Sea State Report

Norfolk
(Year 2 Oct 2007 – Sept 2008)

RP019/N/2010

October 2010

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We operate at the place where environmental change has its greatest impact on people's lives. We reduce the risks to people and properties from flooding; make sure there is enough water for people and wildlife; protect and improve air, land and water quality and apply the environmental standards within which industry can operate.

Acting to reduce climate change and helping people and wildlife adapt to its consequences are at the heart of all that we do.

We cannot do this alone. We work closely with a wide range of partners including government, business, local authorities, other agencies, civil society groups and the communities we serve.

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Anglian Coastal Monitoring Programme Phase VII 2006/07 – 2010/11

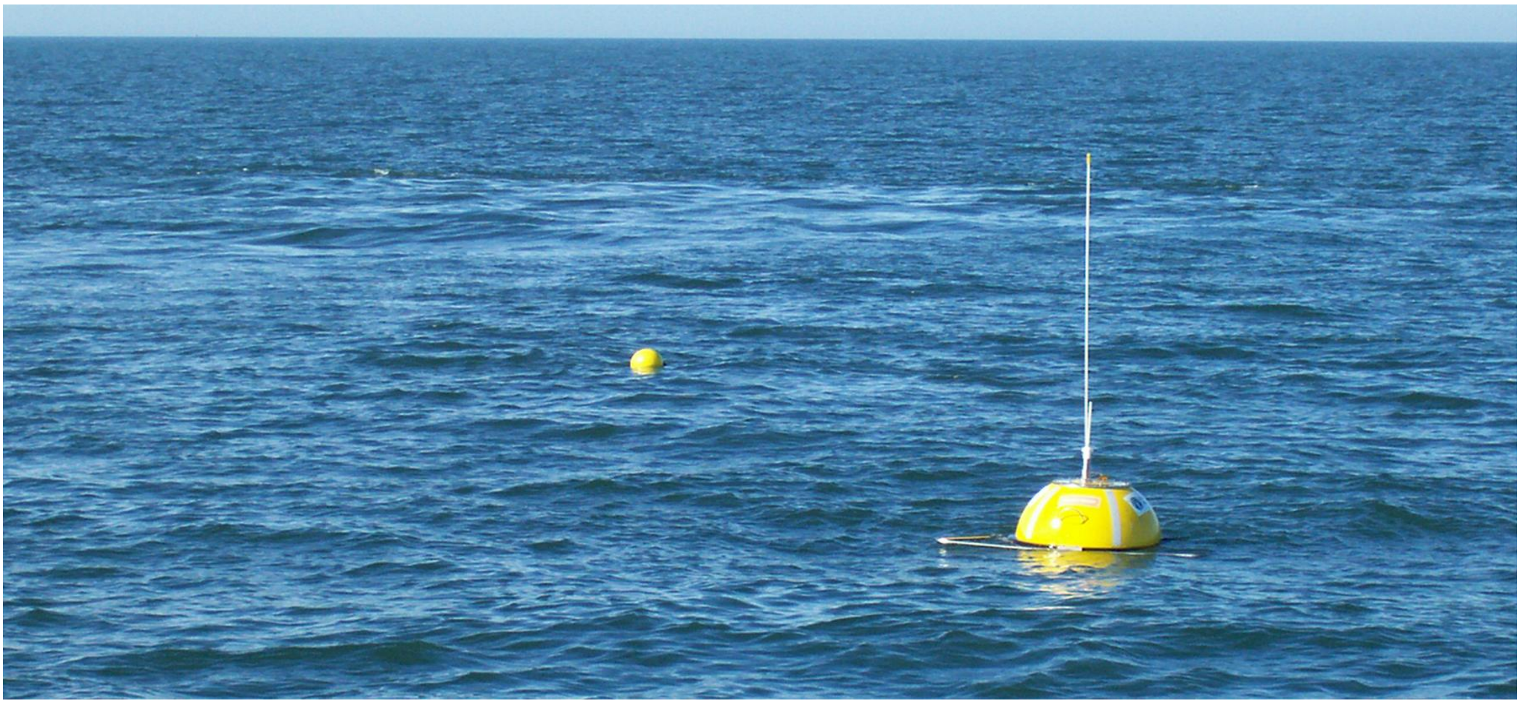

Figure 1: Map of instrument locations

Anglian Coastal Monitoring Programme VII

Wave & tide monitoring

The Shoreline Management Group (SMG) based within the Regional Flood & Coastal Risk Management department of the Environment Agency (EA) (Anglian Region) provides strategic monitoring of the Anglian coast through the 'Anglian Coastal Monitoring Programme'. Phase VII of this programme runs from 2006/07 to 2010/11. For wave and tide monitoring, a network of five Directional Waverider (DWR) buoys and 20 Acoustic Wave And Current meters (AWACs) measured offshore and nearshore sea conditions respectively, along the regional frontage over a 3 year period (2006 – 2009). The positioning of the instruments (Figure 1) provides comprehensive coverage of the region and measurements at key areas of interest regarding wave conditions and coastal processes. In addition this 3 year monitoring period is considered to be broadly sufficient to assemble a dataset able to support future mathematical modelling, and better understand the dynamic mechanisms acting along our coast.

It is hoped that in time, we can create statistical or transformation wave models, to better inform us of the wave climate and that a model would serve to show wave conditions inshore calculated from offshore buoy observations. This will lead to a dataset for statistical forecasting of extreme conditions to assist in flood forecasting and flood risk management. It is also hoped that in the future the wave and currents data can be combined with sediment models to identify the transportation and movement of sandbanks, annual beach sediment movement and erosion following storm events and the impact of sea level rise throughout the region.

The DWR buoys provide real-time wave spectra and GPS positions via satellite link. The real-time wave data is uploaded to the "WaveNet"[1] website maintained by the Centre for Environment, Fisheries and Aquacultural Science (Cefas) on behalf of the Department of Environment Food & Rural Affairs (Defra), allowing public access to the programme's real-time monitoring data.

Wave climate & sea state reports

This report presents processed onboard instrument logged data from the four AWAC instruments and one offshore buoy located along the Norfolk coast. Logged data is processed and quality checked by our survey contractor, Gardline Environmental[2]. The QA process for the AWACs uses Nortek's control software[3] and includes compass, pressure drift, acoustic degradation checks and tide level adjustment to Ordnance Datum (Newlyn). There are further adjustments for atmospheric pressure, accounting for instrument 'settling' periods, such as frame settlement on the bed and an initial temperature offset and differences in AWAC deployment periods. The wave buoys are fully calibrated before deployment and data translation and processing is carried out using the instrument manufacturer's software including Datawell's W@ves 21[4].

The data used within this series of sea state reports is not entirely continuous. The monitoring programme is subject to disruption, the DWR buoys are vulnerable to accidental and intentional damage from shipping traffic. The AWAC instruments are occasionally moved by trawling activities. The AWACs are also subject to burial as sediment accumulates over the 2 month deployment period; this is especially notable in The Wash.

This is the second of three sea state reports that will be produced annually for the region during phase VII. To date the AWACs have now been recovered, with delivery of a final year of quality checked records to be available shortly. The buoys are now maintained by Cefas, with funding from the SMG and the UK Coastal Monitoring and Forecasting service (UKCMF). This has allowed the buoys to remain in-situ and for continued wave recording.

The specific aims of this and subsequent reports are to

- Analyse wave parameters and water elevations at each instrument in a regional context
- Summarise the wave climate and sea state in the region
- Compare annual variability with the previous year
- Identify storm and significant surge events

The Anglian Coastal Monitoring programme's wave and tide data feed into many aspects of Environment Agency work such as modelling the impact of waves on existing flood defences, flood forecasting, and incorporation in to Shoreline Management Plans (SMP) to inform policy decision making processes. This report is intended as a tool to assist coastal managers in a variety of their functions including; strategic planning, capital engineering works and maintenance programmes. In addition the report will be of assistance with general education and awareness raising of coastal issues.

The reports and data collected also provide an opportunity for further joint probability studies, identifying extreme offshore and nearshore water levels, wave transformation, tidal propagation and coastal response studies.

The 3 year monitoring period is not sufficient to draw long term conclusions regarding sea and climate trends. Although this report will assess changes in sea state from the previous year, the main purpose of these reports is an assessment of the current sea state influencing the Anglian coast. The report presents the monitoring data to show the types of waves and the seasonal variation over the year and thus gives a picture of the wave climate. The AWAC instruments present the nearshore climate of waves and currents that are complicated by bed topography and the coastline while the wave buoys give an indication of the offshore waves approaching the region's shoreline. Knowledge of the Anglian wave climate is important to determine and model regional movement of sediment and the impact of forces acting on our sea defences, coastal structures and habitats.

Acoustic Wave & Current meter

The 20 AWAC instruments were placed at strategic locations distributed along the 5 coastal monitoring units of the Anglian coast. The instrument sits within a frame on the sea bed at a depth of approximately 6 m Chart Datum (CD) with sensors pointing up towards the surface and recording tidal elevations, waves, currents and surge information.

The AWAC is a current profiler with a directional wave system. The instrument measures current velocity and direction at different bin depths throughout the water column. The AWAC has 3 sensor pads which emit a pulse acoustic signal in different directions radiating out from the instrument towards the surface. The scattered return signal has a Doppler shift with respect to the transmitted signal and this allows the along beam velocity to be calculated. The instrument also has a central sensor pointing vertically at the sea surface, similar to an upward looking echo-sounder, the Acoustic Surface Tracking feature of the instrument gives water depth and non-directional spectrum measurements.

The number of measurements allows the instrument to calculate the velocity and direction of currents throughout the water column, wave direction, heights and identification of long swell waves, wind waves, ship wake, pressure and temperature. The AWACs sample pressure, temperature, currents and acoustic back scatter intensity (ABSI) every 5 minutes at 20, 25, 30, 35, 40, 45, 50 and 55 minutes past each hour. Waves are sampled every hour, with 2048 samples taken at 2 Hz, over 17 minutes. The instrument has a maximum error of +-50 mm for water levels, +5% for waves. However we consider a consistent achievable height accuracy to be 10 mm. AWAC instruments and the onboard logged data were recovered approximately every 6 weeks, with a new instrument redeployed at this time. There were 12 backup AWACs, used to cycle the instruments or as emergency standbys in the event of instrument failure. This allows the Shoreline Management Group a near uninterrupted and continuous record of waves and tides as they enter the shallow waters of our coast.

Photo 1: AWAC in frame being deployed (Photo: Gardline Environmental)

Directional Waverider Mark 2 wave buoy

The DWR buoys provide ‘real-time’ information on waves approaching the Anglian coast. The buoys are moored to the seabed by an elasticated line allowing them to float on the surface and record wave movements. Similar to the AWAC the buoys measure the orbital motions of the water at the surface rather than the surface slope. These continuous measurements are then sent ashore through high frequency radio signals to base stations such as RNLI Life Boat stations. We can then monitor and log these data streams through a broadband internet connection. Wave spectra and GPS positions are also sent via satellites. The real-time wave data is available on the WaveNet[1] website and allows public access to the programme’s wave buoy data.

Every 30 minutes the DWR logs processed spectral data of 2304 samples measured over a 19.2 minute period. The logged spectra have a 64 frequency band energy density resolution. The first 30 minutes of each hour is processed and quality checked to give a representative value of the hour, and is used as comparison against the hourly AWAC data which is sampled over the first 17 minutes of every hour. DWR buoys are serviced approximately every 5 months to check the buoy and retrieve the onboard logged data. There are also 2 back up buoys ready for deployment.

Photo 2: Deployed Waverider buoy (Photo: Environment Agency)

Site Information

Instrument location

Instrument locations match those of previous Norfolk wave and tide monitoring deployments (HR Wallingford, 2003) (Figure 1). Instruments were also located in line with bathymetric transect surveys carried out by the Shoreline Management Group as part of the ACM. As part of Phase VII the bathymetry surveys in Norfolk were carried out in 2007.

AWAC S9N is located offshore of Scolt Head Island (53° 00.027' N 000° 41.065' E) at a depth of approximately 5 m (CD). The AWAC is located in an area relatively sheltered from wave action, and surrounded by shallow water (Figure 2). It has been recognised from previous deployments that this location is stable and that there is little sand suspension during storms.

Scolt Head Island is an area of saltmarsh with vegetated dunes on the north face, as shown in Photo 3. Scolt Head is connected to the mainland and offers good protection from wave impact. The mainland is further protected by vegetated earth embankments with a 1:10 year standard of defence.

Photo 3: Dunes on the north facing coast of Scolt Head Island in 2008 (EA survey transect N1B1).

The S10N AWAC is positioned just north of Cley (52° 57.80' N 001° 04.80' E) in an area of high swell and wave exposure (Photo 4). However the bank of Sheringham Shoal is located approximately 10 km north north-east (Figure 2) and offers some shelter. The instrument is on a stable sea bed although there are high levels of sand suspension during storms.


Photo 4: The shingle ridge at Cley in 2007 (location of EA survey transect N2C8).
(Photo: Environment Agency)

Onshore the coast at Cley has a shingle/gravel beach with a ridge offering a 1:10 year defence standard according to the National Flood and Coastal Defence Database (NFCDD). The ridge was graded with the use of bulldozers, but this profiling stopped after winter 2005, and the ridge is being allowed to take a more natural shape.

AWAC S11N is located at Walcott Gap, north of Happisburgh and south of Mundesley (52° 50.64’ N 001° 30.41’ E). The instrument is situated on a relatively unstable ridge running parallel to the shore approximately 400 m offshore. High levels of sand and gravel are brought up from the bed and held in suspension during storms. Sand ingress has been a problem on instruments previously deployed at Walcott (HR Wallingford, 2003). The site is very exposed with Haisborough Sand bar 14.5 km north east of the instrument (Figure 2).

Photo 5: The sandy beach at Walcott, backed by sheet piling and concrete sea defence at EA survey transect N3C8 at Walcott in 2008. (Photo: Environment Agency)

S12N is deployed about 500 m off the Horsey coast (Photo 6) (52° 45.515’ N 001° 39.77’ E) in a depth of 5 m (CD). The AWAC sits on the same ridge as S11N to the north, and the area has a similar coastal orientation. The location is very exposed with sand suspension during storm events but the bed is considered relatively stable. The bathymetry here slopes down to depths of 50 m within 7 km of the shore. The beach on this frontage is sandy. The frontage has a standard of defence of around 1: 4 years due to the presence of vegetated dunes, embankments, and timber groyne defences.

Photo 6: The beach at Horsey (EA survey transect N3A6) is backed by vegetated dunes and embankments, there are also timber groynes along this stretch of coast. (Photo: Environment Agency)

The Blakeney Overfalls Waverider buoy (NWB1) is situated just to the north east of Blakeney Overfalls at 53° 03.690, N 001° 02.050 E. The buoy is located 10 km offshore and in the deep water between the Overfalls and Sheringham Shoal. The depth where the buoy is moored is 18 m CD. The shallower banks flanking the buoy provide some shelter to the exposed north facing coast. North easterly waves have a relatively long fetch to develop as they propagate through the North Sea and therefore waves reaching the North Norfolk coast are relatively high for the Anglian coast.

Instrument data & recording

The ACM programme phase VII 'ZERO HOUR' was designated 00:00h (GMT) on 20th September 2006 (Julian Day 263). Instruments were deployed from this date, and 'Year 2' of the project is defined as the period from 1st October 2007 to 30th September 2008.

Table 1 details the percentage of valid data from the wave and tidal data recorded by each instrument in Year 2, and Table 2 below, shows significant wave height records as an indicator for instrument data recording and deployment periods. Data collection within the region was nearly continuous. The main disruptions to data recording was operation work to re-armour defences at Horsey, which required the suspension of a deployment at site S12N in autumn 2008. Also the Blakeney buoy went adrift on the 15th March, resulting in a data gap until a replacement buoy was redeployed on the 2nd April 2008.

Instrument	Tide data return	Wave data return
S9N	99.99%	99.98 %
S10N	98.82%	98.82 %
S11N	99.94%	99.91 %
S12N	98.76%	74.69 %
NWB1		86.84%

Table 1: Annual data return for logged records of tidal and wave parameters in Year 2.

Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep

S9N AWAC Scolt Head	05/10/2007 - 22/11/2007	22/11/2007 - 29/01/2008	29/01/2008 - 15/03/2008	15/03/2008 - 10/05/2008	10/05/2008 - 02/07/2008	02/07/2008 - 27/08/2008	27/8/2008 -
S10N AWAC Cley	05/10/2007 - 17/11/2007	17/11/2007 - 25/01/2008	29/01/2008 - 15/03/2008	15/03/2008 - 23/05/2008	23/05/2008 - 30/06/2008	30/06/2008 - 27/08/2008	27/8/2008 -
S11N AWAC Walcott	06/10/2007 - 16/11/2007	16/11/2007 - 23/01/2008	23/01/2008 - 14/03/2008	14/03/2008 - 10/05/2008	10/05/2008 - 30/06/2008	30/06/2008 - 27/08/2008	27/8/08 - 25/9/08
S12N AWAC Horsey	06/10/2007 - 16/11/2007	16/11/2007 - 23/01/2008	23/01/2008 - 14/03/2008	14/03/2008 - 10/05/2008	10/05/2008 - 30/06/2008	30/06/2008 - 27/08/2008	27/8/2008 -
NWB1 DWR Blakeney	- 15/3/2008	02/04/2008 -					

Table 2: Deployment periods for Year 2 for Norfolk instruments used in this report, based on significant wave height records.

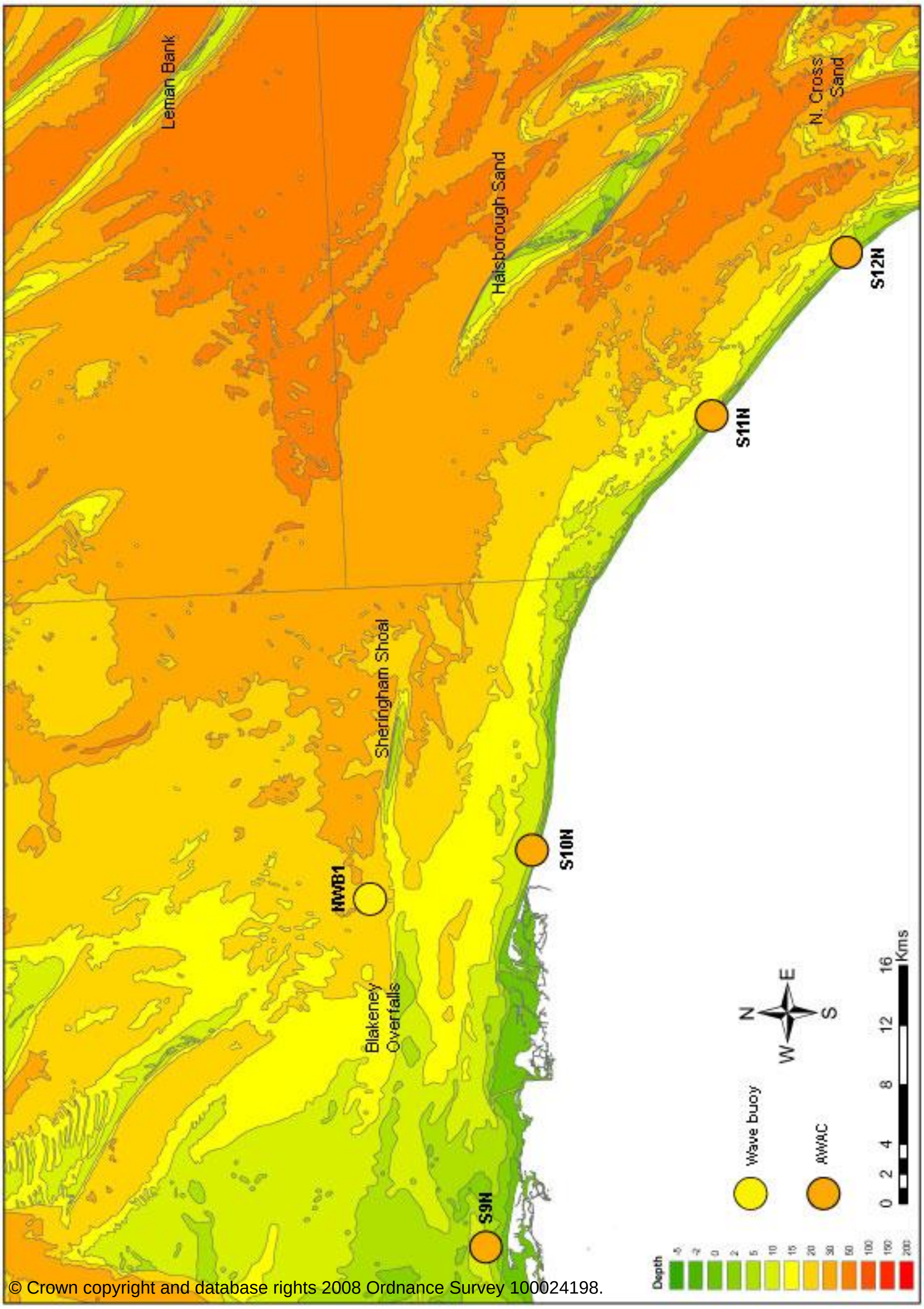

Figure 2: Bathymetry plot showing water depths and locations of Norfolk instruments.

AWAC S9N is located offshore of Scolt Head Island, there is a relatively shallow approach to the AWAC from the north. S10N is located off Cley, the Sheringham Shoal bank is located to the north north-east with shallower water to the west. Offshore of Walcott, Haisborough Sand runs between S11N and the deep water to the north east. S12N is located at Horsey with North Cross Sands located to the east of the AWAC. The orientation of the coast here is north east facing, the same as the S11N location. The wavebuoy NWB1 is located approximately 10 km north of Blakeney in the deeper water seaward of Blakeney Overfalls.

Wave statistics

This section presents the key wave parameters in the annual time series to describe the sea conditions at each instrument location. This shows the general pattern of waves represented by a spectrum of waves of different frequencies, heights and directions through statistical measurements, time series and averages over the duration of a year. This section also includes the comparison and association of measured data sets, such as the comparison of wave height and wave period, and wave spectra plots. This analysis identifies consistency in the data, trends, quality and a summary of the data recorded. A description of all of the parameters can be found in the glossary section.

Monthly means

Mean significant wave height (Hs)

Month Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
S9N Scolt Head	0.4	0.8	0.5	0.6	0.5	0.8	0.6	0.6	0.5	0.5	0.4	0.4
S10N Cley	0.5	1.0	0.7	0.6	0.5	1.0	0.7	0.7	0.5	0.5	0.4	0.5
S11N Walcott	0.6	1.0	0.7	0.7	0.6	1.0	0.7	0.7	0.5	0.5	0.4	0.6
S12N Horsey	0.6	1.0	0.7	0.7	0.5	1.0	0.7	0.7	0.5	0.5	0.4	0.6
NWB1 Blakeney	0.7	1.4	1.0	1.1	0.9	0.6	-	0.9	0.7	0.7	0.7	0.8

Table 3: Monthly mean significant wave heights Hs (m).

Mean maximum wave height (Hmax)

Month Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
S9N Scolt Head	0.7	1.2	0.9	0.9	0.7	1.3	0.9	1.0	0.7	0.7	0.7	0.7
S10N Cley	0.8	1.6	1.0	1.0	0.8	1.6	1.0	1.2	0.8	0.8	0.6	0.9
S11N Walcott	0.9	1.6	1.1	1.0	0.9	1.6	1.0	1.1	0.8	0.8	0.6	0.9
S12N Horsey	0.9	1.5	1.1	0.8	1.5	1.0	1.1	0.8	0.8	0.8	0.6	0.9
NWB1 Blakeney	1.1	2.2	1.6	1.7	1.4	0.9	-	1.4	1.1	1.1	1.1	1.3

Table 4: Monthly mean maximum wave heights Hmax (m).

Mean peak wave period (Tp)

Month Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
S9N Scolt Head	5.1	6.2	4.8	5.1	5.6	5.6	5.4	4.5	4.7	4.5	4.2	4.7
S10N Cley	6.4	8.1	6.8	7.5	8.1	7.7	6.8	5.4	5.6	5.6	5.6	6.2
S11N Walcott	6.2	7.8	6.3	7.4	8.1	7.6	6.5	5.4	5.8	5.8	5.8	6.3
S12N Horsey	6.0	7.7	6.1	7.1	7.1	7.3	6.4	5.3	5.7	5.7	5.6	6.0
NWB1 Blakeney	6.2	15.3	5.6	5.9	7.3	3.0	-	5.1	5.3	5.2	5.0	5.7

Table 5: Monthly mean peak wave period (Tp) (s).

Mean of mean wave period (Tz)

Month Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
S9N Scolt Head	2.9	3.3	3.0	2.8	2.8	3.3	3.0	2.9	2.7	2.7	2.5	2.7
S10N Cley	3.5	4.1	3.3	3.3	3.3	4.0	3.7	3.4	3.3	3.2	2.9	2.9
S11N Walcott	3.6	4.5	3.9	4.0	4.0	4.4	3.8	3.4	3.5	3.5	3.5	3.6
S12N Horsey	3.5	4.4	3.7	3.6	3.7	4.2	3.6	3.3	3.3	3.4	3.2	3.4
NWB1 Blakeney	3.7	6.7	3.9	3.9	4.0	1.9	-	3.6	3.7	3.6	3.4	3.7

Table 6: Monthly mean wave period (Tz) (s).

Mean wave direction (Mdir)

Month Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
S9N Scolt Head	111	172	157	189	168	175	113	51	140	158	193	115
S10N Cley	92	116	108	133	140	138	82	42	149	147	148	95
S11N Walcott	61	5	75	61	54	45	60	48	63	60	54	51
S12N Horsey	56	45	73	69	49	43	60	57	47	48	57	64
NWB1 Blakeney	125	359	166	180	154	94	-	63	172	154	178	126

Table 7: Monthly mean wave direction (Mdir) (°).

Significant Wave Height

There is a consistent pattern in wave heights across the Norfolk instruments. All the AWACs identify the same high wave events, with significant peaks occurring in November and March. The pattern in wave heights is similar to the previous year, with high waves at the beginning of the year through to March, and again in the month of September. The nearshore instruments also show agreement with what is recorded offshore at the Blakeney Overfalls buoy. However there are some noticeable discrepancies in this fit, such as the 4 m wave recorded by the buoy in February. No waves reach threshold levels at any of the nearshore instruments, and S12N at Horsey only logs a maximum wave (Hs) of 1.85 m at this time. The offshore waves on this date were coming from the north north-west.

The instruments along the coast are in close alignment regarding the significant wave height values recorded. Mean wave heights range from 0.2 – 0.7 m across the year on the nearshore. The AWAC off Horsey records the highest monthly mean wave heights throughout the year. Offshore wave heights reduce slightly after June and peaks in high waves become less frequent. Although this is reflected at the nearshore instruments, the peaks in wave heights are still of a similar amplitude and so match the offshore conditions more closely.

A threshold level was set for each instrument to identify storms and monitor the frequency of storm events. Waves measured over the threshold level height are determined to be storm waves. The storm threshold at Scolt Head is 2.8 m, this reflects a shallow water depth but also a potentially long fetch for northerly waves. The threshold at the other three AWAC sites is only slightly higher at 2.9 m. The thresholds are denoted on the below graphs with a red line. There are occurrences of wave heights reaching the storm threshold level set for each AWAC within Year 2. There were two particular events in the year that caused these high waves heights. These storm events, the Peaks over Threshold method and the maximum significant wave height values are detailed in the Storminess and extremes section.

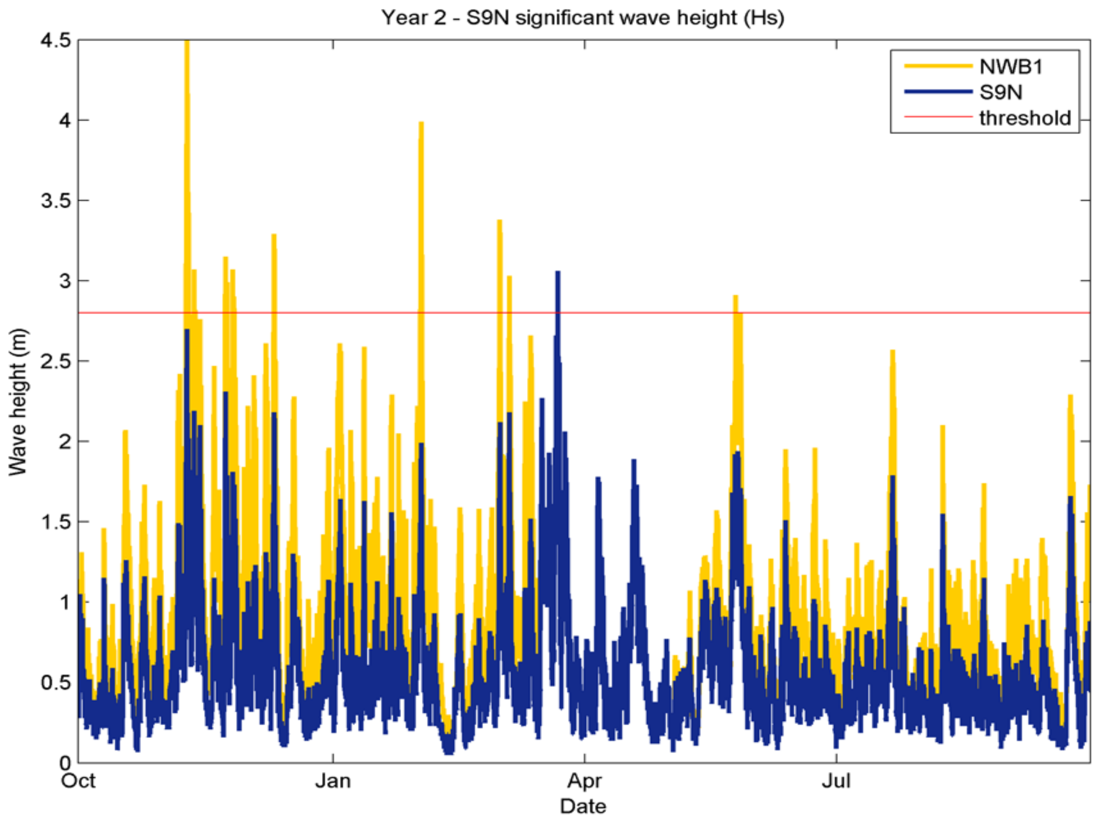

Figure 3: Plot showing significant wave height (Hs) records from October 2007 to September 2008 for the AWAC S9N at Scolt Head Island and the Blakeney Overfalls wavebuoy (NWB1). The horizontal red line denotes the 2.8 m storm threshold.

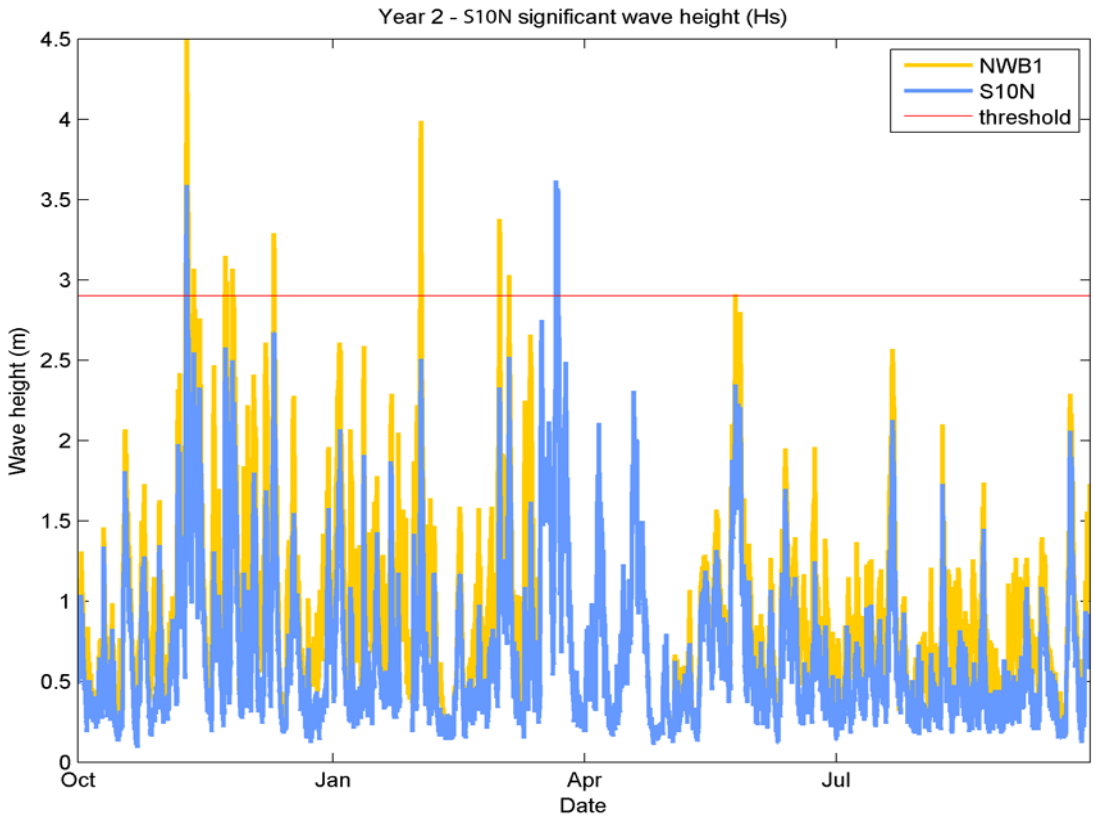

Figure 4: Plot showing significant wave height (Hs) records from October 2007 to September 2008 for the AWAC S10N at Cley and the Blakeney Overfalls wavebuoy (NWB1). The red line denotes a 2.9 m threshold.

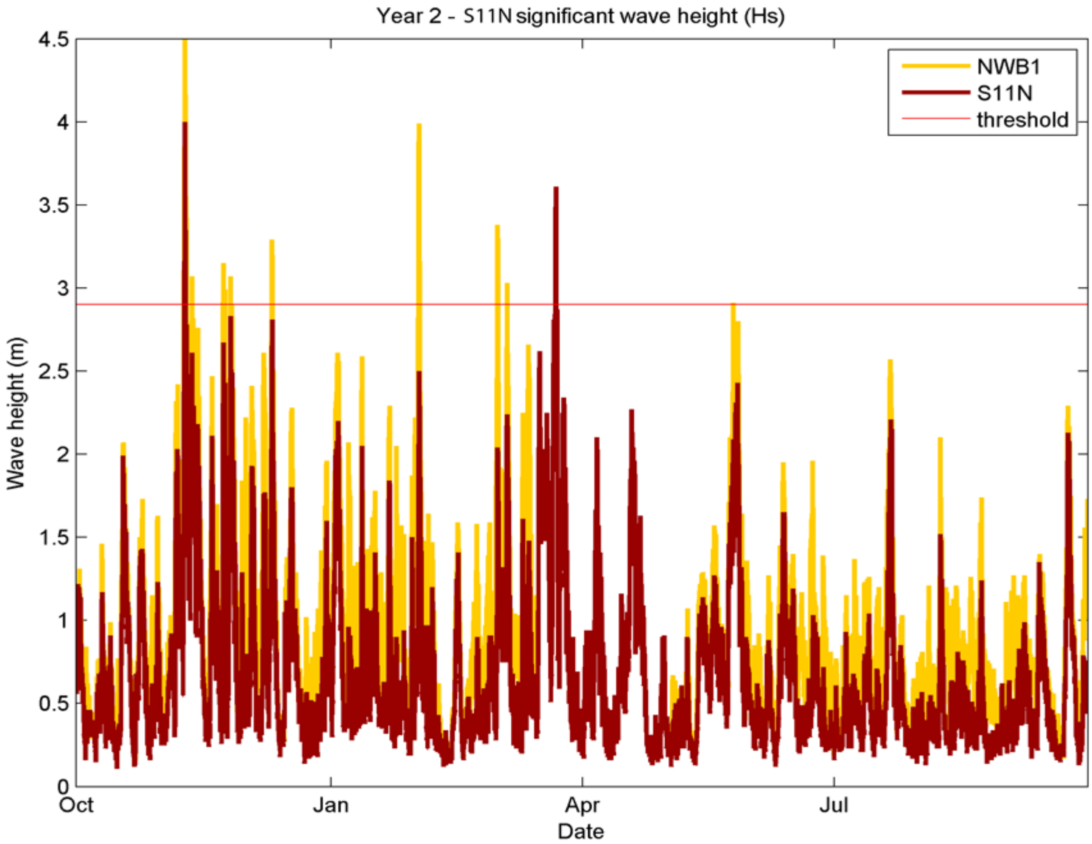

Figure 5: Significant wave height (Hs) records from October 2007 to September 2008 for the AWAC S11N at Walcott and the Blakeney buoy (NWB1). The horizontal red line denotes a 2.9 m threshold.

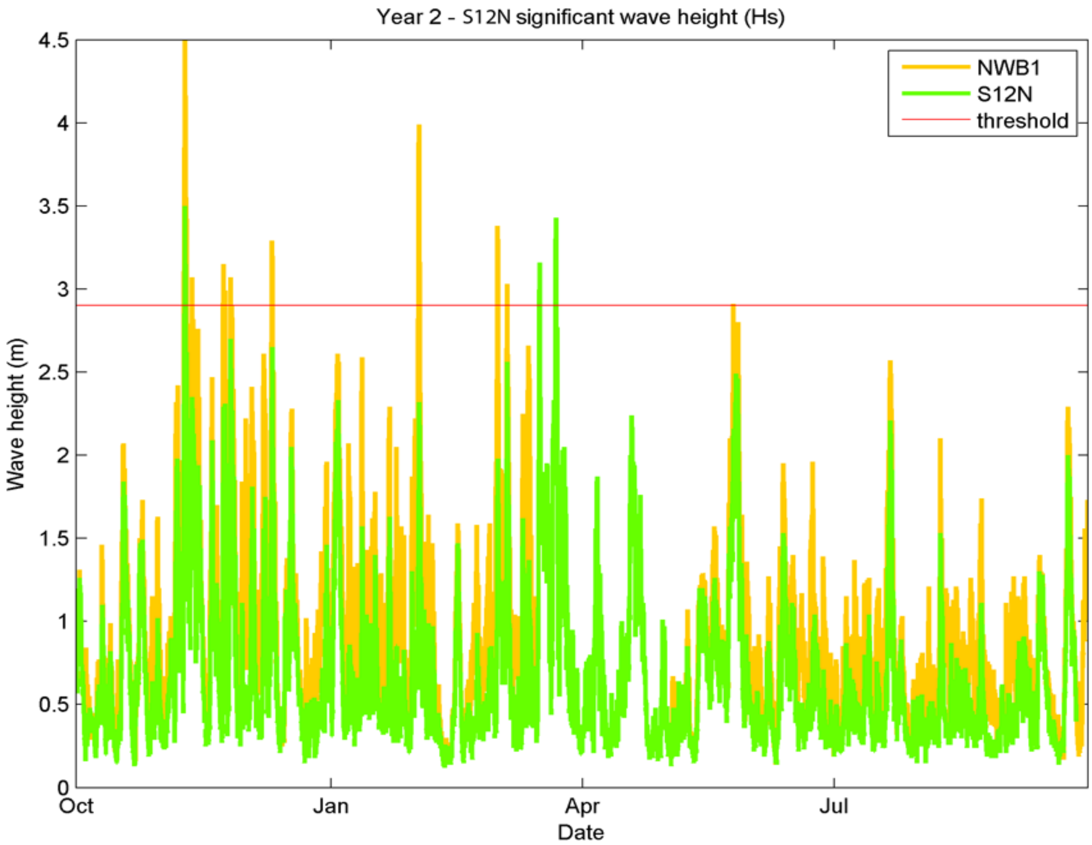

Figure 6: Significant wave height (Hs) records from October 2007 to September 2008 for the AWAC S12N at Horsey and the Blakeney Overfalls buoy (NWB1). The horizontal red line denotes a 2.9 m storm threshold.

Wave direction

Figure 7: Main wave coming direction (Mdir) and occurrences for the Norfolk AWACs and the offshore waverider buoy, from October 2007 to September 2008.

The prominent wave direction (Mdir) is from the north to north east. The frontage where the two AWACs S11N and S12N are sited has a north easterly orientation and both instruments record a main wave direction from the north east. Located 10 km from the coastline of Blakeney Point the wave buoy identifies a significant number of waves from the east and west. In Year 1 the buoy was generally only logging waves coming from the north. Many of the waves approaching from these flanks will have interacted with either Sheringham Shoal or Blakeney Overfalls.

Peak period

Peak period is also known as the dominant wave period, and describes the frequency with the highest energy. The logged data shows a similar distribution of wave periods as observed in Year 1. The majority of waves reaching the Norfolk coast are between 4 - 9 seconds. These waves are wind driven waves, characteristically under 2 m in height. AWAC S9N at Scolt Head again shows a peak in waves with a period of around 3 -4 seconds. This is most likely due to the shallower water and the gentle slope of the bed on approach to the instrument causing waves to shorten. There are occurrences of waves with a peak period over 15 seconds approaching the coast. These are long swell waves that have propagated over a longer fetch to reach the exposed Norfolk coastline. These waves can come from depressions passing across the north of Scotland and storms around the Northern North Sea.

Long period waves refract more and therefore can focus more energy. This has a greater impact on the sea defence and possible risk of breaching. The below plots show the wave distribution at each instrument site on the Norfolk coast. It is of use to know that conditions at Scolt Head Island, based on the first two years data, show that long period waves are less prevalent and less of a risk. The impact of waves however is proportional to the standard of the sea defence at that coastline. The height a wave will rise to as it enters shallow coastal waters is not only dependent on its period but also the bathymetry of the area; the water depth and beach slope. For example the presence of an offshore bank can cause waves to slow, rise and break.

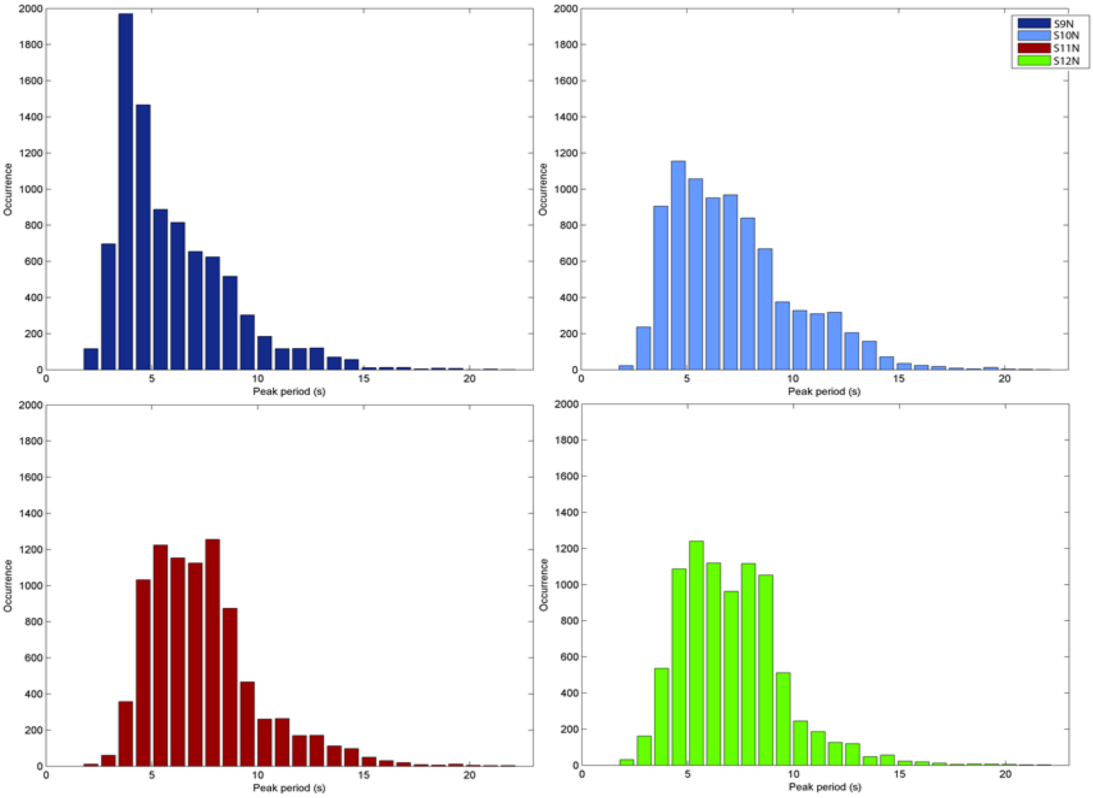

Figure 8: A distribution plot of wave periods (Tp) for each AWAC (S9N, S10N, S11N, S12N).

The wavebuoy records a similar pattern in wave periods (Tp) as were seen in Year 1. Wave periods are not longer than the nearshore instruments and the buoy records a peak in waves with a period around 3 – 4 seconds (Figure 9).

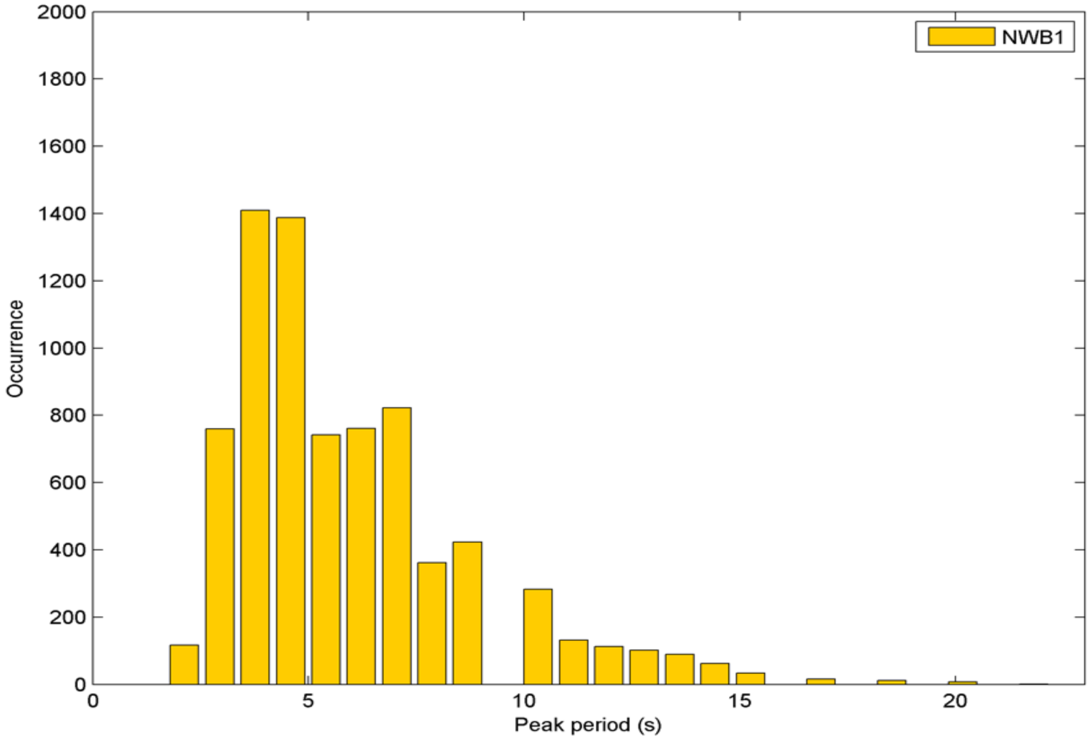

Figure 9: Occurrences of peak wave periods (Tp) recorded by NWB1, Blakeney Overfalls from October 2007 – September 2008.

Period and significant wave height

Plotting peak wave period (Tp) and significant wave height (Hs) are of value in determining heights that can be expected for various distributions of waves, and therefore applied to defence overtopping studies and in determining beach response to wave loading. The plot below (Figure 10) of wave periods and significant wave heights at S12N during Year 2 is representative of the area. The mean wave period (Tz) shows an increase in wave heights with an increase in period, within the average wave period range of 2 – 6 seconds. The frequency with the highest energy shows rougher conditions and wind driven waves with a peak period between 4 and 8 seconds. The peak wave period plot also shows longer wave period waves of over 10 seconds that are most likely modified swell waves and include those waves generated from the storm surge in November. Table 5 shows that the longest mean peak wave period was in September, where waves averaged 6 seconds. Table 17 shows the longest wave period reached 15.7 seconds at both Cley and Walcott in this month. The longest maximum wave period was actually 20.6 seconds recorded at Cley in February.

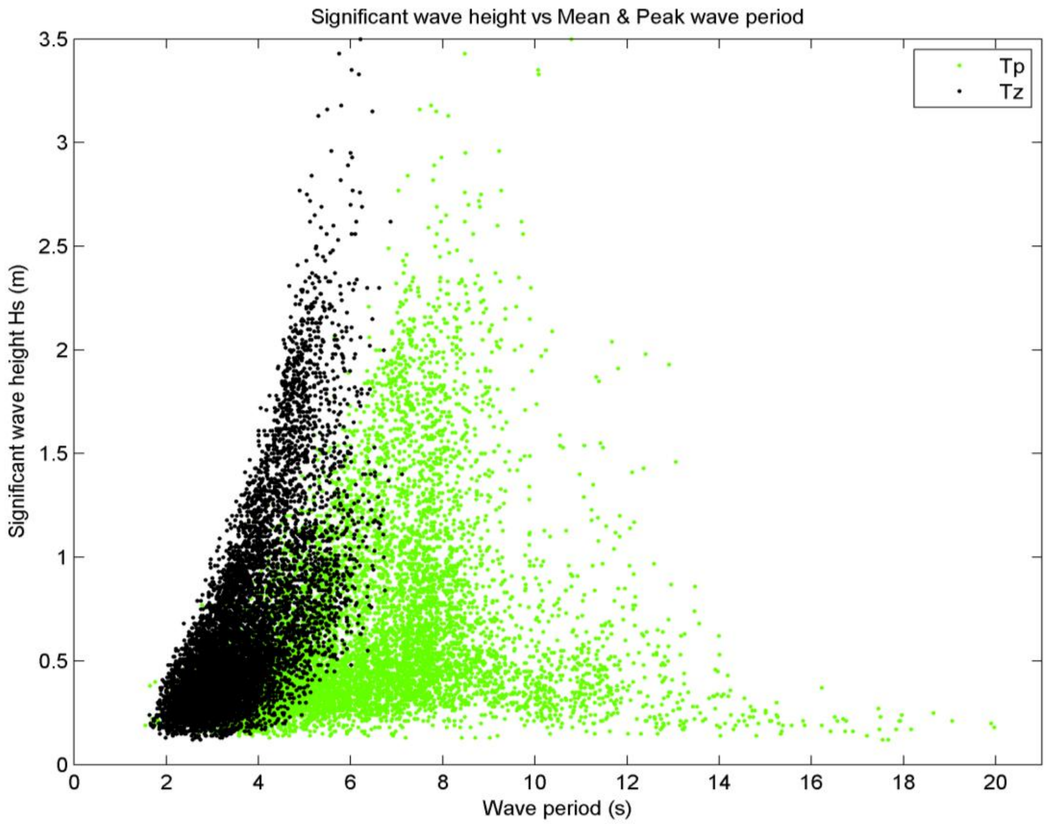

Figure 10: Scatter plot indicating joint distribution of significant wave height (Hs) and wave period for October 2007 – September 2008 at Horsey (S12N). The green shows the peak wave period (Tp) against Hs and the black shows the mean wave period (Tz) against Hs. The Tp data shows several wave distributions; waves generated locally by wind are seen to have short periods, where as storm waves have moderate wave periods and greater heights. There are also swell waves identifiable in heights under 0.5 m and with peak periods extending to 20 seconds.

Wave energy

Wave energy is analysed for frequency bands carrying the most energy out of the 64 bands recorded by the AWAC's onboard data logger. The wave spectra plots (Figures 11 and 12) show the spread of energy (m^2/Hz) across different wave periods at Walcott and Horsey during two different months. Below this plot in the figure are two further plots showing the corresponding coming wave direction and wave height. The spectra plots show examples of high energy waves events that occurred on the Norfolk coast this year, and how wave energy, direction and height are related.

High energy waves can be seen throughout wave periods during the November storm surge (Figure 11). The high energy patches, shown in red on the plot correspond with north to north-easterly waves, coloured in blue on the centre plot. Energy is the most intense on the 9th November, and high energy is spread along wave periods from 5 to over 20 seconds. Wave heights can be seen to peak at the same time. There are three further peaks in wave height in the month shown in the figure, on the 19th, 24th and 26th. For each peak in wave height, corresponding patches of high energy can be seen in the top plot. During the 19th, wave heights do not reach as high as the other events in the month and the waves remain under 2 metres. In turn the wave periods containing the highest energy are also relatively shorter than during the other events. The high energy is contained within waves with periods below 10 seconds. The direction of these waves is also more to the south east, where as in the events, with longer period, high energy waves, the main direction (Mdir) was from the north north-east.

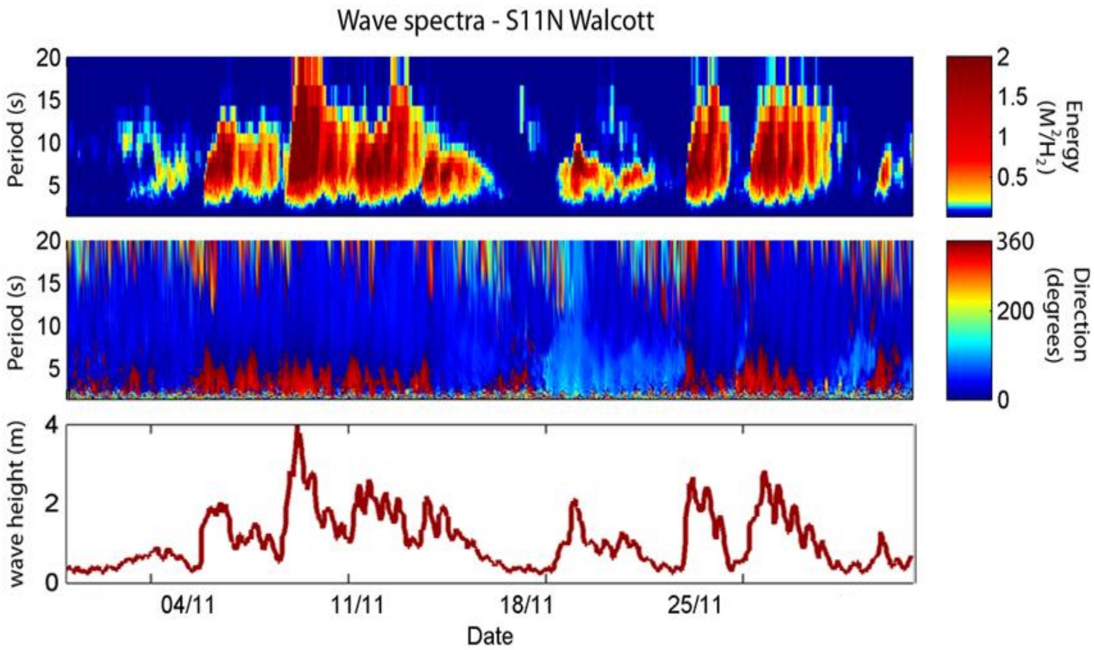

Figure 11: Wave spectra plot for S11N at Walcott during November 2007. The top plot shows high energy (up to 2 m^2/Hz) waves coloured in red and low energy waves in blue. The centre plot shows the corresponding wave directions, which are coloured according to their coming direction in degrees. Northerly waves coming from around 0° or 360° are either dark red or dark blue, southerly waves in turn are green. The bottom plot shows significant wave height (Hs). Periods of high energy waves can be seen to correspond with peaks in wave heights.

AWAC S12N at Horsey logged a period of high energy waves during storm conditions in March. The high energy was contained within waves of around 5 to 10 seconds, this differs from the pattern in wave periods shown in Figure 11 during the November surge. The pattern in March indicates more localised storms. The wave heights rise to a height of around 2 m during the stormy conditions, peaking at over 3m on the 16th and during the event on the 22nd. The centre plot shows the majority waves, with a period of over 5 to 10 seconds come from the north to north east.

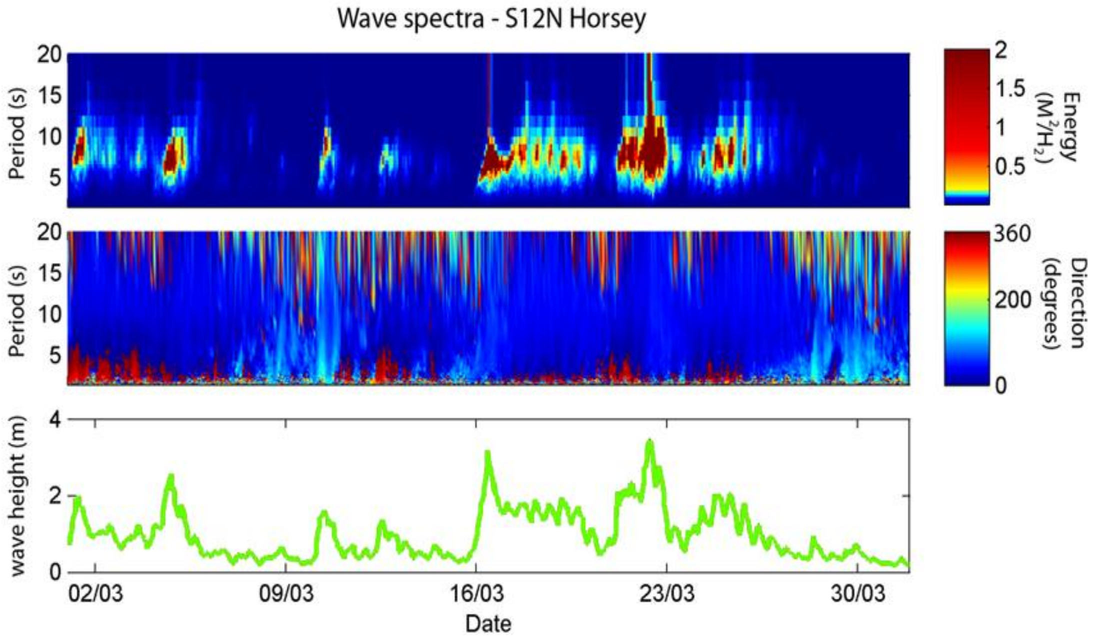

Figure 12: Wave spectra plots for Horsey (S12N) during the month of March 2008. Peaks in energy and wave heights can be seen during the storm events on the 16th and 22nd.

The plots below show mean annual energy in the Norfolk waves. The plots show the amount of energy within waves remains around the same level as the previous year. There is a slight increase in wave energy at Cley (S10N) and Walcott (S11N), but the Scolt Head AWAC (S9N) and Horsey (S12N) show a slight decrease in energy levels.

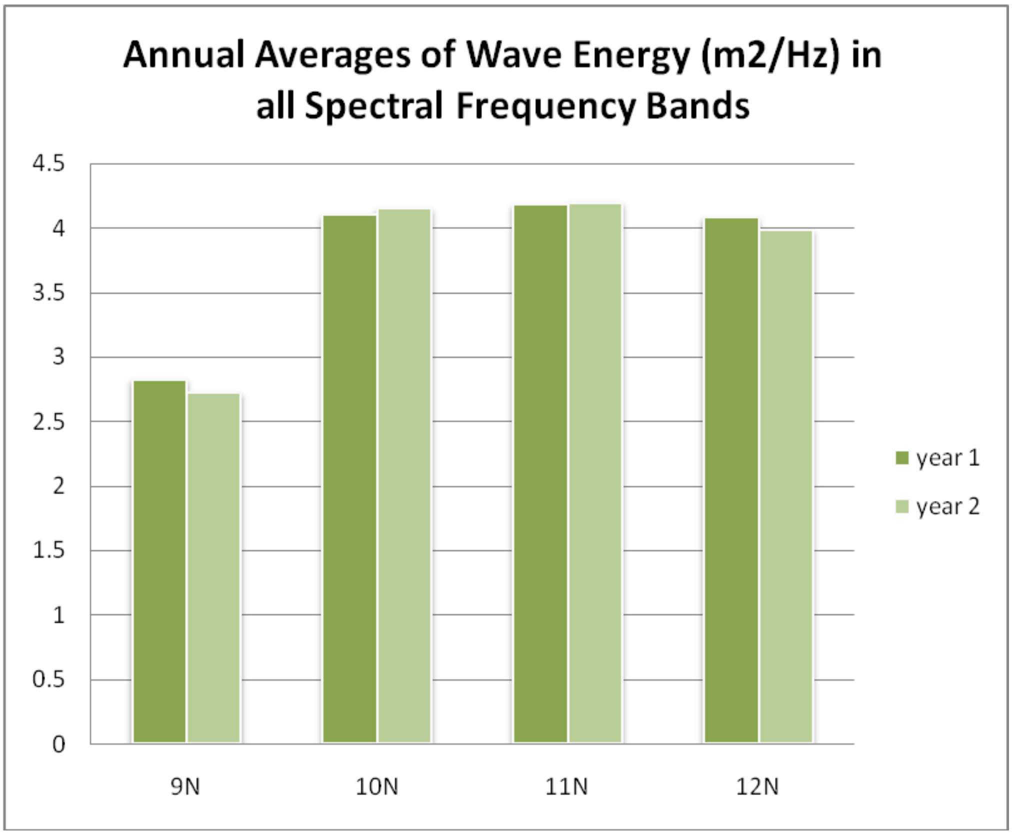

Figure 13: Comparison of the average wave energy at each AWAC for monitoring years 1 and 2.

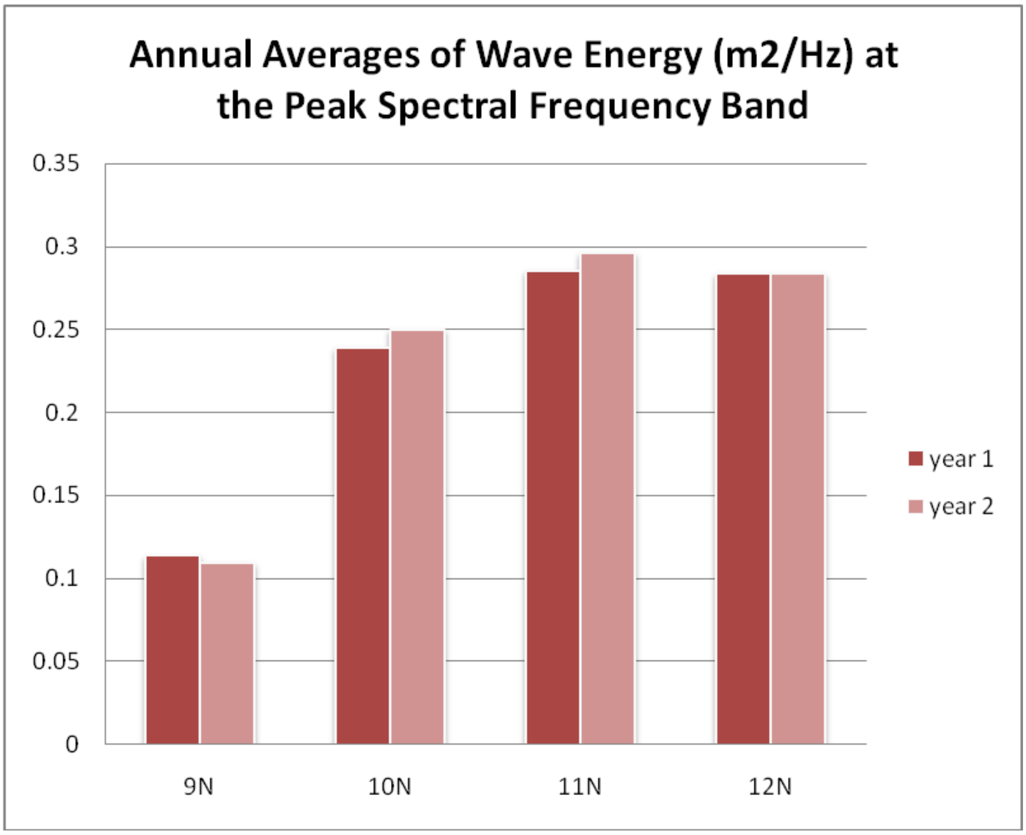

Figure 14: Comparison of the peak wave energy at each AWAC between Year 1 and Year 2.

Wave return periods

Return periods are an indicator of the frequency a wave can be expected from a certain height and direction sector. The below values detail the frequency of a particular event occurring in years. The lower the number the less frequent the event. For example a return period of 0.25 would mean the event would occur every 0.25 years or 91 days and a return period of 0.005 would occur once every 1.8 days. It is of course possible that an event with a frequency of every 2 days will occur on successive days, and does not mean an event will occur only at these intervals.

Direction band	Significant wave height (Hs) (m) band							Total
	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	
0-30	0.0189	0.0359	0.0902	0.2759	1.0912	6.0014		7.5135
30-60	0.0168	0.0452	0.1727	0.4139	6.0014	24.0055		30.6554
60-90	0.063	0.0734	0.3693	4.0009				4.5066
90-120	1.8466	2.1823	12.0027					16.0316
120-150		12.0027						12.0027
150-180								0
180-210	12.0027	24.0055						36.0082
210-240	8.0018	3.0007						11.0025
240-270	0.2182	0.1936	24.0055					24.4173
270-300	0.0353	0.0415	0.9602	6.0014				7.0384
300-330	0.0463	0.0886	0.6155	2.0005	24.0055			26.7564
330-360	0.0474	0.0656	0.16	0.4069	2.6673	6.0014		9.3486
Total	22.2971	41.735	38.3763	13.0994	33.7653	36.0082		

Table 8: Wave return periods at AWAC S9N, Scolt Head Island.

Direction band	Significant wave height (Hs) (m) band 0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	Total
0-30	0.0162	0.0247	0.0669	0.1004	0.3	1.394	3.3855	5.2878
30-60	0.0147	0.0373	0.1129	0.1601	0.7181	2.6332	11.8493	15.5257
60-90	0.0648	0.1234	0.697					0.8852
90-120	2.9623	2.9623						5.9247
120-150								0
150-180								0
180-210								0
210-240								0
240-270								0
270-300	2.1544	1.0304						3.1848
300-330	0.082	0.1129	0.7645	2.9623	11.8493			15.771
330-360	0.0304	0.0406	0.1261	0.2346	0.5386	2.6332	4.7397	8.3432
Total	5.3249	4.3316	1.7673	3.4575	13.406	6.6604	19.9746	

Table 9: Wave return periods at AWAC S10N, Cley.

Direction band	Significant wave height (Hs) (m) band 0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	3.5-4	Total
0-30	0.0209	0.0195	0.0604	0.085	0.2159	0.7049	2.9959	5.9918	10.0942
30-60	0.012	0.0381	0.1115	0.1917	0.9218	4.7934	11.9836		18.0521
60-90	0.0227	0.0438	0.1688	0.4062	1.8436				2.4851
90-120	0.2577	0.1688	0.9218	23.9671					25.3154
120-150									0
150-180									0
180-210									0
210-240									0
240-270									0
270-300									0
300-330	23.9671								23.9671
330-360	0.2031	0.1169	0.3034	0.6478	4.7934	23.9671			30.0317
Total	24.4835	0.3871	1.5658	25.2978	7.7748	29.4655	14.9795	5.9918	

Table 10: Wave return periods at AWAC S11N Walcott.

Direction band	Significant wave height (Hs) (m) band 0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	3.5-4	Total
0-30	0.0409	0.0285	0.0746	0.1325	0.3541	1.6945	7.9078	23.7233	33.9562
30-60	0.0127	0.0258	0.0783	0.1492	0.6243	2.1567	3.9539		7.0009
60-90	0.0152	0.0377	0.1204	0.2524	0.6243				1.05
90-120	0.0639	0.0844	0.7189	2.9654	7.9078				11.7404
120-150	1.1862	1.318							2.5041
150-180	1.9769	11.8616							13.8386
180-210	3.9539								3.9539
210-240	2.9654	11.8616							14.8271
240-270	3.389	23.7233							27.1123
270-300	2.9654	11.8616							14.8271
300-330	3.389								3.389
330-360	1.1297	0.6977	7.9078	11.8616					21.5968
Total	21.0884	61.5004	8.9	15.3612	9.5104	3.8512	11.8616	23.7233	

Table 11: Wave return periods at AWAC S12N, Horsey.

Temperature

The thermometer is located within the AWAC instrument that is mounted in a frame and sitting on the sea bed, therefore the below values are recorded at a depth of approximately 5 m CD. However the wavebuoy measurements are of sea surface temperature. The records show the same seasonal pattern as the previous year. The lowest mean temperatures are in February, the lowest being 5.5 °c at Walcott. The highest are in August, peaking at 18.2 °c at Scolt Head. Details of the maximum recorded temperatures of the year are provided in Table 19 of this report.

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
S9N Scolt Head	13.4	9.1	6.3	6.0	5.6	6.1	8.1	12.3	14.7	17.7	18.2	16.1
S10N Cley	13.5	9.4	6.7	6.0	5.6	6.2	7.8	12.5	15.5	17.3	17.8	16.3
S11N Walcott	13.3	9.3	6.5	6.0	5.5	5.9	7.6	12.6	15.2	17.8	18.1	16.4
S12N Horsey	13.3	9.3	6.5	6.1	5.7	6.1	7.7	12.6	15.3	17.6	18.1	16.8
NWB1 Blakeney	13.7	10.7	8.3	7.1	6.4	7.0	9.0	11.1	13.6	15.5	16.5	15.6

Table 12: Monthly mean temperatures at Norfolk sites for the period October 2007 – September 2008.

Sea level & tides

This section details sea level in Year 2, and provides tide levels at each AWAC site and the class A tide gauge station at Cromer. As in Year 1 Scolt Head Island has the greatest tidal range, and is first to receive the high water of a tide. There is a clear pattern in tidal movement down the coast, from Scolt Head to Horsey, even during surge periods. It takes about 1 hour for the high water off Scolt Head to progress round to S12N off Horsey. Walcott and Horsey are located in fairly close proximity and on a similar stretch of coast, and both show the smallest tidal range. The annual time series of tides is shown in Figure 15, the annual pattern of springs and neap tides and particularly high or low tides can be seen, such as those in November 2007 during the surge event.

Sea level (mODN)

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
S9N Scolt Head	0.28	0.34	0.26	0.19	0.22	0.3	0.15	0.18	0.19	0.23	0.24	0.22
S10N Cley	0.24	0.34	0.27	0.17	0.22	0.29	0.15	0.17	0.2	0.25	0.24	0.22
S11N Walcott	0.16	0.23	0.17	0.2	0.21	0.31	0.15	0.16	0.21	0.23	0.25	0.12
S12N Horsey	0.29	0.35	0.25	0.18	0.21	0.3	0.16	0.18	0.2	0.23	0.26	0.21

Table 13: Monthly mean sea levels relative to Ordnance Datum Newlyn for Year 2 (October 2007 – September 2008).

Norfolk tide levels (mODN) for Year 2

Site	HAT	MHWS	MHWN	MLWN	MLWS	LAT	Mean HW interval	Range on Springs (m)
S9N Scolt Head	3.896	3.061	1.627	-1.159	-2.593	-3.504	5 hrs 54 min	5.654
S10N Cley	3.443	2.633	1.407	-0.937	-2.163	-2.985	6 hrs 5 min	4.796
Cromer[5]	2.962	2.327	1.261	-0.797	-1.863	-2.652	6 hrs 14 min	4.190
S11N Walcott	2.545	1.935	1.047	-0.647	-1.535	-2.151	6 hrs 32 min	3.470
S12N Horsey	2.277	1.705	0.953	-0.483	-1.235	-1.863	6 hrs 56 min	2.940

Table 14: Tidal parameters derived from Gardline Environmental's 60-constituent harmonic analysis of the second year of AWAC data (Gardline, 2008).

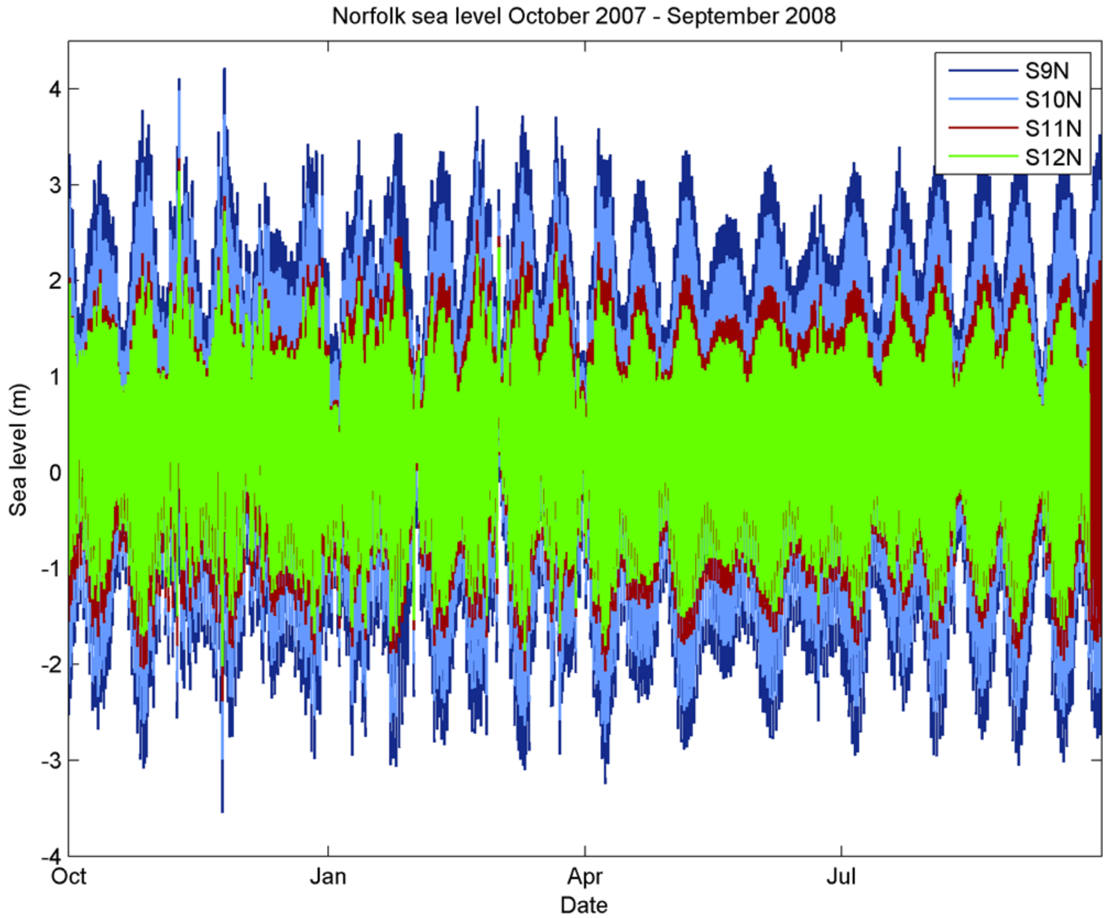

Figure 15: Sea level at each AWAC (S9N, S10N, S11N, S12N) for October 2007 – September 2008.

Storminess & extremes

Storm wave events

Storm analysis including storm frequency are a long term check on climate change. From analysis of extreme values we can determine how the pattern of wave characteristics in calm waters, such as direction and height, change in storm conditions. Storm generated wave directions however may vary across an area of sea, and on their approach to the coast after being recorded by an offshore buoy.

Within this series of reports a storm event is defined according to the Beach Management Manual (CIRIA, 1996) Peaks over threshold method of significant wave heights (Hs) that exceed a defined threshold. This value is based on historic monitoring off the Anglian coast by the SMG, and through literature studies. This level is expected to become more accurate following the 3 year monitoring period. Suspected storms are also identifiable in the wave spectra plots (Figures 11 and 12). The duration of a storm is considered to be 16 hours around the peak wave height (Hs), however high wave events can often be seen to occur on successive high waters.

Monthly wave maxima

Threshold levels for the Norfolk AWACs are set at 2.9 m, with the exception of S9N at Scolt Head, which has a slightly lower level of 2.8 m.

The highest significant wave height of the year was 4 m, recorded in November at AWAC S11N off Walcott. In the previous year the highest recorded wave was 3.4 m, also at Walcott, in March 2007. March 2008 was again a stormy month with three high wave storm events and two recorded surges. November 2007 saw an unusually large surge event, where weather conditions and high water levels led to high waves being logged. Two of the storms identified in March occurred over 24 hours and were associated with the same offshore conditions. Figure 18 shows the initial peak and decay followed by a second rise in wave heights. The duration between the peaks means both wave events are categorised as storms. The two wave height peaks on the 21st and the 22nd of March were 3.62 m and 3.61 m respectively, although the highest wave of each storm was recorded at different AWACs. Compared to Year 1 the peak wave heights recorded during the November and March events are significantly higher this year. The storm waves are also considerable higher than the storm threshold level. However in Year 2 only four storm events are identified, and non storm generated waves are well below the 2.8 – 2.9m threshold.

The below monthly maximum values do not necessarily occur at coincidence times, for example the maximum Hs value for a month may not occur at the same time as the maximum Hmax value recorded in that month.

Maximum significant wave heights Hs (m)

Month Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
S9N Scolt Head	1.3	2.7	2.2	1.6	2.1	3.1	1.9	1.9	1.5	1.8	1.6	1.7
S10N Cley	1.8	3.6	2.7	2.1	2.5	3.6	2.3	2.4	1.7	2.1	1.7	2.1
S11N Walcott	2.0	4.0	2.8	2.2	2.5	3.6	2.3	2.4	1.7	2.2	1.5	2.1
S12N Horsey	1.8	3.5	2.7	2.3	2.3	3.4	2.2	2.5	1.5	2.2	1.5	2.0
NWB1 Blakeney	2.1	4.7	3.3	2.6	4.0	3.4	-	2.9	2.0	2.6	2.1	2.3

Table 15: Monthly maximum significant wave height (Hs) (m).

Maximum wave heights Hmax (m)

Month / Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
S9N Scolt Head	2.2	4.3	3.8	2.6	3.9	5.2	3.0	3.3	2.5	2.8	2.5	2.9
S10N Cley	3.2	7.2	3.9	3.4	4.7	6.9	3.6	3.9	3.1	3.5	2.7	3.6
S11N Walcott	3.3	6.5	4.0	3.9	4.2	5.5	3.7	4.8	3.0	3.6	2.5	3.3
S12N Horsey	3.3	5.7	4.4	4.1	3.6	6.2	3.8	4.8	2.6	3.9	2.5	3.2

Table 16: Monthly maximum wave heights (Hmax) (m).

Maximum peak wave period Tp (s)

Month / Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
S9N Scolt Head	13.8	14.9	13.1	17.4	20.5	14.5	13.2	9.2	9.9	11.3	9.9	15.2
S10N Cley	15.0	17.9	17.9	19.4	20.6	14.6	13.8	10.0	10.7	11.4	10.2	15.7
S11N Walcott	14.3	14.5	13.5	20.1	20.0	15.1	14.2	9.3	11.8	11.8	10.3	15.7
S12N Horsey	14.0	14.2	13.3	18.7	20.	14.2	13.9	9.2	11.6	11.4	10.2	15.3
NWB1 Blakeney	14.3	15.4	14.3	20.0	22.2	16.7	-	10.0	10.5	12.5	11.1	15.4

Table 17: Monthly maximum peak wave period (s).

Maximum mean wave period Tz (s)

Month / Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
S9N Scolt Head	5.4	5.6	6.3	6.3	5.8	5.9	5.2	5.0	5.1	5.1	4.6	6.2
S10N Cley	6.0	6.3	6.5	6.8	6.5	6.7	6.7	5.2	6.1	5.5	5.3	5.4
S11N Walcott	5.7	6.9	8.0	6.8	7.7	6.9	7.5	5.6	6.2	6.2	6.3	7.0
S12N Horsey	5.5	6.9	7.1	6.7	6.8	6.5	6.7	5.5	5.9	6.1	5.6	6.3
NWB1 Blakeney	6.6	6.7	7.6	7.0	6.5	5.8	-	5.9	5.8	5.7	5.2	6.8

Table 18: Monthly maximum mean wave period (s).

Monthly temperature maxima

Month / Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
S9N Scolt Head	14.4	11.9	8.1	7.4	6.6	6.9	11.3	13.8	16.6	19.8	20.0	18.5
S10N Cley	14.5	12.4	8.2	7.2	6.4	6.7	9.7	14.1	17.2	18.9	18.9	18.1
S11N Walcott	14.4	12.1	8.0	7.1	6.3	6.6	9.7	14.5	17.5	19.6	19.8	18.8
S12N Horsey	14.5	12.0	8.2	7.1	6.5	6.8	9.8	14.5	17.3	19.4	19.5	18.9
NWB1 Blakeney	14.5	12.8	9.7	8.2	6.9	8.8	10.7	13.4	15.8	16.7	17.4	21.4

Table 19: Monthly maximum temperature (°c). The AWAC temperature is a measurement at bed depth, the DWR record is a sea surface temperature measurement.

Highest Norfolk storm events in 2007/2008

09 November 2007

The highest wave recorded off the Norfolk coast was 4 m at AWAC S11N at Walcott and was associated with the storm surge event described in the following section. Due to the surge water depths were greater, the Walcott AWAC recorded that this wave occurred in a water depth of 12.5 m. During the event waves crossed respective thresholds at Cley, Walcott and Horsey.

Reports from the event detail that strong winds and the high waves caused minor damage to property and infrastructure at Walcott, and transferred a substantial volume of sand on to the road. Police reported a number of people were evacuated from their homes and several properties in Walcott were flooded. The defences at Walcott were not breached however spray from the high waves on the surge were blown into Walcott by the force 6 winds. Water was also believed to have come through the drainage system during the prolonged high water caused by the surge.

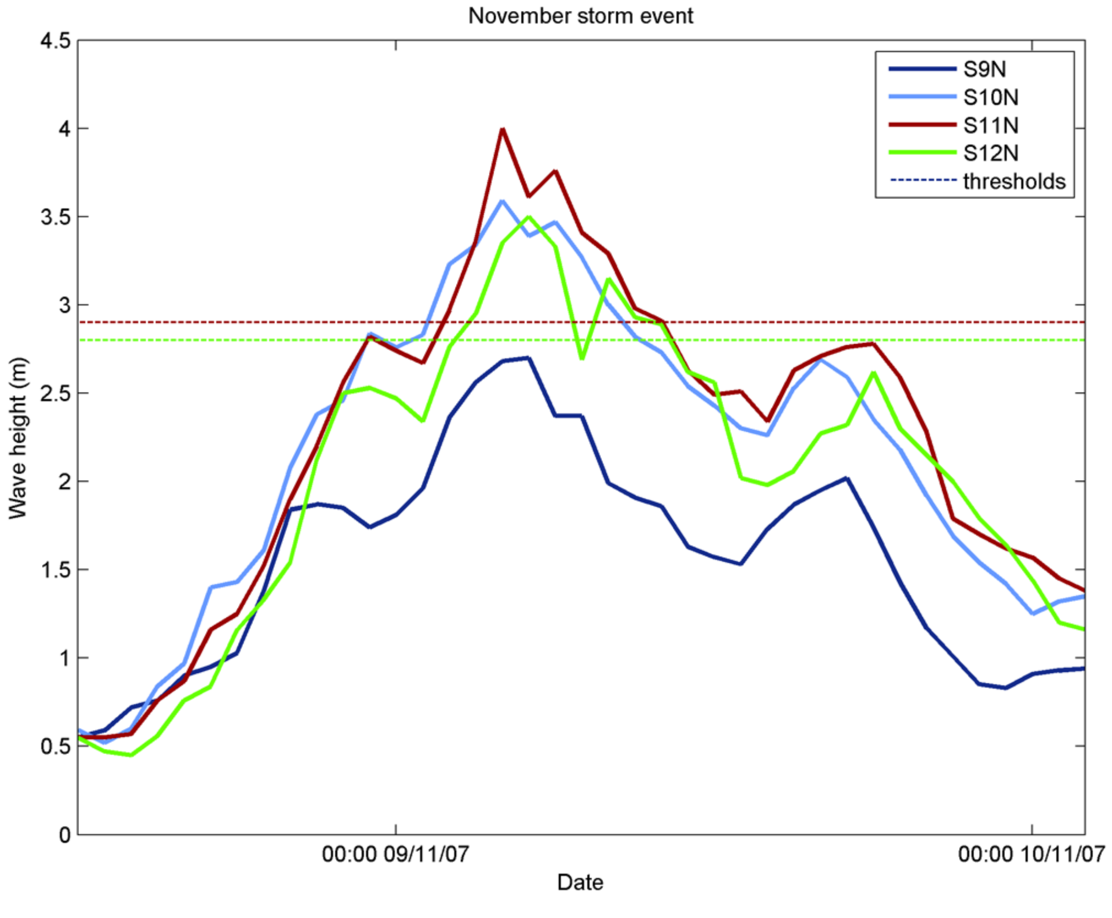

Figure 16 Wave heights during the November event. Three AWACs record waves rising over their threshold levels at 2.9 m, waves at Scolt Head do not cross the site's 2.8 m threshold. The highest wave was 4 m, and recorded at S11N at Walcott.

Figure 17 Image on the 9th November from the Sea Palling Argus station, located between Walcott and Horsey, operated by the University of Plymouth and University of East Anglia (Argus[1])

March 21 & 22 2008

High waves associated with storms in late March were recorded for the second year in a row. A 3.62 m wave was recorded at Cley on the afternoon of the 21st. The wave heights then fell by around a metre at Cley with the ebb of the tide. The waves picked up again on the morning of the 22nd, first at Cley but peaking at Walcott where a 3.61 m wave was recorded. Waves crossed the threshold levels at every location on the morning of the 22nd, although wave heights drop off at Scolt Head when waves are seen to peak at the other instruments.

Strong northerly winds brought snow and rain to the Anglian coast on the 21st and 22nd of March, and a storm had developed by around 05:00 on Friday the 21st (UKMO,2008a). Storm waves with peak wave periods of 7 – 9 seconds and coming from the north east were logged on the Norfolk coast. The storm waves were also identified further north with a peak wave of 3.3 m recorded off Lincolnshire by the Skegness AWAC (S4L) and by the North Well buoy (WWB1) which recorded a peak wave of 2.51 m entering The Wash. Several Flood Watch alerts were issued on the 20th, with a Flood Warning being issued at Cromer in the late afternoon.

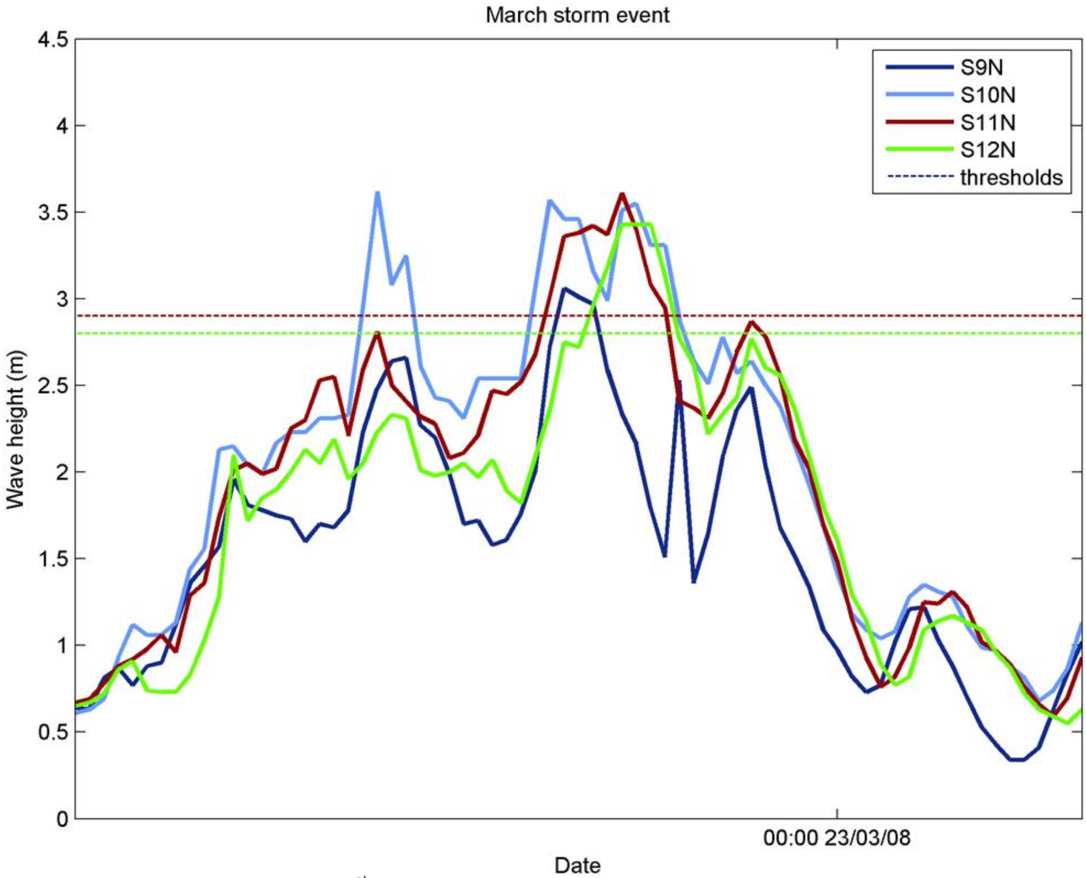

Figure 18: High waves on the 21st March 2008 at S10N cross the 2.9 m threshold, a secondary peak in wave heights is then recorded on the 22nd where waves crossed respective thresholds at every location.

Figure 19: Image from Argus camera at Sea Palling operated by the University of Plymouth and University of East Anglia showing the sea state at 08:30 UTC, 22 March 2008 (Argus[1]).
(Photo: Environment Agency)

Date/Time	H_s (m)	H_{max} (m)	T_p (s)	T_z (°)	Dir. (°)	Water depth (m)	Water level elevation (mODN)	Residual (m)
09/11/2007 04:00	4.00	6.51	10.34	5.29	4.52	12.5	2.56	1.643
21/03/2008 16:00	3.62	6.4	6.69	3.78	356	9.87	1.9	0.794
22/03/2008 09:00	3.61	5.09	8.53	5.53	29.17	11.4	1.65	0.268

Table 20: The three highest Hs storm events recorded in Norfolk, with associated parameters. The highest wave of the storm has been detailed. The highest Hs value was recorded at Walcott (dark red) during November. The next two storms were part of the same event but occurred on different days and peaked at different sites.

Surge events

Tides are not the only variable affecting water levels on the Anglian coast. Any contributing factors that are not part of the astronomical tide, such as non average weather conditions will have an impact. An area of low pressure and a storm can produce large scale tides know as storm surges that propagate through the North Sea. Strong winds also generate high energy waves. The addition of high waves and / or a surge combined with a high astronomical water level can severely impact on coastal defences, and risk overtopping defences and flooding.

A surge or residual is regarded as the difference of sea level, calculated from historical sea levels and the theoretical harmonic tidal curve, and the actual sea level recorded by the AWAC. The reasons why a water level differs from the usual or predicted can be due to a number of causes, such as changes in air pressure or winds. This report highlights significant surge events, but does not seek to explain why there is a difference or isolate the principle components of a surge. Surges are identified based on the 60-constituent harmonic analysis, carried out by Gardline Environmental, which has removed the tidal influence, from the residuals (Gardline, 2008).

The UK Met Office's classification of a surge event is when the residual (surge) exceeds 0.6 m at two or more tide gauges. This report will detail significant surge events where the residual surge is greater than 1 m. The surge has to be visible in neighbouring instruments to be considered significant and to eliminate instances of instrument error.

Highest surge events in Norfolk 2007/2008

09 November 2007

On the 8th November a deep depression moved across the North Sea from Scotland into south Norway. There were gale force winds across the Highlands on the Thursday and early on the morning of the Friday the 9th. In addition a high pressure system developed over the UK on the morning of the 9th. This caused gradient winds through the North Sea and these strong north north-westerly winds caught the high spring tide and brought a surge through the North Sea, and along the Anglian coast. This was the first surge event of the year and the highest recorded in Year 2 (UKMO, 2008b; UKMO, 2008c).

A residual level of 2.2 m was recorded at Walcott at 02:50 on the morning of the 9th, the following high water that morning reached over 3 mODN. In addition to the storm surge the strong winds led to one of the largest wave events of the year on the Anglian coast, as discussed earlier in this section.

A below average low water was recorded prior to the surge in the 9th, associated with a negative residual level. This can be seen in observed sea level at AWAC S11N at Walcott in Figure 20. The surge then grew with the rise of the tide and peaked between the two high waters causing the following low water to only just fall below 1 mODN at Walcott. The surge peaks on the flood of the tide on the 9th. By high water on this first tide of the day there is still a 1.5 m residual, resulting in a sea level of over 3 mODN. The tide height at Cromer peaked at 2.6 mODN and so did not cross the Flood Watch trigger level there. A Flood Watch was issued at 00:56 for the Flood Watch Area between Sheringham and Winterton, which includes Walcott and Horsey. The EA issued 4 Severe Flood Warnings in total for the county including rivers during the event (NCC, 2008) (Table 22). The high water proceeded the astronomical tide due to the surge and extended the high water duration. The combination of high waves on a high spring tide with a high surge brings the greatest risk of overtopping and flood risk. During this event minor flooding was reported in Norfolk including at Great Yarmouth and the Broads.

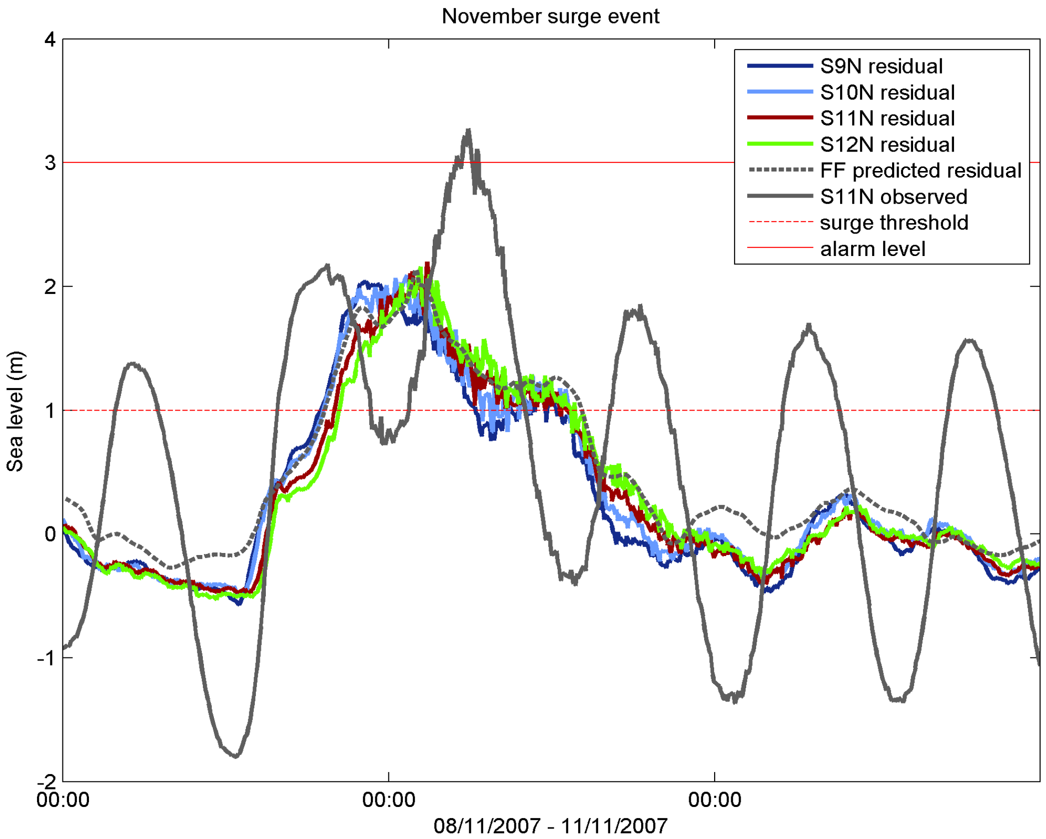

Figure 20: The plot shows the residual levels at all four AWACs, and the Flood Forecasting modelled residual at Cromer (dotted grey). The dotted red line shows the 1 m surge threshold level, and the continuous red line is the alert level at the Cromer forecast station. The observed sea level at AWAC S11N (site of the peak recorded residual) is also shown on the plot (continuous grey line).

Figure 21: Image from Argus camera at the Sea Palling station operated by the University of Plymouth and University of East Anglia, showing high waters and waves breaking over the offshore reefs during the surge on the 9th November (Argus[1]). (Photo: Environment Agency)

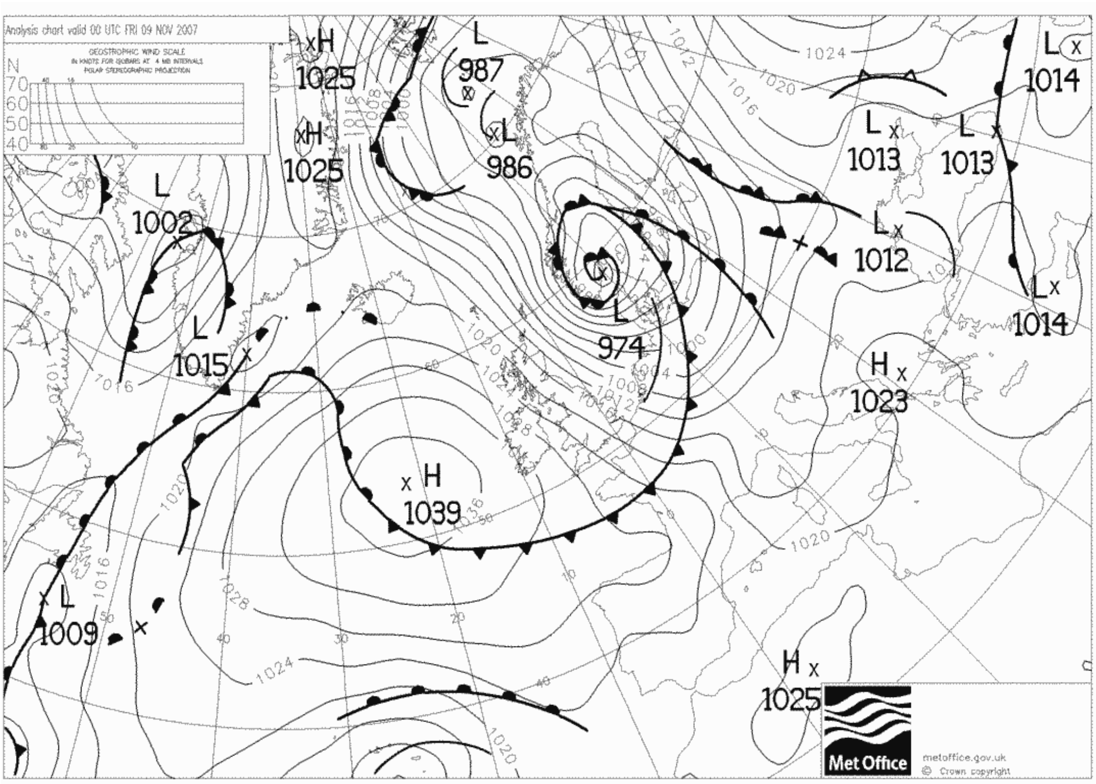

Figure 22: Pressure map of 9th November 2007 showing the depression over Scandinavia and high pressure to the south of the North Sea. (UKMO[1])

01 March 2008

In March 2008 a surge of 1.87 m was recorded at Scolt Head Island. The surge on the 1st March followed a negative surge the previous day which reached -1 m at Scolt Head. The peak of the surge was logged at 10:35 on the rising flood tide, and just preceding the high water. However the surge occurred on a neap tide and did not bring a significant risk of flooding, two Flood Watch alerts were issued, one at Great Yarmouth and one for the tidal rivers in the area.

This event was the first of a stormy month, with high wave occurring throughout March. The surge was caused by a depression moving into the area on Friday 29th February from the west of the Faroes, by 12:00 GMT on the Saturday it reached southern Scandinavia. This caused severe gale force winds within the North Sea early on the Saturday.

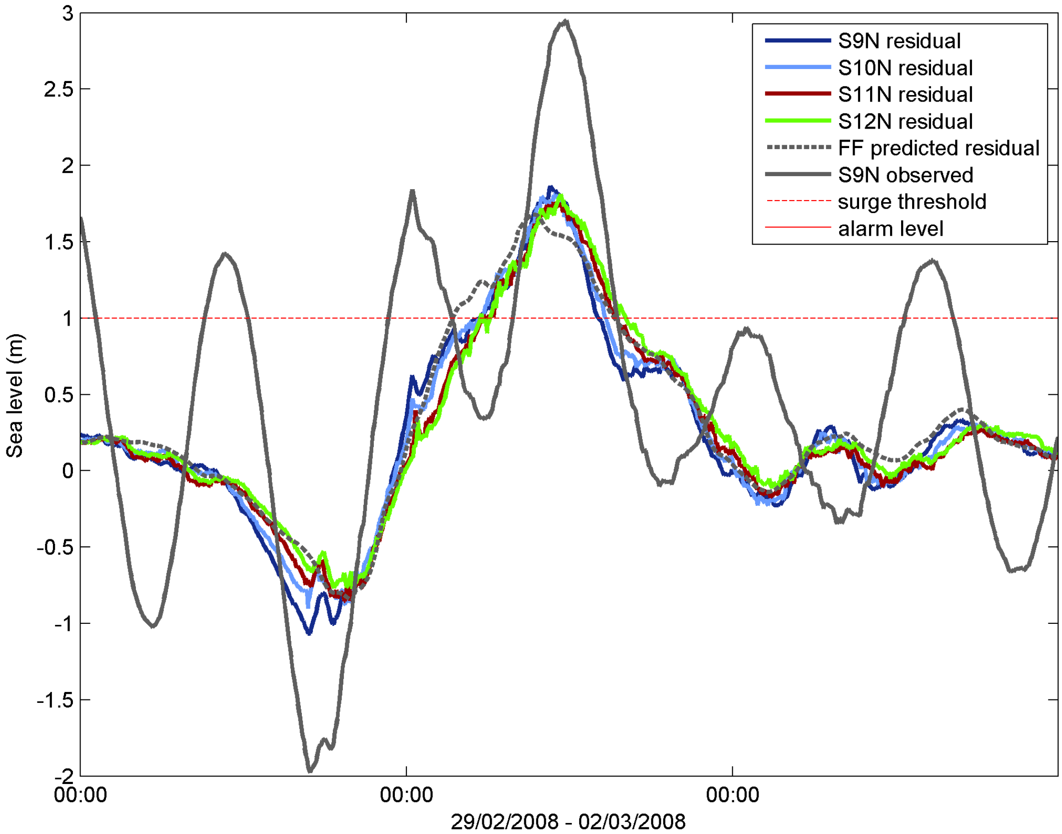

Figure 23: March surge event at each of the four AWACs (S9N, S10N, S11N, S12N), the Flood Forecast modelled residual for Cromer is shown by the grey dotted line, the observed sea level at the S9N AWAC is shown by the continuous grey line and the dotted red line is the 1 m surge threshold level.

01 February 2008

The third surge of the monitoring year was less severe, and like the March event caused no flood risk to the surrounding area. Preceding the event there was a deep depression present to the north west of Scotland on the 31st January. By the 1st there were severe south to south west gale force winds in the North Sea, this led to a large negative surge of almost -2 m recorded by all the AWACs, but lowest at Scolt Head. This was followed by a swollen tide and at 20:25 the surge peaked at AWAC S9N Scolt Head Island at 1.29 m. No Flood alerts were issued during this event.

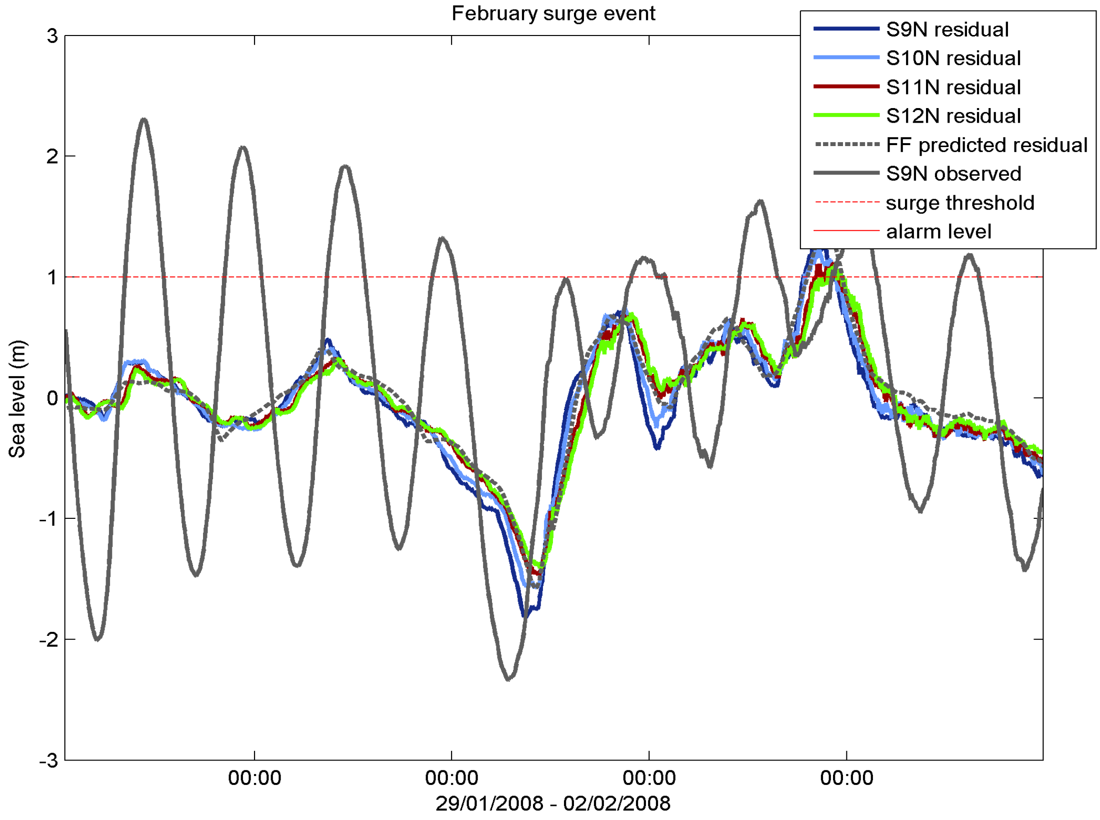

Figure 24: February surge event following the largest negative surge of the year.

Storm surge event date	Residual (m)	Water level elevation (mODN)	HW level elevation (mODN)	HW time & difference to peak surge	H_s (m)	T_p (s)	Dir. (°)
09/11/2007	2.199	2.066	3.055	5:00 (+2:10 hrs)	3.36	9.27	6
01/03/2008	1.865	2.799	2.949	10:45 (+1:10 hrs)	1.79	4.71	326
01/02/2008	1.287	0.631	1.532	01:20 (+4:55 hrs)	1.98	6.55	323

Table 21: The highest 3 surge events (residuals greater than 1 m) in Year 2, listed in rank order. The time and height of the highest surge value of the event is listed. The highest surge was recorded at S11N, during November 2007. The related coincident water level and hourly wave data for the AWAC is shown. The high water on the closest tide, and the time difference from high water and the surge peak is also detailed.

There were seven surge events in total in Year 2. The November surge being the highest, and the only surge over 2 m recorded. The highest surge peaks were recorded either at AWAC S9N at Scolt Head Island or off the coast of Walcott, AWAC S11N. The events are often associated with high wave events as can be seen in the storm calendar section.

Over the two years of monitoring, surge events can be seen to occur during the same times of the year, at the end of October and into November, and from January through to the end of March. The November 2007 surge was the highest recorded level in both years.

Storm calendar

The below plots show the storm and surge events that have occurred in the first two years of monitoring. Surge events can be seen to be confined to October to March in the year, with the November 2007 surge the most severe. The High wave events in Year 2 appear to be more severe than in Year 1, with 3 occurrences of waves events over 3.6 m Hs, however in total there are fewer waves crossing the threshold level than in the previous year.

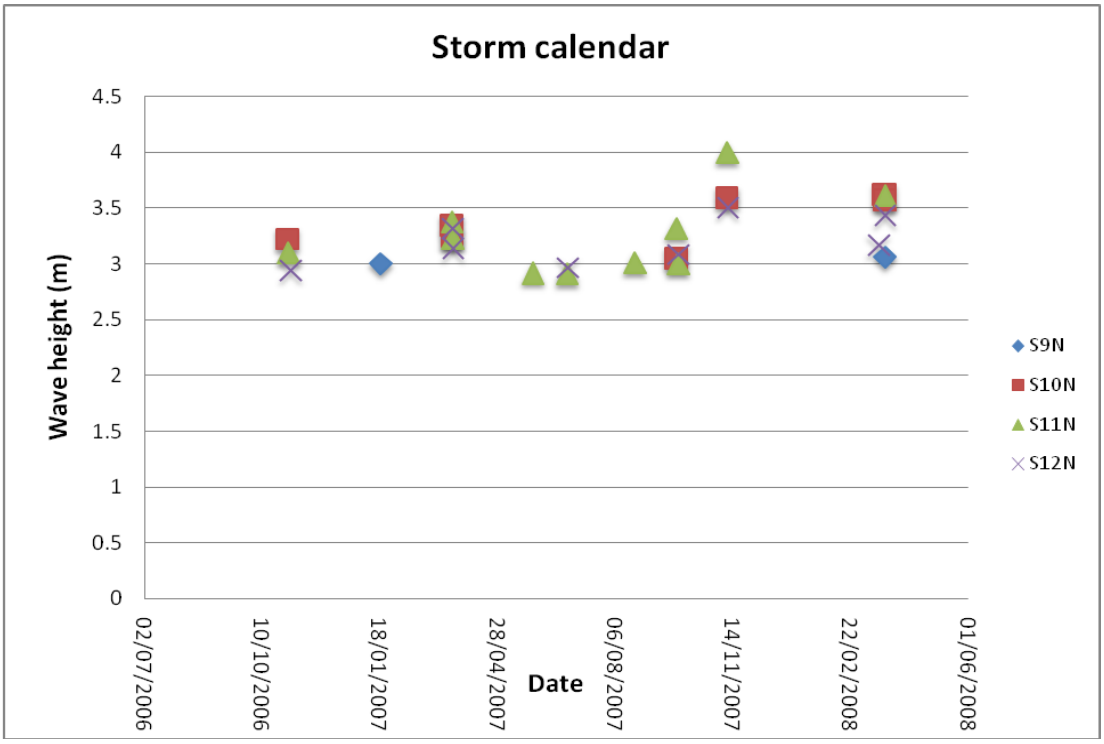

Figure 25: Storm calendar showing the wave events in Year 1 and 2 that crossed site thresholds..

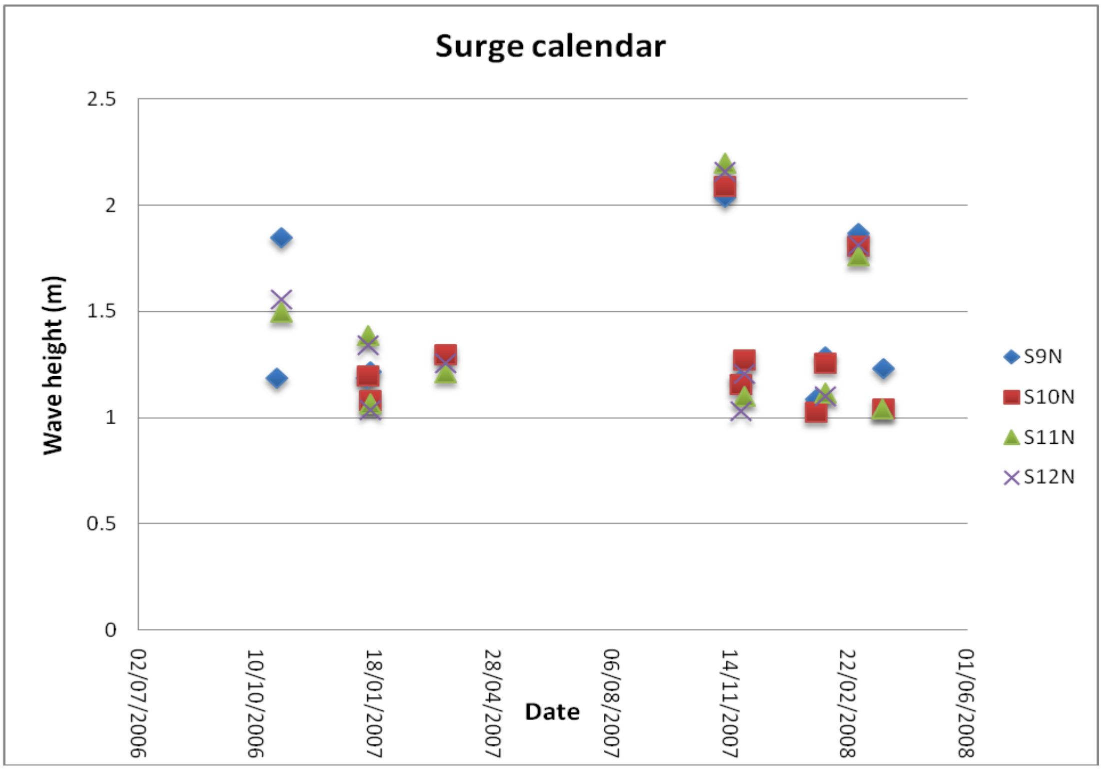

Figure 26: Surge calendar showing occurrences of surge events in Year 1 and 2.

Flood Forecasting records

Event duration	Date	Time	Warnings issued	Forecast site	Threshold Value (mAOD)
High waves & surge on 08 - 09/11/2007	09/11/2007 08/11/2007 08/11/2007 08/11/2007 08/11/2007 08/11/2007 08/11/2007	09:01 09:16 09:16 09:43 09:14 09:15 18:55	Flood Watch Flood Watch Severe Flood Warning Flood Watch Severe Flood Warning Severe Flood Warning Severe Flood Warning	Wells Great Yarmouth Great Yarmouth Great Yarmouth Tidal rivers Tidal rivers Tidal rivers	3.50 1.90 2.77 1.90 Gt Yarmouth LW >= 0.00 AND Lowestoft HW surge +6hrs of Gt Yarmouth LW >= 0.50m
Surge on 31/01/2007 - 02/02/2007	None				
Surge on 29/02/2008 - 02/03/2008	29/02/2008 11/02/2008	11:29 11:54	Flood Watch Flood Watch	Great Yarmouth Tidal rivers	1.90 Gt Yarmouth LW >= 0.00 **AND** Lowestoft HW surge +6hrs of Gt Yarmouth LW >= 0.50m
High waves & surge on 20 - 23/03/2008	20/03/2008 20/03/2008 20/03/2008 20/03/2008 20/03/2008 20/03/2008 20/03/2008	12:39 15:52 16:50 16:02 16:54 17:08 17:04	Flood Watch Flood Watch Flood Warning Flood Watch Flood Watch Flood Watch Flood Watch	Tidal rivers Great Yarmouth Cromer Cromer Wells Great Yarmouth Tidal rivers	As below 1.90 3.20 & F6 N. aspect 3.00 3.50 1.90 Gt Yarmouth LW >= 0.00 AND Lowestoft HW surge +6hrs of Gt Yarmouth LW >= 0.50m

Table 22: Environment Agency Flood Forecasting records of flood alerts[6] for the Cromer and Wells stations and the tidal rivers of Bure, Thurne and Yare issued during storm and surge periods identified in Year 2.

Extreme sea levels

Tidal measurements were lower at Scolt Head Island in Year 2 than the previous year, but levels have increased at the other 3 AWAC locations. AWAC S11N shows an increase in tidal level of half a metre. The maximum water level recorded in Norfolk was 4.22 m at AWAC S9N at Scolt Head, occurring during a surge event on the 25th November. The Extreme Tide Levels report (Royal Haskoning, 2007) states a 1:5 year extreme water level at Blakeney as 4.07 m. During the largest surge event on the 9th November levels at S9N reached 4.108 m.

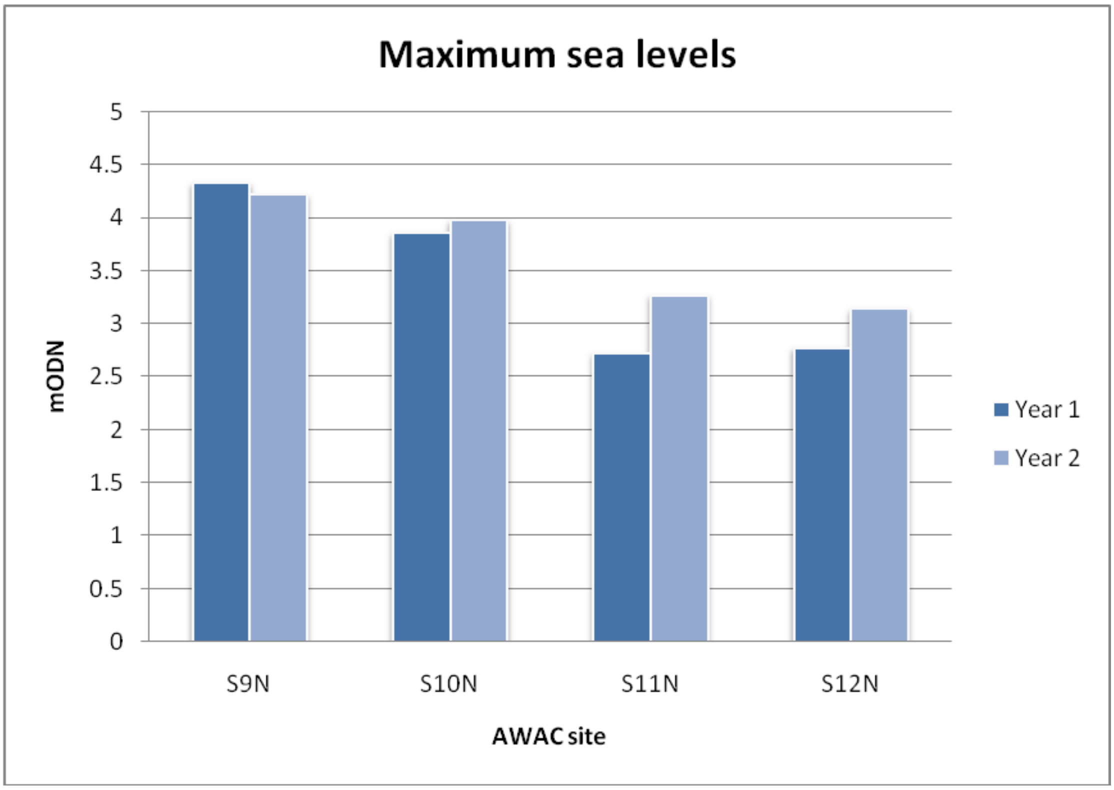

Figure 27: Highest recorded sea level at each Norfolk AWAC in years 1 and 2.

Summary

The wave climate during the first year of monitoring from October 2006 - September 2007 was detailed in the first Sea state report for the Norfolk coast (Environment Agency, 2009). The main wave direction was observed to be from the north to north east. Due to the orientation of the coastline the instruments off Walcott and Horsey recorded more waves from the north east. The peak period (Tp) of the majority of waves was within the 2 – 4 second range. These being short, locally generated wind driven waves. The mean wave heights at Scolt Head island were 0.6 m and at Horsey this was 0.7 m. The maximum wave recorded was 3.38 m at Walcott on the 20th March 2007. The largest surge recorded was 1.868 m, logged on the 31st October 2006 by the S9N AWAC at Scolt Head.

This year of monitoring has shown a similar trend, the same times of the year are identified as being the stormiest, or the calmest periods. November through to March being the stormiest time, and November and March being the stormiest months. Storm waves of 3.6 m were logged on the 21st and 22nd of March and the second largest residual surge was recorded on the first of the month. The surge event on November 9th was the largest of the year, and one of three surge events in November. The increased tidal levels during the event also led to the largest storm waves being recorded for the Norfolk coast. A 4 m wave was logged at Walcott in a depth of 12.5 m.

The dominant wave direction is again from the north to north east, and is consistent throughout the seasons and during storm events. Four storms were identified from the storm threshold, however the peak wave heights during these events were substantially higher than the threshold value. The occurrences of high waves highlight the need for consideration of surge levels in combination with wave direction and heights in coastal management. The 4 m (Hs) wave at Walcott occurred when the water elevation was 2.6 mODN with a coincident surge of 1.6 m. Mean wave heights (Hs) throughout the year range from 0.5 – 1 m, with the mean peak wave period (Tp) ranging from around 5 – 8 seconds. At Scolt Head Island most peak wave periods are around 3 – 4 seconds. The site also receives a lower amount of wave energy than the other Norfolk locations. However the site has the highest tide range, and high water levels. The area is therefore more vulnerable during surge events than to wave impacts. The Defra guidance for sea level rise, as followed in the Shoreline Management Plan is a net rise of 4 mm by 2025. Therefore surge monitoring on the frontage is critical, as an increase in sea level and harsher storm conditions makes low lying land continually more vulnerable to future storms.

The tidal state, bathymetry and weather conditions are seen to be significant factors in the wave climate. In Norfolk a sufficient tidal level is required for higher waves to reach the coastline with less modification from banks and the bed. The waves are quick to react to changes in wind conditions, and the spectral data shows an energy build up and increase in wave periods with prolonged storms. The strong winds during the November event increased the impact of spray at sites such of Walcott, which blew over defences into the town. The surge caused prolonged high water with wind acting on high waves. The event highlights the importance of considering waves in forecasting and management.

Wave climate and extremes are an important consideration in forecasting and coastal management activities. Real time offshore buoy data can inform forecasting duty officers and EA Operations Delivery staff during or preceding an event. The collected data can be valuable for validating models and in determining forecasting errors of surges. It can also inform Mean Sea Level adjustments used in flood forecasting. The determination of wave distributions and wave types from the height / period analysis is of use in studies assessing overtopping and the design of coastal structures in this region. The report also demonstrates a good indication of the current sea state and trends in wave climate and sea level. Although a 3 year period is not suitable for long term trend analysis it is hoped these reports can be used with future/historic datasets. The individual reports can be used in conjunction to directly compare adjacent or nearby instruments and determine relationships in waves and tide progression at each region.

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[4] Datawell W@ves 21: www.datawell.nl/
[5] POL, Cromer tide gauge: http://www.pol.ac.uk/ntslf/tides/?port=0183
[6] Environment Agency Flood Warning system: http://www.environment-agency.gov.uk/homeandleisure/floods/31620.aspx

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Glossary

Bathymetry – The measured shape and depth contours of the sea bed.

Fetch - The uninterrupted distance over water which the wind acts to produce waves.

Intertidal – The coastal area between the Lowest Astronomical Tide (LAT) and Highest Astronomical Tide (HAT).

Maximum wave height (Hmax) – Statistic of the maximum wave height recorded in a period of time.

Mean direction (Mdir) – The average or main direction from which waves have come, measured over a period of time.

Mean Sea Level - Generally refers to 'still water level' above a fixed datum (excluding wave influences), averaged over a period of time such that periodic changes in level (e.g. due to the tides) are smoothed out.

Mean wave period (Tz) – Also referred to as the zero crossing period, a description of the average wave period over a duration of time.

Neap Tide - The tide that occurs when the tide-generating forces of the sun and moon are positioned at right angles to each other. The neap tide has the lowest tidal range.

Ordnance Datum (OD) – A specific datum or plane to which depths or heights are referred to.

Peak period (Tp) – Also called dominant wave period and Tpeak, it is the wave period (time for two successive waves to pass a point) associated with the largest wave energy, obtained from the spectral "peak frequency" i.e. the frequency band that has the largest energy.

Residual surge level – The difference from the predicted (astronomical / harmonic tide level) and the observed / instrument measured level. A surge can be negative or positive relative to the mean sea level.

Return period – A statistical interpretation to describe the frequency an event will occur, for example a 2.5 m wave that may be expected once in every 5 years would have a 1:5 years return period.

Sea (waves) – Waves generated at a storm system, under a height of 2 m.

Significant wave height (Hs) – Statistical calculation of Hm0 taken from the spectral analysis to describe the average wave height.

Spring tide - The tide that occurs when the tide-generating forces of the sun and moon are in alignment and results in a higher than average tidal range.

Storm surge - A storm surge is the additional sea level accounted for by a storm. The rise in water level causes a propagating bulge of water on the open coast caused by the action of wind stress and atmospheric pressure on the sea surface.

Storm waves – Wind driven waves associated with a storm system, these waves have a higher frequency than swell waves and therefore can cause multiply frequency peaks in the spectra. In a multiple peaked spectrum the mean wave period (Tz) may not be a measure of the frequency where the peak energy occurs.

Swell (waves) – Waves that have travelled out of the area they were generated. Swell waves characteristically have a flatter shape and longer period. In spectral analysis swell waves have a low frequency, with a peak period (Tp) where energy decays in the frequencies either side.

Wave climate – The average condition of the waves at a location over a period of time, represented by wave statistics such as height, period and direction.

Wave spectra – The wave energy in a band of frequencies, describing the total energy transmitted by a wave-field.

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