Comparison of *Envisat* ASAR Ocean Wave Spectra with Buoy and Altimeter Data via a Wave Model

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**ABSTRACT**

The Advanced Synthetic Aperture Radar (ASAR) on board the *Envisat* satellite is an important resource for observation of global ocean surface wave spectra. However, assessment of this valuable dataset is not straightforward as a result of a lack of other independent ocean wave spectral observations. The radar altimeter (RA-2) on board the same satellite measures ocean wave height at the same time as the ASAR but at a location about 200 km distant. A small number of moored buoys produce one-dimensional (1D) ocean wave spectra but few ASAR spectra fall on the buoy positions in a given period. Indirect comparison of the *Envisat* ASAR 2D wave spectra with the RA-2 wave heights and 1D spectra of three selected buoys from July 2004 to February 2006 is facilitated by a wave model, which provides coherent spatial and temporal links between these observations. In addition to the conventional significant wave height (SWH), four spectral subrange wave heights (SRWHs) are used to illustrate the spectral characteristics of these observations. A comparison of three *Envisat* ASAR 2D spectra with the closest model and buoy spectra is also attempted to illustrate the qualities of these different observations and to demonstrate the restrictions to their direct comparison. Results indicate that these three independent observations are in good agreement in terms of SWH, though the *Envisat* ASAR shows the largest variance. Comparison of SRWHs indicates that the ASAR spectra agree well with buoy and model in moderately long waves, but the ASAR instrument does not resolve high-frequency waves, especially along the satellite track.

1. **Introduction**

Ocean wave forecasts continue to be important for marine transportation, coastal defense, ship design, offshore oil exploration, search and rescue operations, water sports, and other marine activities. Ocean surface waves also play an active role in the ocean–atmosphere exchange of mass, heat, and momentum (Fairall et al. 2003), especially at high wind speeds (Powell et al. 2003) and hence should be taken into account in coupled ocean–atmospheric models.

Compared to the atmosphere, marine observations are relatively scarce as a result of the limitation of the observation tools and hindrance of the deep water. For centuries marine scientists have relied on sporadic cruise measurements and scattered buoys. The advent of remote sensing by aircraft and satellites in the late twentieth century has greatly enlarged our ocean surface data-set. The Advanced Synthetic Aperture Radar (ASAR) on board the European Space Agency (ESA) *Envisat* satellite is one of a few instruments that measure the directional characteristics of the ocean wave field on a global scale, and such an instrument could be a very useful resource for ocean wave models (Hasselmann et al. 1996).

Assessment of the ASAR data quality is, however, difficult as a result of a lack of independent observations of similar temporal and spatial scales. The ocean wave heights measured by the ESA Radar Altimeter 2 (RA-2) on board the same satellite as the ASAR are of the same spatial coverage, but they do not have any spectral and directional information. Moreover, the location of the RA-2 measured wave height is a few hundred kilometers away from the ASAR spectrum position as a result of the slant arrangement of the ASAR sounding beam. So it is not straightforward to compare the RA-2 wave height observation with the ASAR.

Moored ocean data buoys provide another independent observation of ocean surface waves, and some of them offer wave spectral and directional information.
(Steele et al. 1992). Most of these buoy wave measurements are now available from the National Data Buoy Center (NDBC) Web site (available online at http://www.ndbc.noaa.gov). These datasets are very useful for wave model validation. The major drawback of the buoy wave data is that their spatial coverage is very limited. Most of buoys are moored in coastal waters, and there the ASAR measurement is usually poor as a result of radar echo contamination by coastal land surfaces. A direct comparison of buoy data with ASAR ocean wave spectra is then difficult, as few ASAR spectra fall on the buoy sites in a limited period, or else the ASAR spectra fail the quality control (QC) checks as a result of the proximity to land.

A direct comparison of altimeter data with buoys is achievable, as the RA-2 data density (~7 km between data points) is much higher than for ASAR (~100 km between data points). For instance, Hwang et al. (1998) compared four years (October 1992–September 1996) of Ocean Topography Experiment (TOPEX)/Poseidon altimeter wave data with a few buoys in the Gulf of Mexico. Roughly 1000 altimeter entries were located within a mean distance of 40 km from each buoy during the 4-yr period. If the same spatial criterion was applied to ASAR spectra, the number of ASAR entries would be less than 50 in 4 yr. In fact, Voorrips et al. (2001) attempted collocation of ERS SAR wave spectra with 39 spectral buoys, using criteria of 30 min in time and 80 km in space over 6 yr (1993–98) and ended with 1860 entries in total—equivalent to an average of about 8 entries per buoy per year. Although Envisat ASAR has doubled the data density in comparison with ERS SAR, the total number per buoy over our studied interval (20 months) would be about 30, which is too small for statistical analysis.

A comparison of ASAR wave spectra with modeled ocean wave spectra is the most direct approach for ASAR data validation, though wave models are not perfect and are subject to many variations, such as the quality of the wind forcing and model configuration. In fact, the differences in performance between some of operational global wave models running in major weather centers in the world have been illustrated by Bidlot et al. (2002). So validation of ASAR data with model wave spectra is not fully objective, though it is still quite useful. Heimbach et al. (1998) compared 3-yr coverage of European Remote Sensing Satellite-1 (ERS-1) SAR wave spectra with collocated wave spectra from the European Centre for Medium-Range Weather Forecasts (ECMWF) Wave Model (WAM; Janssen 2004) and found it difficult to judge which represents the “truth” without other independent observations. Johnsen et al. (2002) compared wave model spectra from the same ECMWF WAM model with Envisat ASAR level 2 wave data from May to October 2002 for validation of the inversion algorithm adopted by ESA. Nevertheless, wave model spectra contain more directional information than buoy wave spectra and may produce partitioned wave spectra (Tolman et al. 2002) for comparison in situations where individual swell might be extracted from observations, like the ASAR wave spectra.

The aim of this paper is to gain an objective assessment of the Envisat ASAR wave spectra by comparing them with the other two independent wave observations—RA-2 and buoy—indirectly via a wave model. The wave model is used as a bridging medium to span the spatial and temporal differences of these independent observations, assuming that the wave model is coherent within the vicinity of these observations. The wave model used for this comparison study is the Met Office global ocean wave model (Golding 1983).

A full 2D wave spectral comparison is not feasible because none of the three observations retrieve the full 2D ocean wave spectra. The ASAR instrument is limited by the so-called azimuthal cutoff wavelength (typically 200–400 m). Waves traveling along the satellite direction of motion—and of wavelength shorter than the azimuthal cutoff—cannot be resolved by the ASAR (ESA 2002). This technical restriction results in an ASAR spectrum that is asymmetrical in direction (less reliable in azimuthal direction than in range or transverse direction) and incomplete in spectrum (more long waves than short waves).

The majority of buoy data from the NDBC collection are nonspectral wave data. Only a few buoys produce 1D energy spectra plus four directional parameters (the first and second order Fourier coefficients). These four parameters are insufficient to rebuild the full 2D wave spectrum, though estimation of directional distribution can be derived with advanced processing (e.g., Lygre and Krogstad 1986). This estimation may be fairly good for wave spectra concentrated in one direction, like nearshore waves, which are mainly toward the coast. For mixed swell and wind sea, the directional estimation is not reliable.

Integrated parameters are often used for comparisons and the most widely used parameters include the significant wave height (SWH), mean wave direction, mean direction spread, and mean wave period. As the ASAR can only resolve the long waves, the SWH integration over the ASAR spectra may not be complete. Mean directions and periods derived from the ASAR spectra are then unreliable. This has been revealed by the direct comparison of ASAR mean periods with WAM model values (Johnsen et al. 2002), which showed that ASAR periods were systematically longer than the collocated
WAM model values as a result of the lack of short-period wind sea in the ASAR spectra. Restricting the comparison to periods longer than 12 s reduced the difference. An integrated parameter, equivalent to the SWH but only integrated over a finite subrange of the wave spectrum and hence called the subrange wave height (SRWH), is here used to accommodate the different spectral spans of these observations.

This paper starts with a brief account of the Met Office wave model and the observations used for this comparison study. The comparison results are grouped by buoy sites and presented in sequence of total SWH followed by SRWH. Three ASAR 2D wave spectra closest to the three selected buoy sites are also selected to demonstrate the spectral difference from the model and buoy spectra. Finally, a short summary is followed by our conclusions.

2. The Met Office wave model

The Met Office operational wave model was developed in the 1970s (Golding 1983) and since then has been continuously modified by subsequent development (e.g., Holt 1994). The wave model is based on the 2D spectral wave energy balance equation given by

$$\frac{\partial E}{\partial t} + \nabla \cdot (E \mathbf{c}_x) + \frac{\partial}{\partial \theta} (E \mathbf{c}_\theta \cdot \nabla \theta) = S(f, \theta, x, y, t), \quad (1)$$

where $f$ = wave spectral frequency (Hz); $\theta$ = wave spectral direction (rad); $x, y$ = horizontal space coordinates (m); $\nabla = \partial/\partial x + j \partial/\partial y$ = the horizontal gradient operator; $t$ = time (s); $E(f, \theta, x, y, t)$ = wave spectral energy ($m^2 Hz^{-1} \text{rad}^{-1}$); $S(f, \theta, x, y, t)$ = the source term; and $\mathbf{c}_x = \text{wave spectral group velocity (m s}^{-1}\text{).}$

The advection term [second on the lhs in Eq. (1)] is solved with the Gadd (1978) scheme with a positive filter to reset any negative wave energy components to be zero. The Gadd scheme uses a staggered grid for its prediction step and provides partial spatial smoothing by averaging over the staggered grid. In addition a weighted 3-point space average, (1–2–1)/4 in each dimension, is applied on low-frequency bins to alleviate the garden sprinkler effect caused by the discrete directions of the wave energy spectrum. The refraction term [third on lhs in Eq. (1)] is based on Snell’s law for the bathymetrical refraction and includes the calculation of great-circle turning as well. The source term consists of an exponential wind sea generation term, a white-capping dissipation term, and a so-called second generation parameterized nonlinear interaction term. Except for the non-linear interaction (Janssen 2003), other terms are similar to those used in other wave models (e.g., Tolman and Chalikov 1996). The wave model is driven by the surface (10 m) wind fields from the Met Office unified weather prediction system (Davies et al. 2005).

The global wave model has a spherical grid of 5/9° latitude × 5/6° longitude resolution. The model grid length along the meridian is then a constant (61.5 km), but the longitude grid size decreases with latitude from 92.5 km at the equator to about 15 km at the north and south boundaries (80.6°). The wave energy spectra have 16 direction bins and 13 frequency bands, spaced logarithmically, with their centers between 0.04 and 0.324 Hz. A time step of 1800 s is used for all source terms except for advection, which uses fractional steps (450, 900, and 1800 s) of the major time step for different frequency bands to meet the stability requirement.

Ocean wave energy measurements from buoys and satellites have been used for model validation and data assimilation for many years in the Met Office (Foreman et al. 1994), though wave data assimilation in the operational global wave model was suspended in 2001 when the quality of ERS-2 wind observations degenerated. The overall performance of the Met Office wave model is comparable to other wave models (Bidlot et al. 2002), such as the third generation WAM (WAMDI Group 1988) and WAVEWATCH III (Tolman et al. 2002) models.

The global wave model hindcast produces a few integrated ocean wave parameters (e.g., SWH, peak period, and mean direction) at all model grid points every 30 min time step plus 2D spectra at the closest grid points and the nearest time steps to the ASAR and buoy data. This model output is then collocated with RA-2, ASAR, and buoy data for comparison.

The SRWH is defined similar to the SWH except that SRWH is integrated over a finite frequency range. The relationship between the SRWH, $H_s(f_1, f_2)$, and the 2D ocean wave energy spectrum $E(f, \theta)$ (here the spatial and time variables are omitted for simplicity) within a given frequency range from $f_1$ to $f_2$ is defined by

$$H_s(f_1, f_2) = 4 \left[ \int_{f_1}^{f_2} df \int_0^{2\pi} d\theta E(f, \theta) \right]^{1/2}. \quad (2)$$

This definition is similar to the “narrowband wave height” used by Voorrips et al. (2001), which has a constant interval of 2 s in the wave period. The acronym SRWH is chosen because of its resemblance to SWH. In fact, SWH is equal to SRWH when integrated over the whole frequency range, that is, $H_s(0, \infty)$, or simply $H_s$. The “low-frequency wave height” $H_{12}$ used by Voorrips et al. (2001) and Johnsen et al. (2002) is equivalent to the SRWH of frequency up to 1/12 Hz or wave periods greater than 12 s, that is, $H_{12} = H_s(0, 1/12)$. The 4-bin SRWHs are efficient parameters to represent the wave
spectral characteristics in lieu of the full 2D spectrum, which may contain 600 elements for the configuration of 24 directional and 25 frequency bins.

3. Observation data

The Envisat ASAR wave spectra used here are the fast-delivery level-2 (ASA_WWV_2P) product downloaded daily from the ESA FTP site (ESA 2002). Each ASAR 2D spectrum is derived from a wave mode 5 km × 5 km synthesized image of the ocean surface and can be considered as an average of the same area. Sampling interval along the satellite track is about one image every 100 km. A few quality-control filters are used for the selection of the ASAR data, as recommended by ESA (2002). The major filters are listed below.

1. 0 \leq image\_variance \leq 1.6
2. 2.0 \leq signal\_to\_noise \text{(ratio)} \leq 200
3. land\_flag, quality\_flag, and confidence\_swell = 0

These filters result in a rejection rate of about 15% on average. The time and space location of each selected ASAR spectrum is rounded to the nearest model time step and grid point for the production of the collocated model 2D spectrum. It is worth pointing out that the fast-delivery level-2 products are ready-to-use 2D wave spectra and aimed for operational applications. Ocean wave spectra retrieved from the Envisat ASAR level-1 products (or raw data) with improved retrieval procedures are reportedly of better quality than the level-2 spectra (Abdalla 2006 and Schulz-Stellenfleth et al. 2005). The ESA level-2 data reprocessing algorithm has been updated since October 2007 (Johnsen and Collard 2006), but the improved ASAR data are beyond our study period (July 2004–February 2006).

The Envisat RA-2 altimeter ocean SWH data (RA2_WWV_2P product) are also retrieved from the ESA FTP site at the same time when the ASAR data are downloaded. Both the \( K_u \) and S band RA-2 data are used for our operational validation but only the \( K_u \) band data are used for this comparison study, as the \( K_u \) band data are better than the S band data. The major quality-control filter used to select the RA-2 data is applied to the SWH value because RA-2 data substitute a special value (SWH = 32.77 m) for poor quality data. Varying the filter from SWH <16 to 32 m does not make much difference to the final selection, so SWH <20 m is used. Another filter is the rain\_flag = 0, which excludes rain contaminated RA-2 data. The overall rejection rate by these two filters varies daily from 25% to 50%. The selected RA-2 SWH data within one model grid box (~60 km along satellite track) are then averaged before comparison with the model SWH. As spacing between RA-2 measurements is about 7 km, roughly 9 RA-2 data are used for average over one model grid. Since March 2006 the RA-2 average has been replaced by model interpolation for every RA-2 entry, which allows further filtering of the RA-2 data, especially near coastlines. For this reason the present study assesses data before this change—from July 2004 to February 2006, a total of 20 months.

Both the ASAR and RA-2 measurements deteriorate near coastlines where the radar echo is contaminated by land surface. This land effect manifests itself as erroneously large values. To remove these spurious large values, both the ASAR and RA-2 collocated data are put through an extra filter:

\[
\text{observed SWH} - \text{model SWH} < 5.0 \text{ m}.
\]

That is, any observed SWH larger than the collocated model value by 5.0 m will be removed from the selection. The large difference threshold 5.0 m is chosen so that it would not exclude possible real high waves underestimated by the model. Aouf et al. (2006) have used a similar filter (3.0 m), and Johnsen et al. (2002) might have used an even more restrictive one.

Directional wave energy spectra from moored buoys are retrieved once a month from the NDBC Web site (available online at http://www.ndbc.noaa.gov). Three buoys are particularly selected for this study: the first buoy is near Christmas Island (CI; buoy ID 51028 at 0.02°S, 153.87°W); the second buoy is in the Gulf of Mexico (GM; buoy ID 42001 at 25.86°N, 89.67°W); and the third buoy is near Cape San Martin (SM; buoy ID 46028 at 35.75°N, 121.89°W) on the west coast of California. The CI buoy is located in the middle of the Pacific Ocean where long-traveled swell is expected and wind speed is usually small. The GM buoy is, in contrast, within enclosed water where long-distance swell is rare and only wind sea is expected. The SM buoy is at a mixed-wave environment within reach of both the North Pacific swell and local wind sea. The bathymetry near the SM buoy is simple, with nearly straight contour lines and close to deep water (deeper than 200 m). This avoids refraction and small island shadow effects that the global model could not represent. The buoy data on the NDBC Web site have already gone through quality control and are used directly without further filtering. Each buoy wave spectrum is an average of 20-min measurements and represents a space average of roughly 6–24 km for a wave group speed of 5–20 m s\(^{-1}\). So the buoy space scale is similar to the ASAR one (5 km × 5 km).

For the comparison of these three independent observations, Envisat satellite data within ±5° (latitude and longitude) from the buoy sites are selected for indirect
comparison with the buoys. Figure 1 illustrates the typical daily Envisat track coverage and the locations of the three (CI, GM, and SM) buoys. The background is a sample SWH output from the global wave model. The RA-2 data points are indicated by the black lines, made of individual “-” symbol at each data point. The ASAR data points are shown by the gray “+” symbols to the right (facing along the satellite moving direction) of the RA-2 tracks. The number marked on each satellite track shows the UTC time (hhmm) when the satellite was at the mark position. The buoy sites are marked by the stars, and the squares around the buoy stars indicate the selection areas for satellite data. Note that the selection box around the SM buoy is shifted toward the deep ocean to avoid too much land area inside the box. The SM buoy site is about 3° from the box center along each side. The GM box is also slightly southwest to minimize land area inside the box.

Four frequency subranges are selected for the calculation of the SRWHs, as shown in Fig. 2. Their boundaries (marked by the vertical lines in Fig. 2) in terms of wave period $T = f^{-1}$ are approximately 23, 16, 11, 8, and 5 s. The central frequencies of the spectral bands for the buoy, model, and ASAR spectra are shown by the stacked “+” symbols, and the gray “+” symbols indicate the margins of the bands. The subrange boundaries are chosen to be the nearest frequency bands of each spectrum, so that integration is simplified to be summation of an integer number of bands. The disadvantage is, however, that the subrange bounds are slightly different for the three spectra. Note that the 4 subranges are biased toward long waves for assessment of the ASAR data. Four new subranges bounded at exactly $T = \infty, 16, 10, 5,$ and 0 s (or frequency $f = 0.0, 0.0625, 0.1, 0.2,$ and $\infty$ Hz) have been installed since March 2006 to cover the full wave spectral range. The SRWH integrations are extended by interpolation to the exact bounds, and high-frequency spectral tail proportional to $f^{-3}$ is added beyond the high-frequency end. For consistency, the dataset selected for this study is until February 2006.

Apart from these statistical comparisons, direct comparison of an individual ASAR wave spectrum with the closest buoy spectrum is also attempted at each of the three buoy sites. This direct comparison will illustrate the asymmetrical and incomplete nature of the ASAR level-2 spectra and help with the understanding of the statistical results.

4. Comparison results

The comparison will be divided into three subsections according to the compared quantities—that is, the total wave energy as SWH, the partial wave energy as SRWH, and individual wave spectra. Each subsection will include comparisons for all the three buoy sites.
**Comparison of SWH and wind speed**

For convenience of intercomparison, the observed SWHs from the three independent observations and the RA-2 wind speed are plotted against collocated model values and packed into one figure per buoy site. Figure 3 is the packed diagram for the CI buoy site. The top-left panel in Fig. 3 is a scatterplot of the model and CI buoy SWHs over 20 months from July 2004 to February 2006. Each pair of model and buoy SWHs are plotted as a gray “+” symbol in the diagram, with its x coordinate equal to the buoy SWH and y coordinate equal to the model SWH. The contours indicate the relative data density in percentage within a box of 1/50th of the plot range in both directions. The contour values are 0.25%, 0.5%, 1.0%, and 2.5% and are shared by all the scatterplots (Figs. 3–11). The center of the large cross sign marks the mean values, and the cross sizes indicate the standard deviations (stdev) of the two datasets. There are 12,482 pairs of data in the scatterplot. The mean value of the model SWHs (2.25 m) at the buoy site is higher than the average of the buoy SWHs (1.89 m). The model and buoy standard deviations (SDs) are 0.356 and 0.383 m, respectively. The standard deviation of the difference (SDD) between the model and buoy SWHs is 0.367 m. The correlation coefficient for the model and buoy data is 0.508. These results are comparable to those of another validation work (Bidlot et al. 2002).

The lower-left panel in Fig. 3 compares the model SWHs with the RA-2 altimeter Ku band data within the same 658 (latitudinal and longitudinal) distance from the CI buoy site during the same 20 months (July 2004–February 2006) as the buoy plot. A total of 4721 pairs of data are selected here. Each altimeter SWH represents the average of about 9 data points along the satellite track within the model grid box (~60 km) from which the model SWH is taken. The model mean SWH (2.26 m) is also higher than the altimeter mean (2.08 m). The SDs of the model and RA-2 SWHs are 0.366 and 0.373 m, respectively. The SDD of the model and RA-2 SWHs is 0.329 m, and the correlation coefficient 0.603. Comparing this panel with the top-left buoy one, it is evident that the RA-2 SWH values are very close to the buoy values with comparable mean (2.08 versus 1.89 m) and SD (0.373 versus 0.383 m) values. It also reveals that the wave model has a slightly overestimated ocean swell compared to both the CI buoy and RA-2 observations.

The top-right panel in Fig. 3 is the scatterplot of model SWHs against ASAR level-2 SWHs within the same 658 box from the CI buoy site and the same 20 months time interval as the RA-2 and buoy plots. There are 3741 pairs of data in this selection, and each pair consist of 1 ASAR spectrum and 1 model spectrum at the nearest model grid and output time step. The model mean SWH (2.28) and SD (0.363 m) are similar to those in the RA-2 and buoy comparison. The ASAR mean SWH (2.02 m) is lower than the model mean and close to the RA-2 one (2.08 m). The major difference between the ASAR SWH results and those for the others (RA-2, buoy, and model) is that ASAR SWHs show larger variations (SD 0.741 m). The
SDD of the model and ASAR SWH is 0.760 m—larger than both the RA-2 one (0.329 m) and the buoy one (0.367 m). The correlation between model and ASAR SWHs (0.194) is smaller than the RA-2 (0.603) and buoy (0.508) correlations.

Johnsen et al. (2002) compared the Envisat ASAR level-2 wave spectra with the ECMWF WAM model for 6 months between May and October 2002, finding a RMS error of 0.58 m—smaller than the result here. However, there is no filtering information about their selected ASAR data, so we cannot be sure whether these results are comparable. Nevertheless, from Fig. 5 in Johnsen et al. (2002) there apparently is no ASAR SWH larger than the collocated model value by 1.2 m. It is not known whether they filtered out large outliers, or they were lucky in their collection. Large outliers have been reported by other authors. For instance, Fig. 1 in Aouf et al. (2006) and Fig. II.18 in Abdalla (2006) show quite a few ASAR values more than 2 m above the model values. Johnsen et al. (2002) used the same ECMWF
wave model as Abdalla (2006), and the model is similar to the WAM model used by Aouf et al. (2006). Removing the erroneously large ASAR values has a profound influence on the statistics. For instance, if the 5-m filter were not used here, the SDD between the model and ASAR SWH values would increase from 0.760 to 1.21 m, though the total number of entries would only increase by 27 (total 3768) or 0.7%. The 5-m filter does not have any influence on the RA-2 data at the CI site as no RA-2 SWH exceeded the 5-m difference limit.

The lower-right panel in Fig. 3 is a scatterplot of the model wind speeds against the measured wind speeds from the Envisat RA-2 data. The wind speed pairs correspond to the SWH pairs used in the lower-left panel, and they share the same total number (4721). The mean model wind speed (6.18 m s\(^{-1}\)) is slightly higher than the mean Envisat wind speed (5.92 m s\(^{-1}\)). Notice that the CI buoy site is in the middle of the Pacific Ocean and is under continuous influence of long-distance traveling swell from the broad Pacific Ocean. It is almost on

Fig. 4. Same as in Fig. 3, but at the GM buoy site.
the equator where wind speed is usually small (rarely more than 10 m s\(^{-1}\)). So the local winds near the buoy site contribute only to a part of the total wave energy. This explains why the SWHs around the CI buoy are seldom below 1.5 m—no matter that the local wind speed can be quite small sometimes.

Figure 4 is similar to Fig. 3 except for the GM buoy site. As the GM buoy site is inaccessible to most of ocean swell, wave energy at the GM site is dominated by locally generated wind sea, which is proportional to the local wind speed squared. So the SWH scatterplots for the GM buoy (Fig. 4, top left) and the RA-2 altimeter (lower left) are similar to that of the wind speed scatterplot (lower right). The GM buoy mean SWH is 1.16 m averaged over 13 823 entries in the 20 months, which is slightly lower than the model mean SWH of 1.33 m. The buoy and model SDs are very close, 0.828 and 0.815 m, respectively. The SDD between the model and the GM buoy SWHs is 0.333 m, and their correlation is 0.918—higher than that of the CI buoy (0.508). The improved correlation implies that the model is more accurate for wind sea than for long-traveled swell. The increased
SWH range at the GM site also contributes to the high correlation.

The mean RA-2 SWH over 3675 entries (Fig. 4, lower left) is 1.32 m, slightly higher than the model value of 1.24 m. The RA-2 and model SDs are also close, 0.74 and 0.708 m, respectively. The SDD (0.412 m) is higher than for the buoy, and the correlation (0.840) is lower than for the buoy. Nevertheless, the RA-2 correlation with model for SWH at the GM buoy site (0.840) is still higher than at the CI buoy site (0.603). Notice that the number of RA-2 entries for the GM buoy site is less than that at the CI buoy site. This is because the square selection area for RA-2 data at the GM buoy site covers some land area (refer to Fig. 1). Some RA-2 data near coastlines were excluded by QC filters as a result of land effect, making the effective selection area even smaller than the CI box.

The ASAR SWHs (Fig. 4, top right), however, show a small correlation to the model (0.142) and their SDD value is large, at 1.268 m. The model mean SWH (1.38 m)
and SD (0.703 m) are comparable to those model values selected for RA-2 data. But the ASAR SD (1.160 m) is larger than the model value, though its mean (1.53 m) is not too far from the model one. There are two possible reasons for this poor ASAR performance in the GM area. First, the ocean waves in the Gulf of Mexico are mainly high-frequency wind sea with wave lengths usually shorter than the azimuthal cutoff and hence not resolvable by the ASAR. The other possible cause is land effect caused by the Gulf’s coastlines. These effects are also responsible for the low density of the ASAR data in the Gulf, as affected ASAR data are excluded by QC filters. There are only 664 entries here, in contrast to the 3741 at the CI buoy site over the same 20 months. Using the 5.0-m filter to remove ASAR data 5.0 m larger than the corresponding model values has significant influence on the statistics of this small collection. Without the 5.0-m filter, the ASAR data SD would be as large as 2.20 m, and the SDD would increase to 2.35 m when the total entries increased to 692 (by 28 extra pairs of data).

FIG. 7. Same as in Fig. 6, but for GM buoy.
The altimeter data are also affected by the presence of land, as manifested by a few stray points in the lower-right corner of the RA-2 SWHs plot (Fig. 4, lower left). The 5-m filter has removed 36 large RA-2 SWH values at the GM site. The RA-2 SD and SDD would be 1.02 m and 0.836, respectively, if the 5-m filter was disabled. In addition, the 9-point average over the model grid for RA-2 data may have, to some extent, alleviated the coastal land effect. To facilitate further filtering of the land-affected RA-2 points, the RA-2 data average over the model grid has been replaced by model interpolation to every RA-2 data point since March 2006 in our daily comparison. Large RA-2 values could then be removed directly by a similar filter like the 5-m difference one. This is another reason to limit our study period to February 2006.

Figure 5 shows the comparison at the SM buoy site, which represents mixed ocean-wave conditions with both swell from the North Pacific and locally generated wind sea. The top-left scatterplot of buoy and model
SWHs clearly shows the mixed features. Both the model and buoy SWHs are rarely below 1.0 m because of the swell contribution. They are higher than those at the CI and GM buoy sites as a result of the swell–wind sea combination. The SM buoy mean SWH (2.32 m) is higher than the model one (2.26 m) in contrast to the GM and CI buoy, whose mean values are lower than the corresponding model values. The SDD between the model and the SM buoy SWHs (0.623 m) is also larger than those at the GM (0.333 m) and CI (0.367 m) buoy sites. The increased error at the SM buoy site may indicate that model values are less reliable near coastlines than in deep waters as a result of the coarse resolution. The correlation of the SM buoy (0.716) is higher than that of the CI buoy (0.508) but lower than that of the GM buoy (0.918).

The RA-2 and model SWH plot near the SM buoy site (Fig. 5, lower left) tells a similar story as the buoy plot. Both RA-2 and model SWHs were rarely below 1.0 m though wind speeds sometimes were quite small, as
The RA-2 mean SWH (2.37) and SD (0.83 m) are quite close to those of the SM buoy (mean 2.32 and SD 0.89 m) and slightly higher than the model ones (mean 2.33 and SD 0.625 m). The SDD (0.591 m) and correlation (0.704) of the model via RA-2 SWHs are close to the model via buoy values (SDD 0.623 m and correlation 0.716). The total number of RA-2 entries at the SM buoy site (3413) is also smaller than that at the CI site (4721) as a result of coastal land effect. This total number is comparable to that at the GM site (3675), thanks to the 3° shift of the selection box toward the deep ocean (see Fig. 1).

The ASAR performance near the SM buoy site is also poor, as shown in Fig. 5 (upper right). There are a total of 1594 ASAR entries in the selection. The model and ASAR SDD is 1.54 m at SM buoy site (cf. to 1.27 m at GM buoy site), though the correlation increases to 0.418 (0.142 at GM). The model mean SWH (2.45 m) and SD (0.768) for the ASAR data near the SM buoy site are

![Graphs showing wind speeds and correlation](image)
close to those for the SM buoy and RA-2 data (refer to the left two panels), indicating that the model performance is consistent within the selected box area, and the large error is caused by the ASAR spectra. This can be confirmed by the ASAR mean (2.74 m) and SD (1.70 m) values. A possible explanation for the poor ASAR performance is the coastal land effect because the SM buoy is closer to land than the GM buoy. Once again, the 5-m filter plays a key role in reducing the SDD between the model and the ASAR SWH at the SM site. The 5-m filter has removed 67 large ASAR entries, and the SDD value would be as high as 3.10 m without this filter.

b. Comparison of 4-bin SRWHs

As Envisat RA-2 measures only the SWH, the SRWH comparison is carried out for ASAR and buoy data only. The four panels in Fig. 6 show scatterplots of SRWHs in four subrange spectral bins integrated from the model and the CI buoy wave spectra. The collocated
data are exactly the same as used in Fig. 3 with a total of 12,482 pairs. The data number density contour levels are identical to those used in Figs. 3–5 (i.e., 0.25%, 0.5%, 1.0%, and 2.5%), but the unit area is increased to 1/40th of the axial range in both directions. The subranges are indicated by the wave periods 23–16, 16–11, 11–8, and 8–5 s. The first two subranges or bins (periods 23–16 and 16–11 s) may be considered representing primarily long-distance swell, while the last two bins (periods 11–8 and 8–5 s) are mostly representing the locally generated wind sea, though these do not cover the full wind sea range. At the CI buoy site where both wind sea and swell are expected, the wave spectra from both the model and buoy show a balanced distribution of energy over the four subranges. For the two longer-period bins, the model swell energy is slightly higher than the buoy values, as shown by the SRWHs in the first two bins (23–16 and 16–11 s plots in Fig. 6). The second swell bin (16–11 s) has the largest SDD of 0.376 m among the four bins. The model and buoy wind sea energy is in better agreement than swell, as shown by the SRWHs in the last two bins (11–8 and 8–5 s plots in Fig. 6). The best agreement is in the last bin with the smallest SDD of 0.183 m and largest correlation coefficient of 0.767 among the four subrange bins. Despite the low correlation (0.143), the 11–8 s bin is also considered to be in good agreement because the correlation reflects the linear relationship of the two datasets and it becomes unreliable when the data cluster together. The good agreement is based on their close mean (0.998 and 1.13 m) and SD (0.272 and 0.218 m) values.

Figure 7 shows the scatterplots of 4-bin SRWHs for the GM buoy, integrated from the 13,823 collocated model and the GM buoy wave spectra pairs as used in Fig. 4. A distinctive difference between the CI and GM buoy measurements is that the swell energy at the GM buoy, as shown in the first two plots in Fig. 7, is much smaller than that at the CI buoy (cf. the first two plots in Fig. 6). This is simply because the GM site is inaccessible to long-distance swell, and most of the wave energy at the GM buoy site is locally generated wind sea. In fact, the wave energy at the GM buoy site is, as shown in Fig. 7, concentrated in the highest frequency (period 8–5 s) bin. This shows the best agreement among the four bins with the largest correlation of 0.916. This good agreement confirms that the wave model performs well for the wind sea.

Figure 8 shows the 4-bin SRWHs plots for the SM buoy based on the same 14,083 pairs of buoy-model spectra as used in Fig. 5. The 4-bin SRWHs of the SM buoy shows similarity to that of the CI buoy, as mixed swell and wind sea spectra are present at both buoy sites. The major difference between the SM and CI buoy spectra is that SM buoy spectra contain more wind sea energy than the CI ones as a result of the increased wind speeds at the SM buoy site. All four bins show good agreement between the buoy and model SRWH with the best being the wind sea 8–5 s bin, where the SDD (0.338 m) is the smallest and the correlation (0.767) is the largest among the four bins. The 16–11 s bin has the largest buoy SD (0.814 m) and model via buoy SDD (0.643 m). Although the buoy mean SRWH (1.20 m) in the 16–11 s bin is larger than the model value (1.11 m), model overestimation of swell is indicated by the data density contours.

The 4-bin breakdown of the ASAR wave energy near the CI buoy site is shown in Fig. 9. The SRWHs are evaluated from the same collocated wave spectra as used in the ASAR-model SWHs scatterplot in Fig. 3. As illustrated in the first bin (23–16 s) of Fig. 9, the ASAR spectra contain more long-period swell energy (SRWH mean 0.502) than the model (0.274) and the CI buoy spectra (0.119 m in Fig. 6). However, the mean model SRWH in the 16–11 s bin (1.22 m) is larger than the ASAR (0.921 m) value. The CI buoy mean SRWH (0.839) and SD (0.387 m) in the 16–11 s bin shown in Fig. 6 are comparable with the ASAR mean (0.921) and SD (0.420 m) values here, implying that the model has overestimated the swell in this subrange. In the shorter-period range, the ASAR data have larger variance than model results, and the correlation is relatively poor. The 8–5 s bin is the worst one with the largest SDD (0.529 m) and the lowest correlation (0.156) among the four bins. This might be expected, as wave lengths in this range are usually not resolved by the ASAR instrument.

Figure 10 shows the 4-bin SRWHs of the model and ASAR wave spectra near the GM buoy site, using the same dataset as in Fig. 4. It does confirm that the ASAR spectra contain too-large long wave energy. As illustrated by the SRWHs in the first two bins in Fig. 10, ASAR mean SRWHs are 0.416 and 0.550 m, respectively—much higher than the model values of 0.003 and 0.047 m, which are comparable to the GM buoy values of 0.002 and 0.053 m as in Fig. 7. As there should be no swell energy in the GM buoy site, the presence of this large long-wave energy in the ASAR spectra is definitely spurious. The 11–8 s bin shows the best correlation (0.407) among the four subrange bins. This is reasonable because the ASAR performs better in long wave than short wave. The 8–5 s bin shows a lower correlation (0.200) and larger SDD (0.842 m) than those of the 11–8 s bin, as a result of the restriction of the ASAR instrument on wind sea measurement.

Figure 11 is the 4-bin SRWHs plot for the ASAR data near the SM buoy site. The most prominent feature is the large variation of ASAR spectra with SD value
larger than the model one in every bin. The large variation of the ASAR spectra near the SM buoy site is probably caused by the coastal land effect. ASAR overestimation of long waves is also evident here in the 23–16 s bin. The mean ASAR SRWH is 0.729 m, while the model value is 0.209 m and the buoy value is 0.300 m (refer to Fig. 8). The 16–11 s bin shows relatively good agreement with mean ASAR SRWH (1.23) close to the model (1.14) and buoy (1.20 m in Fig. 8) values. The ASAR SD (0.784 m) is higher than the model (0.520 m) but lower than the buoy (0.814 m). The 8–5 s bin is the worst among the four bins, as in the CI buoy site. This is attributed to the poor resolution of wind sea by the ASAR instrument and possible land effect.

The wave spectral energy breakdown by the 4-bin SRWHs has shown its usefulness here to illustrate the differences among the buoy, ASAR, and model wave spectra. Arising from this intercomparison, the major concern toward the ASAR data is about the spurious wave energy toward the low-frequency end. Aouf et al. (2006) showed a similar result and demonstrated improvement in their Envisat ASAR level-2 wave data assimilation after removing the spurious long-wave energy in the ASAR data. The updated Envisat ASAR inversion algorithm (Johnsen and Collard 2006) since late October 2007 has reduced the erroneous long-wave energy as well. The 4-bin SRWHs also reveal that the model performs well in wind sea estimation and does not produce any swell at the GM site as expected. This may imply that the model overestimation of swell at the CI and SM sites could be due to a low dissipation rate.

c. Comparison of individual spectra

In this section individual wave spectra from the ASAR are compared with the closest buoy and model spectra at each of the three buoy sites. As the model uses constant latitude (5/9 S) and longitude (5/6 W) mesh, the model latitude grid length is fixed at 61.5 km but the longitude grid length varies with the latitude. Around the CI, GM and SM buoy sites they are about 92, 83 and 75 km, respectively. So the collocated spectra are not at exactly the same spot and they may locate as far as half the grid length apart in each direction.

Figure 12 shows the selected ASAR, model, and CI buoy spectra on 20 January 2006 as around 2000 UTC. The exact ASAR spectrum location is 0.03°S, 153.43°W—about 50 km from the CI buoy (0.02°S, 153.87°W). The model grid center is at 0.28°S, 153.75°W—about 30 km from the buoy and 45 km from the ASAR point. As the model grid is about 62 km ⨉ 92 km near the CI buoy site, the maximum distance of ASAR point from the nearest model grid point might be as large as 55 km in diagonal distance here.

Both the ASAR and model 2D spectra are drawn on a polar frame with logarithmic frequency as the radial axis (Fig. 12). The inner-most solid circle marks the 0.04-Hz frequency and the outmost one delimits the 0.4-Hz frequency. The intervening two dotted circles represent 0.1 and 0.2 Hz, respectively. As a rough guide, swell energy will usually be confined within the 0.1-Hz circle and wind sea outside it. The upper-left panel shows the ASAR spectrum, and the arrow indicates the satellite travel (or the azimuthal) direction. The azimuthal cutoff wavelength for this spectrum is 327 m or about 0.07 Hz. This means that the wave energy along the satellite traveling direction (forward and backward) outside this cutoff frequency is not resolved. As the plot shows, there are some nonzero values between the 0.1 and 0.2-Hz circles in the backward direction, and these values ought to have been removed from the ASAR spectrum by the ESA processing. Almost perpendicular to the azimuthal direction there is a westward mixed wave train (wind sea and swell) in the ASAR spectrum with a peak frequency just below 0.1 Hz. There are two further swells traveling in the northwest and southwest directions, respectively. These features are almost matching the model spectrum shown on the upper-right panel. Here the arrow indicates the wind direction. The easterly wind generated a westward wind sea in the model spectrum, which matches the ASAR wind sea direction but has a different peak frequency close to 0.2 Hz. There are also two swells in the model spectrum, traveling south and north, respectively. The northward swell is close to the ASAR one but the southward one is larger in strength and about 50° in direction difference from the ASAR one. The energy differences between the ASAR and model spectra are illustrated more clearly in the integrated 1D spectra shown in the lower-right panel. The model spectrum has a dominant swell peak at about 0.07 Hz and a wind sea peak close to 0.2 Hz. The ASAR spectrum has a single peak at 0.09 Hz.

The lower-left panel in Fig. 12 compares the CI buoy 1D spectrum with the same model spectrum as in the ASAR spectral comparison. The model wind sea part matches with the buoy in the high-frequency end but missed the prominent buoy peak at 0.1 Hz, which nearly matches with the ASAR peak frequency, as shown to the right. Note the different scales used for the buoy and ASAR 1D spectral plots as a result of their peak differences. The buoy peak is more than twice as large (9) as the ASAR one (4 m² Hz⁻¹). The second buoy spectral peak at 0.06 Hz is about 6 m² Hz⁻¹. The model swell peak value is 3.5 m² Hz⁻¹, lower than the buoy one. The matching buoy and ASAR peaks around 0.1 Hz implies that the model missed the swell energy in the wind direction, a known problem in the second generation
wave model as a result of the reshaping of the wave spectrum in the wind direction. The mean buoy spectral direction $109^\circ$ counterclockwise from the north (positive clockwise) is adapted from the buoy A1 parameter and indicates that the buoy spectrum is dominated by the westward swell. The model spectral mean direction is $-138^\circ$, or $29^\circ$ toward the south from the buoy one, indicating that the southward swell in the model spectrum
is overestimated and/or the swell in the wind direction is underestimated.

Figure 13 compares the ASAR, model, and GM buoy spectra on 21 January 2006 at 1600 h. The ASAR spectrum at 24.97°N, 89.75°W is about 32 km from the model one at 24.72°N, 89.58°W. The azimuthal cutoff wavelength for this ASAR spectrum is 184 m, or about 0.09 Hz, so the wave energy between the 0.1 and 0.2 Hz circles in the backward satellite direction is not real and should have been removed. Note that in the transverse direction, the ASAR is capable to resolve wind sea beyond the azimuthal cutoff, as demonstrated by this ASAR spectrum. The ASAR wind sea at about −80° matches well with the model one shown in the upperright panel. Remember that the GM buoy is in the enclosed Gulf of Mexico where no swell is expected. This confirms that the nonzero ASAR spectral values within the 0.1-Hz circle are spurious noises rather than real swell energy. There is no swell energy in the model spectrum, as expected. The integrated 1D spectra shown in the lower-right panel confirms that the ASAR spectrum has more swell energy than either model or buoy.

The lower-left panel in Fig. 13 is the GM buoy 1D spectrum at 25.86°N, 89.67°W, compared with a different model point about 10 km away at 25.83°N, 89.58°W. Note that the selected ASAR point is about 102 km south to the GM buoy and is compared with the model point 2 grids from the one used for buoy comparison. Nevertheless, the two model spectra are quite close in shape (as the 1D spectra revealed in the lower two panels). The model spectrum for the buoy plot has a peak value of about 1.8 m² Hz⁻¹, slightly higher than the model spectrum (≈1.3 m² Hz⁻¹) in the ASAR plot. The mean model direction −61° shows that the two model spectra are nearly in the same direction. The buoy mean direction −81° is close to the mean direction of the westward wind sea in the ASAR spectra, though they are 102 km apart in distance. The model 1D spectrum is in good agreement with the buoy one, apart from the finescale features in the buoy spectrum, which the model could not resolve. Note the swell part; both the model and buoy spectra are virtually zero below 0.1 Hz. This confirms that the ASAR spectral energy below 0.1 Hz is incorrect.

Figure 14 shows the spectral comparison at the SM buoy site on 1 August 2005. The ASAR spectrum at 35.40°N, 121.7°W 1618 UTC is compared with the model spectrum at 35.28°N 122.1°W 1630 UTC, about 39 km to the southwest and 12 min late. The ASAR spectrum shows a single swell traveling at about 45° clockwise from the north. The model spectrum has a northward swell and a southeastern wind sea. The integrated 1D spectra in the lower-right panel show that they share the swell peak frequency at about 0.08 Hz, but the model peak (3.7 m² Hz⁻¹) is more than 2 times the ASAR peak (1.5 m² Hz⁻¹). Beside, there is a wind sea peak at 0.15 Hz in the model spectrum with a peak value of 2 m² Hz⁻¹.

The lower-left panel shows the 1600 h SM buoy 1D spectrum at 35.75°N, 121.9°W and the model spectrum at 35.83°N, 122.1°W. This model spectrum is one grid north and one time step (30 min) earlier from the one used for the ASAR comparison. They both have swell and wind sea peaks but the swell peak (6 m² Hz⁻¹) is higher than the one at the ASAR point (3.7 m² Hz⁻¹). The buoy spectrum, however, does not show much swell energy (below 1 m² Hz⁻¹), though the wind sea part matches well with the model one. The buoy mean direction 134° indicates that the buoy spectrum matches the model wind sea direction, but the model mean direction 45° reflects the overestimated northward swell in the model spectrum. The missing wind sea in the ASAR spectrum may be caused by the azimuthal cutoff (226 m or 0.08 Hz for this spectrum), because the wind direction is close to the satellite travel direction and most of the wind sea spectrum is not resolved by the ASAR instrument.

5. Summary and conclusions

Three independent ocean wave measurements, from the ASAR and RA-2 instruments on board the ESA Envisat satellite and from selected buoys in the Pacific Ocean and the Gulf of Mexico during the 20 months of periods from July 2004 to February 2006, are compared via a global ocean wave model. Direct comparison of these observations is impractical because of the spatial and temporal differences between these observations. Two-dimensional ocean surface wave spectra from the Met Office global wave model have been collocated with individual observations from these instruments for comparison. Indirect comparison of these observations is then achieved by intercomparison of their differences from the wave model. A parameter equivalent to the widely used SWH but integrated over a finite spectral subrange, and hence called subrange wave height (SRWH), is used to show the spectral performance of these observations. Comparisons of three Envisat ASAR 2D spectra with the closest model and buoy spectra are also included to illustrate the qualities of these different observations and to demonstrate the restrictions to their direct comparison. The following conclusions may be drawn from this comparison study.

1) The three independent observations are generally in agreement in terms of SWH or total wave energy,
though the ASAR SWHs show large variations. All the three observations can be usefully taken to validate ocean wave models. The RA-2 SWHs are particularly useful for global coverage, and the buoy spectra are valuable for wave model spectral assessment. ASAR wave data are good guides to 2D swell spectra on the global scale, with caution on the high-frequency end.
2) **Envisat** ASAR level-2 wave product is one of the few available 2D wave spectral observations on the global scale. The ASAR wave spectra are closest to buoy spectra in the moderate long-wave range. For shorter-period waves, the ASAR spectra are limited by the azimuth cutoff. Some ASAR level-2 data have erroneously high values toward the low-frequency end. The ESA inversion algorithm update in late October...

**FIG. 14.** Same as in Fig. 12, but with SM buoy.
2007 has reduced these spurious long waves in the ASAR spectra.

3) The 4-bin SRWHs are useful to illustrate the spectral characteristics of ocean wave spectral observations, especially for partial spectra like the ASAR ones. They are much economical for operational use in lieu of the 1D or full 2D spectrum.

4) The Met Office wave model generally agrees well in the full wave spectral range with the three independent observations, though it slightly overestimates the swell.

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