6. Waves

1. Key points

i. **Introduction**

Waves affect marine operations (e.g. transport, fishing, offshore industry) and coastal communities; they can cause coastal erosion (contributing to flood risk) and structural damage. They influence stratification and enhance air-sea fluxes; in shallow waters they cause near-bed currents and suspend sediment, so affecting nearshore and benthic habitats, communities and demersal fish. Waves occur in all regions but decrease in shallower water (section 2).

ii. **How has the assessment been undertaken?**

The assessment is in terms of characteristic forms of variability and some estimation of trends from regular wave measurements. No common baseline is possible. There are data from satellite altimetry, automatic weather stations on moored buoys and lightships, offshore and many nearshore sites. Modelling for wave prediction, forecasts and state estimation is well-developed (section 2).

iii. **Current and likely future status of waves**

- Wave heights in winter (when largest) increased through the 1970s and 1980s, as shown by data: in the NE Atlantic (significant increase between the 1960s and early 1990s); in the North Sea (increase from 1973 to the mid-1990s); at Seven Stones off Land's End (increase of about 0.02 m/y over 25 years to 1988). However, recent trends are not clear and may depend on region; some series appear to show a decrease. Year-to-year variability is such that there is no clear longer-term trend and no clear change since *Charting Progress* (Defra et al., 2005) (section 4.6).
- Winter wave heights correlate significantly with the North Atlantic Oscillation Index (a measure of the strength of westerly winds at UK latitudes), in the west and the Irish Sea; the correlation is particularly strong in the north west (section 4.7).
- In very shallow waters (e.g. near coasts) trends are reduced; wave heights are limited by water depth (as waves break) (section 4.5); however, if sea levels (raised by climate change) increase depths nearshore, then larger waves may approach the shore.
- Climate change may affect storminess, storm tracks and hence wave heights. Some climate models suggest more frequent very severe storms but there is little confidence in predicted changes of wave heights (section 5).

iv. **What has driven change?**

Waves are directly driven by winds, modified by currents and shallow sea-floor topography, and can thus be affected locally by man-made structures (section 2).

v. **What are the uncertainties?**

Interannual variability introduces uncertainty in estimating longer-term trends, especially in recent years with little clear trend. Locally, waves are strongly affected by local conditions and wider-area projections may not apply directly. Future projections in UK waters are very sensitive to climate model scenarios for storms, themselves uncertain (being sensitive to competing influences) (section 5).

vi. **Forward look**

There will be a continuing need for the recently enhanced monitoring network. Models will (as now) be important for forecasting and state assessment. Management is limited to mitigating impacts and to affecting wave climate locally on the scale of any (possibly 'soft') engineering. Waves are a possible source of renewable energy (section 6).

2. Introduction

The wave climate can be considered as comprising: (1) the long-term mean climate, (2) the annual or seasonal cycle, (3) non-seasonal variability (within-year and interannual). In UK waters, wave climate is strongly seasonal: mean wave heights peak around January, with a high risk of high monthly-mean wave heights and extreme wave heights from October to March. Interannual variability in monthly mean wave heights is large, particularly from December to March, the months primarily associated with the North Atlantic Oscillation (NAO). The NAO Index is a measure of a mean atmospheric pressure difference between the Azores (or Gibraltar) and Iceland (e.g. Jones et al., 1997).

The height of offshore waves depends on the strength of the wind, its duration and the 'fetch' (i.e. the distance) over which the wind has acted on the ocean surface. Waves approaching the UK coastline can be generated locally, in the NE Atlantic, in the NW Atlantic and even in the South Atlantic (with implications for forecasting; also extensive generation is associated with long waves which can affect the seabed down to 200 m). Waves at the coast are influenced by local water depth and by the nature of the seabed: waves can be reduced through dissipation by a broad gently-shoaling beach, a rough seabed nearshore or offshore shoals (banks). Conversely, raised sea level can decrease such dissipation of waves arriving at the coast and so increase coastal wave heights.

High waves are a risk to platforms and pipelines, and may disrupt routine marine operations (e.g. fishing, transport). Estimates of likely extreme waves are essential for the design of ships and offshore structures such as oil rigs. Waves are also a possible source of renewable energy. At the coastline, waves contribute to flood risk as a factor in total sea level through wave setup and overtopping; especially, they often exert the greatest forces and potentially cause structural damage and coastal erosion. Thus waves can affect coastal development and communities, especially on exposed coasts facing the Atlantic. Larger waves can damage seawalls and lead to increased rates of erosion of soft coastlines such as the glacial till cliffs in East Anglia and Yorkshire. The most serious coastal flooding events are often caused by a combination of high tides, storm surges and wave damage to coastal defences and other structures.

Waves are particularly effective (1) as agents of surface mixing, influencing stratification and enhancing air-sea fluxes of all quantities; and (2) at suspending sediment through their thin high-shear bottom boundary layer (if their currents extend to the seabed). Hence they affect nearshore and benthic communities and demersal fish.

Wave measurements before about 1955 were relatively crude. In the 1960s and 1970s, the National Institute of Oceanography equipped some lightships around the coast with wave-recorders that used acceleration and pressure fluctuations to provide information on wave heights and periods (but not directions). The recorders were typically only deployed at each site for 1 to 2 years, the main exception being Seven Stones LV, which provides one of the longest wave records from UK waters. Wave-following buoys using accelerometers replaced pressure-type wave recorders; by the late 1970s most wave recording was being carried out using such wave buoys. More recently, several instruments for measuring waves have been developed, including directional wave buoys, downward-looking lasers and HF radar. The satellite altimeter is particularly good for climate studies, providing global coverage. Tucker and Pitt (2001) described wave-measuring instruments in detail.

Descriptions of the monitoring networks that regularly measure waves can be found on the UKDMOS website (www.ukdmos.org). There are data from satellite altimetry, Marine Automatic Weather Stations (MAWS) on moored buoys and lightships, WaveNet offshore locations, and many nearshore sites especially around the south of England. Modelling for wave prediction, forecasts and subsequent estimation is well-developed. The main limitations are (1) in areas of strong currents which can affect wave propagation; models are formulated but lack much good data for validation; and (2) nearshore where waves may vary greatly on short scales owing to topography which is often not known well enough.

3. Progress since *Charting Progress*

The MAWS network now includes eleven moored buoys, nine of which are in open-ocean locations mostly to the west of the British Isles (Gascogne, K1, K2, K4, RARH, K3, Brittany, K5, K7), and two in coastal inshore waters (Aberporth, Turbot Bank). There are also Light Vessels equipped with automated marine sensors (Seven Stones, Channel, Greenwich, Sandettie and F3). Two North Sea moored buoys (K16 and K17) which contributed data to *Charting Progress* have been taken out of service. The longest (Seven Stones) spans 46 years, albeit with gaps.

The Strategic Regional Coastal Monitoring Programmes of England have developed a coastal wave network around the south of England with nearshore measurements at about 20 locations from Herne Bay (north Kent) to Minehead (Bristol Channel). Wave buoys deployed around Scotland in late 2008 and early 2009 (with funding from the Environment Agency and the Scottish Environment Protection Agency) form Scottish WaveNet and are planned to last up to five years. The buoys are south-west of Mull, west of South Uist, in the Moray Firth, just off Aberdeen (run by the University of Aberdeen) and in the Firth of Forth (Isle of May). A wave buoy just west of Orkney is operated by the European Marine Energy Centre. Buoys are planned in the North Channel/Clyde Sea and south of Galloway.

The longest periods of wave measurements, at consistent locations around the UK, are believed to be as follows (updating Law et al., 2003): coastal wave data – off North Kent (1979–1998 off Whitstable, 1996 to present off Herne Bay); Tees Bay (1988–present); Perranporth (1975–1986; resumed 2007); offshore wave data – Seven Stones Light Vessel (1962–1988 and 1995 to present); Forties Field (1974–present); Frigg QP (1979–present); Ekofisk Field (1980–present). Nevertheless, the density of wave measurements remains rather sparse relative to the short distances on which waves can vary, especially near complex coastlines.

Wave predictions and forecasts continue to be made routinely by the Met Office, and several research groups have continued to develop shallow-water wave modelling to improve the representation of (two-way) wave-current interaction, dissipation and effects of nearshore topography. In some nearshore locations, lidar has been used to update local bathymetry. X-band radar has also been developed as a potential means to monitor bathymetry quasi-continuously over coastal areas within range (a few kilometres; Bell, 1999).

Figure 6.1 shows Significant wave height as measured from a selection of the Met Office MAWS network of buoys and Light Vessels. (Significant wave height, H_S, is approximately the average peak-trough height of the highest third of the waves.) The data are quality controlled and filtered using a running-boxcar 30-day mean. The figure shows largest wave heights in the north and west (exceeding those at Seven Stones), a decrease to the somewhat less exposed southern Irish Sea (off Aberporth) and a big reduction in the southern-most North Sea. Here (Sandettie) long waves from the open ocean have largely dissipated in shallow water; moreover, the fetch is limited for the directions of frequent wind occurrence. The wave heights are strongly seasonal with mid-winter maxima, but there is significant month-to-month and interannual variability. There is no clear trend for the limited period 2003 to 2008 (section 4.6 discusses longer-term trends).

4. Presentation of the evidence

4.1 Mean wave climate and seasonal variability

Estimates of significant wave height (H_S) obtained from May 1992 to September 2007 from satellite altimeters on ERS-1, ERS-2, Envisat, Geosat Follow-On, Jason-1 and Topex (from the SOS 'Wavsat' database) have been used to obtain the description given below of the wave climate in the areas around the UK shown in Figure 6.2. The H_S values were calibrated by comparing altimeter values with those from US National Data Buoy Center buoys when the altimeters passed within 100 km of them.

4.2 Annual cycle

The dominant cycle in H_S is the annual cycle, although in UK waters this explains only 25% to 35% of the variance in H_S in open Atlantic waters and less than 15% in more sheltered locations. A simple sine curve describes most of this annual cycle. Higher frequency components of 2 and 3 cycles per year – although accounting for less than 1% of the variance – are generally statistically significant, and incorporating these higher cycles in the analysis does appear to give a better representation of average conditions than the annual sine curve. For example, the annual sine curve fitted to the data from 59°–60° N, 6°–8° W peaks in January whereas the three-cycle fit peaks in February – as do the monthly means from the data. Figure 6.2 shows the average H_S throughout the year obtained by fitting these three cycles to the data.

4.3 Variation about the annual cycle

There is considerable variation in H_S about this mean curve. Indications of this variability are shown in Figure 6.2 which also shows the 25 percentile and 75 percentile curves – wave heights can be expected to be below the 25 percentile a quarter of the time and above the 75 percentile a quarter of the time.

The figures differ from *Charting Progress*: primarily due to fitting 1, 2 and 3 cycles per year instead of just the annual cycle; also due to using more recent data and to fitting individual H_S values rather than mean values but these make relatively small differences. The quartiles are from fitting log(H_S) so that residuals are more nearly normally-distributed, assuming that the statistical distribution of H_S is lognormal.

4.4 Between-year variability

There are considerable interannual variations in wave climate, especially between winter months; some winters are much stormier than others. Some of this variability in the winter months can be linked to the NAO Index (see section 4.7). MAWS locations K4, K7 and Aberporth possibly show a small increase for the period 2003–2007 relative to the previous period illustrated in *Charting Progress*, but interannual variability is greater.

4.5 Distribution

Wave-heights are greatest in the most exposed waters of the north and west, and decrease markedly into the North Sea and southward therein, into the Irish Sea and into the English Channel. These trends may be attributed to shallow water dissipation of long waves from the open ocean and limited fetch for the directions of frequent wind occurrence. In the Irish Sea, Channel and southern North Sea, the relative magnitude of the seasonal cycle also decreases. Timing of the maximum in the seasonal cycle ranges from mid-January in the south to the end of January or early February in the north. These trends show in data from buoys off eastern and especially southern England. Figures 6.3 and 6.4 show wave heights in the North Sea offshore from the Tyne/Tees and Harwich.

Around southern England the Coastal Wave Network records waves at a recently-increasing number of locations (now 20 wave-riders) from Herne Bay (Kent) to Minehead (Bristol Channel). Typically these are 1 to 2 km offshore in about 10 m water depth. Example plots show histograms of values for: significant wave height H_S, wave direction, wave period (peak of the spectrum Tp, average of the zero-upcross wave periods Tz). The plots are for Folkestone (Figure 6.5), Pevensey Bay (Figure 6.6), Hayling Island (Figure 6.7), Milford-on-Sea (Figure 6.8), Weymouth (Figure 6.11), Perranporth (Figure 6.12) and Minehead (Figure 6.13) – i.e. in sequence along the coast. Also shown are year-by-year extreme wave height statistics (values exceeded by particular small percentages; note the varying duration of the time axis). For Milford, times of occurrences of the highest waves are shown in Figure 6.9. Data from Poole Bay are also shown in sequence (Figure 6.10) and data for Liverpool Bay in Figure 6.14.

These examples show:

- The influence of extensive shallow water limiting wave heights and wave periods; this is a general effect, albeit refraction and consequent focusing or wave-spreading can introduce much local variation in wave heights. The most exposed site illustrated, Perranporth, has much greater wave heights and longer periods than the other locations.

- Strong directionality reflecting exposure (fetch) and probably some refraction of incident waves towards normal-to-shore in shoaling waters; these are general effects but the resulting direction varies strongly with location. Eastern Channel locations (Folkestone, Pevensey Bay) and Minehead show bi-directional distributions; Milford-on-Sea and Weymouth are adjacent but show markedly different directionality as they face SW and SE respectively.
- Strong variability within any month so that the maximum is typically three or more times the mean in that month; seasonally and interannually. However, there is no discernible trend in the series, even for the 11 years at Milford-on-Sea.

As stated in *Charting Progress*, coasts exposed to the west experience the largest wave heights; especially, the Outer Hebrides have a long-term mean wave height of 3 m. The annual range has a pattern similar to the long-term mean: greatest in the north-west; decreasing eastwards into the English Channel and southwards into the North Sea.

4.6 Short- and long-term non-seasonal variability

As stated in *Charting Progress,* much of the observed variability is seasonal, but the average annual cycle explains less than half the variance of wave height in the North Sea and English Channel; interannual variability is relatively important.

At Station Mike (66° N, 2° E; operated by the Norwegian Meteorological Institute DNMI), there is a trend of increasing significant wave height from 1980 to 2007. *Charting Progress* noted that in the NE Atlantic, the annual mean H_S had increased during the 1960s through to the early 1990s. Data from OWS (Ocean Weather Ship) *Polarfront* at Mike showed a similar trend for the 1980s and early 1990s, but from then to 2002 the trend was less clear (Iden, 2003). However, more recent data from OWS *Polarfront* confirm that the increase in H_S has continued from the early 1990s to date; annual mean H_S rose from nearly 2 m in 1980 to nearly 3 m in 2007 (Figure 6.15a). There was no corresponding increase in mean wind speed over this period. Annual maxima in H_S show a similar trend with more noise (Figure 6.15b). The large maximum values of around 15 m are due to strong winds persisting in the same direction for days at a time, allowing the waves to develop over a long period of time (Holliday et al., 2006).

Trends at other Ocean Weather stations (no longer operating) were given in *Charting Progress* (Defra, 2005). It was also reported there that (1) mean winter wave height in the NE Atlantic increased between the 1960s and early 1990s; (2) winter wave heights increased in the North Sea from 1973 to the mid-1990s with a decrease thereafter. Overall, however, year-to-year variability is such that there is no clear longer-term trend.

Monthly-mean wave heights at Seven Stones are shown in Figure 6.16 spanning 1962 to the present (with gaps). The widely reported increase to 1988 appears to have been followed by a decrease from 1995 to a minimum in 2006, with increased values again in the winters 2006/07 and 2007/08.

4.7 Wave climate and the North Atlantic Oscillation

Waves are strongly related to wind conditions, particularly strength and persistence, so a link to the north-south atmospheric pressure gradient over the North Atlantic could be expected. The increase in wave heights from 1962 to 1985 off Land's End (Carter and Draper, 1988) has been correlated with air pressure gradients (Bacon and Carter, 1993). Kushnir et al. (1997) have tied the increase in wave heights to the increase in wintertime storminess and mean wind speeds in the North Atlantic from the 1960s to the 1990s (see sub-chapter 1: Weather and Climate; the increase in storminess is only to levels comparable with those at the start of the 20th century). However, there was also a marked rise in the winter NAO Index between the 1960s and the early 1990s (e.g. Hurrell and Deser, 2009), giving strengthened westerly winds. The WASA Group (1998) considered that any noticeable increase in H_S since the 1960s could be positively correlated with the NAO, rather than with storm intensification; a positive NAO Index is associated with greater wave height than is a negative Index. The ability of the NAO to act as a predictor for the incidence of severe storms – as distinct from waves – appears to vary with location and historically (Allan et al., 2009). This one index does not represent all relevant atmospheric variability.

Mean winter NAO values are plotted in Figure 6.17. The smoothed curve shows the 1960s to 1990s rise from low to high values, as associated with the increase in winter wave heights. Since then the NAO Index has been at about the long-term average, but the considerable variation from year to year makes it impossible to determine any trend. (Note that the NAO has an annual cycle; the winter average is about 0.5 above the overall mean.)

The influence of the NAO on the winter wave climate in the NE Atlantic and UK waters has since been studied in more detail, primarily using satellite altimeter measurements of significant wave height (Cotton et al., 1999; Woolf et al., 2002, 2003). As an example, Figure 6.18 shows a relationship between monthly mean wave heights (from altimeter data) at two UK sites and the NAO Index.

For this report, data from the locations shown in Figure 6.2 were analysed. The NAO Index has the biggest impact on wave heights in the area 59°–60° N, 6°–8° W. Here the mean significant wave height in the 15 Januaries from 1993 to 2007 was 4.5 m. The January NAO indices for 1980 to 2008 (based on pressure differences between Gibraltar and Iceland) had 25% and 75% quartiles of –1.12 and 1.24. Only two Januaries from 1993 to 2007 had indices below –1.12 and their mean significant wave height was 3.7 m; six Januaries had indices above 1.24 – their mean significant wave height was 5.2 m. Average conditions were not a good indicator of conditions in any one January. (Variations in wave power, proportional to (wave height)^2, are yet more marked.)

Figure 6.19 shows a relationship between the mean wave heights for the four months December to March and the NAO indices for those months from December 1992 to March 2007. The linear fit explains 57% of the variance. (There were no significant differences between the lines fitted to the individual calendar months.) An analysis of the average winter conditions (the mean of the four monthly means, December to March, and the mean of the four monthly NAO indices) – also shown in Figure 6.19 – gives an even closer fit, explaining 76% of the variance of the mean winter wave heights.

The goodness of fit of the mean winter values can be illustrated by plotting the mean winter wave heights against the year and adding values calculated from the fitted line; the result is shown in Figure 6.20. The fit is particularly good for the relatively calm winter of 1995/96 (altimeter data 3.51 m, regression fit 3.37 m) and the rough winter of 2006/07 (4.93 m and 4.89 m). There was no significant trend in the mean winter wave heights over this period (1992/93 to 2006/07); nor in the mean winter NAO Index values.

The regression line shown in Figure 6.19 (which also gives the intercept and slope of this line) is statistically significant at $P < 0.1\%$ – i.e. the probability that the slope would have arisen if there were no correlation is less than one in a thousand. The only other location with such significance is in the Irish Sea (53.5°–54° N, 3.5°–4.5° W) – see Figure 6.21. However, here the regression slope (sensitivity of the mean winter wave height to the NAO Index) is only 0.15 metres per NAO index, compared with 0.37 NW of Scotland; hence the range in wave heights explained by the NAO is less in the Irish Sea.

Figure 6.22 shows the variance explained by the NAO and the sensitivity of the mean winter wave height to the NAO Index at the eight locations shown in Figure 6.2. The regression was significant ($P < 10\%$) at seven of the eight locations; only at that site east of Scotland (57°–58°N, 1°W–1°E) was it not significant. But at only two locations did the NAO account for the bulk of the variation in the mean winter wave height.

Figure 6.23 from *Charting Progress* (Defra et al., 2005, and consistent with Figure 6.22) shows sensitivity to the NAO Index of mean monthly wave height offshore of northern Europe – estimated by linear regression analysis of an altimeter-based climatology.

To the west of Scotland, the relationship is particularly strong – describing about 70% of the variance and implying monthly mean wave heights varying from 3 to 7 m for extreme negative winter NAO Index and positive winter NAO Index respectively. The relationship is weaker elsewhere – vanishing on the East Coast of Britain – but is a major feature of the NE Atlantic. In terms of the sensitivity of the winter mean H_S to changes in the NAO, the wave climate off the north-west of Scotland (the Outer Hebrides) is highly sensitive, such that a unit change in the NAO will induce a 0.42 m increase in the mean winter H_S, and a 1.28 m change in the 100-year return value (Cotton et al., 1999; Woolf et al., 2002, 2003).

The wave climate in the Celtic Sea/Irish Sea and Lyme Bay is also sensitive to the NAO (for example: 54% of the variance in Carmarthen Bay, i.e. 0.2 m change in mean H_S and 0.69 m change in 100-year H_S per unit NAO change; 13% of the variance in Lyme Bay). The relationship in the northern North Sea is strong during December to March, but the correlation between the NAO Index and the waves for a region offshore of Holderness (NE England) is insignificant (Cotton et al., 1999; Woolf et al., 2002, 2003).

5. What the evidence tells us about environmental status

Wave heights are related to winds, with their seasonal dependence, and to interannual variability, some of which is related to the NAO Index. The various factors contributing to variance within the system make any long-term trend hard to estimate. Thus the future surge and wave climate is more difficult to predict than sea-level rise, for example. However, it will clearly depend on the future atmospheric climate, and specifically winds. An ancillary factor nearshore is altered water depth as a consequence of sea-level rise; this may enhance the ability of higher waves to approach the coast, increasing their impact.

It is generally accepted that in a warming climate the intensity of tropical cyclones will increase as their generation is closely linked to sea-surface temperature (Emanuel, 2005). On the other hand, the number of mid-latitude depressions may not necessarily increase as there is evidence of two opposing mechanisms: the equator-to-pole temperature difference decreases with global warming; and the number of winter storms may increase at the downwind end of northern hemisphere storm tracks (Wolf and Woolf, 2006). A significant increase in cyclonic activity over the North Atlantic has been observed during the second half of the 20th century and storminess increased in the NE Atlantic and NW Europe (Alexandersson et al., 1998, 2000). Trends toward higher storm surge levels have recently been reported for various locations in northern Europe (Lowe et al., 2001; Lowe and Gregory, 2005; Woth et al., 2006). However, the trend of increasing storminess and wave heights in the North Atlantic, from the 1960s to the 1990s, has ended with a return to calmer conditions (Matulla et al., 2008). The trend in storminess and wave heights coincided with increasingly positive NAO Index over the 1960s to 1990s (Figure 6.17); however, the ability of the NAO Index to act as a predictor for storminess appears to vary with location and in time: winter NAO is a significant but historically-varying factor in the incidence of severe storms (Allan et al., 2009). Nearshore wave parameters can be modelled given the offshore wave climate for future scenarios (Leake et al., 2007, 2008; Wolf, 2008). UKCP09 model projections for future wave climate in UK waters indicate (with large uncertainties) a slight increase south-west of the UK, a reduction north of the UK and little change in the North Sea (Lowe et al., 2009); these changes reflect a shift of storm tracks to the south (likewise uncertain).

The summary table (Table 6.1) includes an assessment of trend but not status (‘traffic-light’) because (1) no accepted criteria apply for waves giving significant risk of adverse effects; and (2) the UK (government), or even the EU, cannot itself take measures to improve the status.

Waves are subject to a wide range of natural variability on many time scales from storm duration to interannual, reflecting the multiple factors affecting the wind that drives them (e.g. season, NAO). This variability and (annual-average) wave heights have shown changes perhaps related to the character of storms on interannual to decadal time scales. However, given the greater range of seasonal variability (e.g. in monthly-averaged wave heights) it is hard to argue that these changes have had a significant impact on the environment or human health. (A distinction is made from the ongoing occasional high risk posed by high waves.) Longer-term or future climate-related trends might have an impact, but further research is needed to clarify these. For example, knowledge of the likely future trend in the NAO Index would be useful – but at present there is no agreement on what this might be (Woolf and Coll, 2006). Local construction, for example in harbours and around wind turbine pylons, has the potential to introduce local changes and significant impacts on the spatial scale of the construction. There is little basis to distinguish between CP2 Regions except in respect of such local activities and overall wave heights. There are large differences in average wave heights between locations within any one CP2 Region, as values (but not necessarily impacts) decrease nearer to shore.

6. Forward look and need for further work

There will be a continuing need to monitor waves for their impact on offshore operations and the coast. Thus the reasons for recent enhancement of the monitoring network remain valid. The advanced state and continuing development of models gives them an important role in prediction, forecasting and state assessment, supported by data for model validation and assimilation. Little management can be done except to mitigate impacts and the immediate inshore wave climate locally (by nearshore structures of various types). There is continuing interest in waves as a possible source of renewable energy (total wave energy arriving in UK waters is of magnitude comparable with UK electricity consumption).

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Figure captions

Figure 6.1: Wave height (m) at a) K4, at 55° 24'N, 12° 12'W; b) K7, at 60° 36'N, 4° 54'W; c) Aberporth, at 52° 24'N, 4° 42'W; d) Seven Stones Light Vessel at 50° 06'N, 6° 06'W; e) Sandettie at 51° 06'N, 1°48'E. Data from Moored Automatic Weather Stations, courtesy of the Met Office.

Figure 6.2: Means & quartiles (25% & 75%) of significant wave height throughout the year determined from altimeter data 1992-2007. The location boxes indicate the areas from which the data were taken. Courtesy of D J T Carter and SOS Ltd.

Figure 6.3: Wave height by month,Tyne/Tees, 2007-2008: means (colour), maxima (bars). Courtesy of J. Rees, Cefas.

Figure 6.4: Wave height by month, West Gabbard (Harwich), 2003-2008: means (colour), maxima (bars). Courtesy of J. Rees, Cefas.

Figure 6.5: Histograms of wave parameters, and wave height exceedance over time, Folkestone. Courtesy of T. Mason, Channel Coastal Observatory.

Figure 6.6: Histograms of wave parameters, and wave height exceedance over time, Pevensey Bay. Courtesy of T. Mason, Channel Coastal Observatory.

Figure 6.7: Histograms of wave parameters, and wave height exceedance over time, Hayling Island. Courtesy of T. Mason, Channel Coastal Observatory.

Figure 6.8: Histograms of wave parameters, and wave height exceedance over time, Milford-on-Sea. Courtesy of T. Mason, Channel Coastal Observatory.

Figure 6.9: Time-series of storms (highest waves). Courtesy of T. Mason, Channel Coastal Observatory.

Figure 6.10: Wave height by month, Poole Bay, 2005-2008: means (colour), maxima (bars). Courtesy of J. Rees, Cefas.

Figure 6.11: Histograms of wave parameters, and wave height exceedance over time, Weymouth. Courtesy of T. Mason, Channel Coastal Observatory.

Figure 6.12: Histograms of wave parameters, and wave height exceedance over time, Perranporth. Courtesy of T. Mason, Channel Coastal Observatory.

Figure 6.13: Histograms of wave parameters, and wave height exceedance over time, Minehead. Courtesy of T. Mason, Channel Coastal Observatory.

Figure 6.14 shows Cefas data for wave heights in Liverpool Bay.

Figure 6.14: Wave height by month, Liverpool Bay, 2003-2008: means (colour), maxima (bars). Courtesy of J. Rees, Cefas.

Figures 6.15 (a-left; b-right): Annual mean significant wave height H_S, maximum H_S and wave period each year, from OWS Polarfront at Mike. Error bars in annual means show ± 1 standard error. Note: the wave period is not correlated with wave height H_S. Courtesy of Norwegian Meteorological Institute.

Figures 6.16: Monthly-mean wave heights at Seven Stones from 1962 to present, using data held by BODC (1962-1988) and data from the Met Office (1995 to present). Courtesy of G. Evans, BODC and Met Office.

Figure 6.17: NAO index, 1867-2009, based on the normalized pressure difference between Ponta Delgada (Azores) and Stykkisholmur (Iceland). Courtesy of Met Office.

Figure 6.18: NAO Index versus wave height at Malin Head (MH) and Sea of Hebrides (SoH). The NAO index here (from Gibraltar and Iceland) follows Jones et al. (1997) updated by P.D. Jones (UEA, pers. comm, 2000). Courtesy of D. Woolf, NOC (now at UHI Thurso).

Figure 6.19. Mean winter (Dec.-March) wave heights against mean winter NAO values, December 1992 to March 2007 (large red 'X') and individual monthly values (small blue 'x'). The dashed line is the fit to the 15 mean winter values. Courtesy of D.J.T. Carter.

Figure 6.20. Mean winter (Dec-March) wave heights and values estimated from regression with the NAO index. (Actuals from altimeter data: solid blue line; estimated: red dashed line.) Courtesy of D.J.T. Carter.

Figure 6.21. Mean winter (December-March) wave heights against mean winter NAO values, December 1992 to March 2007 and regression lines at the Irish Sea location. Courtesy of D.J.T. Carter.

Figure 6.22. Variances of mean winter wave height explained (%) by linear regression with the NAO index, and sensitivity of the wave height to the NAO index (metre/index); the latter shown outside the area of analysis. Courtesy of D.J.T. Carter.

Figure 6.23: Sensitivity of winter monthly mean significant wave height to NAO. Courtesy of D. Woolf, NOC (now at UHI Thurso).

Table 6.1 Summary assessment of trends.

Parameter	**CP2 Region**	**Key factors and impacts**	**What the evidence shows**	**Trend**	**Confidence in assessment**	**Forward look**
Waves (significant wave height H_S)	1, 2, 3, 4, 5, 6, 7 (all UK shelf-seas)	Winds, site. Affects coast, benthos, demersal fish	Interannual variability; bigger waves in winter; strongly directional near coasts; in shallows, heights are limited, seasonality and trends are reduced.	Rise to mid-1990s; no clear trend or possibly slight decrease since	Medium	Unclear trend
Waves (significant wave height H_S)	8 (adjacent North Atlantic)	Winds, site. Affects benthos, demersal fish	Interannual variability; bigger waves in winter;	Rise to mid-1990s; no clear trend or possibly slight decrease since	Medium (mean H_S at 66° N, 2° E (just to the north-east) continued to rise to 2007	Unclear trend