EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

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Satellite Oceanography: Ocean surface waves
Figure 1. Future role of wave models as an essential coupling component for ocean-atmosphere-carbon-cycle models developed in the context of the World Climate and Global Change programs.
Sea-spray aerosol particles enriched in organic material are possibly generated when the air-sea interface is bursting.
Examples: IR images with overlapped altimeter tracks


Altimeter Significant Wave heights
Model approach: based on self-similarity of wave generation (Kudryavtsev et al., 2015)

Self-similarity:

\[ \tilde{e} = c_e \tilde{x}^p; \]
\[ \tilde{\omega}_p \equiv \alpha = c_\alpha \tilde{x}^q, \]
\[ g^{-2} \omega^5 E(\omega) = B(\omega / \omega_p, \alpha), \]
\[ c_e, p \text{ and } c_\alpha, q \text{ are "constants"}, \]
\[ \tilde{x} = \lambda g / u_{10} \text{ is dimensionless fetch}, \]
\[ \tilde{e} = eg^2 / u_{10}^4 \text{ is dimensionless energy}, \]
\[ \tilde{\omega}_p = \omega_p u_{10} / g \text{ is dimensionless spectral peak frequency}. \]

Wave spectrum and energy source obey the energy balance equation:
\[ \partial E / \partial t + c_g \partial E / \partial x = S \equiv S_w + S_D + S_N. \]

Using growth rate laws, this energy balance helps consistently define the energy source:
\[ S / c_g = \partial E / \partial x \]
\[ = q c^{1/q}_\alpha \alpha^{1-1/q} (gu_{10}^{-2}) E^{\prime}_{\omega} \]
\[ (S / c_g)_{\omega} = (\partial \omega_p / \partial x) E^{\prime\prime}_{\omega} \]
\[ = q c^{1/q}_\alpha \alpha^{1-1/q} (g^2 u^{-3}) E^{\prime\prime}_{\omega}. \]
Right sector (wave enhancement):

\[
\left( \frac{\alpha_L}{\alpha_0} \right)^{\frac{1}{q}} \left[ 1 - (1 + q)^{-1} \alpha_L / \alpha_T \right] = 1 - \frac{\tilde{L}_{cr}}{\tilde{L}} \\
\frac{\tilde{\epsilon}_L}{\tilde{\epsilon}_0} = \left( \frac{\alpha_L}{\alpha_0} \right)^{p/q}
\]

Left sector (wave diminution):

\[
\left( \frac{\alpha_L}{\alpha_0} \right)^{\frac{1}{q}} \left[ 1 - (1 + q)^{-1} \alpha_L / \alpha_T \right] = 1 \\
\frac{\tilde{\epsilon}_L}{\tilde{\epsilon}_0} = \left( \frac{\alpha_L}{\alpha_0} \right)^{p/q}
\]

where \( \alpha_L, \tilde{\epsilon}_L \) - inverse wave age and energy, respectively;

\( \alpha_0 = c_a \tilde{L}^p; \tilde{\epsilon}_0 = c_e (\alpha_0 / c_a)^{p/q} \) - expected wave parameters (not accounting for TC movement);

\( c_a, c_e, p, q \) - "standard" coefficients in JONSWAP parameterizations;

\( \alpha_T = u / 2V \) - wave age of trapped waves, \( u \) - wind speed, \( V \) - translation speed;

\( \tilde{L}_{cr} = -c_a \frac{q}{1+q} \alpha_T^{1/q} \) - critical fetch;

\( \tilde{L} \) - dimensionless fetch.
Identifying swell field source

- Linear theory of swell propagation:
  - in open ocean, far from islands
  - swell propagates at group speed, \( C_g = \frac{gT_p}{4\pi} \)
  - along great circles of direction \( \theta_p \)
  → compensate for sparse and track-based sampling of the swell partitions.
- Refocusing of the swell partitions
  → converge in space and time to regions systematically (96% collocations) coinciding with Storms events
Great-Circle propagation determined by the detected wavelength direction and related group velocity
Example of Sentinel-1 A Acquisition
2015 Sept 8. From 16:40 to 16:46 UTC
Example of Sentinel-1 A Acquisition
2015 Sept 8. From 16:40 to 16:46 UTC

From 2015/09/08 16:40:00 to 2015/09/08 16:46:00
Example of Sentinel-1 A Acquisition
2015 Sept 8. From 16:40 to 16:46 UTC

Jimena: wave generation
Example of retro-propagated Sentinel-1 A Swell Measurements. Data acquired the 2015 Sept 8 16:40 to 16:46 UTC

3 tracks corresponding to the 3 hurricanes Kilo, Ignacio and Jimena (from left to right) are overplotted. Color code is time.
Example of retro-propagated Sentinel-1 A Swell Measurements. Data acquired the 2015 Sept 8 16:40 to 16:46 UTC.

Refocalisation area is found along the Jimena track the 6th of September. On the right hand side of the track.
Back-propagation coupled with hurricane track should allow us to analyse the swell properties during the cyclones lifetime with respect to:
- Hurricanes speed
- Hurricanes wind speed
- Hurricanes radius of maximum wind speed
- Hurricanes phases (decay/increase)

Different wavelengths are observed depending on the swell direction of propagation.
Kilo wave generation: trapping fetch
Kilo wave generation: intensity peak
Stormwatch + wavetracker

RED: ENVISAT ASAR
GREEN: ENVISAT RA2
YELLOW: JASON ALTIMETER
Fireworks
Example of seismic - SAR synergy

Storm location
From seismic (blue bands)

And location from SAR (colors)
S1 Imagette #016 from first track over Pacific

#016 / lon=-118.54 / lat=-5.90 / inc=38.24
Long swell 800m
Regular swell 400m
Short swell 200m
Wind sea 150m
Synthetic Aperture Radar (SAR)

- Side-looking
- Active antenna that transmits/receives electromagnetic radiation in VV, HH, VH, HV pol. (C-band 5.6 cm)
- Records both signal amplitude and phase
- Works both day and night
- Can “see” through clouds
A decisive breakthrough: the cross-spectral analysis

- Based on ERS Image products, G. Engen and H. Johnsen (NORUT) proposed the use of Single Look Complex (SLC) products, to separate looks (SAR products at 2 different epoch times) and to using cross-spectra methodology (Engen et al., 1995, TGARS)

**Improvements:**
- Direct uncorrelated noise removal
- Hands-off resolved wave propagation ambiguity
SAR Wave algorithm philosophy

**Inversion Model:**

\[
\chi(k, \tau) = [T(k)]^2 S_{\text{wave}}(k)e^{i\phi k \xi} + \chi^{\text{nl}}(k; U_{10})
\]

**where**

\[
\chi^{\text{nl}}(k; U_{10}); \text{ from look-up table}
\]

\[
T(k) = \left\{ik_y \frac{R}{V} \omega_k + 2k_{\text{rad}}k_x \nabla \sigma \right\}G(\theta)
\]

\[
G(\theta) \equiv \frac{k_x}{|k|} \sin \theta + i \cos \theta
\]

\[
\nabla \sigma \equiv \frac{\Delta \sigma_{\text{mod}}}{\Delta \theta} \frac{1}{\sigma_{\text{mod}}} \frac{1}{2k_{\text{rad}} \cos \theta}
\]
Sentinel-1 VV roughness SAR image over Brest and the Iroise, France (2014-09-01)

Microbreaking and surface waves – the gearbox of the air-sea interaction "engine"
Lisbon from Sentinel-2A MSI 05/05/2017 & 27/09/16

Costa da Caparica on 27/09/2016
Waves across the Pacific revisited

« A comparison with meteorological events in the Southern Ocean would be far more meaningful if such Observations could be made at a time when a weather satellite is in suitable orbit » (Munk et al. 1963)

Data sources:
- NDBC buoys
- ENVISAT ASAR
- Altimeters (+propagation models)

SAR is the swell instrument
- SAR wave mode products
Observed propagation of 13s to 17s swell from July 8 to July 20, 2004

- 6 hour time step
- Wavelength from 300 to 450m
- Wave period from 13 to 17 seconds
The interaction of (peak) waves on deep water with spatially varying currents may be described by ray theory, with the wave amplitudes determined by the conservation of wave action.

\[
\frac{\partial \theta}{\partial t} + \Omega(x, \bar{\nabla} \theta) = 0, \quad \Omega = \tilde{\Omega} + k \cdot \bar{U}.
\]

\[
\frac{d\bar{x}}{dt} = \Omega_k(\bar{x}, \bar{k}), \quad \frac{d\bar{k}}{dt} = -\bar{\nabla} \Omega(\bar{x}, \bar{k}),
\]
Local swell direction
As white segment
Sentinel-2 image, January 4th 2016. The stripes results from the specific instrumentation and configuration of S2 multi-channel detectors. It enables to derive 2D directional wave spectra for wavelength range > 20 m, and to also assess the local dispersion relation.
Sentinel-2 MSI Features = New Opportunities to image ocean surface waves and dispersion properties

12 clusters (detectors), 13 lines of sensors (bands) in each

Odd clusters are looking forward, even clusters are looking backward, spectral channel sensors also have relative displacement

Parallax angle between the two alternating odd and even clusters of detectors results in a shift along track of approximately 46 km (maximum).

Inter-band measurement parallax amounts to a maximum along track displacement of approximately 14 km.
Left: S2 B04 (665nm) Imagette off the Californian coast used to extract 2D wave spectrum

Bottom: (a) In situ buoy wave spectrum (b) Sentinel-2 wave spectrum (c) Comparison of S2 and buoy spectra.


SST field, January 04, 2016, 12:20 GMT. Overlaid, color-coded wave energy derived from S2 imagettes.
Set of selected S2 imagettes overlaid on the altimeter geostrophic current. Imagettes are color-coded according to the derived wave energy level.
Wave-rays of an incoming 75 degree (counter clockwise from the East) 250 m swell at -45 degree latitude,
Geostrophic surface current velocity corresponding to January 4th 2016, and SWH anomalies, along the altimeter tracks, from a 250 km moving average along the altimeter track.