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

Jantien Hartog
with cooperation of
Jacobus van de Kreeke

PREFACE

For my study applied mathematics at the university of Delft I did an internship for ten weeks at the RIKZ (Rijksinstituut voor Kust en Zee / National Institute for Coastal and Marine Management). RIKZ is located in Den Haag, but for my internship I worked 6 weeks in Den Haag and four weeks in Miami. During my internship my advisor had to be in Miami and gave me the opportunity the go with him. For four weeks in the summer I worked at the university of Miami at the Rosentiel school of marine and atmospheric science. I got there the opportunity to meet people of all kind of nationalities. It was a great experience for me to work in a different environment then I was used in the Netherlands.

For my internship I had access to an enorm amount of data. My internship was 10 weeks, but there was enough data for 10 months work. My analysis of this data is the begin of a larger study about the behavior of suspended sediment. The only information about suspended sediment was based of measurements by a ship. At certain times the ship will go to sea to measure the amount of suspended sediment. The measurements the ship took during the period 1975 till 1983 were analyzed and with that data the figures below were made. My internship is the start to a new chapter about suspended sediment and will give better insight in the behavior of the suspended sediment.

Of course I would like to thank my advisors, Michiel van der Loeff and esspecially Co van de Kreeke who helped me during my internship. This report is a cooperation between Co and I. We both did a great part of the writing for this report. The analysis and calculations are my own work.

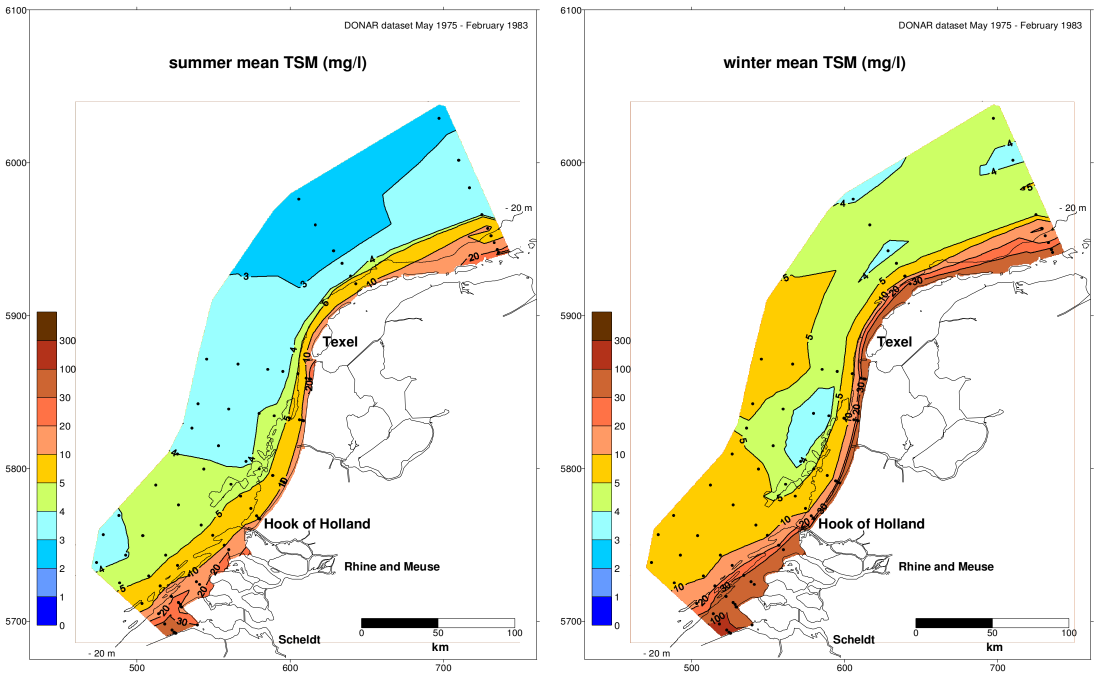


TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

All the knowledge there was about suspended sediment was know through ship measurements. At certain times the ship would go the sea and measure the amount of suspended sediment. Those measurement were analyzed and put together in a kind of suspended sediment atlas (see preface). The ship only would not go the sea in a storm and especially the storm periods are interesting. Because we want to know what happens during a storm period, the SmartBuoy project was started.

1.1 SmartBuoy

The SmartBuoy is the name of a buoy with a lot of measurement equipment. For my analysis only the OBS (Optical Backscatter) was important. The OBS is a device which uses light to measure the amount of suspended sediment. It sends a beam of light and short distance further the OBS catches the uninterrupted beam of light and the decreasing of the light is a measure of the suspended sediment in the water. The unit of the OBS is ftu, this is an optical unit. In the winter this unit will correspond with mg/l, but in the summer it is not such a good comparison.

Fig 1.1: Seapoint OBS and SmartBuoy

The SmartBuoy was every month replaced by a duplicate. There were two identical systems which were alternated every month. After such a switch the ‘old’ SmartBuoy could be cleaned and fixed if necessary. When the SmartBuoy was located at two kilometers offshore of Noordwijk, the SmartBuoy was taken by a passing ship. RIKZ could pick it up at Urk. It took two month before the SmartBuoy was fixed and that is why the SmartBuoy was replaced at five kilometers offshore two months later.

2. SUSPENDED SEDIMENT CONCENTRATION AT NOORDWIJK 10.

2.1 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, 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 RIKZ (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 2.1

Table 2.1

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	3.8637	25.0102
B	07-11-00 09h - 14-03-01 23h	6.5121	40.6019
C	20-03-01 10h - 05-07-01 23h	2.7497	14.5013
D	21-08-01 10h - 18-09-01 08h	8.4845	71.4461

The data in RIKZ (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.

2.2 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 2.2 together with the mean and the variance of the OBS.

Table2.2

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. 2.1 – 2.6. 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/π times the tidal amplitude. The "tidal strength" is used to distinguish between periods of spring- and neaptide.

Visual inspection of the plots shows no clear correlation between the trend in OBS and the “tidal strength” with the possible exception of the data in Fig. 2.3. The OBS shows considerable variation in the tidal period band. These variations are further investigated by calculating the power spectra (Fig. 2.1 – 2.6) . 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. (note: contrary to what is suggested in Bendat and Piersol (1971), in calculating the power spectra no cosine taper window was applied)

2.3 Sediment concentration during storm periods

A storm period is defined as a period in which the maximum waveheight $H_s > 3$ m. The storm period begins when $H_s > 1$ m and ends when $H_s < 1$ m adjusted such that after smoothing the wave height is at least 1.50 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 mean and variance of the OBS are presented in Table 2.3.

Table 2.3

Noordwijk 10. Maximum significant wave height, 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. 2.7. 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. For the different storms the mean and 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 2.4

Table 2.4

Noordwijk 10. Maximum significant wave height and variance of low-pass and high-pass filtered OBS data for different storms

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. 2.8. 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, there are pronounced variations in the diurnal and semi-diurnal period band. 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 2.9. 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.

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

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 five storms listed in Table 2.3, the OBS is plotted versus the significant wave height in Fig.2.10. 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. 2.11 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.2.12. 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 2.13 and 2.14. Maximum values of *cf* and the corresponding lag are presented in Table 2.5.

Table 2.5

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

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	0.6133	0	0.7386	0
X1	08-07-00 12h – 13-07-00 12h	0.9678	7	0.7569	7
B1	07-12-00 23h – 17-12-00 15h	0.8881	6	0.7491	3
C1	16-05-01 15h – 19-05-01 00h	0.5999	6	0.7957	4
C2	01-06-01 17h – 08-06-01 06h	0.7689	10	0.5640	7
D1	03-09-01 12h – 14-09-01 01h	0.7856	15	0.6614	8

Values of the time lag in the last columns 4 and 5 of Table 2.5 reasonably agree with the earlier estimates of 5-10 hours based on visual inspection of the plots in Fig. 2.12. 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 2.5). 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

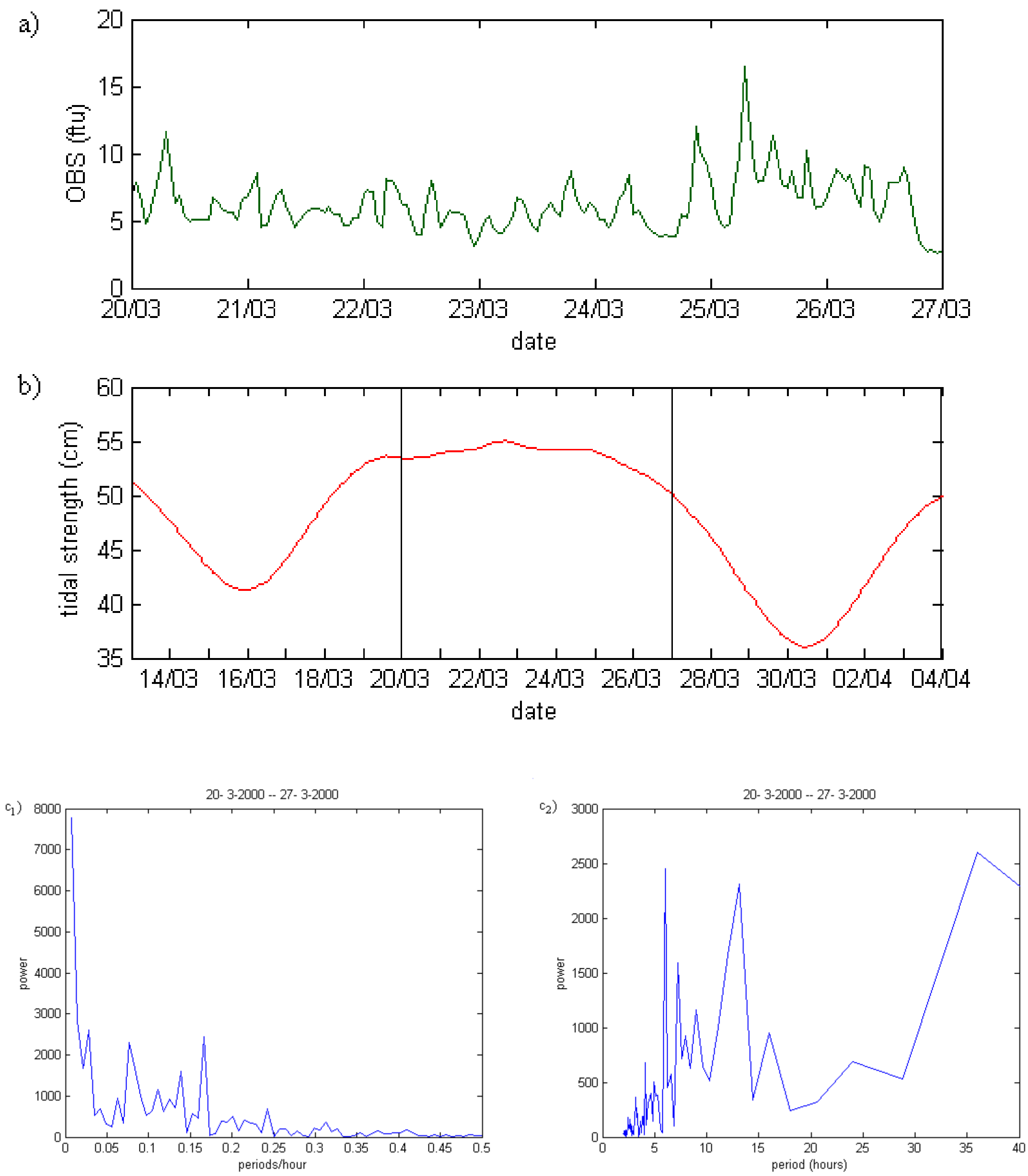


Figure 2.1: Noordwijk 10. Period of relative calm 20-03-00 0h – 27-03-00 0h. a) OBS, b) “tidal strength”, c) power spectra OBS.

19-04-00 0h – 02-05-00 0h

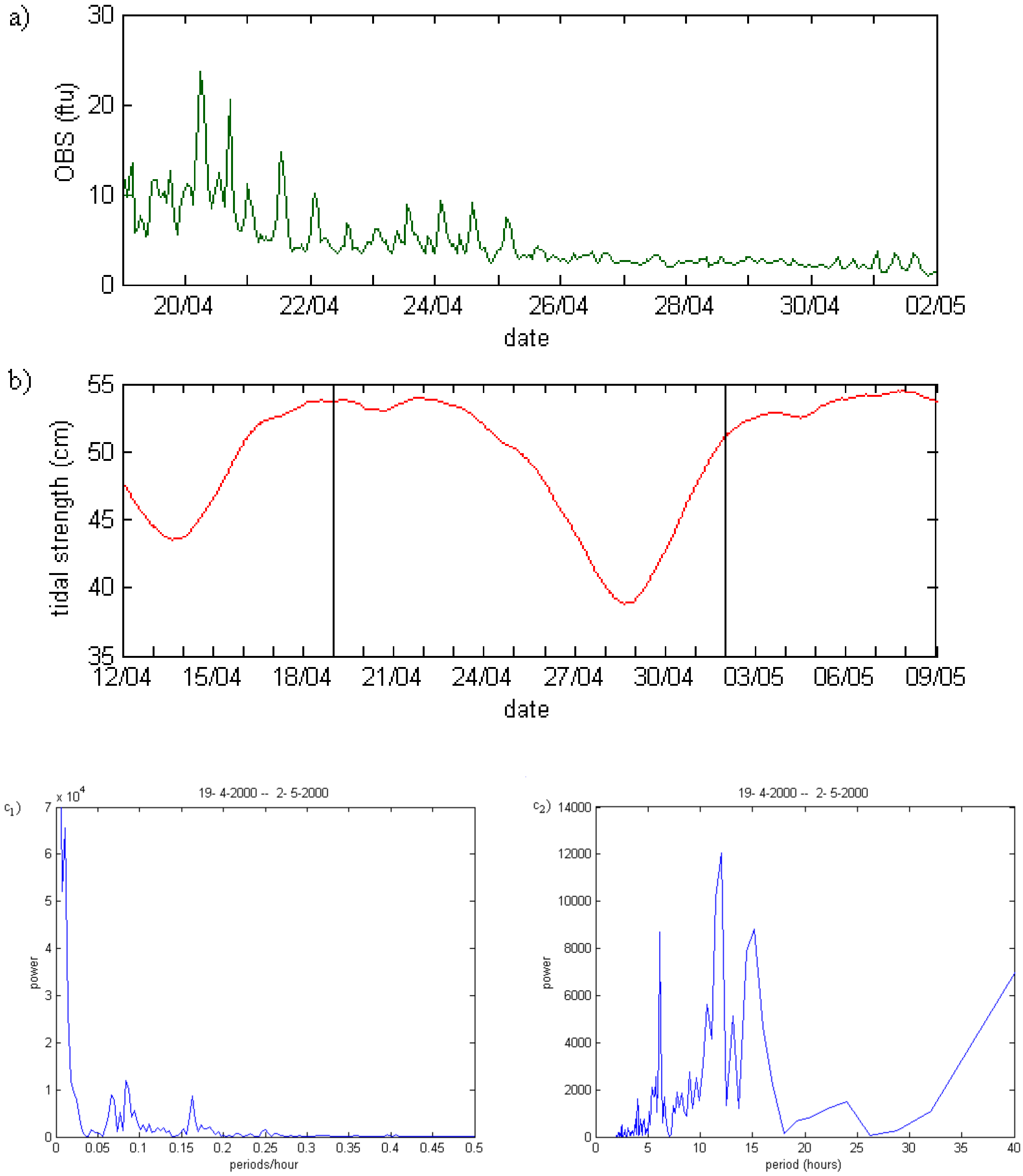


Figure 2.2: Noordwijk 10. Period of relative calm 19-04-00 0h – 02-05-00 0h. a) OBS, b) “tidal strength”, c) power spectra OBS.

12-01-01 0h – 23-01-01 0h

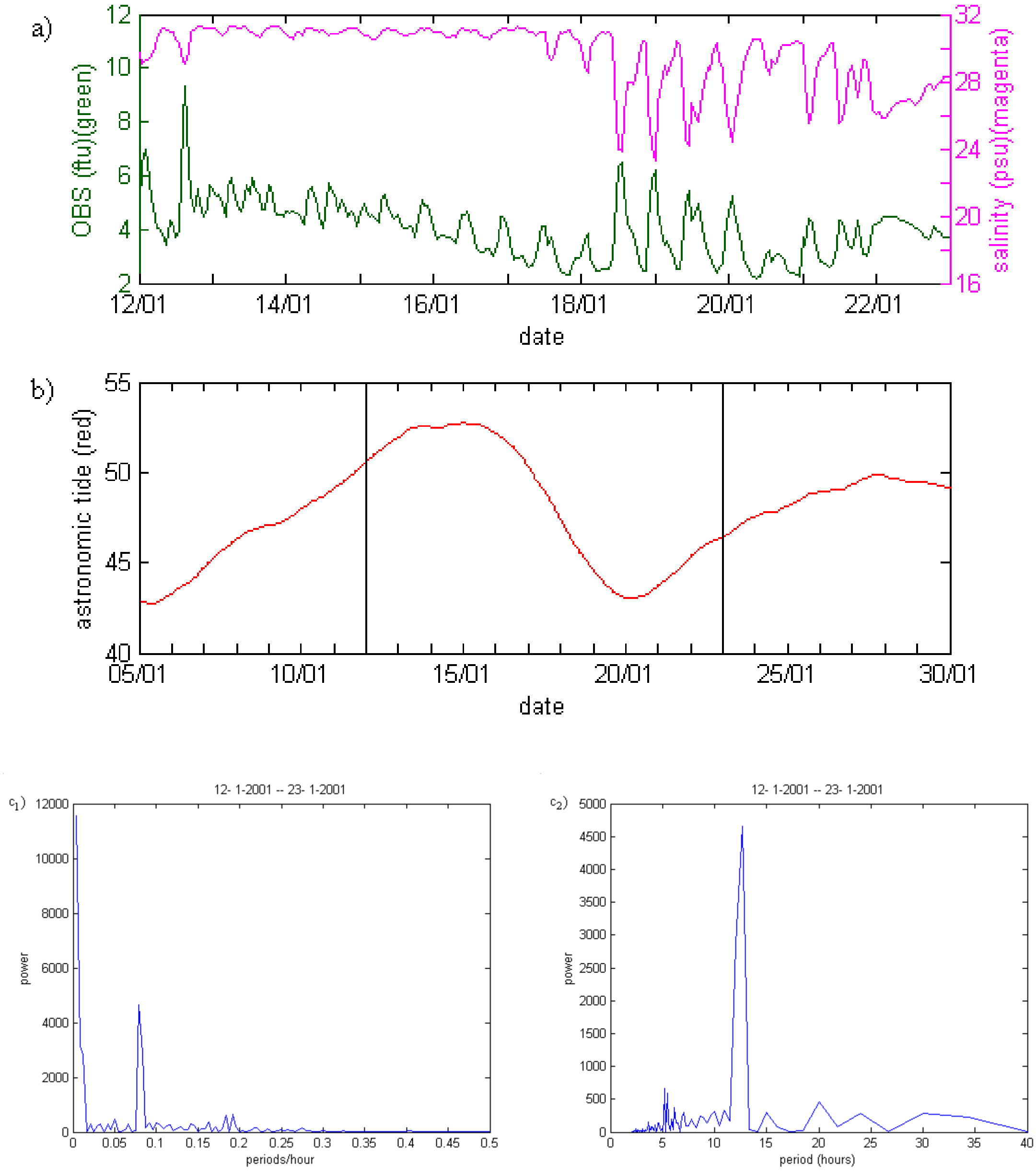


Figure 2.3: Noordwijk 10. Period of relative calm 12-01-01 0h – 23-01-00 0h. a) OBS, b) “tidal strength”, c) power spectra OBS.

09-05-01 0h – 16-05-01 0h

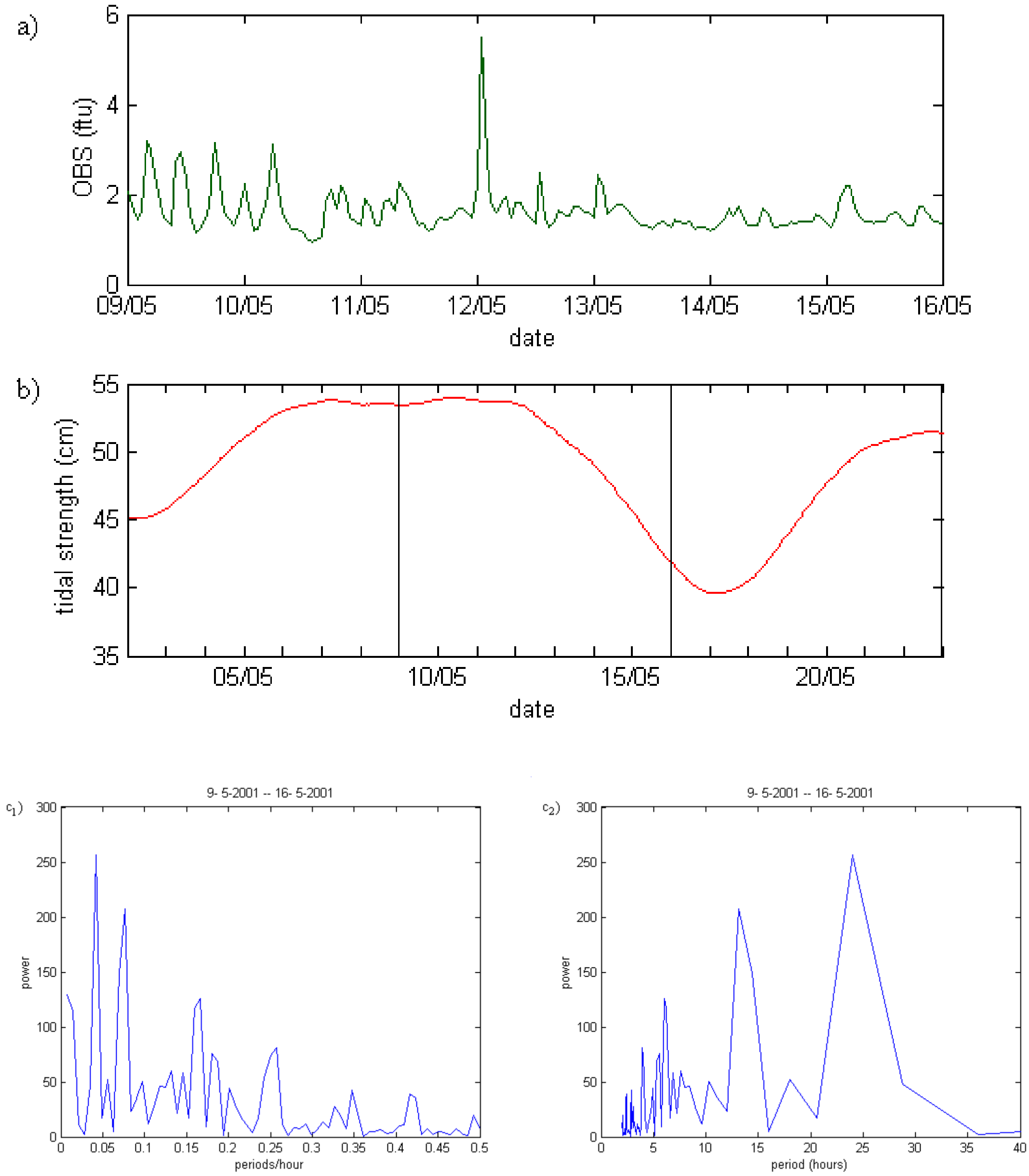


Figure 2.4: Noordwijk 10. Period of relative calm 09-05-01 0h – 16-05-01 0h. a) OBS, b) “tidal strength”, c) power spectra OBS.

30-06-01 0h – 05-07-01 23h

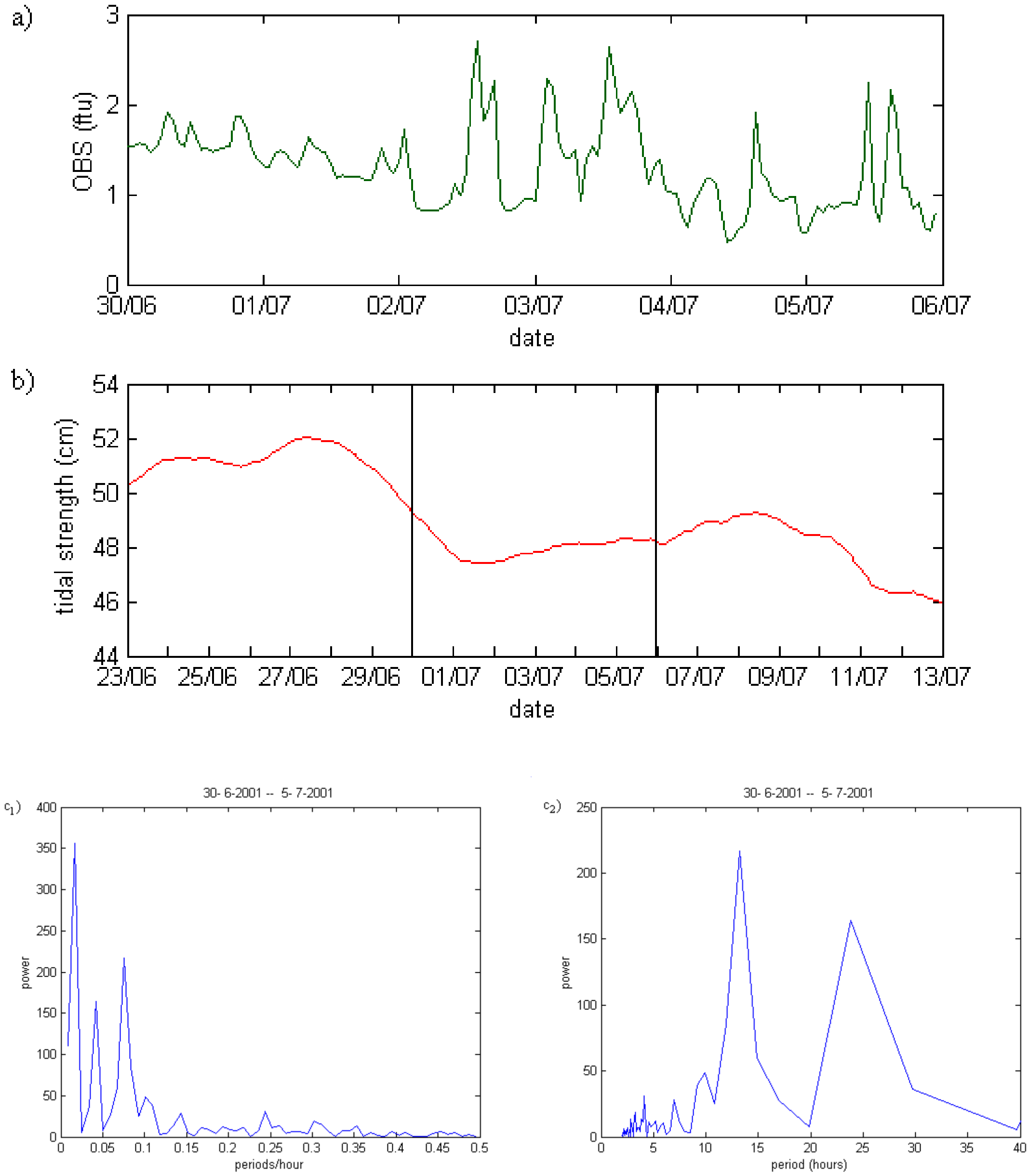


Figure 2.5: Noordwijk 10. Period of relative calm 30-06-01 0h – 05-07-01 23h. a) OBS, b) “tidal strength”, c) power spectra OBS.

24-07-01 10h – 29-07-01 23h

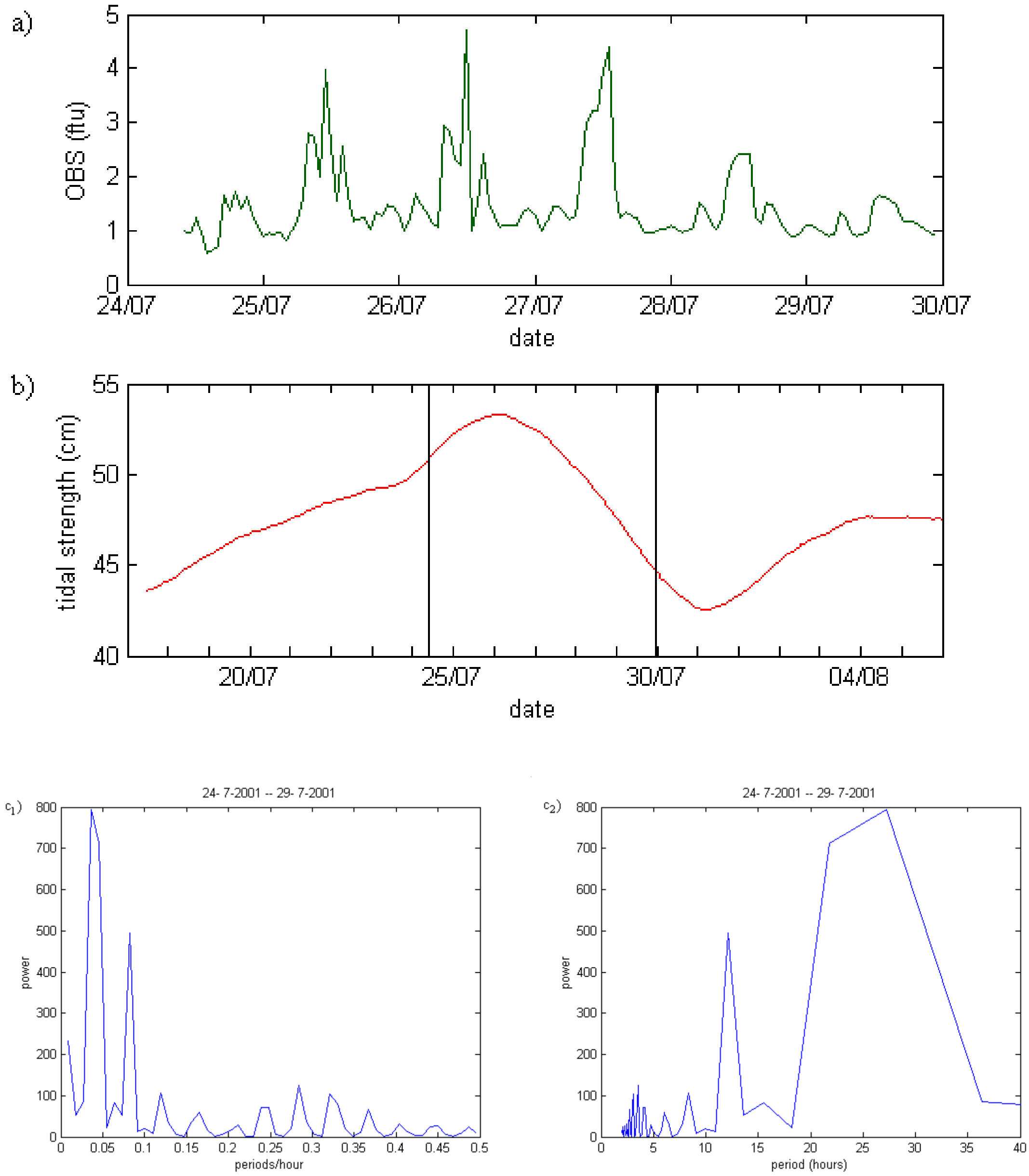


Figure 2.6: Noordwijk 10. Period of relative calm 24-07-01 10h – 29-07-01 23h. a) OBS, b) “tidal strength”, c) power spectra OBS.

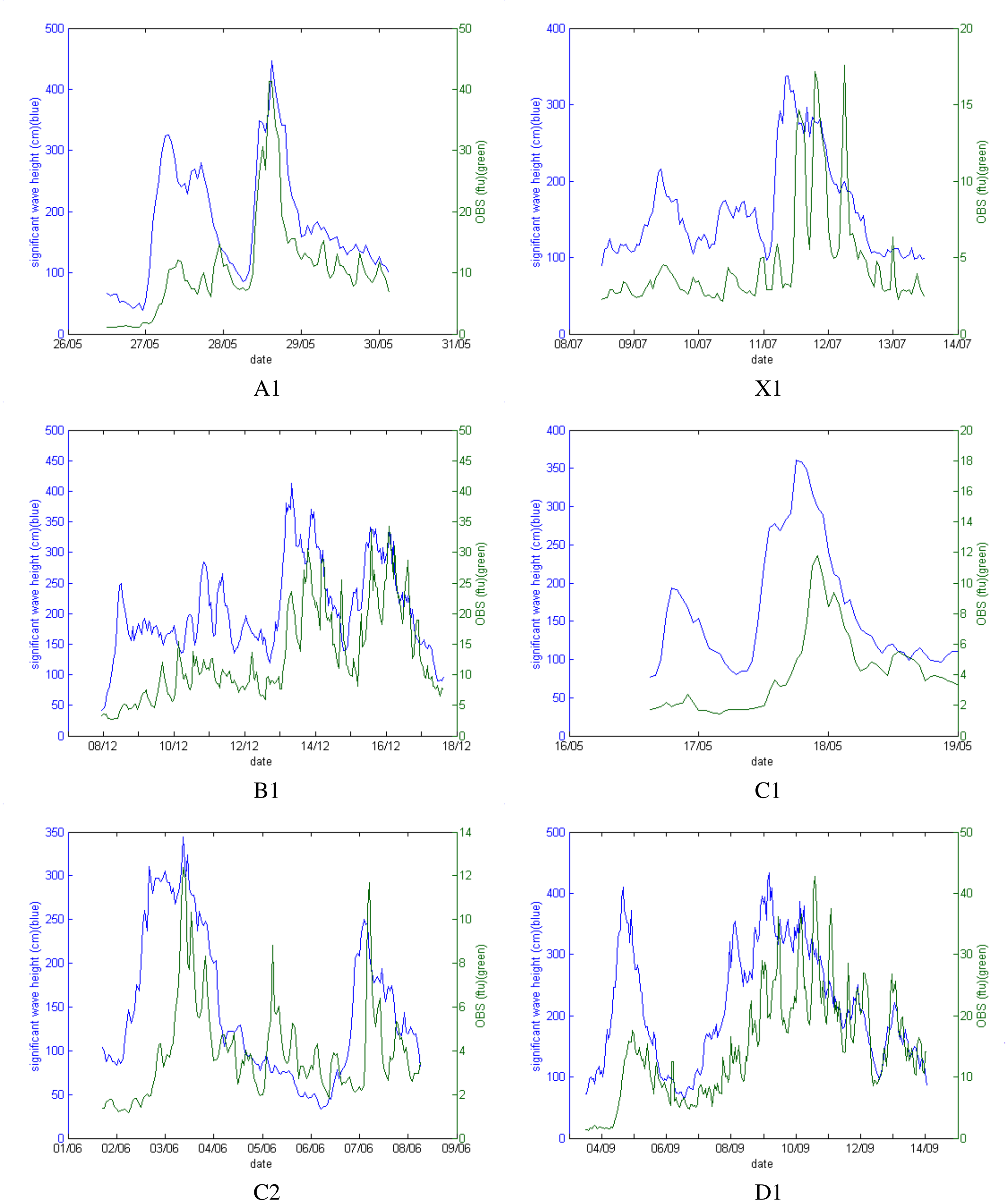


Figure 2.7: Noordwijk 10.Hourly values of OBS and significant wave height for different storm periods

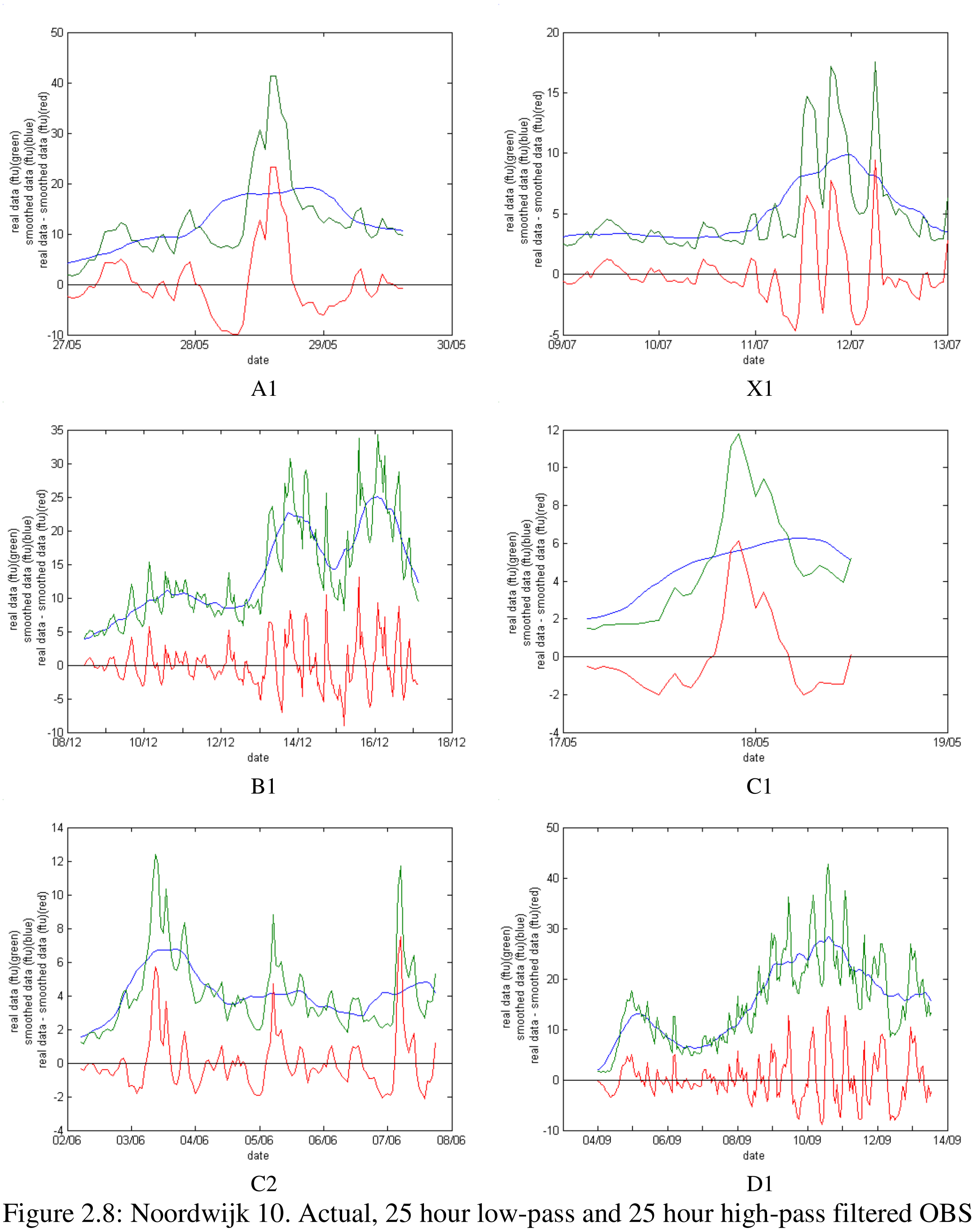


Figure 2.8: Noordwijk 10. Actual, 25 hour low-pass and 25 hour high-pass filtered OBS data for different storms.

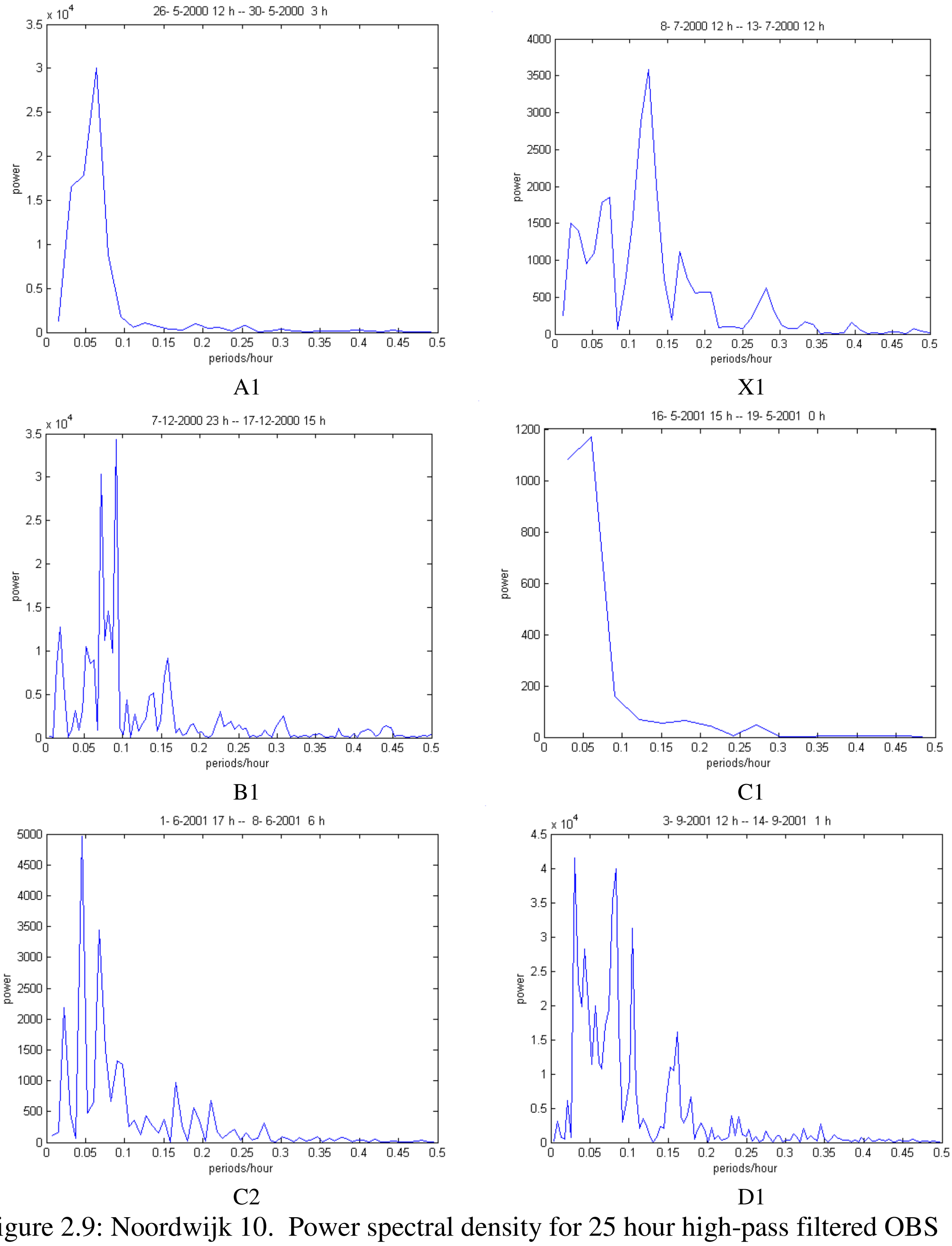


Figure 2.9: Noordwijk 10. Power spectral density for 25 hour high-pass filtered OBS data for different storms.

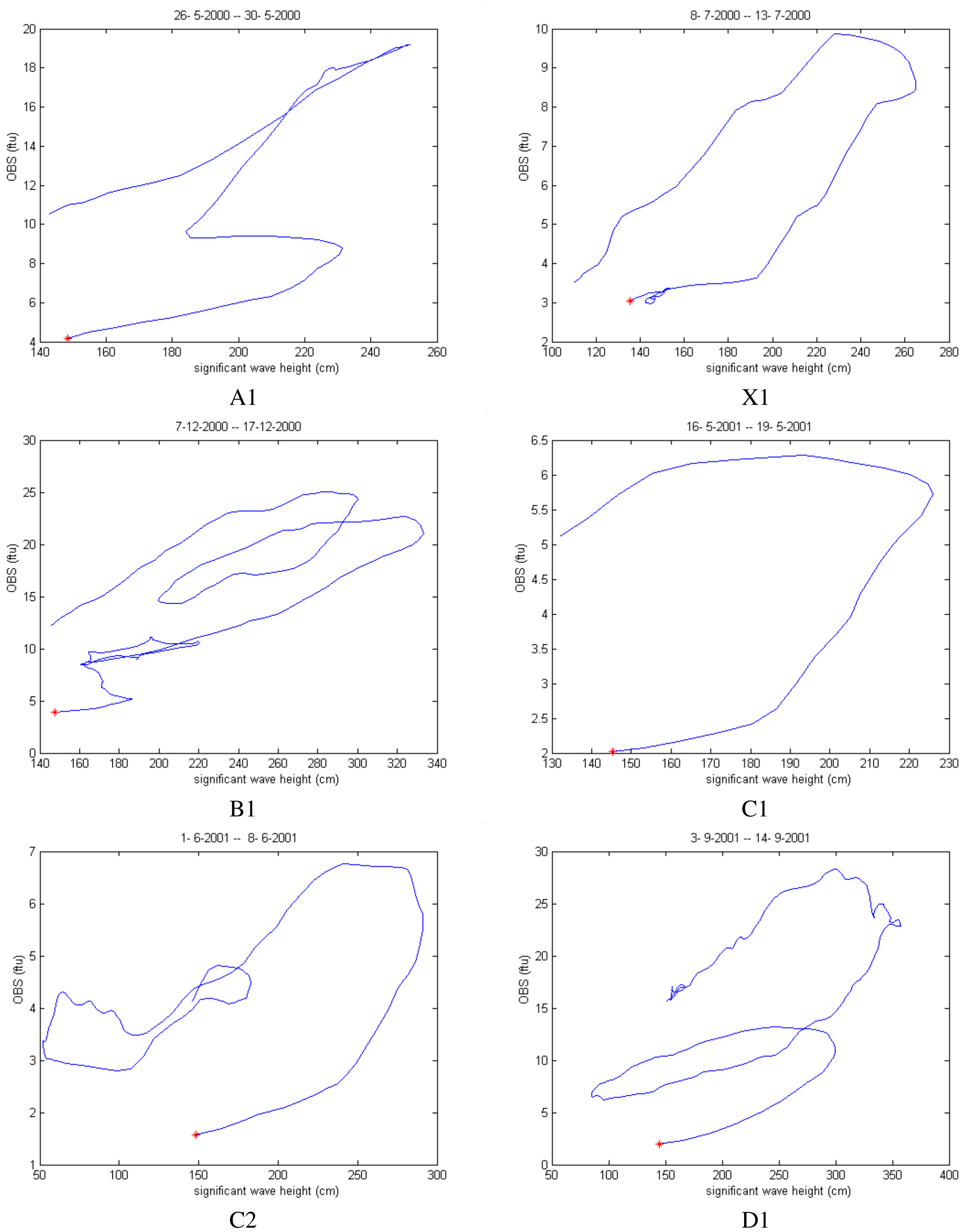
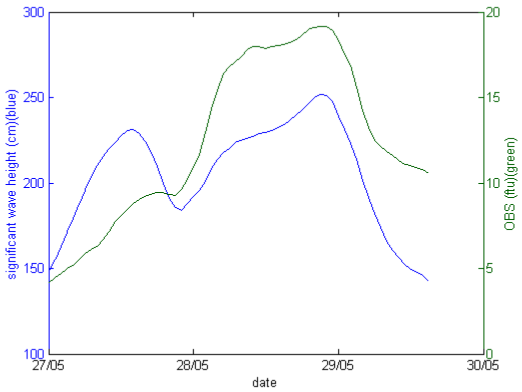
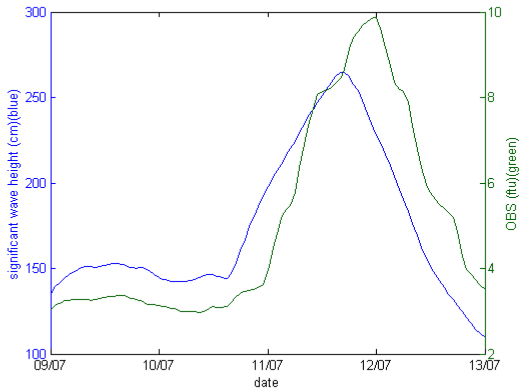


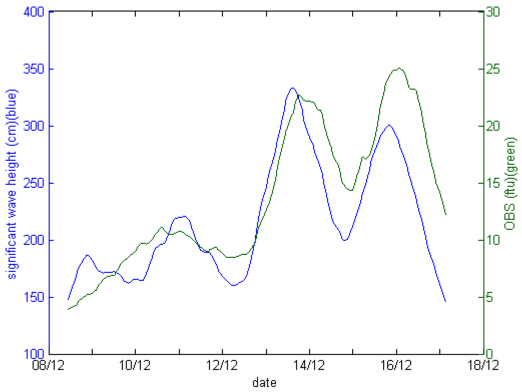
Figure 2.10: Noordwijk 10. OBS data versus significant wave height for different storms.



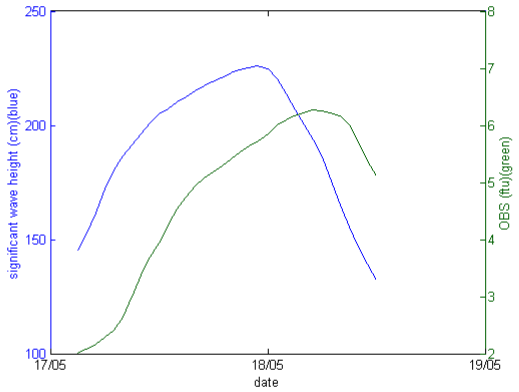
A1



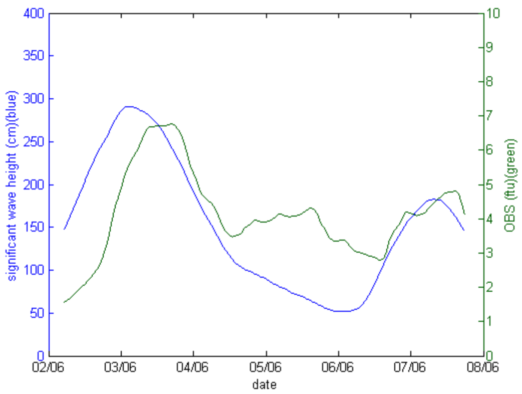
X1



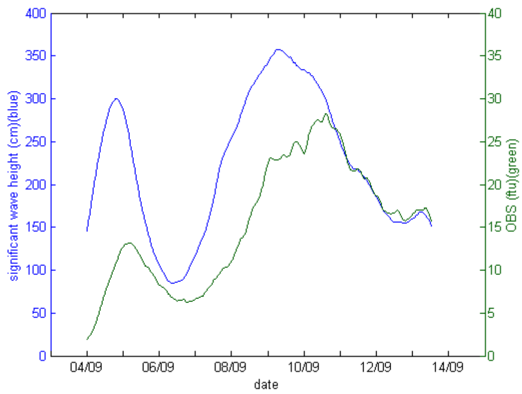
B1



C1



C2



D1

Figure 2.11: Noordwijk 10. Low- pass OBS data and low-pass significant wave height for different storms

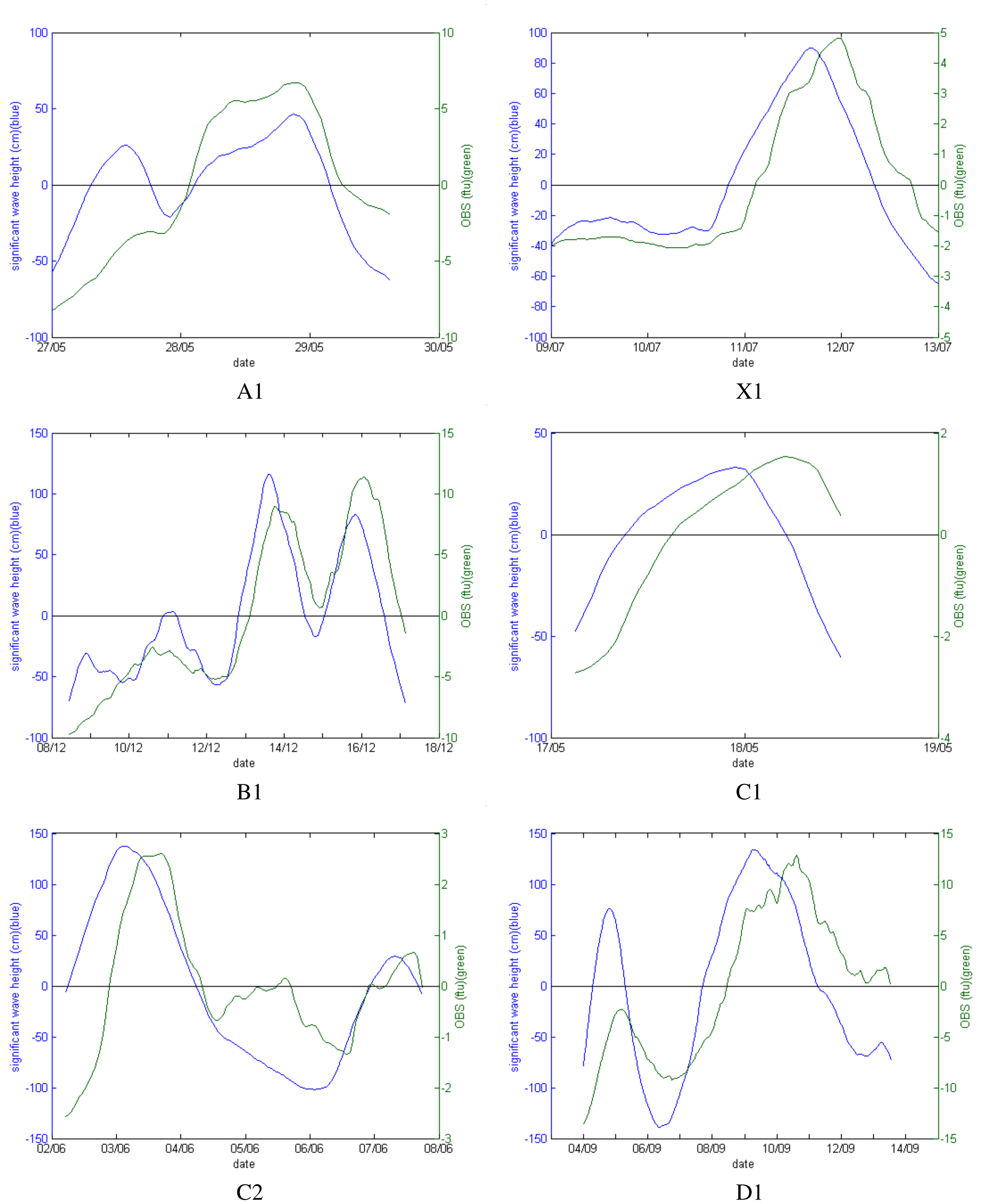


Figure 2.12: Noordwijk 10. Low-pass OBS data and low-pass significant wave height for different storms after removing the mean over the time series. For mean OBS values see Table 2.3

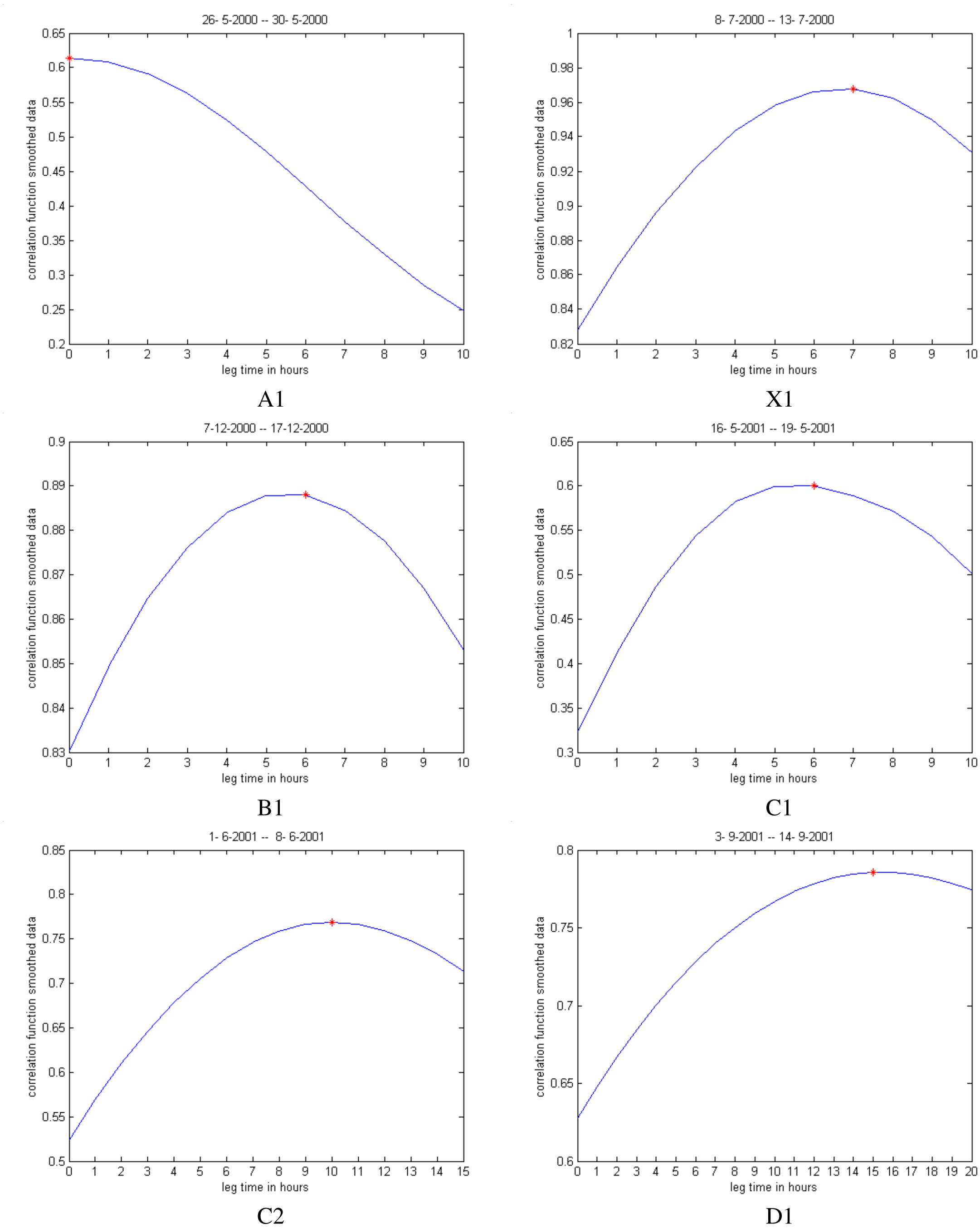
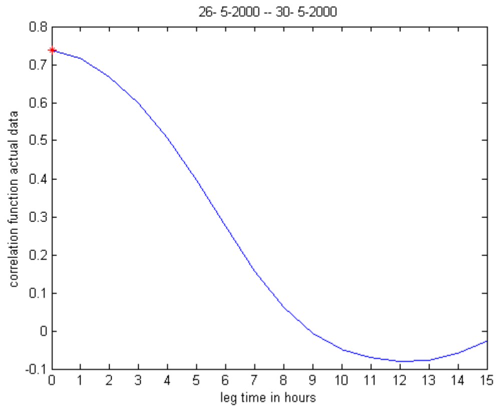
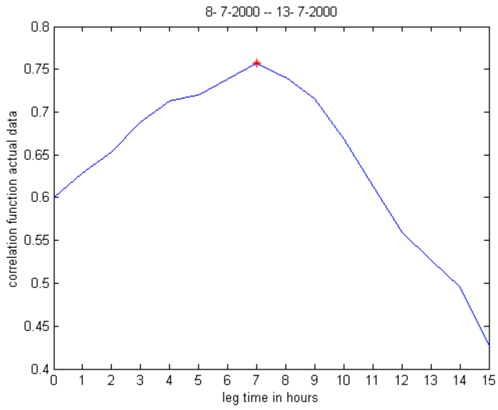


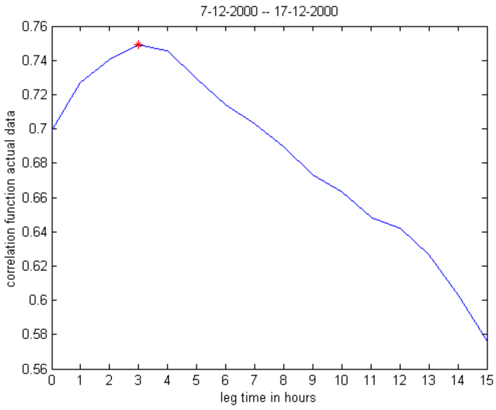
Figure 2.13: Noordwijk 10. Correlation function for suspended sediment concentration and significant wave height for different time lags (low-pass filtered data)



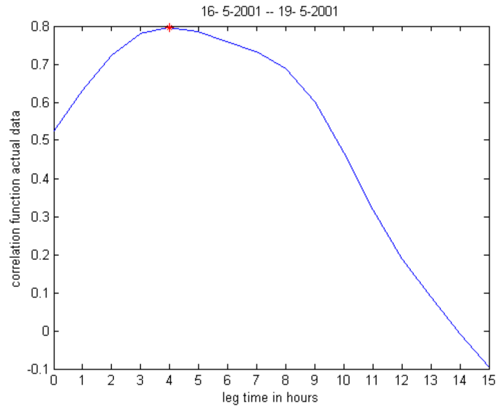
A1



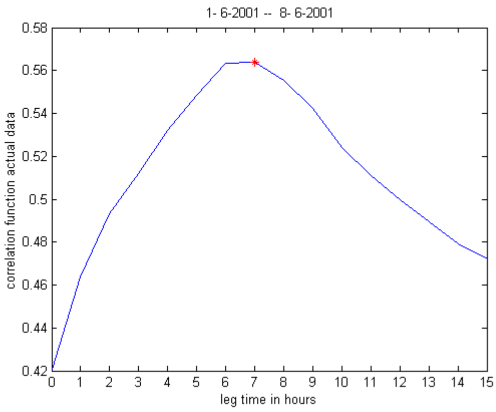
X1



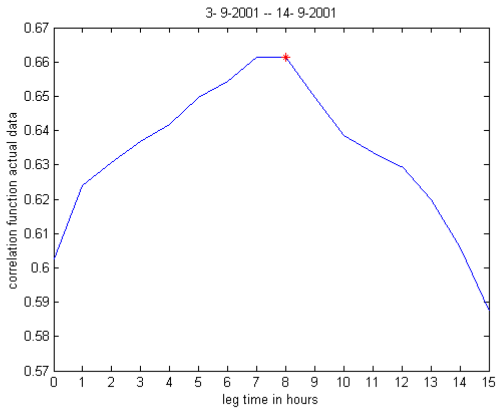
B1



C1



C2



D1

Figure 2.14: Noordwijk 10. Correlation function for suspended sediment concentration and significant wave height for different time lags (actual data)

3. SUSPENDED SEDIMENT CONCENTRATION AT NOORDWIJK 5.

3.1 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 (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 2.3.

3.2 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- 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. 3.1. For definition of "tidal strength" see 2.2. Visual inspection shows little correlation between OBS and "tidal strength". OBS shows considerable variation in the tidal period band. This is further investigated using the power spectrum of the OBS (Fig. 3.1). 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 a result of resuspension of sediment during the ebb and flood phase. Variations with a period of 12 hours are contributed to along-coast gradients in the sediment concentration passing by the measurement station.

3.3 Sediment concentration during storm periods

Within the measurement period two storms can be identified. The storm periods together with maximum significant wave height, mean and variance of OBS are presented in Table 3.1

Table 3.1

Noordwijk 5. Maximum significant wave height, 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. 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 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 3.2

Table 3.2

Noordwijk 5. Maximum significant wave height and variance of low-pass and high-pass filtered OBS data for different storms

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. 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, 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 3.4. 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 most likely dominated by corresponding variations in significant wave height.

3.4 Time lag between significant wave height and OBS at Noordwijk 5

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 two storms listed in Table 3.1, the OBS is plotted versus the significant wave height in Fig.3.5. 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. 3.6 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.3.7. 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 3.8 and 3.9. Maximum values of *cf* and the corresponding lags are presented in Table 3.3

Table 3.3

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

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	0.8051	9	0.4528	9
ii	18-03-02 04h – 20-03-02 18h	0.8232	6	0.4472	0

Except for the value for storm (ii) in column 6, values of the time lag in Table 3.3 reasonably agree with the earlier estimate of 5-10 hours based on visual inspection of the plots in Fig. 3.7. Time lags for maximum correlation are somewhat higher for the low-pass filtered data than for the actual data (compare columns 4 and 6 in Table 1.5). The anomalous value for storm (ii) 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 the same as 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.

24-03-02 0h – 05-04-02

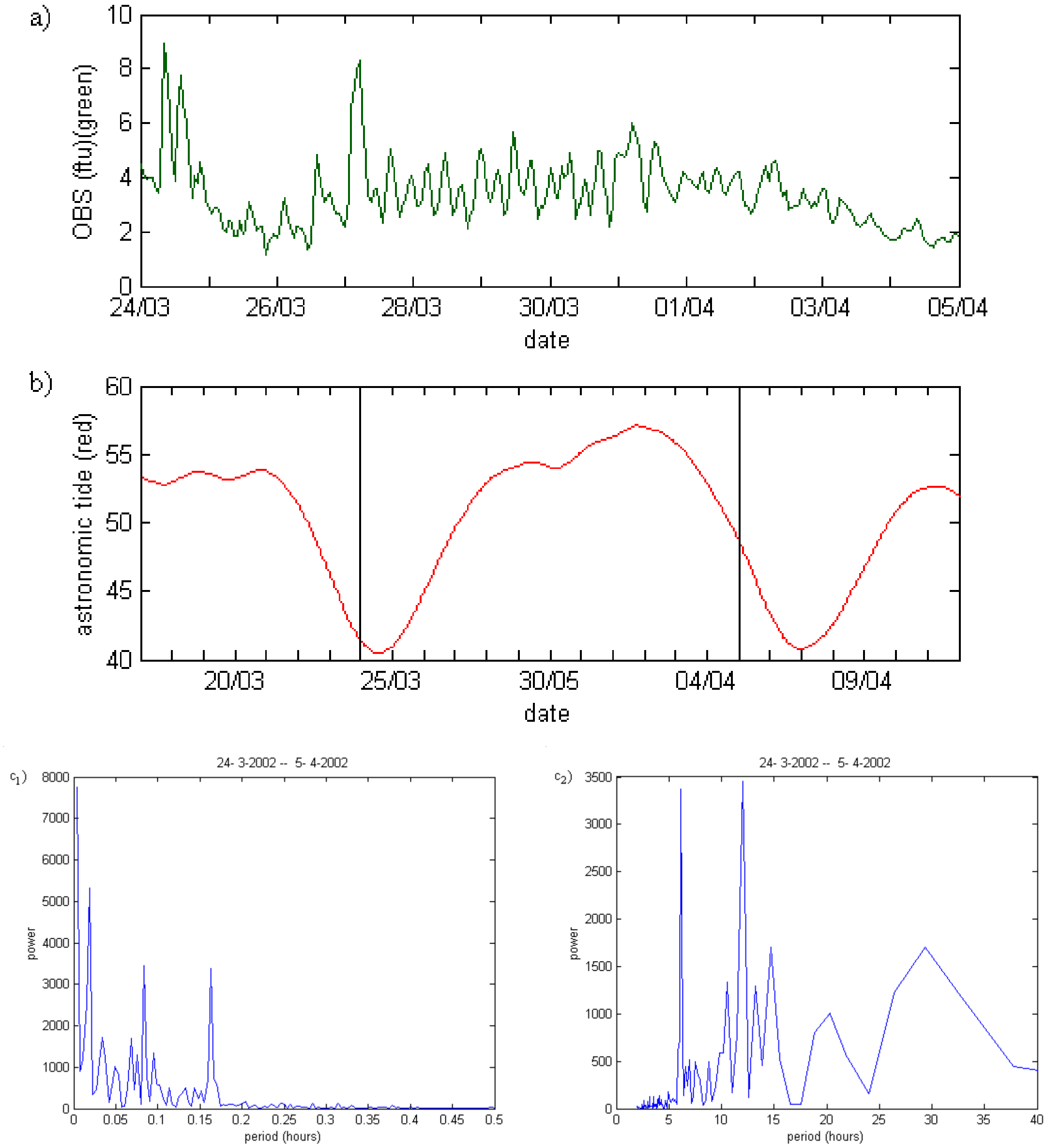
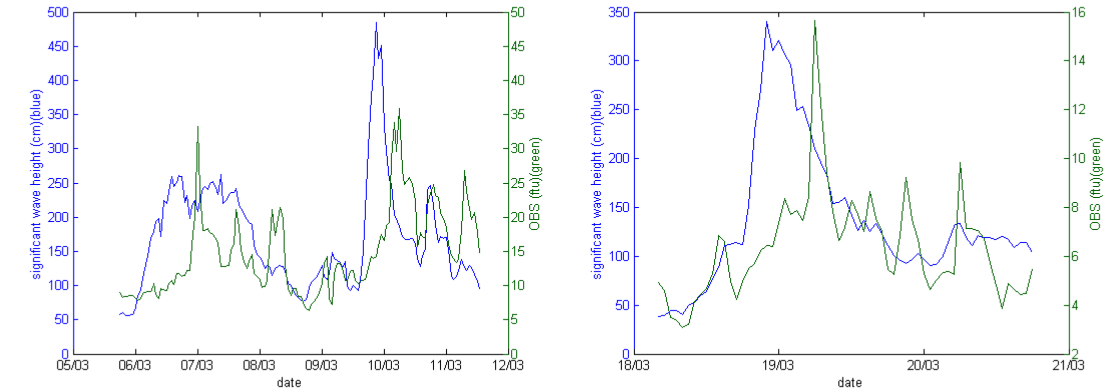
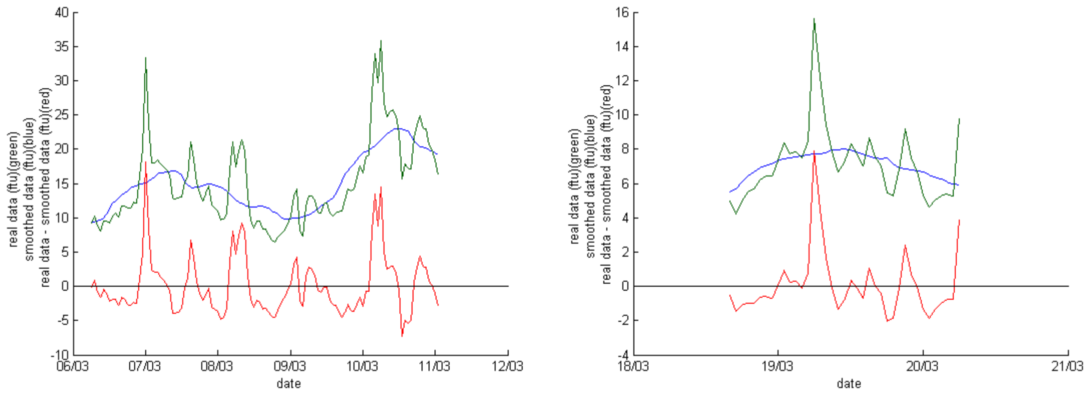


Figure 3.1: Noordwijk 5. Period of relative calm 24-03-02 0h – 05-04-02 0h. a) OBS, b) “tidal strength”, c) power spectra OBS.



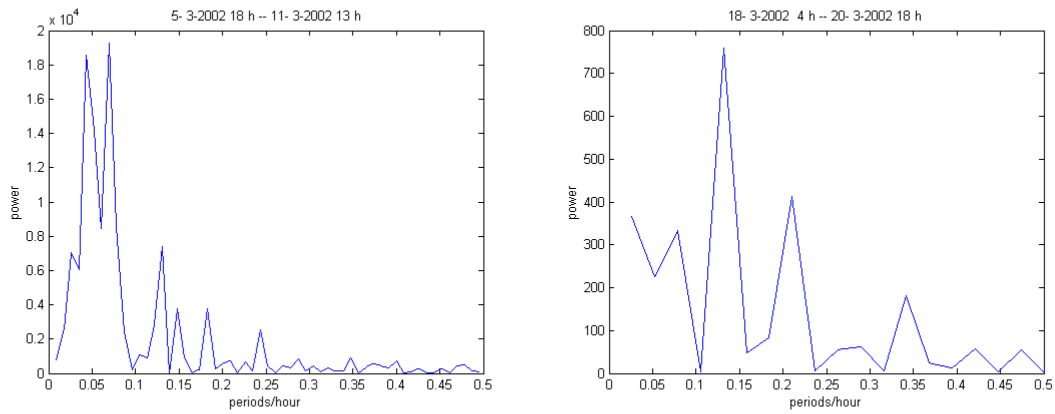
i ii

Figure 3.2: Noordwijk 5. Hourly values of OBS and significant wave height for different storm periods



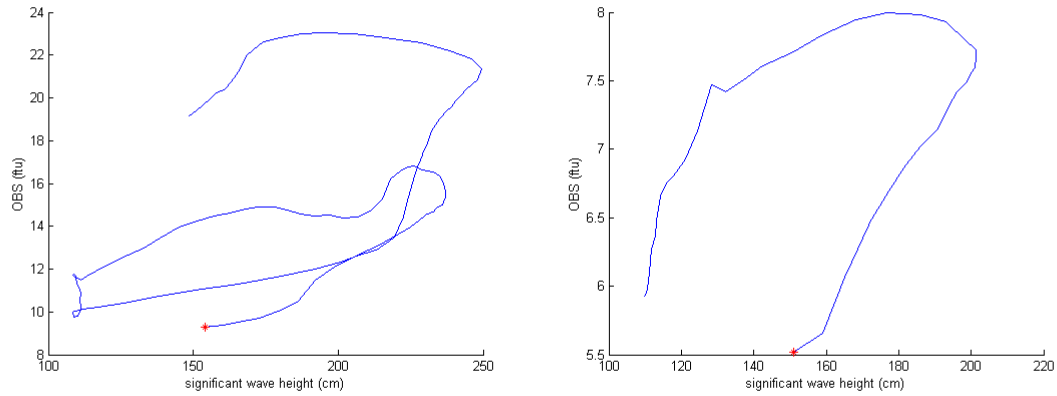
i ii

Figure 3.3: Noordwijk 5. Actual, 25 hour low-pass and 25 hour high-passfiltered OBS data for different storms



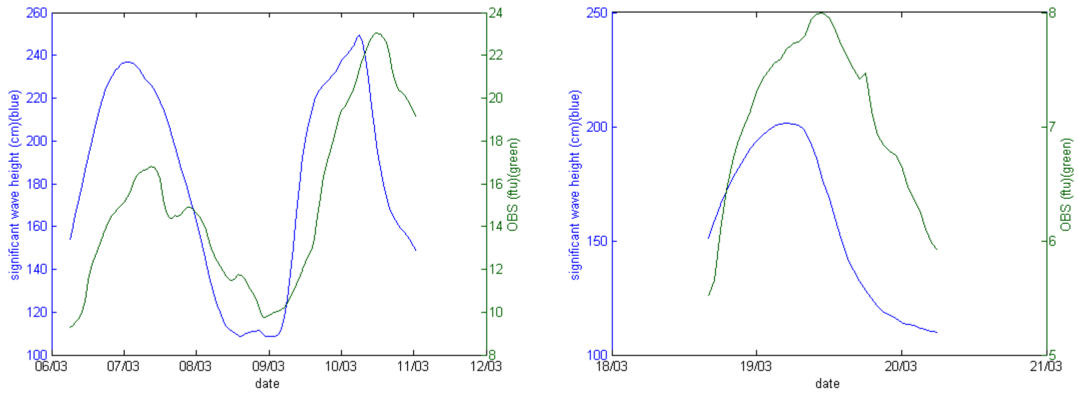
i ii

Figure 3.4: Noordwijk 5. Power spectral density for 25 hour high-pass filtered OBS data for different storms



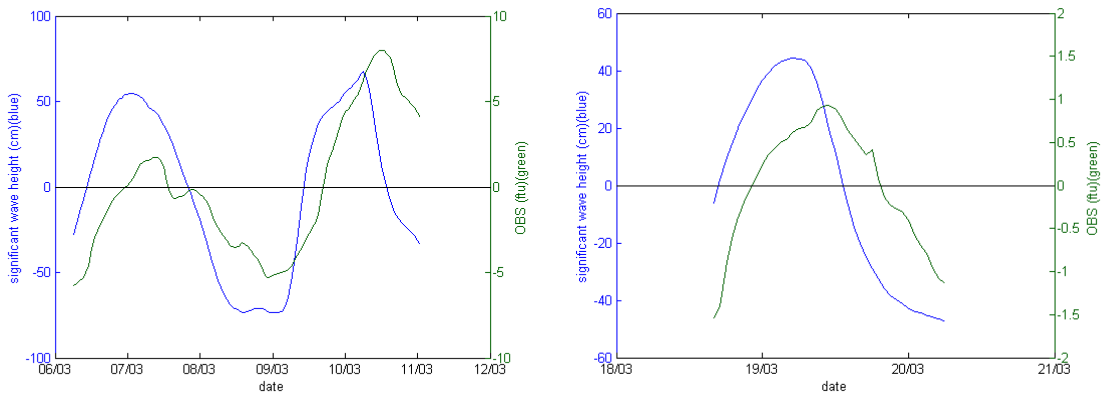
i ii

Figure 3.5: Noordwijk 5. OBS data versus significant wave height for different storms.



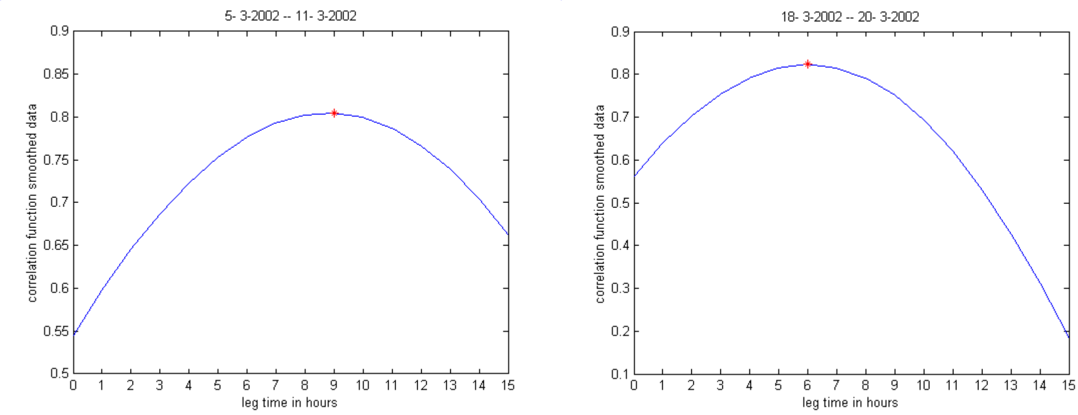
i ii

Figure 3.6: Noordwijk 5. Low-pass OBS and low-pass significant wave heightr for different storms



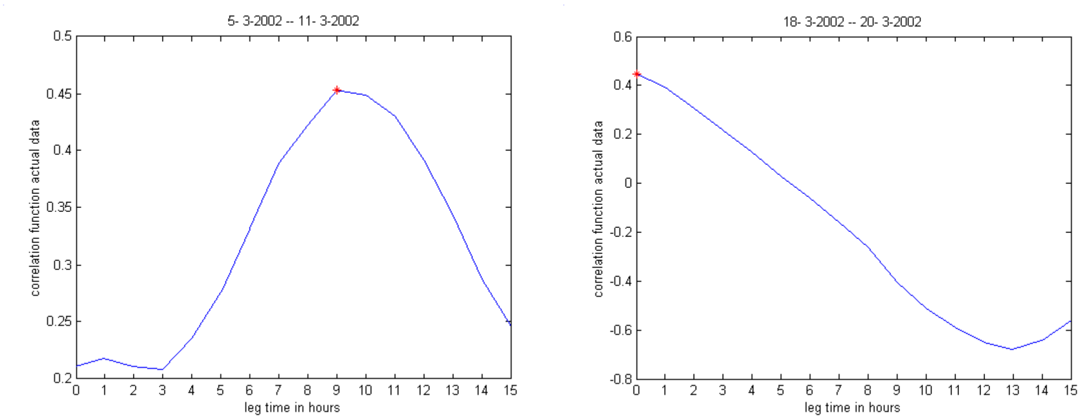
i ii

Figure 3.7: Noordwijk 5. Low-pass OBS data and low-pass significant wave height for different storms after removing the mean over the time series. For mean OBS values see Table 3.1



i ii

Figure 3.8: Noordwijk 5. Correlation function for suspended sediment concentration and significant wave height for different time lags (low-pass)



i ii

Figure 3.9: Noordwijk 5. Correlation function for suspended sediment concentration and significant wave height for different time lags (actual data)

4. SUSPENDED SEDIMENT CONCENTRATION AT NOORDWIJK 2

4.1 Observations

During the period 18-09-01 – 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 (2002) . As a result of fouling during certain periods the OBS sensors occasionally malfunctioned. Two periods of continuous data were selected for further analysis. The mean and variance of these periods are presented in Table 4.1.

Table 4.1

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 1.4.

4.2 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 – 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. 4.1. For definition of "tidal strength" see 1.2. Visual inspection shows no 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. 4.1. 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.

4.3 Sediment concentrations during storm periods

Within the measurement period five storms can be identified. The storm periods together with maximum significant wave height, mean and variance of OBS are presented in Table 4.2.

Table 4.2

Noordwijk 2. Maximum significant wave height, 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. 4.2. 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 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 4.3

Table 4.3

Noordwijk 2. Maximum significant wave height and variance of low-pass and high-pass filtered OBS data for different storms

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. 4.3. 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, there are in storm clearly variations with a 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 4.4. In all storm there is a clear presence of energy in the 12 and 24-hour period band. In addition Storm (I) hsows a significant contribution in the 6-hour period band.

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

In section 4.3 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 4.2, the OBS is plotted versus the significant wave height in Fig.4.5. 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. 4.6 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.4.7. 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 4.8 and 4.9. Maximum values of *cf* and the corresponding lags are presented in Table 2.4.

Table 4.4

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

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	0.7786	8	-0.1930	14
II	04-11-01 02h – 11-11-01 15h	0.6227	2	0.3598	0
III	20-11-01 10h – 24-11-01 16h	0.9030	0	0.6401	0
IV	03-12-01 21h – 07-12-01 03h	0.8056	4	0.6855	8
V	18-12-01 20h – 23-12-01 18h	0.5761	0	0.6349	0

When using the low-pass filtered data the calculated lags reasonably agree with the lags estimated from Fig 4.7 with the possible exception of Storm V. For this storm calculations should have been carried out with negative lag values to determine the lag value that leads to a maximum correlation. 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 relative large part of the variance in OBS; compare variances in Tables 2.4, 3.2 and 4.3. Taking storm I as an example, OBS values exhibit strong variations in the 12 hour period band (Fig. 4.4).

These variations are not present in the wave height (Fig 4.2) leading to a low and even negative correlation (last column in Table 4.4).

07-12-01 0h – 17-12-01 0h

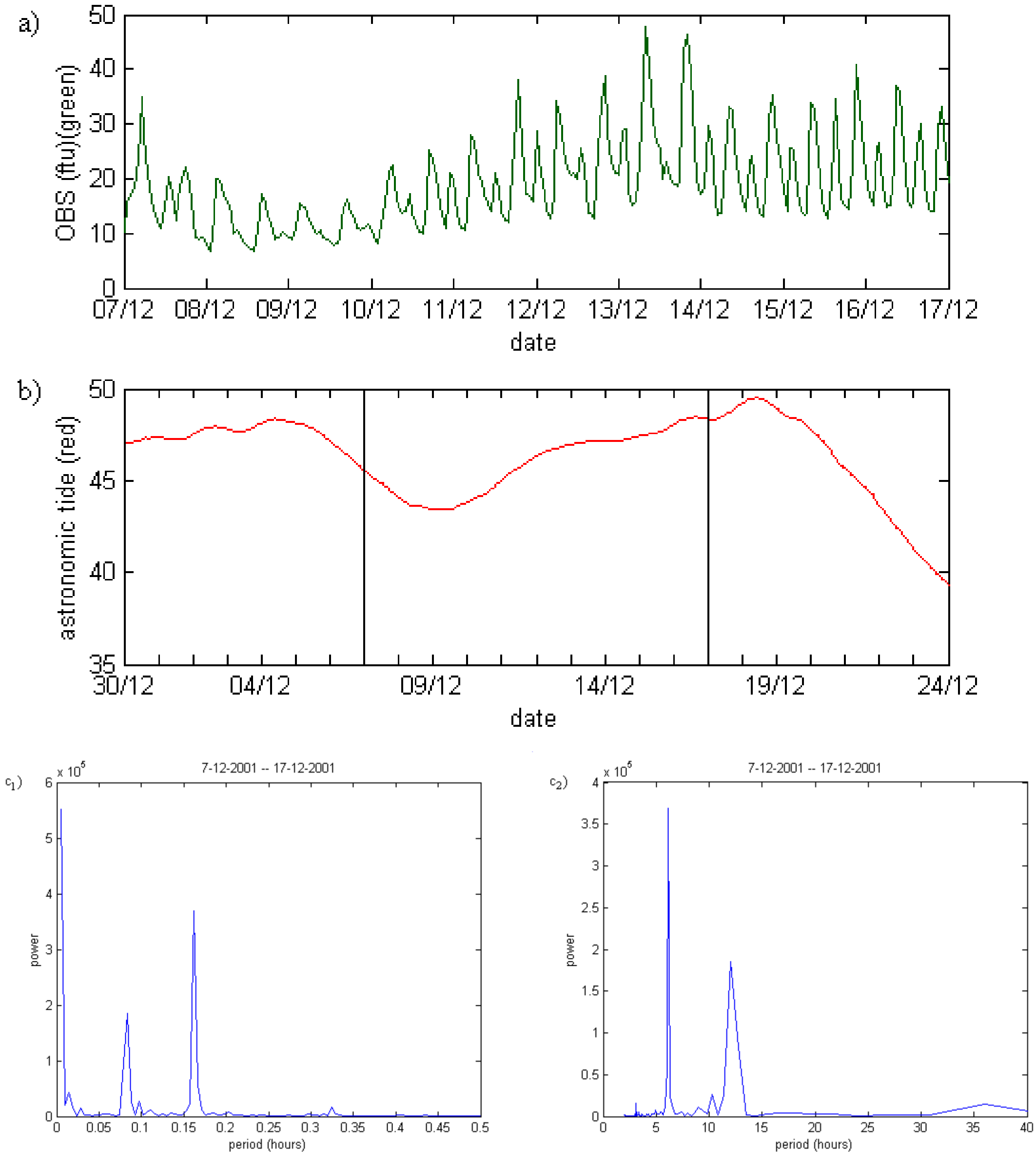


Figure 4.1: Noordwijk 2. Period of relative calm 07-12-01 0h – 17-12-01 0h. a) OBS, b) "tidal strength", c) power spectra OBS.

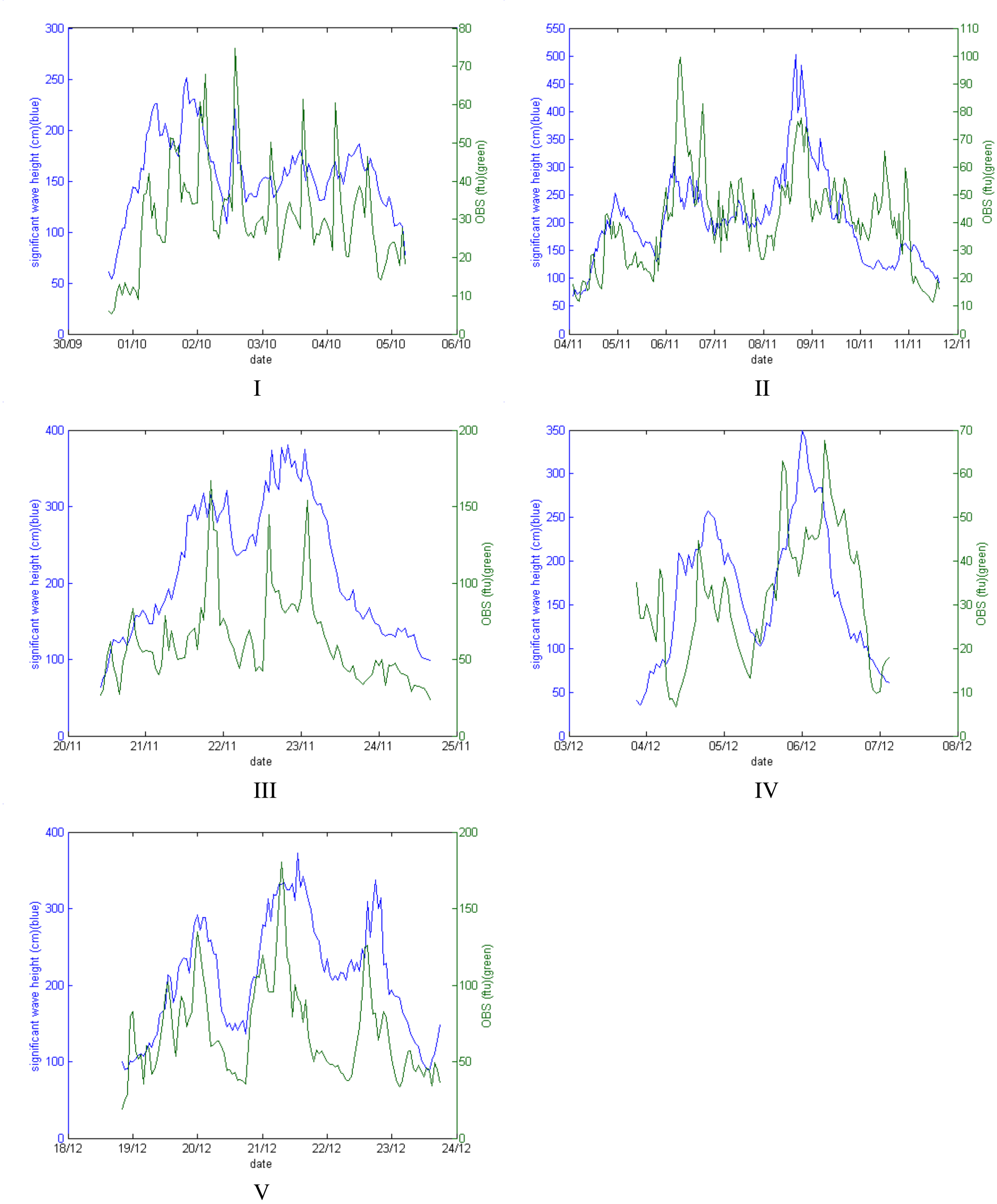


Figure 4.2: Noordwijk 2. Hourly values of OBS and significant wave height for different storm periods

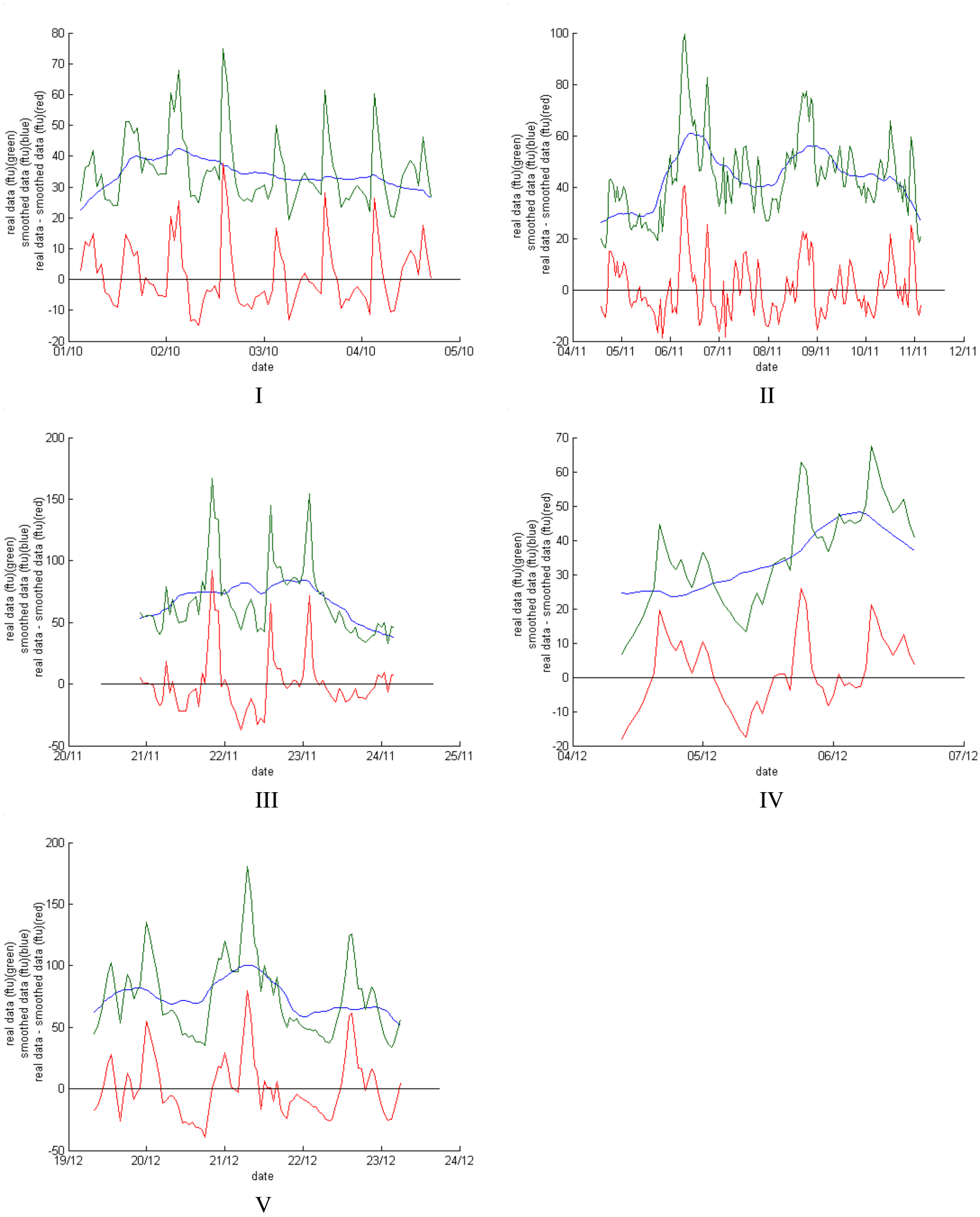


Figure 4.3: Noordwijk 2. 25 hour low-pass and 25 hour high-pass filtered OBS data for different storms.

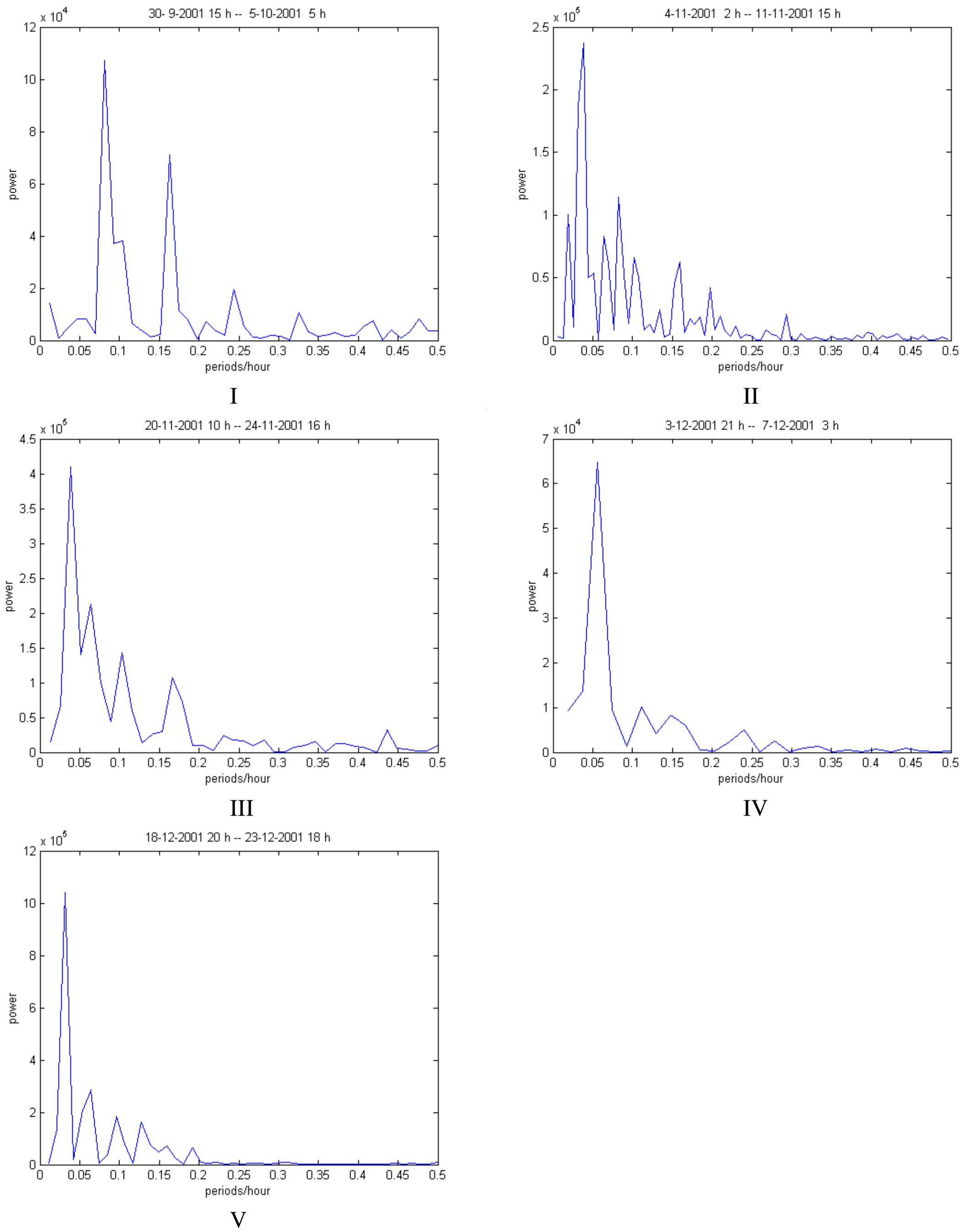


Figure 4.4: Noordwijk 2. Power spectral density for 25 hour high-pass filtered OBS data for different storms.

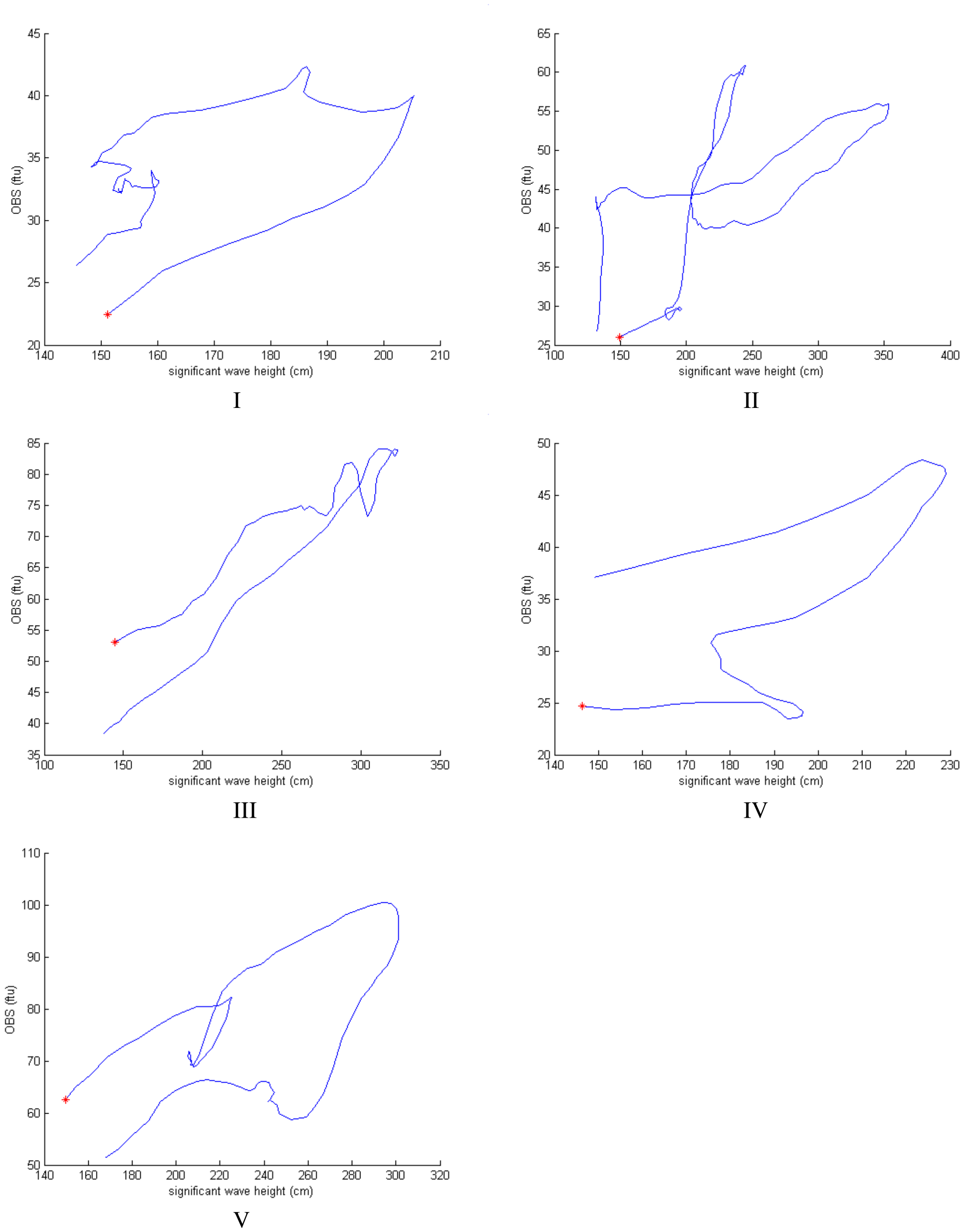


Figure 4.5: Noordwijk 2. OBS data versus significant wave height for different storms.

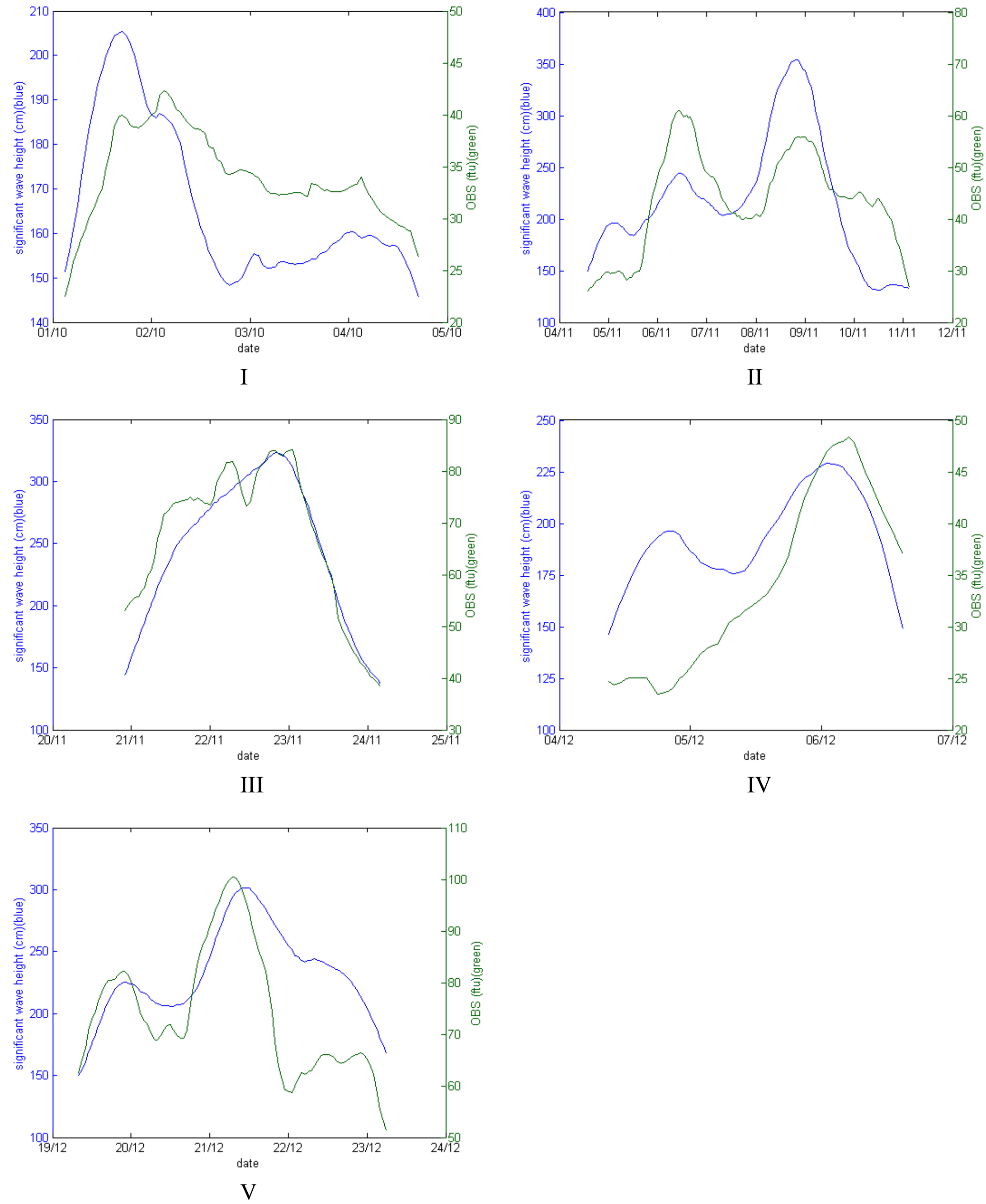


Figure 4.6: Noordwijk 2. Low-pass OBS data and low-pass significant wave height for different storms.

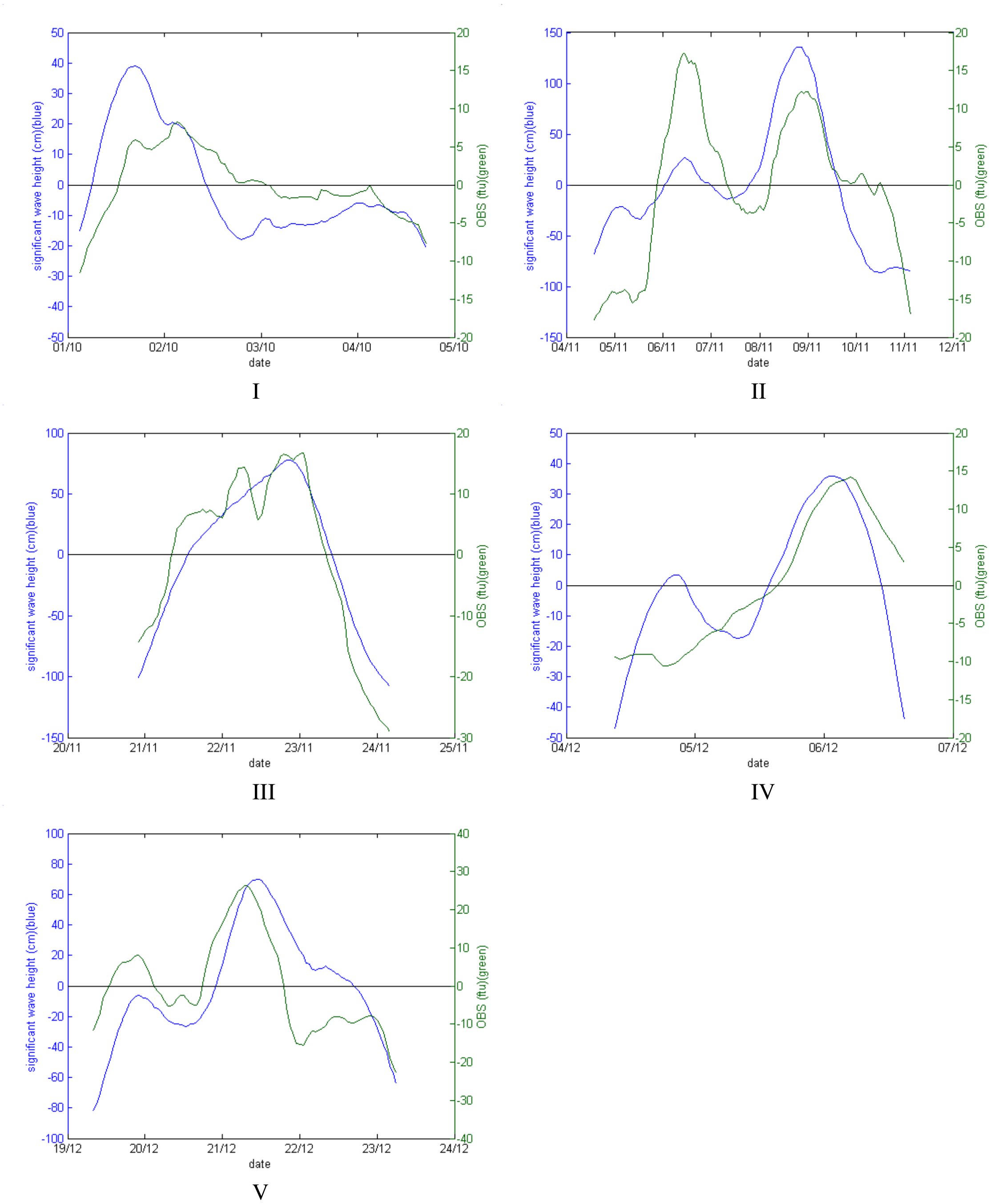


Figure 4.7: Noordwijk 2. Low-pass OBS data and low-pass significant wave height for different storms after removing the mean over the time series. For mean OBS values see Table 2.1

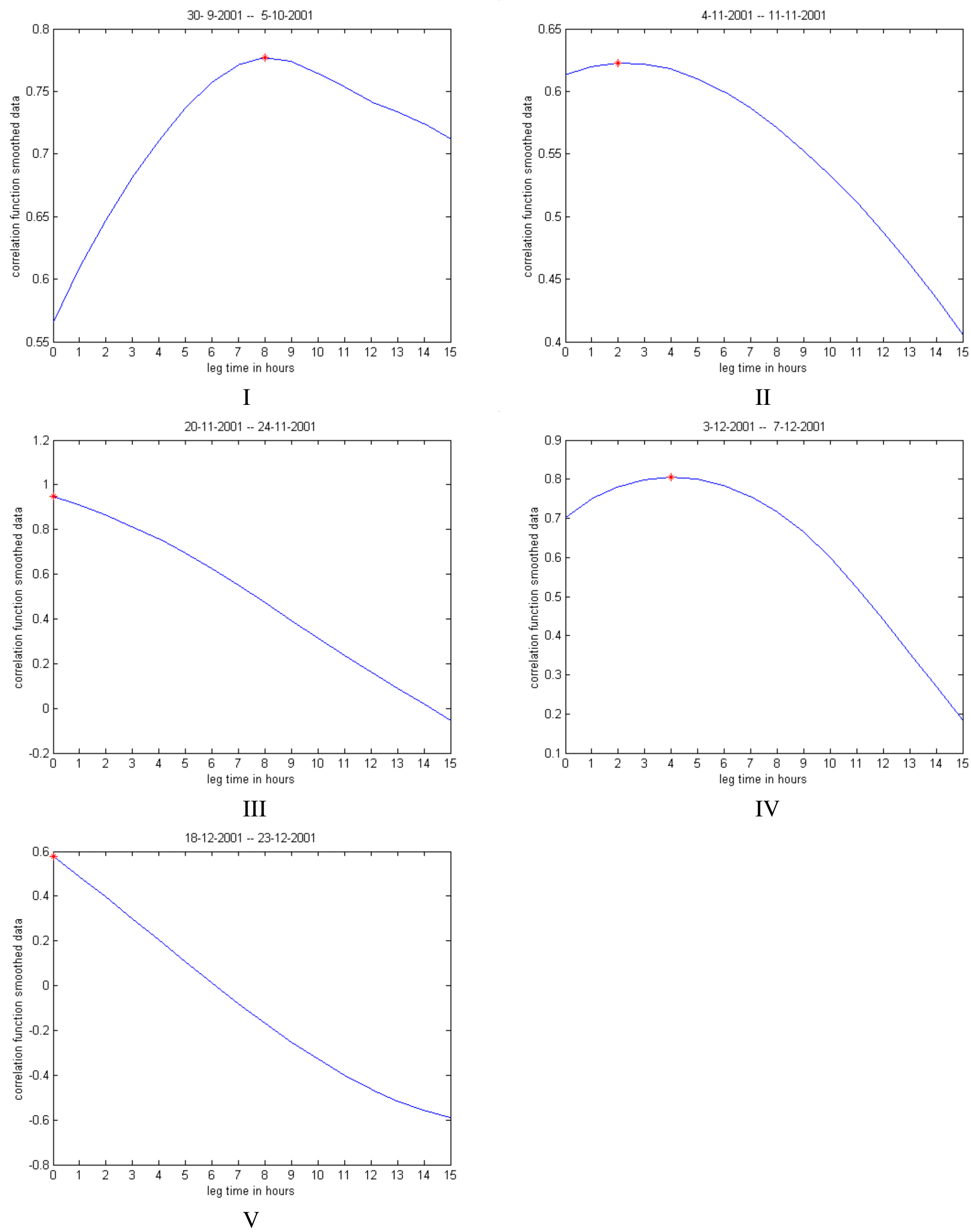


Figure 4.8: Noordwijk 2. Correlation function for suspended sediment concentration and significant wave height for different time lags.9 (low-pass filtered data)

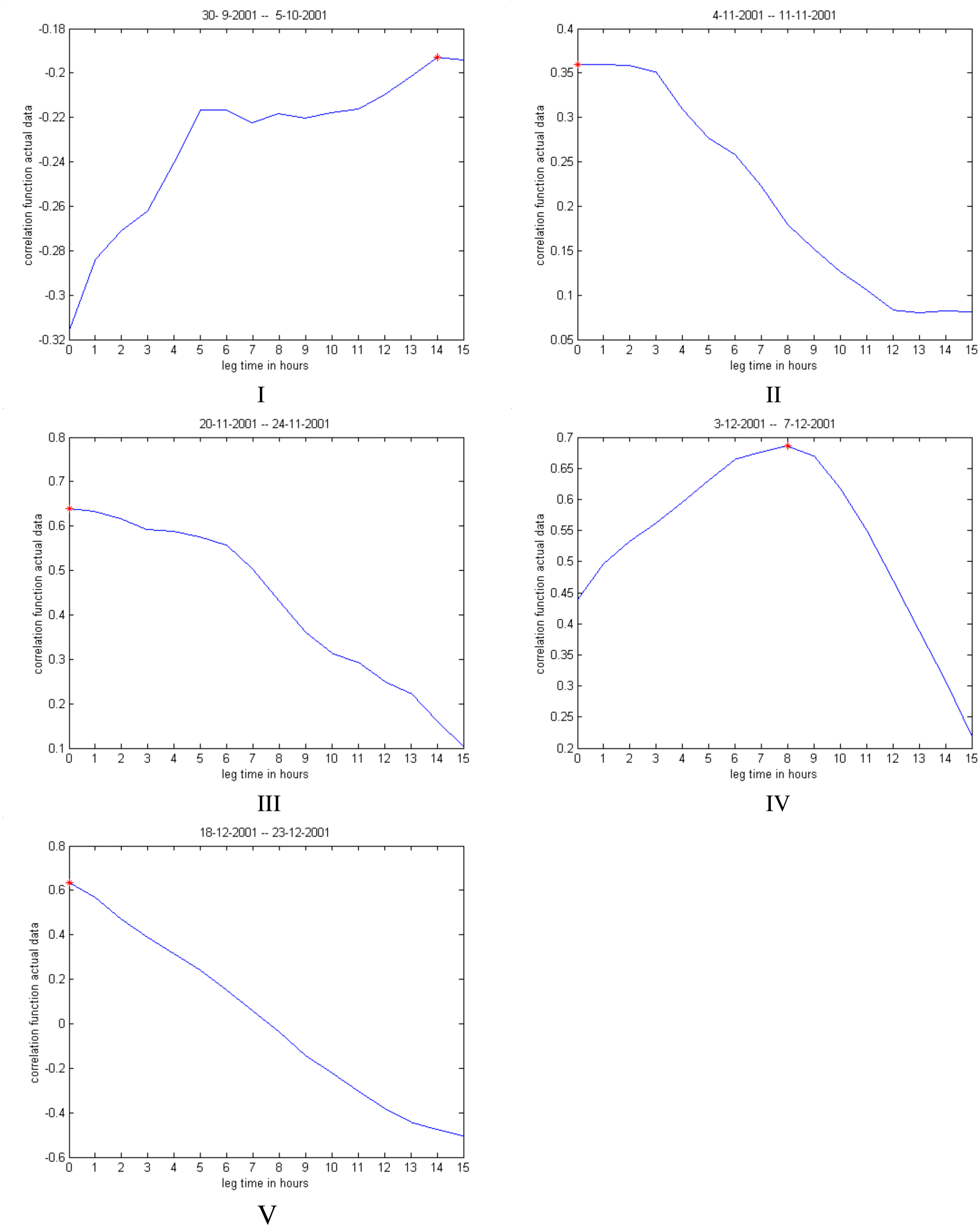


Figure 4.9: Noordwijk 2. Correlation function for suspended sediment concentration and significant wave height for different time lags (actual data)

5. SUMMARY AND CONCLUSIONS

OBS values and variations are forced by waves and tidal currents. Of the two, 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.

Restricting attention to the observations during the summer period, mean OBS values are 3.9 ftu at Noordwijk 10, 5.6 ftu at Noordwijk 5 and 21.9 ftu at Noordwijk 2. Assuming 1 ftu corresponds to approximately 1 mg/l TSM (Mills, 2002), these values are within the range of long term averaged TSM values of 5-10 mg/l for Noordwijk 5 and 10 and 10-20 mg/l for Noordwijk 2 (Suijlen en Duin, 2002). The corresponding mean values for the winter period are, 6.5 ftu at Noordwijk 10 and 32.2. ftu at Noordwijk 2. No measurements were carried out at Noordwijk 5 during the winter period. The long term averaged TSM values for the winter period are 5-10 mg/l for Noordwijk 10, 10-20 mg/l for Noordwijk 5 and 30-100 mg/l for Noordwijk 2.

The observational data during periods when the significant wave height was less than 1m does not show obvious spring-neap variations in OBS. However, there are distinct variations in the OBS in the diurnal and semi-diurnal 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.

OBS during storm periods is characterized by a trend with a relative steep increase and a more gentle decrease. Superimposed on the trend are variations with periods of less than 24 hours. For Noordwijk 10 and 5 the contribution of the daily variations and the trend to the total variance are approximately the same. (Tables 2.4 and 3.2). For Noordwijk 2, the contribution of the daily variations is much larger than the contribution of the trend (Table 4.3).

Analysis of the daily variations in OBS show 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 shallower depth at this station, 10 m at Noordwijk 2 and 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.

For most storms the trend in OBS resembles the trend in significant wave height. In general the wave height leads the OBS. For Noordwijk 10 and 5 the average time lag, corresponding to a maximum in correlation between 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 equal to 2.5 hours with some storms showing a slightly negative time lag i.e. OBS leads significant wave height; see Table 4.4. The average correlation coefficient, corresponding to the time lag for Noordwijk 10, 5 and 2 are respectively 0.76, 0.81 and 0.75 (Tables 2.5, 3.3 and 4.4)

Although this was not extensively investigated, a comparison of mean OBS and maximum significant wave height during storms shows that a simple correlation between these variables is not to be expected. For this see Tables 2.3, 3.1 and 4.2. Obviously other factors, in addition to wave height, play a role in establishing the OBS value. The first one of those that comes to mind is the availability of silt in the bottom.

From the foregoing it follows that OBS values and variations 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.

REFERENCES

Bendat, J.S. and A.G.Piersol, 1971. Random Data: Analysis and measurement procedures.Wiley-Interscience

Mills, D.K., 2002. Developing a common UK- Netherlands approach to North Sea monitoring. Werk document RIKZ/OS/2002.409.

Seapoint - http://www.seapoint.com/stm/html

Suijlen, J.M. and R.N.M.Duin, 2002. Atlas of near-surface total suspended matter concentrations in the Dutch coastal zone of the North sea. Report RIKZ/2002.059