FUTURE EXPLOITATION OF IN-SITU WAVE MEASUREMENTS AT STATION MIKE.

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ABSTRACT

As part of a UK-SOLAS (Surface Ocean-Lower Atmosphere Study) project the National Oceanography Centre (NOCS) has instrumented the Norwegian weather ship *Polarfront* with the directional wave radar "WAVEX". This system complements the *Polarfront's* existing ship borne wave recorder which was installed by the Norwegian Meteorological Institute in 1978. The *Polarfront* and its predecessors have occupied Station Mike (66˚N, 2˚E) all year round for nearly 60 years. NOCS also equipped the ship with digital cameras and the autonomous air-sea flux system "AutoFlux". The NOCS systems were installed in September 2006 and will operate continuously for at least 3 years. Project information and real-time data from the ship can be found via http://www.noc.soton.ac.uk/ooc/CRUISES/HiWASE/index.php . The sea-state dataset being obtained on the *Polarfront* is unparalleled in that the SBWR provides reliable wave height data but no directional information, whereas the wave radar provides excellent directional wave spectra but infers wave heights indirectly. It is believed that, until now, the two systems have never been deployed together for more than brief periods. On *Polarfront* the two systems provide very comprehensive information on sea state, in a region of the world's oceans which experience a wide range of conditions (e.g. 3-hourly significant wave height of 15.5 m in November 2001). The main research aim of the project is the parameterisation of the air-sea fluxes, including wind stress, in terms of wind speed, sea state etc. However, the wave data set being collected has potential uses which fall outside the project aims and we would welcome proposals for collaboration from members of the remote sensing and modelling communities. Here we describe initial results which show that the two wave systems agree reasonably well for wave period, but that significant wave heights from the WAVEX are overestimated in the presence of swell.

Keywords: wave radar, sea state, wind stress, Station Mike, SBWR, ship borne wave recorder

INTRODUCTION

In September 2006 scientists from the National Oceanography Centre (NOCS) instrumented the Norwegian weather ship *Polarfront* with a range of sensors and systems for obtaining measurements of sea state and of the turbulent air-sea fluxes of momentum, heat and CO_2. The *Polarfront* is owned and operated by Misje Rederi AS under contract to the Norwegian Meteorological Institute (DNMI). This ship and its predecessors have occupied Station Mike in the Norwegian Sea (66˚N, 2˚E) continuously for nearly 60 years, and the *Polarfront* currently only comes in to port for 8 hours once every 4 weeks. As well as the DNMI's meteorological program, a hydrographic program is run by the Geophysical Institute of the University of Bergen. The NOCS installation on the *Polarfront* is funded through the HiWASE (High Wind Air-Sea Exchanges) project which aims to improve the parameterisation of the turbulent air-sea fluxes, particularly under high wind speed conditions. Detailed sea-state information is needed in order to improve the flux parameterisations.

In 1978 DNMI equipped the *Polarfront* with a ship borne wave recorder (SBWR) which was upgraded in 1996 and again in 2006. Although providing reliable wave height information the SBWR system does not produces any directional information. In order to complement the SBWR, a marine wave radar system “WAVEX” was installed as part of the HiWASE project. The WAVEX system provides reliable wave direction and period data, but infers wave heights in real time using a commercially-confidential algorithm. It is believed that, until now, the two systems have rarely been deployed together for more than brief periods and that published comparisons between wave radar systems and other more direct measurements of wave heights have been rather limited.

Near real-time (24 hours delay) summary results are transmitted to NOCS from the ship via an IRIDIUM satellite link and are displayed on the project web page http://www.noc.soton.ac.uk/ooc/CRUISES/HiWASE/index.php . The *Polarfront* operates in a region of the world’s oceans which experiences extreme conditions in terms of wind speed and sea state. The various systems on the ship all operate continuously, and the NOCS system will do so at least until the end of the project in late 2009. Continuous operation allows data to be obtained under a wide range of wind speeds and sea states: since the NOCS systems were deployed the maximum 10 minute mean wind speed measured was 25 m/s, with maximum significant wave heights (Hs) of 10 m.

In this paper we give a brief description of the SBWR and WAVEX systems in turn, along with a summary of previous validation studies. An initial comparison of the data from the two systems is then presented.

THE SHIP-BORNE WAVE RECORDER SYSTEM

The SBWR was devised by Tucker (1956) and developed at the Institute of Oceanographic Sciences (later to become part of NOCS) and for many years was used extensively for offshore wave measurement in the North-East Atlantic, for example on light-vessels and weather ships (Pitt, 1991). Such long time-series records from the SBWR have been used to identify a climatological increase in wave heights in the North Atlantic (Bacon and Carter, 1991). Today the SBWR is in continued routine use on a number of research ships world-wide, one of which recently measured a number of peak-to-trough wave heights of nearly 30 m (Holliday et al., 2006).

The principles of operation of the SBWR are described in Tucker and Pitt (2001). In brief, two pairs of accelerometers and pressure sensors are mounted port and starboard on the ship's hull below the waterline (1.5 m below for the *Polarfront*), close to the pitch axis of the ship. Data from the port and starboard instrument pairs are combined to eliminate the effects of ship roll both in accelerations and pressure, and the accelerometer signal is double-integrated with respect to time to generate ship heave. The pressure sensors provide a wave height signal additional to the heave and the two are combined to calculate *in situ* sea surface height variability (i.e. the wave height). Sections of the wave height signal are used to derive energy spectra which are used in turn to calculate various statistical parameters including significant wave height (Hs, four times the standard deviation of sea surface elevation). On the *Polarfront* the SBWR records data continuously, sampling at 1 Hz for 30 minutes out of every 45 minutes. Raw surface elevation data as well as spectral information and summary parameters such as Hs are stored automatically.

The accelerometers and pressure sensors are regularly calibrated and are both robust and accurate (to within 1%), and comparisons between data from the SBWR and a directional wave buoy have shown reasonable agreement between the two (e.g. Hatori, 1983). However, the limitation on the accuracy of the SBWR data is uncertainty in assessing the response to the waves of the ship on which it is mounted. Pitt (1991) produced an empirical calibration which depends on ship length and sensor depth, using data from a number of ships compared to data from directional wave buoys. Pitt also discussed a rather limited comparison between SBWR Hs and that from the *Geosat* altimeter and found that the two agreed reasonably well, with the altimeter Hs being about 10% low compared to the SBWR data (data up to Hs of about 9 m were available). Similarly, Clayson (1997) reported results from a comparison between the SBWR on the *Polarfront* with 30 hours of co-located directional wave buoy data. In this case Hs varied from about 2 to 6 m. Before applying the Pitt response correction, the comparison showed:

$$SBWR_{HS} = 0.753*BUOY_{HS} + 0.557 \qquad r=0.854 \qquad (1)$$

i.e. for the typical Hs of 4 m the SBWR underestimated by about 10%. However, this fit was derived from a one-way regression and since the scatter in the data can be attributed to both instruments a two-way fit would be more appropriate: this suggests a simple bias correction of just +0.4 m for the SBWR Hs. After applying the empirical Pitt correction Clayson found a (one-way) regression of;

$$SBWR_{HS} = 0.692*BUOY_{HS} + 1.636 \qquad r=0.866 \qquad (2)$$

i.e. for a 4 m Hs the SBWR now overestimated by about 10% (similar to the earlier SBWR/altimeter comparison).

The Pitt correction can be automatically applied to the SBWR spectra during data acquisition but on the *Polarfront* this facility is not used. For this reason the SBWR Hs data shown here will be adjusted by +0.4 m.

THE WAVE RADAR SYSTEM

The WAVEX system installed on the *Polarfront* uses data from a standard marine X-band (3 cm) radar to map the sea surface in 2 dimensions. The marine X-band scanner has to be operated in "short pulse" mode to optimise the backscatter from the sea surface. In contrast, for navigation purposes such scatter from the sea surface ("clutter") is tuned out as far as possible. In principle the ship's existing radar could be used to provide input to the WAVEX system, but this would require the ship's crew switching the ship's radar into short pulse mode when wave data were required. This option was not feasible for the long-term continuous deployment on the *Polarfront*. For this reason the *Polarfront* was equipped with a separate 6-foot scanner (at 17 m above sea level) in order for the wave system to be entirely independent from the navigation system. The WAVEX system captures radar images of the sea surface and uses a time series of images to produce directional wave spectra. The amplitude of the radar sea-echo depends on the roughness of the sea surface, as well as on the local grazing angle (or wave slope), but there is no unique relationship between the amplitude and the wave height. Wave slope information can be extracted from the radar images and processed in order to obtain directional wave height spectra. During the processing the WAVEX system performs an "automatic calibration" of the measured wave spectrum to produce absolute spectral densities (m^2/Hz) (MIROS, 2004). On *Polarfront*, the system was set to record spectra and mean parameters from a 2 minute sample once every 5 minutes and raw data (32 radar images) every 20 minutes.

A brief survey of the literature shows relatively few attempts to make direct comparisons between wave height data from marine wave radar systems with data from systems which make more direct wave height measurements, such as directional wave buoys. As far as we are aware almost all such comparisons have been made using the WaMoS system, which is, like WAVEX, based on marine X-band radar images. The exception is the study by Nielsen (2006) who used WAVEX to validate a new system for estimating the wave field from ship motion measured on a container ship: the few data shown in this comparison showed that the WAVEX Hs were significantly larger than those from the novel system.

Almost all WaMoS/buoy comparisons described in the literature show results after the WaMoS system has been calibrated against a wave buoy deployed specifically for the purpose (e.g. Borge et al., 1999; Wyatt et al., 2003). In these cases it was assumed that the signal to noise ratio (SNR) of the wave radar signal can be linearly related to the actual significant wave height as measured by a buoy:

$$Hs = A + B*SNR^{1/2} \qquad (3)$$

For these studies a good agreement between WaMoS and buoy Hs data is only to be expected. It is not clear how these empirical calibrations vary from one installation to another, and how site- or sea-state dependent they may be.

One study that does not use this empirical calibration method is that described by Dankert et al. (2005), who instead describes a novel algorithm to obtain significant wave heights without reference to any external measurement. The results of this algorithm were then tested against (rather than calibrated by) data from 3 *in situ* sensors including a wave buoy. Three weeks of data were obtained with wind speeds above 4 m/s (the minimum required for good radar images) and Hs up to 6m, and good agreement was found, with the radar Hs being biased low by only 15 cm on average. The experiment took place in the southern North Sea and it is not known whether significant swells were present at the time.

PRELIMINARY RESULTS

Here we present preliminary results from the comparison of the SBWR and WAVEX system deployed on the *Polarfront*. Both systems operate continually and have done so since deployment of the WAVEX in September 2006. Both systems automatically output a limited number of wave field parameters (e.g. Hs, Tz) via a serial link: these data are logged via the AutoFlux system and transmitted daily via IRIDUM to NOCS. Spectra and raw data are recorded internally on both systems, but these data are yet to be analysed. The data shown here are limited to the mean parameters output automatically, with Hs from the SBWR being adjusted upwards by 0.4 m to allow for the offset found from the data shown by Clayson (1997). The 2 minute sample WAVEX data have been averaged over the 30 minute sample periods of the SBWR.

Figure 1 shows a typical time series of Hs and Tz, where Tz is the zero up-crossing period defined as;

$$Tz = (m0/m2)^{1/2} \qquad (4)$$

and Hs is defined as;

$$Hs = 4 * m0^{1/2} \qquad (5)$$

where m0 and m2 are the zeroth- and second-order spectral moments. It should be noted that the Tz from the WAVEX is therefore derived from m0, which is dependent on the "automatic calibration" of the wave spectra which is carried out to obtain wave heights (MIROS, 2004).

It can be seen that Tz from the SBWR and WAVEX agree reasonably well for this period. No allowance has been made for ship speed on the measured SBWR Tz, apart from selecting data where the speed is less than 1.5 m/s. When on station the ship drifts beam-on to the wind with a mean ship speed over the ground of about 0.6 m/s. The ship only turns bow-on to the wind when wind speeds exceed about 20 m/s: in these cases the ship steams at about 1 m/s into the wind.

For Hs the data from the WAVEX appear rather scattered but this may be due to the shorter sampling period (six 2 minutes sample periods averaged over the 30 minute sampling periods of the SBWR). The Hs time series often shows the general features seen here, i.e. the WAVEX Hs tends to be significantly larger than that from the SBWR when the wave heights are relatively low, but agrees better for larger wave heights.

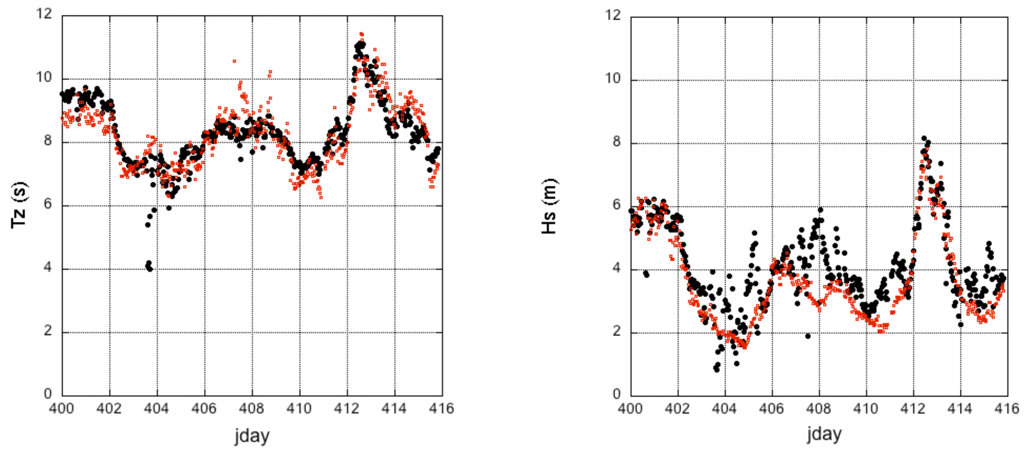

FIGURE 1. SIXTEEN DAY TIME SERIES OF (LEFT) TZ AND (RIGHT) HS FROM THE SBWR (RED) AND THE WAVEX (BLACK).

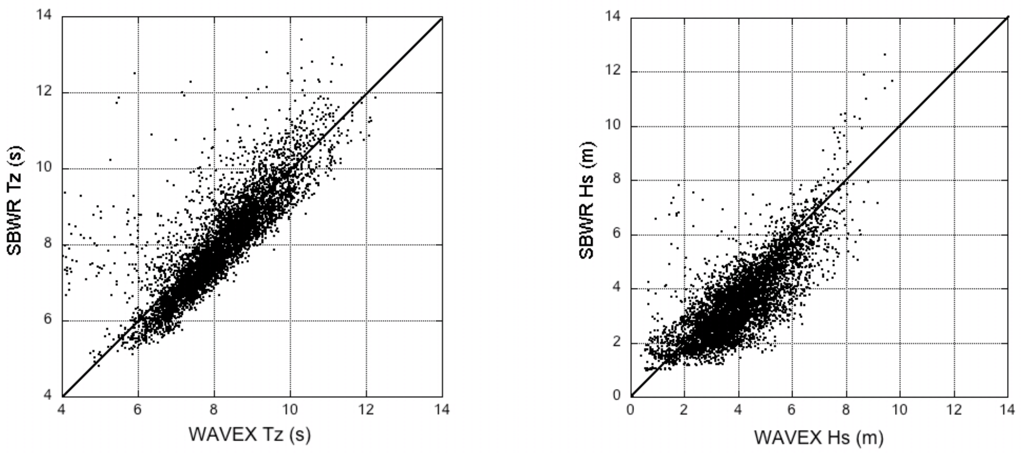

FIGURE 2. TZ (LEFT) AND HS (RIGHT) FROM THE TWO SYSTEMS. THE SOLID LINE INDICATES A 1:1 RELATIONSHIP.

A direct comparison of Hs and Tz from the two systems is shown for all available data (about 280 days) in Figure 2. Here it can be seen that the mean agreement in Tz is reasonably good, if scattered, for the longer period waves. For shorter period waves, the WAVEX Tz tends to be larger than that from the SBWR: this is the opposite of what may be expected if the ship is drifting in the same directions as the waves since the SBWR does not account for ship motion over the ground and would therefore be expected to overestimate Tz to some extent. For Hs the comparison is more scattered than for Tz, but the WAVEX shows a persistent tendency to overestimate Hs compared to the SBWR. This is probably related to the overestimate of the WAVEX Tz since both are derived from the m0 parameter (equations 4 and 5), which depends on the "automatic calibration" of the wave spectra.

Examination of the whole data set showed only one occasion where the Hs from the WAVEX was consistently low compared to the SBWR data. This rather unusual period is shown by the handful of data at the top right of the Hs comparison in Figure 2: the corresponding time series is shown in Figure 3. Figure 3 also shows that when the wind and sea state are dropping, the WAVEX may again tend to over-estimate Hs. During this storm, as for other storms, the ship steamed in to the wind at about 1 m/s. This may account for the SBWR Tz being slightly low but should not affect the Hs measurements.

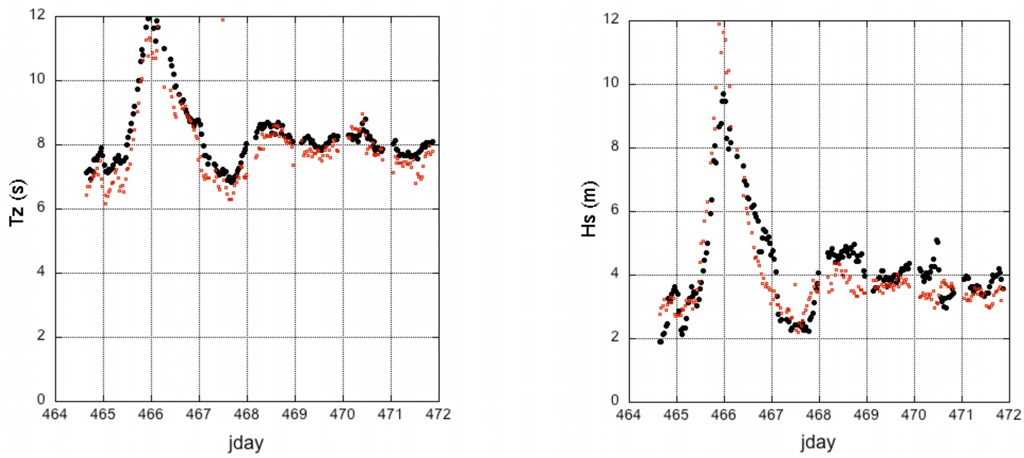

FIGURE 3. TIME SERIES OF TZ (LEFT) AND HS (RIGHT) SHOWING THE ONE EVENT ON DAYS 465 TO 466 WHERE THE WAVEX HS (BLACK) WERE SMALLER THAN THOSE FROM THE SBWR (RED).

The WAVEX system identifies primary and secondary waves, with different periods and directions associated with each. It was thought that the over-estimate of Hs by the WAVEX may be caused by swell waves being identified as the primary waves, but treated as wind waves for the purpose of calculating Hs. In order to examine this, the data were separated into three classes: swell (or decaying wind sea), fully developed seas and wind sea. The peak wave period, T_{PM}, was calculated from the wind speed using the Pierson and Moskowitz (1964) relationship adjusted for winds at a height of 10 m, U_{10} (Carter, 1982);

$$T_{PM} = 0.785 * U_{10} \qquad (6)$$

The WAVEX primary wave period T_{P1} was then compared to T_{PM} and data were classed as swell if $T_{P1} > T_{PM}+0.25$, fully developed $T_{P1} = T_{PM} \pm 0.25$s and wind-sea if $T_{P1} < T_{PM}-0.25$. The data from both systems were classed using this method, i.e. the SBWR data classes correspond exactly to the WAVEX classes.

Figure 4 shows the Hs and Tz comparisons as shown in Figure 2, but this time the data have been separated into the three different classes. For wind sea and fully developed seas, the Tz comparison shows little scatter, but the WAVEX Tz are consistently high compared to those from the SBWR. For swell data the scatter is much larger, and the WAVEX Tz may tend to be low. For Hs, the scatter is again much larger for swell-dominated seas than for wind seas or fully developed seas, and the WAVEX Hs tends to be overestimated for swell.

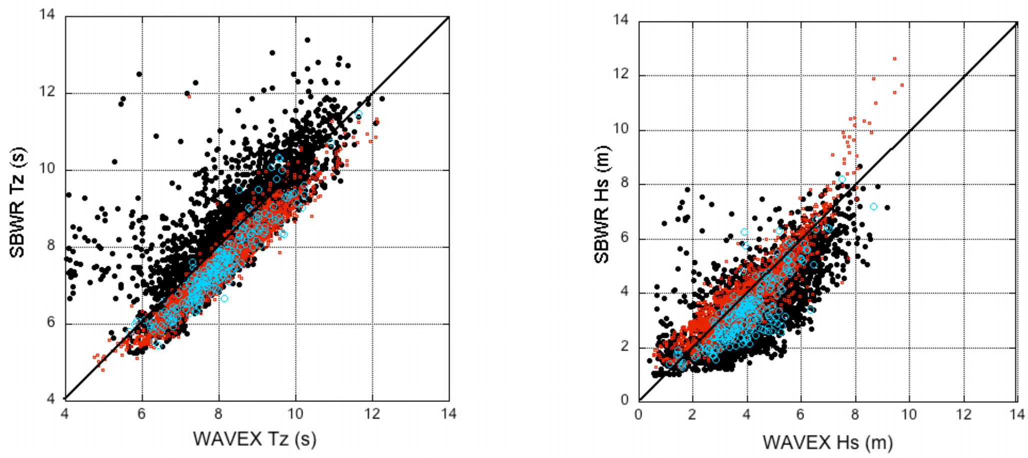

FIGURE 4. TZ (LEFT) AND HS (RIGHT) COMPARISONS FOR THE TWO SYSTEMS. DATA ARE SEPARATED INTO SWELL (BLACK), FULLY-DEVELOPED (BLUE) AND WIND-SEA (RED) BY COMPARING THE WAVEX PRIMARY WAVE PERIOD WITH THE PIERSON AND MOSKOWITZ DERIVED PEAK PERIOD. THE SOLID LINE INDICATES A 1:1 RELATIONSHIP.

Figure 5 shows Hs versus Tz for the SBWR and the WAVEX for the three classes. For the SBWR, the behaviour of the swell data is clearly different from the fully developed or wind sea cases, generally having lower Hs values for a given Tz. In contrast, for the WAVEX data all classes appear to be very similar to each other and behave in the same fashion as the SBWR fully developed class. This is shown more clearly in Figure 6, where data from each system and class have been averaged and are shown together. This suggests that the WAVEX algorithm does not perform as well for swell-dominated (or decaying wind sea) conditions as for wind waves or fully developed sea. For the data examined here, about 65% had primary waves which were classed as swell.

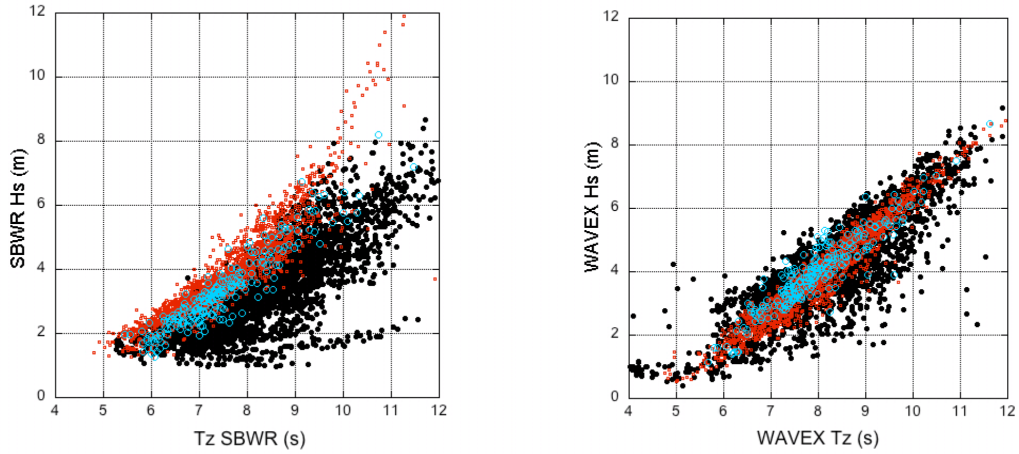

FIGURE 5. HS AGAINST TZ FOR THE SBWR (LEFT) AND THE WAVEX (RIGHT). DATA ARE SEPARATED INTO SWELL (BLACK), FULLY-DEVELOPED (BLUE) AND WIND-SEA (RED) BY COMPARING THE PRIMARY WAVE PERIOD WITH THE PIERSON AND MOSKOWITZ DERIVED PEAK PERIOD.

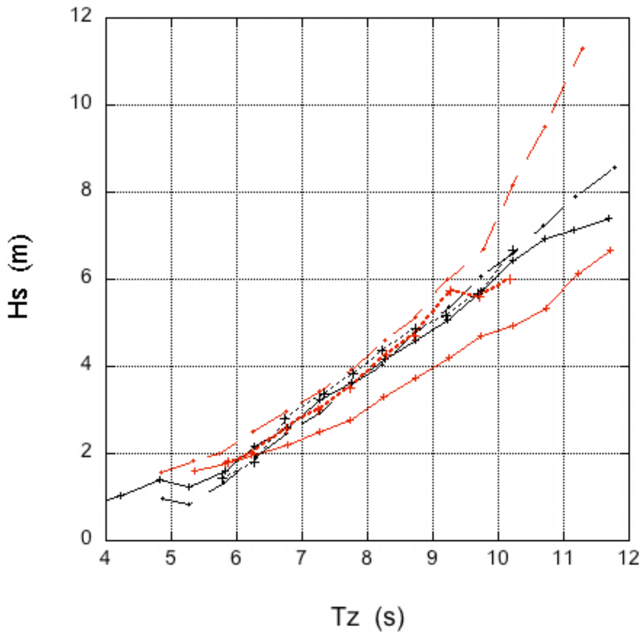

FIGURE 6. HS DATA FROM THE SBWR (RED) AND THE WAVEX (BLACK), BINNED ON TO TZ FROM EACH SYSTEM RESPECTIVELY. DATA ARE SPLIT INTO SWELL (SOLID LINES), FULLY-DEVELOPED (DOTTED) AND WIND-SEA (DASHED) CASES USING THE PRIMARY WAVE PERIOD FROM THE WAVEX.

CONCLUSIONS

This paper has shown very preliminary results of a comparison between the ship-borne wave recorder (SBWR) and WAVEX wave radar systems as deployed on the weather ship *Polarfront*. The errors or biases in the data from both systems are not well know. However, the behaviour of the SBWR Hs data is more realistic in that it shows clearly different behaviour for seas that are swell-dominated compared to those that are wind-driven. In contrast, the WAVEX wave heights showed no dependence on wind sea / swell classification and the wave heights from WAVEX may be significantly over-estimated for conditions where swell dominates or the wind sea is decaying. From these results it appears that the WAVEX system is optimised for fully developed seas. Future collaboration with MIROS (the manufacturers of WAVEX) may include developing the WAVEX algorithm to utilise wind speed and direction data inputs to identify swell waves or decaying wind seas, i.e. those waves which are not being actively forced by the wind. Further analysis of the spectra obtained from both systems will result in a comprehensive directional sea-state data base.

It is hoped that funding will be found to support a deployment of a direction wave buoy at the location of the ship. This would allow a more quantitative evaluation of the wave systems on *Polarfront*. Similarly, we may be able to use satellite altimeter data to detect biases in either system, since the altimeter algorithms have been calibrated to wave buoys around the world.

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