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Modelling of waves and set-up for the storm of 11-12 January 2005

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Abstract

On 11-12 January 2005 a severe storm hit the Outer Hebrides and there was flooding on the islands of South Uist and Barra, caused by storm surge and waves. Five lives were lost in one family as they attempted to cross a causeway near Balgarva on South Uist in two cars. Here we investigate the magnitude of the local wave height and the associated wave set-up which caused an additional increase in water level above that due to the astronomical tide and storm surge, using a suite of nested wave models. Wave data from buoys and altimeter are used to validate the model. The wave set-up was found to be nearly 0.5m due to the proximity of exceptionally high waves reaching over 14m less than 50km offshore.

1. Introduction

The storm of 11-12 January 2005 was exceptionally severe with wind-speeds reaching hurricane force. A deep depression (~944 mb) passed to the north of Scotland during the night of 11/12 January (Woolf, 2006). Woolf (2006) described the background and damage done by this event and discussed the observations made of wind-speed, sea-level and waves by means of satellite altimeter records.

Previous studies using wave models on the NW European continental shelf seas include Osuna and Wolf (2005) in which a one-year run of a wave model for the UK continental shelf was carried out on the CS3 grid, forced by six-hourly (~ 1.5° by 1.5°) ECMWF wind data for the period September 1999 to August 2000. In a further study Met Office mesoscale model winds were used to perform a 5-year CS3 wave model hindcast for 2000-2004. Osuna et al. (in press) used the same model, mainly focusing on the effect of different white-capping source terms at selected locations in the Irish Sea for January and March 2003, using mesoscale winds, which proved much more accurate than the ECMWF model winds over the same area due to the better time and space resolution. Wolf and Flather (2005) modelled waves and surges for the 1953 storm, again using the CS3 model, but with a wind reconstruction since detailed model winds were not available for that time. Wolf et al. (2002a,b) and Wolf and Woolf (2005) set up other nested models, using Pro-WAM for the ocean and regional scale models and SWAN for coastal areas. Wolf and Woolf (2005, 2006) used the NE Atlantic model to study waves off NW Approaches and Sea of Hebrides.

Predictions of the storm surge of January 2005 were made at the time with POL's CS3 model run by the UK Storm Tide Warning Service (Flather and Williams, 2004). Here we use the same Met Office mesoscale model winds to reconstruct the wave conditions during this storm event, using a wave model of the NW European continental shelf with the same grid as CS3 (12 km resolution) and nested within a North Atlantic (1-degree resolution) wave model, driven by NCEP/NCAR reanalysis winds. The model winds and waves were validated against available observations. The maximum winds at South Uist from the mesoscale model are shown in Fig. 1, for 22:00 on 11 January 2005. The maximum wind-speed from this time is 34.6m/s i.e. hurricane force. The synoptic chart for midnight on 11 January in Fig. 2 shows that the model storm centre is in good agreement with observations. Detailed results for the Sea of the Hebrides and the western side of the Outer Hebrides, including wave set-up, were then made using the SWAN model on a 1 nautical mile grid.

Section 2 describes the wave models, both WAM and SWAN, and their implementation on the various grids. Section 3 describes the validation of the model winds and waves against existing datasets, for the first half of January 2005. Section 4 describes the wave predictions for the storm event of 11-12 January, with details of the wave set-up in section 5. The results are discussed in the context of their return period, in section 6.

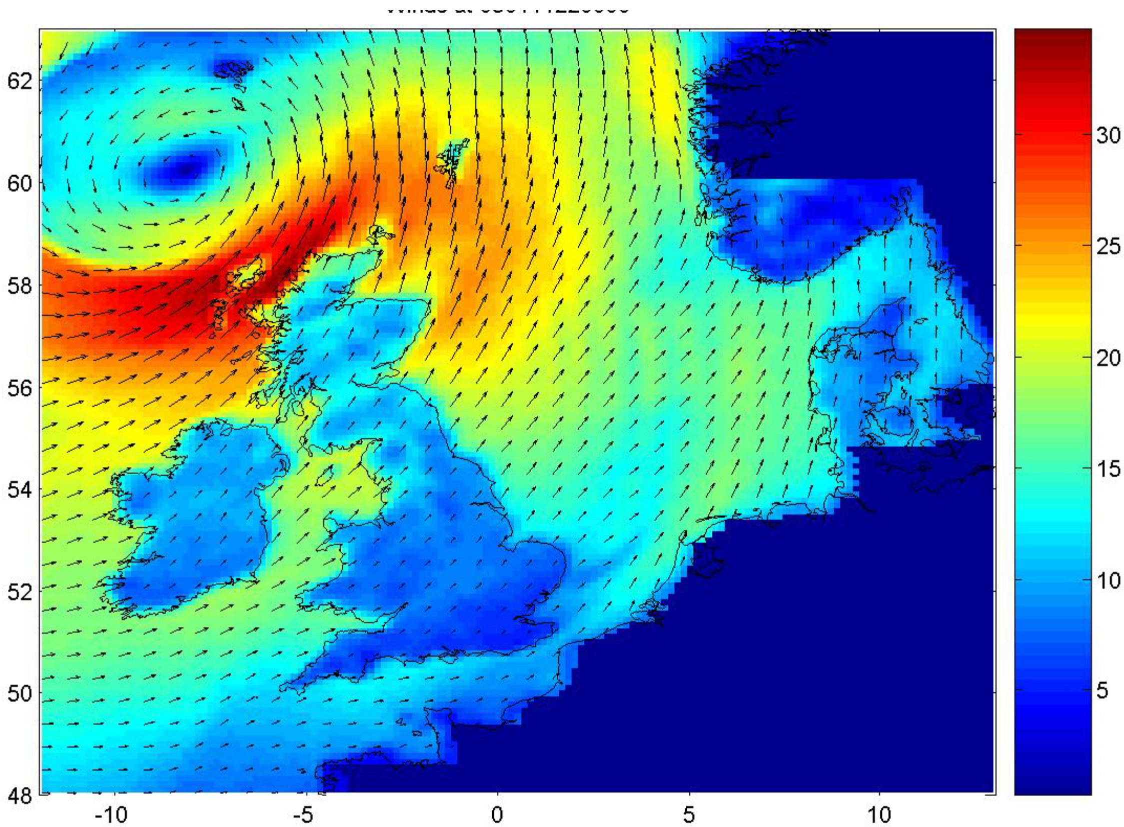


Figure 1: Mesoscale winds at time of maximum wind-stress at South Uist (22:00 11 January 2005)

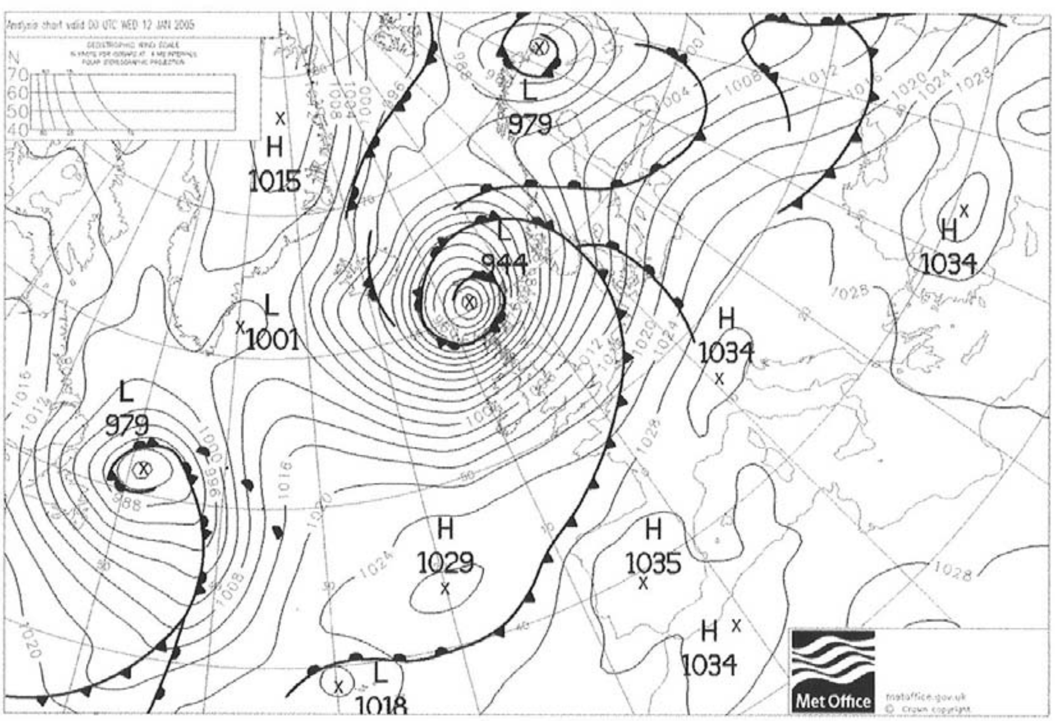


Figure 2: Met Office synoptic chart for 00:00 12 January 2005

2. Wave Models

In order to examine the details of the storm event it is necessary to model the waves at the resolution of the best available wind fields, which, in this case, are the Met Office mesoscale model winds at 12km resolution. The wave model was therefore run on the CS3 grid, at the same resolution as the surge model and the mesoscale winds. However it is also necessary to provide boundary conditions for the wave input from the North Atlantic and a wave model on a 1-degree resolution was used to provide this, as has been done previously e.g. Wolf and Woolf (2005). The set of nested model grids is shown in Fig. 3, with details of the bathymetry in the Hebrides model shown in Fig. 4, in which the islands of South Uist and Barra are identified.

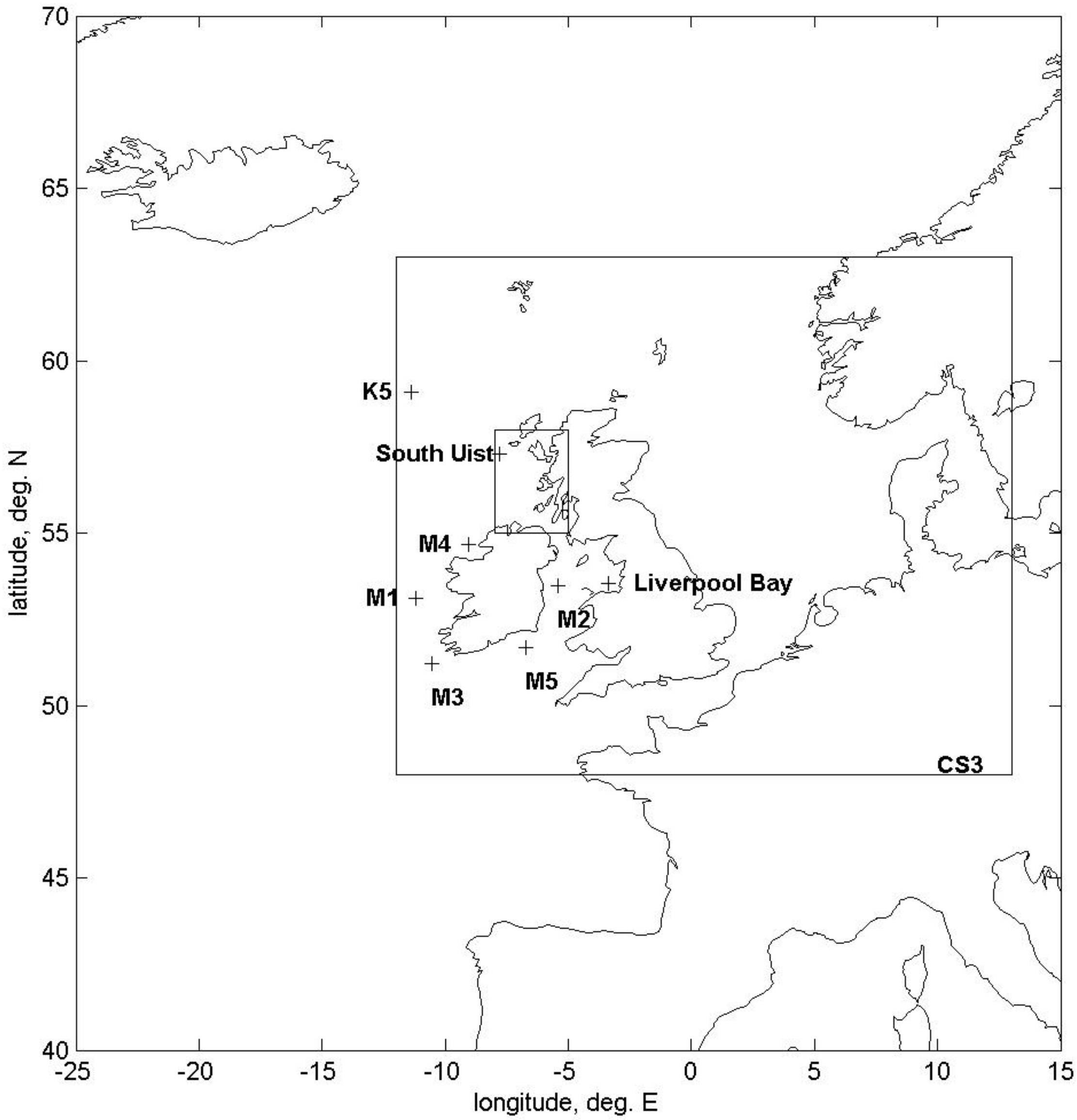


Figure 3: North-east Atlantic model extent with nested CS3 and Hebrides models, also showing locations of model validation and output points

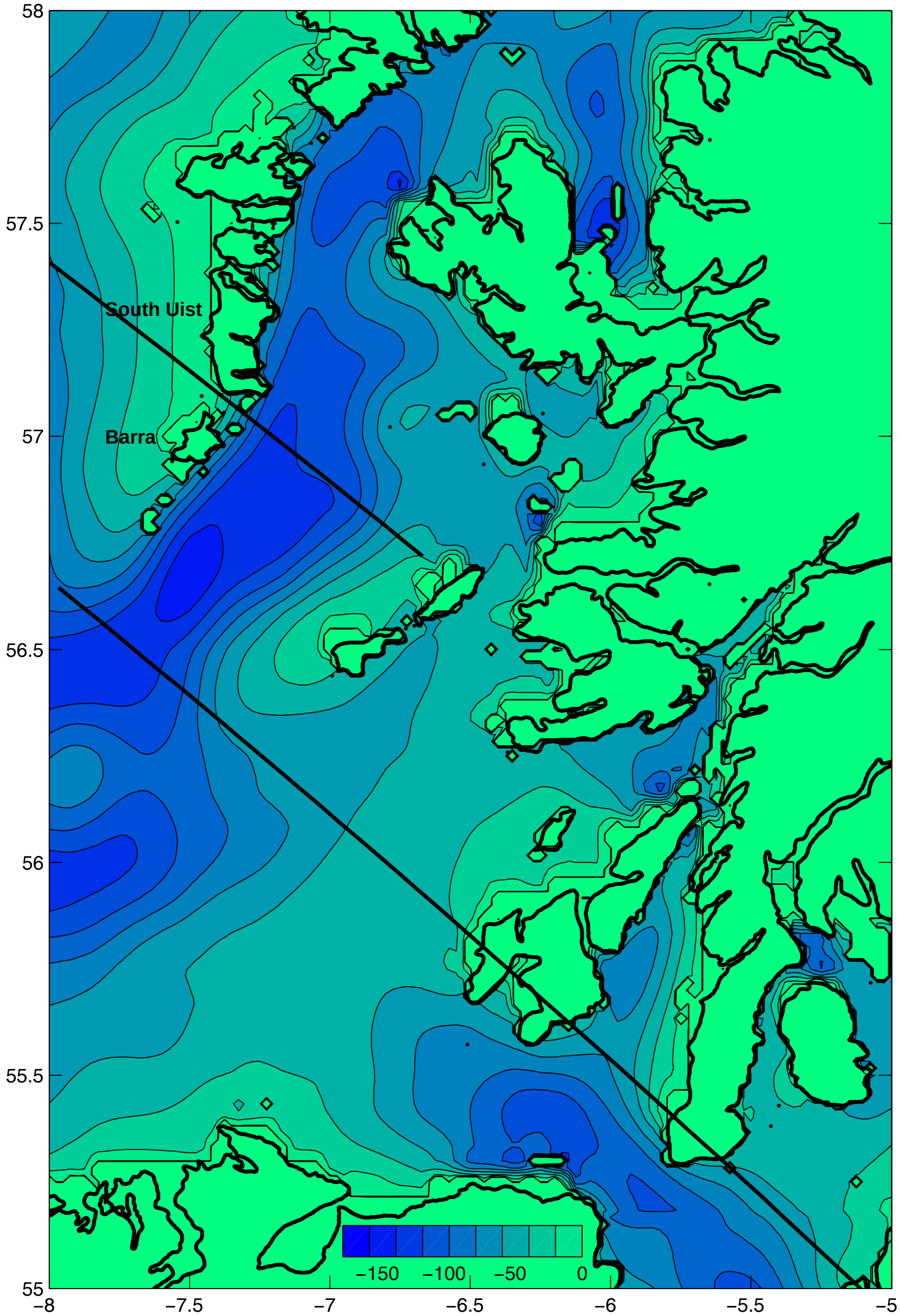


Figure 4: Bathymetry of Sea of Hebrides model, depth in metres, also showing altimeter tracks: JASON to north of TOPEX

2.1 WAM

A modified version of the third-generation spectral WAMC4 model for shallow water and high spatial resolution was used, here referred to as ProWAM (Monbaliu et al., 2000). This was implemented on the CS3 grid, driven by Met Office mesoscale winds. Boundary forcing was derived from a 1-degree deep-water run over the NE Atlantic (NEA model) from 25°W to 15°E and 40-70°N, forced by NCEP/NCAR reanalysis winds. These winds are available from 1948 to the present (http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml) and have been produced, with data assimilation, from a global spectral atmospheric model (Sela, 1982) on a latitude/longitude grid at approximately 2.5° resolution over the NE Atlantic, then interpolated onto a 1° by 1° grid. The NCEP/NCAR wind data were used in preference to the ECMWF ERA-40 reanalysis winds since they seemed to give better results, being slightly higher (Wolf and Woolf, 2006). The NEA model was run for the first half (1st-15th) of January, with the CS3 run from 8-13th January 2005 inclusive.

2.2 SWAN

The SWAN model (Simulating Waves Nearshore) is a 3rd-generation phase-averaged spectral wave model, specifically designed for modelling shallow water coastal regions (Booij et al., 1999; Ris et al., 1999). It uses essentially the same physics as WAM but the numerical solution is different, particularly for the wave propagation. The SWAN model was implemented on the Sea of the Hebrides 1.85km grid, as in Wolf et al (2002b) and Wolf and Woolf (2005). It was forced, in stationary mode, by spatial arrays of mesoscale winds with wave boundary conditions taken from the CS3 model. The default settings were used, with version 40.51, except that the Madsen option for bottom friction was selected. Note that the area of interest is rather close to the western boundary. A second implementation, representing the west coast of South Uist, was set up on a rectangular Cartesian grid since the wave set-up calculation does not work in the spherical polar coordinate system (SWAN user manual). The effect of increased water levels due to tide and storm surge has not been taken into account at this stage.

3. Model Validation

Wind and wave validation has been carried out using the available data. In the Hebrides area these consist of wind and wave data at buoy K5 (59°N 11.4°W) and wind-speed and wave height from altimeter data. Wave data are also available for the Irish Marine Institute buoys M1-M5 and the Wavenet buoy in Liverpool Bay (see Table 1 below).

Name	WMO ID	Buoy type	Lat	Lon	Water depth (m)	Anemometer height (m)
K5	64045	ODAS	59°6'0" N	11°24'2" W		3.0
M1	62090	ODAS	53° 07.36'N	11° 12.00'W	140	4.5
M2	62091	ODAS	53° 28.80'N	05° 25.50'W	95	4.5
M3	62092	ODAS	51° 13.00'N	10° 33.00'W	155	4.5
M4	62093	ODAS	54° 40.00'N	09° 04.00'W	72	4.5
M5	62094	ODAS	51° 41.40'N	06° 42.24'W	70	4.5
Liverpool Bay	62287	Datawell Waverider	53° 32.02'N	03°21.26'W	24	-

Table 1: Location of in-situ validation data

Altimeter data were provided by David Woolf from TOPEX and Jason passes on 11 January (Woolf, 2006). Unfortunately these were not at the time of maximum winds, but allow some assessment of the spatial variation of wind and waves to be made. A summary of some of these data for the most useful passes on 11 January 2005 is given in Table 2 (extracted from Woolf, 2006).

Date /time	Satellite	Cycle	Pass	Description: Swh = significant wave height, U10 is 10m wind speed, Sla = sea level anomaly
11Jan 09:02	JASON	111	37	North Eastwards passing west and north of Scotland. Swh ~4.5m in south, ~3.5m in north. U10 ~16m/s in south, 12m/s in north. Sla~0.1m
11Jan 09:09	TOPEX	454	37	North Eastwards passing west and north of Scotland. Swh 4.5-5m in south, ~4.5m in north. U10 ~15m/s in south, 13m/s in north. Sla~0.
11Jan 14:53	JASON	111	44	South Eastwards passing through Sound of Barra and to Coll. Swh 6-8m in exposed waters, 4-5m in Sea of Hebrides. U10 ≤22m/s. Sla~0.1m off-shelf increasing up to 0.5m near Barra
11Jan 15:00	TOPEX	454	44	South Eastwards passing through Islay and Kintyre to Galloway (adjacent to North Channel). Swh ~9m in exposed waters, 3-4m in most sheltered waters. U10 ≤24m/s. 13m/s in north. Sla~0 off shelf, increasing to nearly 1m in North Channel.

Table 2: Altimeter data

The Jason and TOPEX pass 44 at approximately 15:00 is used because it is nearest to the time of maximum winds, the tracks for this pass are shown in Fig. 3. The TOPEX track appears to cover more sea than Jason but the altimeter does not lock onto the signal again after first crossing land, therefore only about the same amount of data are obtained from each.

3.1 Wind validation

Winds are critical in getting good wave model results and poor time and space resolution is the most likely cause of poor wind model output. Here we examine the available wind observations, both from buoys and altimeters and compare them with NCEP/NCAR and mesoscale model winds. We focus on the buoy K5 because it is in the vicinity of the NW Approaches and Outer Hebrides but data from the Irish Marine Institute buoys and Liverpool Bay are also examined: see figures in the Appendix.

(a) Buoy data

Fig. 5 shows the comparison of observed and model wind-speed at buoy K5. The NCEP/NCAR winds appear rather overestimated in the earlier part of the month, but slightly underestimate the peak observed winds on 11-12 January. The mesoscale model winds from 8-13 January are in quite good agreement with observations, especially for the timing of events but have a tendency to overestimate the observed peak wind-speed. The observed peak wind speed is 22.1m/s, the NCEP/NCAR model peak is 21.6m/s and the mesoscale model peak is 24.2m/s (the ratio for observed/mesoscale = 0.91). However note that the observed winds are at 3m above the surface, whereas the model winds are at 10m, therefore will be higher. Assuming a logarithmic wind profile and a Charnock parameter of 0.0275 (as chosen for the POL storm surge model) the reduction factor, for neutral stability, for a wind-speed of 20m/s will be about 0.85. Thus the maximum observed wind at 10m could be as much as 25.9m/s (storm force 10). It is not surprising that the mesoscale model, with much better spatial and temporal resolution, does a better job of capturing the maximum wind-speed of this intense depression than the NCEP/NCAR model. Comparisons of the observed winds with the model, at buoys M1-M5, are shown in the Appendix. A similar scaling factor should apply as the buoy winds are measured nearer the surface than the standard 10m height for the model winds. The mesoscale winds are better than the NCEP/NCAR winds at each location as would be expected. The timing of peaks is in very good agreement with observations and the magnitude is similar, allowing for the difference in anemometer height.

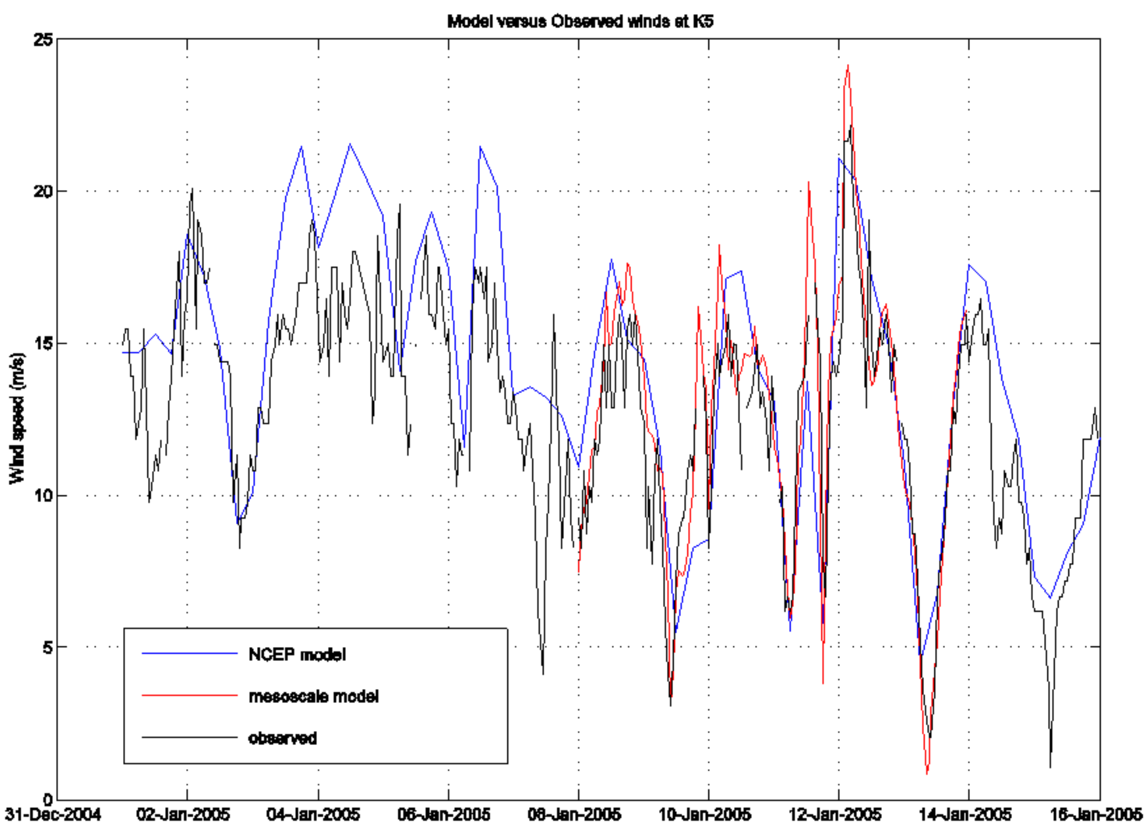


Figure 5: Model versus observed winds at buoy K5

Fig. 6 shows a scatter plot of mesoscale model winds versus observed winds. In fact the model only slightly overestimates the observed winds, not as much as was estimated from the differences in height above the sea surface (see above). The R^2 value shows good correlation.

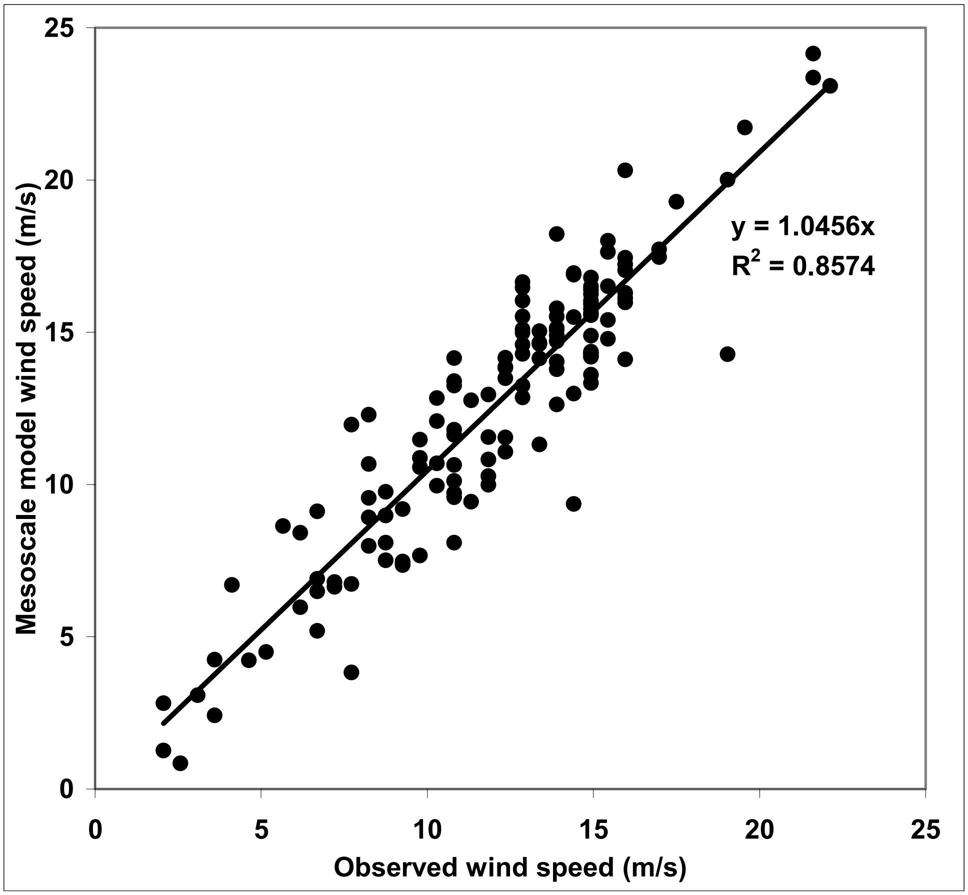


Figure 6: Mesoscale model versus observed winds at buoy K5, 8-13 Jan 2005

(b) Altimeter data

Figs. 7 and 8 show the altimeter and mesoscale model winds, for the Sea of Hebrides model, along the altimeter tracks for 15:00 on 11 January.

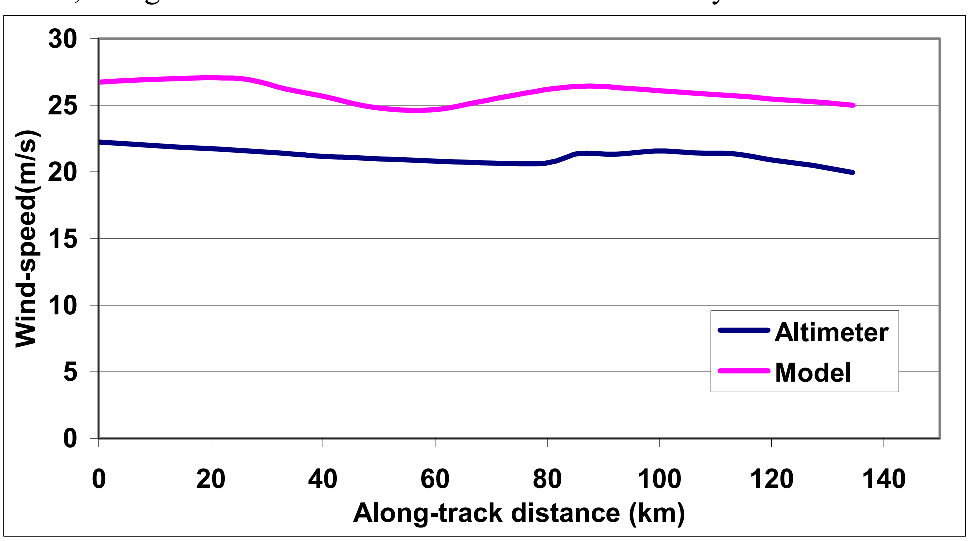


Figure 7: Wind-speed along JASON track at 15:00 11 January

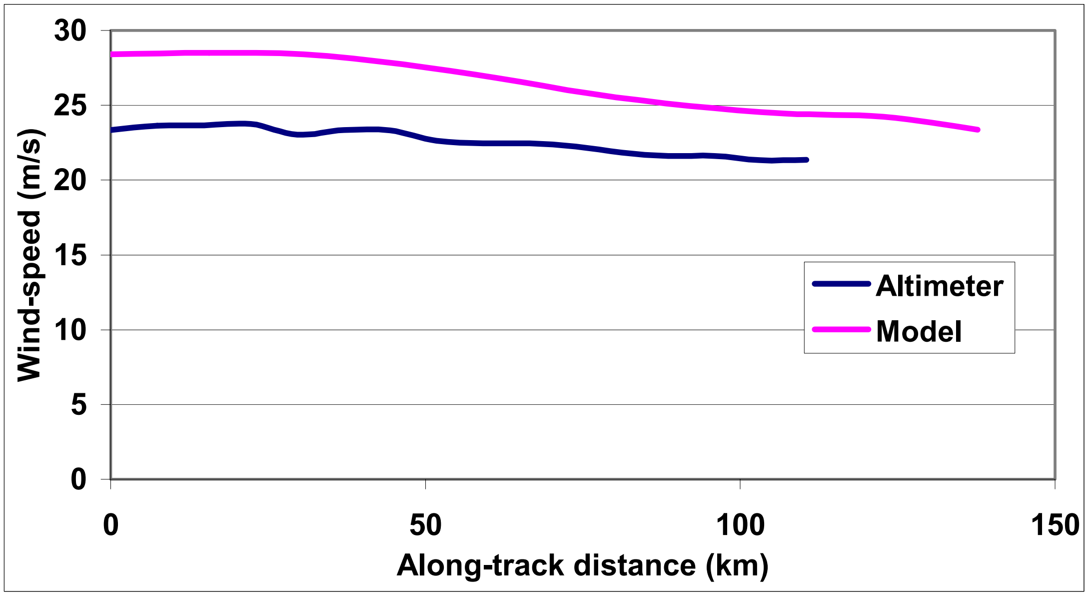


Figure 8: Wind-speed along TOPEX track at 15:00 11 January

The model winds are significantly higher than the altimeter winds although the spatial variation is rather similar. Unfortunately we do not know whether this overestimate of wind speed is consistent due to lack of more altimeter data. Fig. 5 shows a particularly large peak in mesoscale winds, reaching 20m/s, much higher than that observed, at K5, at 13:00, just before the altimeter pass. It may be that the leading edge of the storm is more intense than it should be, in the model. In general, Fig. 6 shows the model winds to be quite good at K5 with no systematic bias.

The dip in the wind-speed along the Jason track may be due to the effect of the passage between the islands of South Uist and Barra. This is more marked, and earlier, in the model results, probably due to the rather coarse grid resolution (12km) of the wind field not resolving the narrow strait south of South Uist, the Sound of Barra. The effect of the coastal boundary layer reduces wind speed near land, since the surface drag is increased over land. The real winds in fact may be locally intensified by funnelling through the strait but this effect is not included in the mesoscale model. Fig. 9 shows the mesoscale model winds at the time of the altimeter pass, showing the strong winds in the leading edge of the depression. This overestimate of wind-speed may thus be very localised in space and time.

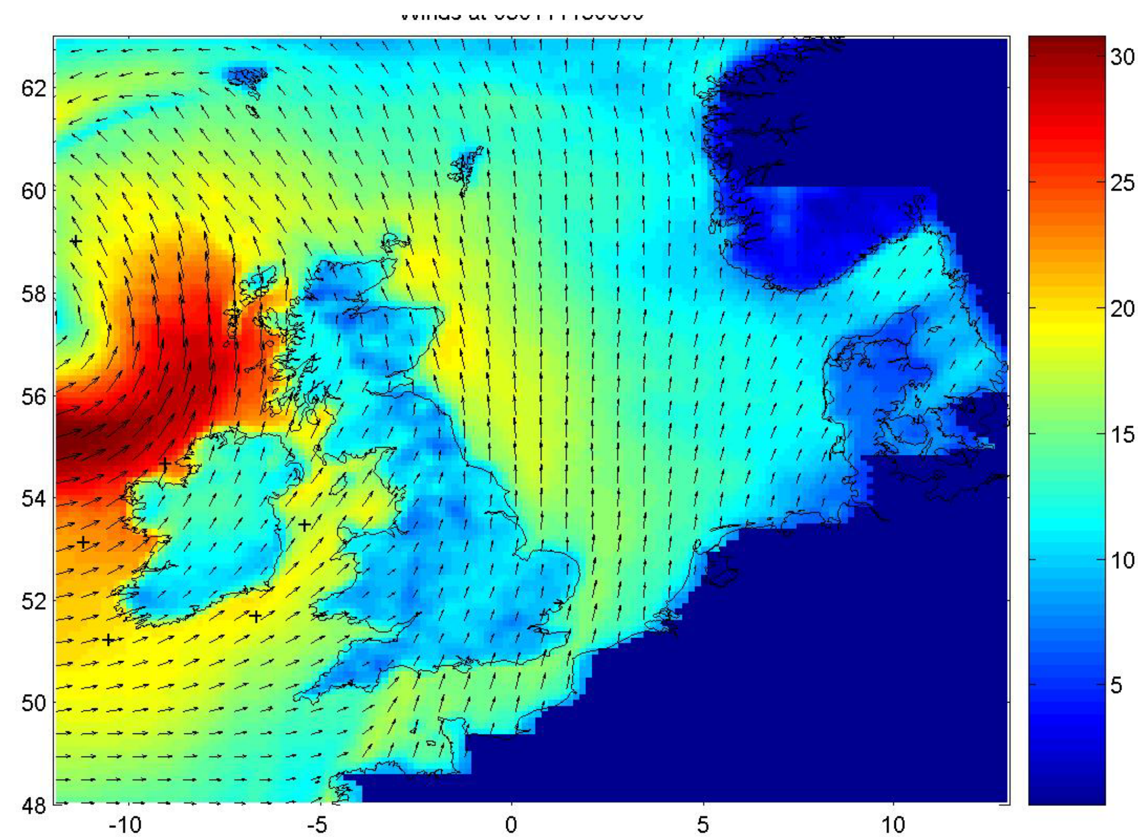


Figure 9: Mesoscale winds at time of altimeter pass: 15:00 11 January

3.2 Wave validation

(a) Buoy data

Fig. 10 shows the model versus observed wave height at K5. Results for M1-M5 buoys are in the Appendix. Both NEA and CS3 model results are compared with the observations. An important point to note is that several of the validation points are quite near the boundary of the CS3 model. The effect of improved resolution in the CS3 model and better local winds is therefore not clear at K5, M1 and M3. The model wave heights are rather low at K5, M1 and M3, and very similar for both NEA and CS3, showing that the CS3 results are dominated by the boundary forcing and the NEA model underpredicts the wave height. M2, M5 and Liverpool Bay show very good agreement for CS3. M2 and M5 are not resolved in the NEA grid and M5 is very close to the coast so the NEA gives poorer results. At M4 the timing of the wave peak on 11 January is much improved in CS3.

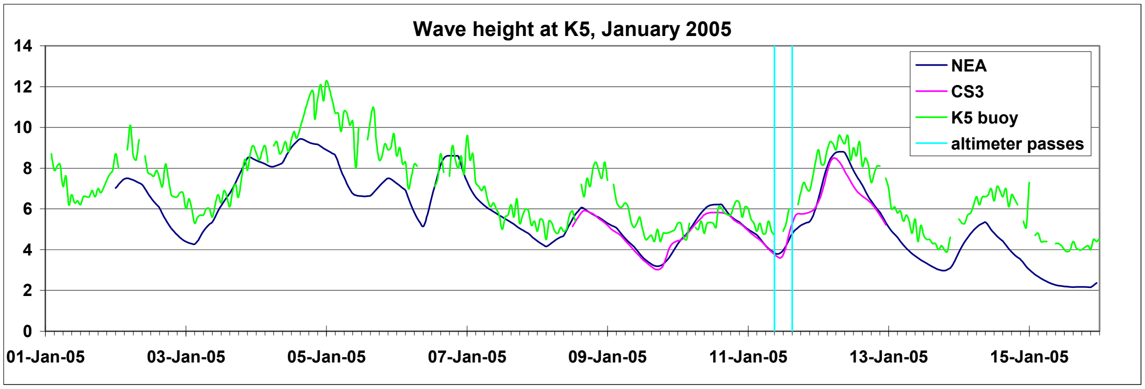


Figure 10: Wave height at K5. Blue vertical lines show times of altimeter passes

(a) Altimeter data

Figs. 7 and 8 seem to indicate that the mesoscale model at this time over-estimates the altimeter observed winds. The wave heights are also over-estimated. Therefore a constant scaling factor of 0.83 was applied to the wind-speed. The Hebrides SWAN wave model results for the reduced wind forcing are shown in Figs.11-13 for the time of the altimeter passes.

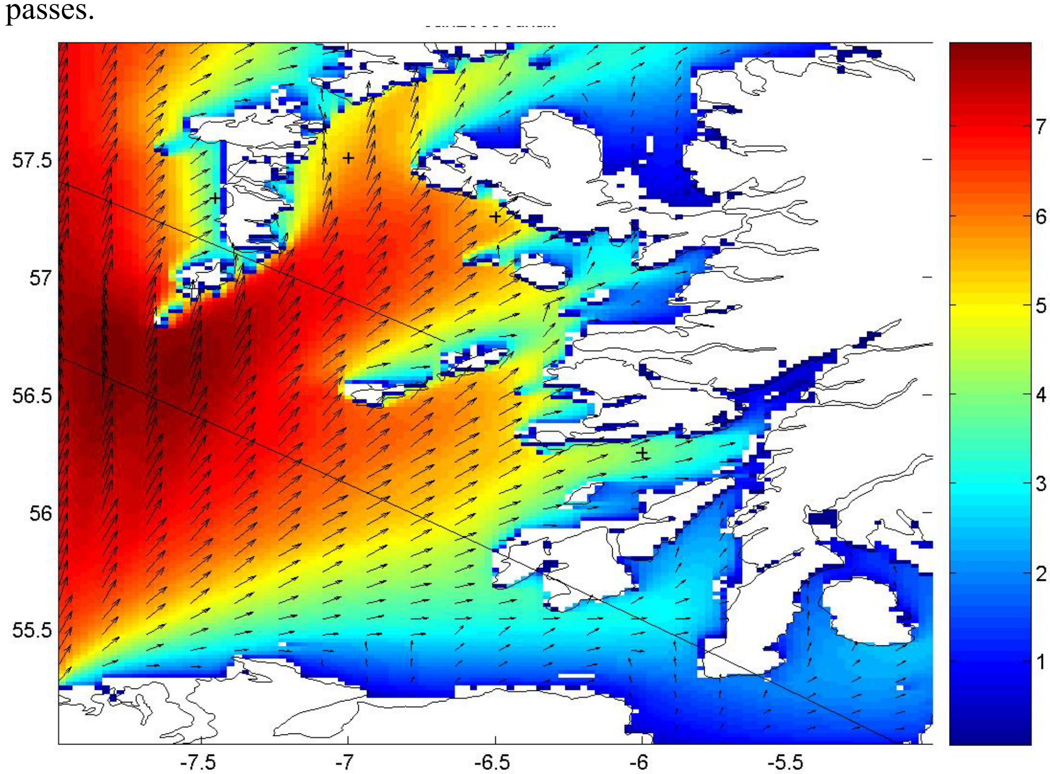


Figure 11: SWAN wave height and mean wave direction (using corrected wind-speed) for 15:00 11 January

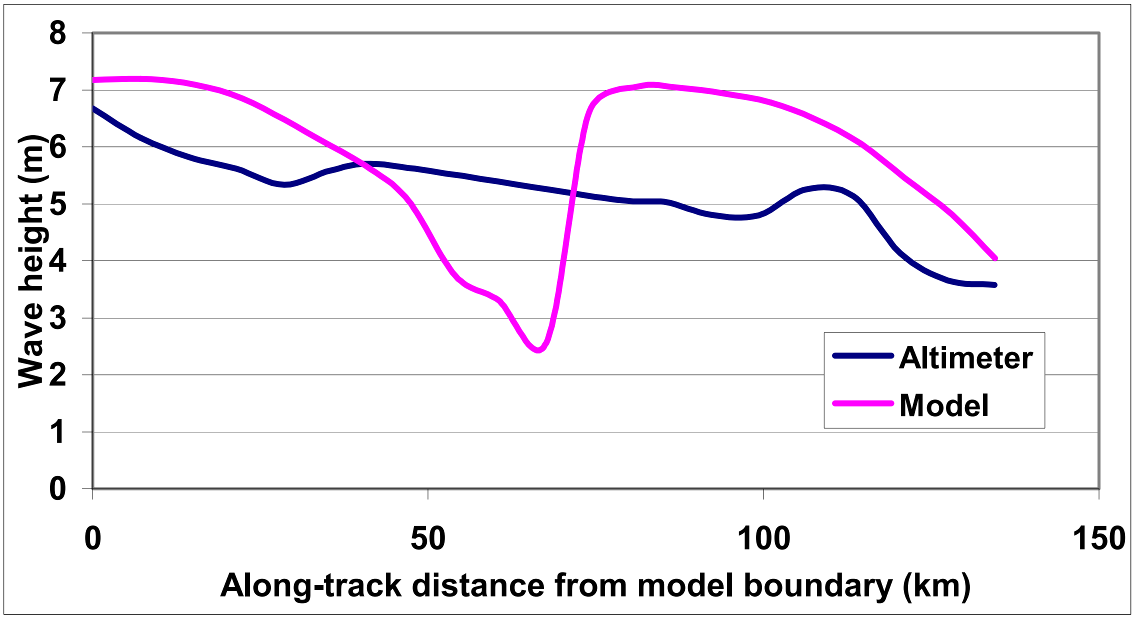


Figure 12: Model versus altimeter wave height along JASON track at 15:00 11 January, using reduced wind-speed

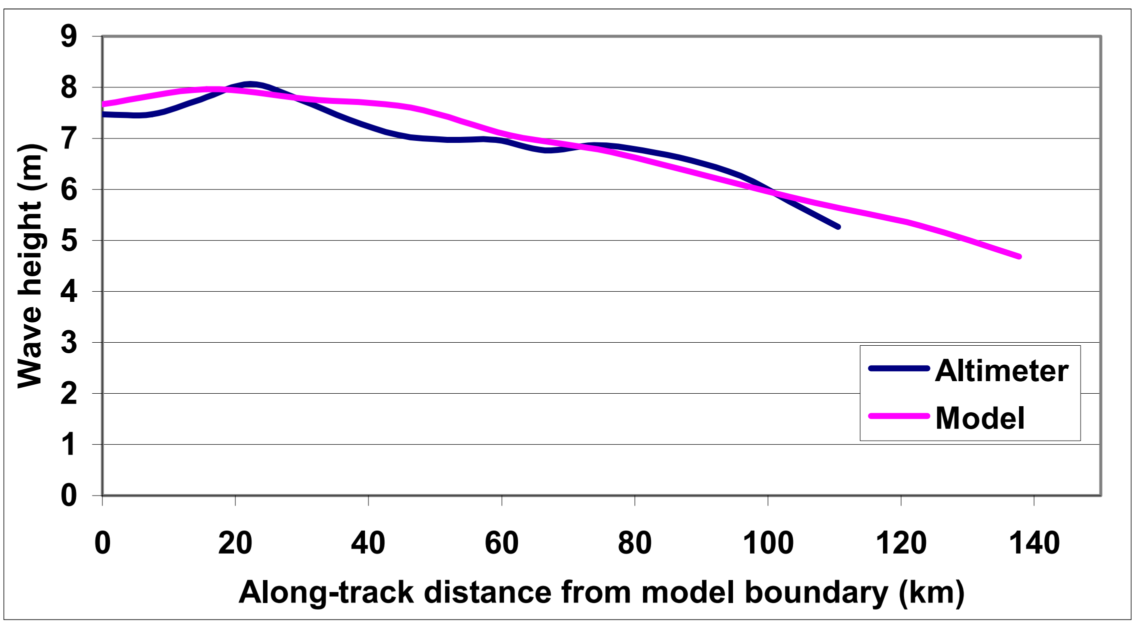
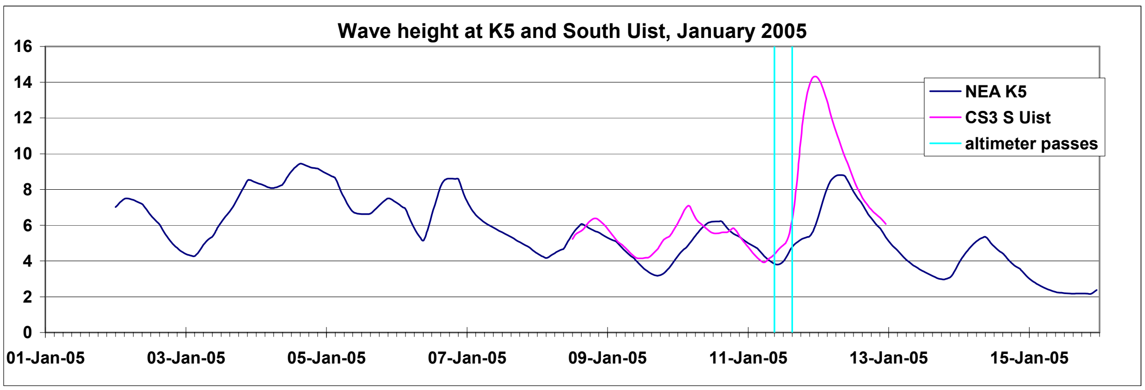


Figure 13: Model versus altimeter wave height along TOPEX track at 15:00 11 January, using reduced wind-speed

Fig. 13 shows excellent agreement, suggesting that the reduction in model wind speed was appropriate along the TOPEX track, which crosses open water. The model still seems to overestimate the wave height along the Jason track, Fig. 12. The reason for this is uncertain. Fig. 12 also shows a very strong dip in the model results as the altimeter passes south of South Uist, not seen in the altimeter data. This may be due to the reduction in model wind speed as mentioned in section 3.1, compounded by excessive shoaling in the wave model in the Sound of Barra.

4. Model results

Overall the model validation seems acceptable. It is unfortunate that the winds seem to be most severely overestimated at the time of the altimeter pass, but in general the mesoscale winds are very good and the CS3 wave model is performing well at locations in the Irish Sea, although this is well south of the area of interest and maximum winds and waves. The maximum wave height predicted by the CS3 model is 14.3m at 23:00 11 January at a location just west of South Uist as shown in Fig. 14. This figure also shows how much higher wave heights are reached at South Uist compared to K5.



`Figure 14: Wave height at K5 and South Uist**

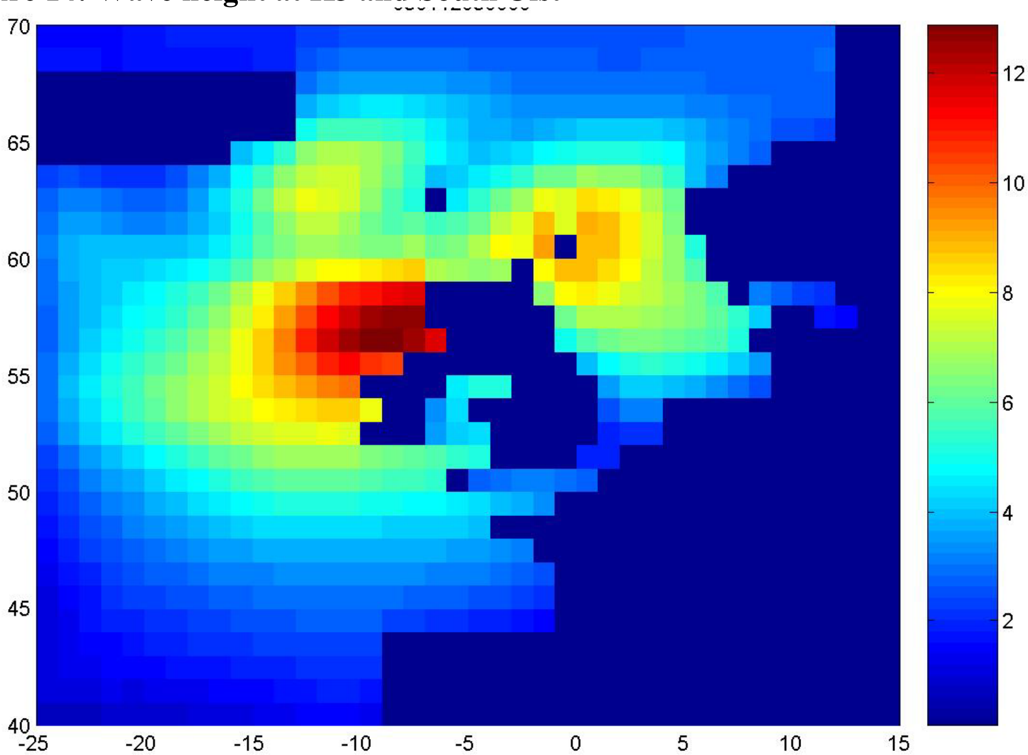


Figure 15: NEA model wave height at time of maximum modelled waves at South Uist

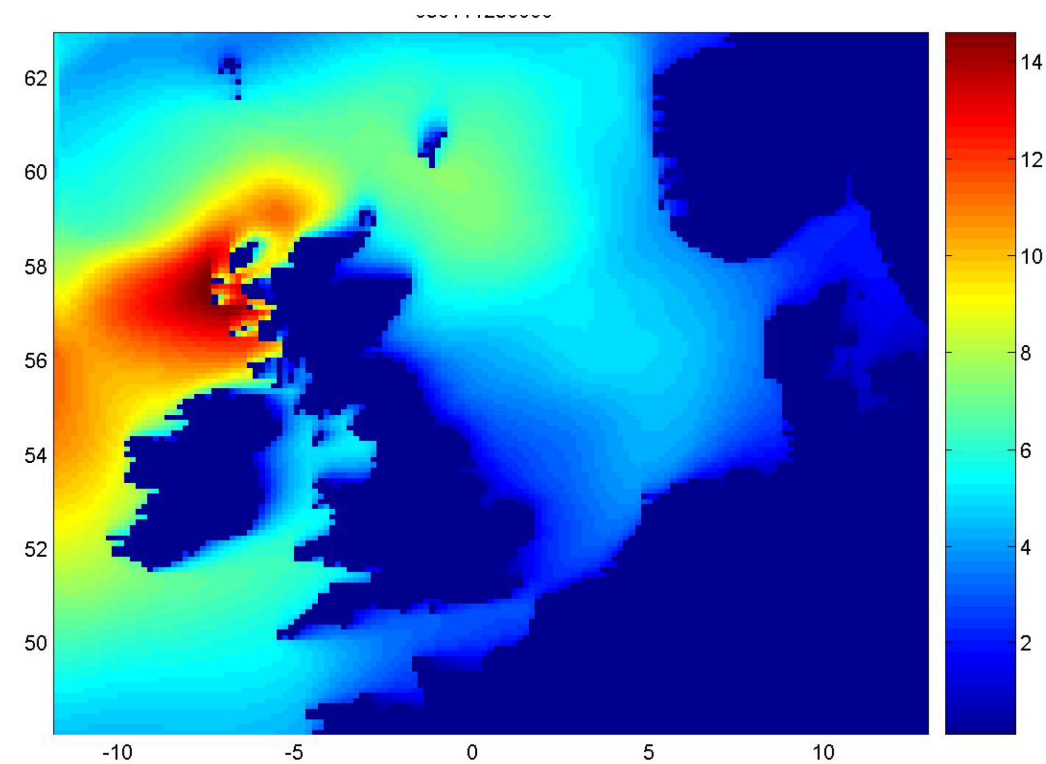


Figure 16: CS3 model wave height at time of maximum modelled waves at South Uist

Fig. 15 shows the NEA model results for the peak of the storm. Waves west of Scotland reach over 12m even in this coarse model. Fig. 16 maps the highest waves generated in the CS3 model, which shows how localised and intense the waves are, with the focus of maximum wave over 14m just west of South Uist.

5. Wave Set-up

Wave set-up (or set-down) is the change in mean water level due to waves propagating in shallow water. It is calculated from the gradient of the radiation stress (Longuet-Higgins and Stewart, 1962). The SWAN model makes an approximate calculation of wave set-up, assuming the wave-induced currents are zero. In a 2D case, the computation of the wave-induced set-up is based on the divergence of the vertically integrated momentum balance equation being zero. The model has a warning that set-up is not calculated correctly in spherical (lat–lon) coordinates, so the model was converted into Cartesian coordinates. Results for the wave set-up show a maximum concentrated on the western side of North Uist, Benbecula and South Uist. In a simple model, representing the bottom slope west of South Uist, set-up reaches 48.8cm at the height of the storm and waves close to the shore-line still have significant wave height of over 2m in 5m of water depth. Fig. 17 shows the set-up over the whole Hebrides model, which illustrates that maximum set-up is confined to the west coast of the three islands. Fig. 18 shows the cross-shore variation of wave height/depth and set-up. The reason for the very large set-up is the very high wave height close to shore, which therefore produces a large gradient of wave height as the waves shoal.

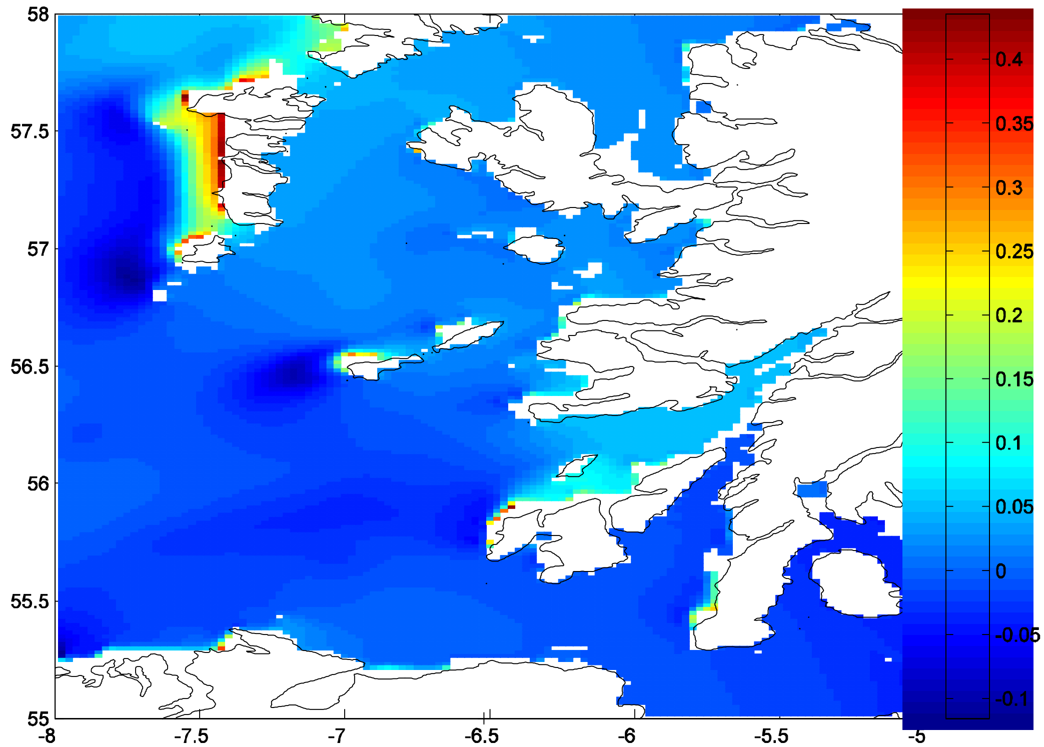


Figure 17: Wave set-up at peak of storm: 23:00 11 January

For validation purposes the set-up at the time of the altimeter pass was also calculated. In this case the set-up reaches only 14cm off North Uist and about 5 cm at Barra. As may be seen from Table 2 the altimeter seal level anomaly varies from 10cm offshore to 50cm at Barra. The difference is almost certainly due to storm surge, but this needs to be confirmed.

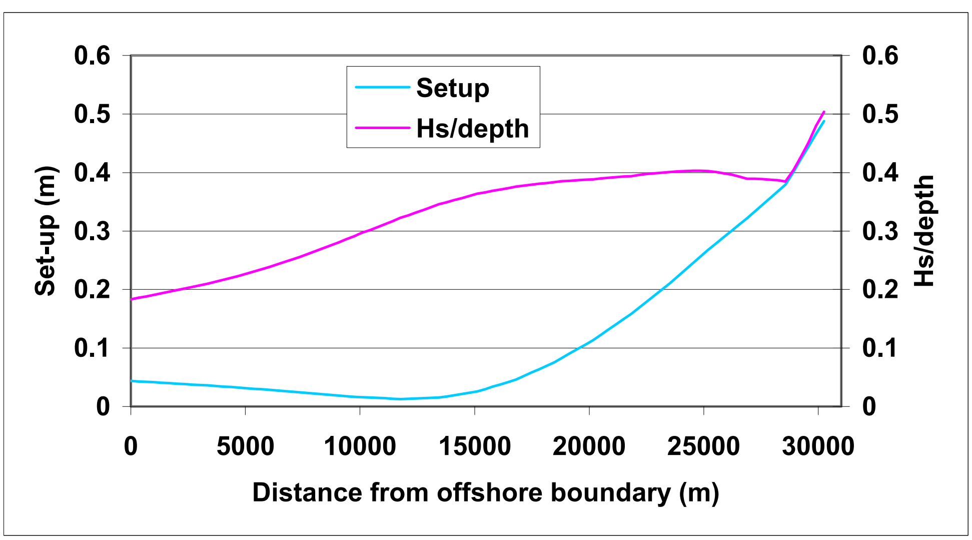


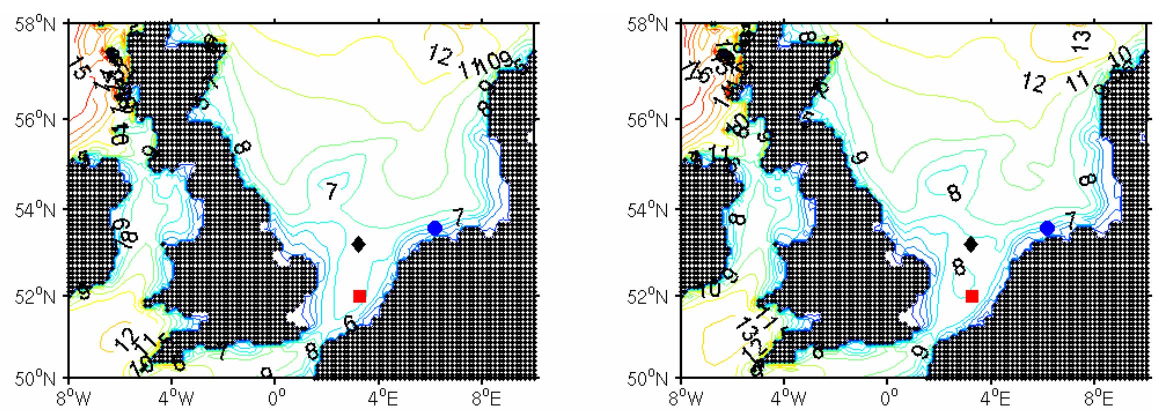
Figure 18: Cross-shore profile of set-up and wave height-depth ratio at peak of storm

6. Discussion

The explanation for the flooding at South Uist and Barra on 11-12 January 2005 must be related to the exceptional wave heights and associated wave set-up, during a severe storm with its centre near to the west coast of the Western Isles. Although surge levels for the storm are not yet available, a maximum set-up of nearly 0.5m is predicted from the SWAN wave model on a 1.85km grid, together with offshore wave heights over 14m and nearshore wave heights over 2m. Such extreme wave set-up is unusual and due to the close proximity of very high waves close inshore

The validation of the wind and wave models is reasonable although at the time of the altimeter passes nearest to the peak of the storm it appears the mesoscale model may have overestimated the intensity of the winds in the leading edge of the storm. The models also show reduced winds and especially wave heights as the altimeter track passes through the Sound of Barra. This may be due to the coarse grid resolution, not resolving the details of land and sea grid-points. Resolving narrow straits would be better addressed by an irregular/unstructured grid using the finite element method. Localised wind effects, especially the effects of orography may be included in a local mesoscale wind model such as the PSU/NCAR mesoscale model MM5 (http://www.mmm.ucar.edu/mm5/).

An obvious question is: how does this event compare to a worst case scenario? First of all we compare the wave height to the 10-year and 50-year return period wave height, calculated by Osuna and Wolf (in preparation, see Figure 19) from a CS3 wave model run from 2000-2004 inclusive i.e. a 5-year wave hindcast. This suggests that the 50-year extreme wave west of South Uist could be as high as 17m (which is corroborated by other sources), so the event of 11-12 January 2005 may not be as large or infrequent as the 50-year event. In fact it may be close to the 10-year extreme event.



(a) (b)

Figure 19: (a) 10-year and (b) 50-year return period wave height estimated from CS3 wave model simulation 2000-2004 (Osuna and Wolf, in preparation)

We can compare a fully-developed sea state versus storm waves. The wave height corresponding to a fully developed sea state in deep water can be calculated by the corrected method of Resio et al. (1999) which only depends on wind-speed. In fact this state is unlikely to be reached for the highest storm winds because the duration of the wind and the fetch are not unlimited. Also the waves in this area are not in infinitely deep water but in depths of about 100m, which will reduce the maximum wave height which can be achieved. A wave height of 14m corresponds to the fully-developed sea for a wind-speed (at 10m, U_{10}) of 23m/s whereas a wave height 17m corresponds to a wind-speed of 25m/s. The maximum predicted wind, nearly 35m/s, does not persist for very long and cannot build up the equivalent wave height of nearly 40m. To calculate the fetch-limited wave height in finite depth we can use the formula in Hurdle and Stive (1989). For a wind speed of 23m/s in 100m depth we can obtain a wave height of 14.3m using an effective fetch of 800km. This fetch is quite difficult to estimate independently in a storm event.

Finally, the effect of increased water levels due to tide and storm surge has not been taken into account at this stage. This will be likely to affect the inshore wave height and set-up. When this information is available the wave model can be re-run.

Acknowledgements

NCEP/NCAR re-analysis winds were obtained from the web site http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml. Mesoscale model winds were provided by Met Office via Kevin Horsburgh (POL). Altimeter data were from David Woolf, NOCS and M1-M5 buoy data from the Irish Marine Institute.

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Appendix

A: Wind time series comparison

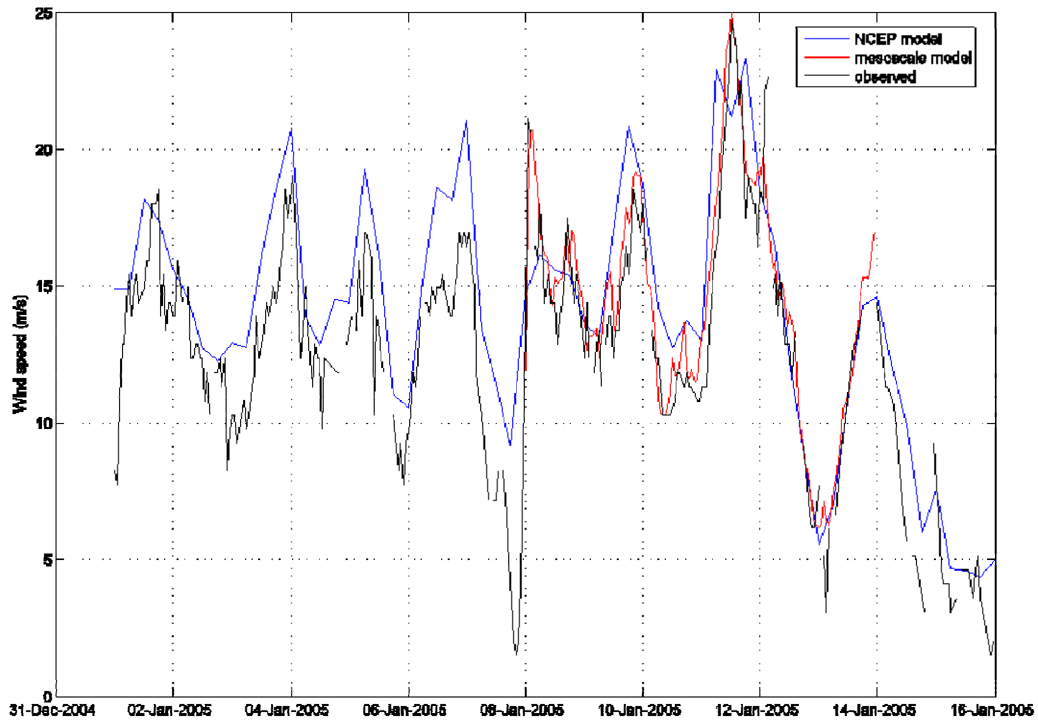

Figure A1: Model versus observed winds at buoy M1

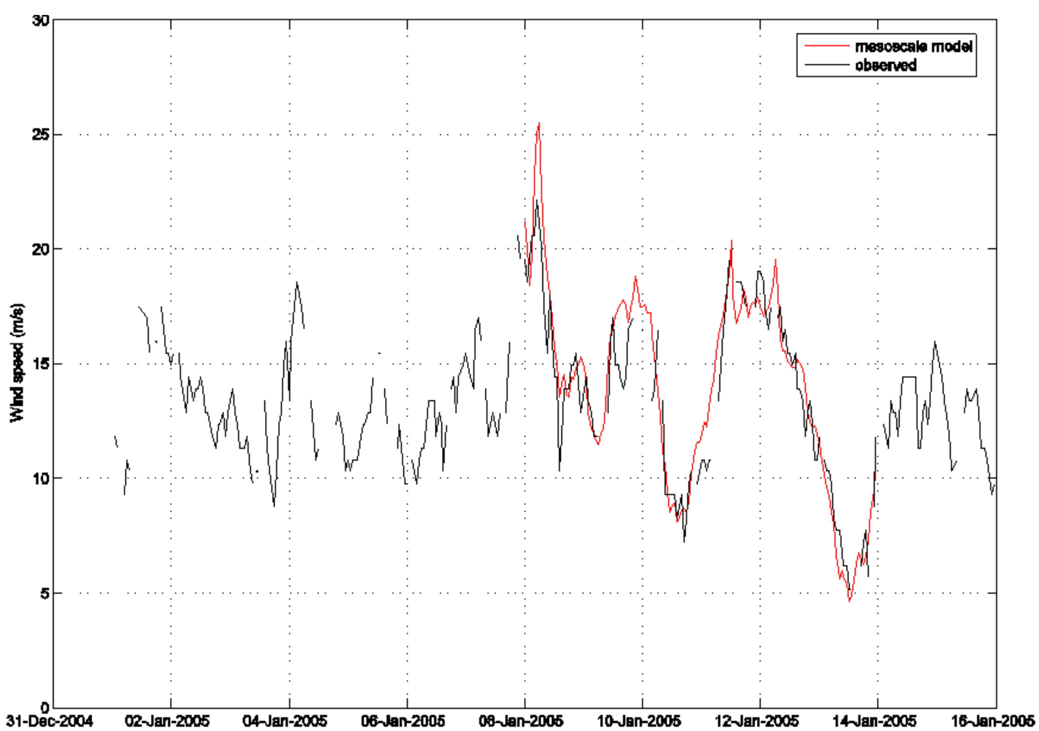

Figure A2: Model versus observed winds at buoy M2

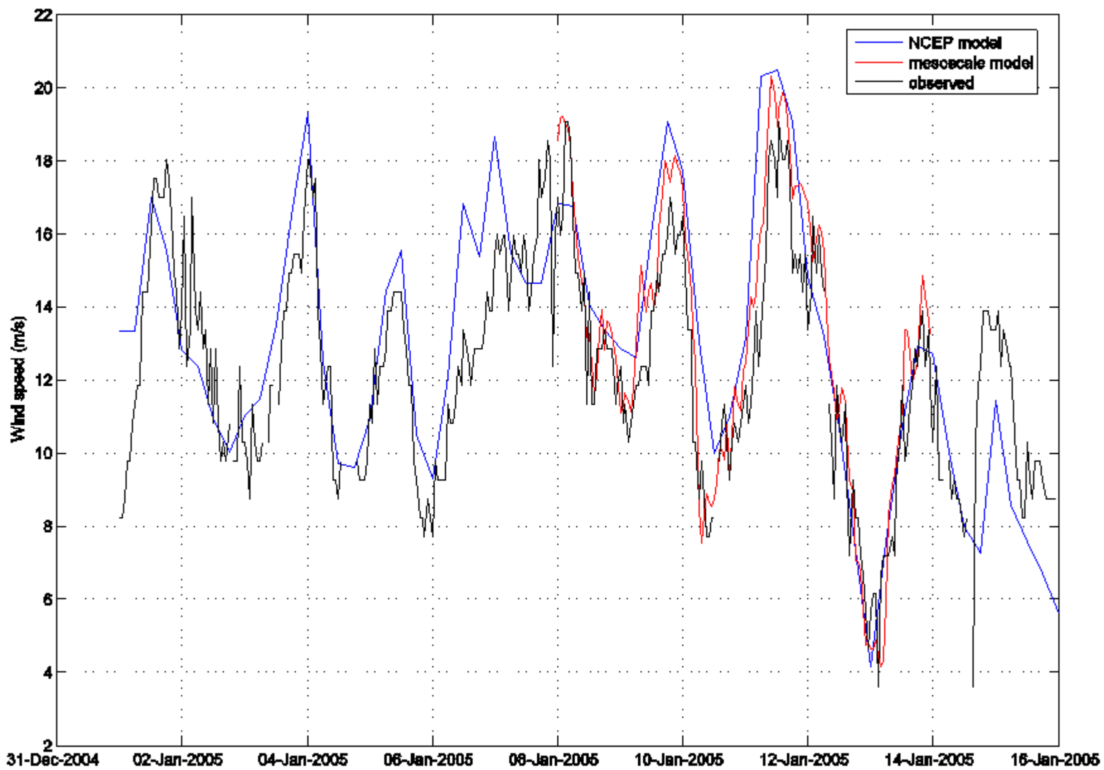

Figure A3: Model versus observed winds at buoy M3

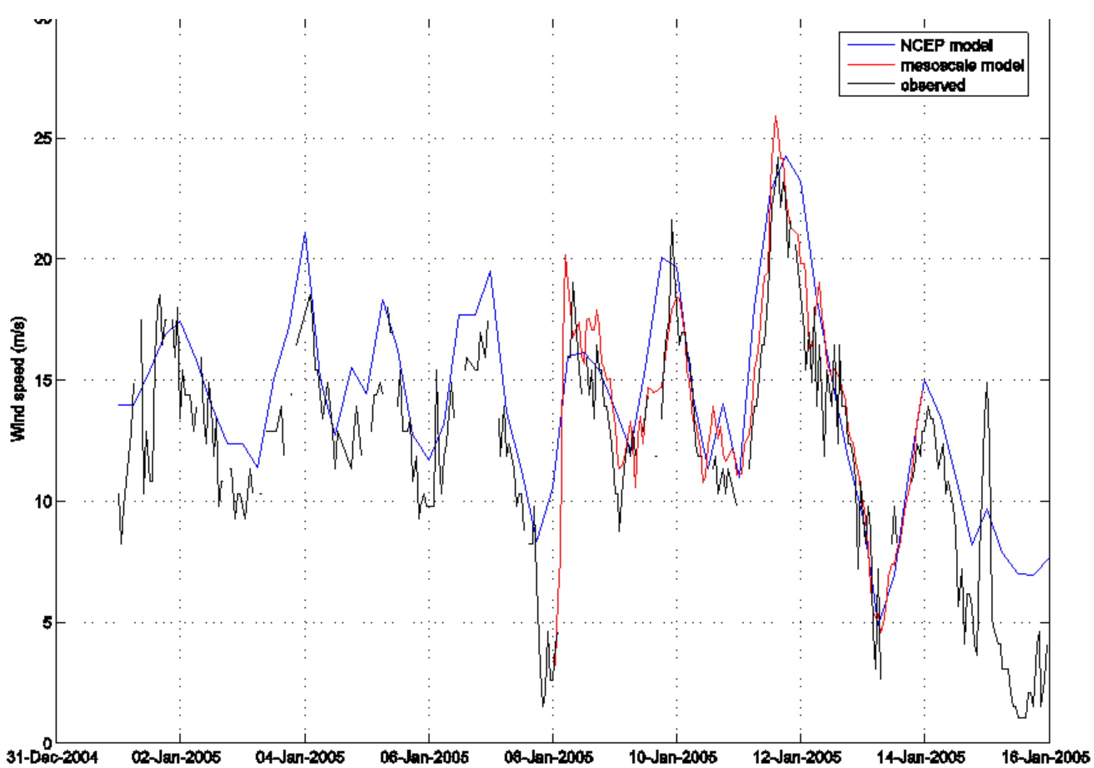

Figure A4: Model versus observed winds at buoy M4

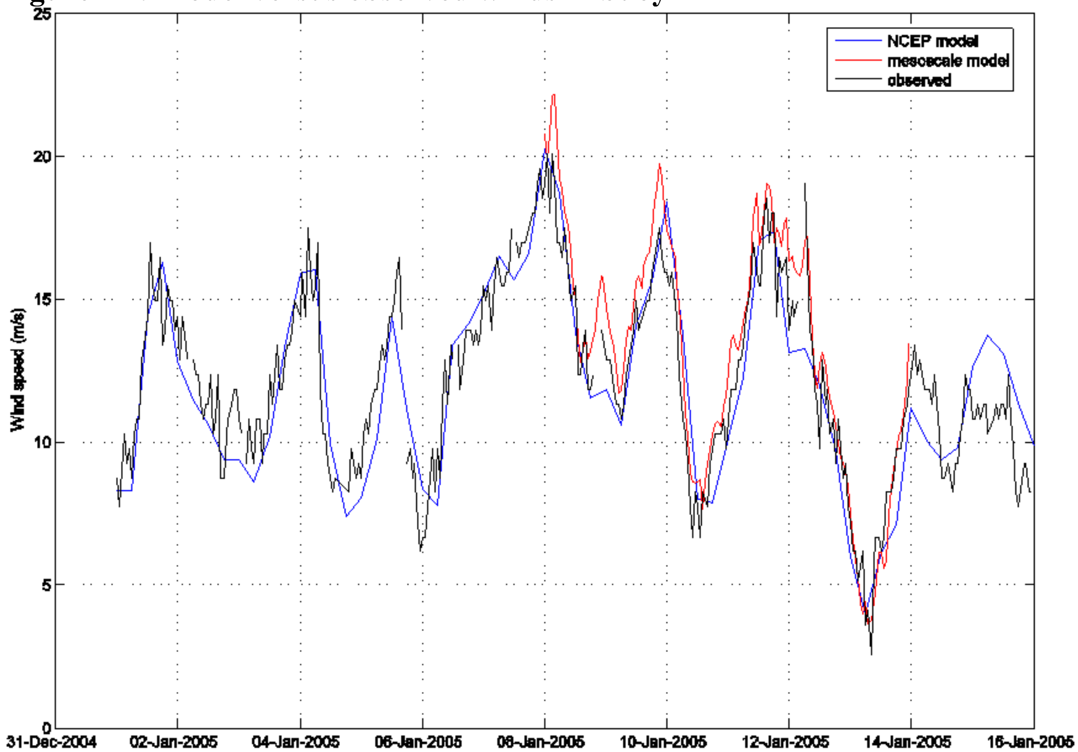

Figure A5: Model versus observed winds at buoy M5

B: Wave time series comparison

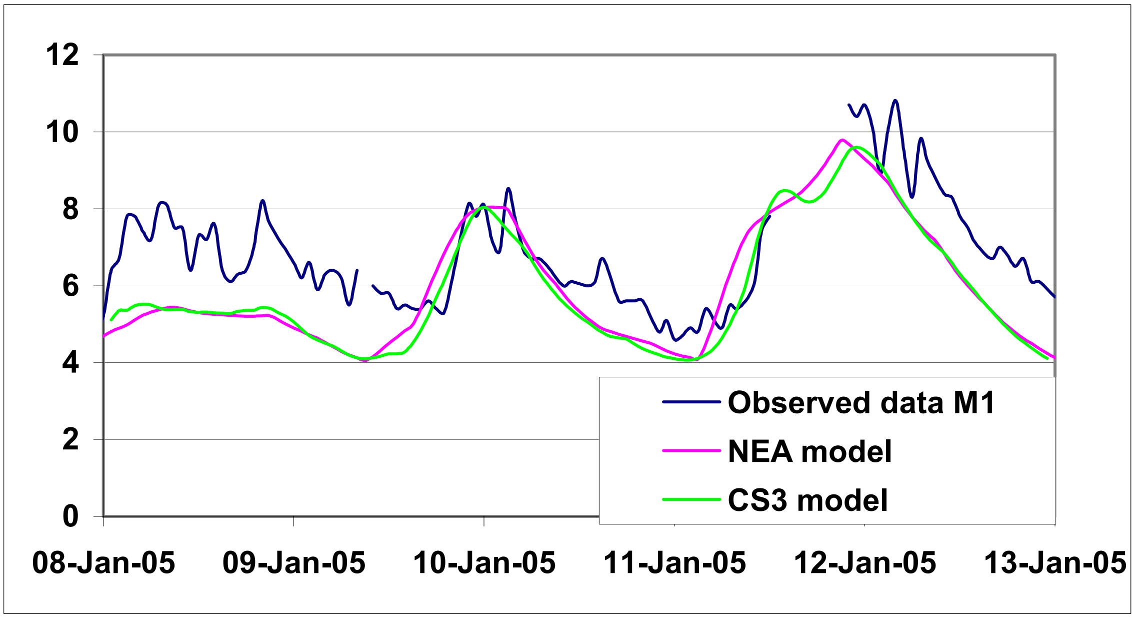

Figure B1: Model versus observed waves at buoy M1

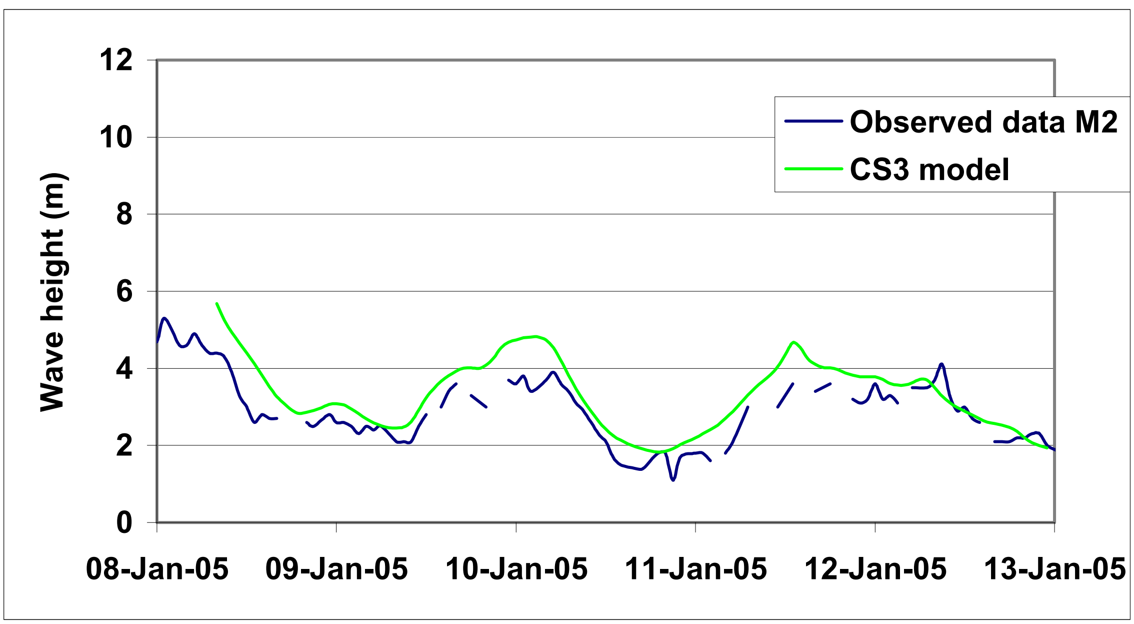

Figure B2: Model versus observed waves at buoy M2

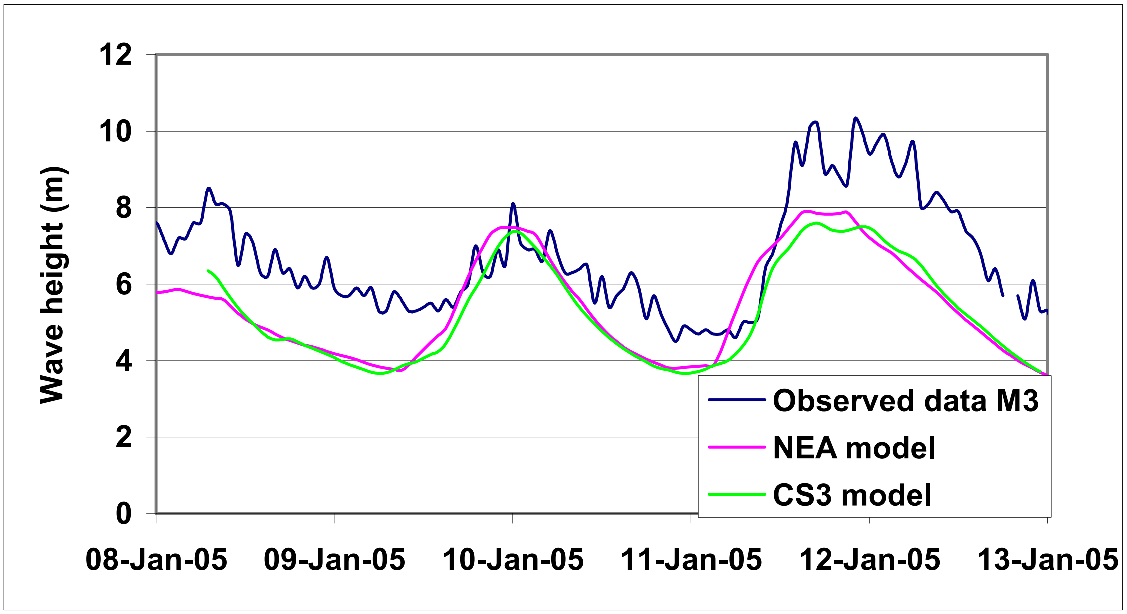

Figure B3: Model versus observed waves at buoy M3

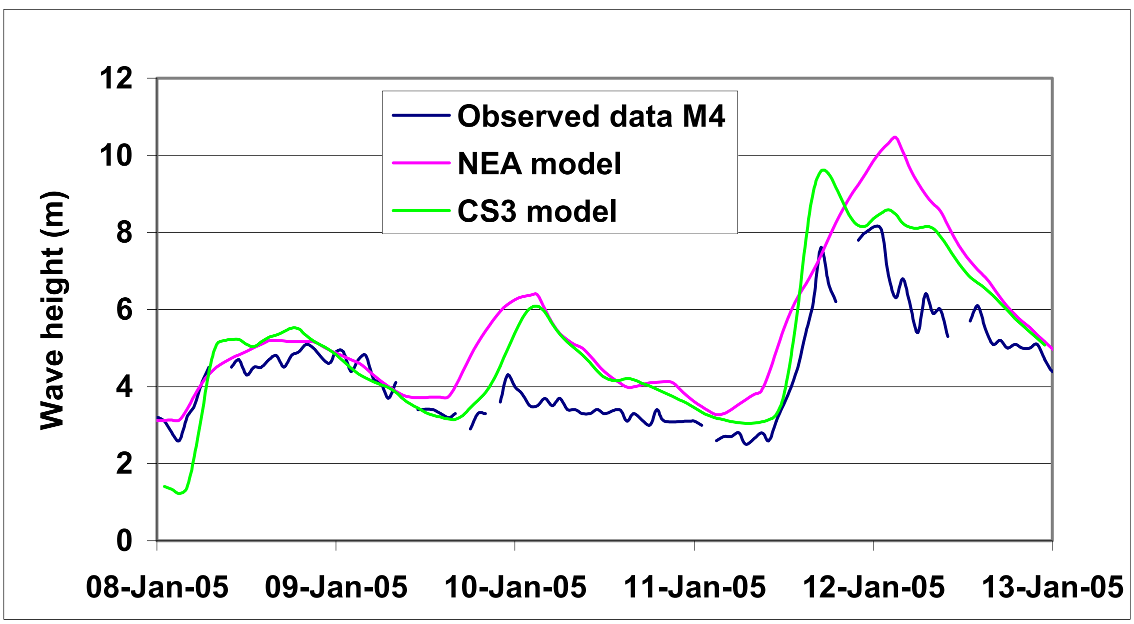

Figure B4: Model versus observed waves at buoy M4

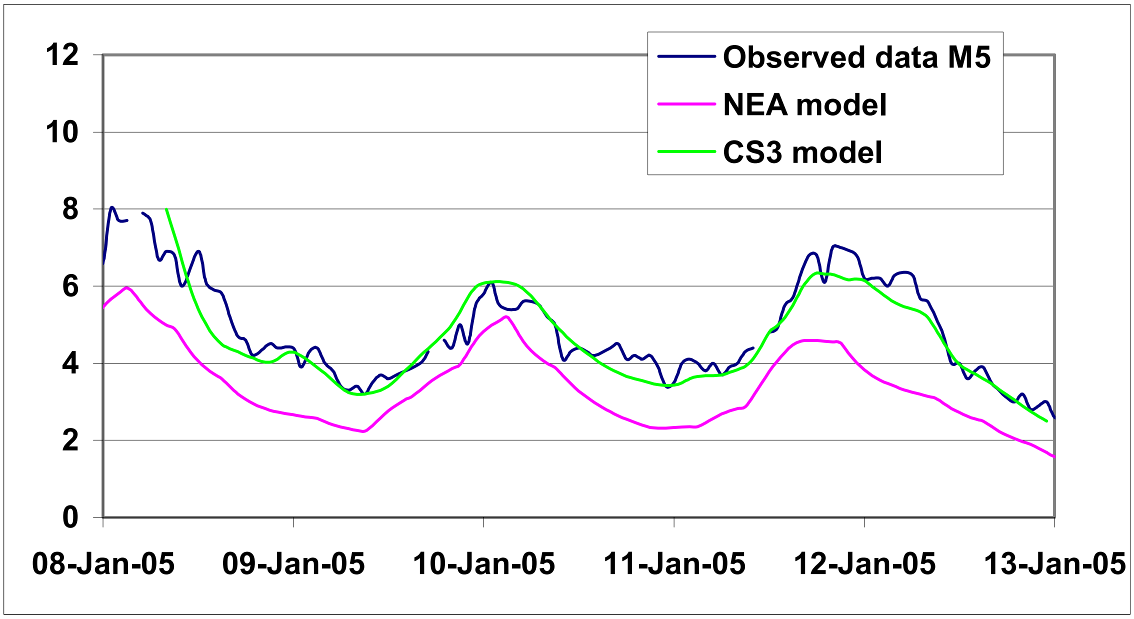

Figure B5: Model versus observed waves at buoy M5

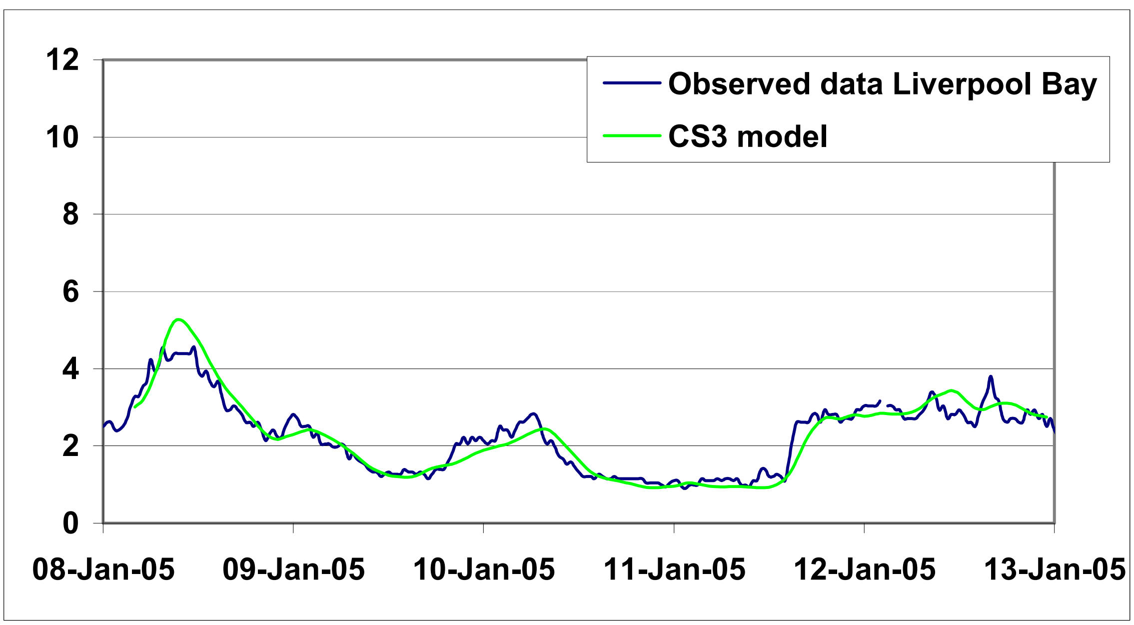

Figure B6: Model versus observed waves at Wavenet buoy in Liverpool Bay