DANISH METEOROLOGICAL
INSTITUTE

—— TECHNICAL REPORT ——

02-20

Verification of DMI wave forecasts 1st quarter of 2002

Jacob Woge Nielsen

Copenhagen 2002

ISSN 0906-897X (trykt)
ISSN 1399-1388 (online)

Verification of DMI wave forecasts
1st quarter of 2002

Jacob Woge Nielsen
e-mail: jw@dmi.dk

The Danish Meteorological Institute, Copenhagen, Denmark

Contents

1 Introduction

We analyse the quality of wave forecasts valid for the 1st quarter of 2002 (2000/1), produced by *DMI-WAM* - DMI's operational set-up of the 3rd generation wave model *WAM Cycle4*.

The significant wave height H_s is the primary parameter of interest, but other wave parameters (wave period, direction, swell parameters) 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 extreme waves. Grand averages are calculated as mean values over all stations, and over all ranges. Averages are also calculated for a number of separate geographical regions.

All model results are forecasts. This means that errors in the parameters do not necessarily imply errors of the model, but may reflect errors in the meteorological forcing data and initial conditions.

DMI has produced short-range operational wave forecasts since 1999. A pre-operational validation study was carried out in 1999 [6], a combined wave-wind validation in 2000 for a 14 month hindcast period [5], and a verification pilot study in 2002 [4].

Ch. 2 briefly describes the DMI wave model set-up, ch. 3 lines out the data material, and ch. 4 presents the statistical error measures used to describe the forecast quality. Ch. 5 presents and discusses 2002/1 results. Ch. 6 concludes the work. Comprehensive results for each station are put into the Appendix. References and lists of figures/tables are found at the end of the report.

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 detail in [3],[1]), forced by DMI's numerical weather prediction model *HIRLAM*. The geographical model domain includes a large part of the Northern Atlantic, the North Sea and Baltic Sea, and the Mediterranean. The current model setup 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; $c(f, \theta)$ is the 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. The present DMI-WAM still lacks current data (S_{cu}=0) and information about sea ice.

2.2 Model setup

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

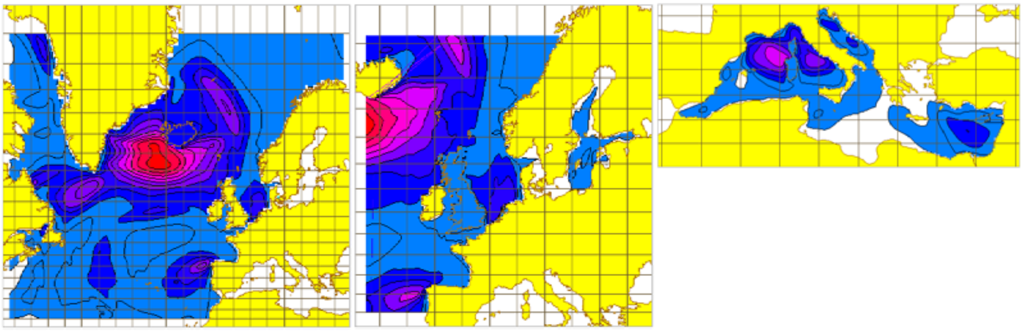

Figure 1. DMI wave models. North Atlantic, North Sea-Baltic, and Mediterranean model

The model open boundaries are chosen as follows. The coarse grid North Atlantic model uses the JONSWAP wind-sea spectrum (see [2],[1]). The fine grid North Sea - Baltic model is nested into the North Atlantic model, and uses spatially interpolated 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 1 for a model setup summary.

The wave forecasting system is coldstarted using fully developed sea. Subsequent model runs are initialised using the sea state at analysis time, calculated by the previous run. Changes to the model setup (cf. Table 1) would require a new coldstart.

Model	North Atlantic	North Sea - Baltic	Mediterranean
Space res.	30’	10’	10’
Time step	4 min	4 min	2 min
Frequencies	25	25	25
Direction res.	15^o	15^o	15^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 1. 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.

2.3 Weather models

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 covers a larger area than the E model, but in coarser spatial resolution (50km vs. 16km 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.

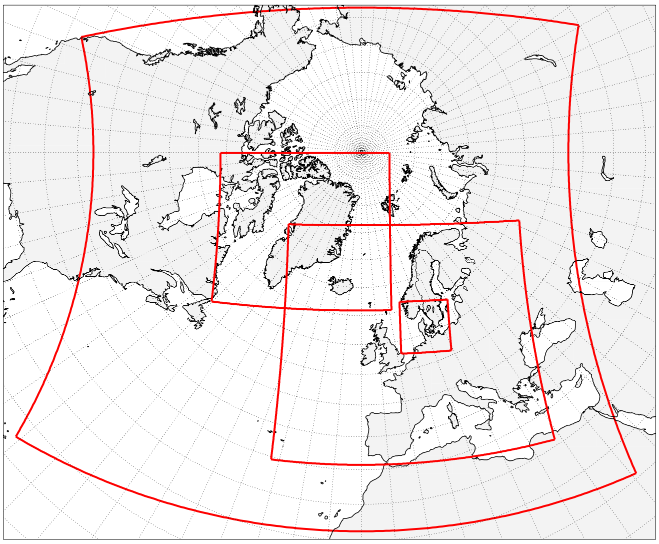

Figure 2. DMI Hirlam. The outermost red box is the G model, the red box covering most of Europe is the E model.

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 2.

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 2. DMI-WAM wave parameters

The forecasts are stored as hourly maps in model resolution, and time series for each station are sampled using the closest model grid point. This is done for each analysis and each parameter. During the 2002/1 season, 360 forecasts were produced. The forecast data coverage is almost 100%, with a total of 18 incomplete or missing forecasts.

Except for the dominant wave period T_p, all wave parameters are obtained by integrating the wave energy spectrum. In contrast, T_p is just the discretized model frequency (inverse) containing the highest energy, picked from a small set of predefined values. This leads to low accuracy of T_p. In cases with two competing wave energy maxima (wind sea and swell), T_p may flip between the two, as first one, then the other has the highest energy. This means that T_p is not a smooth function of time or space.

3.2 Observations

The wave recorder positions are shown on Fig. 3 below. A total of 30 stations that record more or less regularly are selected for verification. Comprehensive station information is found in Appendix 7.1, Table 10.

Wave data is obtained from a number of sources, as indicated in table 3. SMHI, KDI and NCMR data is kindly provided by each agency in question. NDBC data is retrieved via the GTS. Table 4 shows the number of stations for each wave parameter, and for each of 8 geographical domains.

The standard sampling rate is 1 hour, with 9 stations (cf. Table 10) sampling every 3 hours. At these stations, we consider steady 3 hour sampling as full data coverage. The mean data coverage is 77%. Figure 4 shows the fraction of missing data at all stations.

The normal sampling accuracy is H_s:0.1m, T_p:1s, T_{02}:0.01s, θ_w:1^o. Two buoys (62101, 62301) use low 0.5m H_s accuracy. Four buoys (Danish West Coast) use variable T_p accuracy of 0.1-0.7s, while

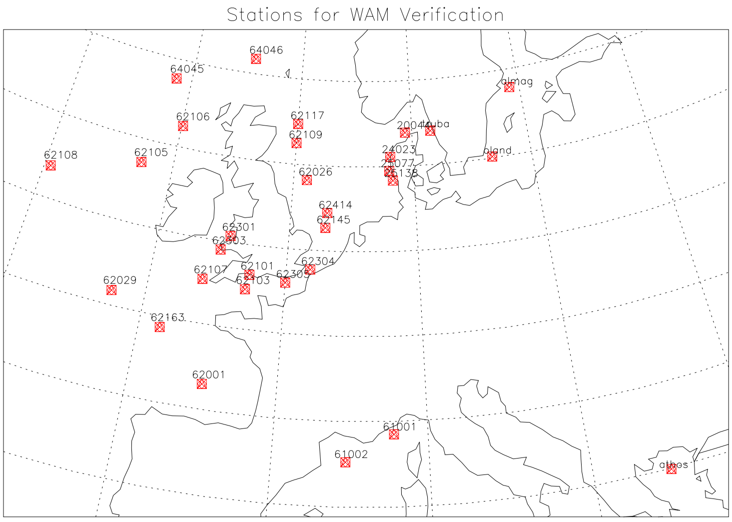

Figure 3. Wave recorder locations.

Wave Data providers	
NDBC	National Data Buoy Center (UK)
SMHI	Swedish Meteorological Institute
KDI	Danish Coastal Authority
NCMR	National Center for Marine Research (Greece)

Table 3. Wave data providers.

one (Athos) uses high 0.01s T_p accuracy. Statistics on the observed wave parameters, and wave period vs. wave height plots, are shown in the Appendices 7.2 and 7.3.

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
Baltic Sea	3	3	-	-	3
Mediterranean	3	1	3	1	-
Total	30	8	26	5	7

Table 4. Number of wave stations in each domain, and for each wave parameter. Maximum wave height H_m, recorded at Baltic and Danish West Coast stations only, is not verified in the present report.

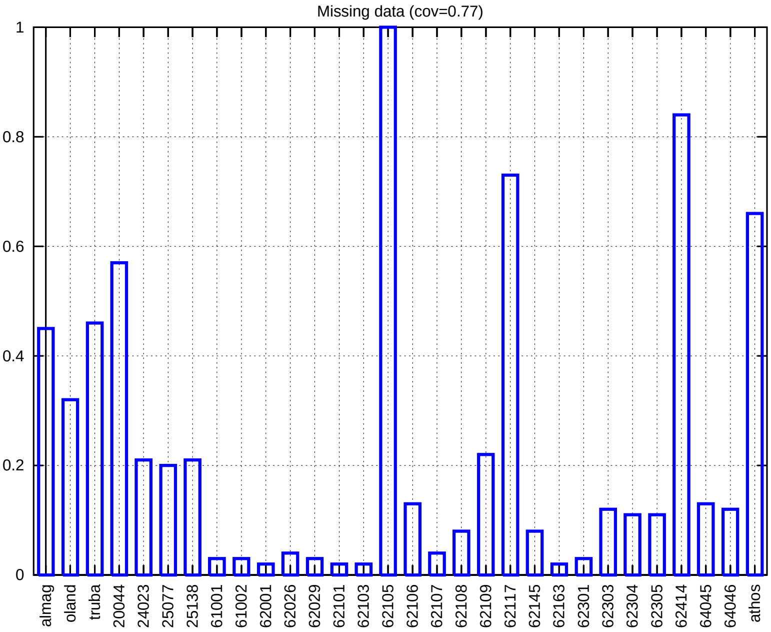

Figure 4. Missing data. St. 20044, 24023, 25077 and 25138 sample every 3rd hour, but revert to 1h sampling in storm situations. St. 61001, 61002, 62117, 62414 and Athos only sample every 3rd hour. Station 62105 has not recorded at all.

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 residual matrix reads (brackets indicate a dependency)

$residual(station, analysis, range)$

with the number of stations depending on the parameter in question (cf. Table 4), analysis every 6 hours, and forecasts ranging from 1-54 hours in 1 hour steps. 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 full 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. The peak bias is calculated both as absolute and relative values, and averaged as above.

5 Results

This section describes wave verification results for 1st quarter of 2002, for significant wave height, mean and dominant wave period, and mean wave direction. Swell parameters are not observed at any fixed location and maximum wave height is not calculated by the wave model.

Below, we discuss grand averages and regional averages. Detailed results for each station are found in the Appendix at the end of the report.

5.1 Significant wave height

Table 5 shows bias and relative bias, rms error, scatter index and correlation coefficient, averaged over the full forecast range. The total number of data points (residual matrix) used to produce the statistics is 583200. 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	-5	-1	77	0.18	0.91
Scotland-Faroe	1	-42	-9	93	0.19	0.88
Irish Sea	2	6	2	55	0.25	0.91
Br.Channel	4	52	34	79	0.55	0.87
North Sea	5	14	7	58	0.27	0.85
Danish West Coast	4	22	14	56	0.37	0.85
Baltic	3	15	14	45	0.43	0.84
Mediterranean	3	-26	-20	55	0.42	0.85
All Waters	30	9	7	65	0.33	0.87

Table 5. Significant wave height results

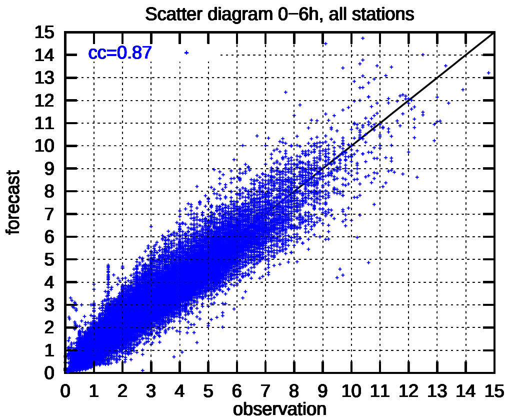

Figure 5. Significant wave height: short range (1-6h) scatter diagram

The wave model has a small positive bias of 9 cm (7%) on average and an rms error of 0.65 m. Scatter index is low (0.33) and correlation coefficient high (0.87). There is a large regional spread. Waves are underestimated on average (positive bias) at the Shetland station and in the Mediterranean, and overestimated (negative bias) in the British Channel, at the Danish West Coast and in the Baltic Sea. RMS errors range roughly from a half to a full metre. The scatter index is well below an acceptance level of 0.4 in most regions, with only the British Channel largely in excess of 0.4. Fig. 6 shows the scatter index at each station.

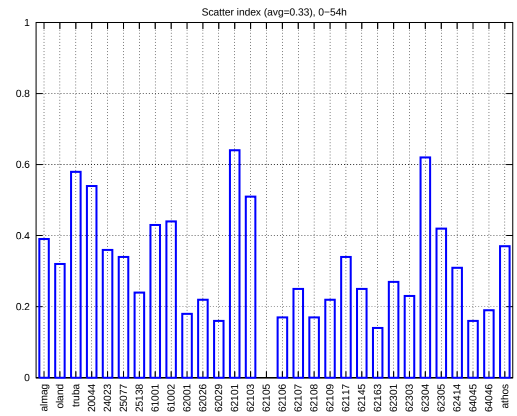

Figure 6. Significant wave height: scatter index

The error dependency on forecast range and on wave height is shown in Fig. 7 for the full model system.

The model bias is almost independent of forecast range, while the rms error increases slowly, from 0.57m at short range to 0.80m at 54h range. The rms error is significant already at analysis time since the model is initialised without any use of the observed sea state.

Scatter index increases with forecast range, from 0.27 at short range to 0.38 at 54h range. Conversely, the correlation coefficient decreases, from 0.91 at short range to 0.82 at long range.

There is a strong dependency on wave height. Small waves are slightly overestimated, while high waves (in excess of 7m) are underestimated by roughly 0.5m on average. Very high waves (>12m) may be underpredicted by a metre or two. The rms error increases steadily with increasing wave height. Except for very small waves (less than about 2m), the relative bias and rms error only depend weakly on wave height. The bias is just a few percent. Only very high waves have a significant bias of about 5%. The relative rms error decreases slowly with wave height, with a standard level of about 20%.

Averaged results for each single station is shown in Table 14, Appendix 7.4.

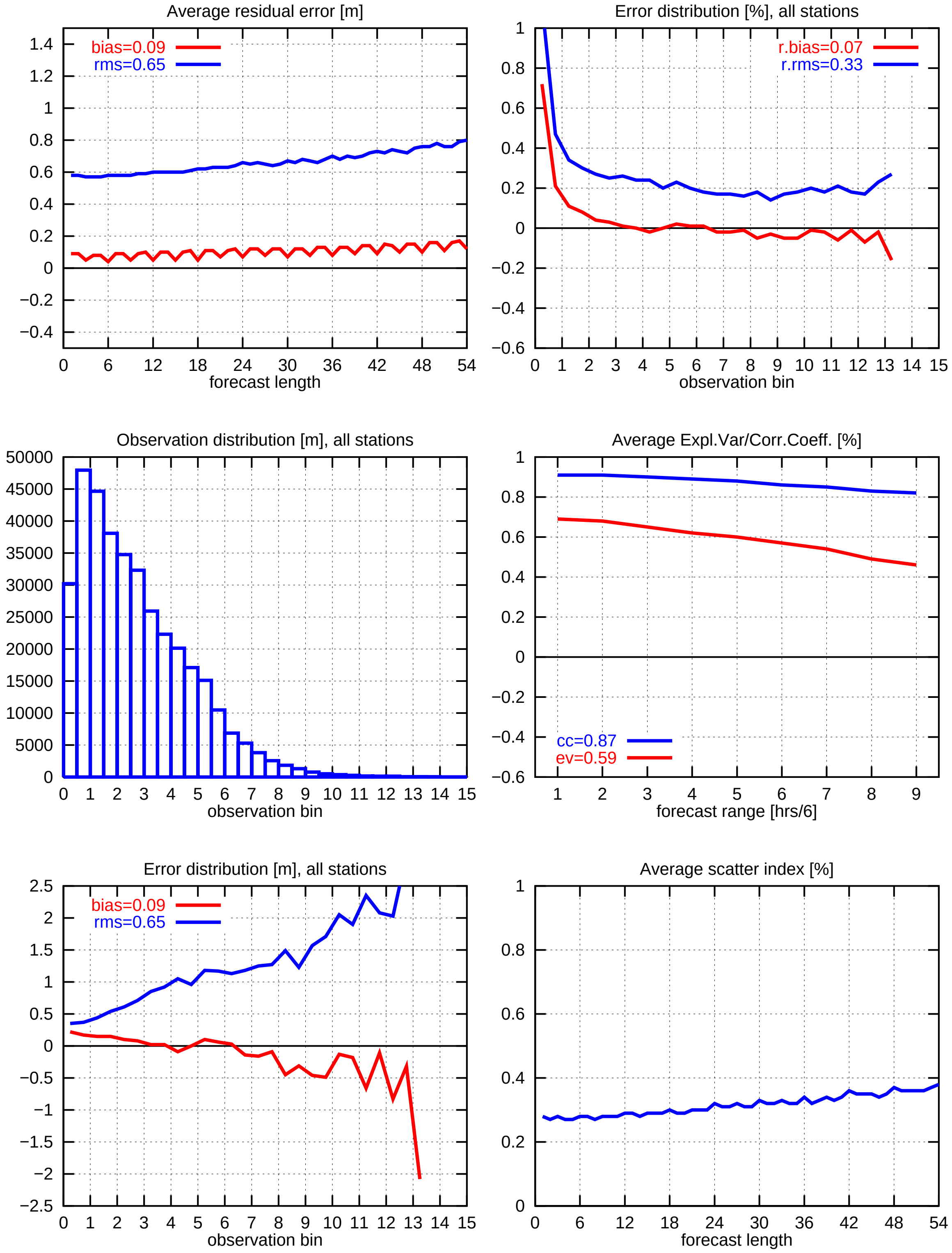

Figure 7. Significant wave height

5.2 Extreme wave height

The error on extreme waves is calculated by singling out the 5 highest events at each station, and then calculate the forecast error, allowing for a few hours' phase displacement. Table 6 shows peak biases for each of the 8 geographical domains, averaged over all forecast ranges.

Parameter Region	#st	peak bias cm	 %
Atlantic	8	-28	-2
Scotland-Faroe	1	-257	-22
Irish Sea	2	-21	-4
Br.Channel	4	26	5
North Sea	5	6	6
Danish West Coast	4	34	6
Baltic	3	-19	-2
Mediterranean	3	-35	-6
All Waters	30	-13	0

Table 6. Extreme wave height results

There is a large negative peak bias at the Shetland station, with a relative error of about -20%. At this stationn, a single 17.4m event is underpredicted by several metres. On average, the system has a small negative bias of -13cm or less than 1%. The average absolute peak error (or peak accuracy, not shown) is 1.1m or 19%.

The dependency of the peak bias on forecast range is shown in Fig. 8. The peak bias is small at short range (day 1), but increases on day 2 and beyond.

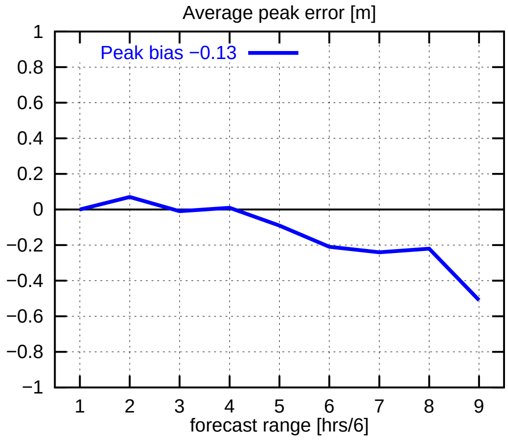

Figure 8. Extreme wave height

Table 15 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 8 stations. Grand averages are shown in Table 7, and a short-range scatter diagram in Fig. 9.

Parameter Region	#st	bias sec.	bias %	rms sec.	si	cc
Danish West Coast	4	2.1	47	2.3	0.52	0.72
Baltic	3	0.6	15	0.8	0.20	0.80
Mediterranean	1	0.5	11	0.8	0.20	0.80
All Waters	8	1.3	30	1.6	0.36	0.76

Table 7. Mean wave period results

At the Danish West Coast stations T_{02} is overestimated by almost 50%. The reason for this is unresolved. At the stations in the Baltic and the Meditteranean T_{02} is only slightly overestimated. The scatter index at these stations is well below the acceptancy level of 0.4.

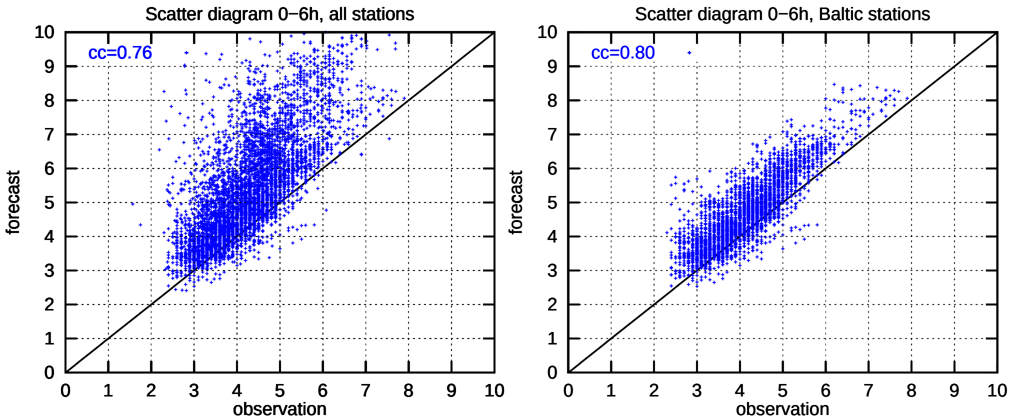

Figure 9. Mean wave period, 1-6h range. Left panel: all stations, right panel: Baltic stations only

Results for each station are shown i Table 16, 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 8, short-range scatter diagrams in Fig. 10.

Parameter Region	#st	bias sec.	 %	rms sec.	si	cc
Atlantic	8	3.6	40	4.0	0.45	0.64
Scotland-Faroe	1	3.6	41	4.0	0.45	0.66
Irish Sea	2	3.8	59	4.7	0.72	0.61
Br.Channel	4	1.3	24	3.4	0.54	0.41
North Sea	4	2.6	45	3.6	0.62	0.27
Danish West Coast	4	0.7	10	2.7	0.38	0.53
Mediterranean	3	0.0	0	1.7	0.31	0.46
All Waters	26	2.2	30	3.4	0.49	0.50

Table 8. Dominant wave period results

T_p shows very bad verification results 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. The last reason is the worst. 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). An example of this is seen in the Athos data plot, Appendix 7.7, where in mid-March the observed T_p is 2-3 s while the forecasted value is 18 s.

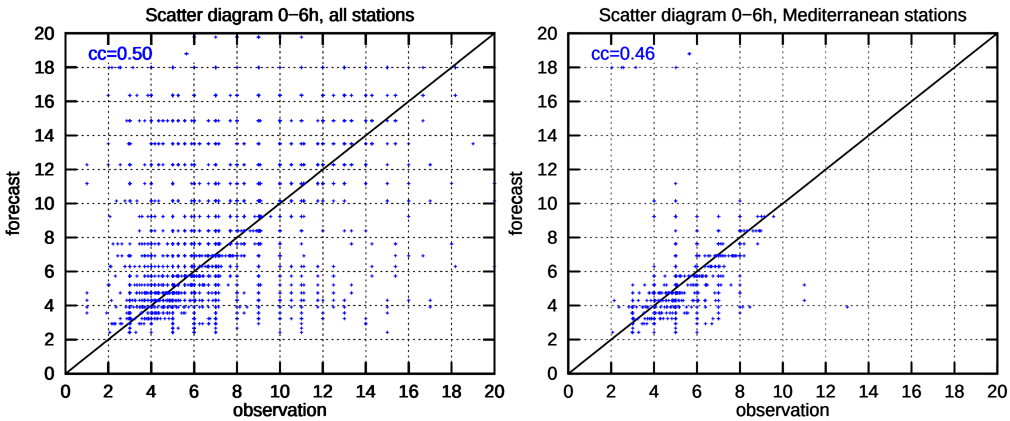

Figure 10. Dominant wave period, 1-6h range. Left panel: all stations, right panel: Mediterranean stations only

Results for each stations is found in Table 17, Appendix 7.4. Data sheets in Appendix 7.7.

5.5 Mean wave direction

The mean wave direction θ_w is recorded at 5 stations. The results are presented in Table 9 and the scatter diagram in Fig. 11.

Parameter Region	#st	bias deg.	std deg.	cc
Danish West Coast	4	1	33	0.80
Mediterranean	1	4	49	0.92
All Waters	5	2	36	0.82

Table 9. Mean wave direction results

The mean wave direction predictions fit the observations very well, with almost no bias and a high correlation coefficient.

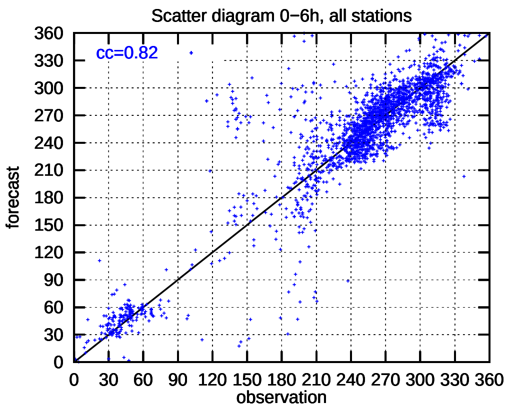

Figure 11. Mean wave direction, 1-6h range.

Results for each stations is found in Table 18, Appendix 7.4.

6 Conclusion

DMI wave forecasts valid for the 1st quarter of 2002 are verified, using wave data from 30 buoys.

Main conclusions are:

- The significant wave height H_s gives reasonable results
- Other wave parameters are either not recorded or have some data problem
- The forecast quality decreases slowly with increasing forecast range
- There is a large regional spread in forecast quality
- There is a strong error dependency on wave height
- Extreme waves are underpredicted in some regions

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 bias is small on average. There is a large geographical spread, and some dependency on wave height. Low waves are overpredicted, while very high waves (in excess of 7m) are underpredicted by about 5%.

The average rms error is 0.65m, with a large regional spread. The rms increases gradually with forecast range, and increases also with wave height so that waves higher than about 3m have a relative rms error of 20%.

An average scatter index SI=0.33 is acceptable, with just a few stations having si$>$0.4 (sometimes used as an acceptance level) due to low recording accuracy. The average correlation coefficient CC=0.87. Both si and cc scores get a bit worse as the forecast range increases.

Extreme waves are underpredicted in certain regions (Shetland, Mediterranean) but there is no peak bias on average. There tends to be a negative bias on day 2 and beyond.

Two types of wave period are recorded; the mean wave period and the dominant (peak) wave period. The *mean wave period* is recorded at 8 locations, half of which have a data interpretation problem. At the remaining 4 stations the model overestimates the mean wave period by roughly half a second, with a scatter index of 0.20 and a correlation coefficient of 0.80.

Dominant wave period predictions are not good. This is 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. Only the Meditteranean stations show good results, with no bias and a scatter index of 0.31.

Mean wave direction show insignificant bias, a standard deviation of 36^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 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 Station table

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}
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 10. Wave stations. Station name/number, driving agency, position, and wave parameters. SMHI=Swedish Meteorological Institute, NDBC=National Data Buoy Center (UK), NCMR=National Center for Marine Research (Greece), KDI=Coastal Authority (Denmark). 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

Station	min	mean	max	stdev
almag	0.1	1.1	4.4	0.7
oland	0.1	1.3	4.9	0.7
truba	0.1	0.9	3.7	0.6
20044	0.1	1.3	5.2	0.8
24023	0.2	1.7	6.4	0.9
25077	0.2	1.7	6.3	1.0
25138	0.2	1.4	6.8	0.9
61001	0.2	1.0	4.1	0.6
61002	0.3	1.5	7.0	1.0
62001	0.1	3.6	10.4	1.5
62026	0.5	2.3	7.6	1.0
62029	1.5	4.7	12.5	1.7
62101	0.0	1.4	5.0	0.9
62103	0.3	2.0	6.8	1.1
62105	-	-	-	-
62106	1.5	5.0	15.1	1.9
62107	0.8	3.4	9.0	1.5
62108	1.5	5.3	13.4	1.7
62109	0.5	2.8	7.5	0.9
62117	0.8	2.3	5.4	0.9
62145	0.3	1.7	5.4	0.9
62163	1.3	4.1	10.2	1.7
62301	0.5	1.7	5.5	0.9
62303	0.4	2.7	7.8	1.4
62304	0.1	0.9	4.5	0.6
62305	0.1	1.6	5.4	1.0
62414	0.4	2.0	5.2	1.0
64045	1.5	5.1	15.3	1.8
64046	0.3	4.9	17.4	1.7
athos	0.1	1.4	5.1	1.1

Table 11. Observed wave height. The fraction of missing data is shown in Fig 4.

Station	min	mean	max	stdev
almag	2.6	4.1	5.7	0.6
oland	2.4	4.5	7.9	0.9
truba	2.3	3.7	6.8	0.8
20044	1.6	4.1	7.7	1.0
24023	2.5	4.8	9.1	0.9
25077	2.8	4.8	9.1	1.0
25138	2.2	4.3	9.5	1.0
athos	2.4	4.2	7.2	1.0

Table 12. Observed mean wave period

Station	min	mean	max	stdev
20044	1.9	6.5	15.4	2.5
24023	3.7	8.4	20.0	2.8
25077	2.0	8.2	20.0	3.0
25138	2.1	6.4	16.7	2.3
61001	3.0	5.2	13.0	1.1
61002	3.0	5.3	11.0	1.3
62001	5.0	8.8	15.0	1.7
62026	2.0	6.0	10.0	1.1
62029	6.0	8.9	13.0	1.3
62101	3.0	4.9	9.0	1.1
62103	5.0	9.4	26.0	2.1
62105	-	-	-	-
62106	2.0	8.9	14.0	1.4
62107	1.0	10.0	14.0	1.4
62108	1.0	9.1	14.0	1.3
62109	5.0	6.4	11.0	1.0
62117	3.0	5.7	8.0	1.0
62145	3.0	4.8	8.0	0.9
62163	5.0	8.7	13.0	1.4
62301	3.0	5.8	11.0	1.5
62303	4.0	7.6	13.0	1.4
62304	2.0	6.4	9.0	0.8
62305	1.0	8.1	26.0	2.1
64045	5.0	8.9	14.0	1.3
64046	2.0	8.8	16.0	1.5
athos	2.0	5.5	9.6	1.5

Table 13. Observed dominant wave period

7.3 Wave height/period diagrams

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}.

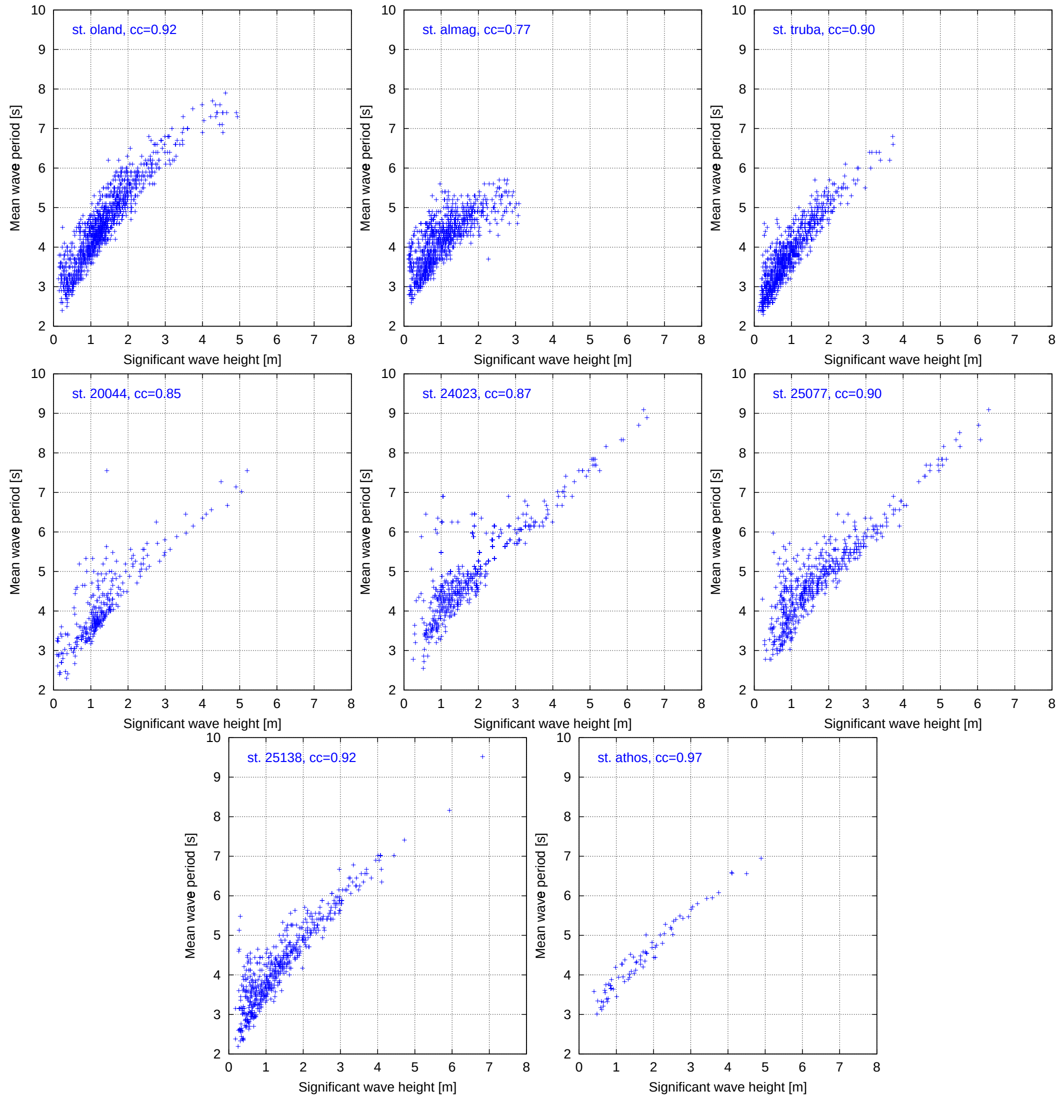

Figure 12. Significant wave height vs. mean wave period

7.4 Wave forecast statistics

Parameter	bias		rms	si	cc
Station	cm	%	cm		
almag	-1	-1	41	0.39	0.79
oland	17	13	42	0.32	0.90
truba	27	30	53	0.58	0.82
20044	25	20	70	0.54	0.68
24023	32	18	63	0.36	0.88
25077	38	22	57	0.34	0.92
25138	-7	-5	34	0.24	0.93
61001	-22	-21	44	0.43	0.80
61002	-37	-24	67	0.44	0.85
62001	-27	-7	64	0.18	0.92
62026	2	1	49	0.22	0.89
62029	-15	-3	75	0.16	0.92
62101	71	49	92	0.64	0.91
62103	79	38	104	0.51	0.90
62105	-	-	-	-	-
62106	-4	-1	86	0.17	0.91
62107	37	11	86	0.25	0.90
62108	-14	-3	90	0.17	0.88
62109	2	1	60	0.22	0.82
62117	44	19	79	0.34	0.79
62145	10	6	41	0.25	0.92
62163	-4	-1	60	0.14	0.94
62301	0	0	46	0.27	0.90
62303	12	4	63	0.23	0.92
62304	25	29	54	0.62	0.78
62305	34	22	66	0.42	0.89
62414	14	7	62	0.31	0.84
64045	-9	-2	82	0.16	0.90
64046	-42	-9	93	0.19	0.88
athos	-19	-14	53	0.37	0.89

Table 14. Predicted significant wave height

Parameter	Obs	peak	
Station	m	m	%
almag	4.1	-1.7	-42
oland	4.3	0.3	9
truba	2.8	0.8	26
20044	3.9	0.4	7
24023	4.9	0.9	17
25077	4.7	0.5	10
25138	4.5	-0.4	-10
61001	2.9	0.0	1
61002	5.1	-0.9	-18
62001	8.7	-0.6	-6
62026	5.8	-0.6	-11
62029	10.4	-0.7	-6
62101	4.4	0.9	20
62103	5.8	1.0	18
62105	-	-	-
62106	12.8	0.8	6
62107	8.3	0.2	2
62108	12.2	-0.8	-7
62109	5.8	-0.1	-2
62117	3.4	1.1	32
62145	4.7	-0.2	-3
62163	9.4	0.4	4
62301	4.7	-0.3	-6
62303	6.9	-0.1	-2
62304	3.8	-0.7	-16
62305	5.0	-0.1	-2
62414	1.5	0.1	13
64045	11.9	-1.3	-11
64046	11.8	-2.6	-22
athos	4.2	-0.1	-1

Table 15. Average of top 5 wave events (peaks) and corresponding mean peak error (peak bias)

Parameter	bias		rms	si	cc
Station	sec	%	sec		
almag	0.4	9	0.7	0.17	0.74
oland	0.5	10	0.7	0.15	0.89
truba	0.9	24	1.1	0.29	0.76
20044	1.8	44	2.1	0.51	0.63
24023	2.3	47	2.5	0.52	0.73
25077	2.2	46	2.4	0.50	0.80
25138	2.1	49	2.4	0.55	0.71
athos	0.5	11	0.8	0.20	0.80

Table 16. Predicted mean wave period

Parameter	bias		rms	si	cc
Station	sec	%	sec		
20044	0.6	9	2.6	0.40	0.48
24023	0.3	3	2.4	0.28	0.60
25077	0.4	5	2.7	0.33	0.64
25138	1.5	24	3.4	0.52	0.41
61001	0.0	0	1.5	0.29	0.38
61002	0.1	2	0.9	0.18	0.77
62001	4.1	46	4.5	0.51	0.62
62026	2.1	36	3.4	0.56	0.33
62029	3.9	44	4.2	0.47	0.67
62101	4.8	98	5.9	1.19	0.41
62103	1.9	20	3.1	0.33	0.49
62105	-	-	-	-	-
62106	3.7	41	4.0	0.45	0.69
62107	2.4	24	3.1	0.31	0.58
62108	3.4	37	3.7	0.41	0.69
62109	2.6	41	3.8	0.58	0.23
62117	3.6	63	4.4	0.78	0.05
62145	1.9	40	2.7	0.57	0.47
62163	4.3	50	4.7	0.54	0.58
62301	4.2	74	5.1	0.89	0.62
62303	3.4	44	4.2	0.55	0.60
62304	-0.8	-12	1.9	0.29	0.48
62305	-0.8	-10	2.9	0.36	0.25
64045	3.6	41	4.0	0.44	0.63
64046	3.6	41	4.0	0.45	0.66
athos	-0.1	-3	2.6	0.46	0.25

Table 17. Predicted dominant wave period

Parameter	bias	std	cc
Station	deg	deg	
20044	8	58	0.69
24023	-3	23	0.80
25077	-6	24	0.84
25138	6	26	0.87
athos	4	49	0.92

Table 18. Predicted mean wave direction

7.5 Significant wave height station plots

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

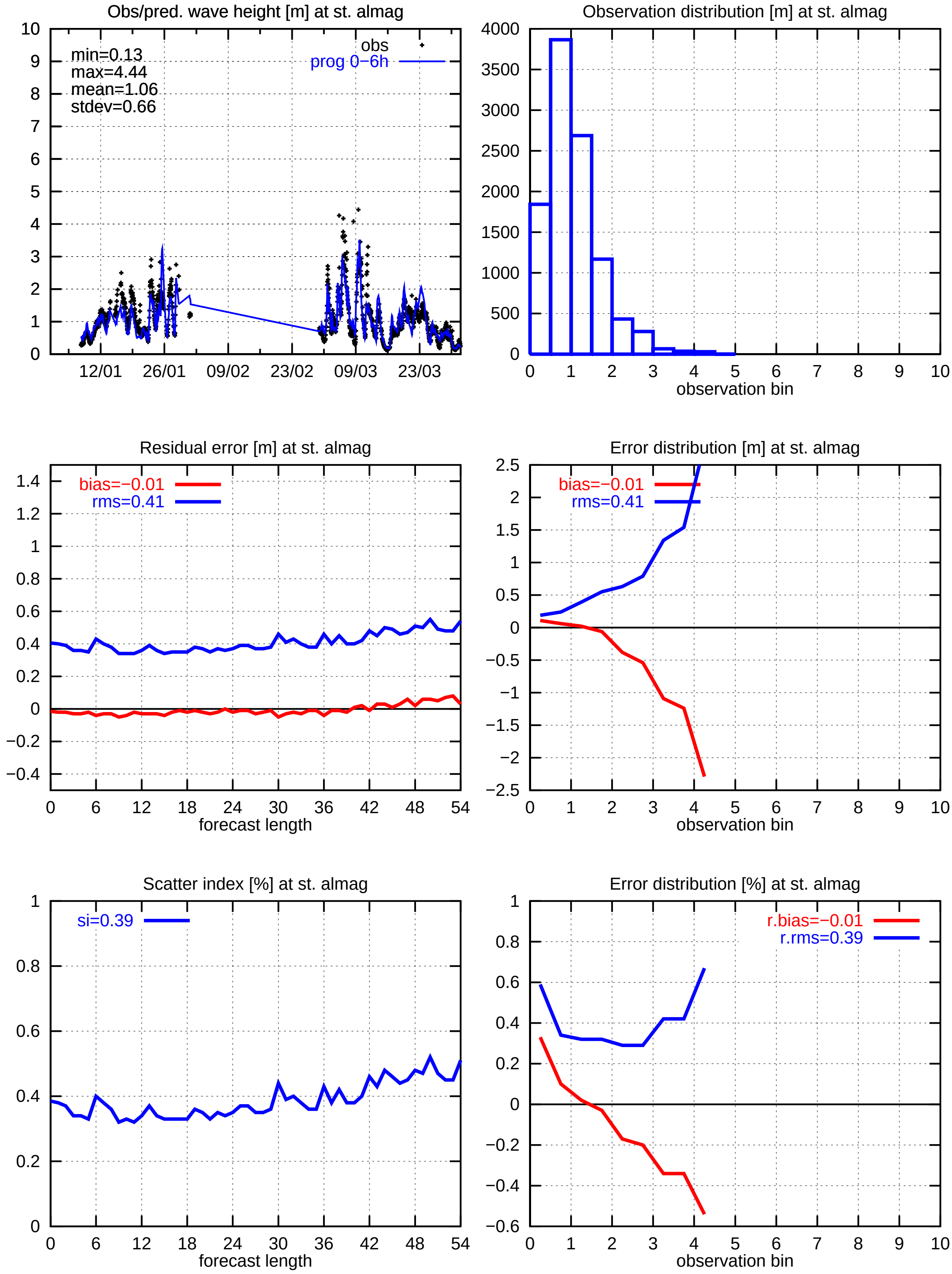

Figure 13. Significant wave height: Almagrundet

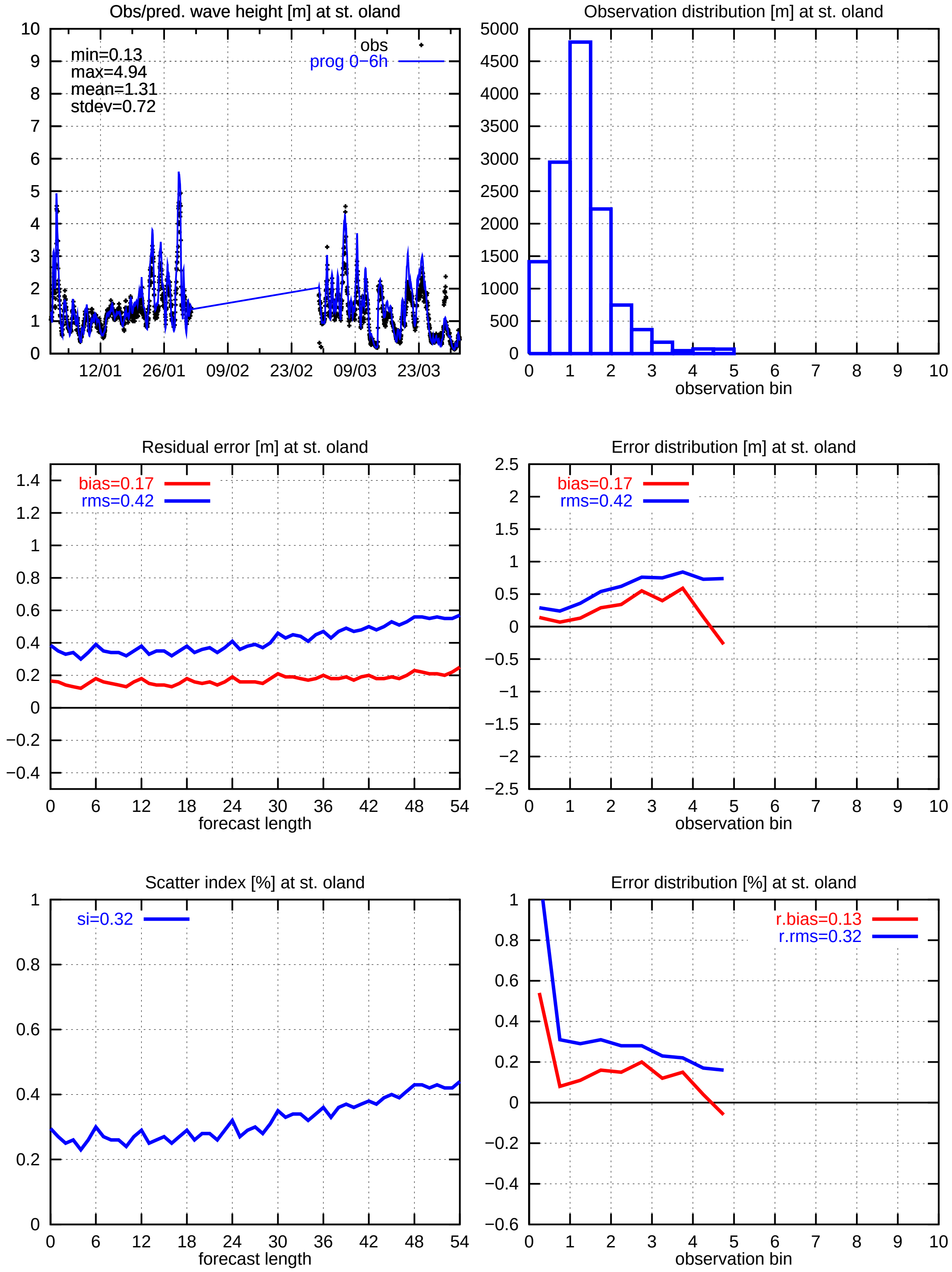

Figure 14. Significant wave height: Øland

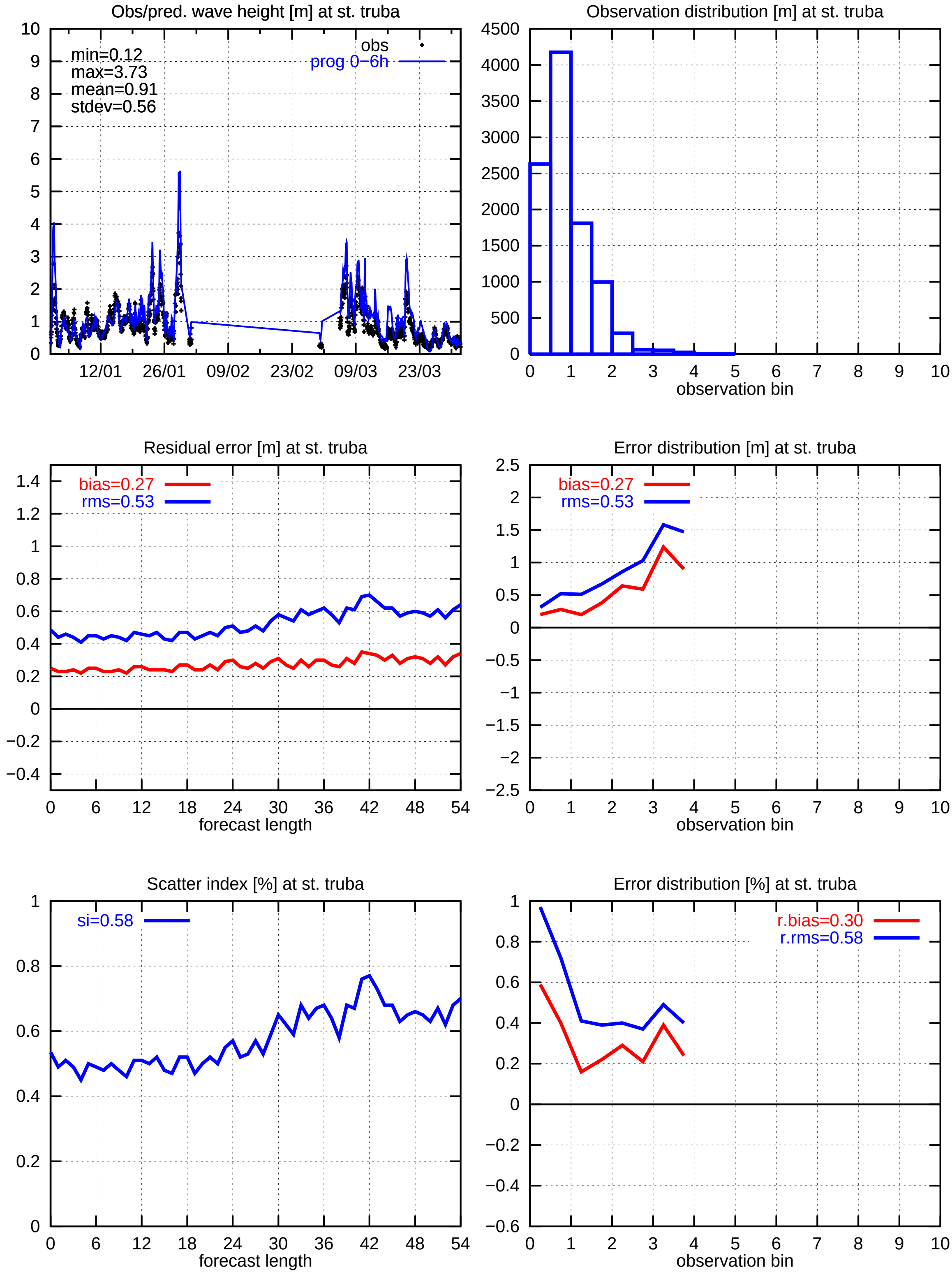

Figure 15. Significant wave height: Trubaduren

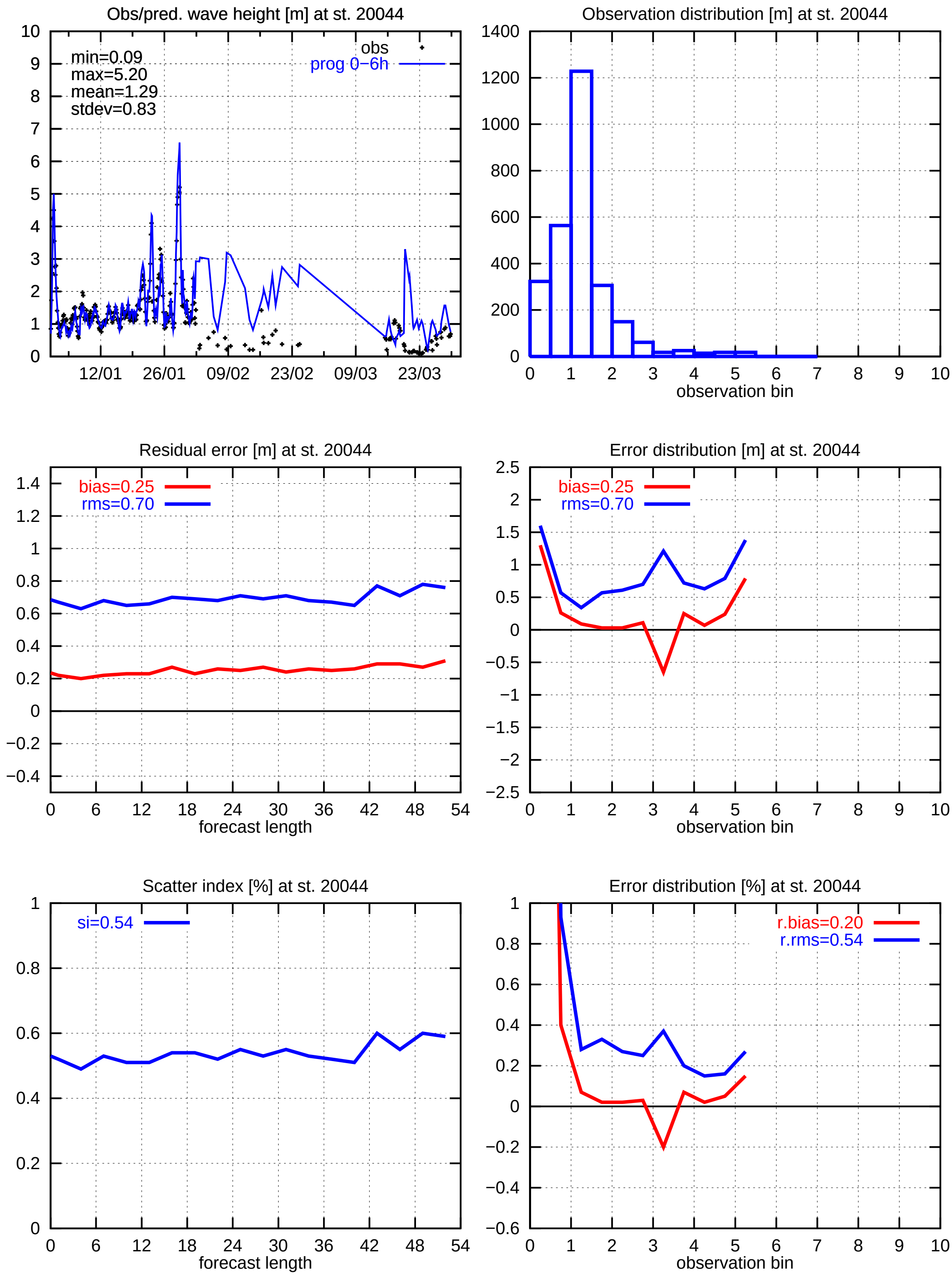

Figure 16. Significant wave height: 20044

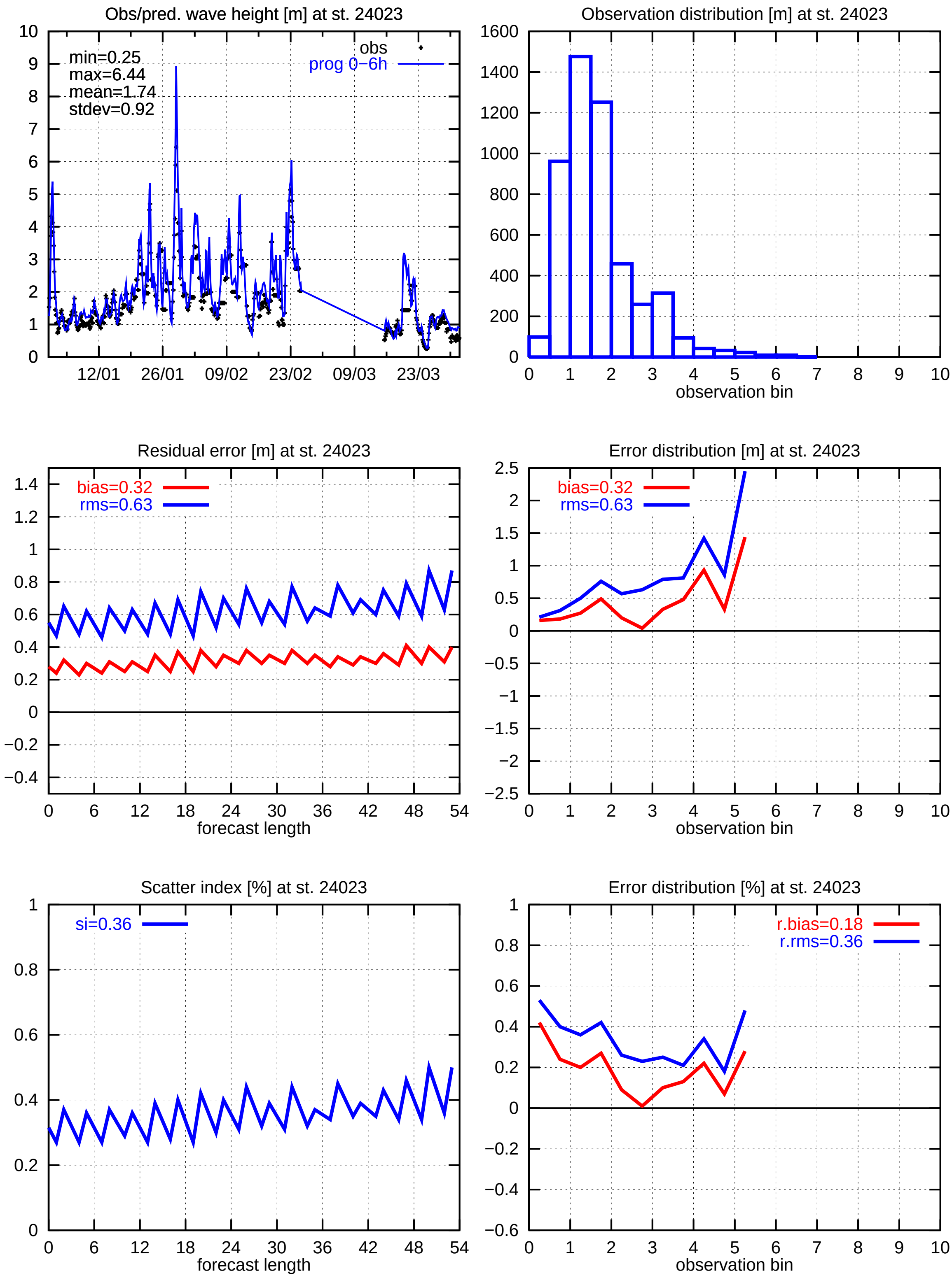

Figure 17. Significant wave height: 24023. The zig-zag curves are caused by irregular 3h sampling.

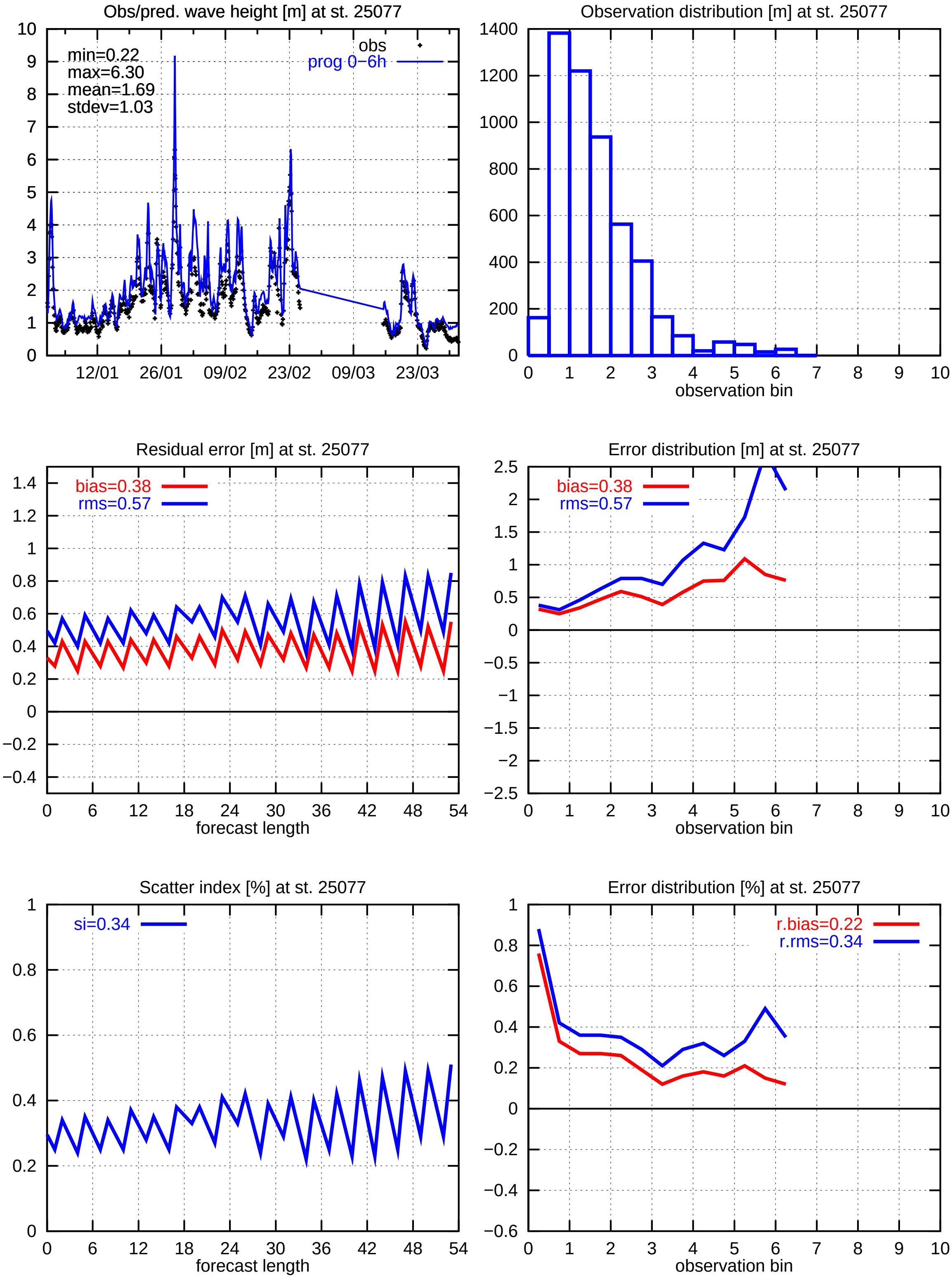

Figure 18. Significant wave height: 25077. The zig-zag curves are caused by irregular 3h sampling.

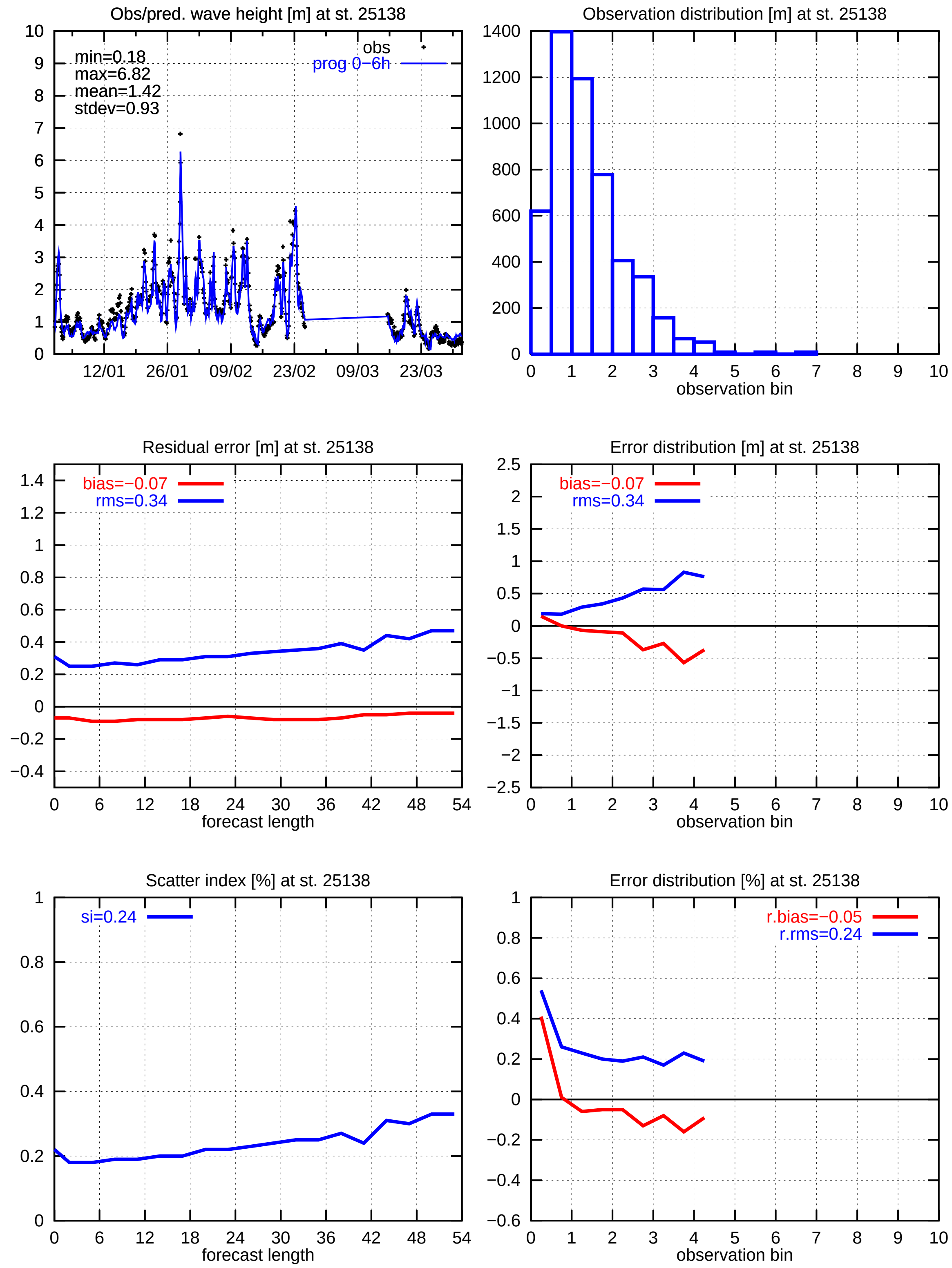

Figure 19. Significant wave height: 25138

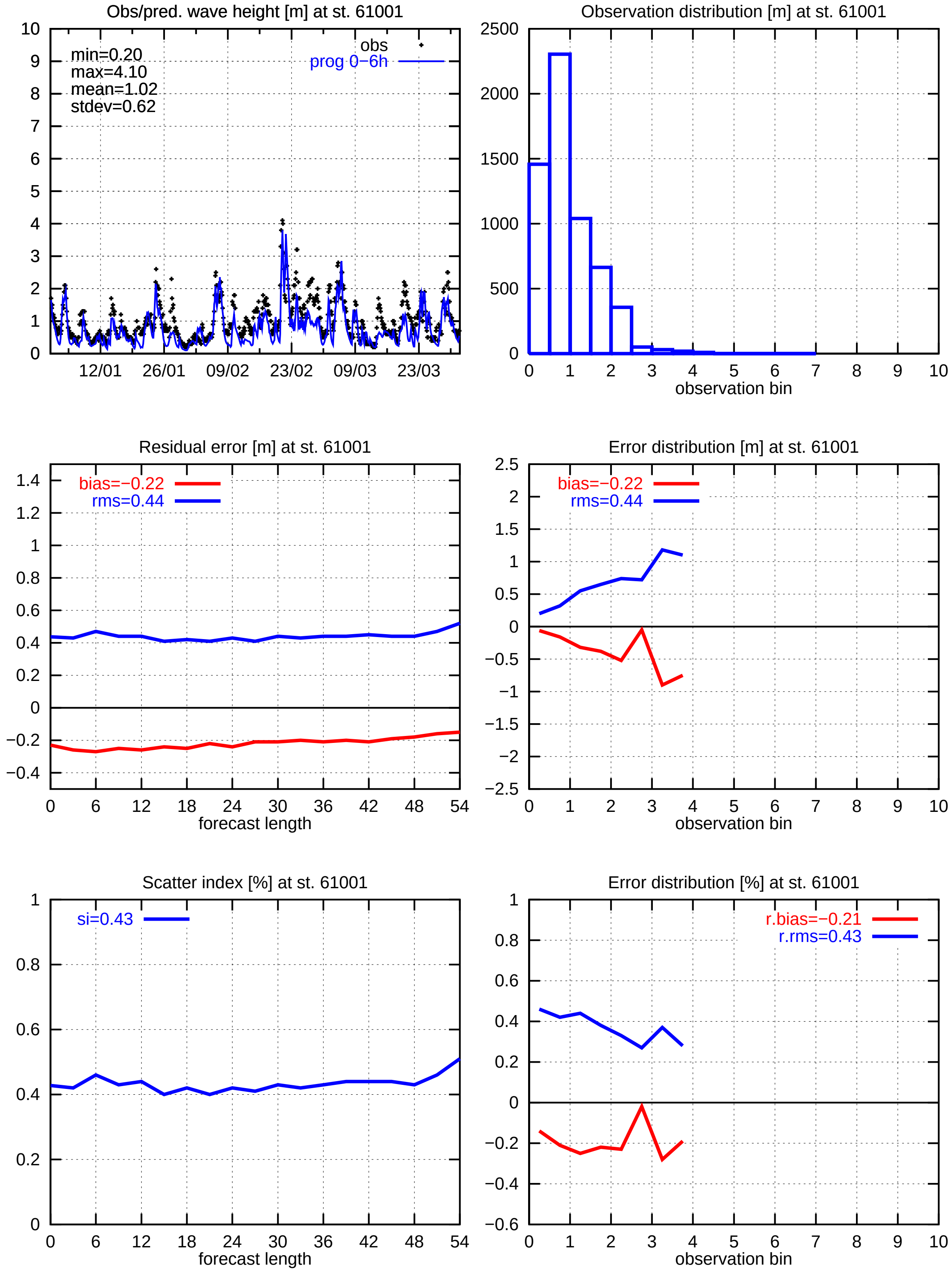

Figure 20. Significant wave height: 61001

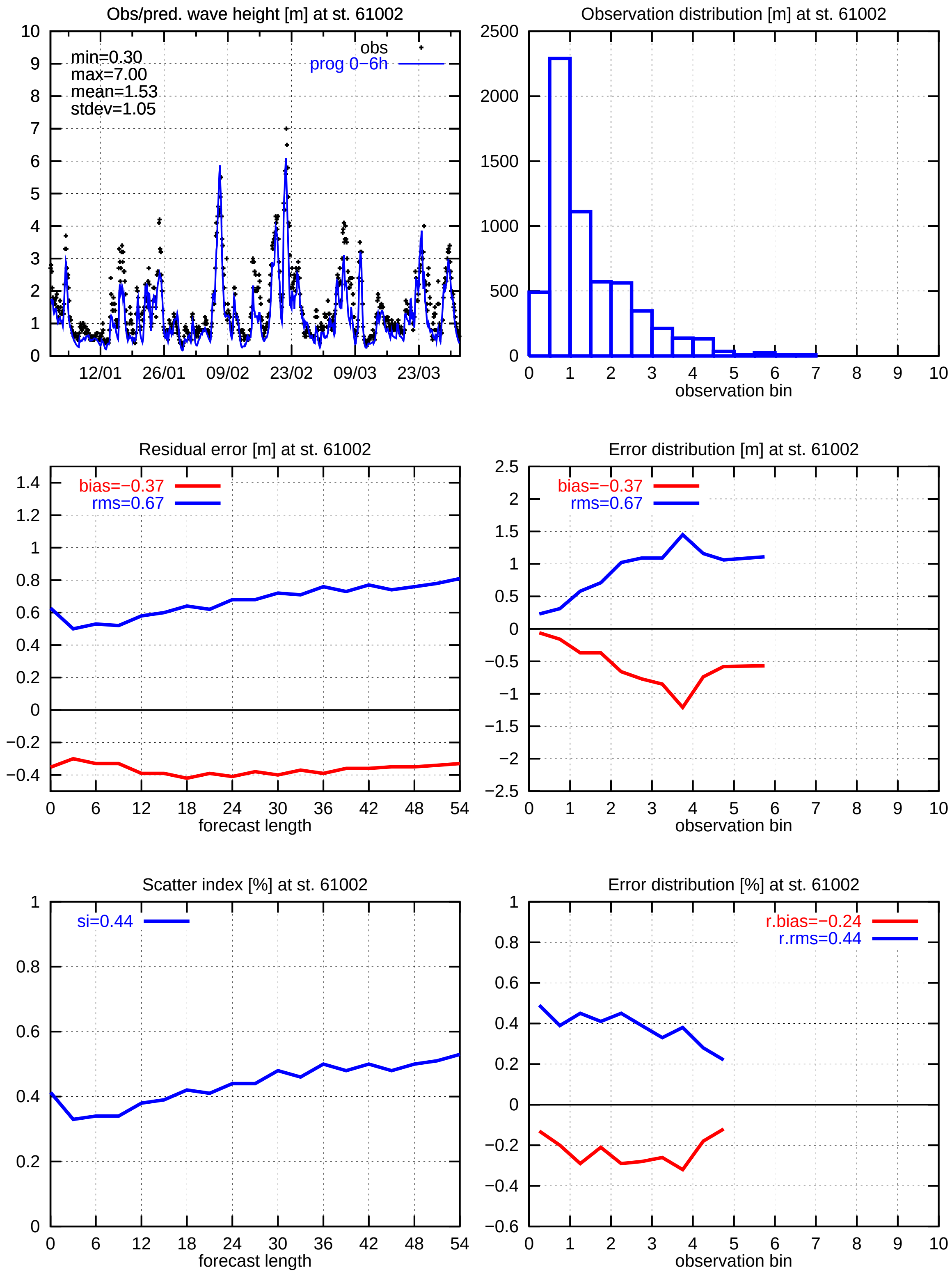

Figure 21. Significant wave height: 61002

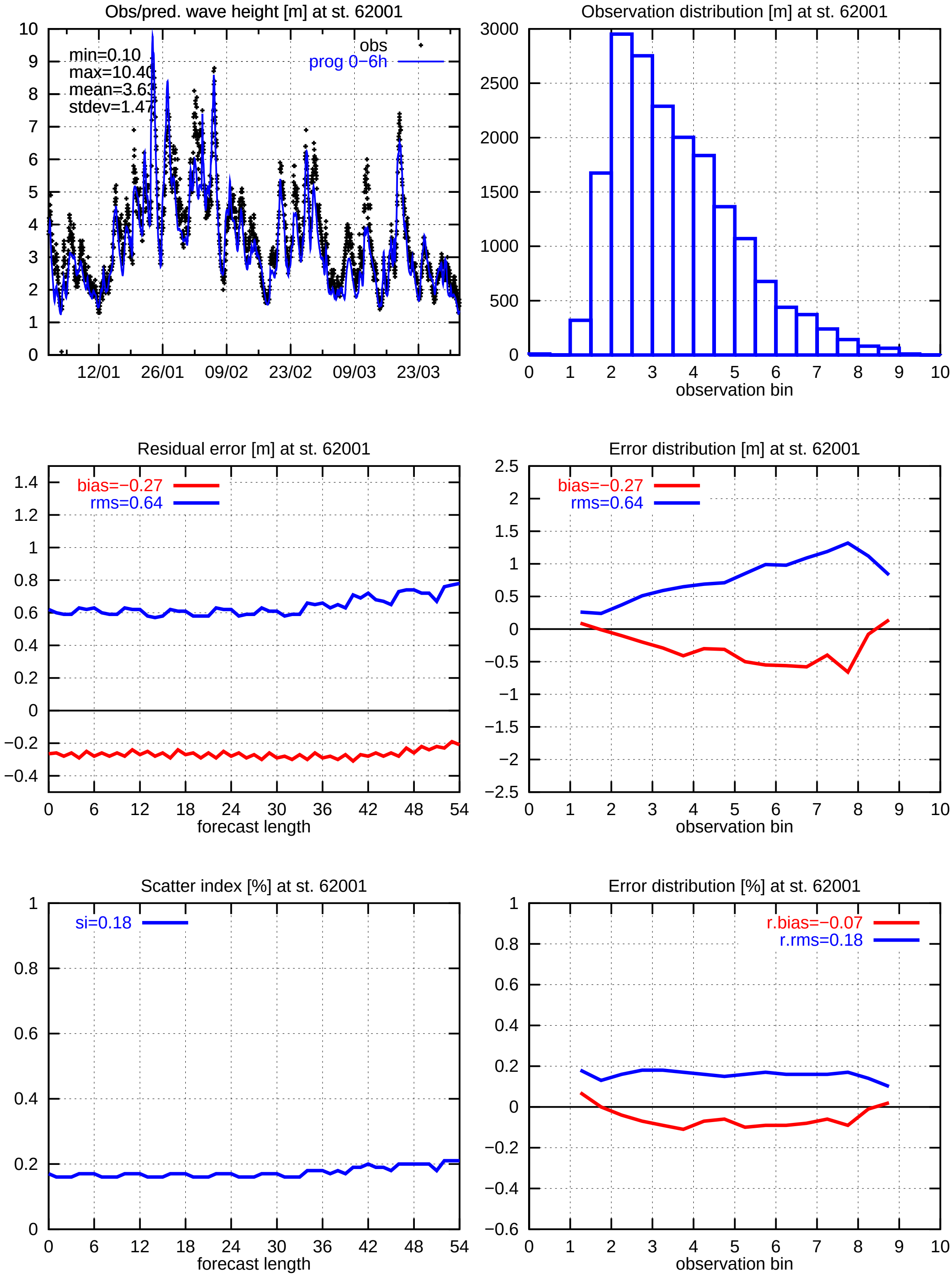

Figure 22. Significant wave height: 62001

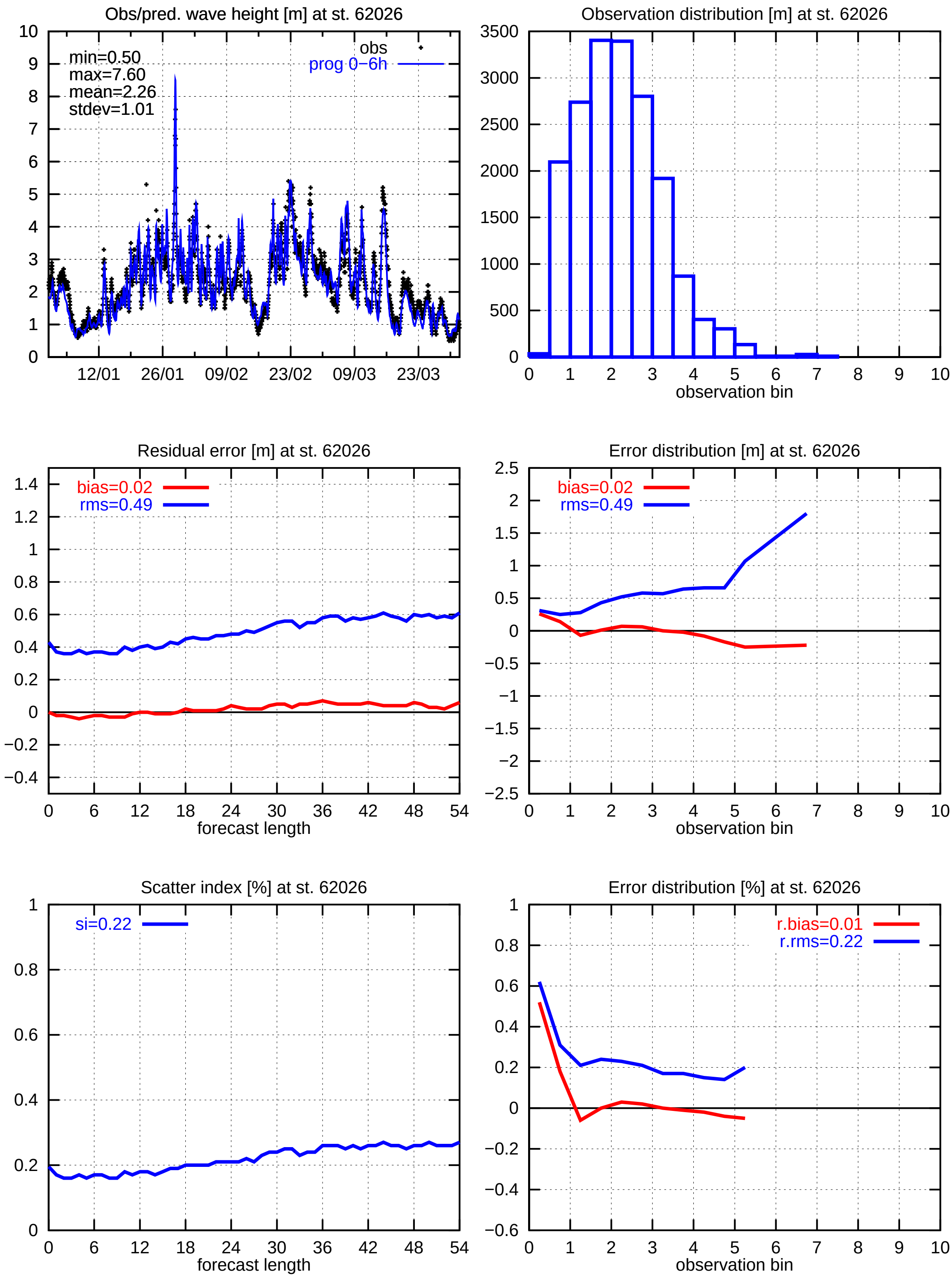

Figure 23. Significant wave height: 62026

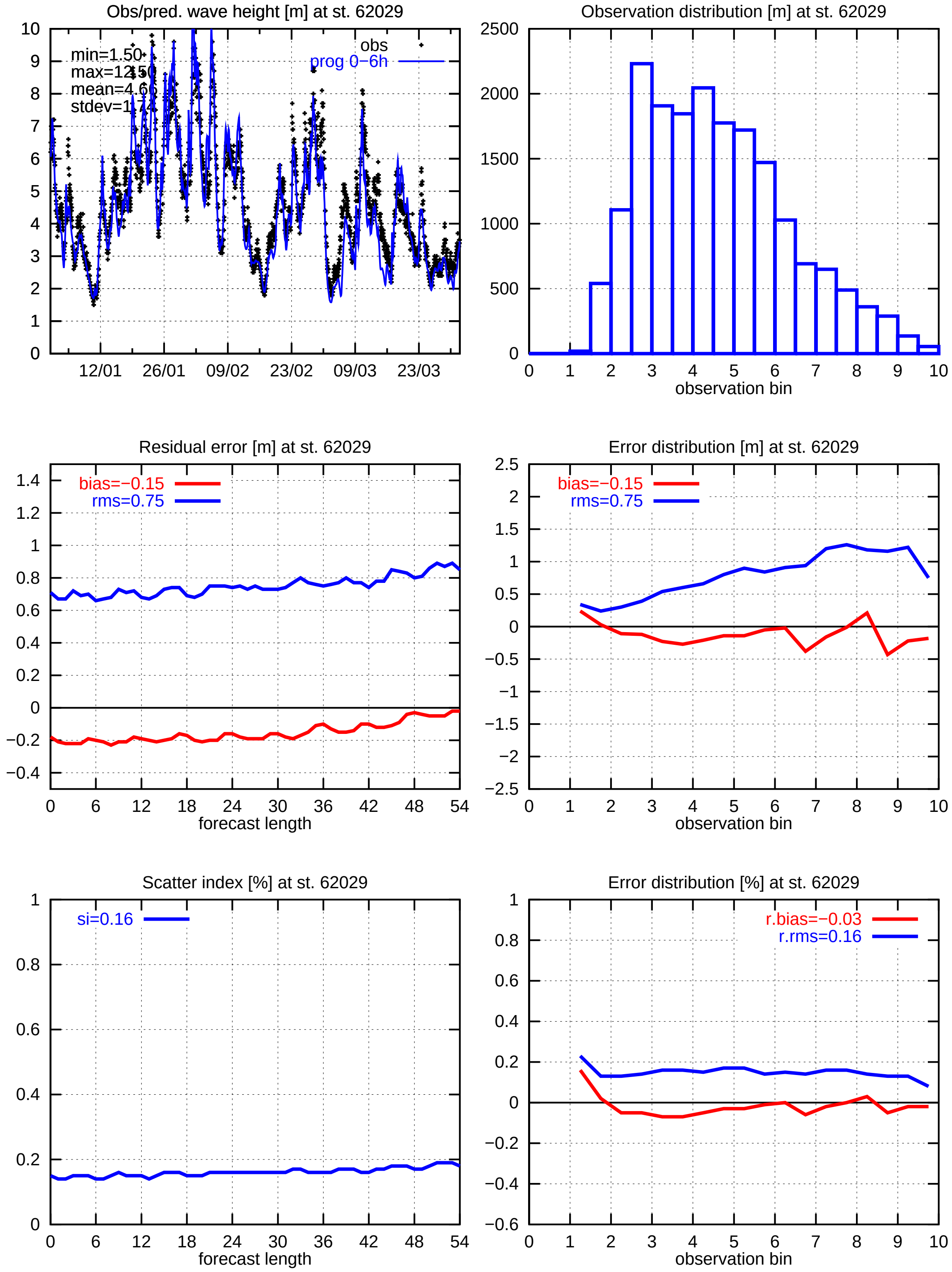

Figure 24. Significant wave height: 62029

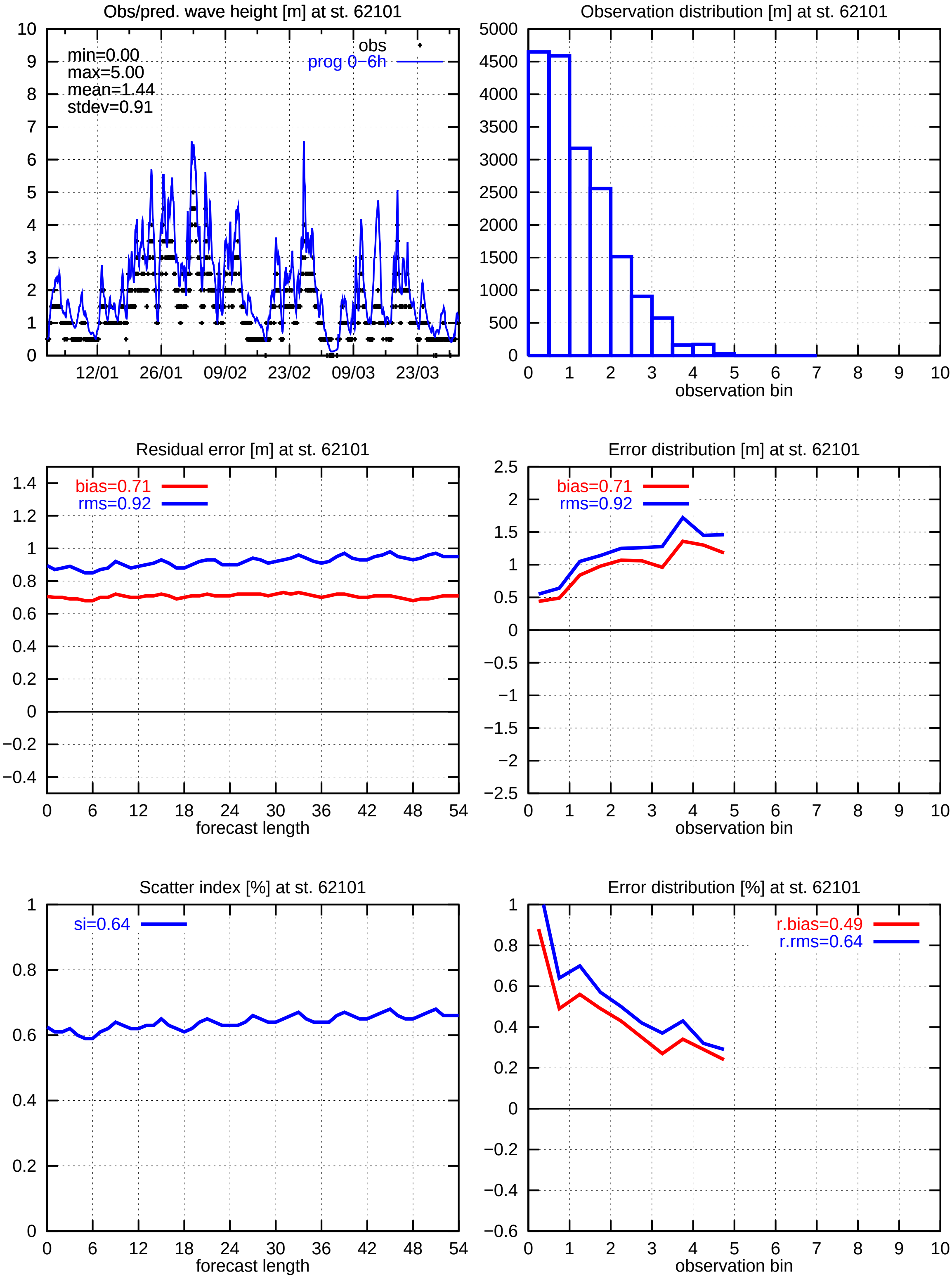

Figure 25. Significant wave height: 62101

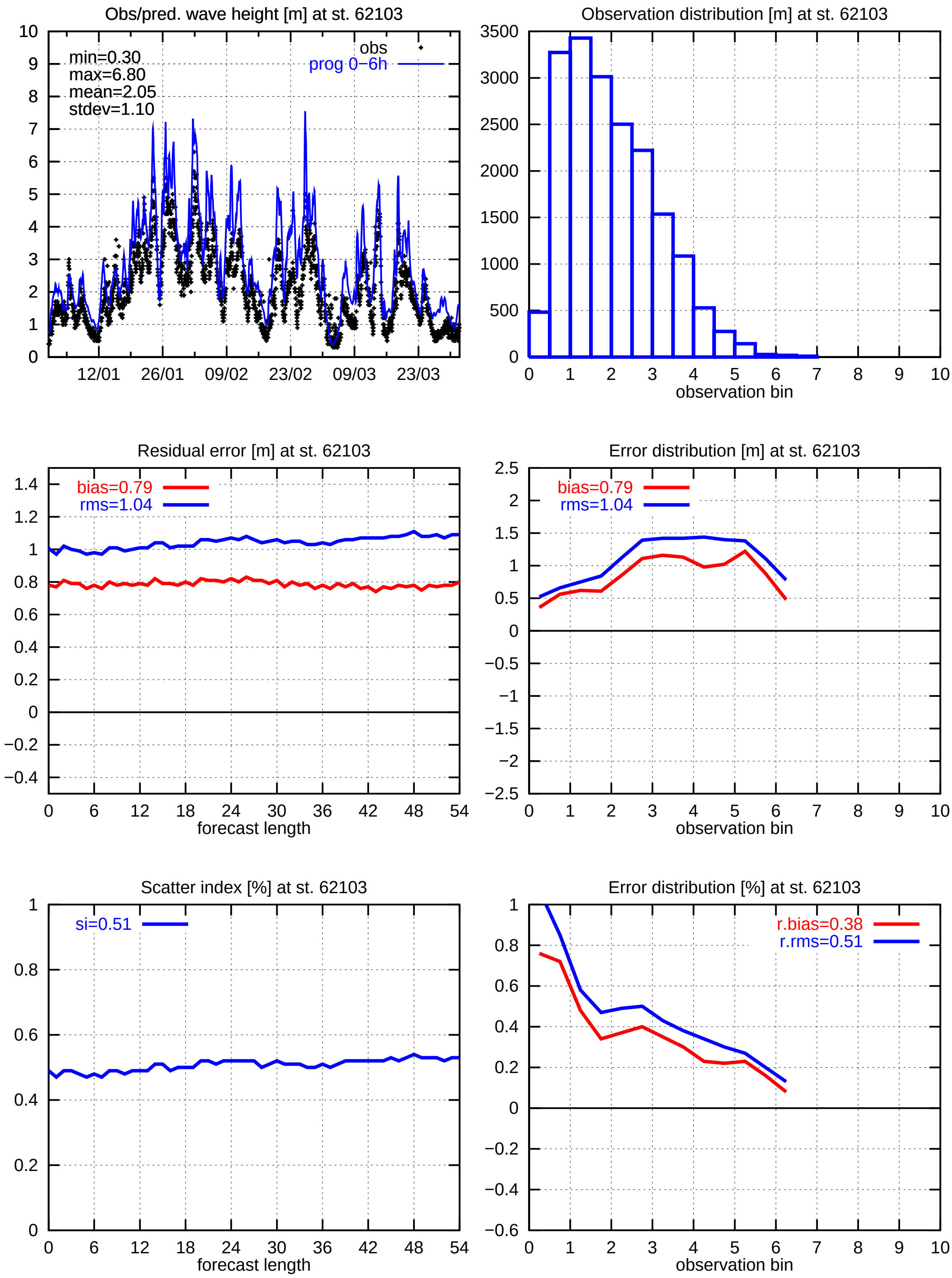

Figure 26. Significant wave height: 62103

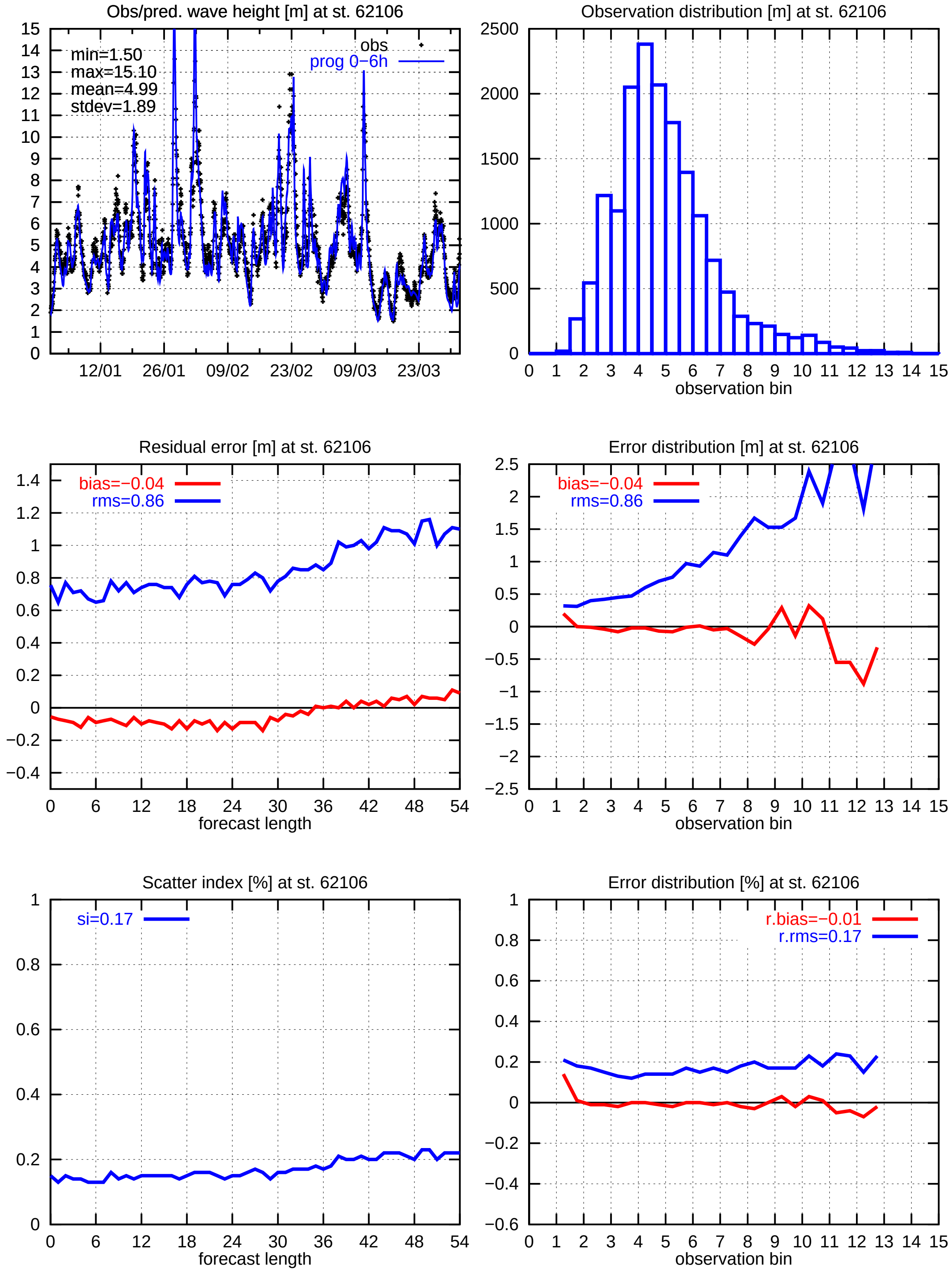

Figure 27. Significant wave height: 62106

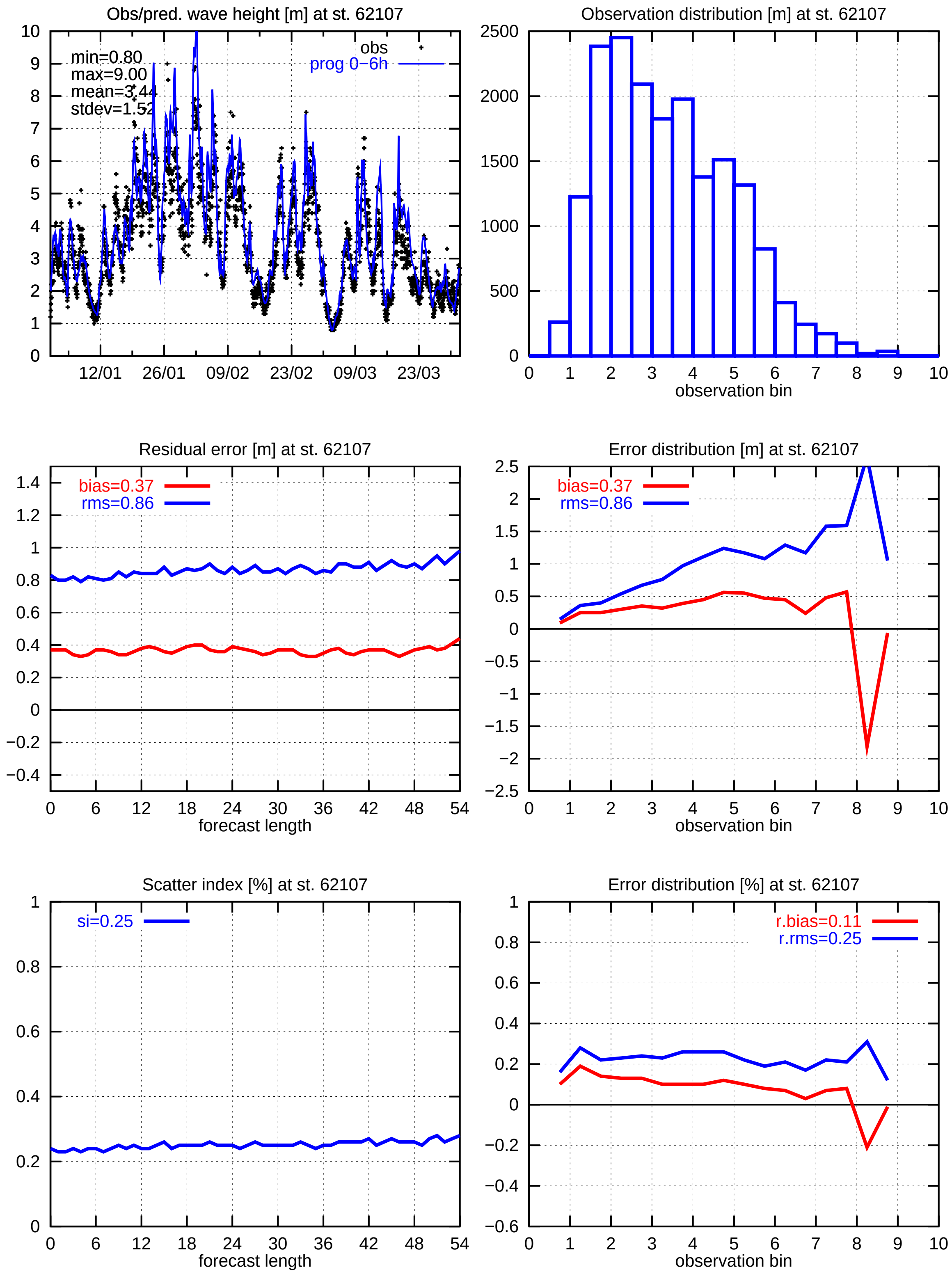

Figure 28. Significant wave height: 62107

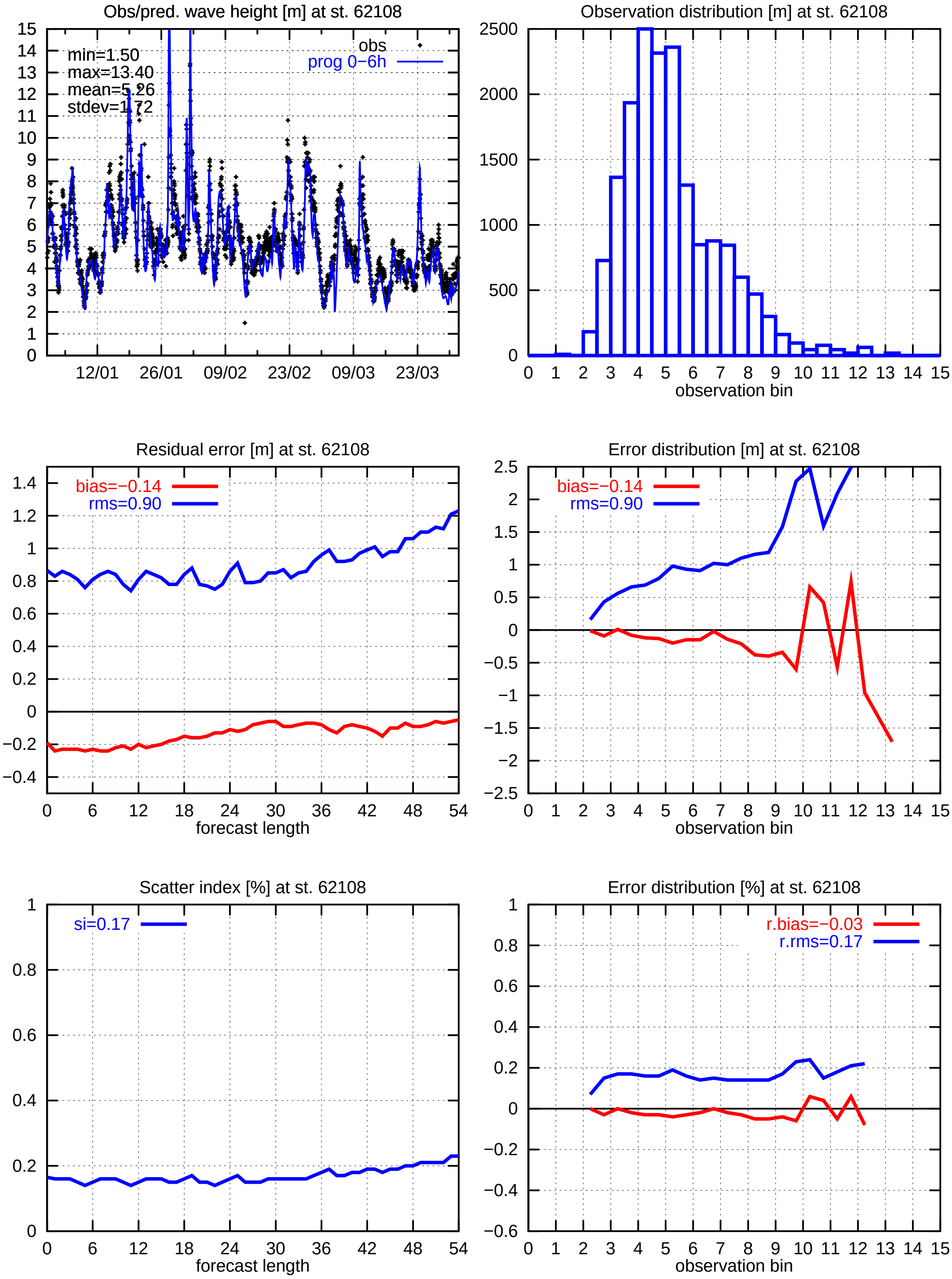

Figure 29. Significant wave height: 62108

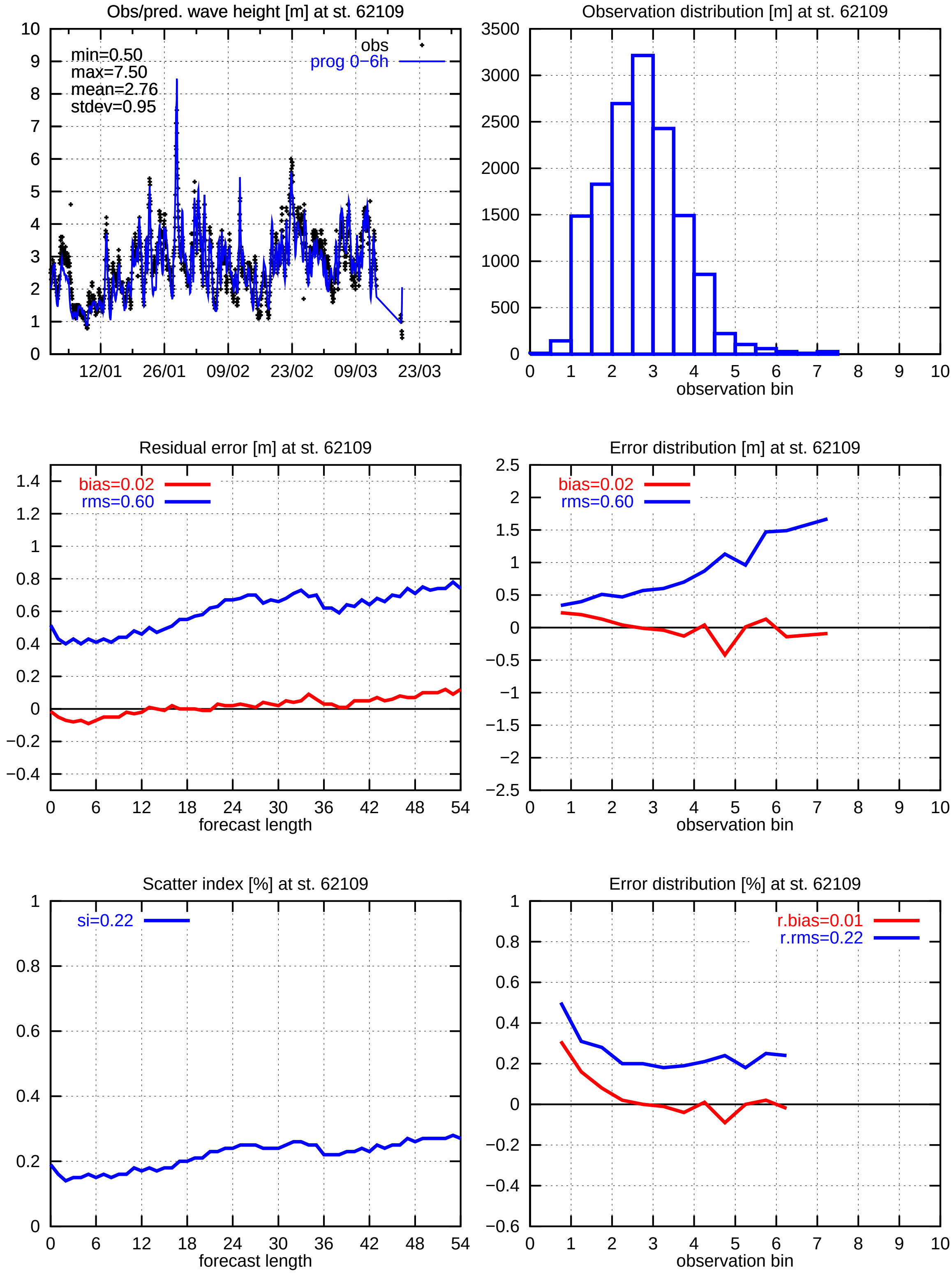

Figure 30. Significant wave height: 62109

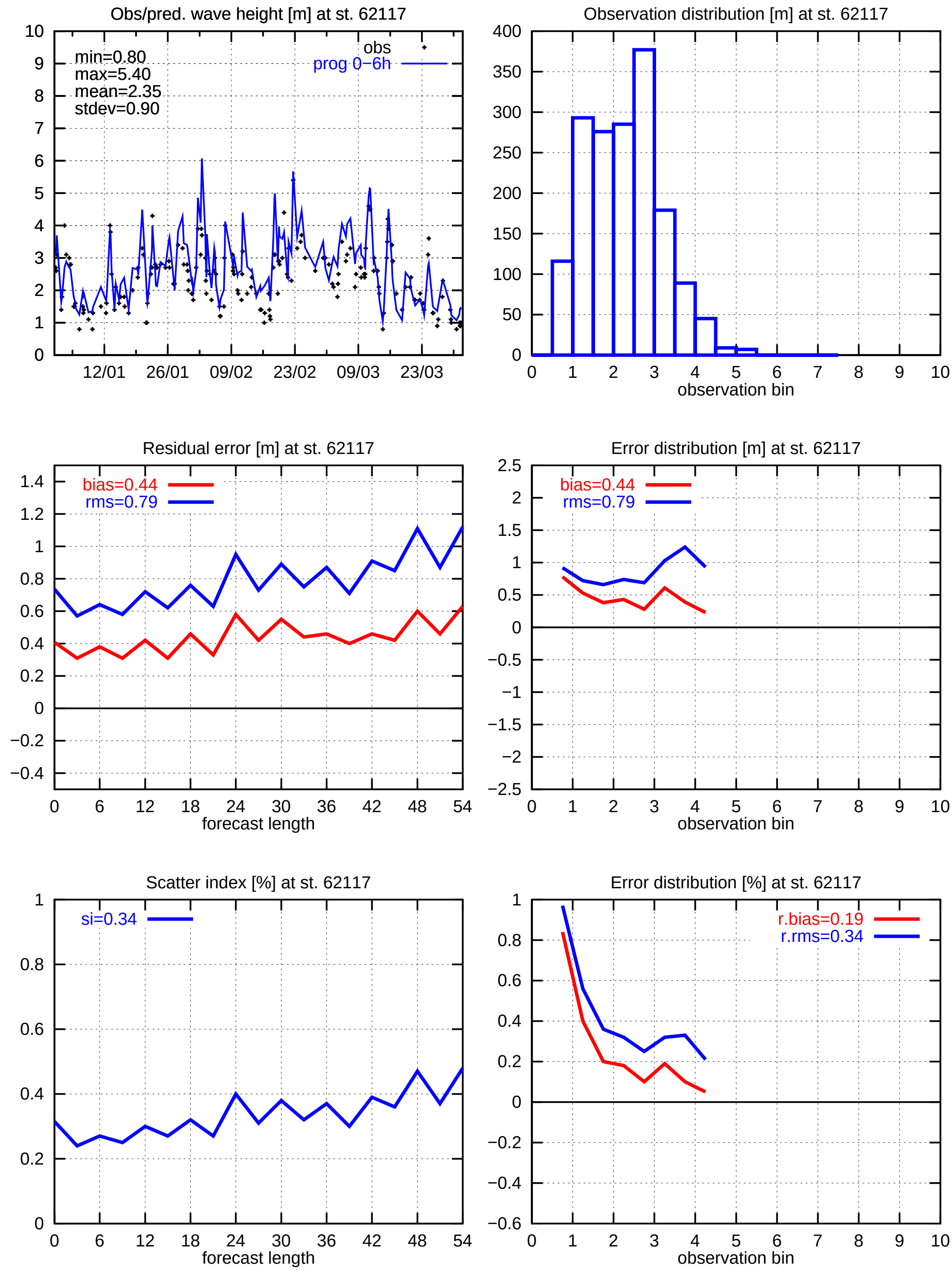

Figure 31. Significant wave height: 62117. The zig-zag curves are caused by irregular 3h sampling.

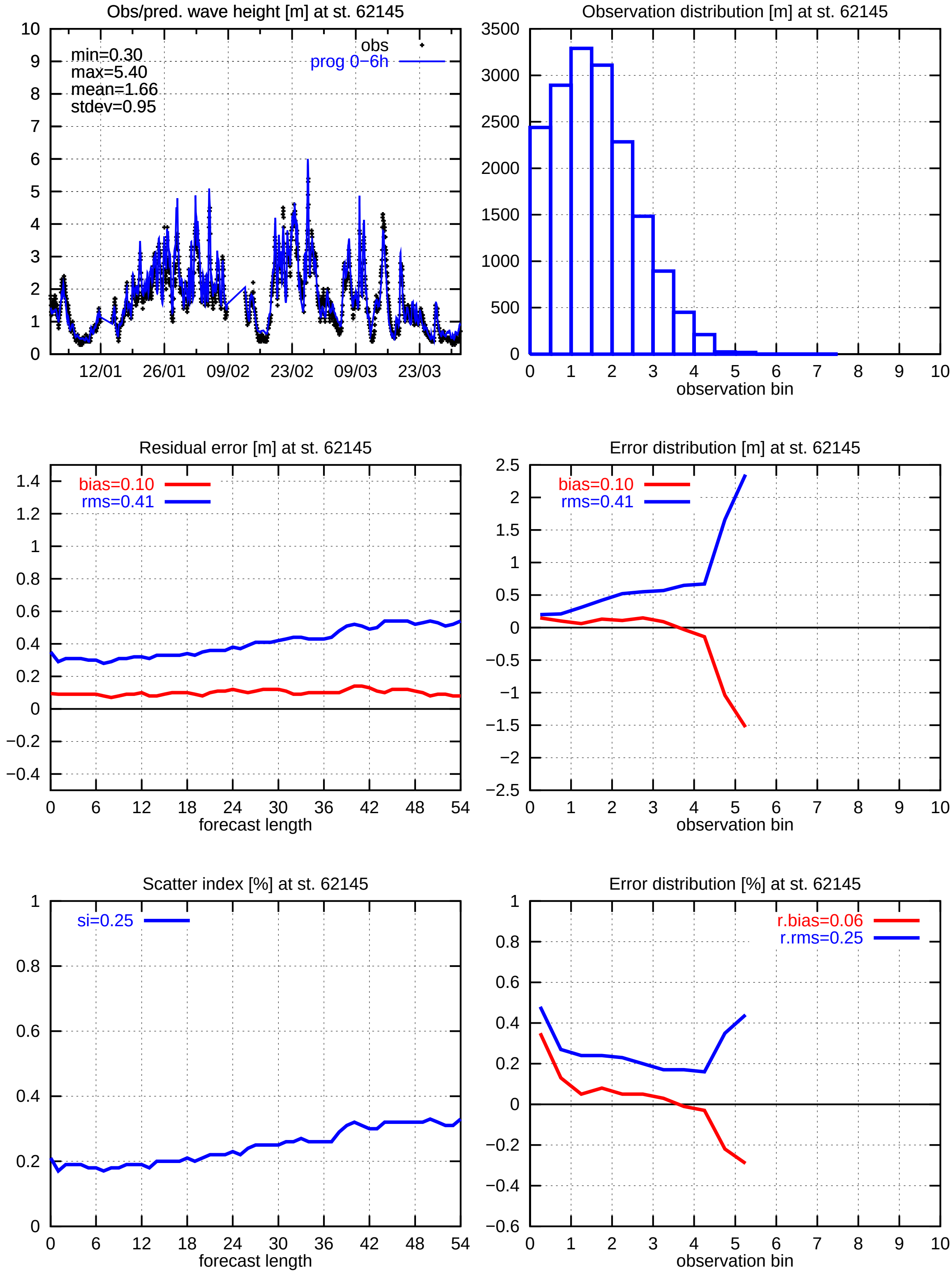

Figure 32. Significant wave height: 62145

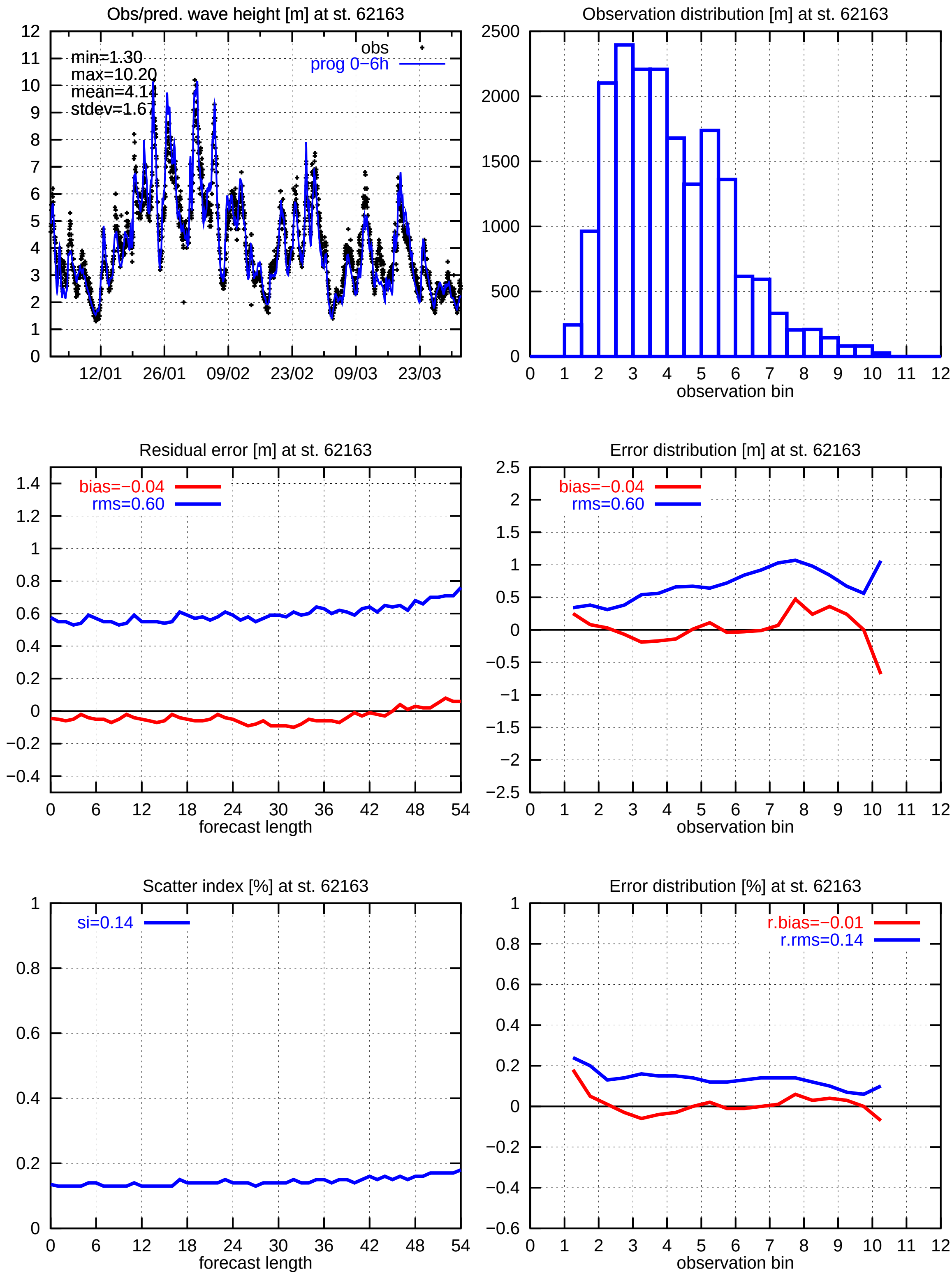

Figure 33. Significant wave height: 62163

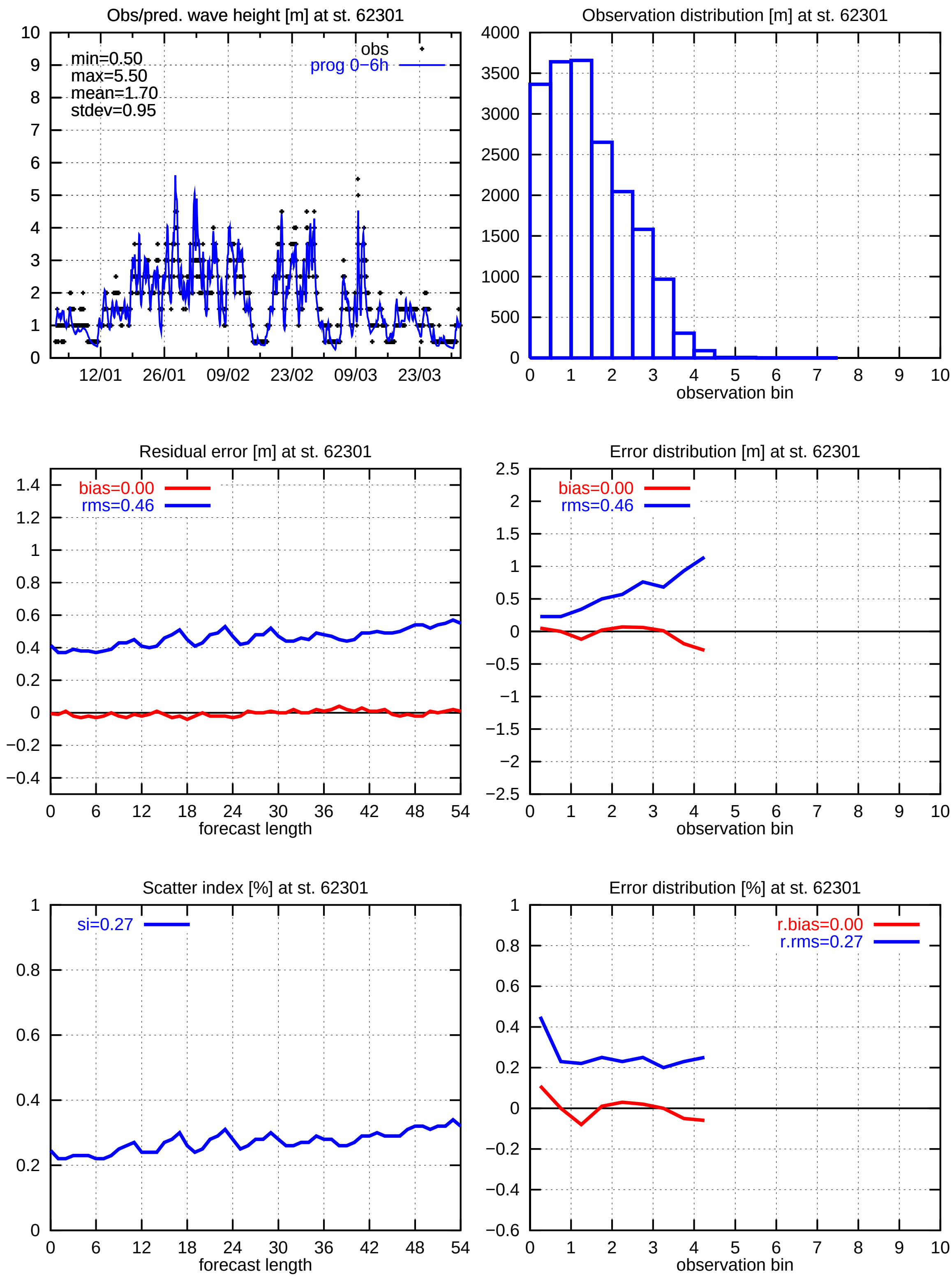

Figure 34. Significant wave height: 62301

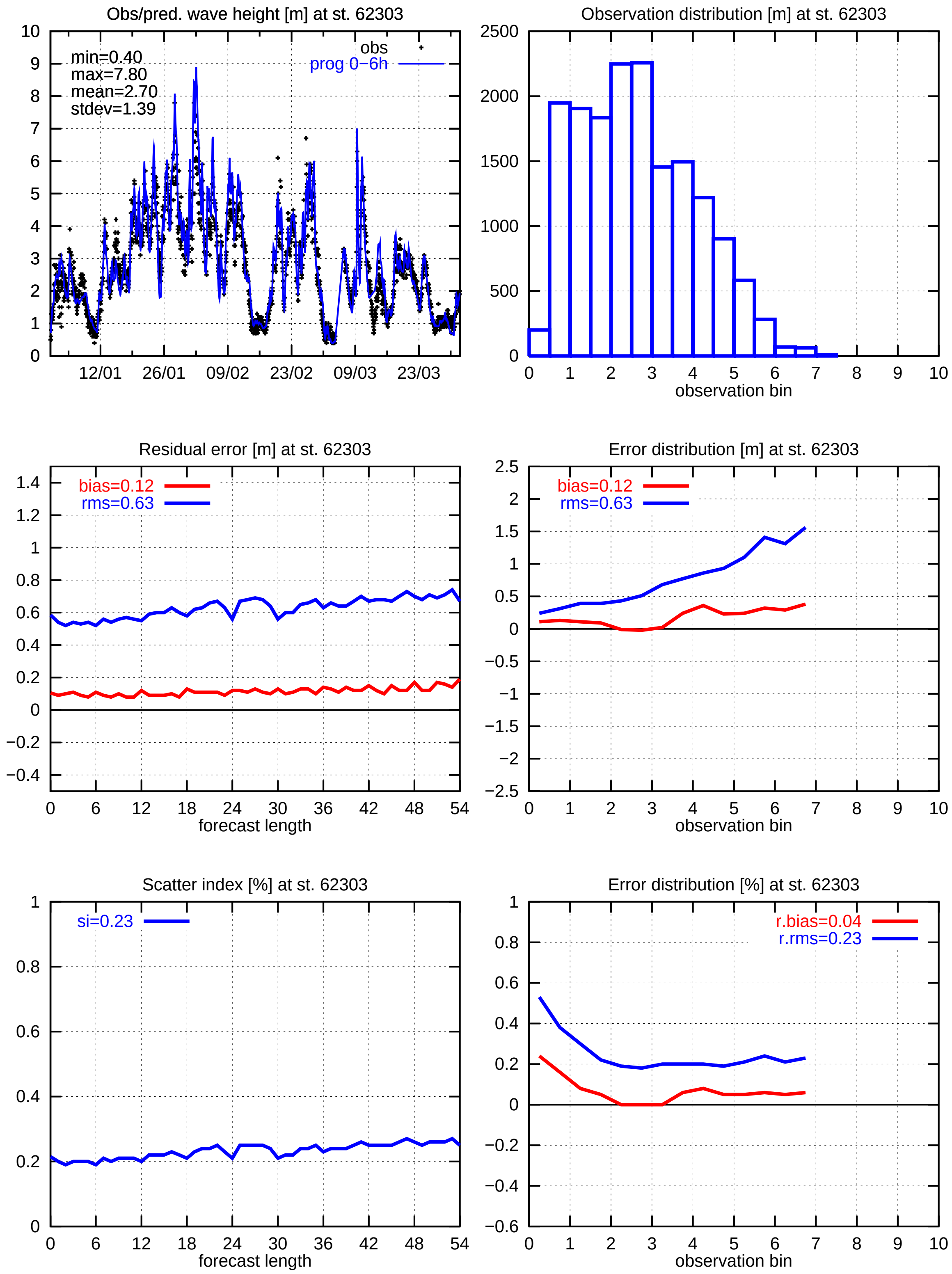

Figure 35. Significant wave height: 62303

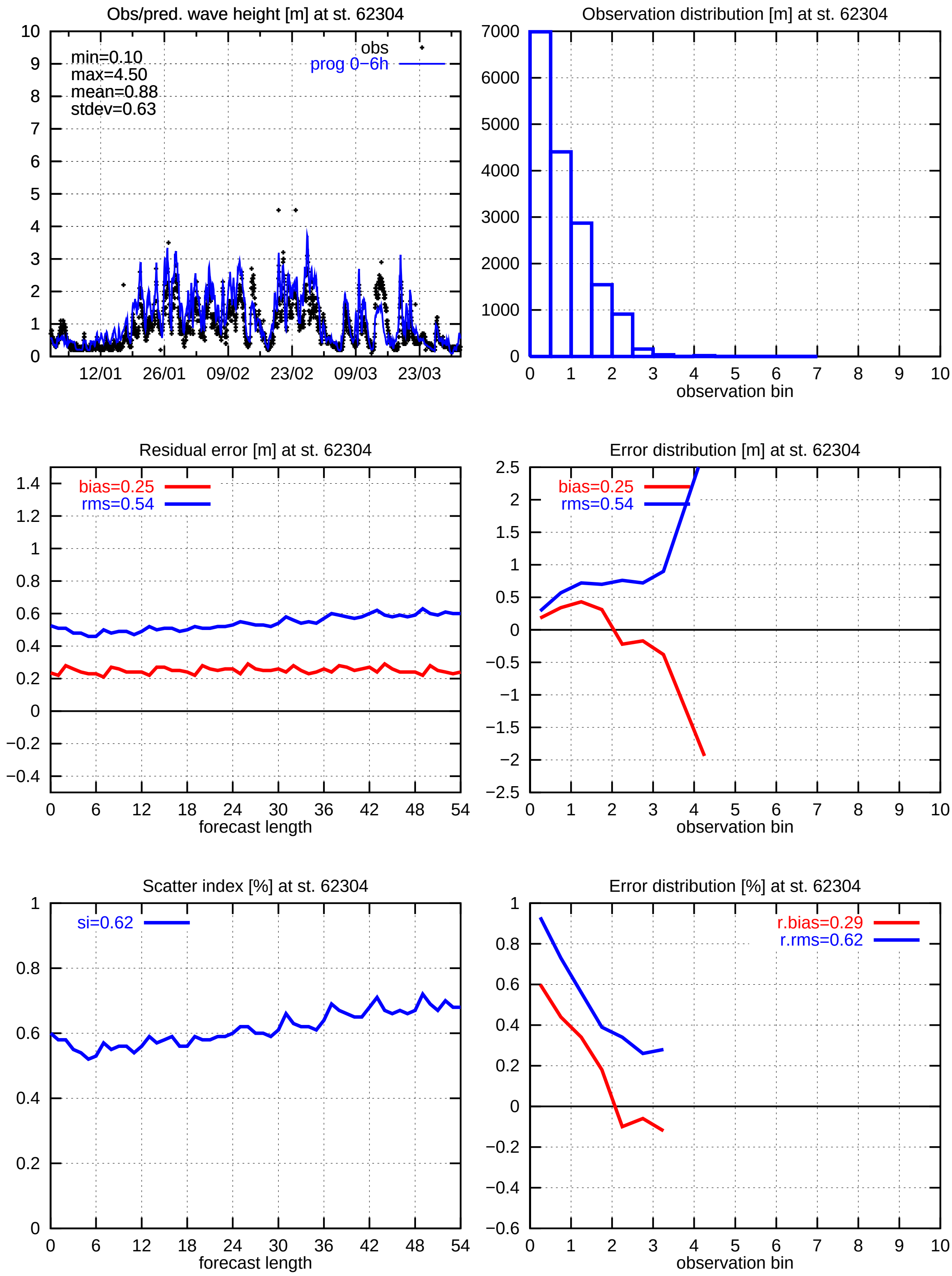

Figure 36. Significant wave height: 62304

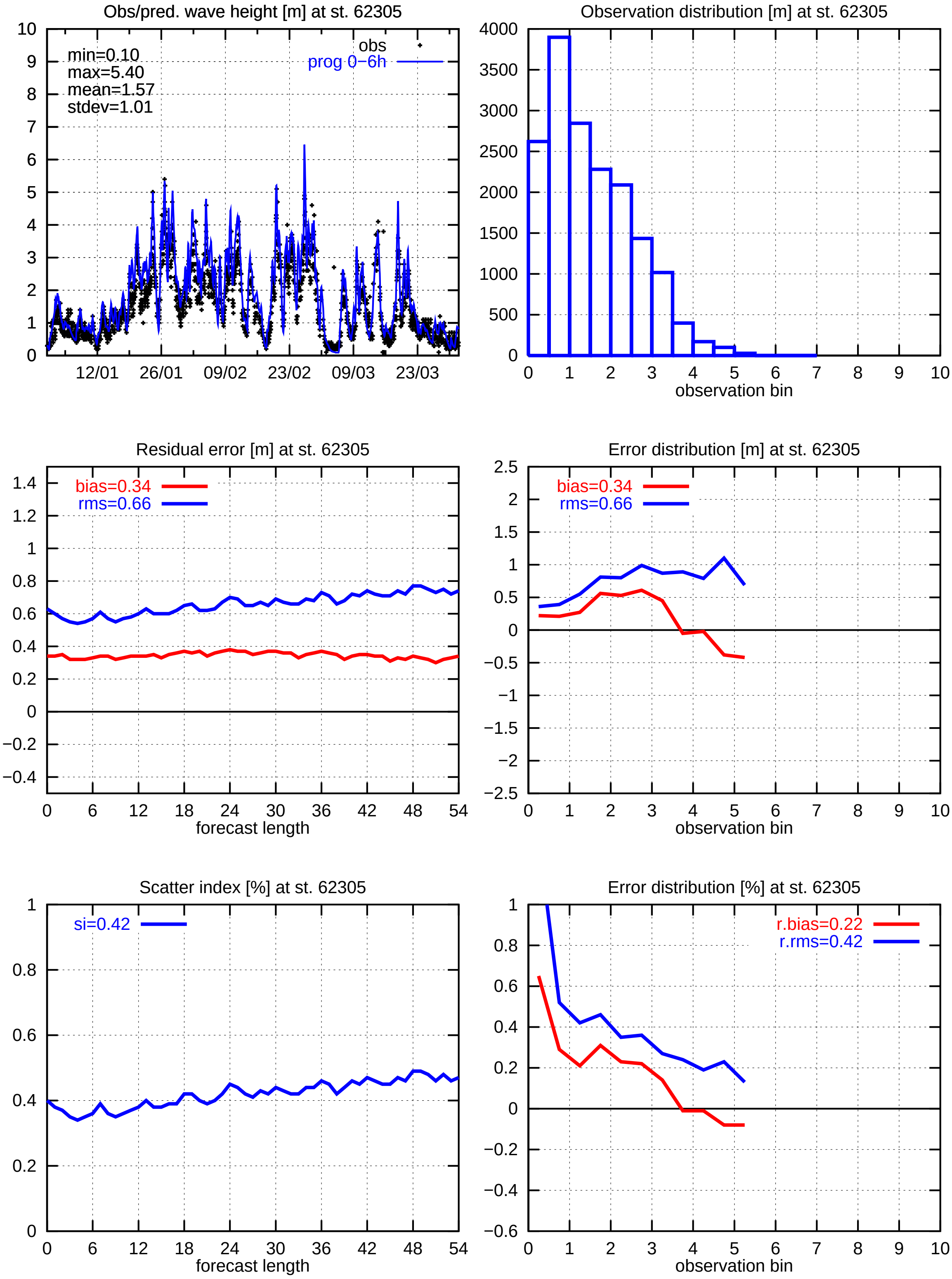

Figure 37. Significant wave height: 62305

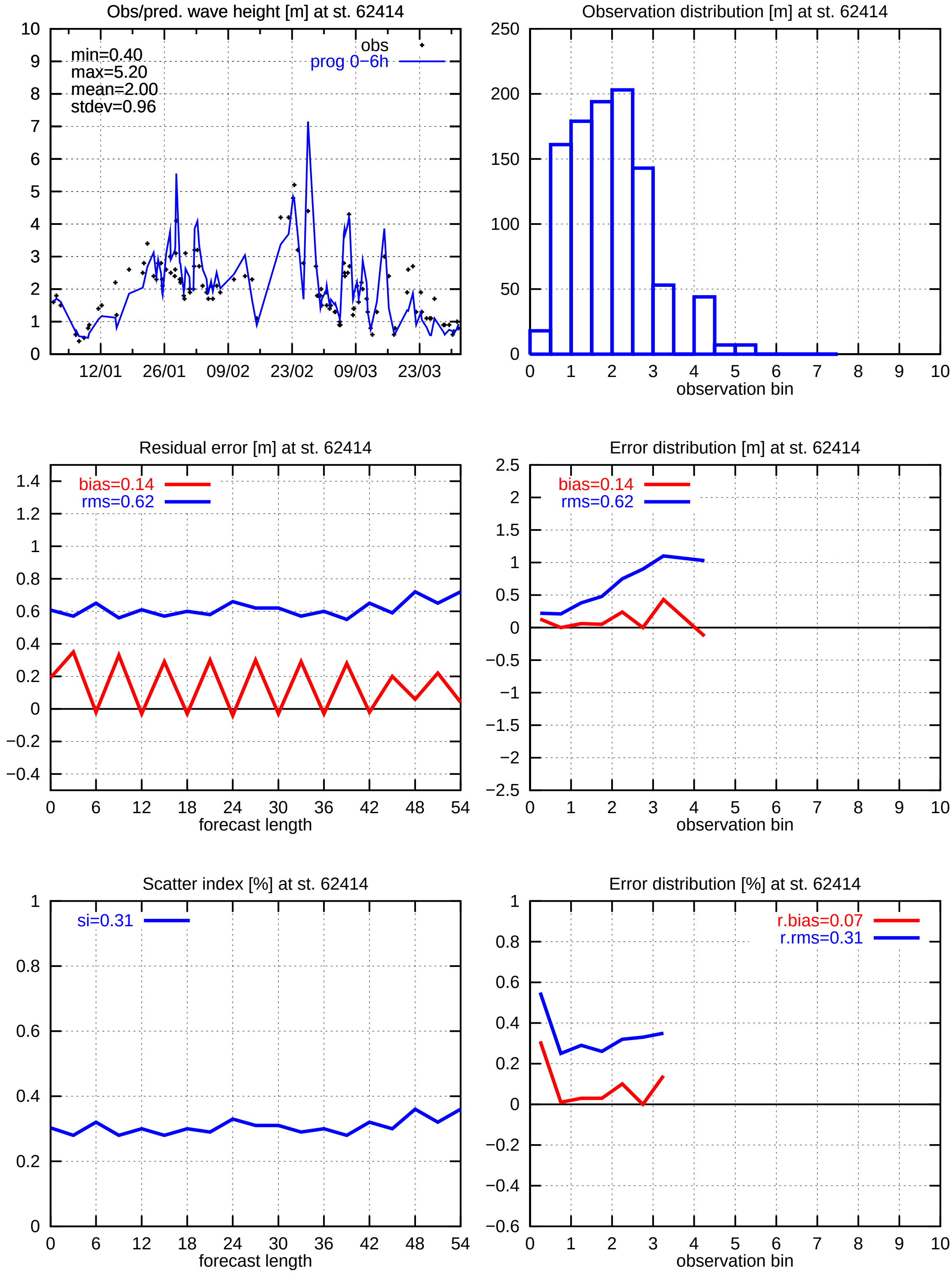

Figure 38. Significant wave height: 62414. The zig-zag curves are caused by irregular 3h sampling.

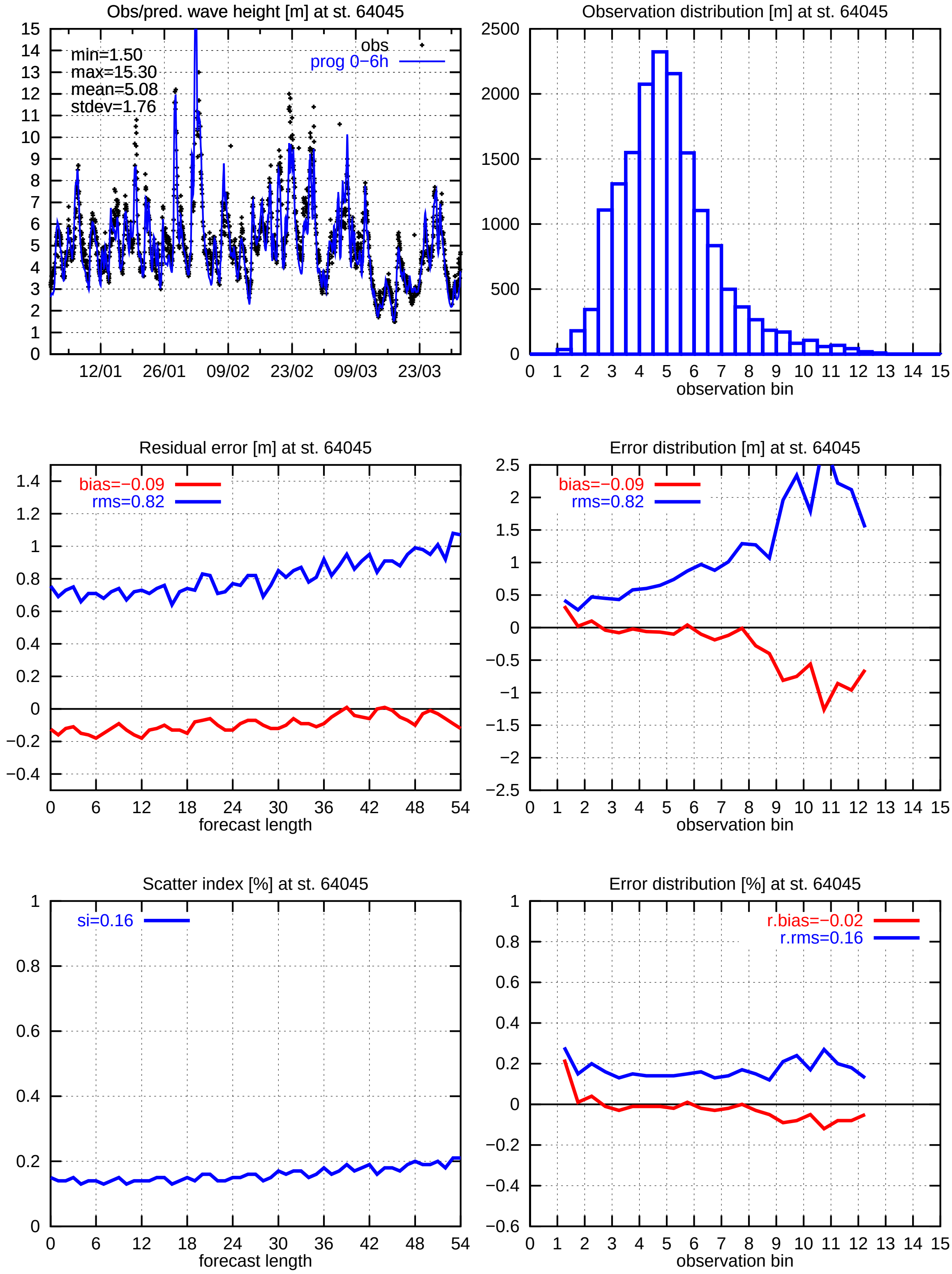

Figure 39. Significant wave height: 64045

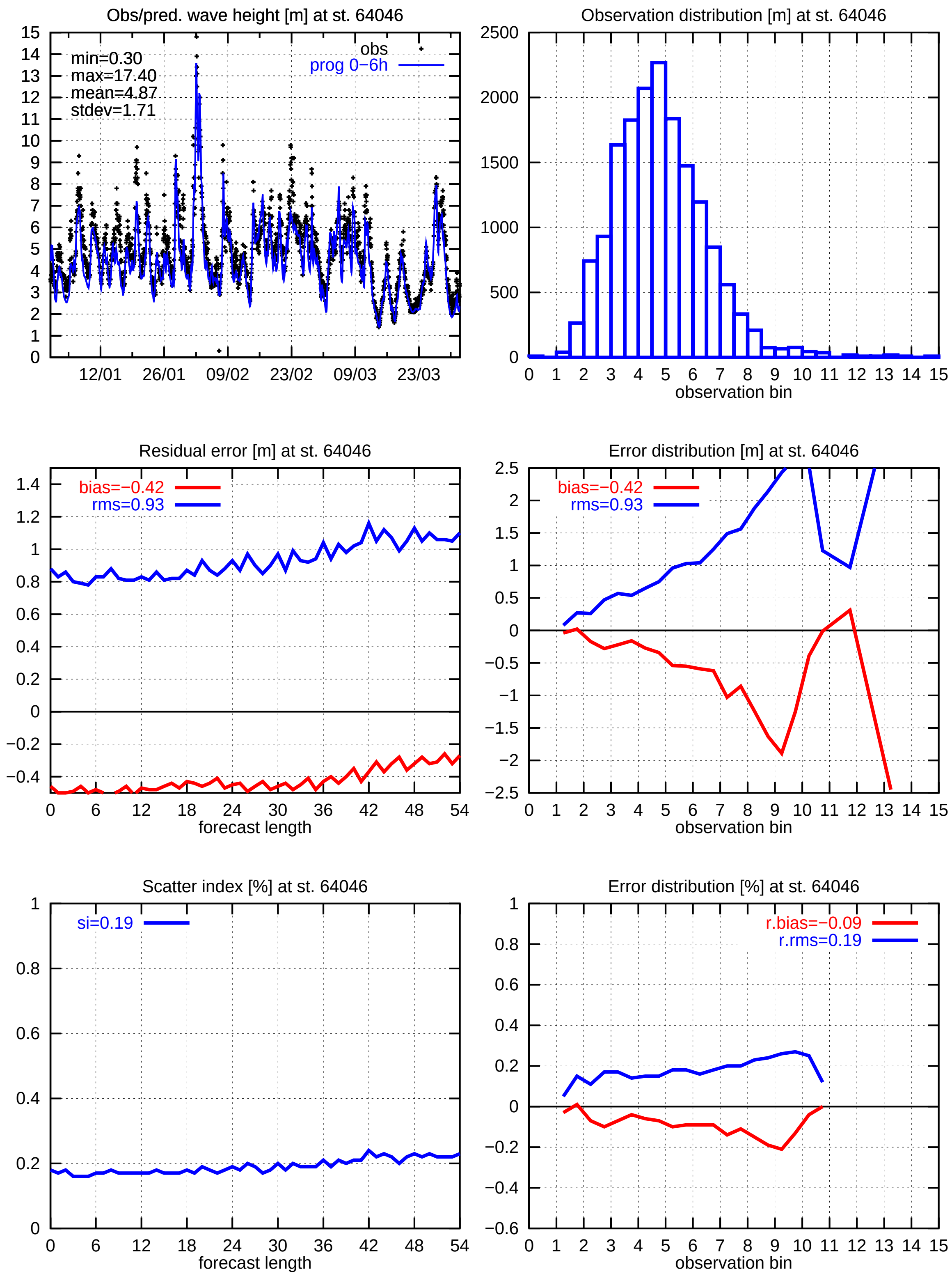

Figure 40. Significant wave height: 64046

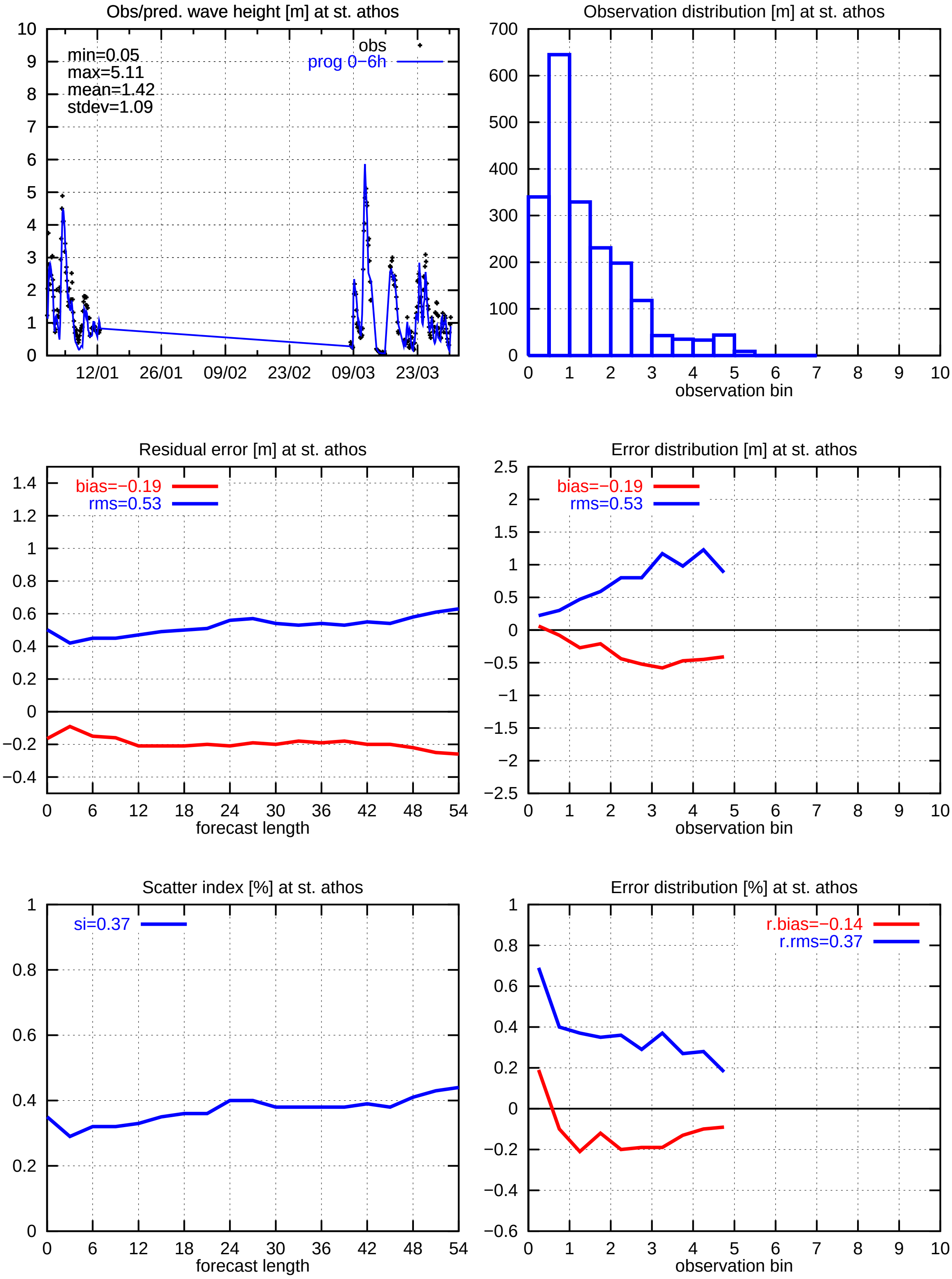

Figure 41. Significant wave height: Athos

7.6 Mean wave period station plots

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

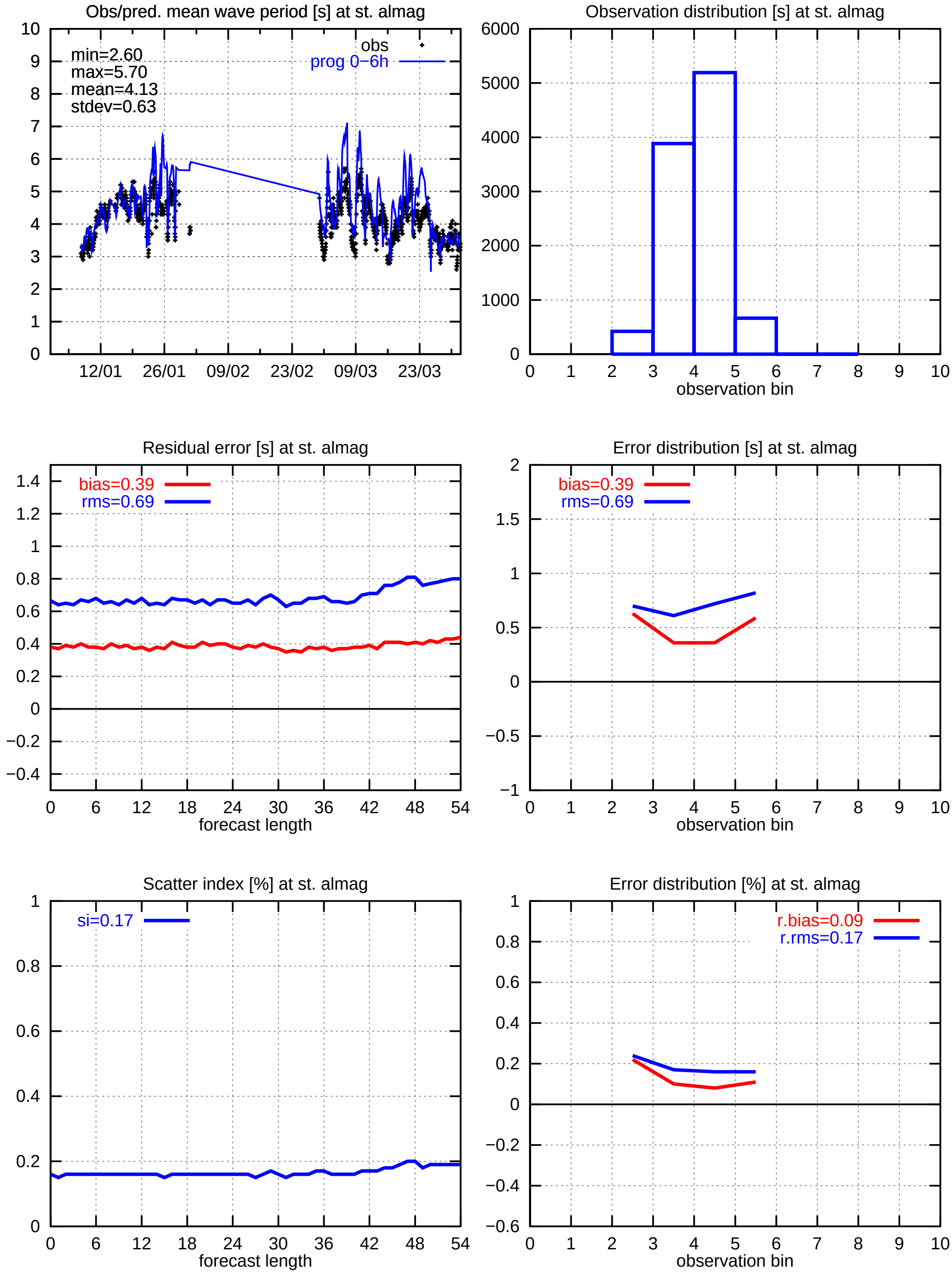

Figure 42. Mean wave period: Almagrundet

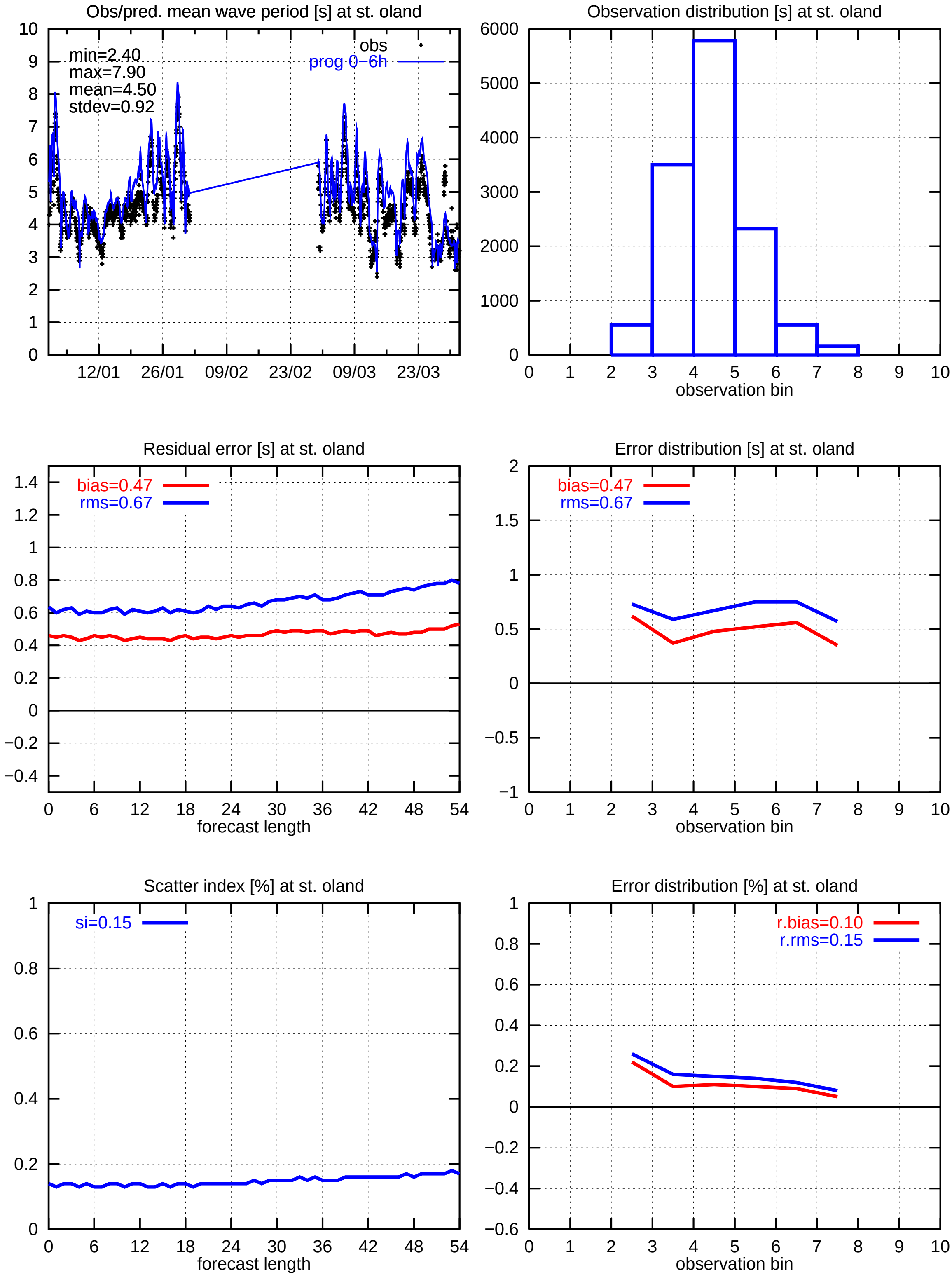

Figure 43. Mean wave period: Øland

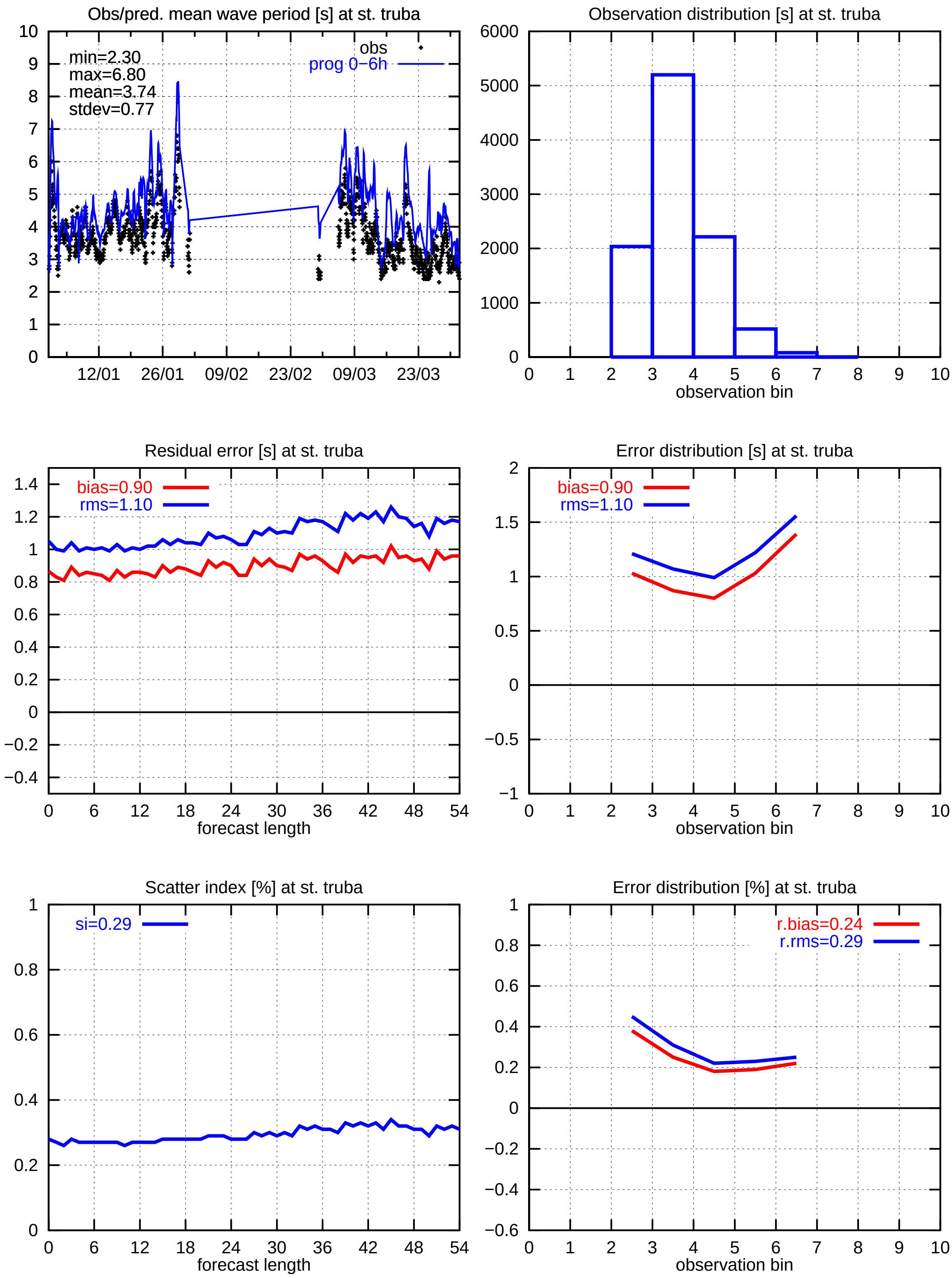

Figure 44. Mean wave period: Trubaduren

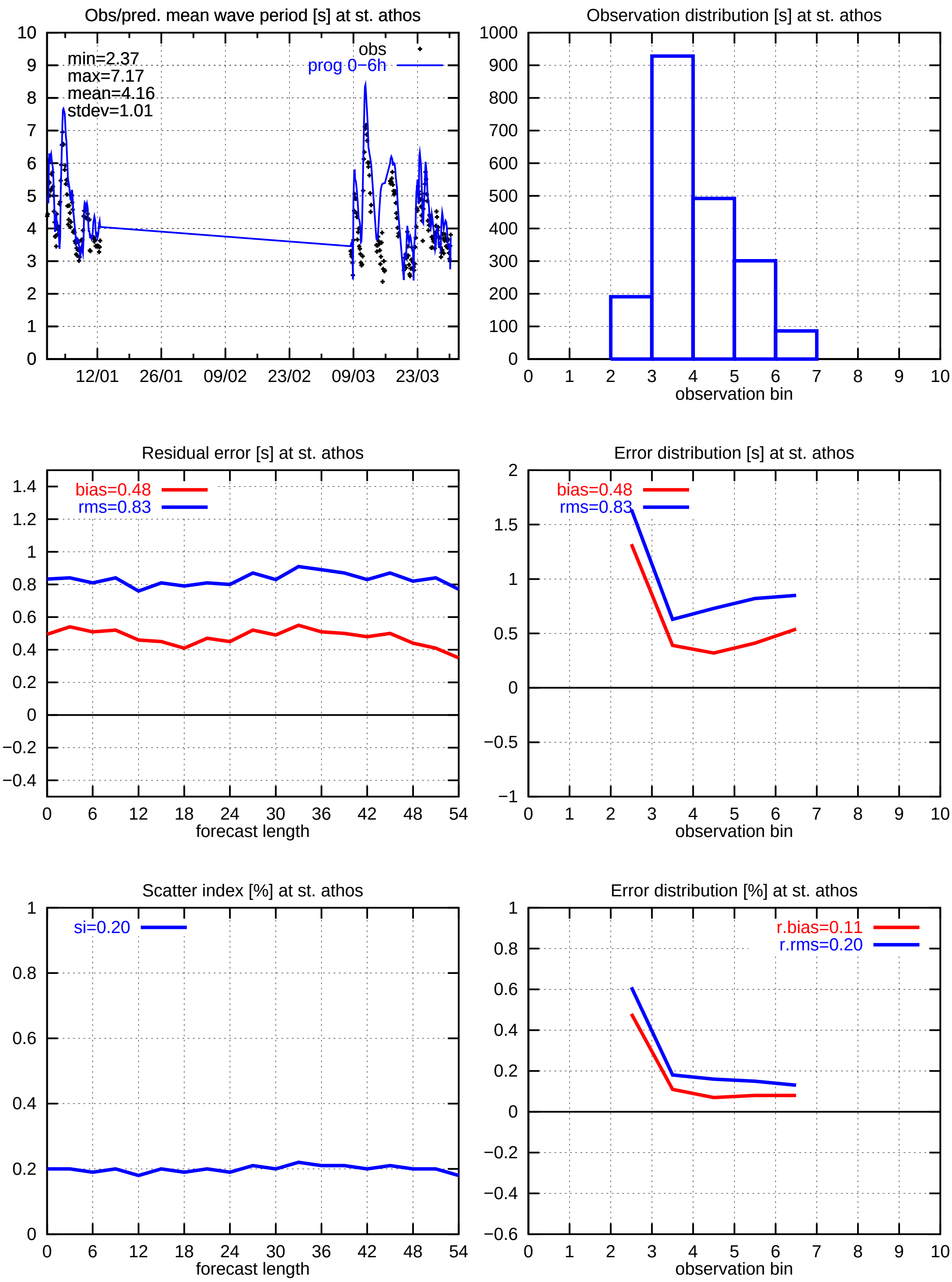

Figure 45. Mean wave period: Athos

7.7 Dominant wave period station plots

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

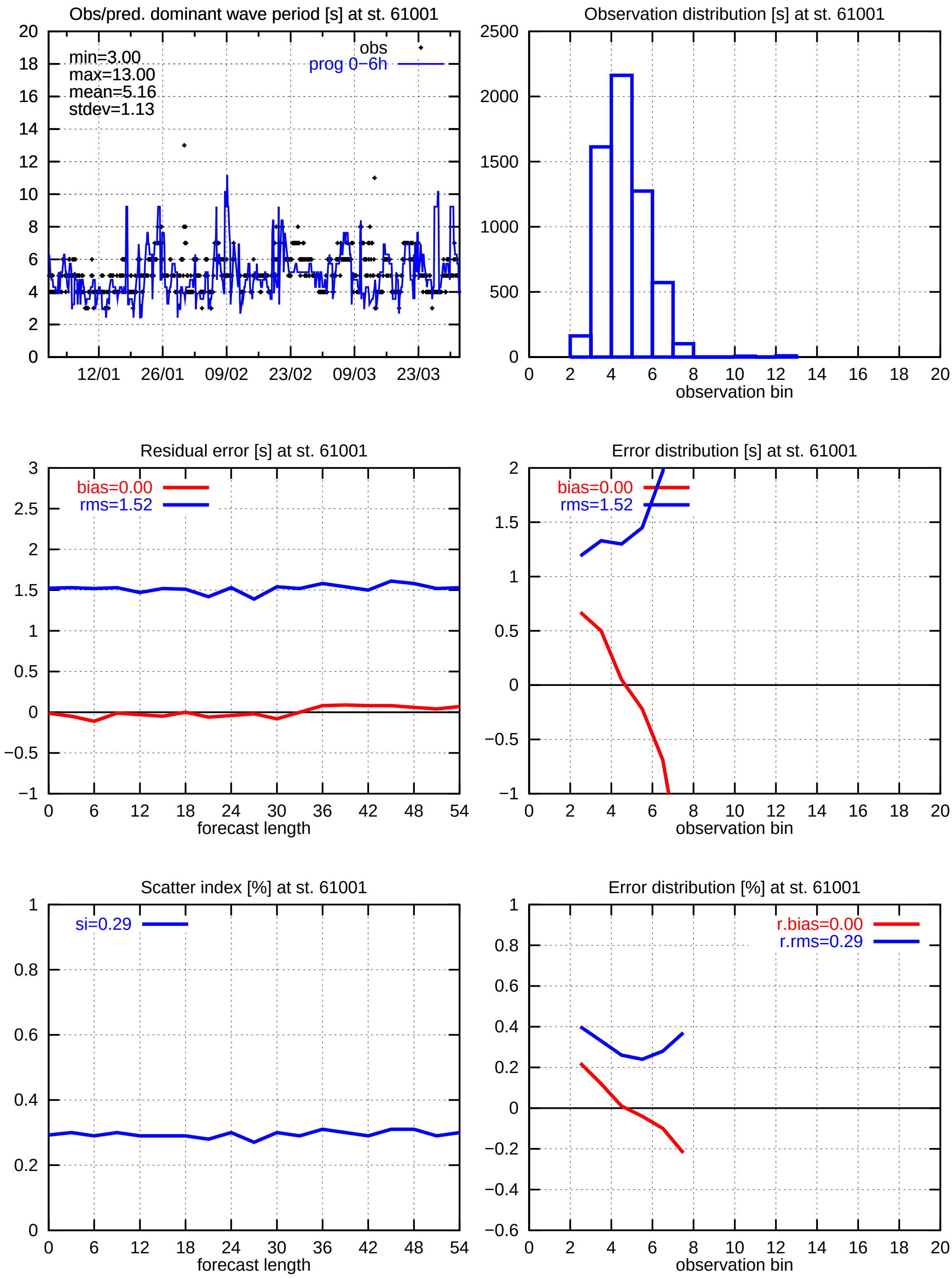

Figure 46. Dominant wave period: 61001

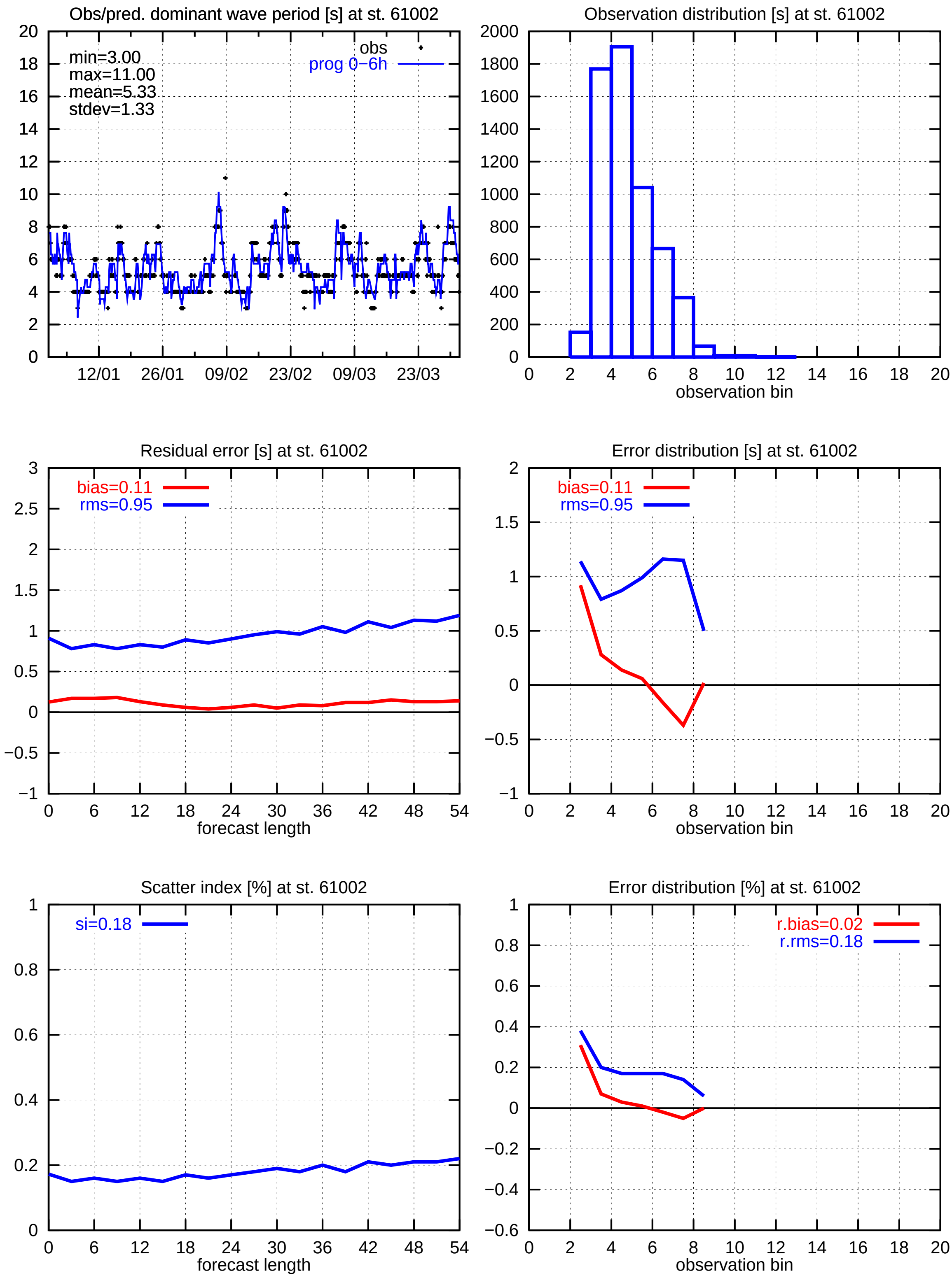

Figure 47. Dominant wave period: 61002

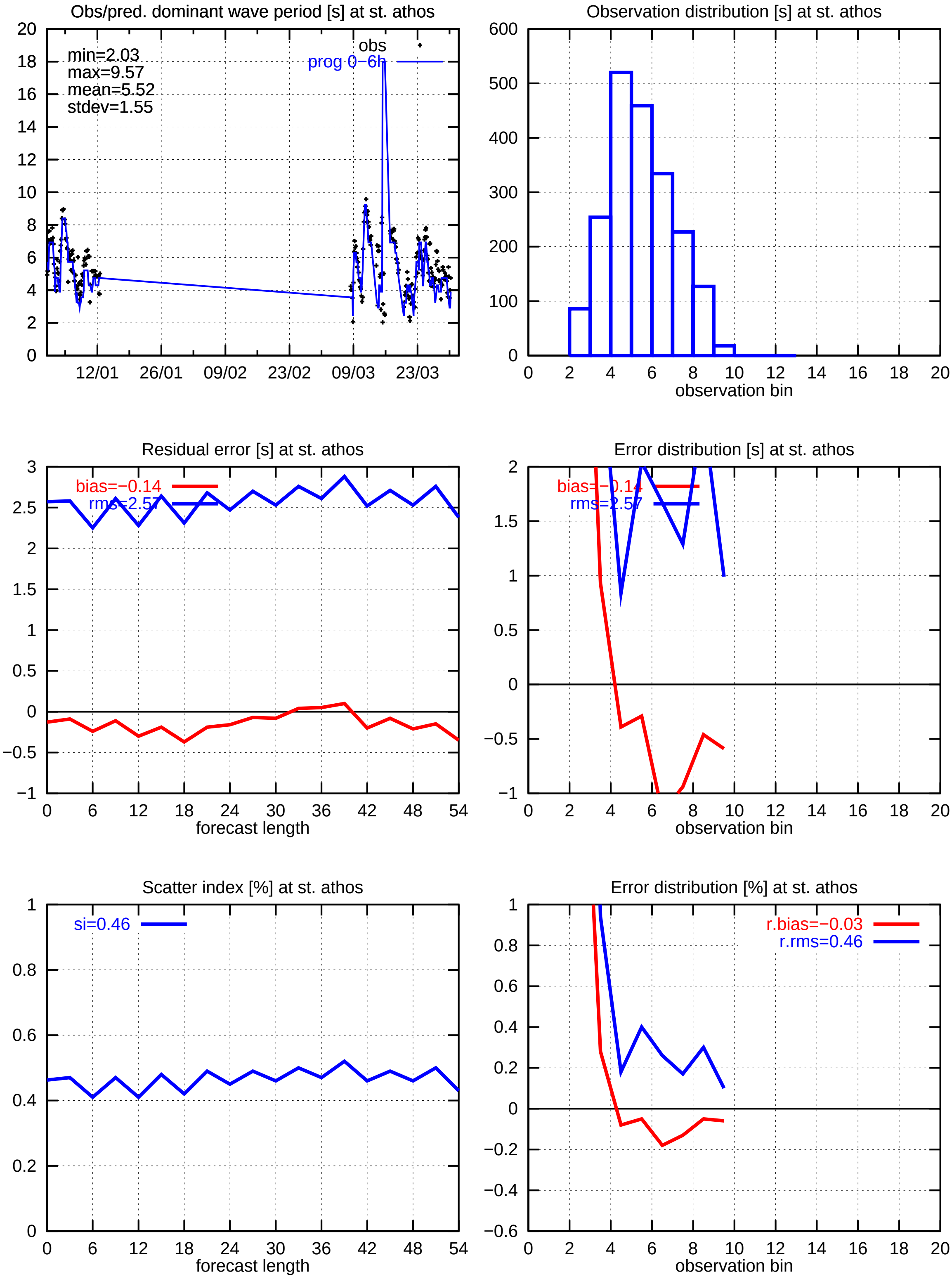

Figure 48. Dominant wave period: Athos

References

[1] G. Komen et al. *Dynamics and Modelling of Ocean Waves.* Cambridge University Press, 1994.

[2] The SWAMP group. *Ocean Wave Modelling*. Plenum Press, New York, 1985.

[3] H. Günther, S. Hasselmann, and P. Janssen. Wamodel cycle4 (revised version). Technical Report 4, Deutches Klimarechnenzentrum, 1992.

[4] J. W. Nielsen, J. B. Jørgensen, and J. She. Verfication of wave forecasts: DMI-WAM nov-dec 2001. Technical Report 02-18, Danmarks Meteorologiske Institut, 2002.

[5] J. She. Hirlam-wam quality assessment on winds and waves in the North Sea. Scientific Report 00-27, Danish Meteorological Institute, 2000. Copenhagen, Denmark.

[6] J. She and J.W. Nielsen. Operational wave forecasts in Baltic and North Sea. Scientific Report 99-07, Danish Meteorological Institute, 1999. Copenhagen, Denmark.

List of Tables

List of Figures