SUPPLEMENT

PHENOMENAL SEA STATES AND SWELL FROM A NORTH ATLANTIC STORM IN FEBRUARY 2011: A COMPREHENSIVE ANALYSIS

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ALTIMETRIC OBSERVATIONS AT HIGH WAVE HEIGHTS. While estimates of H_s at high sea-states are considered to be relatively robust, altimeters are neither designed nor calibrated for such large values. Here, however, the lack of evidence of saturation errors in the sensor waveform data, the consistency of the along-track patterns in the full 20-Hz data, and the low 1-Hz standard deviation (1.46 m) all give a measure of confidence in these measurements. This is supported by the consistency between the very high waves and the long swells, which is presented in this study. In general, H_s measurements from altimeters are calibrated using buoy comparisons and interaltimeter comparisons. Recent analysis of *Jason-2* observations indicates that a slight linear correction to H_s should be applied, which would give a maximum value of 20.4 m rather than 20.1 m on 14 February. As this correction was estimated using very few buoy observations between 8 m and 12 m, and none above 12 m, the very high altimeter H_s values are not directly validated, and estimation of the error in the measurement is difficult.

DISCUSSION OF HIGH WIND SPEED RETRIEVAL FROM SATELLITES. Calibration at high wind speeds is one of the goals of the "International Ocean Vector Winds Science Team," and performing cross-calibration for different satellite sensors with reference in-situ data is an active topic of research. The comparison of the winds in Quirin up to hurricane force between the altimeter and radiometer onboard *Jason-1* and *Envisat* and the ASCAT scatterometer shows that the gale-, storm-, and hurricane-force wind scales can be consistently estimated (see also Quilfen et al. 2011). However, the ultimate goal of having accurate measurements of high wind speeds from sensors operating at different resolutions and on different principles is a topic requiring considerable further research. Satellite-based high wind speed retrievals are difficult to obtain, and the errors associated with the measurements are difficult to characterize for three main reasons discussed in a 2010 *Monthly Weather Review* article by Quilfen et al. and outlined below.

1. *Saturation at high wind speed.* Using aircraft data, Fernandez et al. (2006) found that active measurements of the radar cross section (RCS) can saturate with increasing wind speed, and the RCS may even decrease beyond a given wind speed value. This behavior depends on the instrument characteristics, such as the wavelength, polarization, and incidence angle. The high incidence angles and horizontal polarization of the QuikSCAT scatterometer make it more sensitive at high winds than the ASCAT instrument. Passive radiometric measurements of brightness temperatures is not affected as much by the issue of saturation, but the coarser resolution of satellite-based radiometers is not ideal for high wind speed retrievals.
2. *Calibration/validation issues.* The usual specifications for a satellite instrument designed to observe winds are an accuracy of 2 m s^{-1} and 20 degrees for winds up to 24 m s^{-1}. Very few reliable reference data are available beyond that threshold, equivalent to storm-force winds, for calibration of the instruments' geophysical model functions (GMFs), so errors are likely to be greater. For example, the ASCAT GMF has been shown to overestimate the RCS sensitivity at high wind speeds when compared with QuikSCAT high winds, resulting in underestimation of high winds. This is common knowledge among operational forecasters and is often mentioned in the *Mariner Weather Log* publications. On the other hand, although the QuikSCAT winds are sometimes considered a "reference" measurement—as the GMF has been tuned to passive radiometer measurements whose sensitivity to high winds does not saturate—comparisons with well-calibrated platform measurements have shown that they can, in fact, overestimate winds [with a mean positive bias of 3 m s^{-1} above 25 m s^{-1}, as shown by Cardone et al. (2009)]. Validation of the *OceanSat-2* scatterometer to refine its GMF in high wind speeds is currently underway.
3. *Representativeness of the Geophysical Model Function (GMF).* Satellite sensors that are sensitive to surface turbulent wind stress are calibrated to equivalent neutral winds due to the paucity of stress observations, and the effect of atmospheric stability on the GMF is effectively ignored. Other geophysical effects, such as the surface current and the degree of development of the sea state can also impact the surface stress and modify the measured RCS for a given neutral wind speed, but are not

Table S1. Information on wave buoys shown in Fig. 5 showing buoy positions, values of peak periods, and significant wave heights at the time of the maximum peak period observed from 1D spectra.

Buoy (WMO code or other ID)	Institute	Country	Longitude	Latitude	Maximum peak period (s)	H_s at time of peak period (m)
13,130	Puertos del Estado	Spain	-15.82	28.18	20	3
62,024	Puertos del Estado	Spain	-3.03	43.63	25	4.5
62,025	Puertos del Estado	Spain	-6.17	43.73	20	4.4
62,047	CEFAS[1]	UK	-7.06	56.06	25	3.4
62,048	CEFAS[1]	UK	-7.91	57.29	25	4
62,069	Ifremer	France	-4.97	48.29	23.5	4.4
62,083	Puertos del Estado	Spain	-9.22	43.48	22.2	6.6
62,085	Puertos del Estado	Spain	-6.97	36.48	22.2	2.9
Belmullet	Marine Institute	Ireland	-10.15	54.23	21.1	5.7
Oléron	SHOM	France	-1.59	46.11	23.5	3.8
Ponta Delgada	UAC-M[2]	Portugal	-25.72	37.73	21.1	2.7

[1] Centre for Environment, Fisheries and Aquaculture Science

[2] Universidade dos Açores, CLIMAAT-MacSIMAR

accounted for in the GMF. In stormy conditions, the sea maturity is very variable and the retrieved satellite winds can have errors of several meters per second as a result.

DATA.

Wave buoy processing. 1D spectra from the buoys were averaged over periods of either 2 or 3 h, depending on the noise level of the spectra. The spectra were partitioned using the 1D algorithm proposed by Portilla et al. (in a 2009 *Journal of Atmospheric and Oceanic Technology* article), which removes partitions above a certain frequency threshold, those with low total energy, those spanning few spectral bins, and those that fall between two other peaks that both have higher energy. The swell was identified using the ratio between the peak energy of a partition and that of a Pierson-Moskovitz spectrum at the same frequency. When this ratio is less than one, the partition is considered to be swell rather than wind-sea. The peak at the lowest frequency was taken as that emanating from the Quirin storm, as directional information was not available for most buoys.

WW3 model runs. The numerical model hindcasts were run on a quasiglobal grid, with a resolution of 0.5° in latitude (79.5°S to 79.5°N) and longitude (–180°E to 180°W). The model numerical schemes are described by Tolman (2008), including third-order schemes with garden-sprinkler correction, and subgrid island and iceberg blocking. The parameterizations combine the Discrete Interaction Approximation (Hasselmann et al. 1985), a wind-wave–generation term adapted from Janssen [1991, see Ardhuin et al. (2010) for the adjustment details], and dissipation parameterizations (Ardhuin et al. 2010). The model uses 24 directions and 32 frequencies (0.037–0.72 Hz). In the cases shown here, the hindcast was run from 1 December 2010 until 28 February 2011, with output every 3 h. Forcing was provided by NCEP analysis winds corrected globally by a 10% factor.

Seismic station analysis. Seismic noise at different frequencies has been correlated with different types of generation mechanisms due to waves. Waves interacting with the shore, for example, produce a modest primary peak, at the same frequency as the waves, typically in the 0.05–0.1 Hz frequency band. Nonlinear interaction between waves having similar frequencies and moving in almost opposite directions produces pressure perturbations at the ocean surface that excite seismic Rayleigh waves in the ocean and crust waveguide with frequencies double that of the interacting waves. This phenomenon yields a stronger secondary peak in the 0.1–0.3 Hz frequency band. This type of secondary microseismic generation can be found inside storms. It can also result from wave reflection at the shore or from the encounter of two swells or a swell and a wind-sea that may come from the same or from different sources. Here, the 3-hourly and daily medians of the vertical ground variance were calculated from filtered spectra for the February 2011 study and 15-yr climatology, respectively.