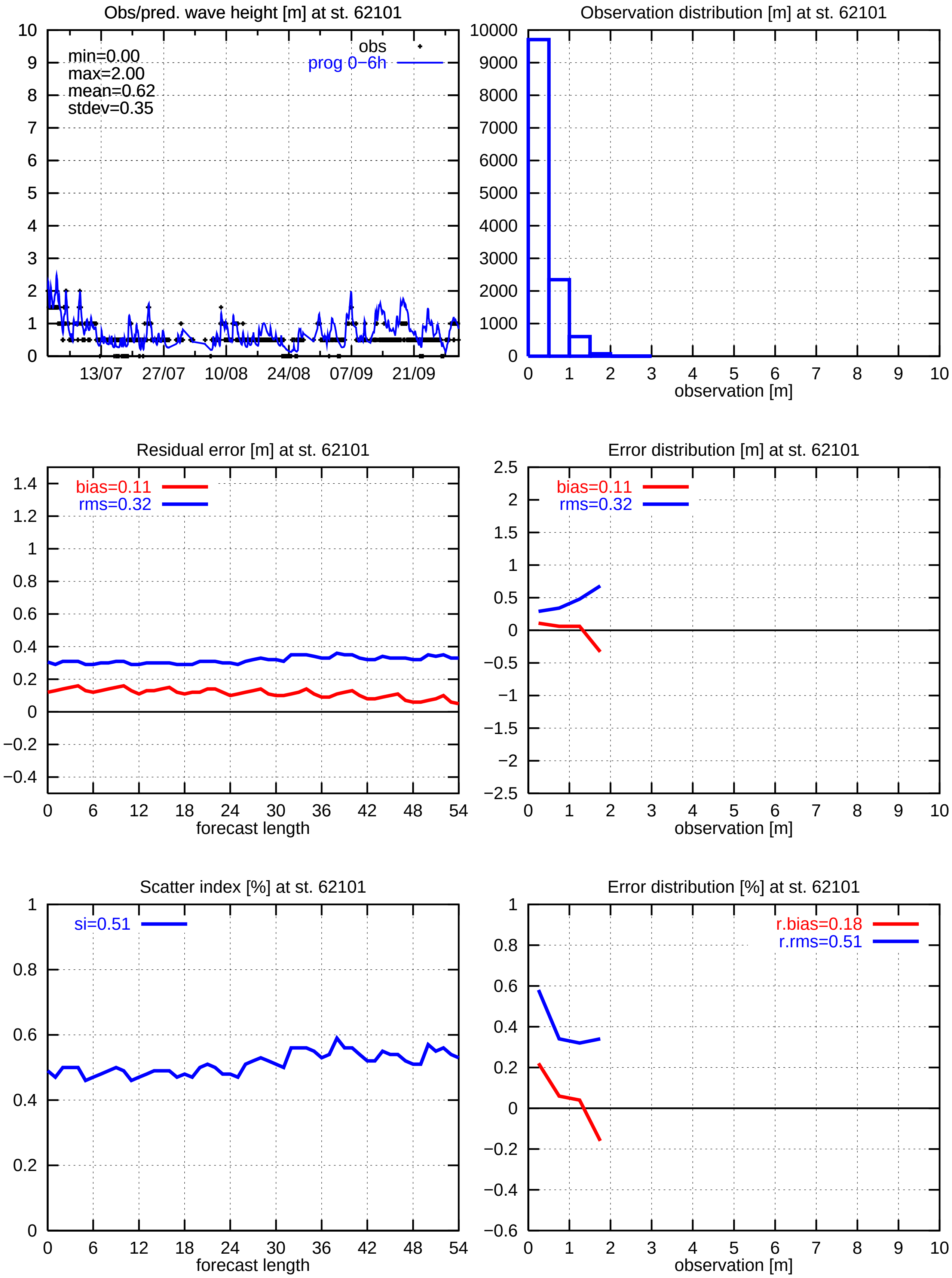

Figure 26. Significant wave height: 62101. The sampling accuracy is 0.5m

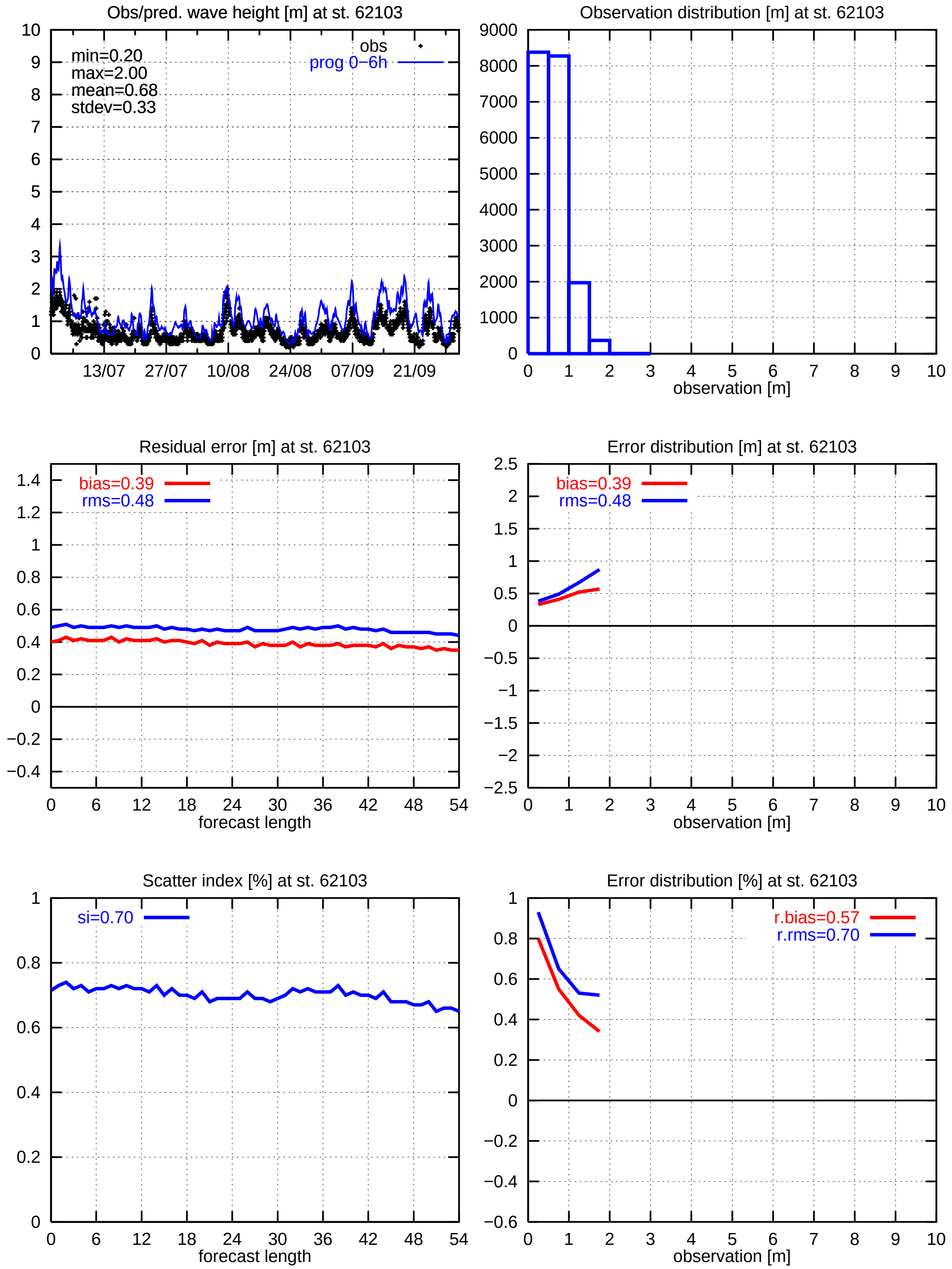

Figure 27. Significant wave height: 62103

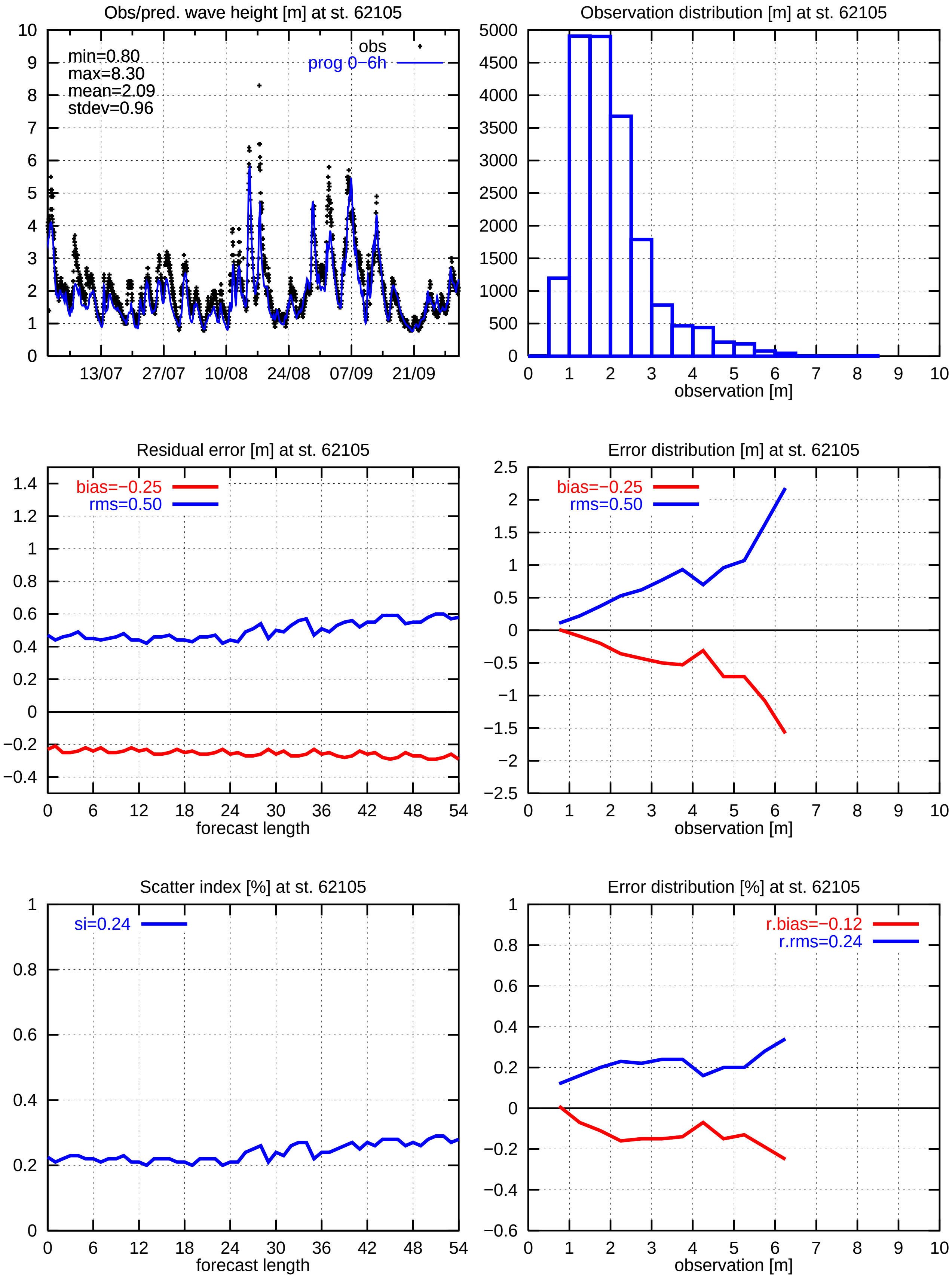

Figure 28. Significant wave height: 62105.

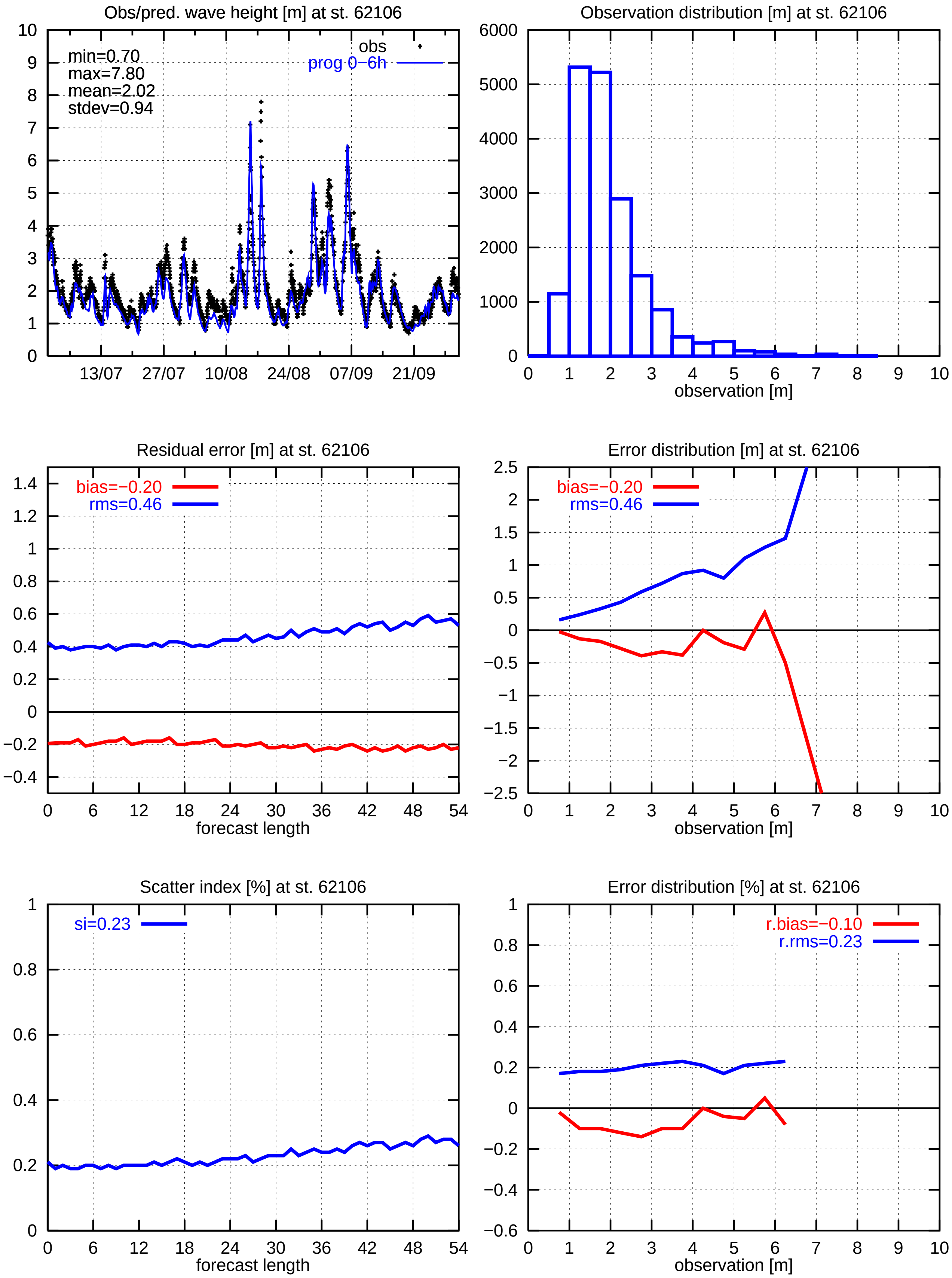

Figure 29. Significant wave height: 62106.

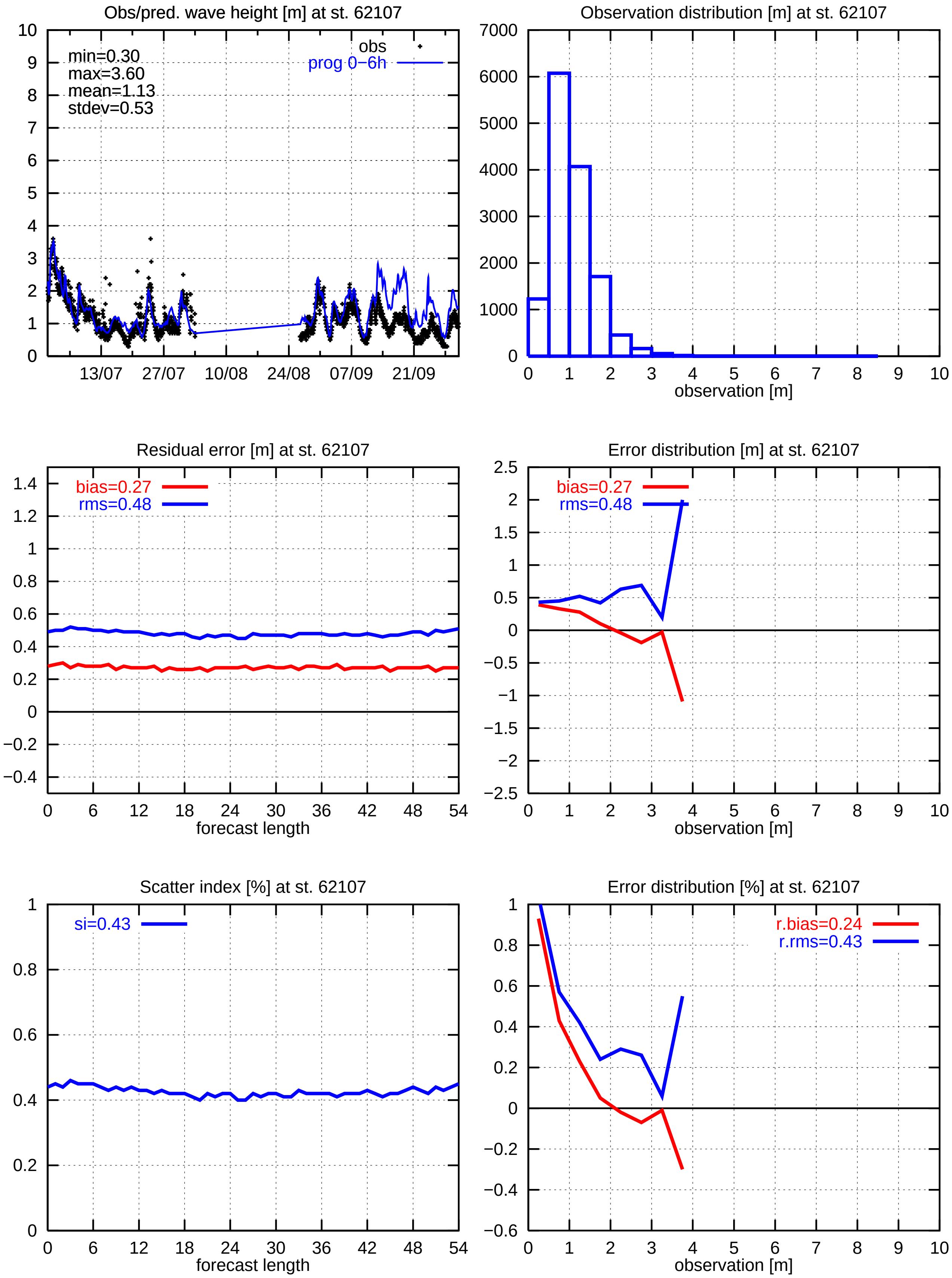

Figure 30. Significant wave height: 62107

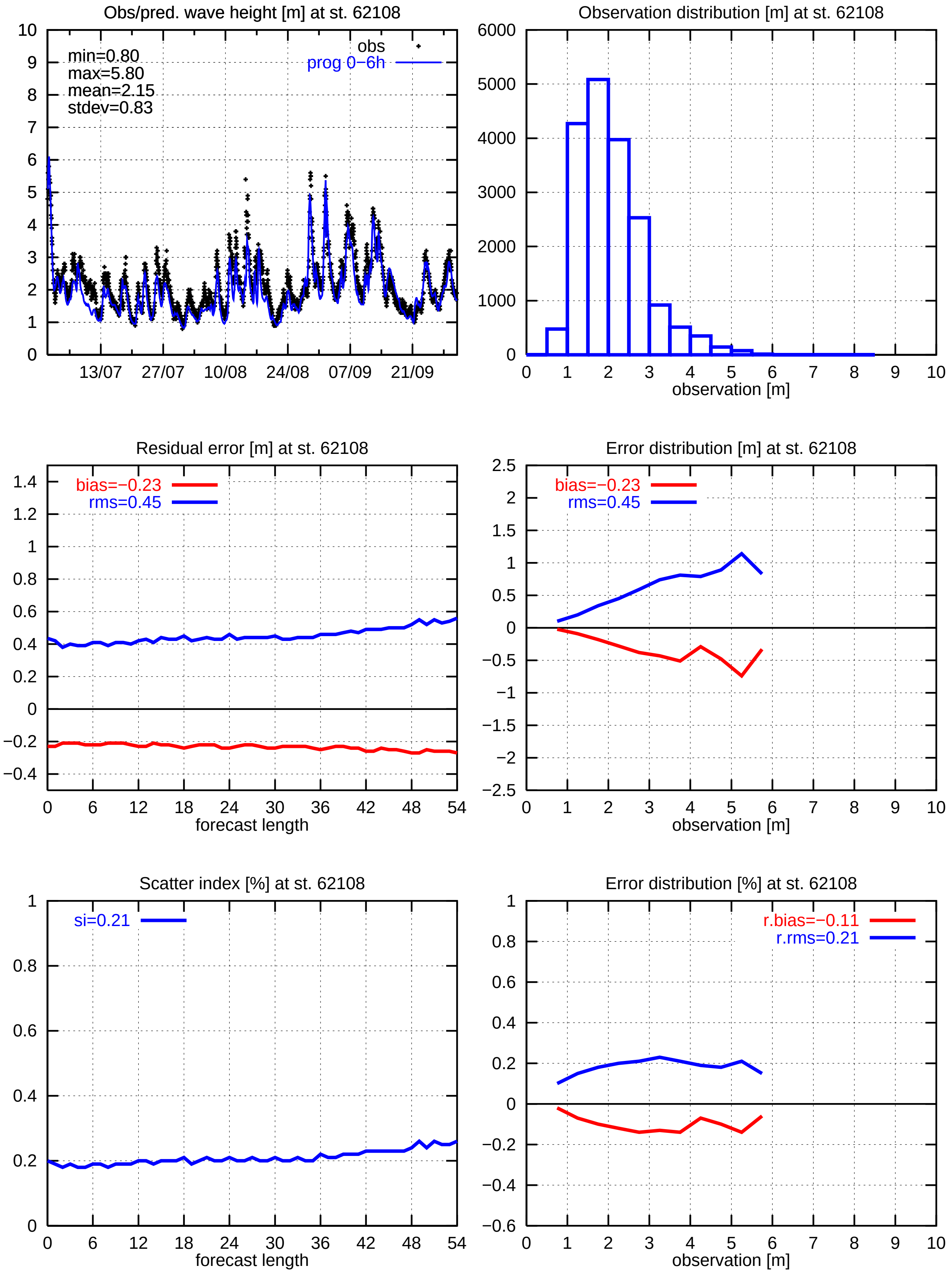

Figure 31. Significant wave height: 62108

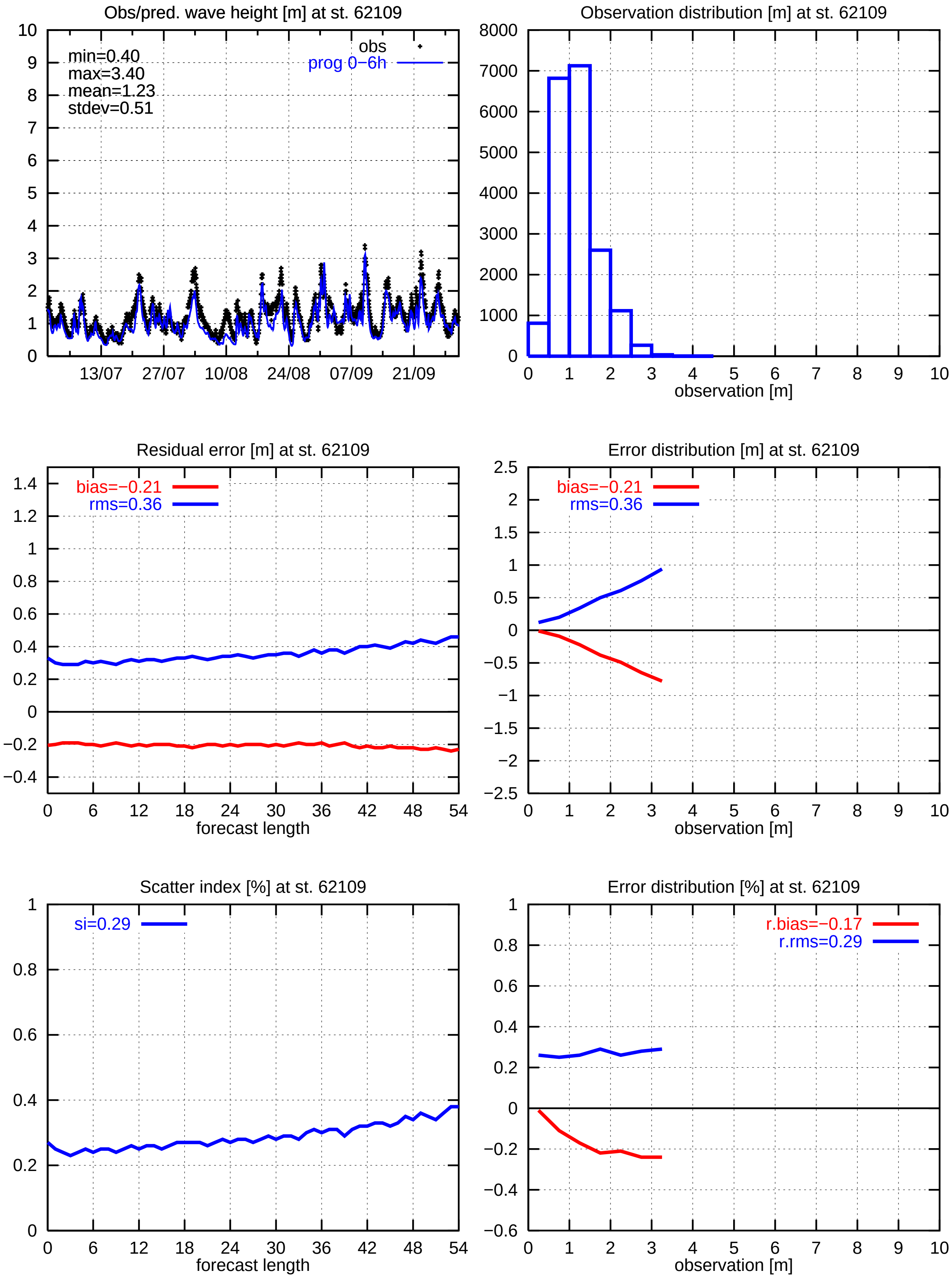

Figure 32. Significant wave height: 62109

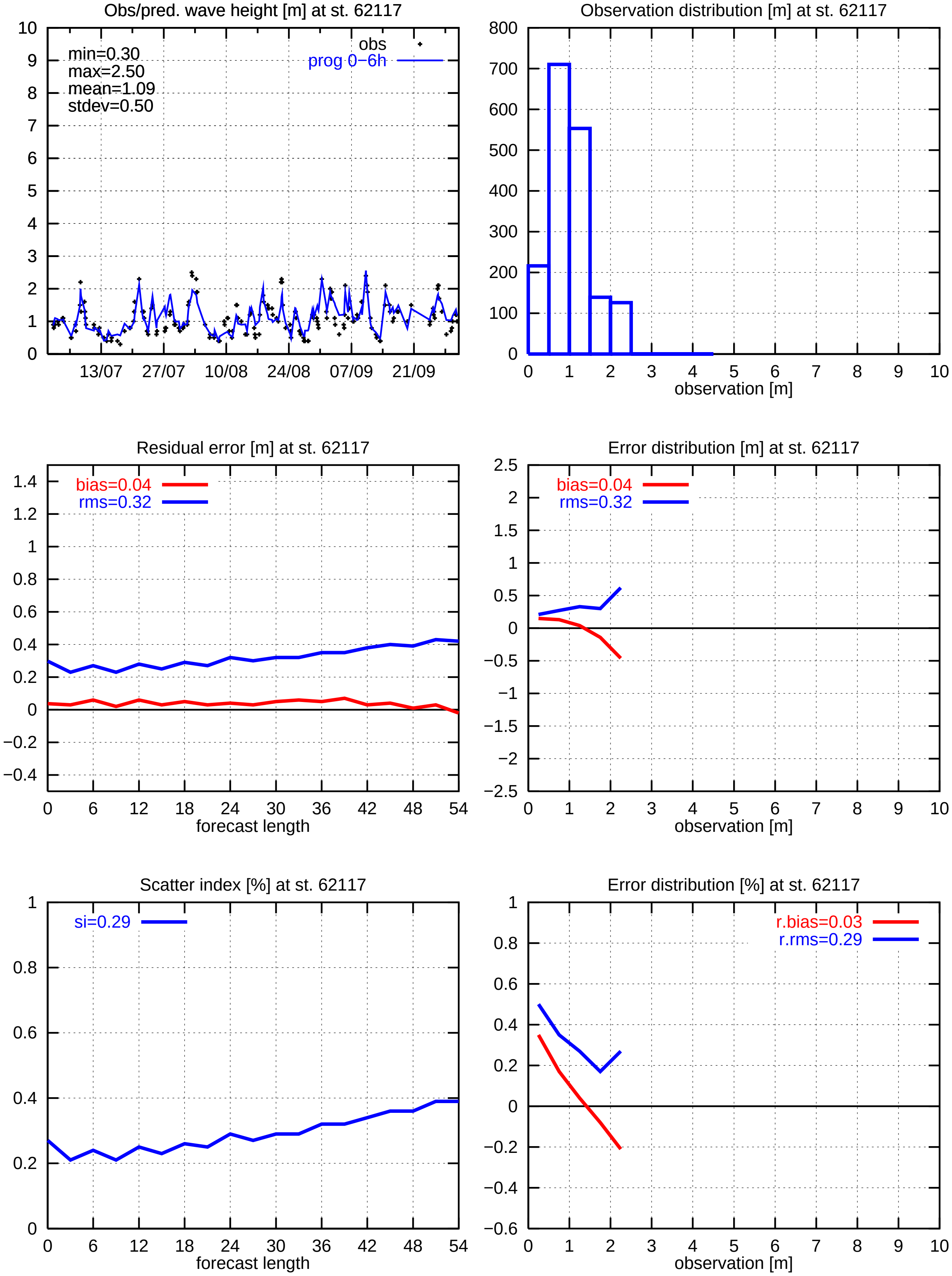

Figure 33. Significant wave height: 62117.

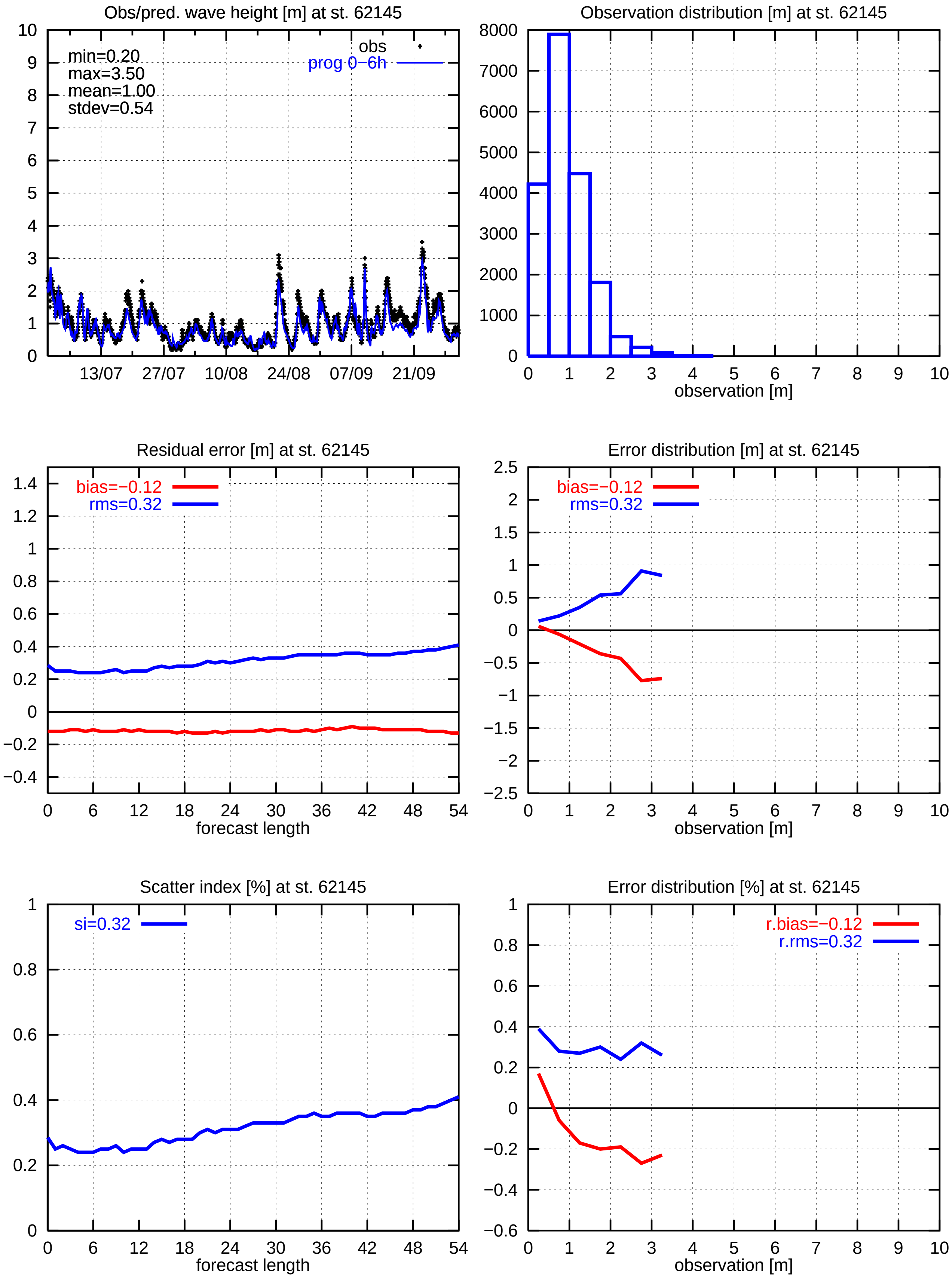

Figure 34. Significant wave height: 62145

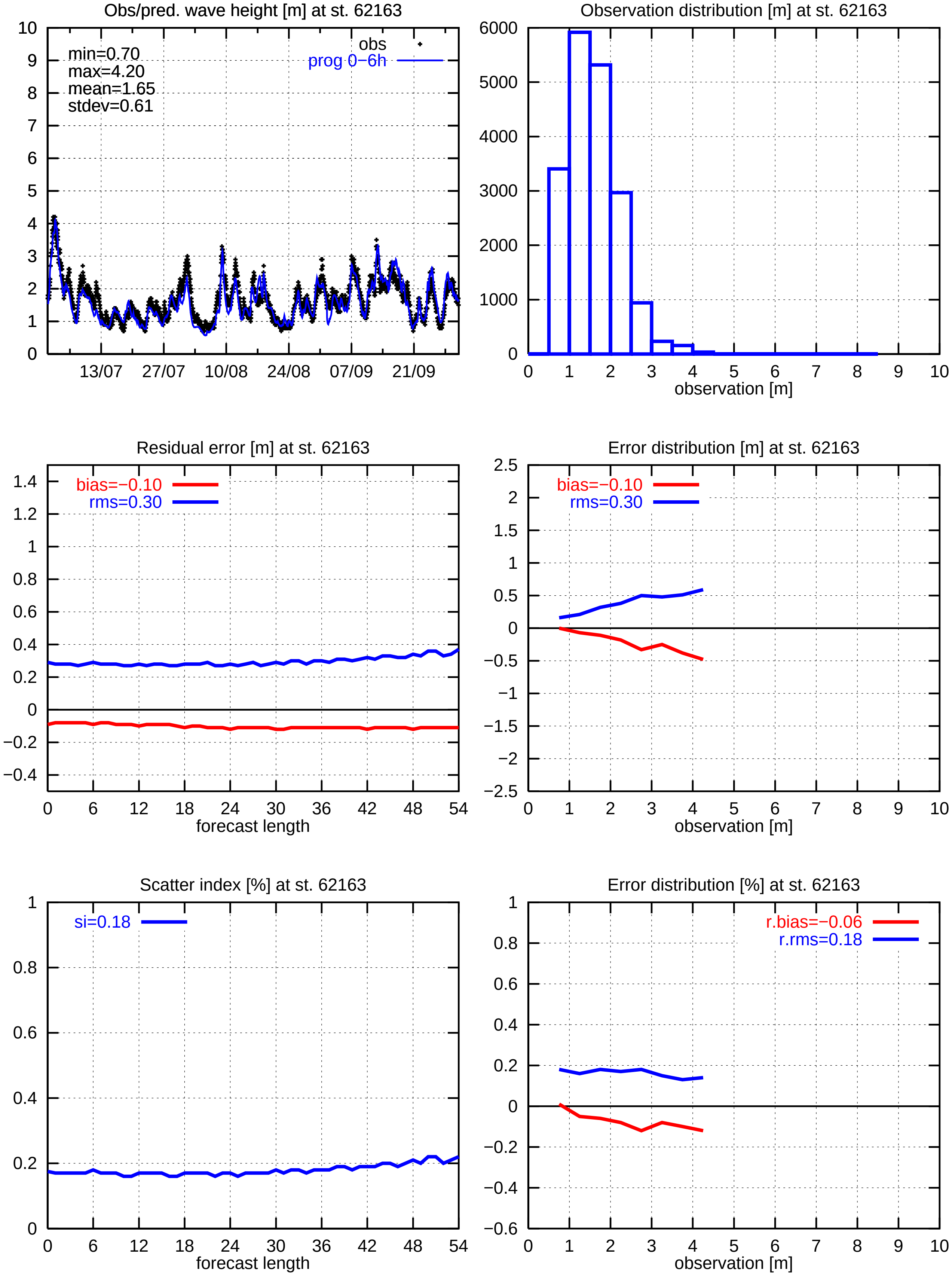

Figure 35. Significant wave height: 62163

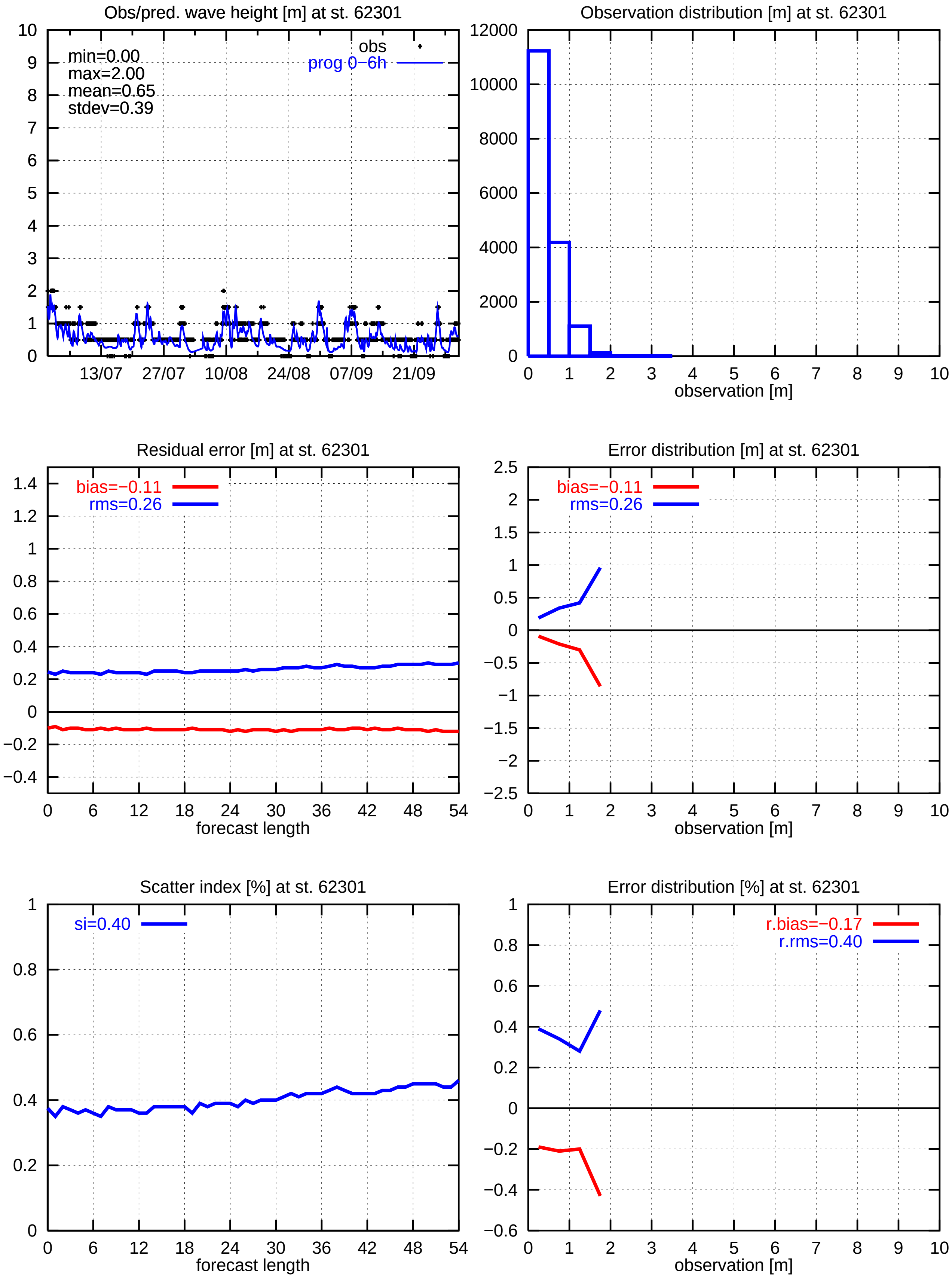

Figure 36. Significant wave height: 62301. The sampling accuracy is 0.5m

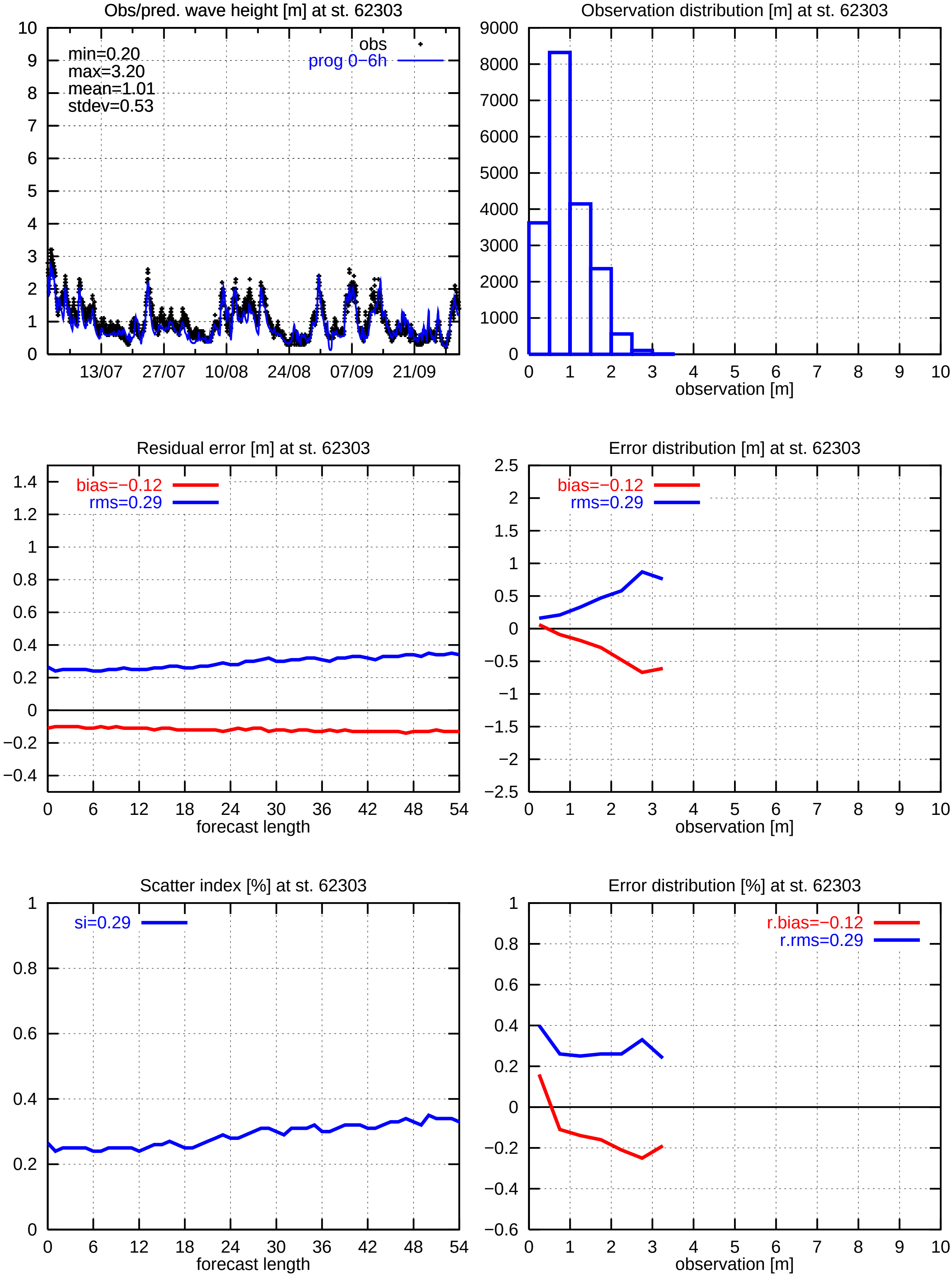

Figure 37. Significant wave height: 62303

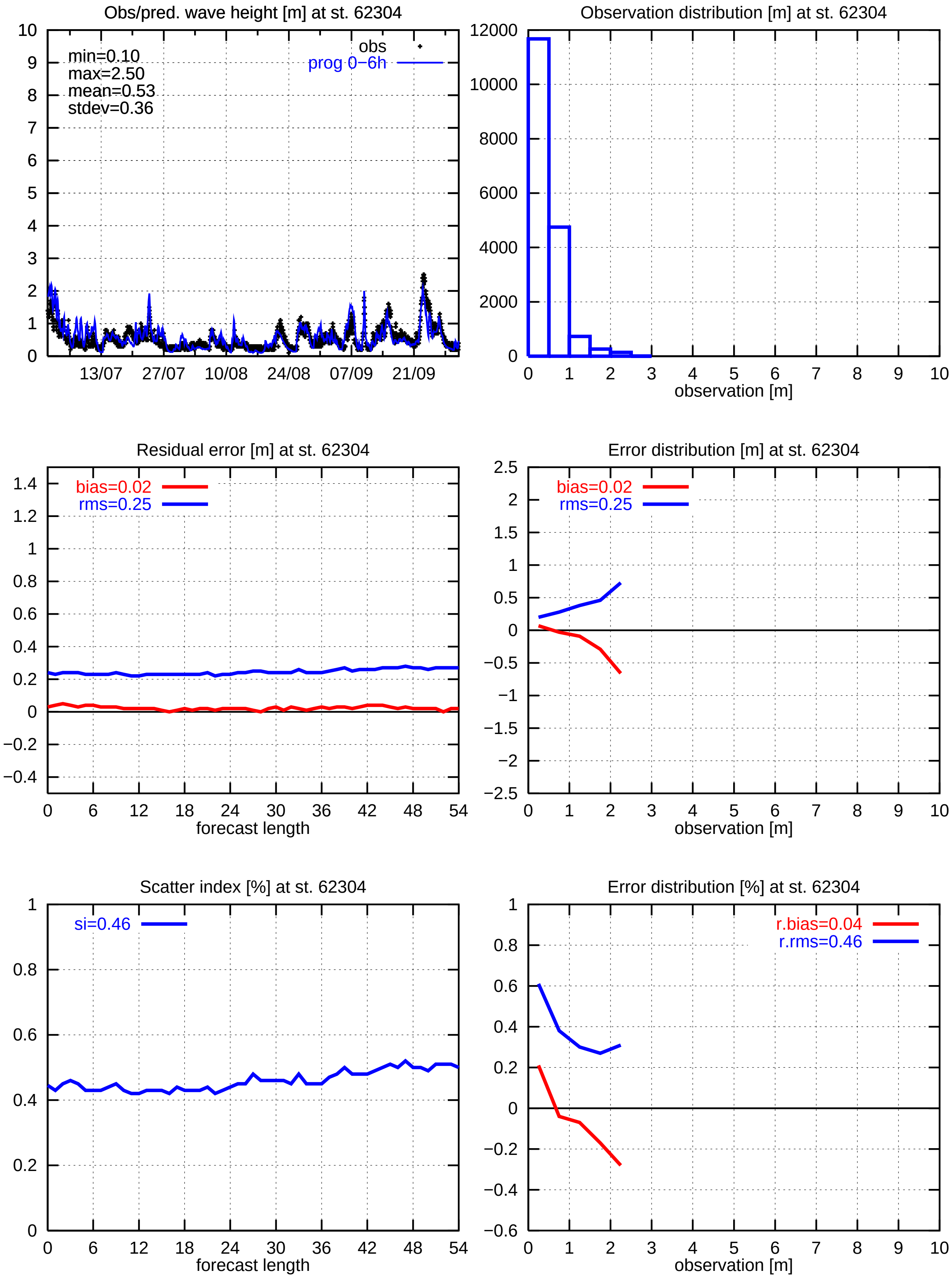

Figure 38. Significant wave height: 62304

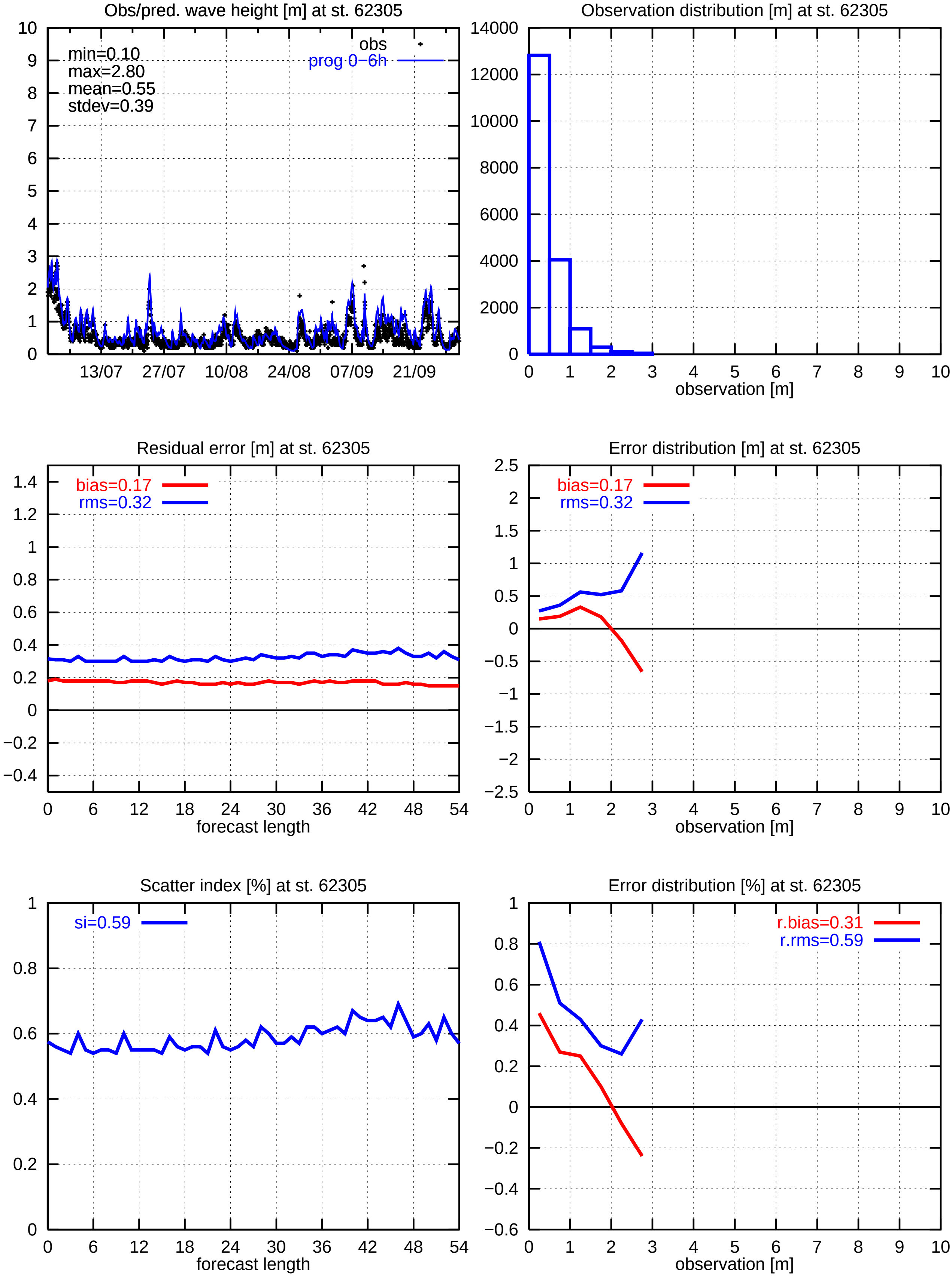

Figure 39. Significant wave height: 62305

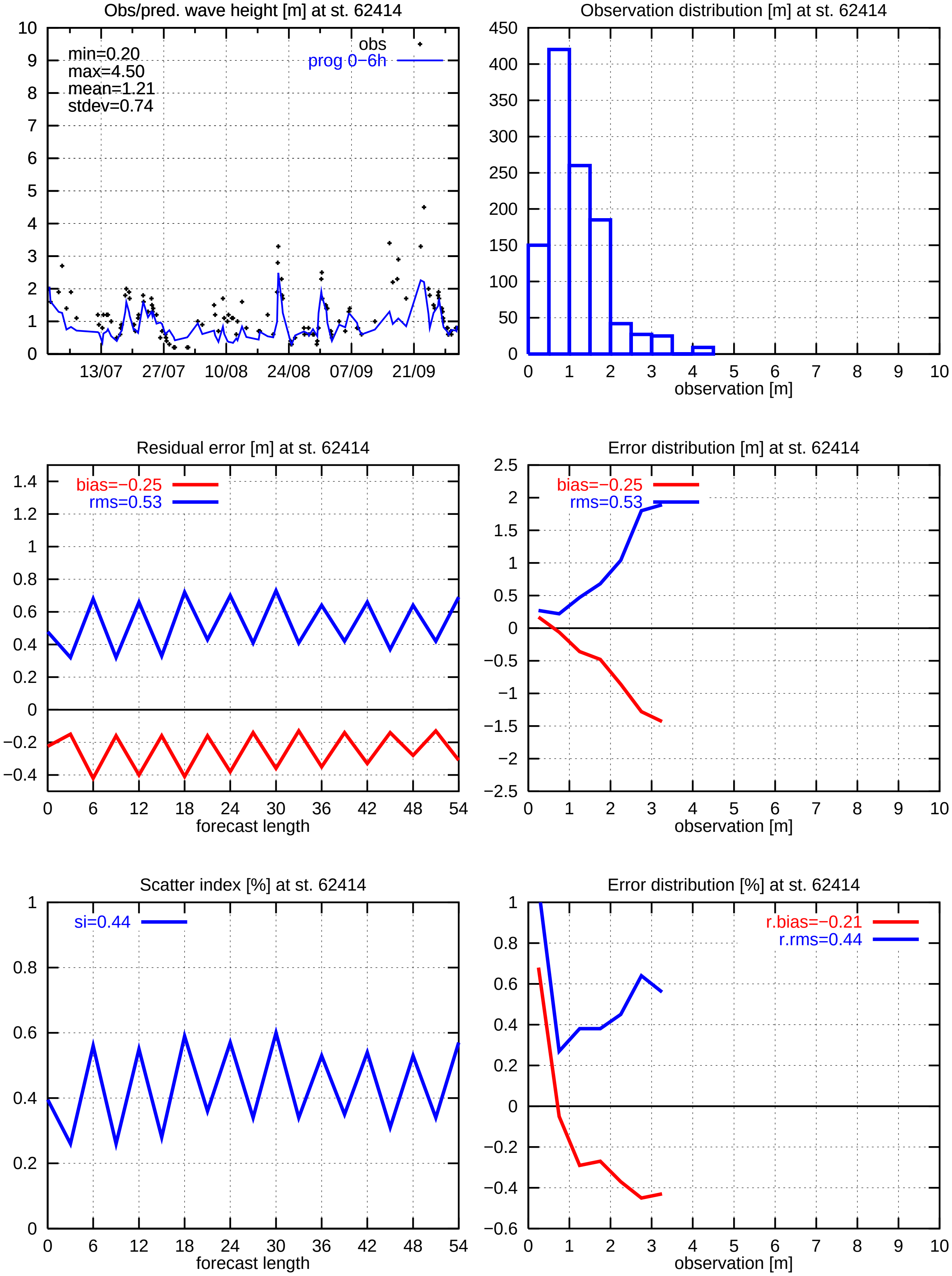

Figure 40. Significant wave height: 62414. The zig-zag curves are caused by irregular 3h sampling.

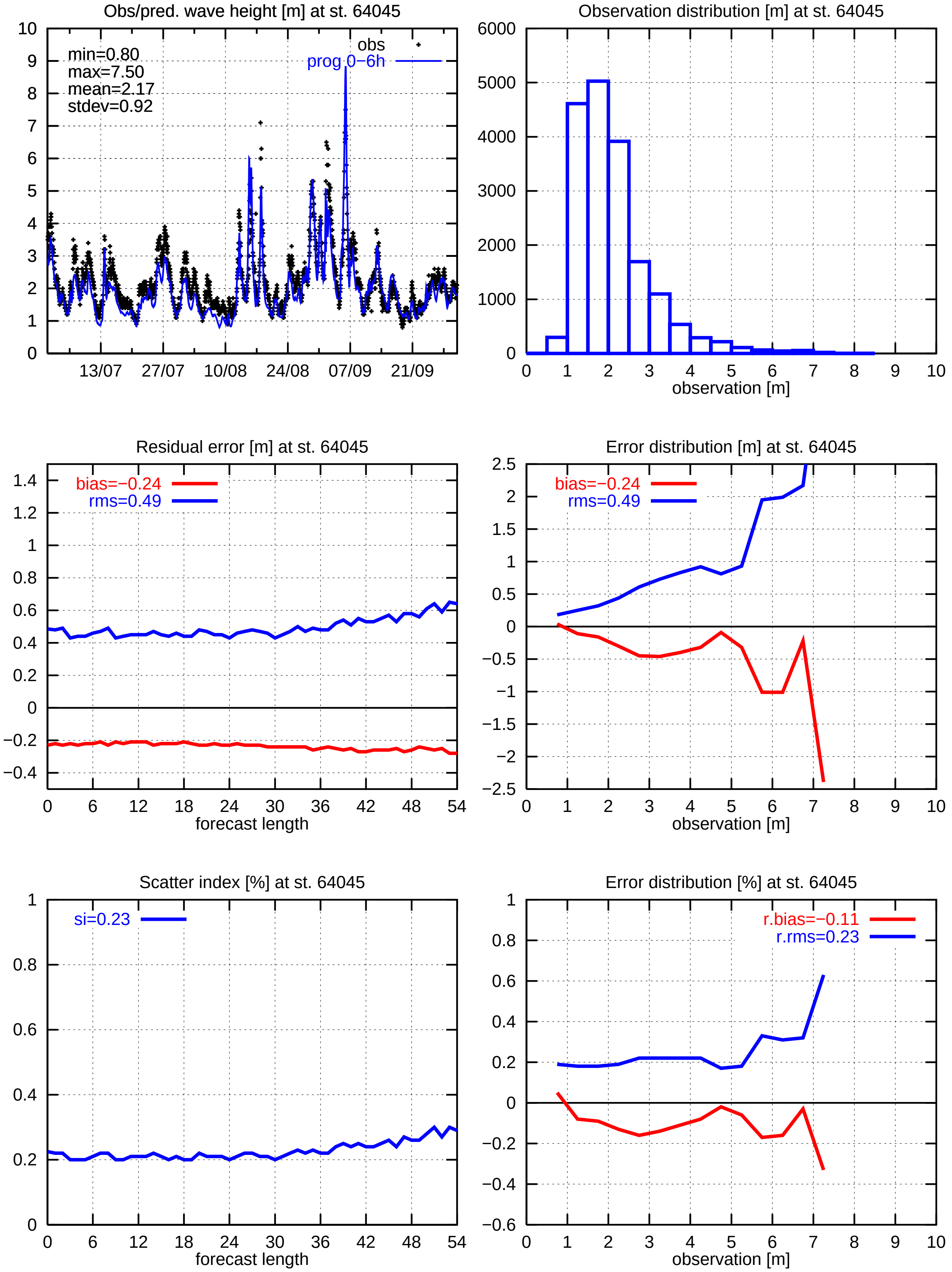

Figure 41. Significant wave height: 64045.

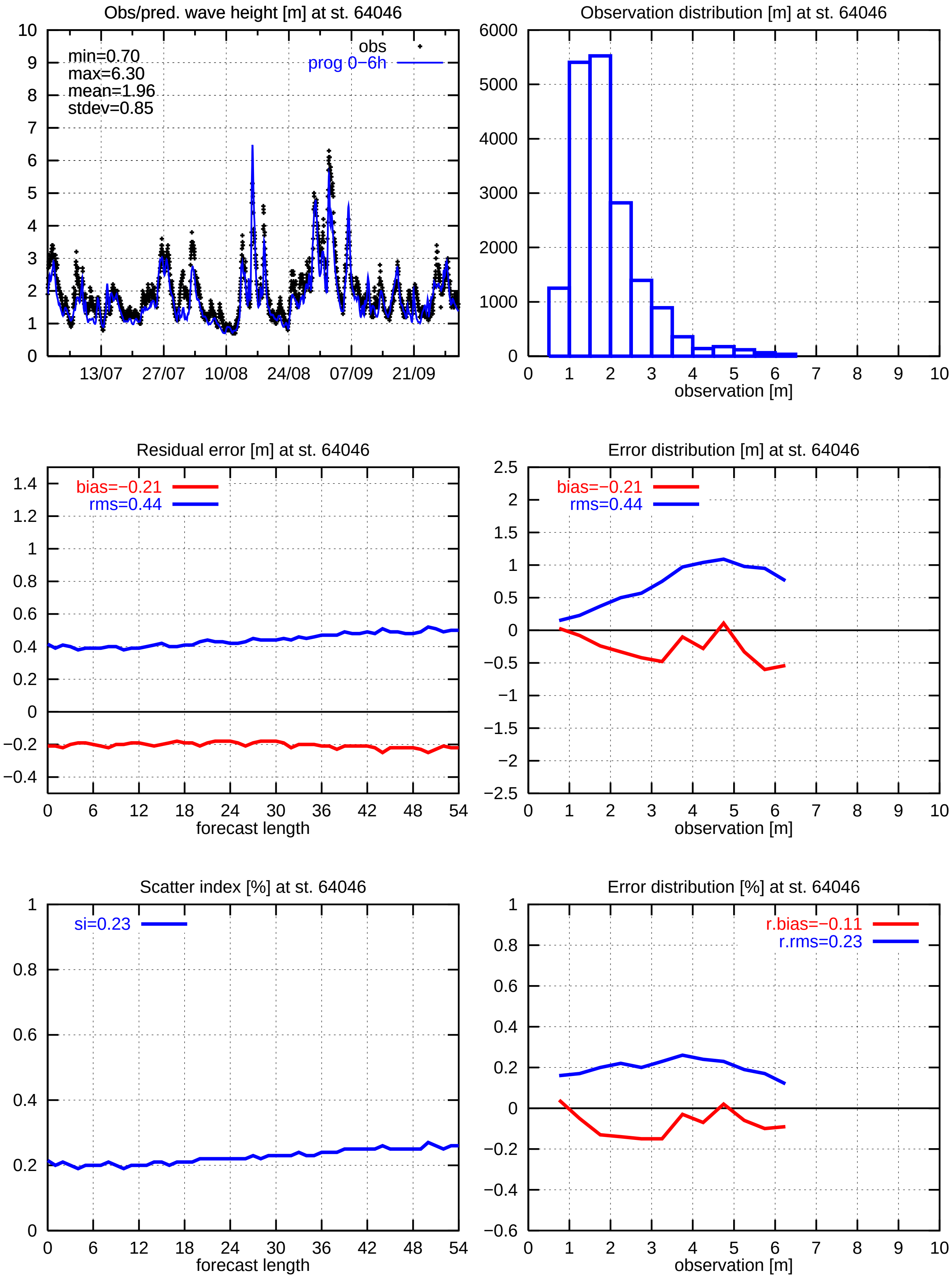

Figure 42. Significant wave height: 64046

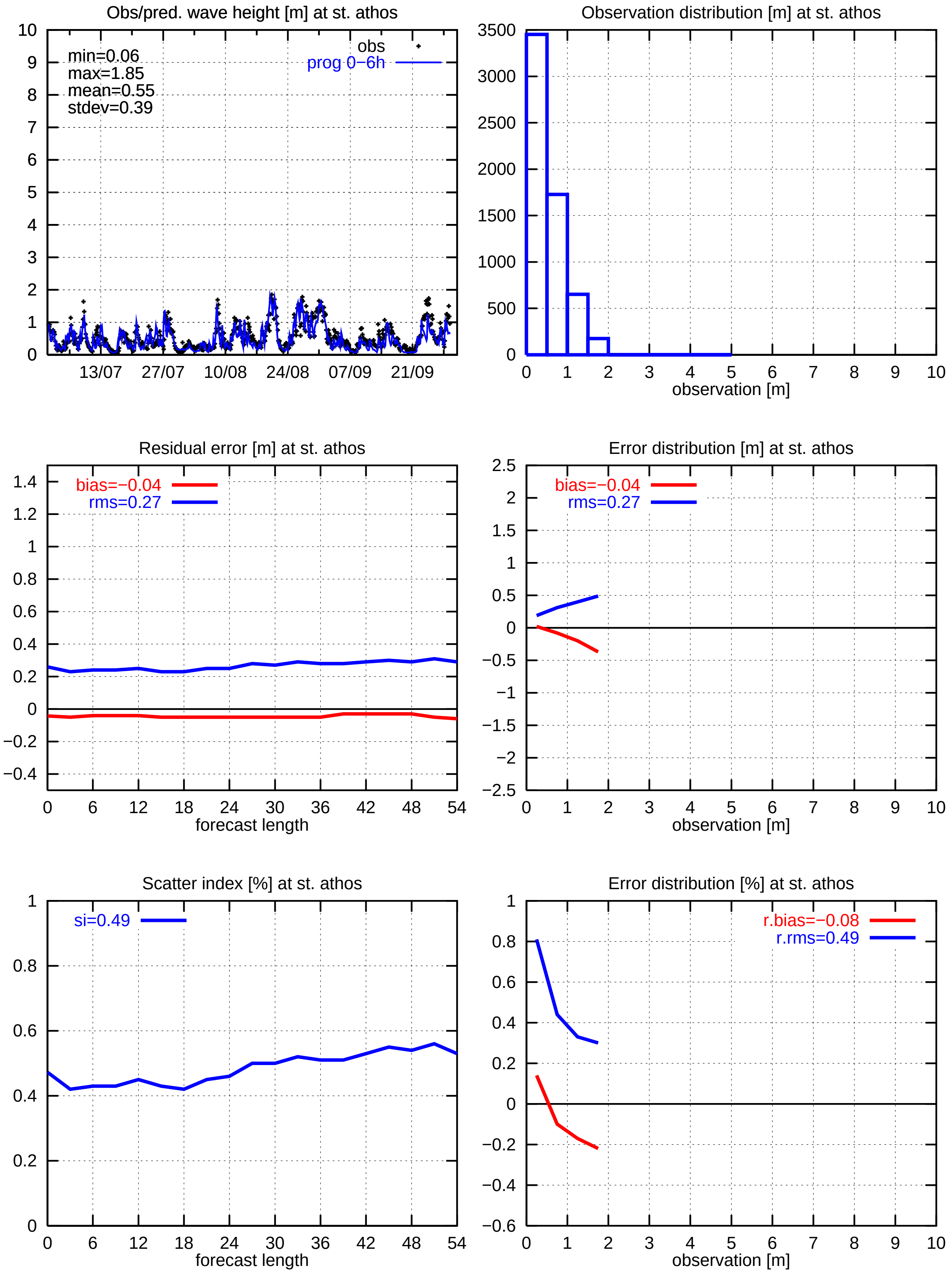

Figure 43. Significant wave height: Athos

7.6 Mean wave period plots

The following pages show mean wave period error statistics for each station. Only stations with reasonable statistics are included.

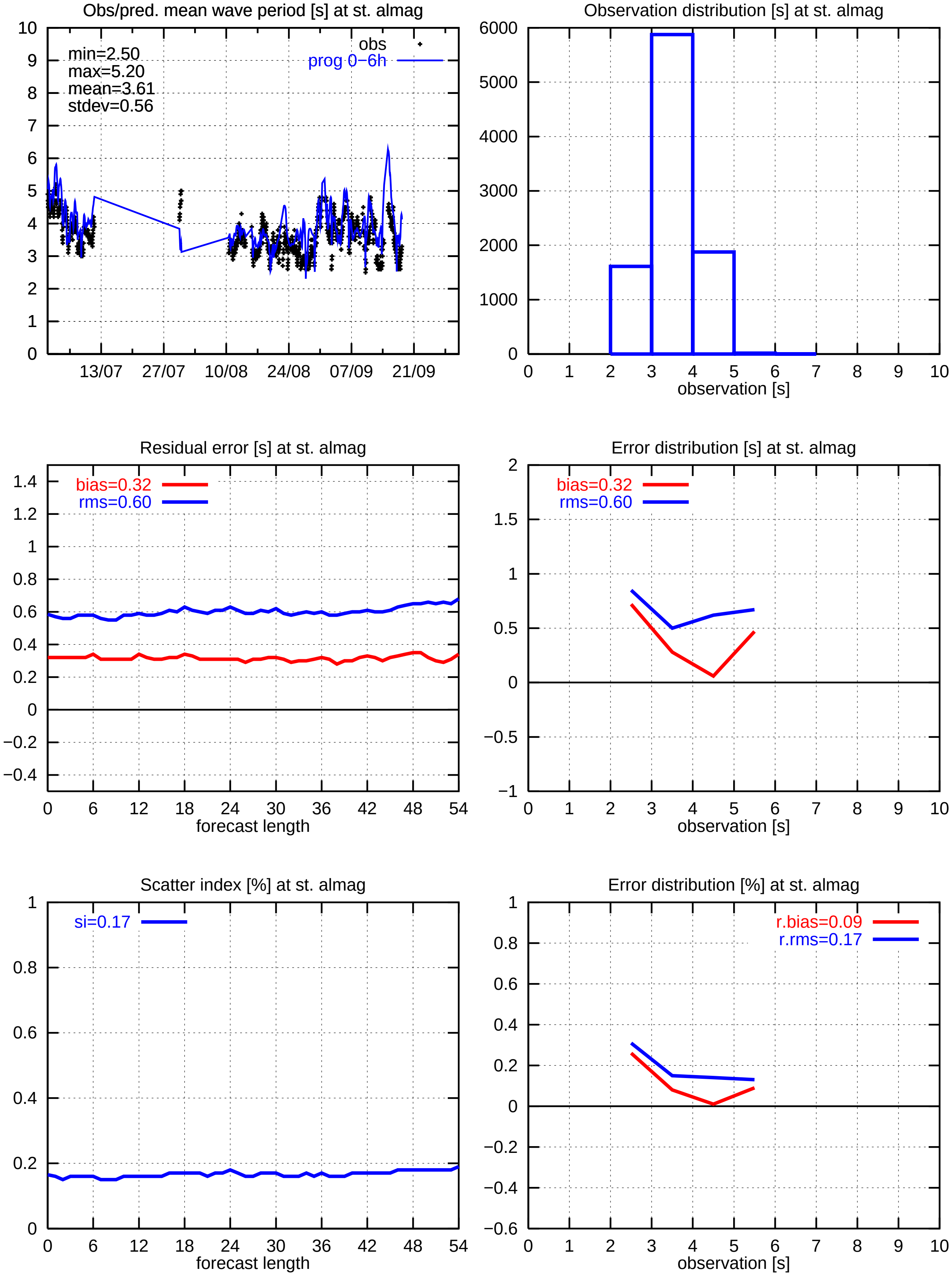

Figure 44. Mean wave period: Almagrundet

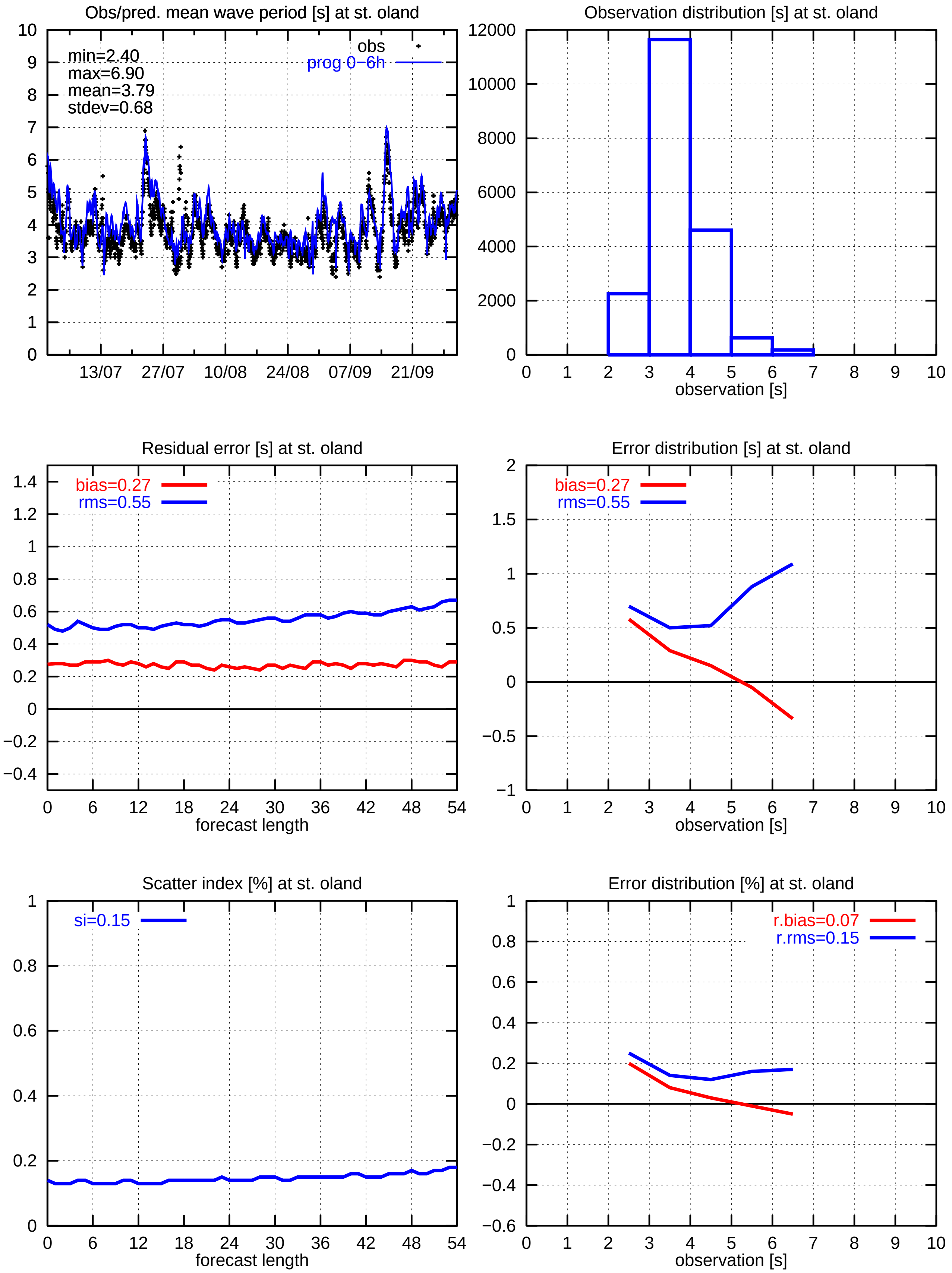

Figure 45. Mean wave period: Øland

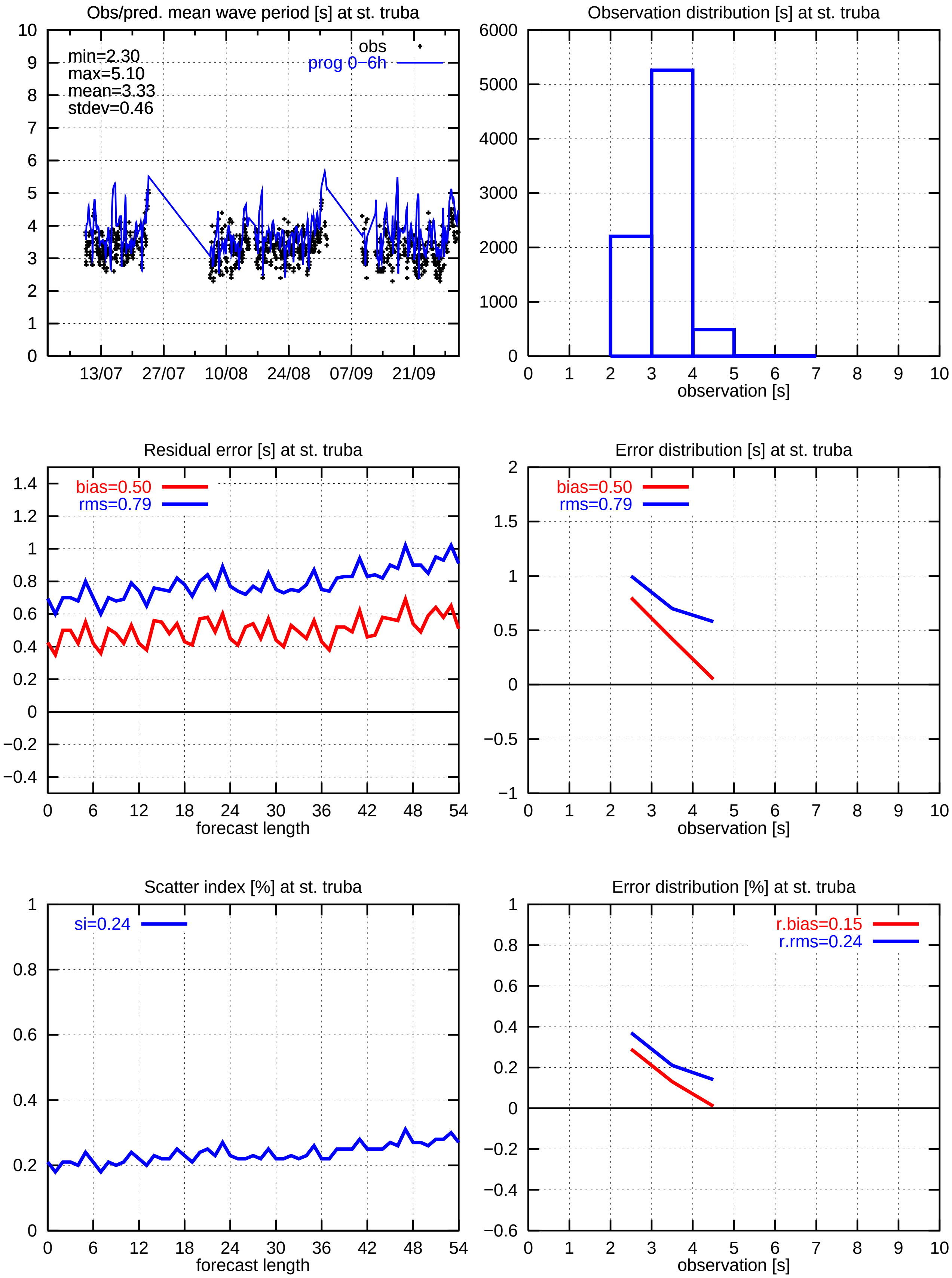

Figure 46. Mean wave period: Trubaduren

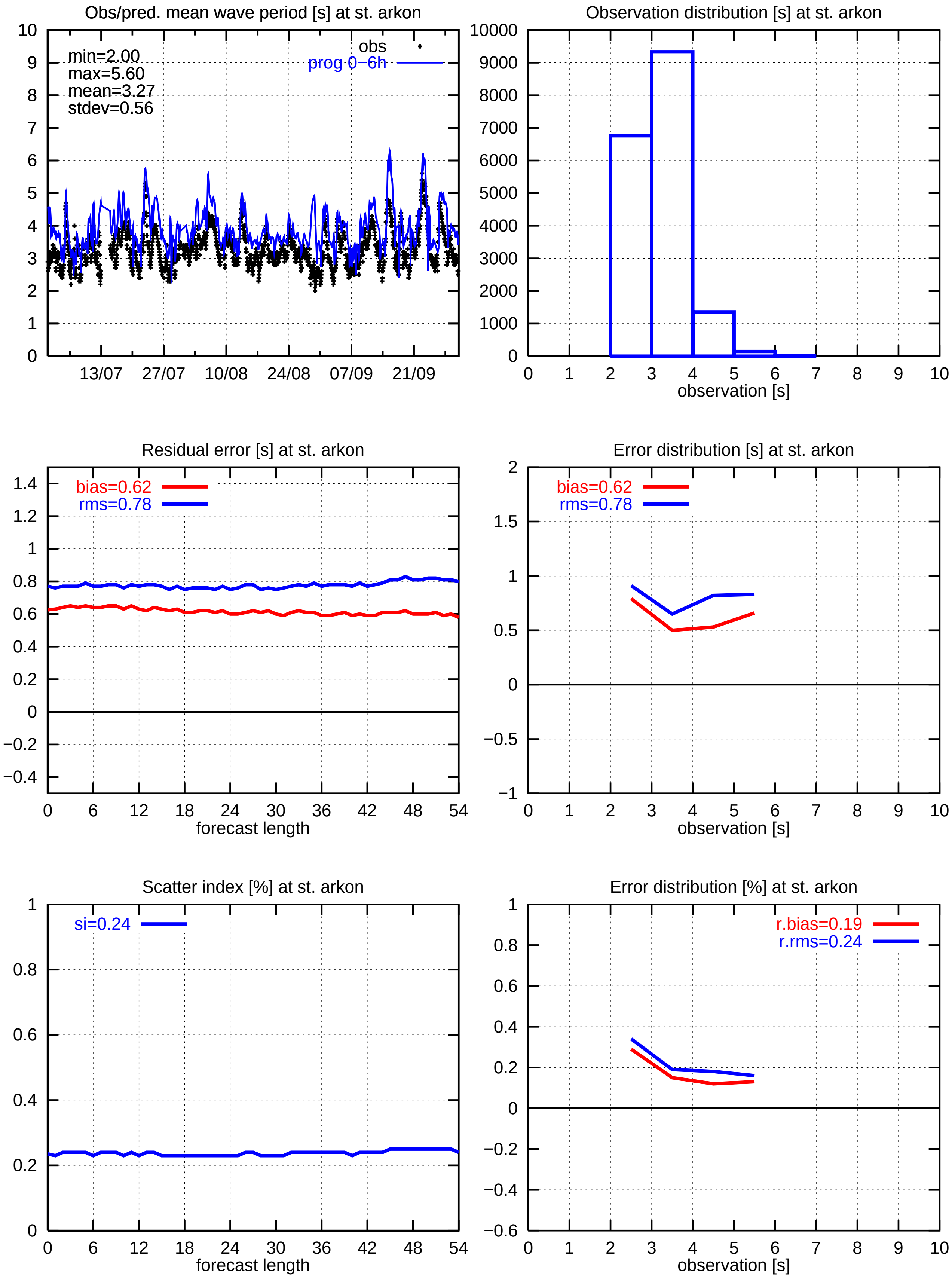

Figure 47. Mean wave period: Arkona

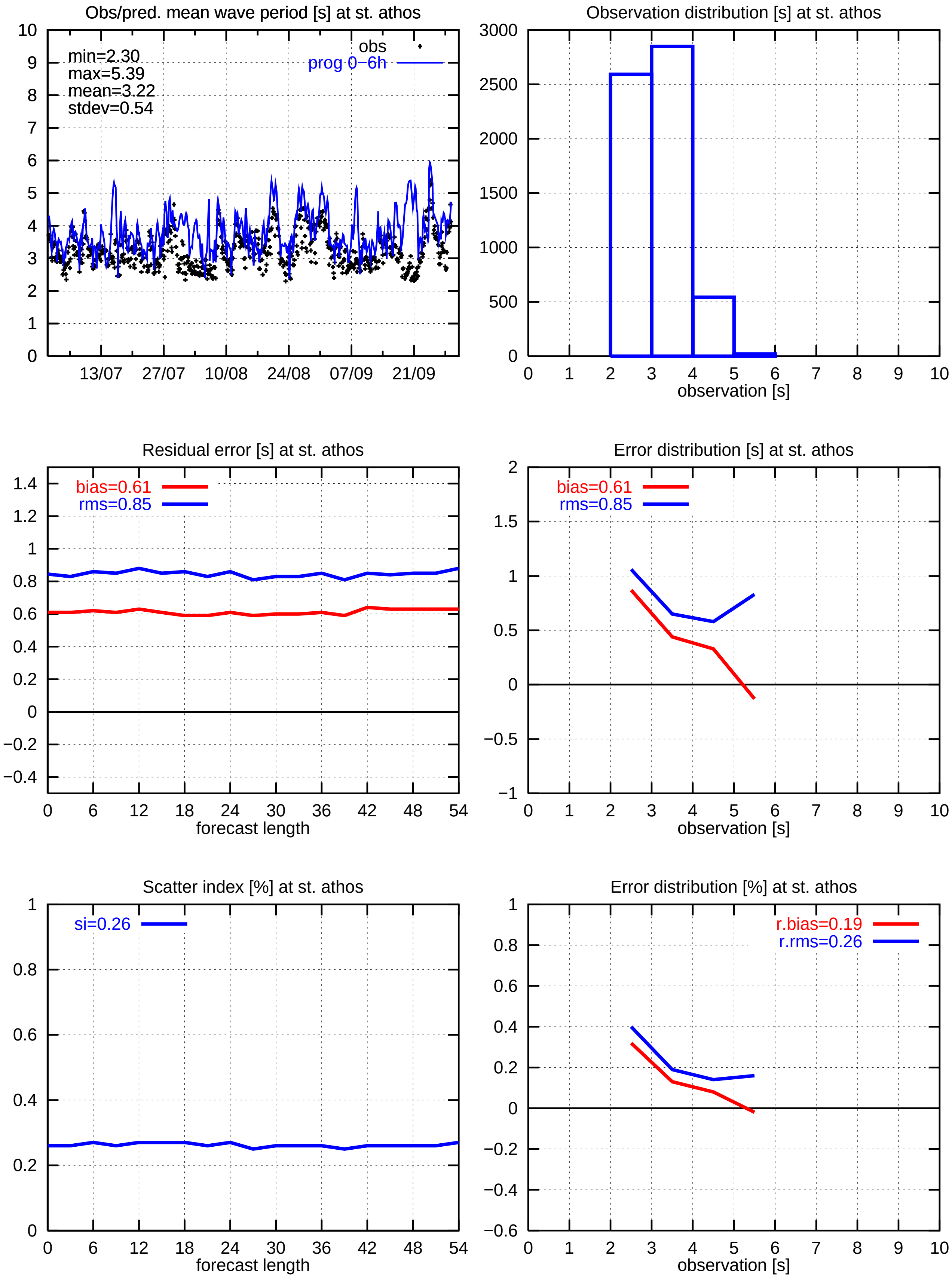

Figure 48. Mean wave period: Athos

7.7 Dominant wave period plots

The following pages show dominant wave period error statistics for each station. Only stations with reasonable statistics are included.

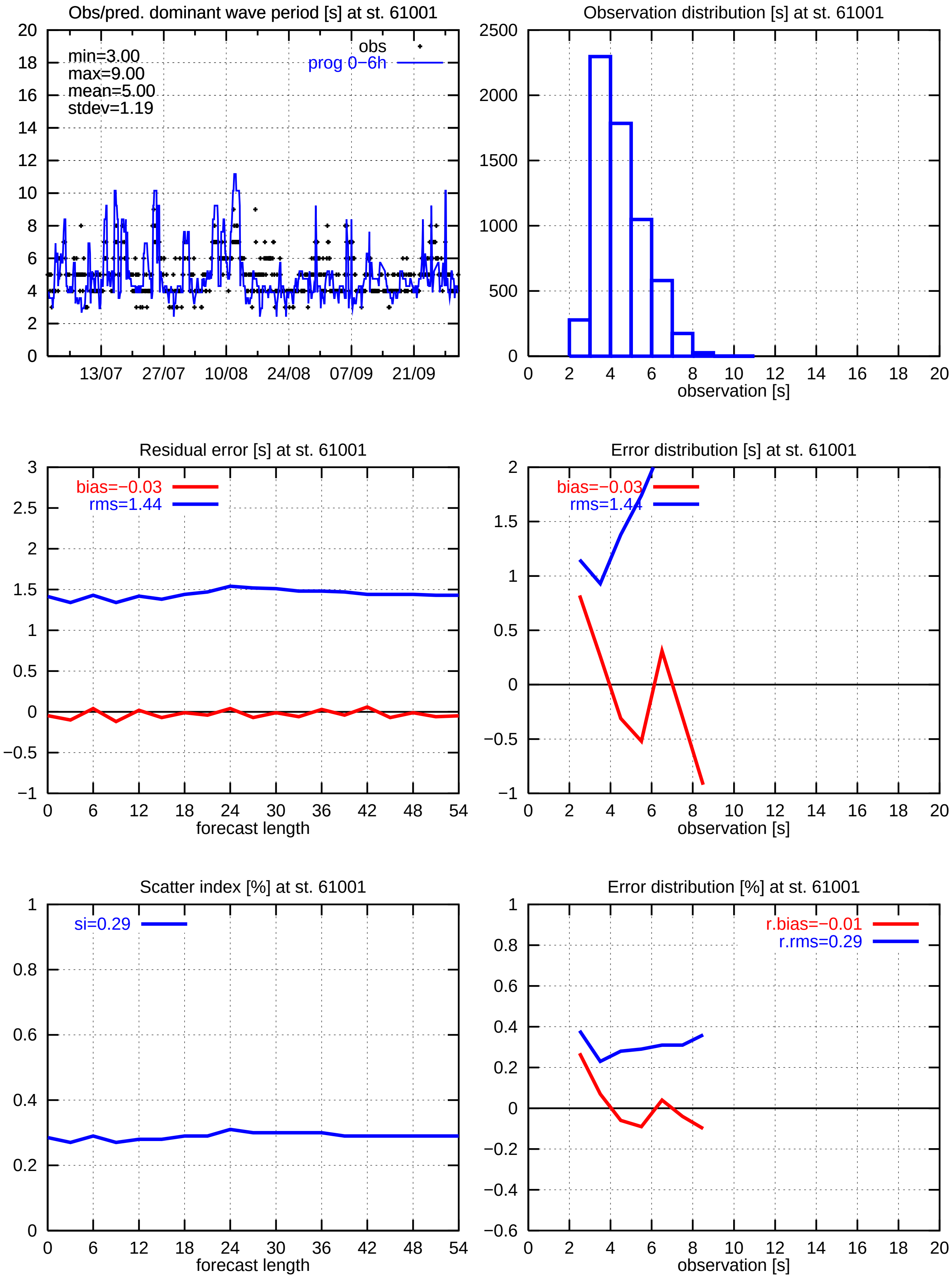

Figure 49. Dominant wave period: 61001

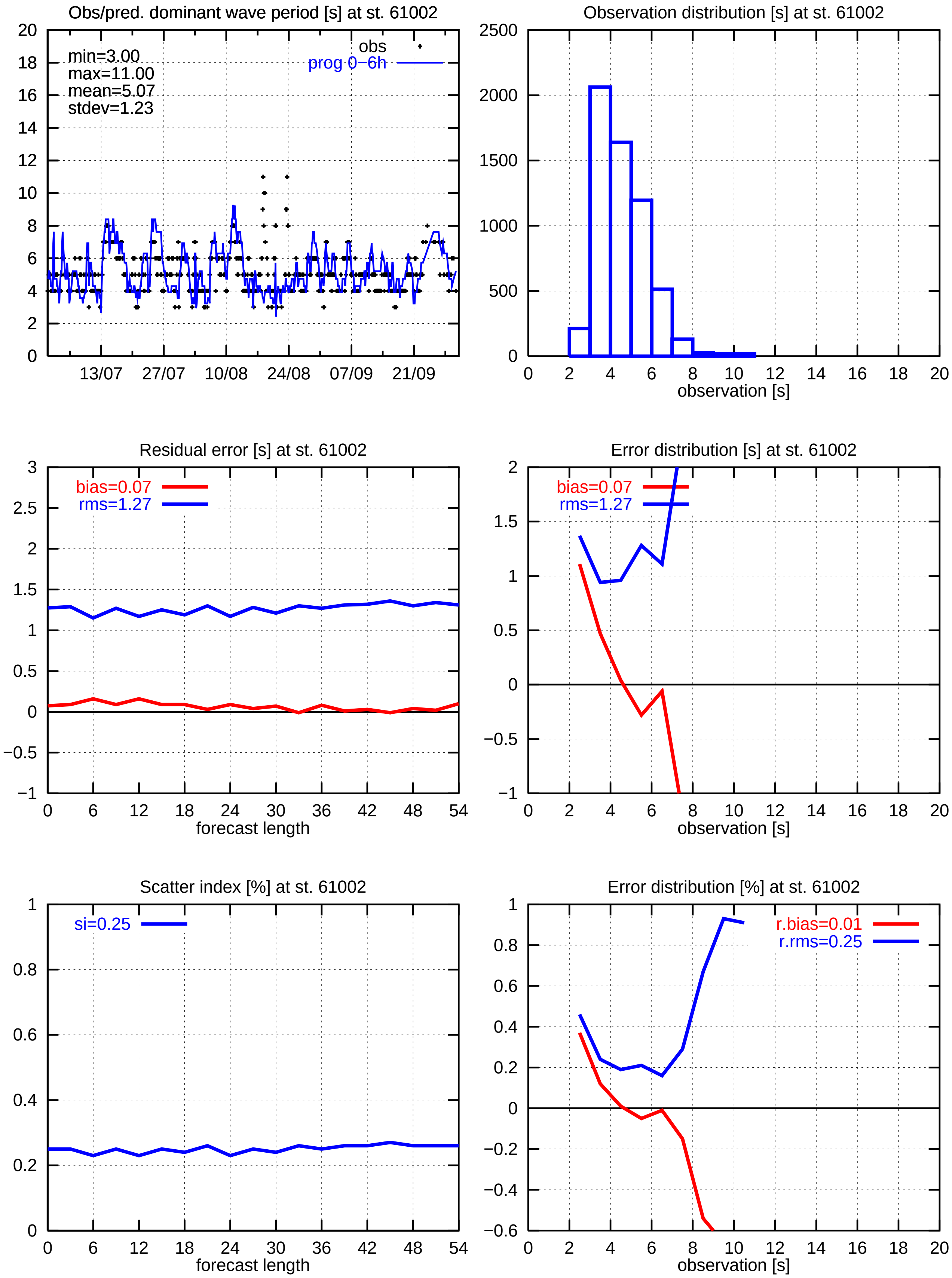

Figure 50. Dominant wave period: 61002

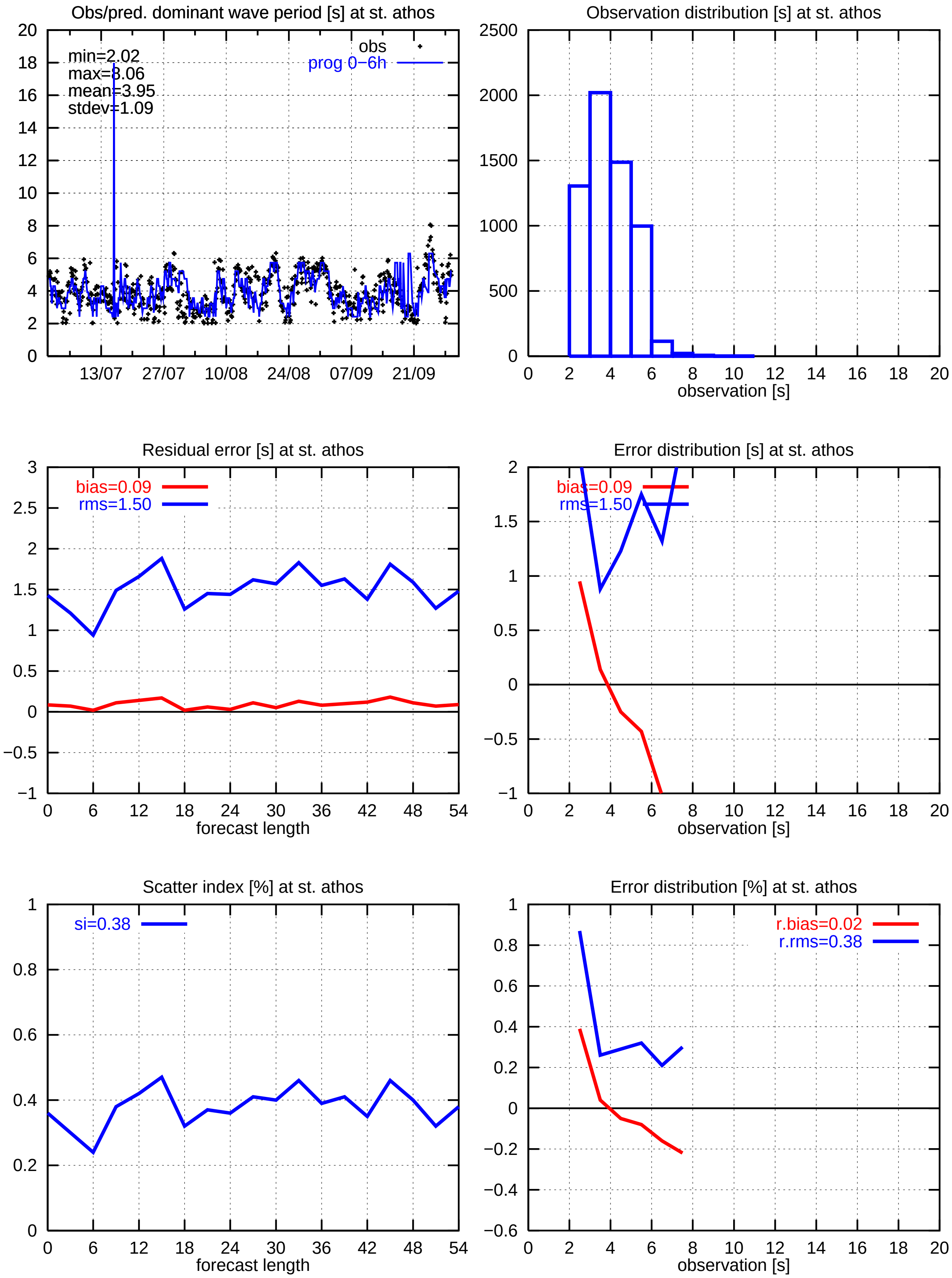

Figure 51. Dominant wave period: Athos

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