ANALYSIS OF OPTICAL BACK SCATTER DATA OBSERVED BY THE SMART BUOY AT THE STATIONS NOORDWIJK 10, NOORDWIJK 5 AND NOORDWIJK 2

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BACKGROUND

For a period of two years, using moored systems, measurements of waves, currents, silt concentration, chlorophyll and other oceanographic parameters (temperature, salinity, nitrate) were carried out at the sea surface in the North Sea off Noordwijk. For part of this period measurements were carried out also near the sea bottom. All measurements were the result of a collaboration between the Rijks Instituut voor Kust en Zee (RIKZ, NL) and the Centre for Environment, Fisheries and Aquaculture Science (CEFAS, UK). The data is available as hourly and 10-minutes averaged values. The objective of the measurements is to improve the understanding of the role of the different physical (waves and tide) and biological (algal blooms, bioturbation) processes in determining silt concentrations in the coastal zone. Implementation of the improved knowledge in models will allow for better predictions of the effects of human activities on the silt climate and on the ecosystem, and to judge these effects in the perspective of the natural variability.

Emphasis in the present study is on the silt concentrations measured at the sea surface using the Smart Buoy in the stations Noordwijk 10, Noordwijk 5 and Noordwijk 2. In particular attention will be given to the effect of waves and tide on the silt concentration. To extract the tidal components the data will be subject to spectral analysis. Correlation techniques will be applied to determine the effect of wind, waves and tide and to determine the time lags of the various transfer mechanisms

1 SUSPENDED SEDIMENT CONCENTRATION AT NOORDWIJK 10.

1.1 Observations

During the period March 2000 – September 2001, Optical Back Scatter (OBS) data was collected continuously at the station Noordwijk 10. This station is located in the North Sea in a water depth of 18 m, 10 km offshore of the city of Noordwijk. OBS was measured using two Seapoint (http://www.seapoint.com/stm/html) sensors mounted on a Smart Buoy (Mills and Rutgers van der Loeff, 2002). The sensors were located approximately one meter below the water surface. The main OBS sensor measured at 1 Hz for four minutes and rested eight minutes. During these eight minutes the back-up sensor measured at 1 Hz. Using both the main and back-up data one-hour average OBS values were calculated using the data one half hour before and one half hour after the hour. Resulting one-hour values of suspended sediment concentration are stored in file Dep19-mtot.xls

The hourly values of OBS are plotted in Figs 1 through 19 in Mills and Rutgers van der Loeff (2002). As a result of fouling during certain periods of the year, mainly during the summer, the OBS sensors occasionally malfunctioned. Making use of Figs 1 through 19 four periods of continuous observations each longer than one month were selected for possible further analysis. The selected periods, together with the mean and variances of the OBS data, are presented in Table 1.1

Table 1.1

Noordwijk 10. Periods of continuous OBS data with mean and variance for each period

	Time interval (day – month –year – hour)	Mean OBS (ftu)	Variance OBS (ftu^2)
A	10-04-00 20h - 01-06-00 23h	3.86	25.01
B	07-11-00 09h - 14-03-01 23h	6.51	40.60
C	20-03-01 10h - 05-07-01 23h	2.74	14.50
D	21-08-01 10h - 18-09-01 08h	8.48	71.44

The data in Mills and Rutgers van der Loeff (2002) suggest that the larger OBS values occur during periods of higher waves. For example for waves smaller than $H_s = 2$ m, OBS is seldom higher than 10 ftu. An exception with no obvious explanation is the period 13-04-00 – 21-04-00 when Hs < 2 m and OBS reaches values of 25 ftu. In the following the concentration variations for periods of relative calm (Hs < 1 m) and for storm periods will be dealt with separately.

1.2 Sediment concentration during periods of relative calm

The effect of the tide on the sediment concentration will be investigated using the data of six periods for which the significant wave heights are less than 1 m. These periods are summarized in Table 1.2 together with the mean and the variance of the OBS.

Table1.2

Noordwijk 10. Periods of continuous OBS data with Hs< 1 m. mean and variance of OBS

Time interval (day-month-year)	Mean OBS (ftu)	Variance OBS (ftu^2)
20-03-00 0h – 27-03-00 0h	6.41	4.42
19-04-00 0h – 02-05-00 0h	4.52	11.05
12-01-01 0h – 23-01-01 0h	3.96	1.12
09-05-01 0h – 16-05-01 0h	1.65	0.26
30-06-01 0h – 05-07-01 23h	1.30	0.21
24-07-01 10h – 29-07-01 23h	1.47	0.50

For each of the periods a plot of the OBS data together with information on the “tidal strength” is presented in Fig. 1.1 – 1.6. The "tidal strength" is determined by applying a running average of 25 hours to the absolute values of the astronomical tide (i.e. water levels with respect to the mean water level). The resulting time series then is subjected to a 24 hour running average. The "tidal strength" is roughly $2/\pi$ times the tidal amplitude. The "tidal strength" is used to distinguish between periods of spring- and neaptide.

Visual inspection of the plots in Figs 1.1-1.6 shows no clear correlation between the trend in OBS and the “tidal strength” with the possible exception of the data in Fig. 1.3. Here the trend in OBS follows the “tidal strength” with maximum concentrations during springtide and minimum concentrations during neap tide.

In addition to a trend, the OBS shows considerable variation in the tidal period bands. These variations are further investigated by calculating the power spectra (Figs. 1.1 – 1.6). (note: contrary to what is suggested in Bendat and Piersol (1971), in calculating the power spectra no cosine taper window was applied). From the power spectra it follows that most of the energy is concentrated in the 12 and 24 hour period band with a minor contribution in the 6 hour period band. Most likely variations in the 12 and 24 hour period band are the result of along-coast gradients in sediment concentration traveling past the measurement station. The power in the 6 hour period band is associated with the resuspension of sediment during the ebb and flood phase. Similar to the trend, there seems to be little correlation between the magnitude of the OBS variations in the tidal period bands and the “tidal strength”. During three of the periods of relative calm (Figs 1.2, 1.4 and 1.6) maximum variations occur during spring tide and during two periods of calm (Figs 1.3 and 1.5) maximum variations occur during neap tide. No conclusions can be drawn from the remaining period (Fig. 1.1). During the period 12-01-01 to 23-01-01 (Fig.1.3) tidal variations in OBS are negatively correlated with salinity.

1.3 Sediment concentration during storm periods

Here, a storm period is defined as a period in which the maximum wave height $H_s > 3$ m. The storm period begins when $H_s > 1$ m and ends when $H_s < 1$ m. The effect of storms on the sediment concentration is investigated for six storm periods. For each storm period, the maximum significant wave height together with the maximum, mean and variance of the OBS are presented in Table 1.3.

Table 1.3

Noordwijk 10. Maximum significant wave height, maximum, mean and variance of OBS data for different storm periods

Storm	Storm period	Max significant wave height (m)	Max OBS (ftu)	Mean OBS (ftu)	Variance OBS (ftu^2)
A1	26-05-00 12h - 30-05-00 03h	4.46	41.35	10.71	66.31
X1	08-07-00 12h - 13-07-00 12h	3.38	17.58	4.64	11.51
B1	07-12-00 23h - 17-12-00 15h	4.13	34.27	12.92	55.51
C1	16-05-01 15h - 19-05-01 00h	3.61	11.77	4.08	6.46
C2	01-06-01 17h - 08-06-01 06h	3.44	12.40	3.91	4.81
D1	03-09-01 12h - 14-09-01 01h	4.34	42.77	14.75	75.82

For each of the storms a plot of the OBS and the significant wave height versus time is presented in Fig. 1.7. From the different plots in this figure it follows that the trend in OBS follows the trend in the wave heights. To further substantiate this a 25- hour running average is applied to the OBS and wave data, resulting in low pass signals. The corresponding high-pass signals are obtained as the difference between the unfiltered and the low-pass signals. For the different storms the variance of the low-pass and high-pass OBS together with the maximum significant wave height in the 25-hour averaged records are presented in Table 1.4

Table 1.4

Noordwijk 10. Maximum significant wave height (25-hour filtered) and variance of low-pass and high-pass filtered OBS data for different storm periods

Storm	Storm period	Max significant wave height (m)	Variance OBS High pass (ftu^2)	Variance OBS Low pass (ftu^2)
A1	26-05-00 12h – 30-05-00 03h	2.52	22.69	43.62
X1	08-07-00 12h – 13-07-00 12h	2.65	5.34	6.02
B1	07-12-00 23h – 17-12-00 15h	3.33	37.03	11.15
C1	16-05-01 15h – 19-05-01 00h	2.26	2.07	4.84
C2	01-06-01 17h – 08-06-01 06h	2.91	1.57	2.63
D1	03-09-01 12h – 14-09-01 01h	3.58	49.86	19.33

For each storm the low- pass and high- pass filtered OBS data together with the actual data are presented in Fig. 1.8. The low-pass filtered data confirms the earlier conclusion that the trend in OBS follows the trend in significant wave height. Focusing on the high-pass filtered data, we can detect from Fig.1.8 pronounced diurnal and semi-diurnal variations. Most likely the variations in the12 hour band are the result of spatial gradients in the concentration passing by the measurement station. The same explanation could apply to the variations in the 24 hour band . However it seems more likely that in some cases these variations are associated with the growth and decay of the storm; for example see storms A1 and C1.

To further investigate the variations in OBS with period smaller than one day, the power spectral density for the high-pass OBS data for each storm is presented in Fig 1.9. The spectra confirm the presence of variations in the diurnal and semi-diurnal period band (corresponding to a frequency of 0.04 and 0.08 periods/hour). The same as for the periods of relative calm there is little energy in the quarter-diurnal period band (corresponding to a frequency of 0.16 period/hour). This suggests that during storms at Noordwijk 10 the tidal currents play a minor role in the upward mixing of the sediment.

1.4 Time lag between significant wave height and OBS at Noordwijk 10

In section 1.3 it was already observed that OBS and wave height follow the same trend. In this section the relationship between significant wave height and OBS is further investigated. In particular, attention is given to the time lag between wave height and OBS.

Using the low-pass filtered data for each of the five storms listed in Table 1.3, the OBS is plotted versus the significant wave height in Fig.1.10. In the different plots the beginning of a storm is marked with a red star. The different plots clearly show hysteresis whereby for the same significant wave height the OBS is lower for increasing storm activity than for decreasing storm activity. The OBS lags the wave height. This is also confirmed by the plots in Fig. 1.11 where for each storm the low-pass filtered OBS and wave height data are plotted versus time. To estimate the time lag, the low-pass OBS and wave data after removing the mean are presented in Fig.1.12. From this the time lag is estimated to vary between 5 and 10 hours.

To more accurately determine the value of the time lag corresponding to a maximum in correlation, for each storm the correlation function

$$cf = S_{xy}(\tau)/\sqrt{(S_{xx}(0)S_{yy}(0))}$$

is calculated. In this equation τ is the time lag, S_{xy} is the covariance of the significant wave height and the OBS, S_{xx} is the autocovariance of the significant wave height and S_{yy} is the autocovariance of the OBS. The value of the correlation function is a measure for how much of the variation in the OBS can be explained by the variation in significant wave height.

The correlation functions are is calculated using the actual and low-pass filtered data. The results are presented in respectively Figs 1.13 and 1.14. Maximum values of *cf* and the corresponding lag τ (τ is positive when the waves lead OBS) are presented in Table 1.5.

Table 1.5

Noordwijk 10. Time lag corresponding to the maximum value of the correlation function of OBS and significant wave height for different storm periods.

Storm	Storm period	Maximum cf (low-pass)	τ corresponding to maximum in cf (hours) (low-pass)	Maximum cf (actual)	τ corresponding to maximum in cf (hours) (actual)
A1	26-05-00 12h – 30-05-00 03h	0.61	0	0.73	0
X1	08-07-00 12h – 13-07-00 12h	0.96	7	0.75	7
B1	07-12-00 23h – 17-12-00 15h	0.88	6	0.74	3
C1	16-05-01 15h – 19-05-01 00h	0.59	6	0.79	4
C2	01-06-01 17h – 08-06-01 06h	0.76	10	0.56	7
D1	03-09-01 12h – 14-09-01 01h	0.78	15	0.66	8

Values of the time lag in the last columns 4 and 5 of Table 1.5 reasonably agree with the earlier estimates of 5-10 hours based on visual inspection of the plots in Fig. 1.12. Time lags for maximum correlation are somewhat higher for the low-passed filtered data than for the actual data (compare columns 4 and 6 in Table 1.5). On the average values of the correlation functions are somewhat lower for the actual than for the low-pass filtered data.

20-03-00 0h – 27-03-00 0h

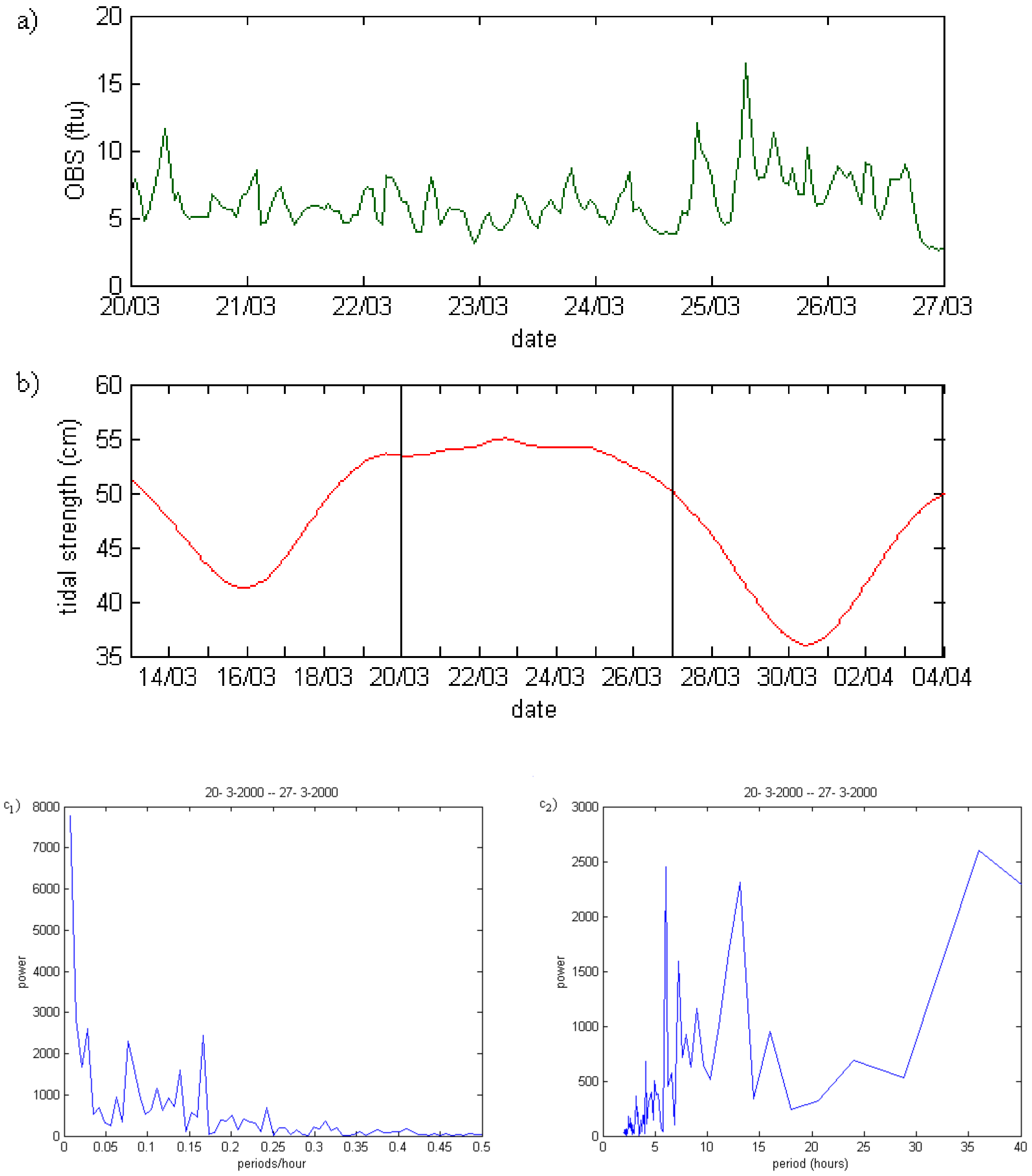


Figure 1.1: Noordwijk 10. Period of relative calm 20-03-00 0h – 27-03-00 0h. a) OBS, b) “tidal strength”, c) power spectra OBS.

19-04-00 0h – 02-05-00 0h

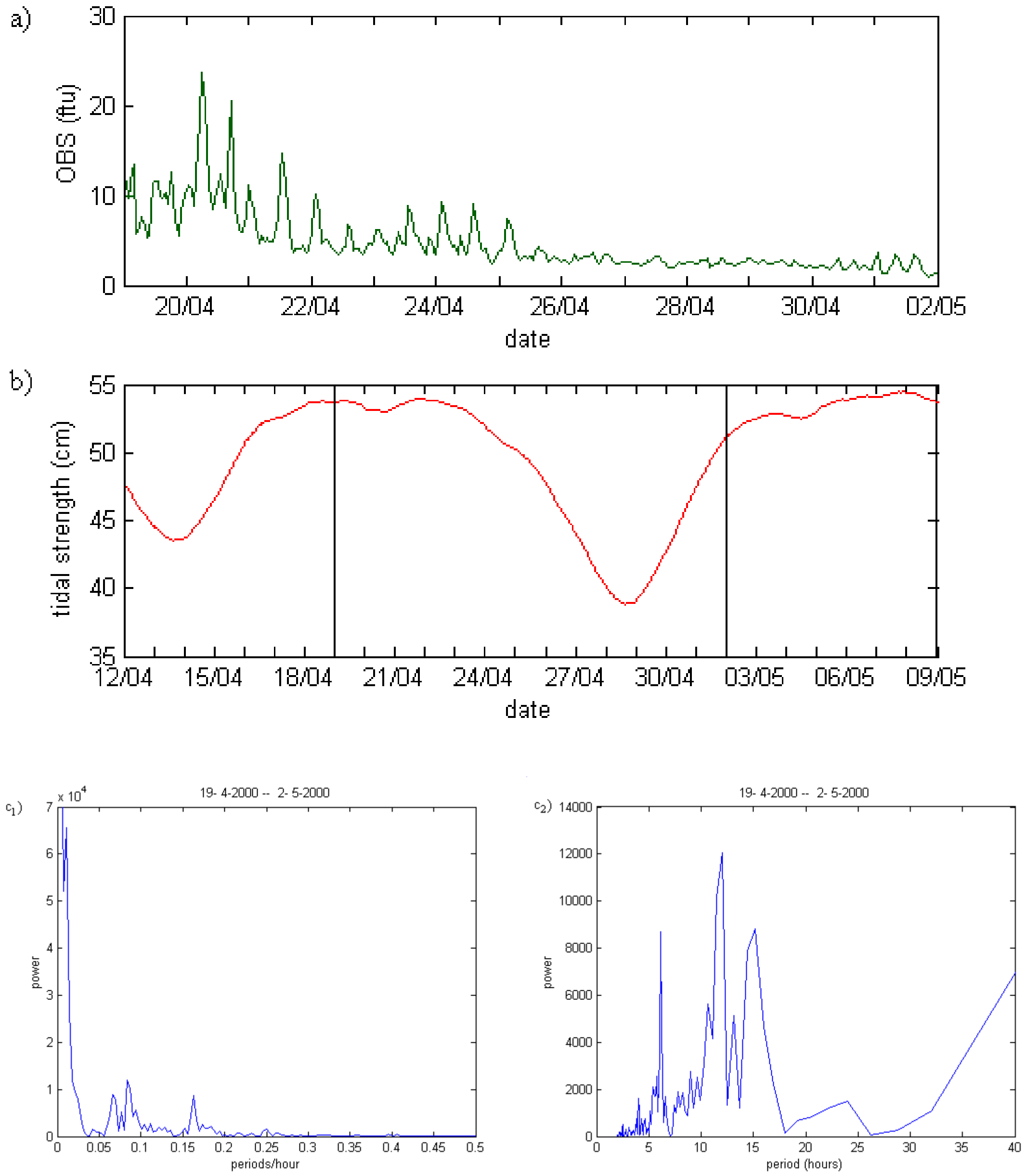


Figure 1.2: Noordwijk 10. Period of relative calm 19-04-00 0h – 02-05-00 0h. a) OBS, b) “tidal strength”, c) power spectra OBS.

12-01-01 0h – 23-01-01 0h

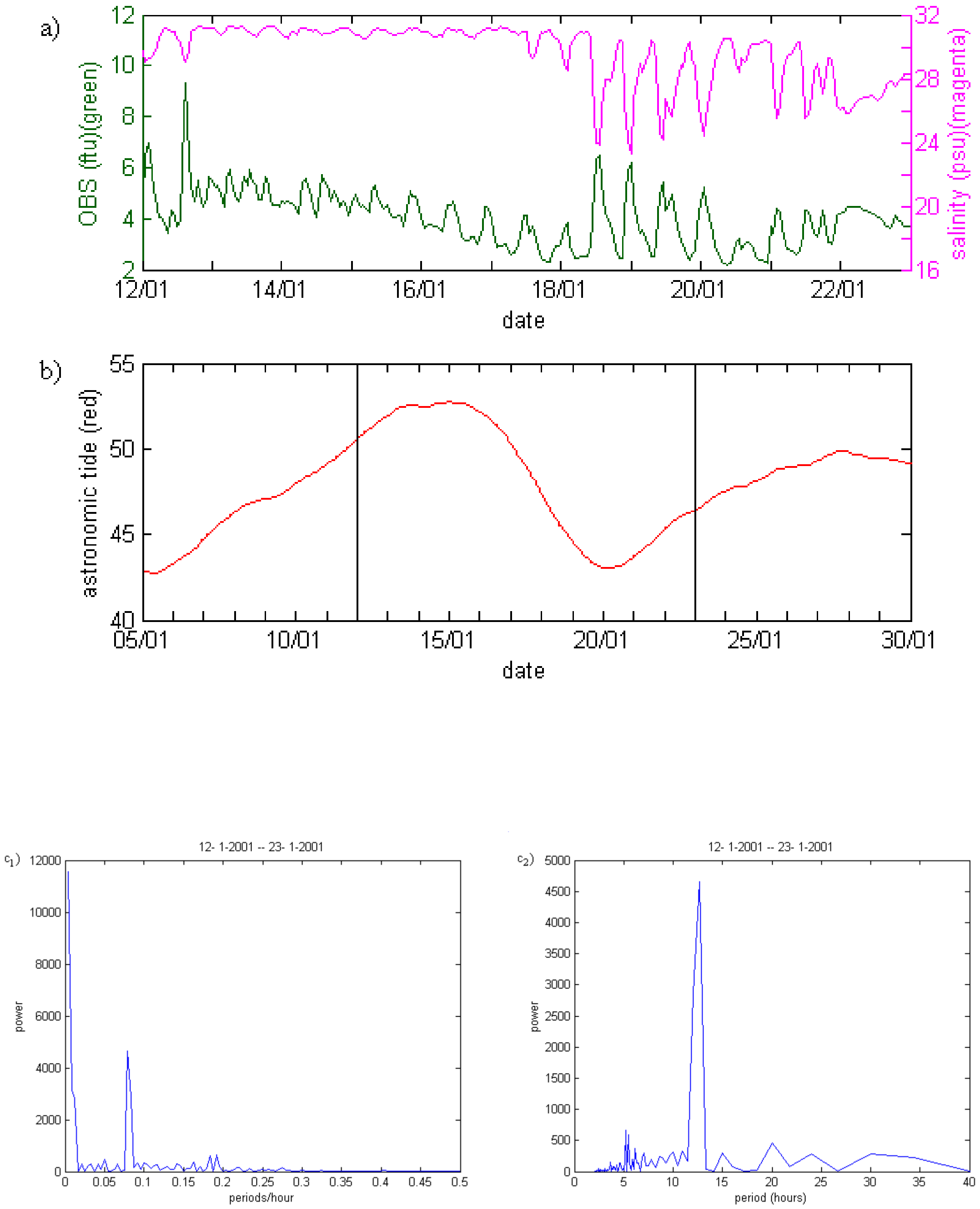


Figure 1.3: Noordwijk 10. Period of relative calm 12-01-01 0h – 23-01-00 0h. a) OBS and salinity, b) "tidal strength", c) power spectra OBS.

09-05-01 0h – 16-05-01 0h

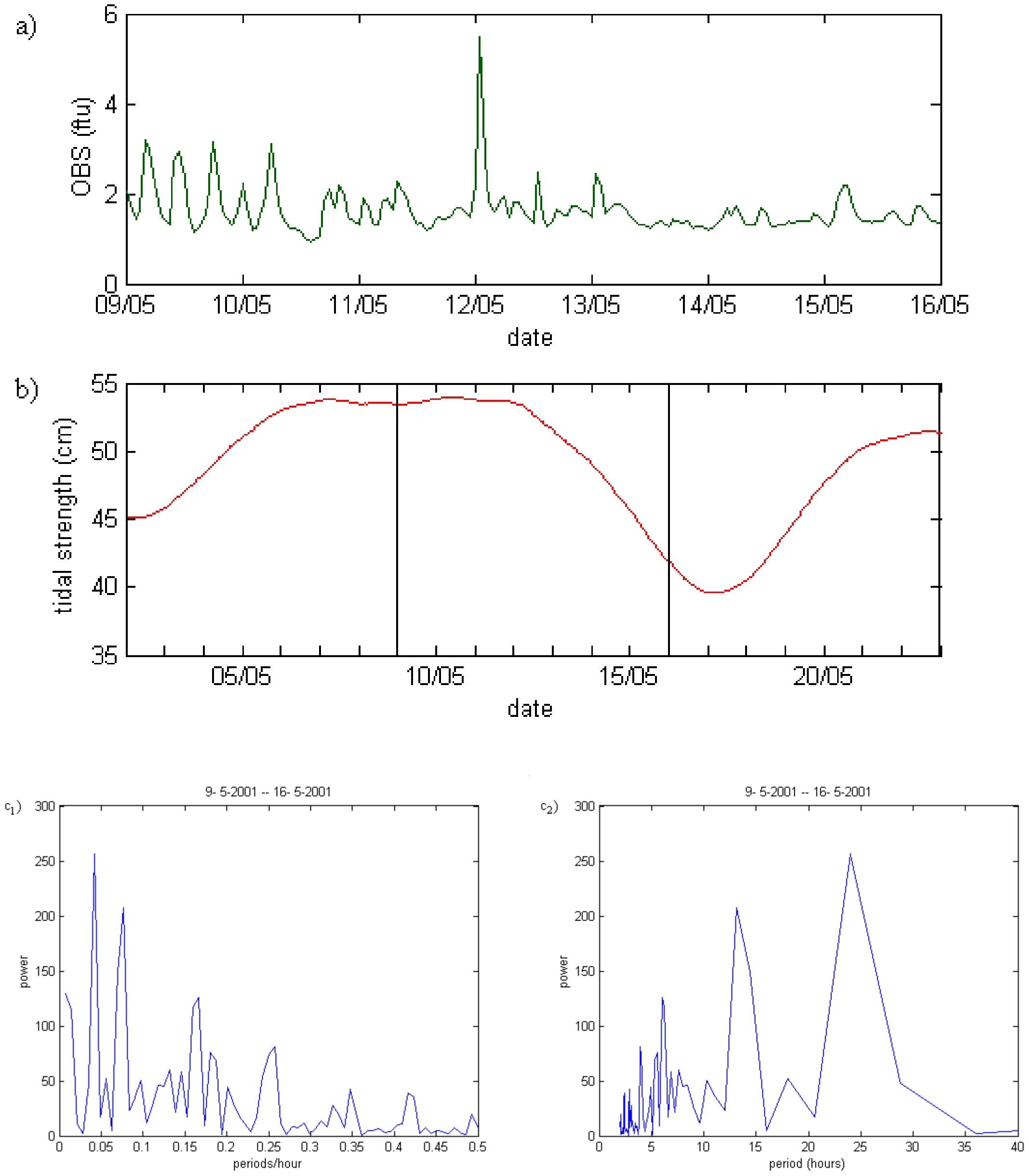


Figure 1.4: Noordwijk 10. Period of relative calm 09-05-01 0h – 16-05-01 0h. a) OBS, b) “tidal strength”, c) power spectra OBS.

30-06-01 0h – 05-07-01 23h

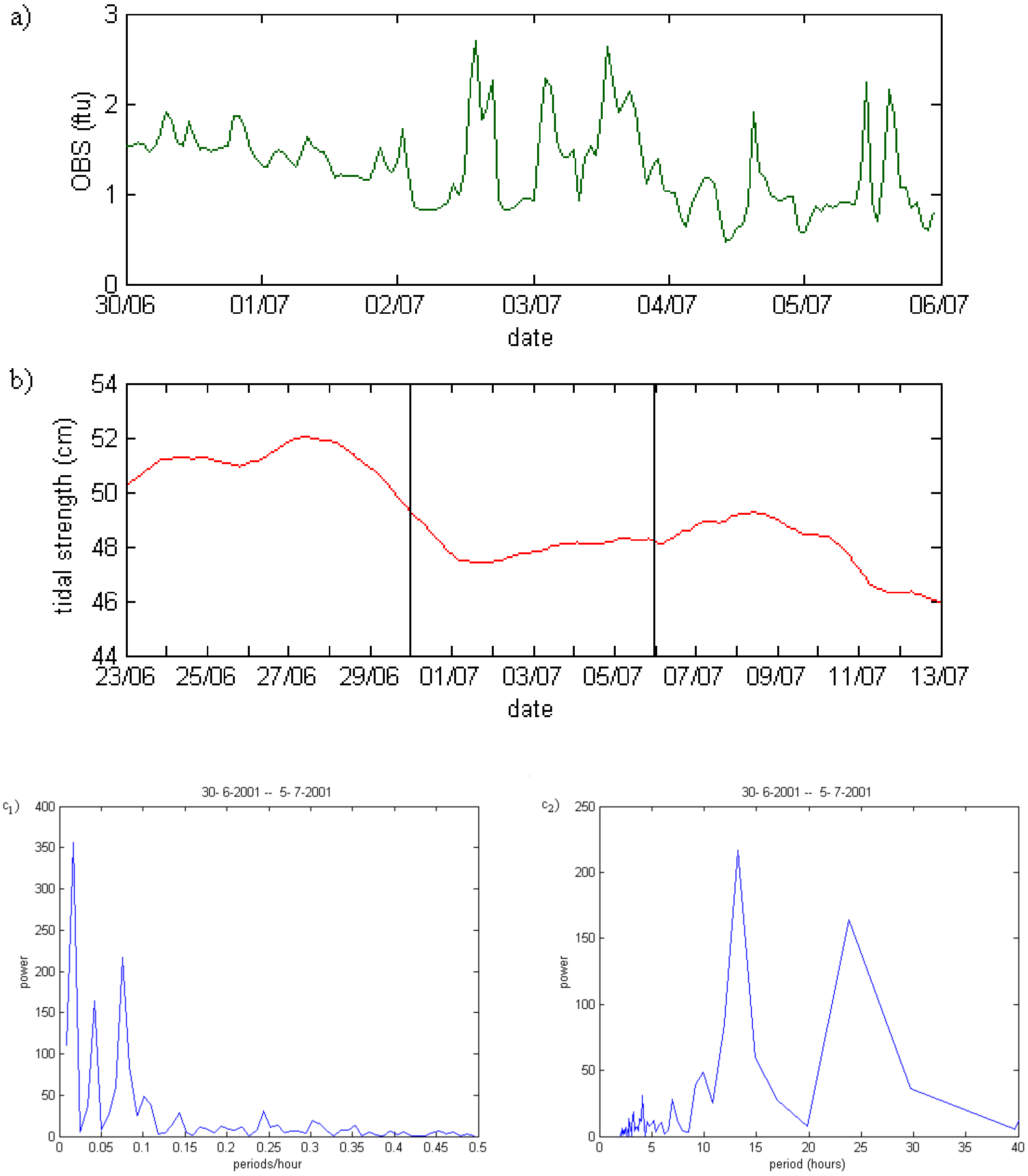


Figure 1.5: Noordwijk 10. Period of relative calm 30-06-01 0h – 05-07-01 23h. a) OBS, b) “tidal strength”, c) power spectra OBS.

24-07-01 10h – 29-07-01 23h

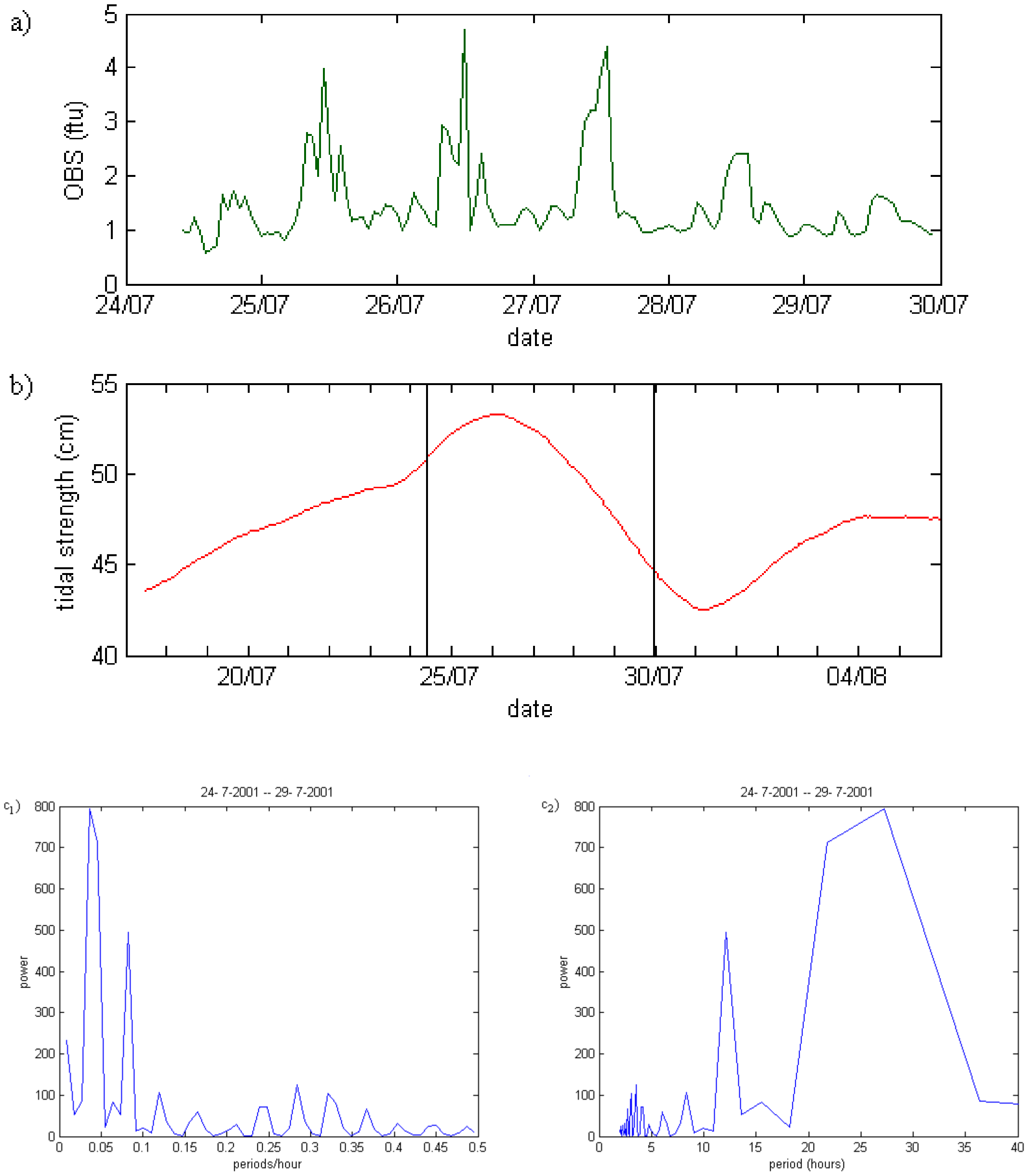
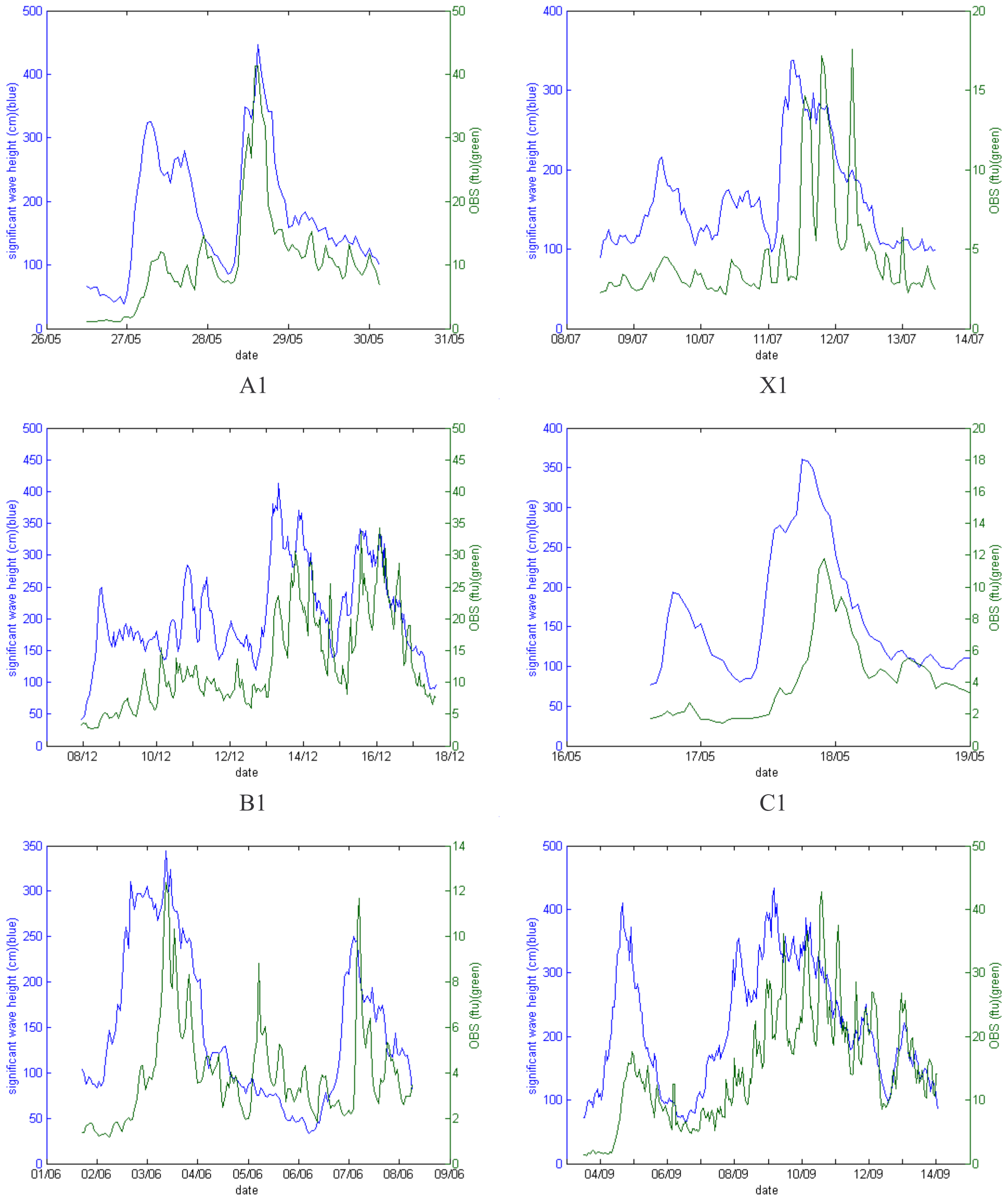


Figure 1.6: Noordwijk 10. Period of relative calm 24-07-01 10h – 29-07-01 23h. a) OBS, b) “tidal strength”, c) power spectra OBS.

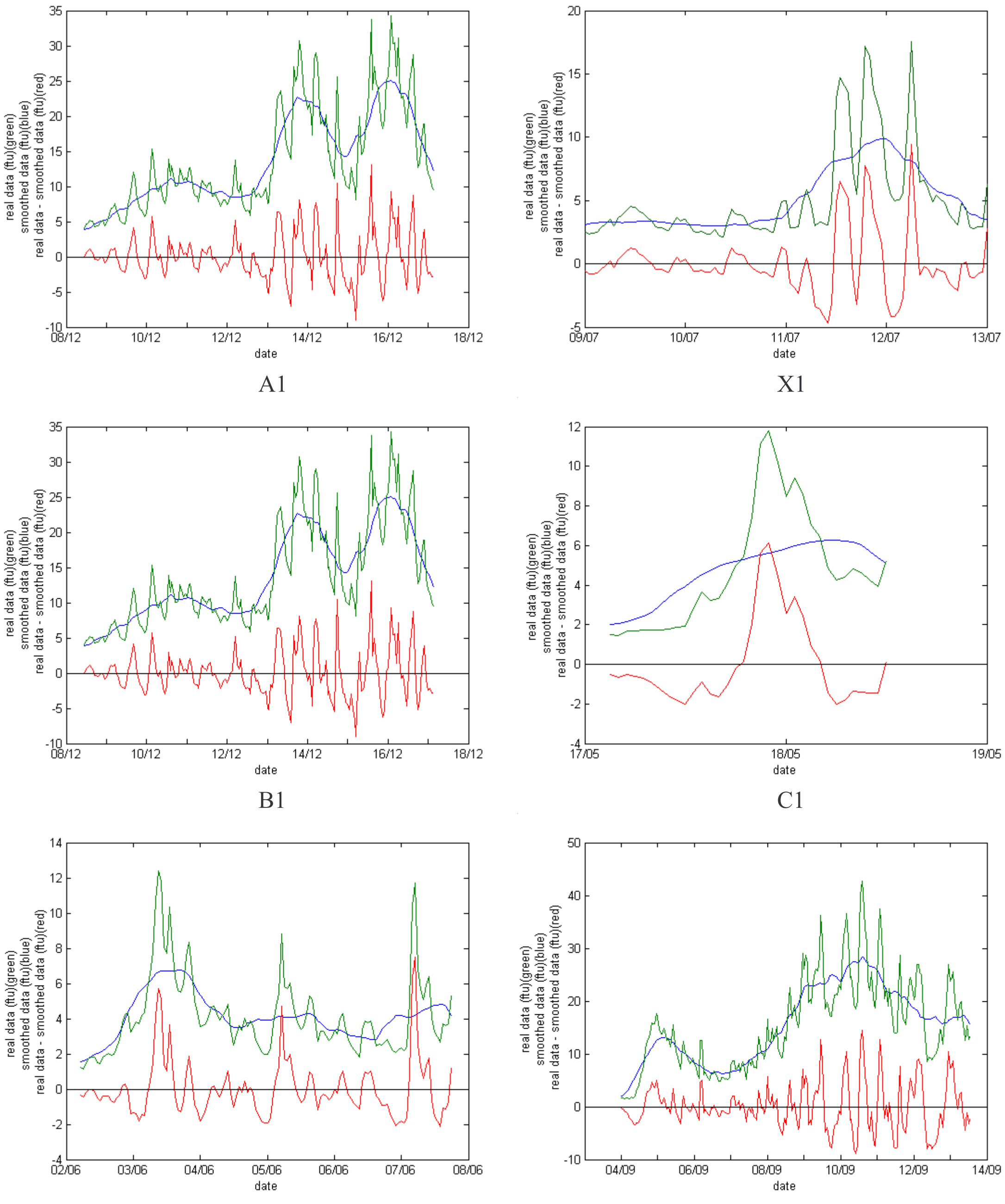


A1 X1

B1 C1

C2 D1

Figure 1.7: Noordwijk 10. Hourly values of OBS and significant wave height for different storm periods

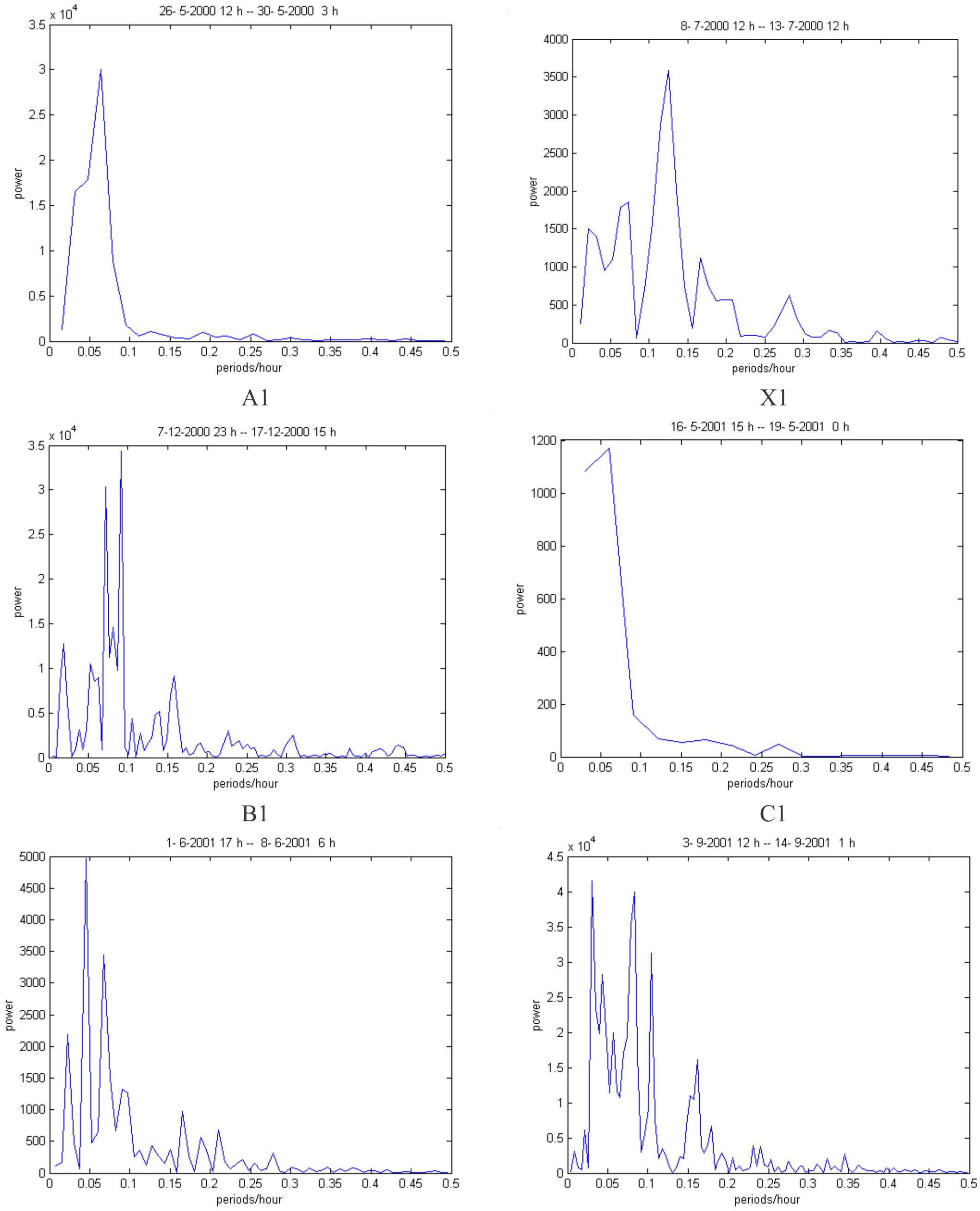


A1 X1

B1 C1

C2 D1

Figure 1.8: Noordwijk 10. Actual, 25 hour low-pass and 25 hour high-pass filtered OBS data for different storm periods.

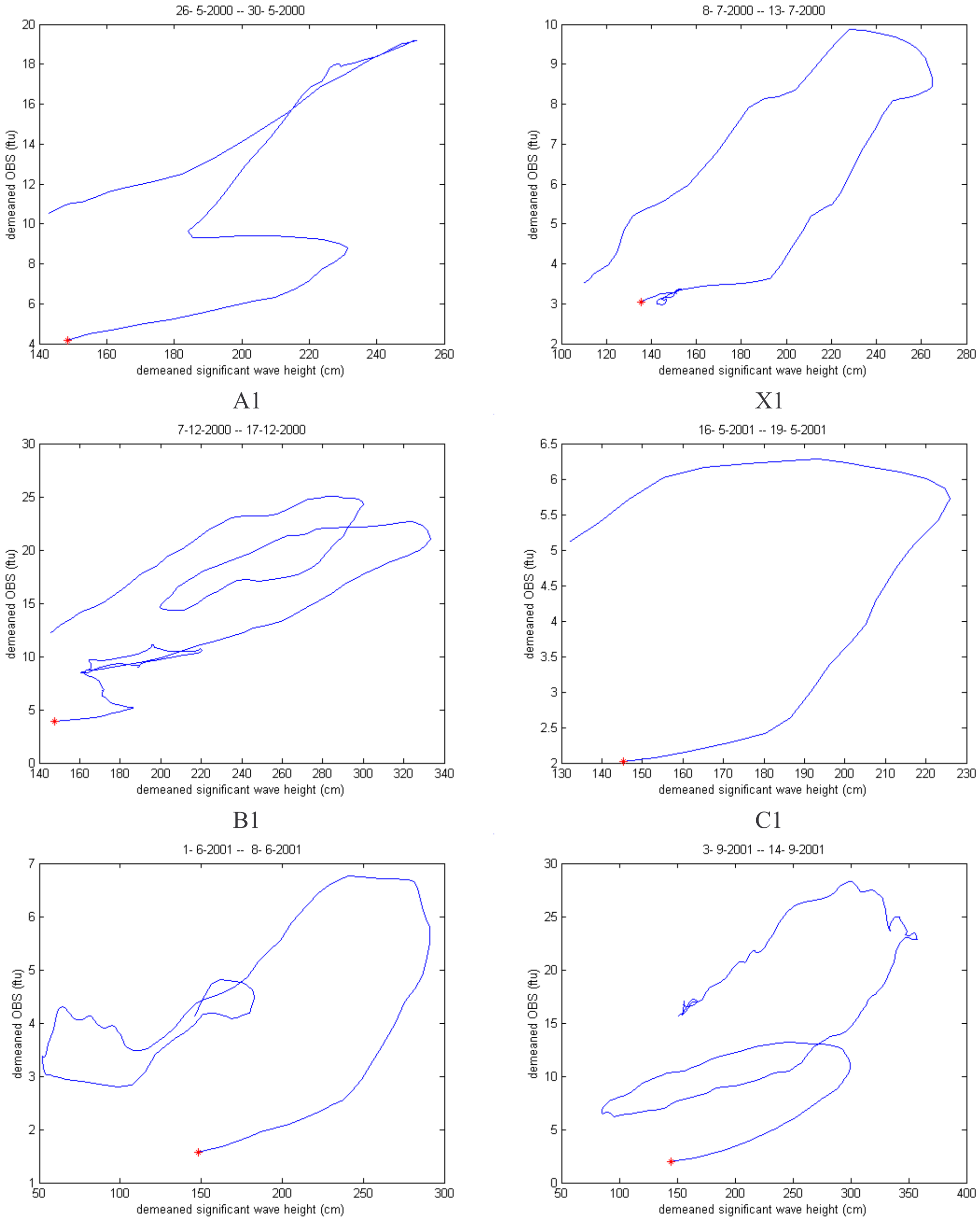


A1 X1

B1 C1

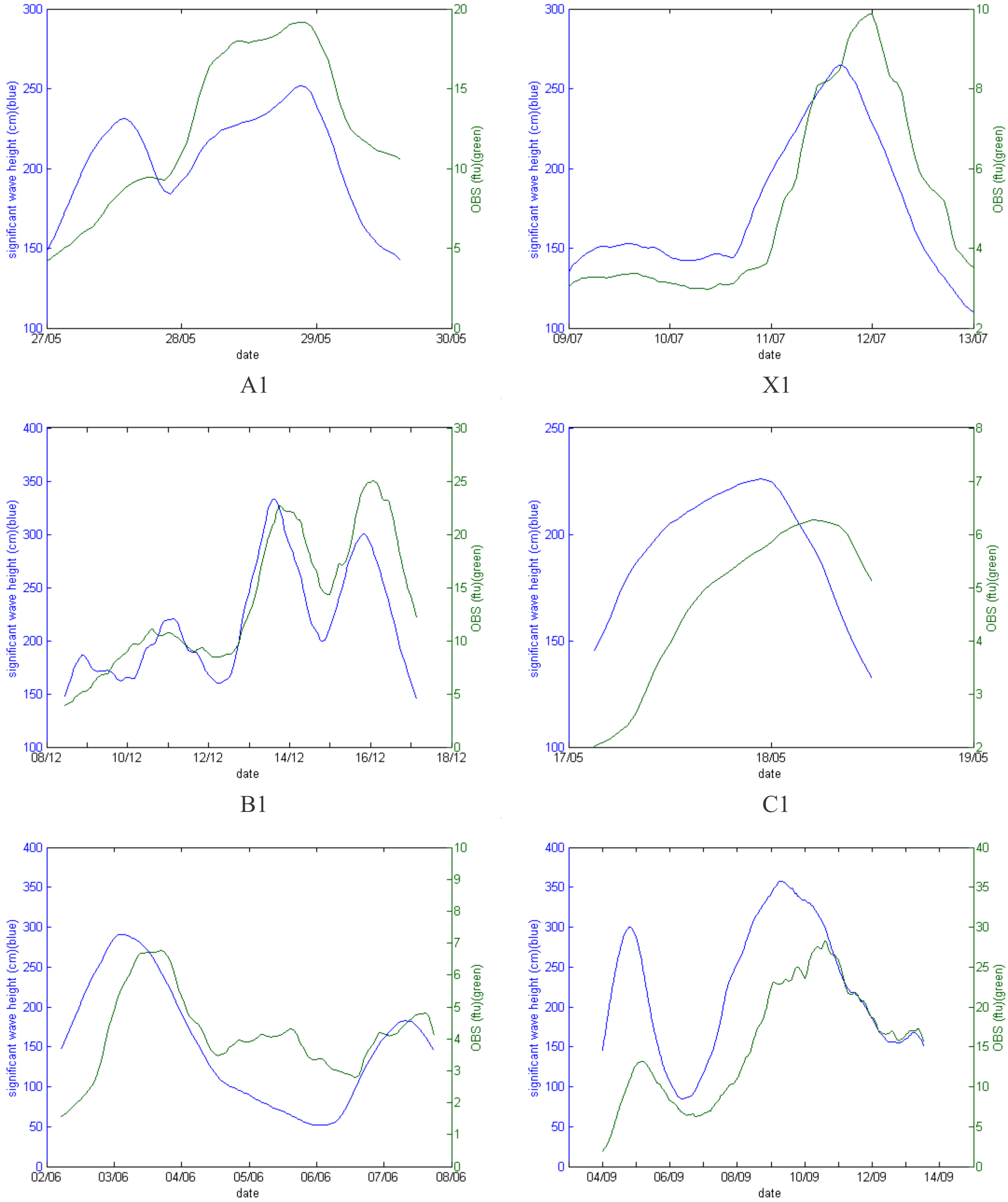
C2 D1

Figure 1.9: Noordwijk 10. Power spectral density for 25 hour high-pass filtered OBS data for different storm periods.



A1 X1 B1 C1 C2 D1

Figure 1.10: Noordwijk 10. OBS data versus significant wave height for different storm periods.



A1

X1

B1

C1

C2

D1

Figure 1.11: Noordwijk 10. Low- pass OBS data and low-pass significant wave height for different storm periods

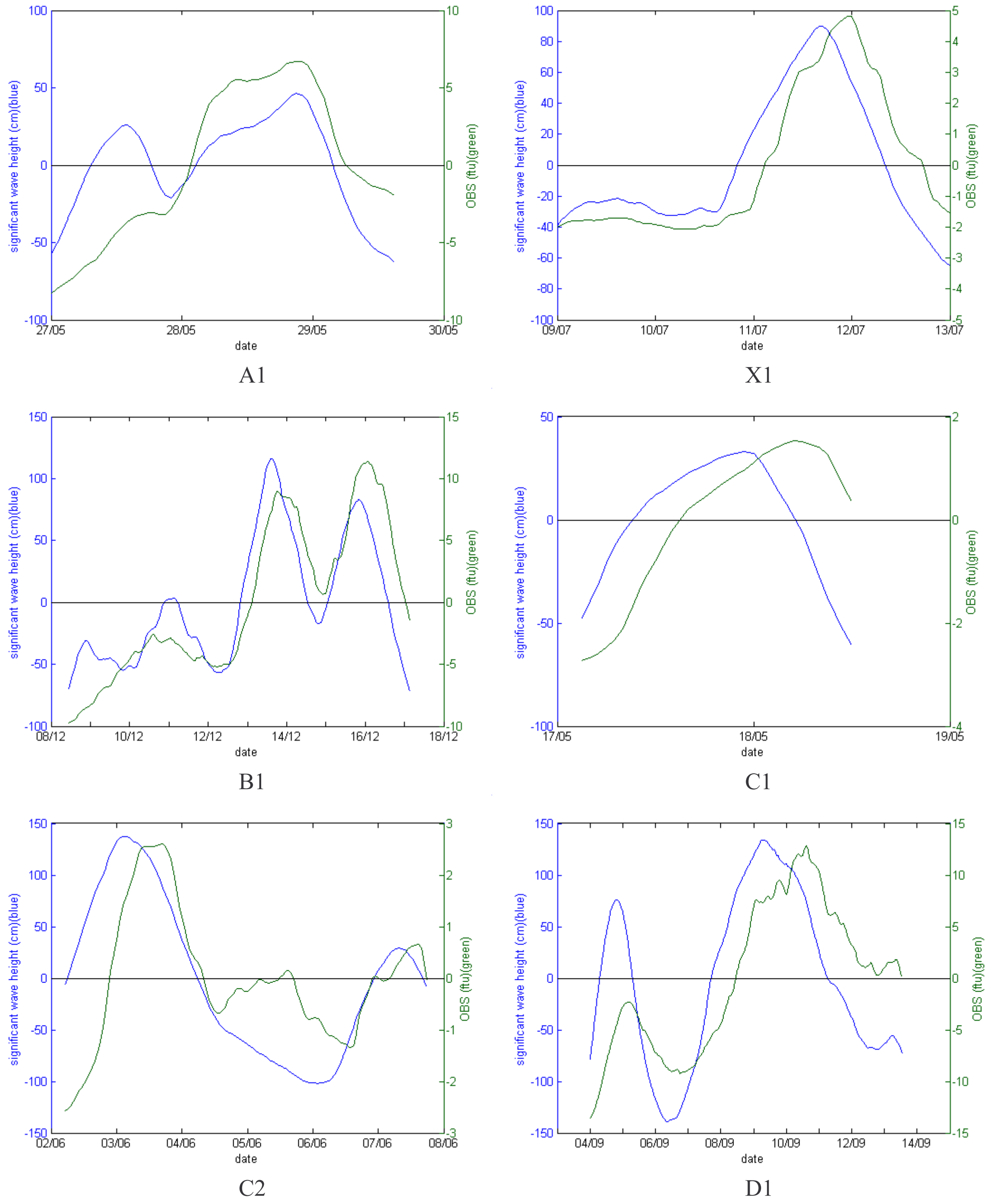
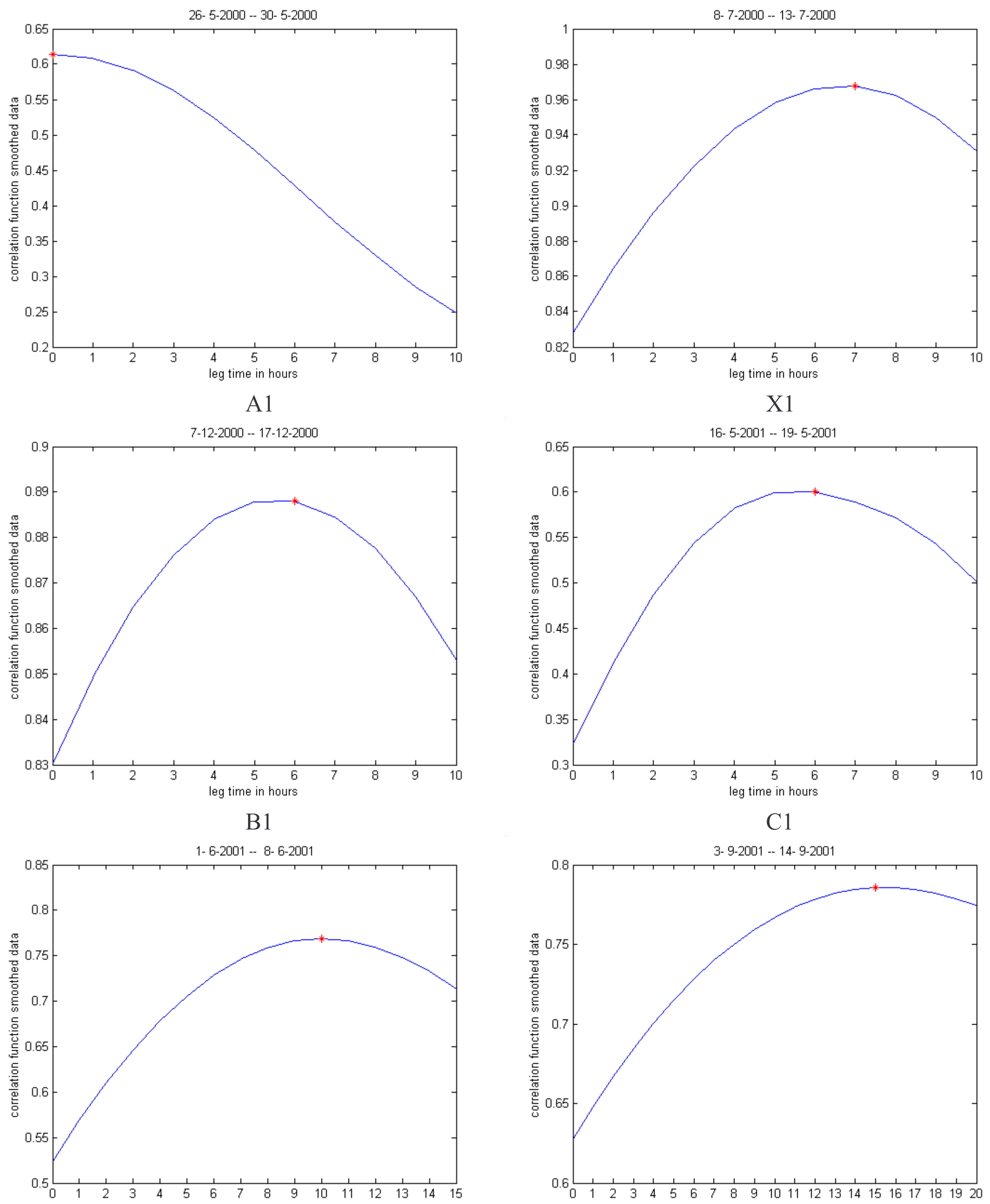
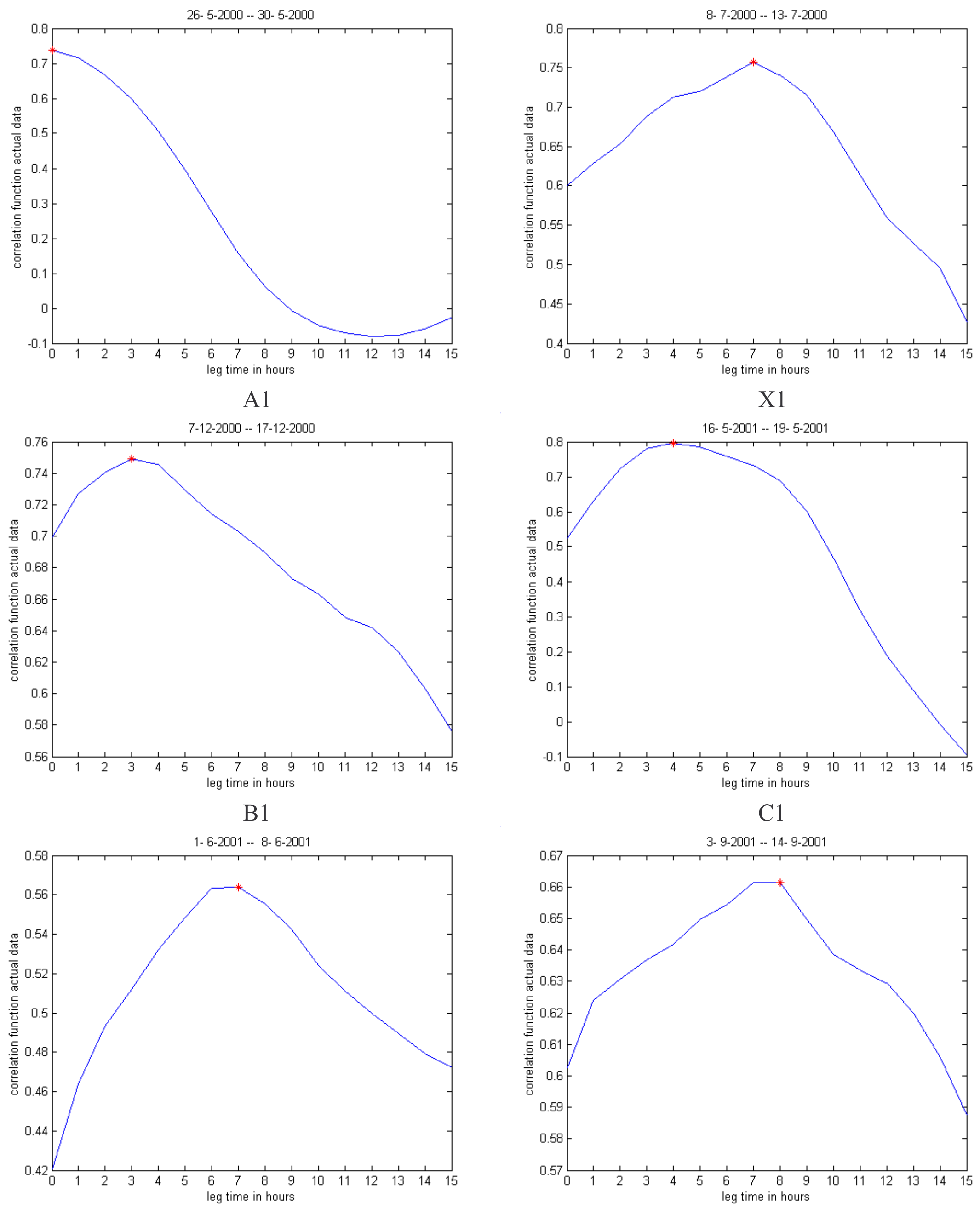


Figure 1.12: Noordwijk 10. Low-pass OBS data and low-pass significant wave height for different storm periods after removing the mean over the time series. For mean OBS values see Table 1.3



A1 X1 B1 C1 C2 D1

Figure 1.13: Noordwijk 10. Correlation function for OBS and significant wave height for different time lags (low-pass filtered data)



A1 X1

B1 C1

C2 D1

Figure 1.14: Noordwijk 10. Correlation function for OBS and significant wave height for different time lags (actual data)

2 SUSPENDED SEDIMENT CONCENTRATION AT NOORDWIJK 5.

2.1 Observations

In the period 05-03-'02 – 22-04-'02 OBS was measured at station Noordwijk 5 using the SmartBuoy. The sensors were located at approximately 1 m below the surface. Noordwijk 5 is located 5 km offshore of Noordwijk at a water depth of 18 m. The hourly OBS data are plotted in Figs 24 and 25 in Mills and Rutgers van der Loeff(2002). The mean and variance of the OBS data for the approximately 48 day period are respectively 5.63 ftu and 23.68 ftu^2.

Similar to Noordwijk 10 the larger OBS values are associated with storms. During periods of little wave action it is obvious that also tidal variations in the OBS are present. To investigate the effects of tides and storms on the OBS, concentrations during periods of relative calm and storm periods will be dealt with separately. For the definitions of periods of relative calm and storm periods see 1.3.

2.2 Sediment concentration during periods of relative calm

The effect of the tide on the sediment concentration is investigated using the OBS data for the period 24-03-02 to 05-04-02. for this period the significant wave height is less than 1 m. The mean and variance of the OBS data are respectively 3.41 ftu and 1.62 ftu^2.

The OBS data together with the data on "tidal strength" is presented in Fig. 2.1. For definition of "tidal strength" see 1.2. Visual inspection shows little correlation between OBS and "tidal strength". OBS shows considerable variation in the tidal period bands. This is further investigated using the power spectrum of the OBS (Fig. 2.1). From the power spectrum it follows that in the tidal period band significant energy is present in the 6 and 12 hour period band. There is little energy in the 24-hour period band. The 6 hour fluctuations are attributed to resuspension of sediment during the ebb and flood phase. Variations with a period of 12 hours are attributed to along-coast gradients in the sediment concentration passing by the measurement station. Similar to Noordwijk 10 there is no clear indication that OBS variations with periods smaller than 25 hours are stronger during spring than neap tide or vise versa.

2.3 Sediment concentration during storm periods

Within the measurement period two storms can be identified. The storm periods together with maximum significant wave height, maximum, mean and variance of OBS are presented in Table 2.1

Table 2.1

Noordwijk 5. Maximum significant wave height, maximum, mean and variance of OBS data for different storm periods

Storm	Storm Period	Max significant wave height (m)	Max OBS (ftu)	Mean OBS (ftu)	Variance OBS (ftu^2)
i	05-03-02 18h – 11-03-02 13h	4.84	35.85	14.80	37.48
ii	18-03-02 04h – 20-03-02 18h	3.40	15.64	6.34	4.58

For each storm a plot of OBS and significant wave height versus time is presented in Fig. 2.2. From this figure it can be seen that in general the trend in OBS closely follows the trend in significant wave height. To further substantiate this and to separate the storm and tide related fluctuations in OBS, a 25-hour running average is applied to the OBS and wave data. For the two storms the variance of the low–pass and high-pass filtered OBS, together with the maximum wave height in the 25-hour averaged wave records is presented in Table 2.2

Table 2.2

Noordwijk 5. Maximum significant wave height (25-hour filtered) and variance of low-pass and high-pass filtered OBS data for different storm periods

Storm	Storm Period	Max significant wave height (m)	Variance OBS High pass (ftu^2)	Variance OBS Low pass (ftu^2)
I	05-03-02 18h – 11-03-02 13h	2.49	18.03	15.87
Ii	18-03-02 04h – 20-03-02 18h	2.01	3.59	0.50

For each storm the low- pass and high- pass filtered OBS data together with the actual data are presented in Fig. 2.3. The low-pass filtered data confirms the earlier conclusion that the trend in OBS follows the trend in significant wave height.. Focusing on the high pass filtered data, in storm (i) there are clearly variations with a period of 24 hours . The dominant period of the fluctuations in storm (ii) is less clear.

To further investigate the variations in OBS with periods smaller than one day, the power spectral density for the high-pass OBS data for each storm is presented in Fig 2.4. In storm (i) there is a clear presence of energy in the 24-hour period band but also in the 12 –hour period band. There is no clear indication of energy in the 6-hour period band. In storm (ii) there is little energy in any of the tidal period bands. In this storm variations in OBS with periods smaller than one day are most likely dominated by corresponding variations in significant wave height.
Time lag between significant wave height and OBS at Noordwijk 5

In section 2.3 it was already observed that OBS and wave height follow the same trend.

In this section the relationship between significant wave height and OBS is further investigated. In particular, attention is given to the time lag between wave height and OBS.

Using the low-pass filtered data for each of the two storms listed in Table 2.1, the OBS is plotted versus the significant wave height in Fig.2.5. In the two plots the beginning of a storm is marked with a red star. The plots clearly show hysteresis whereby for the same significant wave height the OBS is lower for increasing storm activity than for decreasing storm activity. The OBS lags the wave height. This is also confirmed by the plots in Fig. 2.6 where for each storm the low-pass filtered OBS and wave height data are plotted versus time. To estimate the time lag, the low-pass OBS and wave data after removing the mean are presented in Fig.2.7. From this the time lag is estimated to vary between 5 and 10 hours.

To more accurately determine the values of the time lags corresponding to a maximum in correlation, the correlation function as defined in 1.4 is calculated. Calculations are carried out using the actual and low-pass filtered data. The results are presented in respectively Figs 2.8 and 2.9. Maximum values of *cf* and the corresponding lag τ (τ is positive when the waves lead OBS) are presented in Table 2.3

Table 2.3

Noordwijk 5. Time lag corresponding to the maximum value of the correlation function of OBS and significant wave height for different storm periods.

Storm	Storm period	Maximum cf (low-pass)	τ corresponding to maximum in cf (hours) (low-pass)	Maximum cf (actual)	τ corresponding to maximum in cf (hours) (actual)
i	05-03-02 18h – 11-03-02 13h	0.80	9	0.45	9
ii	18-03-02 04h – 20-03-02 18h	0.82	6	0.44	0

Except for the value for storm (ii) in column 6, values of the time lag in Table 2.3 reasonably agree with the earlier estimate of 5-10 hours based on visual inspection of the plots in Fig. 2.7. The anomalous value for storm (ii) using unfiltered data most likely is the result of the short duration of this storm which does not allow for an accurate determination of cf. Overall, time lags for Noordwijk 5 are similar to those for Noordwijk 10. When using low-pass filtered data the values of the correlation functions corresponding to maximum correlation are of the same order as those for Noordwijk 10. When using actual data values are lower than for Noordwijk 10. There is no obvious explanation for this.

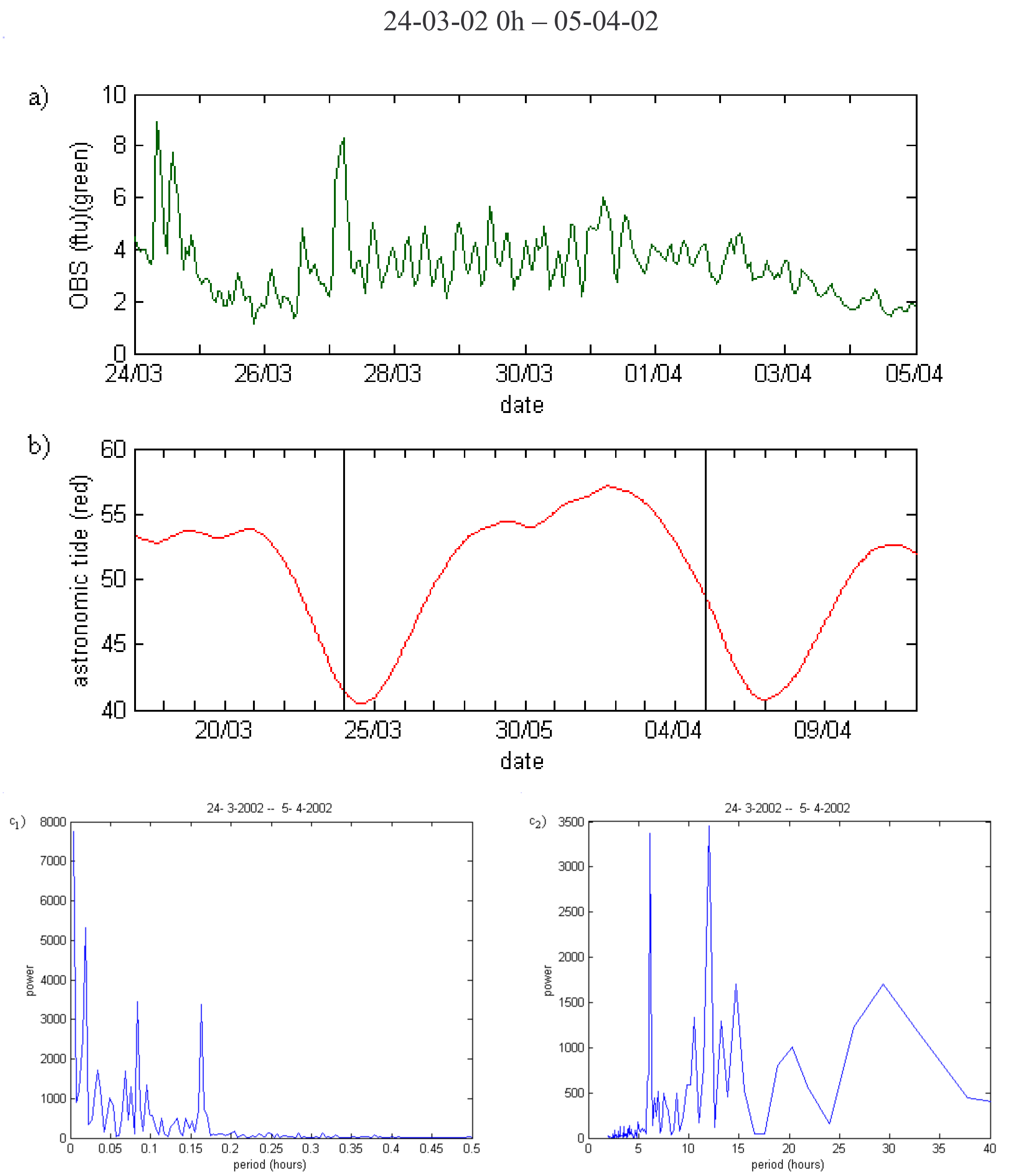
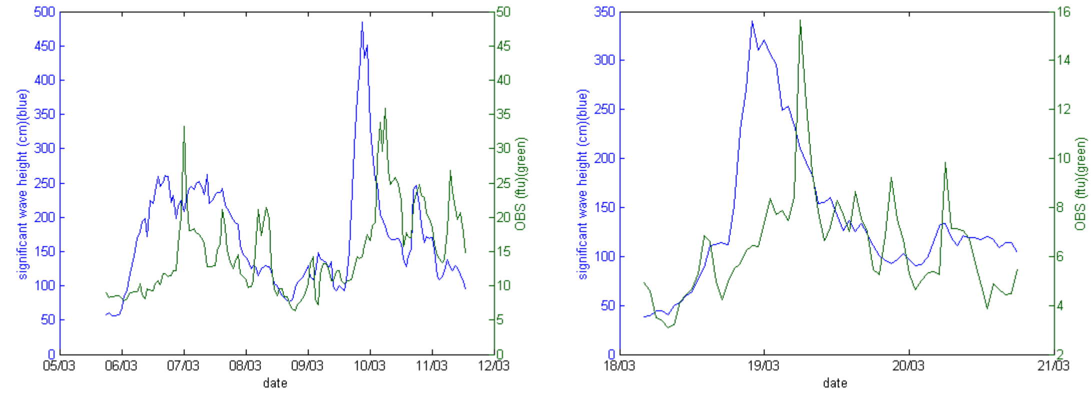


Figure 2.1: Noordwijk 5. Period of relative calm 24-03-02 0h – 05-04-02 0h. a) OBS, b) “tidal strength”, c) power spectra OBS.



i ii

Figure 2.2: Noordwijk 5. Hourly values of OBS and significant wave height for different storm periods

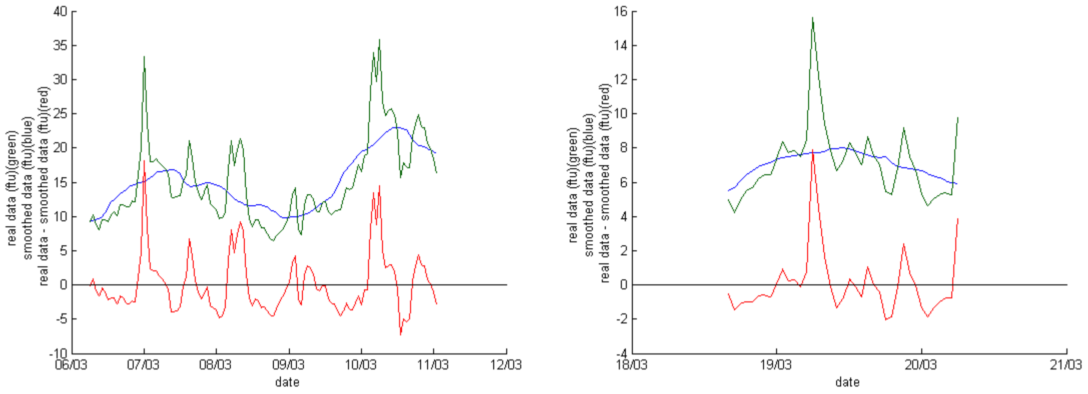


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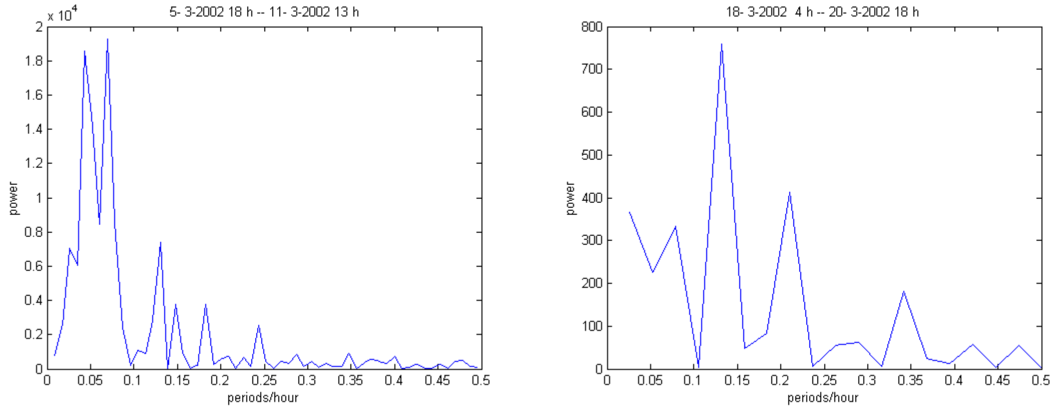
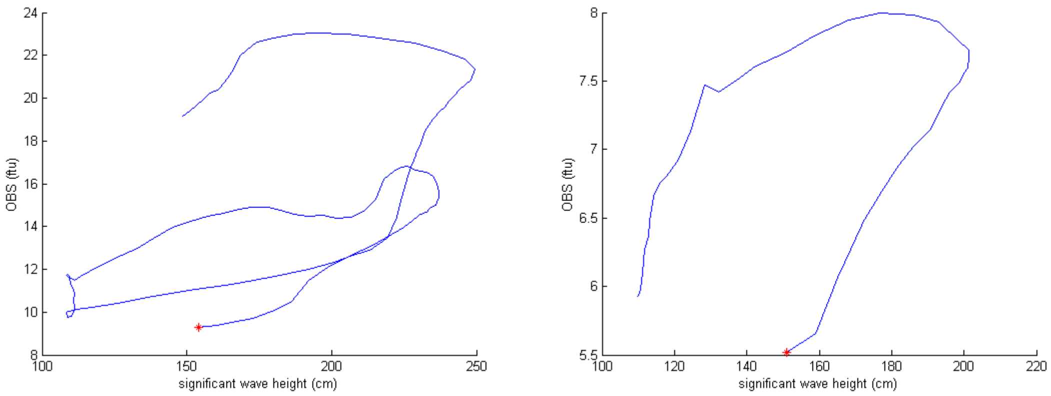
Figure 2.3: Noordwijk 5. Actual, 25- hour low-pass and 25- hour high-pass filtered OBS data for different storm periods



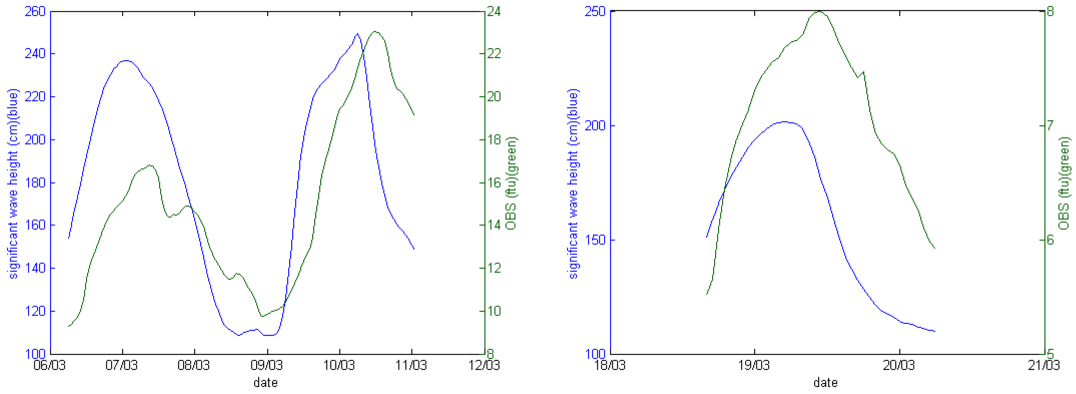
i ii

Figure 2.4: Noordwijk 5. Power spectral density for 25- hour high-pass filtered OBS data for different storm periods



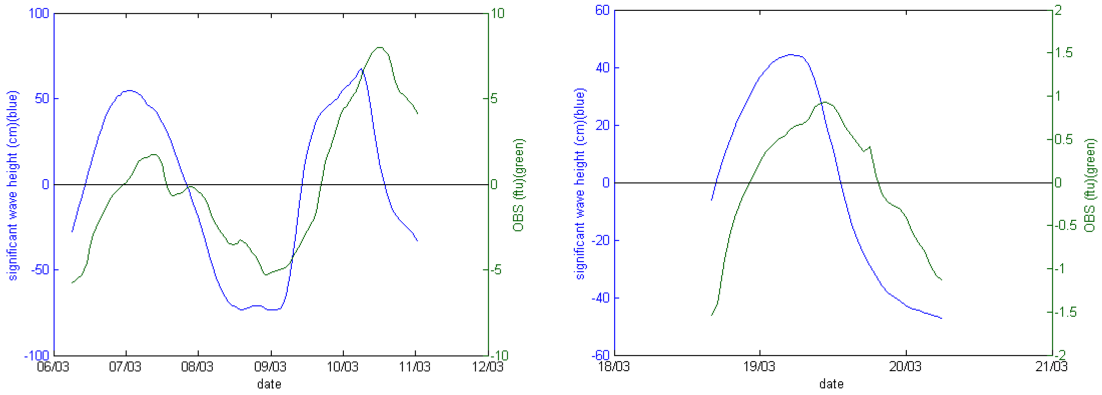
i ii

Figure 2.5: Noordwijk 5. OBS data versus significant wave height for different storm periods.



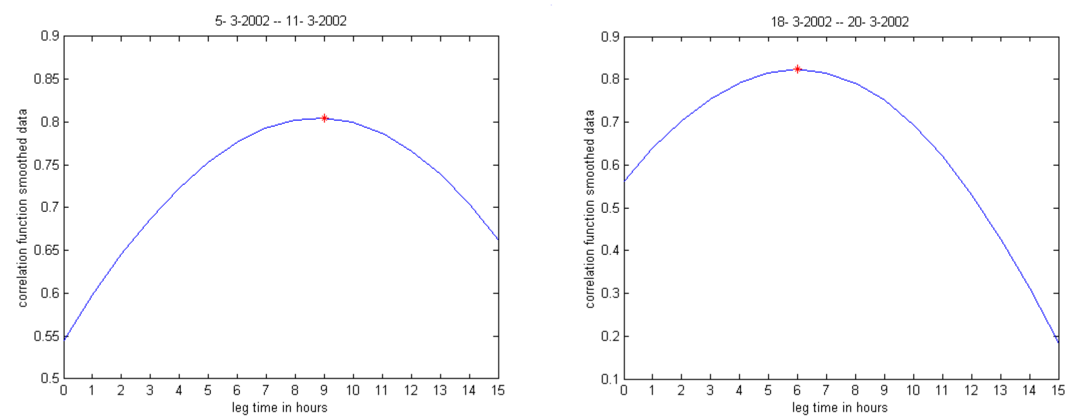
i ii

Figure 2.6: Noordwijk 5. Low-pass OBS and low-pass significant wave height for different storm periods



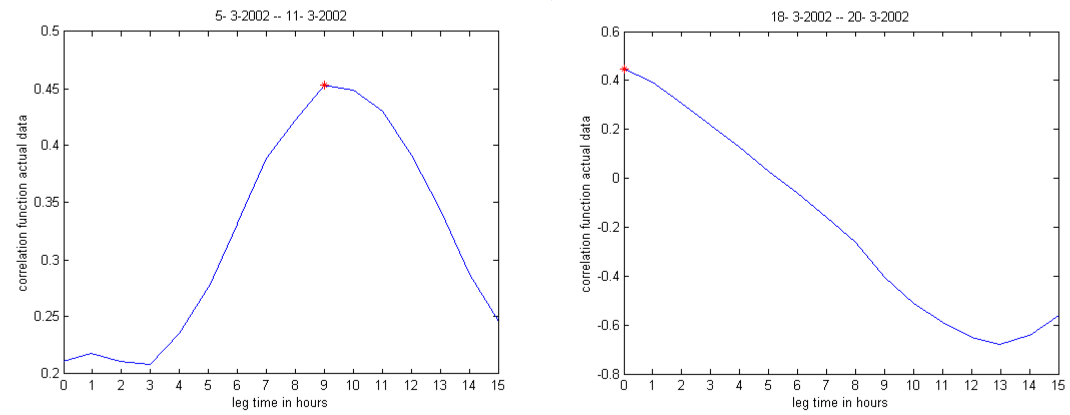
i ii

Figure 2.7: Noordwijk 5. Low-pass OBS data and low-pass significant wave height for different storm periods after removing the mean over the time series. For mean OBS values see Table 2.1



i ii

Figure 2.8: Noordwijk 5. Correlation function for OBS and significant wave height for different time lags (low-pass)



i ii

Figure 2.9: Noordwijk 5. Correlation function for OBS and significant wave height for different time lags (actual data)

3 SUSPENDED SEDIMENT CONCENTRATION AT NOORDWIJK 2

3.1 Observations

During the period 18-09-01 to 09-01-02 the Smart Buoy collected OBS data at the station Noordwijk 2. This station is located in a water depth of 10 m, 2 kilometers offshore of Noordwijk. The hourly OBS data are plotted in Figs 20 through 23 in Mills and Rutgers van der Loeff (2002). Two periods of continuous data were selected for further analysis. The mean and variance of these periods are presented in Table 3.1.

Table 3.1

Noordwijk 2. Periods of continuous OBS data with mean and variance for each period

	Time interval (day – month – year – hour)	Mean OBS (ftu)	Variance OBS (ftu^2)
1	18-09-01 10h – 12-10-01 13h	21.94	228.27
2	17-10-01 19h – 28-12-01 13h	32.29	574.79

Similar to Noordwijk 10 the larger OBS values are associated with storms. During periods of little wave action it is obvious that also tidal variations in the OBS are present. To investigate the effects of tides and storms on the OBS, concentrations during periods of relative calm and storm periods will be dealt with separately. For the definitions of periods of relative calm and storm periods see 1.3.

3.2 Sediment concentration during periods of relative calm

The effect of the tide on the sediment concentration is investigated using the data of the period 07-12-01 to 17-12-01. For this period the significant wave height is less than 1 m. The mean and variance of the OBS data are respectively 19.02 ftu and 68.17 ftu^2.

The OBS together with the data on “tidal strength “ is presented in Fig. 3.1. For definition of “tidal strength” see 1.2. Visual inspection shows clear correlation between the trend in the concentration and the “tidal strength”. The OBS shows considerable variation in the tidal band. This is further investigated using the power spectra in Fig. 3.1. From the spectra it follows that most of the energy is in the 6 and 12 hour period band. The 6 hour fluctuations are associated with the resuspension of sediment in the ebb and flood phase. Most likely the 12 hour variations are a result of along-coast sediment gradients passing by the measurement station. There is no clear indication that the variations in OBS with periods smaller than 25 hours are more pronounced during spring than neap tide or vise versa.

3.3 Sediment concentrations during storm periods

Within the measurement period five storms can be identified. The storm periods together with maximum significant wave height, maximum, mean and variance of OBS are presented in Table 3.2.

Table 3.2

Noordwijk 2. Maximum significant wave height, maximum, mean and variance of OBS data for different storm periods

Storm	Storm Period	Max significant wave height (m)	Max OBS (ftu)	Mean OBS (ftu)	Variance OBS (ftu^2)
I	30-09-01 15h – 05-10-01 05h	2.51	74.78	30.95	177.80
II	04-11-01 02h – 11-11-01 15h	5.02	99.55	40.64	303.88
III	20-11-01 10h – 24-11-01 16h	3.81	167.08	61.74	782.71
IV	03-12-01 21h – 07-12-01 03h	3.50	67.56	31.68	212.81
V	18-12-01 20h – 23-12-01 18h	3.72	180.51	69.26	922.94

For each storm a plot of the OBS and the significant wave height versus the time is presented in Fig. 3.2. From this figure it can be seen that in general the trend in OBS closely follows the trend in significant wave height. To further substantiate this and to separate the storm and tide related fluctuations in OBS, a 25-hour running average is applied to the OBS and wave data. For the five storms the variance of the low–pass and high-pass filtered OBS, together with the maximum wave height in the 25-hour averaged wave records is presented in Table 3.3

Table 3.3

Noordwijk 2. Maximum significant wave height (25-hour filtered) and variance of low-pass and high-pass filtered OBS data for different storm periods

Storm	Storm Period	Max significant wave height (m)	Variance OBS High pass (ftu^2)	Variance OBS Low pass (ftu^2)
I	30-09-01 15h – 05-10-01 05h	2.05	111.49	18.42
II	04-11-01 02h – 11-11-01 15h	3.54	122.67	90.44
III	20-11-01 10h – 24-11-01 16h	3.23	538.96	190.54
IV	03-12-01 21h – 07-12-01 03h	2.29	107.74	72.98
V	18-12-01 20h – 23-12-01 18h	3.01	568.18	150.39

For each storm the low- pass and high- pass filtered OBS data together with the actual data are presented in Fig. 3.3. The low-pass filtered data confirms the earlier conclusion that the trend in OBS follows the trend in significant wave height.. Focusing on the high pass filtered data, during storms there are in storm clearly variations with periods of 12 and 24 hours .

To further investigate the variations in OBS with periods smaller than one day, the power spectral density for the high-pass OBS data for each storm is presented in Fig 3.4. In all storms there is a clear presence of energy in the 12 and 24-hour period band. In addition Storm (I) shows a significant contribution in the 6-hour period band.

3.4 Time lag between significant wave height and OBS at Noordwijk 2.

In section 3.3 it was already observed that OBS and wave height follow the same trend. In this section the relationship between significant wave height and OBS is further investigated. In particular, attention is given to the time lag between wave height and OBS.

Using the low-pass filtered data for each of the five storms listed in Table 3.2, the OBS is plotted versus the significant wave height in Fig. 3.5. In the different plots the beginning of a storm is marked with a red star. The different plots clearly show hysteresis. However the five storms do not all show the same pattern. In storms I, II and IV for the same significant wave height the OBS is lower for increasing storm activity than for decreasing storm activity. The OBS lags the wave height. The opposite holds for storms II and V where the OBS leads the wave height. This is also confirmed by the plots in Fig. 3.6 where for each storm the low-pass filtered OBS and wave height data are plotted versus time. To estimate the time lags, the low-pass OBS and wave data after removing the mean are presented in Fig. 3.7. From this it is estimated that for storms I, II and IV the time lag is between 5 and 10 hours, i.e. OBS leads wave height. For storm III it is estimated that OBS leads wave height by 0-5 hours. For storm V, OBS leads wave height by 5-10 hours.

To more accurately determine the value of the time lag corresponding to a maximum in correlation, the correlation function as defined in 1.4 is calculated. Calculations are made using actual as well as low-pass filtered data. The results are presented in respectively Figs 3.8 and 3.9. Maximum values of *cf* and the corresponding lag τ (τ is positive when the waves lead OBS) are presented in Table 3.4.

Table 3.4

Noordwijk 2. Time lag corresponding to the maximum value of the correlation function of OBS and significant wave height for different storm periods

Storm	Storm period	Maximum cf (low-pass)	τ corresponding to maximum in cf (hours) (low-pass)	Maximum cf (actual)	τ corresponding to maximum in cf (hours) (actual)
I	30-09-01 15h – 05-10-01 05h	0.77	8	-0.19	14
II	04-11-01 02h – 11-11-01 15h	0.62	2	0.35	0
III	20-11-01 10h – 24-11-01 16h	0.94	0	0.64	0
IV	03-12-01 21h – 07-12-01 03h	0.80	4	0.68	8
V	18-12-01 20h – 23-12-01 18h	0.57	0	0.63	0

When using the low-pass filtered data the calculated lags reasonably agree with the lags estimated from Fig 3.7 with the exception of Storm V. For Storm V, Fig.3.7 suggests a negative lag whereas the maximum value of the correlation function is at zero lag (note: closer examination of the correlation function suggested a value slightly lower than zero). More so than for Noordwijk 10 and 5, values of the correlation function differ for low-pass filtered and actual data. The reason is that at Noordwijk 2, the high pass filtered data is responsible for a relatively large part of the variance in OBS; compare variances in Tables 1.4, 2.2 and 3.3. Taking storm I as an example, OBS values exhibit strong variations in the 12 hour period band (Fig. 3.4). These variations are not present in the wave height (Fig 3.2) leading to a low and even negative correlation (column 5 in Table 3.4).

07-12-01 0h – 17-12-01 0h

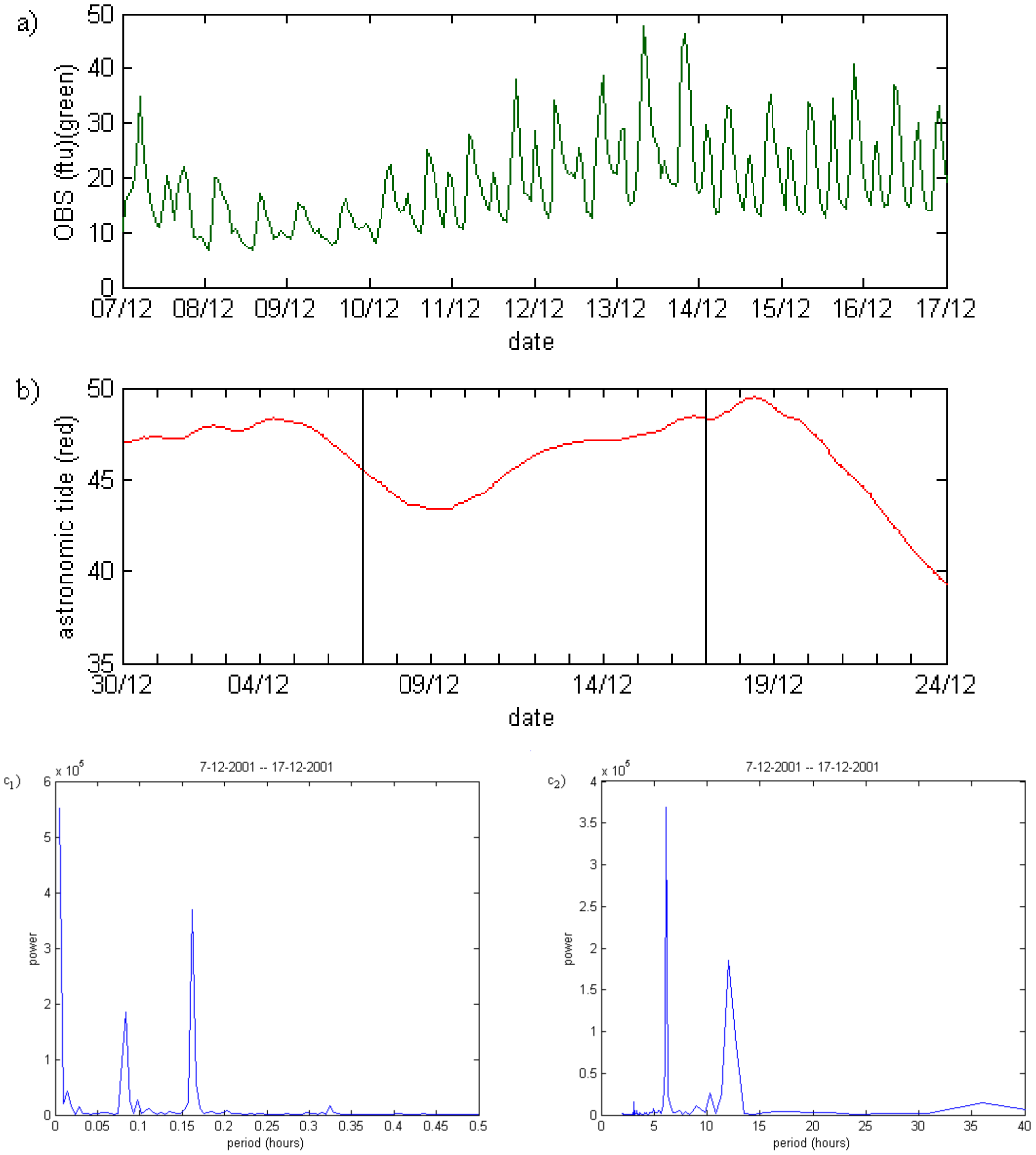
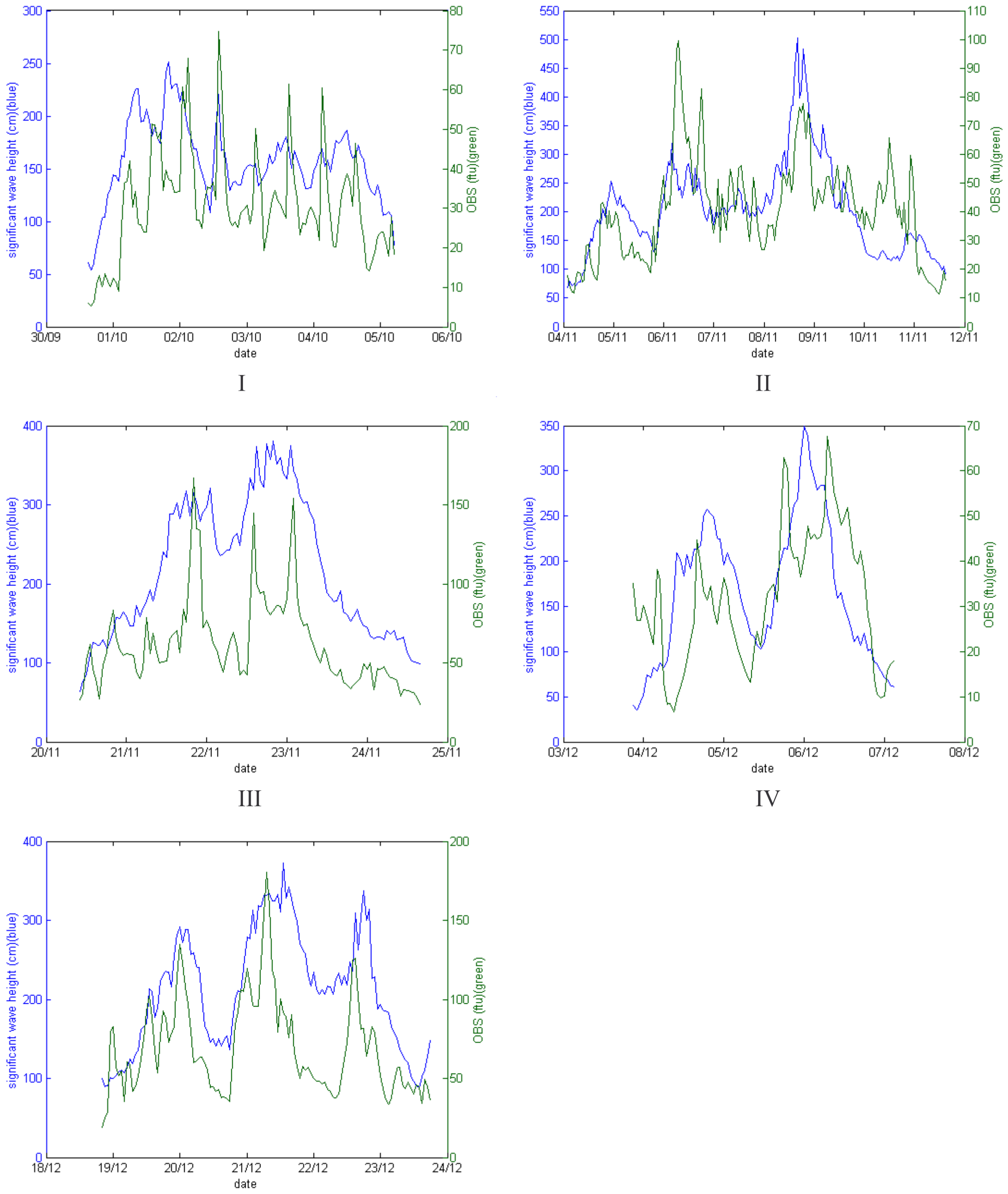


Figure 3.1: Noordwijk 2. Period of relative calm 07-12-01 0h – 17-12-01 0h. a) OBS, b) “tidal strength”, c) power spectra OBS.



I

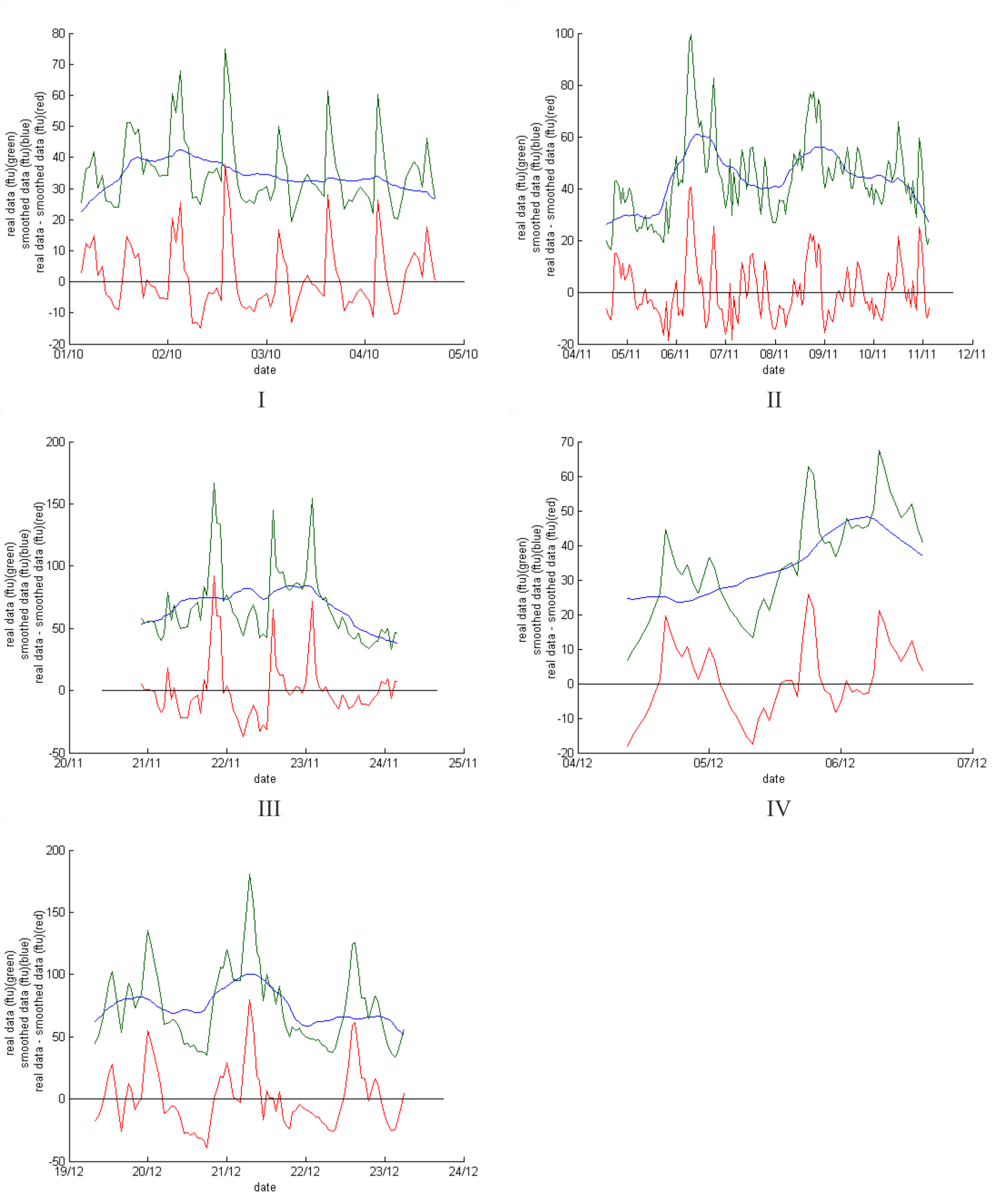
II

III

IV

V

Figure 3.2: Noordwijk 2. Hourly values of OBS and significant wave height for different storm periods



I

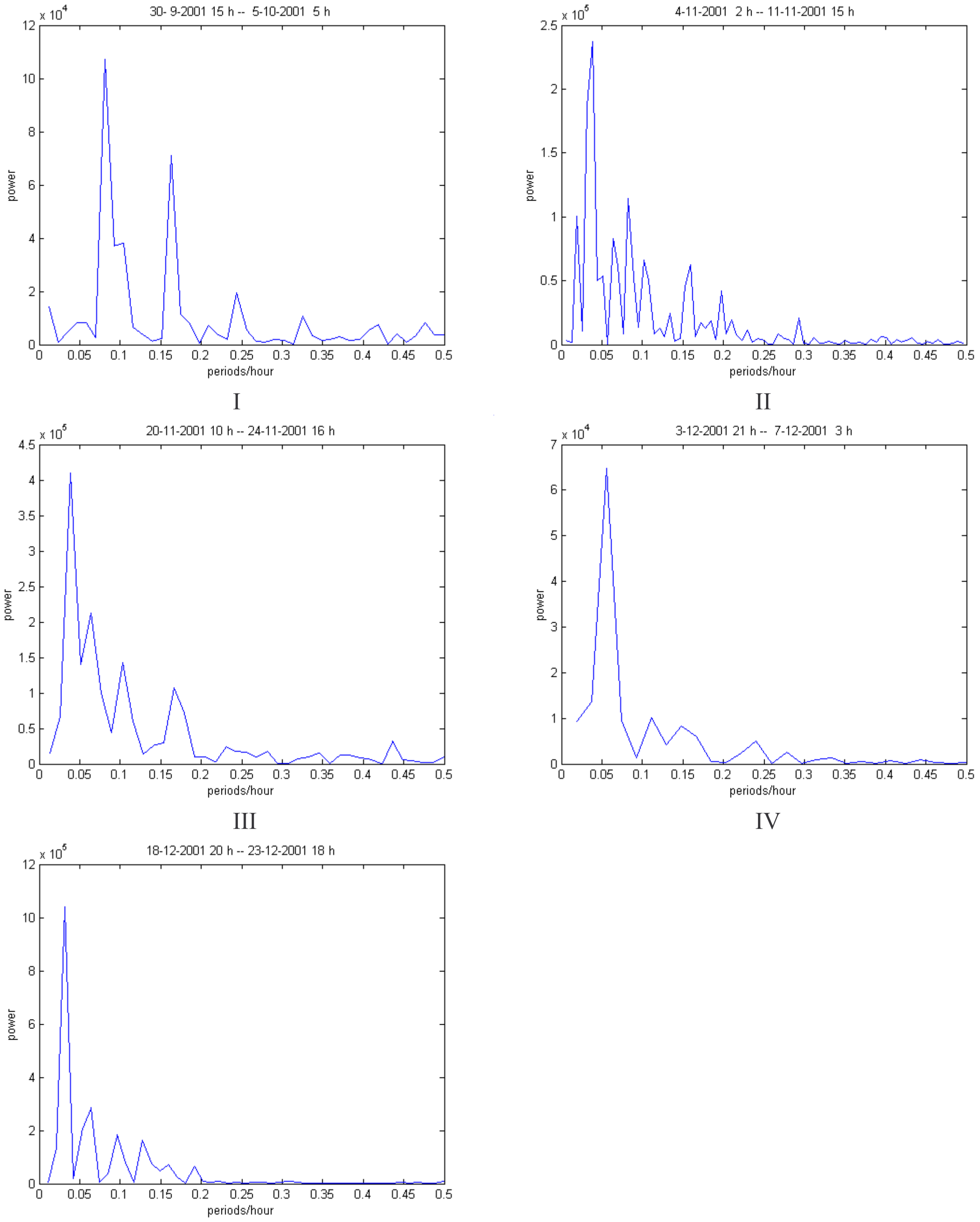
II

III

IV

V

Figure 3.3: Noordwijk 2. Actual 25- hour low-pass and 25- hour high-pass filtered OBS data for different storm periods.



I

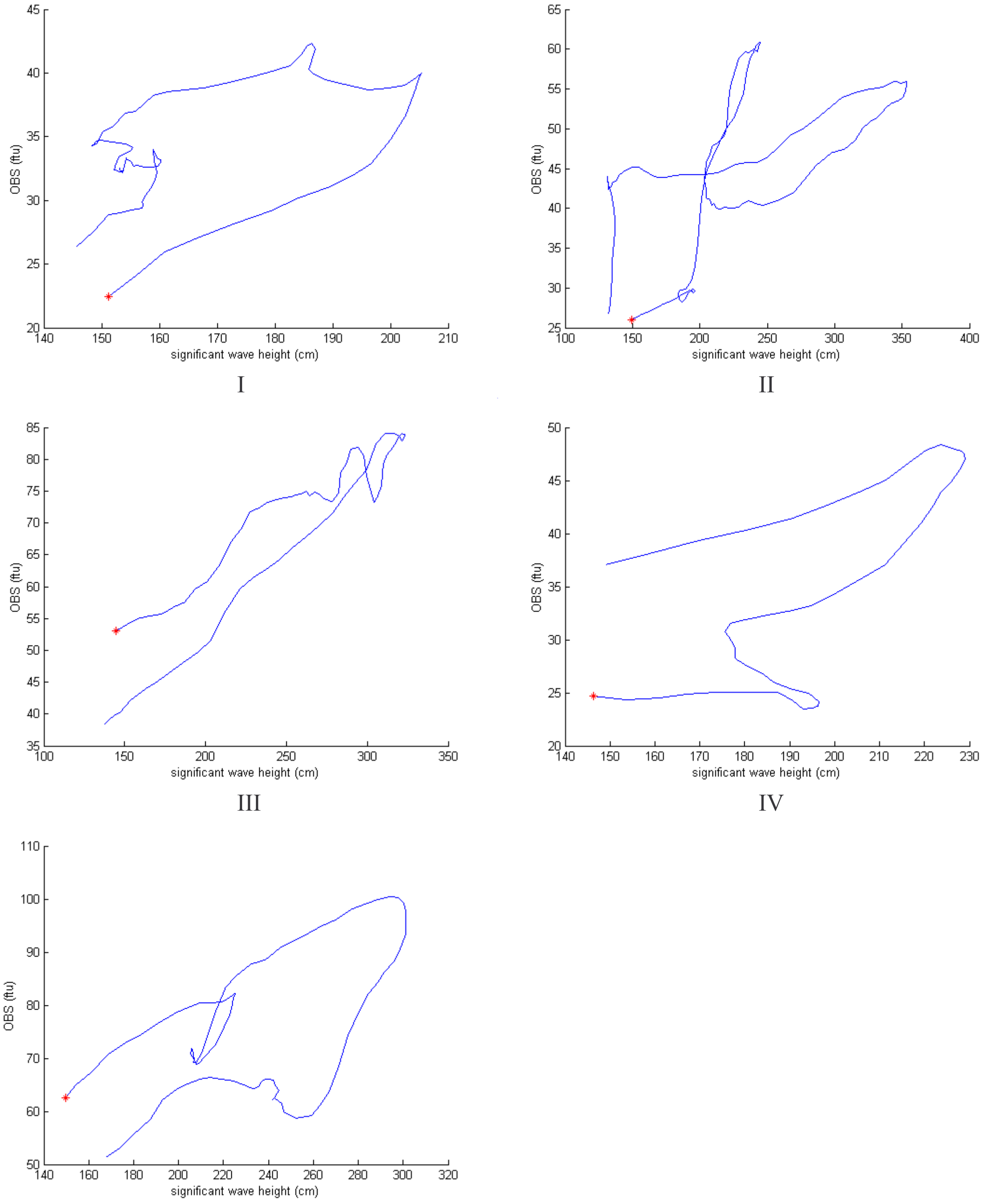
II

III

IV

V

Figure 3.4: Noordwijk 2. Power spectral density for 25- hour high-pass filtered OBS data for different storm periods.



I

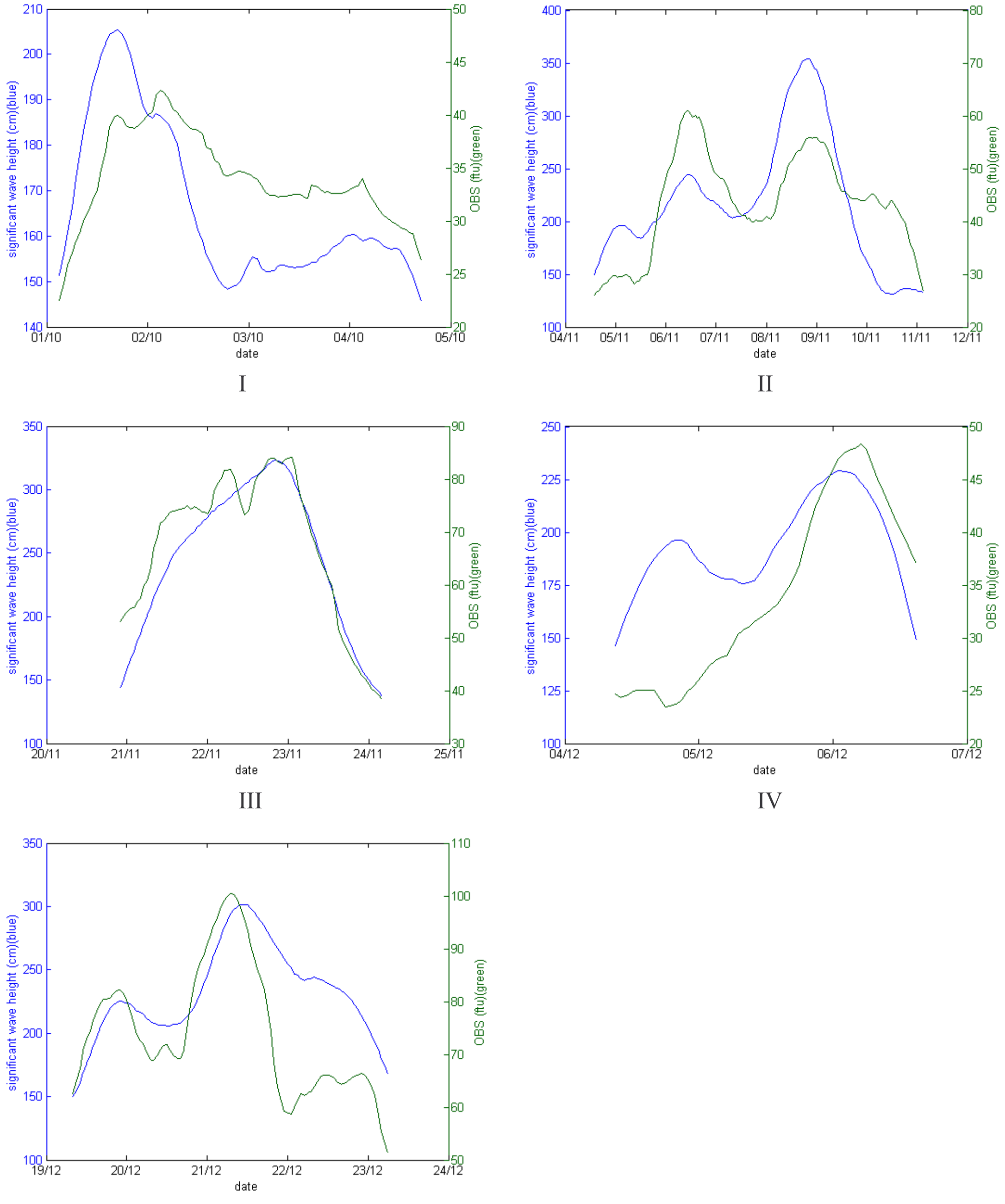
II

III

IV

V

Figure 3.5: Noordwijk 2. OBS data versus significant wave height for different storm periods.



I

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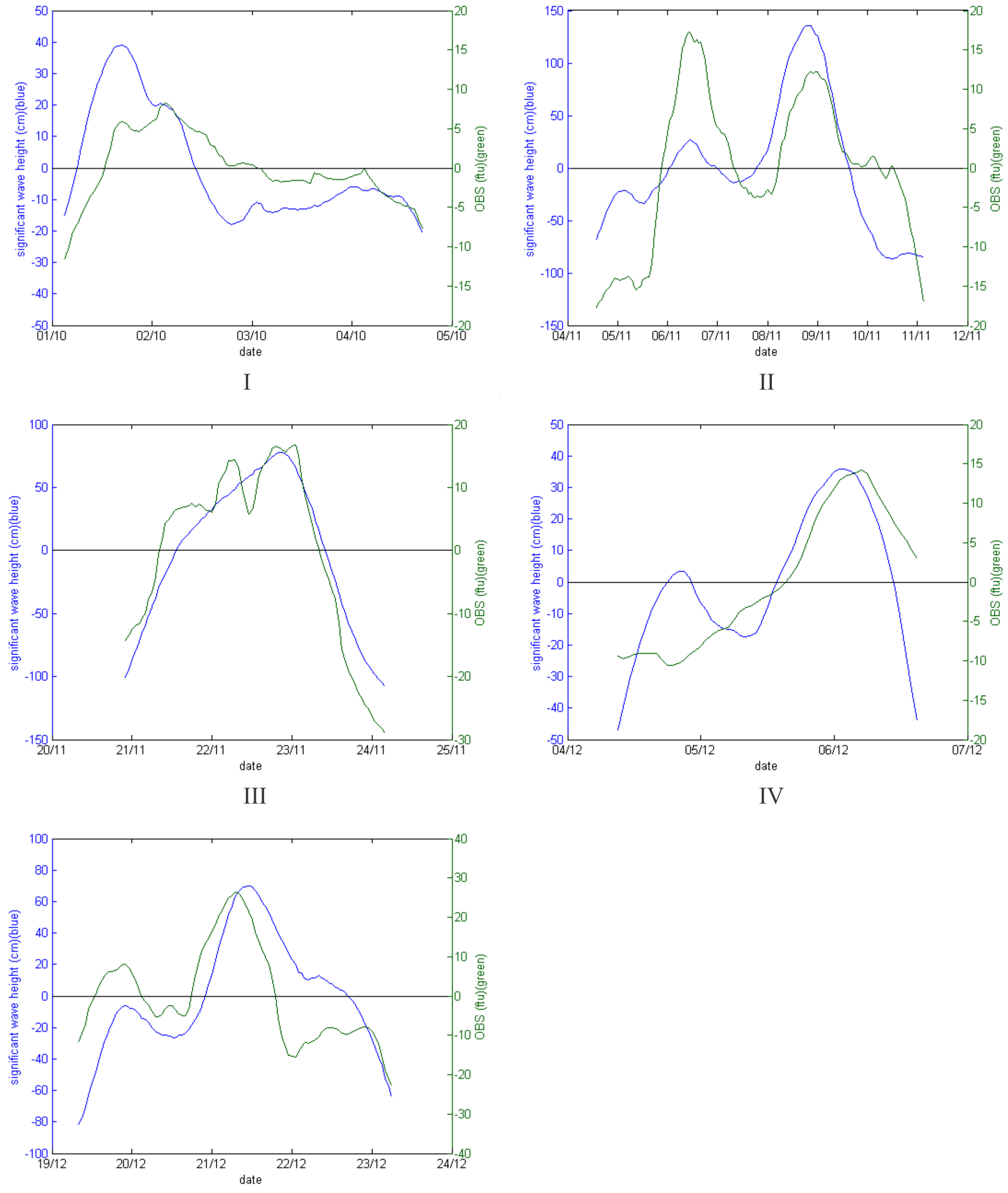
Figure 3.6: Noordwijk 2. Low-pass OBS data and low-pass significant wave height for different storm periods.



I

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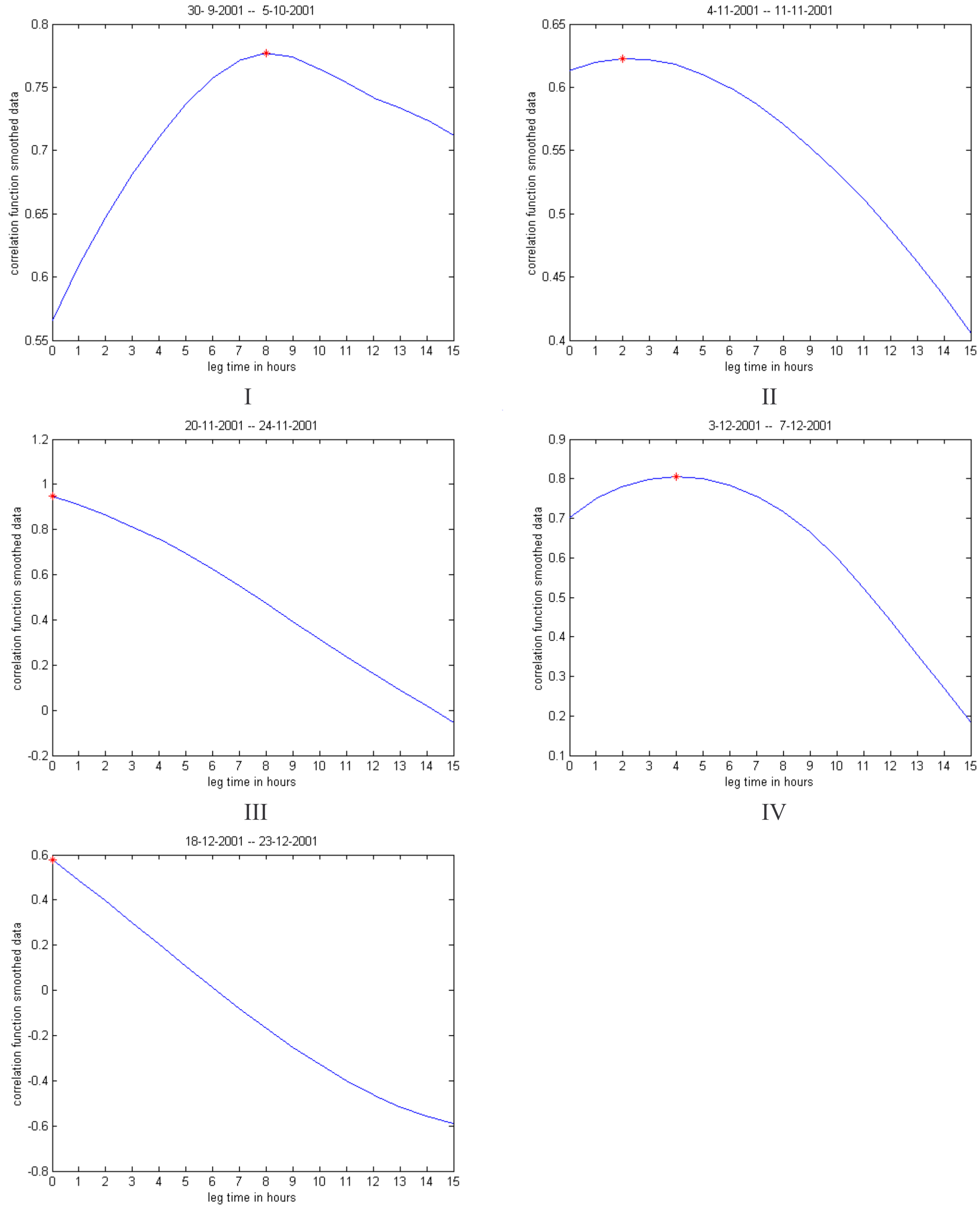
Figure 3.7: Noordwijk 2. Low-pass OBS data and low-pass significant wave height for different storm periods after removing the mean over the time series. For mean OBS values see table 3.2



I

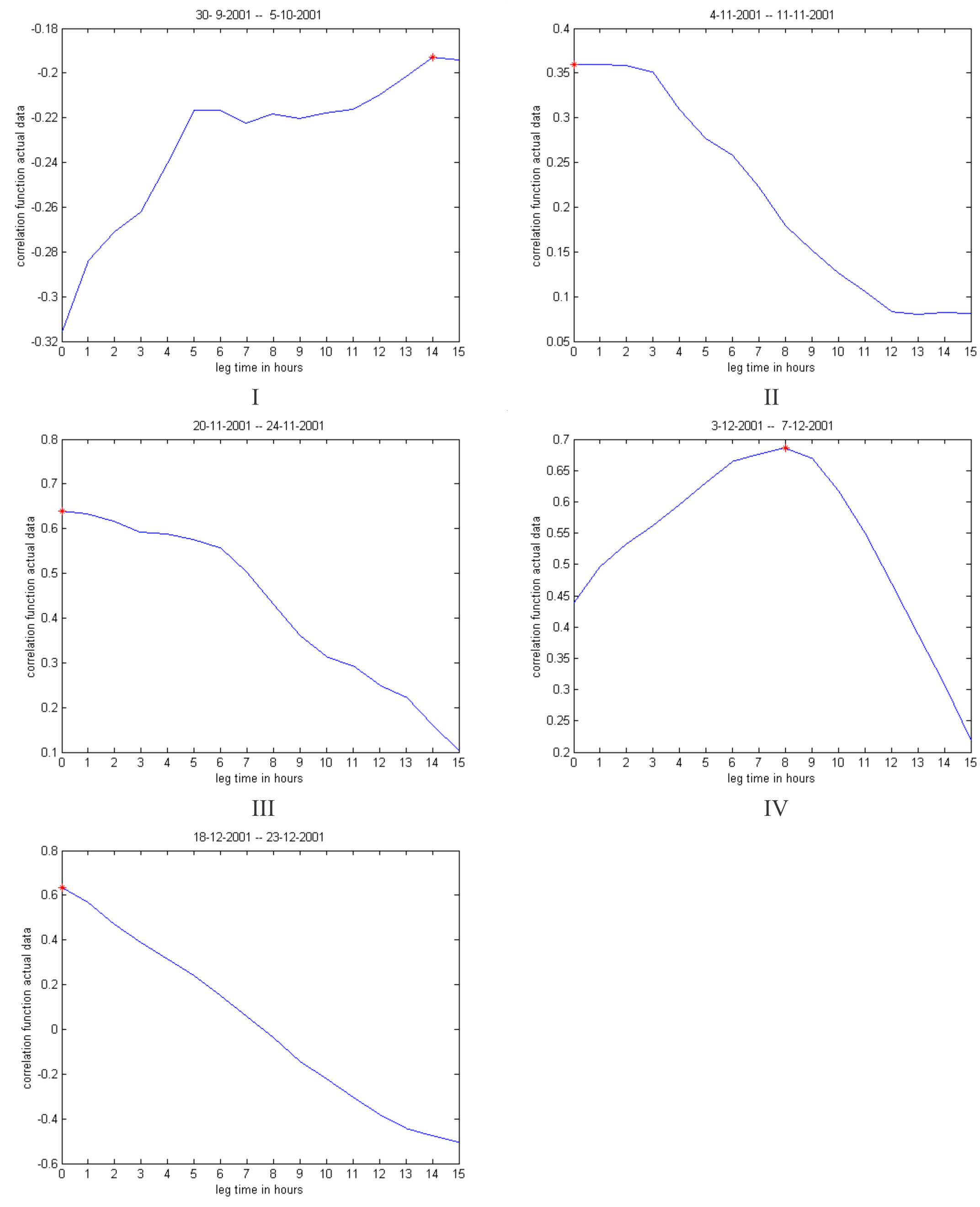
II

III

IV

V

Figure 3.8: Noordwijk 2. Correlation function for OBS and significant wave height for different time lags. (low-pass filtered data)



I

II

III

IV

V

Figure 3.9: Noordwijk 2. Correlation function for OBS and significant wave height for different time lags. (actual data)

4 SUMMARY AND CONCLUSIONS

OBS values and variations are forced by waves and tidal currents. Of these, the waves seem to be the more dominant forcing mechanism. During storm periods OBS values as high as 40-50 ftu were observed at Noordwijk 10 and 5 and maximum values in the 150 – 200 ftu range were observed at Noordwijk 2. During periods when significant wave heights were less than 1m, OBS values seldom exceeded 10 ftu in either of these stations. Comparison with the data obtained from ship observations as reported in Suijlen and Duin (2002) shows good agreement with winter values being higher than summer values and Noordwijk 2 having considerably higher values than Noordwijk 5 and 10. In comparing the values of Smart Buoy and ship observations 1 ftu at the Smart Buoy is assumed to correspond approximately with 1 mg/l TSM (Mills and Rutgers van der Loeff , 2002).

In the present analysis emphasis is on variations in OBS that are forced by the tide inclusive the spring–neap effect and variations that are forced by waves in combination with tide. To separate these variations, the observational periods are divided in periods of relative calm and storm periods. Periods of relative calm are defined as periods during which the significant wave height is always less than one meter. Storm periods have a maximum significant wave height larger than three meter. In the analysis the OBS data is divided in a set of low-pass filtered data (the trend) and high-pass filtered data. To separate the two a simple 25-hour running average was used.

To determine the effect op spring-neap variations in the tidal current on the OBS, the periods of relative calm were analyzed. For Noordwijk 10 there are six periods varying in length from 5 to 13 days. For the stations Noordwijk 5 and 2 there is only one period of relative calm with a length of 12 days for Noordwijk 5 and 10 days for Noordwijk 2. The analysis showed that only for one period at Noordwijk 10 (Fig. 1.3) and the period for Noordwijk 2 (Fig. 3.1) there exists a correlation between the trend in OBS and the spring-neap cycle, with the larger OBS values occurring at spring tide and the smaller values at neap tide.

During the periods of relative calm there are distinct variations in the OBS in the diurnal and semi-diurnal tidal period band as well as in the quarter–diurnal band. The latter are most pronounced at the stations Noordwijk 2 and 5. Variations of OBS in the diurnal and semi-diurnal period band are most likely associated with spatial gradients in the OBS that are advected passed the measurement station by the tidal currents. The quarter-diurnal variations in OBS are the result of upward mixing of sediment during the ebb and flood phase. There is little correlation between the magnitude of the OBS variations in these tidal period bands and the spring-neap cycle. For some periods of relative calm maximum OBS variations occur during spring tide and for others maximum variations occur during neap tide.

OBS during storm periods is characterized by a trend similar to the trend in significant wave height i.e. a relative steep increase and a more gentle decrease. Superimposed on the trend are variations with periods of less than 25 hours. For Noordwijk 10 and 5 the contribution of the daily variations and the trend to the total variance are of the same order of magnitude. (Tables 1.4 and 2.2). For Noordwijk 2, the contribution of the daily variations to the total variance is much larger than the contribution of the trend (Table 3.3). In general OBS lags the wave height. For Noordwijk 10 and 5 the average time lag, corresponding to a maximum in correlation between the low-passed filtered OBS and wave height, is 7.5 hours; see Tables 1.5 and 2.3. For Noordwijk 2 the average time lag is less and amounts to 2.5 hours with some storms showing a slightly negative time lag i.e. OBS leads significant wave height; see section 3.4 and Figs 3.5 and 3.6. The average correlation coefficients, corresponding to the time lag-adjusted low-pass filtered wave height and OBS for Noordwijk 10, 5 and 2 are respectively 0.76, 0.81 and 0.75 (Tables 1.5, 2.3 and 3.4)

Analysis of the daily variations in OBS shows that most of the energy is in the tidal bands of 12 and 24 hours. Most likely these variations are the result of spatial gradients in OBS that are advected passed the measurement station. In the OBS data for Noordwijk 5 and even more so for Noordwijk 2, energy is also present in the 6-hour period band. This suggests upward mixing of sediment by tidal currents. That this signal is strongest at Noordwijk 2, can be attributed to the relative shallow depth of 10 m at this station as opposed to 18 m at Noordwijk 10 and 5. Compared to the periods of relative calm, energy in the 6-hour band is less pronounced. In determining surface concentrations upward mixing of sediment by the tide plays less of a role during storms than during periods of relative calm.

Although this was not extensively investigated, a comparison of maximum OBS and maximum significant wave height during storm periods shows that for Noordwijk 10 (table 1.3) these are reasonably correlated but not so for Noordwijk 2 (table 3.2). Obviously other factors, in addition to wave height, play a role in establishing the OBS value. The first one that comes to mind is the availability of silt in the bottom.

OBS values and variations in response to waves and tide in Noordwijk 10 and 5 show strong agreement. OBS values and variations at Noordwijk 2 are distinctly different from those at Noordwijk 10 and 5.

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