Phenomenal sea states and swell radiation: a comprehensive analysis of the 12-16 February 2011 North Atlantic storm

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Abstract: Several storms with hurricane-force winds cross the North Atlantic every year. Observing the dynamics of these storms is a particular challenge because in situ observations are scarce in the middle of the ocean, and opportunities to validate remote sensing techniques are rare. As a result of sensor saturation and/or reduction in SNR, satellite observations of wind speeds above hurricane force (32.7 m/s), significant wave heights above 15 m and wave periods above 18 s are considered to have low levels of confidence. Additionally, numerical models, both of the ocean and of the atmosphere, are generally believed to underestimate the severity of such extreme events. In February 2011 the north Atlantic storm Quirin produced the largest sea state ever recorded by a satellite altimeter, with a significant wave height of 20.1 m.. Observations from wave buoys and seismometers show swell periods of 21-25 s along the western coast of Europe, from the Canary Islands to the Hebrides and as far west as Greenland. These exceptionally long swells were also captured by Envisat's Synthetic Aperture Radar observations in wave mode with a peak wavelength of 700m, corresponding to a 22 s peak period.

We intend to present for this particular storm a comprehensive view of wave energy and periods using information from satellites, in situ buoys, and land-based seismometers. The relationship with the storm power can be analyzed using hindcasts of the wave fields produced by the WAVE-WATCH III model. It shows that, despite known limitations of both model and observations, we obtain a fairly coherent description of the wave field that can be comprehensively related to the Quirin storm characteristics. The fact that the model is capable of reproducing the wave properties well in extreme conditions requires further validation, but also encourages us to use it as a tool to study the ocean energy fluxes due to this particular storm, and to investigate the mechanisms leading to such conditions.

Hurricane-force winds in extra-tropical storm Quirin (11/16 February 2011)

Figure 1*: Annual average frequency of storms with hurricane-force winds based on the NOAA Ocean Prediction Center 6-hourly surface pressure analyses and QuikSCAT winds. Average was calculated based on data from September though May 2002-2009. The track of Quirin at 6-hourly intervals from 00Z on 13th February till 18Z on 14th February is overplotted. The size of the circle symbol at each time step reflects the effective fetch of the storm and the colour represents the maximum wind speed.*

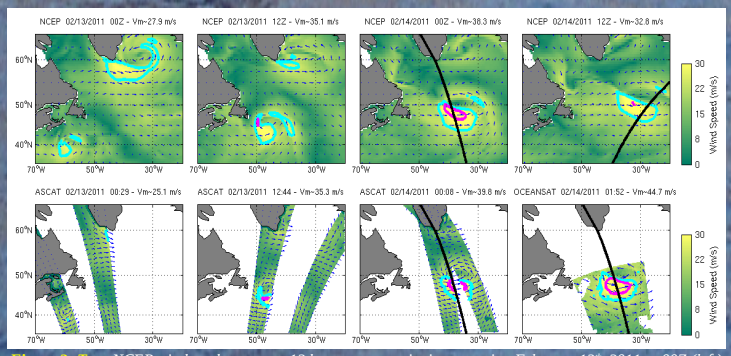

Figure 2: Top*: NCEP wind analyses every 12 hours at synoptic times starting February 13th 2011 at 00Z (left), ending February 14th 2011 at 12Z (right). Two storms are active on the 13rd , **Paoloni** southeast of Greenland and **Quirin** traveling south of Newfoundland. Estimated maximum wind speed for Quirin is given for each synoptic time.* ***Bottom****: Scatterometer winds available for that time period: ASCAT winds (three left panels) at times close to the three first synoptic times, and OCEANSAT winds (right panel) at 01:52 UTC 02/14/2011.*
The contours of storm-force (cyan, V>=24.5 m/s) and hurricane-force (magenta, V>=32.7 m/s) winds are displayed. Two black lines give the location of one Envisat and one Jason-2 altimeter passes crossing the storm force winds.

…p to12 hurricane-force …irin storm was exceptional …nd radiated swells have …o maximum winds blowing … at least 24 hrs, to the very large extent of storm-force winds (24.5 m/s) that cover about 500,000 km², and to the increased fetch duration that results from the resonance between the group speed of the largest waves and the storm translation speed.

We observe at first glance good agreement between the NCEP and the ASCAT scatterometer winds, as well as concerning the estimated maximum wind speed as concerning the extent of storm and hurricane-force winds. Further comparison with altimeter winds, that are used as an independent reference (Quilfen et al., 2011), is given in figure 3.

Phenomenal sea-states estimated from altimeters, SAR, buoys, seismometers, and WaveWatch-III model

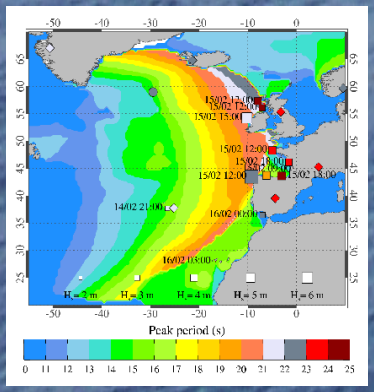

Figure 4: *Peak periods as calculated by the Wavewatch III model, from SAR, wave buoy, and seismometers observations. The background shows the model values at 12:00 on the 15, as the longest swells were encroaching on the west coast of Scotland. The square symbols represent the wave buoy data, the size of the symbol signifying the SWH at the time of the maximum peak period and the color signifying the value of the peak period at this time. Beside each symbol is printed the time of arrival of the maximum peak period at each buoy. The circle gives the location of the SAR observations and diamond symbols represent the seismic stations, also colored according to the peak periods observed.*

References:

F. Ardhuin, E. Stutzmann, M. Schimmel, and A. Mangeney, 2011: Ocean wave sources of seismic noise. J. Geophys. Res., 116:C09004, doi: 10.1029/2011JC006952.

Y. Quilfen, D. Vandemark, B. Chapron, H. Feng, and J. Sienkiewicz. 2011: Estimating gale to hurricane-force winds using the satellite altimeter. J. Atmos. Ocean Technol., 28,453-458, doi: 10.1175/JTECH-D-10-05000.1

The figure 3 (right) displays Significant Wave Height (SWH) values recorded by the various operational altimeters on February 13th and 14th . On the 13th , the former Paolini hurricane-force storm generated storm-force seas with SWH over 10m in a large part of the Atlantic Ocean. Late on the same day, the Envisat altimeter measured a maximum SWH value of 18.1 m where Quirin was blowing hurricane-force winds (black square, top left panel). The day after, Quirin had moved east-north-east and an area of hurricane-force seas (SWH >= 14m) developed over a wide part of the north Atlantic ocean with a maximum registered at 20.1 m by the Jason-2 altimeter (right panels). The latter SWH value, as well as the associated satellite maximum wind speed value, are in the same range as the 100-year return values in the Atlantic ocean (Caires et al., 2005). The middle panels display SWH values for the Envisat (left) and Jason-2 (right) altimeters. It features the exceptional length over which these phenomenal sea states developed. As measured by Jason-2, storm-force seas developed over more than 1000 km and hurricane-force seas developed over more than 500 km. SWH values computed from the WaveWatch-III model are superimposed to show that increasing the NCEP winds, used to drive the model, by 10% results in a fairly good agreement with altimeter's SWH. The NCEP wind underestimation is illustrated on bottom panels by comparison with different satellite sensors winds. The Jason-2 altimeter and radiometer wind profiles agree well and give some confidence in the satellite retrieved storm and hurricane force wind radii (Quilfen et al., 2011). However, significance of such estimated maximum winds still requires more thorough investigation.

The figure 4 (left) represents the peak period of the swell field as computed by the WaveWatch-III model, superimposed with in-situ observations (buoys, seismometers) and satellite SAR observations. The longest swells were encroaching on the west coast of Scotland with peak periods equal or larger than 22 s. The maximum reached over 23 s for two buoys off the west coast of France and up to 25 s for some of the more exposed buoys: two located near the Outer Hebrides and one to the north of Bilbao, Spain. The values observed for this particular storm represent exceptional conditions, as further shown from seismometers measurements analysis. Long records of seismic data are available at several stations around the Atlantic basin and can be used to quantify the relative importance of major events such as Quirin. Indeed, the analysis of the frequency content of secondary seismic noise provides information on the longest periods generated by a given storm (Ardhuin et al., 2011). Analyzing data from the french Saint Sauveur seismic station, located over 300 km from the coast, the swell field from Quirin produced a displacement of 0.38 microns, which is the most energetic event in the last 2 years. Only 5 events surpassed a threshold of 0.3 microns between January 2000 and December 2010.

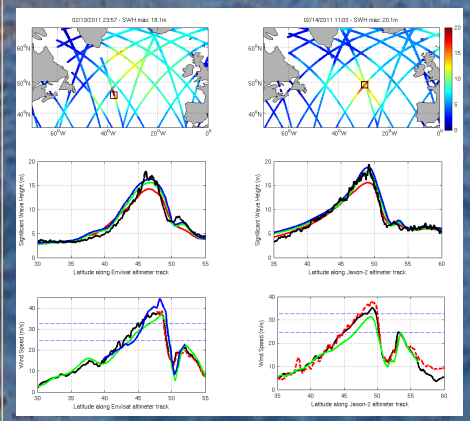

Figure 3. Top panels*: altimeter significant wave heights (SWH) estimated along the tracks of 4 altimeters (Geosat, Jason-1 and -2, Envisat) on February 13th 2011 (left panel) and February 14th 2011 (right panel). The black square in the left (right) panel indicates the location of the most extreme sea states measured during these two days by the Envisat (Jason-2) altimeter, respectively.*

Middle panels*: Altimeter (black) SWH values estimated along the Envisat (left) and Jason-2 (right) tracks, and computed from the WaveWatch-3 numerical model and ECMWF (red), NCEP (green) and NCEP+10% (blue) winds.*

Bottom panels: *Wind speed interpolated on the Envisat (left) and Jason-2 (right) altimeter tracks. For both panels, black (green) lines give the altimeter (NCEP) wind speed. For the left (right) panel, the dashed red line gives the ASCAT scatterometer (Jason-2 radiometer) wind speed. On the left panel, the blue line gives the Oceansat-2 wind speed. The two dashed blue lines give the limits of storm force winds (V>=24.5 m/s) and hurricane-force winds (V>=32.7 m/s).*

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