Storm waves sharpening in the Agulhas current: satellite observations and modeling

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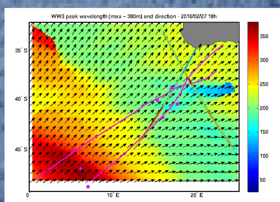
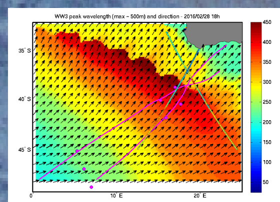
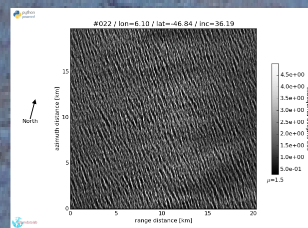
Abstract: *Strong ocean currents can modify the height and shape of ocean waves, possibly causing extreme sea states in particular conditions. The risk of extreme waves is a known hazard in the shipping routes crossing some of the main current systems. Modeling surface current interactions in standard wave numerical models is an active area of research that benefits from the increased availability and accuracy of satellite observations. We report a typical case of a swell system propagating in the Agulhas current, using wind and sea state measurements from several satellites, jointly with state of art analytical and numerical modeling of wave/current interactions. In particular, Synthetic Aperture Radar and altimeter measurements are used to show the evolution of the swell train and resulting extreme waves. A ray tracing analysis shows that the significant wave height variability at scales less than 100 km is well associated with the current vorticity patterns. Predictions of the WAVEWATCH-III numerical model in a version (1/6°) that accounts for wave / current interactions are consistent with observations, although their effects are under-predicted in the present configuration. From altimeter measurements, very large significant wave height gradients are systematically associated with the current patterns that cause a strong focusing and trapping of waves over surface currents gradients.*

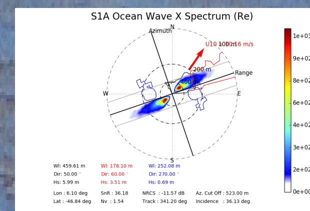
Observation field





The WaveWatch-3 peak wavelength (m) and direction fields show a swell system propagating away from the storm that generated it . Timely Sentinel-1 wave-mode images (magenta circles) and Jason-2 altimeter tracks (Hs values scaled to fit the wavelength scale) recorded its evolution. The two magenta lines give the envelope of swells converging towards the Grand Agulhas current as computed with a ray tracing analysis.





The incident swell is characterized using the Sentinel-1 SAR wave-mode image sea surface roughness and wave spectrum, 2016.02.27 18:36, at the southwestern corner of the region, wavelength estimated at ~ 460 m

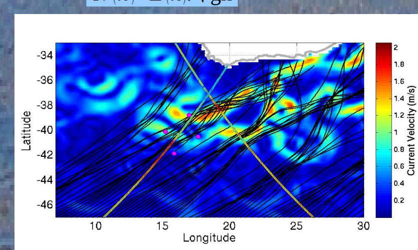
Refraction and advection of the incident swell system by the surface current: ray tracing analysis

Different processes interplay to explain the wave spectrum evolution in presence of currents. The main factors are: refraction of waves that is a function of the current vorticity to the wave group velocity; advection of wave action by the current vector; local influence of the wind vector relatively to the current vector. Following Dysthe (2001) and Kudryavtsev et al. (2017) equations of the wave train evolution can be written as follows:

$d\,x/\mathrm{dt}=\dfrac{\partial\Omega}{\partial k}$ $\quad$ $\mathrm{d\,k/dt}=-\dfrac{\partial\Omega}{\partial x}$ $\quad$ $\mathrm{dN/dt=0}$ $\quad$ where $\Omega(\mathrm{k,x})=\sqrt{\mathrm{gk}}+\mathrm{k}.u$ is the dispersion function and $N(k)=\mathrm{E}(k)/\sqrt{\mathrm{gk}}$ the wave action

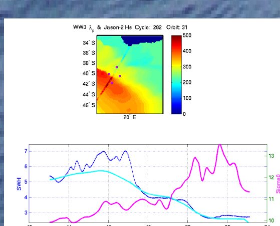
Forward ray-tracing is done by solving for the two first equations iteratively in time, and gives the swell trajectories, i.e. rays ***x***, and the wave number ***k***. As shown on the figure beside, one result is swell focusing and trapping in the Grand Agulhas current in areas called "caustics". As results are very sensitive to small changes in surface current curvature (Agulhas meanders), wave / current interactions modeling requires accurate mapping of surface currents.

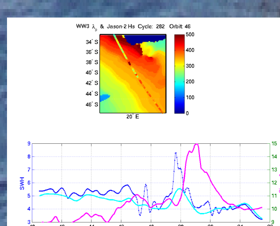
For estimation of the transformed two-dimensional spectrum in every point of the domain where the swell is propagating, a backward ray-tracing technique is used, following the wave action conservation law (eq. 3) . The 2-D energy spectrum of the incoming swell Eo is specified as a gaussian function, and different width parameters have been specified (see results in the right figure below).



Swell rays in the Globcurrent surface currents vortivity, 2016.02.28. Two Jason-2 altimeter tracks are shown, whose Hs values are scaled to fit the current scale.

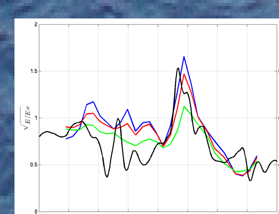
Wave energy and shape transformation by surface currents



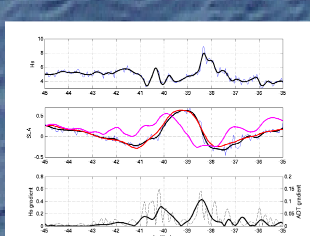


Top: WW3 peak wavelength (m) on 28th (left) and 29th (right), and re-scaled altimeter Hs. Bottom: Jason-2 (blue) and WW3 (cyan) Hs (m, left axis), and Jason-2 (sigma0, dB, right axis) .

The Jason-2 altimeter measurements show large Hs increase when the swell front crossed the Grand Agulhas branch, where ray-tracing analysis shows swell trapping to form a caustic. Computed energy increase, right figure, agrees remarkably well with altimeter data, showing also secondary peaks induced by other current patterns. As shown in left figures, WW3 predictions underestimate wave/current interactions. Whether it comes from too coarse current field resolution (1/4°) or from the WW3 model itself is subject to current research.



Jason-2 Hs (black line, m) on 29th, and energy increase (left axis) calculated along the altimeter track for three spectrum widths: narrow (blue), medium (red), wide (green).

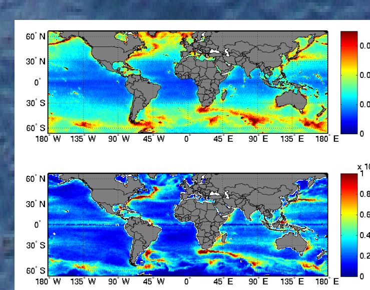


Jason-2 Hs, SLA, and ADT on 29th Top panel: Hs raw (blue) and filtered (black) values; middle panel: Jason-2 raw (blue) and filtered (black) SLA values, and altimeter mean daily SLA field (1/4°) spatially interpolated (red), and Mercator model hourly SLA field (1/12°) spatially interpolated (magenta); bottom panel: absolute values of Hs (dashed) and ADT (solid) gradients

Hs variability at scales < 100 km are shown to be associated with current variability at similar scales. The presented results show that large Hs gradients at ~ 10 km scale are systematically associated with current gradients, and verify the relationship:

$$\nabla Hs \approx \frac{1}{2} Hs\, \nabla U / Cg$$

It gives exciting perspectives for better understanding and mapping of the surface current signature in the wave field, to improve extreme sea state predictions. It will rely on high quality observations of waves and surface currents from modern altimeters and SAR, SWOT and CFOSAT missions..



4 year mean (2012-2016) computed using the constellation of 4 altimeters, onto a .5°x.5° grid, of top: normalized gradient of significant wave height (m / 10km); bottom: absolute value of surface current vorticity (s⁻¹).

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