Satellite information on the ocean surface: Scatterometer, Altimeter and SMOS

5 March 2020

Giovanna De Chiara (presented by Lars Isaksen)

with contributions from Saleh Abdalla, Magdalena Balmaseda, Hao Zou, Tony McNally, Patrick Laloyaux, Cristina Lupu, Nicolas Reul (Ifremer)
Outline

Scatterometer Winds
✓ The importance of scatterometer wind observations
✓ Scatterometer principles
✓ Data usage at ECMWF and their impact
✓ How we can improve usage and impact

Altimeter Wind, Waves, Sea Surface Height
✓ Altimeter principles
✓ Use of altimeter data in the wave and ocean models
✓ Altimeter data impacts

SMOS winds
✓ Principles
✓ Database available
✓ TC examples
Why is Scatterometer important?

The scatterometer measures the ocean surface winds (ocean wind vector).

Ocean surface winds:
- affect the full range of ocean movement
- modulate air-sea exchanges of heat, momentum, gases, and particulates
- direct impact on human activities

Wide daily coverage of ocean surface winds
Ex: 1 day of ASCAT-A data

Wind observations below 850 hPa
FSOI values relative quantities (in %)

[Horanyi et al., 2013]
A Scatterometer is an active microwave instrument (side-looking radar)
- Day and night acquisition
- Not affected by clouds

The return signal, backscatter ($\sigma_0$ sigma-nought), is sensitive to:
- Surface wind (ocean)
- Soil moisture (land)
- Ice age (ice)

Scatterometer was originally designed to measure ocean wind vectors:
- Measurements sensitive to the ocean-surface roughness due to capillary gravity waves generated by local wind conditions (surface stress)
- Observations from different look angles: wind direction
Scatterometer

Bragg scattering occurs from the ocean capillary-gravity waves (cm-range) that are in resonance with the microwaves

The amount of backscatter depends on:
✓ The frequency and polarization of the emitted wave
  ▪ C-band (5.3 GHz): $\lambda \sim 5.7$ cm
  ▪ Ku-band (13.5 GHz): $\lambda \sim 2.1$ cm

Backscatter highly depends on:
✓ Incidence angle (largest sensitivity to changes in winds between 30 and 60 deg)
✓ Wind speed
✓ Relative direction between the surface wind and look angle
C- band scatterometers (Fan beam)

Used on European platforms (1991 onwards):
✓ SCAT on ERS-1, ERS-2 by ESA
✓ ASCAT on Metop-A, Metop-B, Metop-C by EUMETSAT
  ▪ f~5.3 GHz (λ~5.7 cm)
  ▪ Two sets of three antennas
  ▪ $\sigma_0$ on a 12.5 km or 25 km grid

Pros and cons:
✓ Hardly affected by rain
✓ High quality wind direction (especially ASCAT)
✓ Two nearly opposite wind solutions
✓ Rather narrow swath:
  ▪ ERS-1/2: 500 km
  ▪ ASCAT-A/B/C: 2x550 km
Ku-band scatterometers (Rotating pencil beam)

Used on US, Japanese, Indian and Chinese platforms:
- NSCAT, QuikSCAT, SeaWinds by NASA (and Japan)
- Oceansat, ScatSAT by ISRO
- Haiyang-2A/B by China
- RapidSCAT on the ISS

- \( f \approx 13.5 \text{ GHz} (\lambda \approx 2.1 \text{ cm}) \)
- Two rotating pencil-beams (4 look angles)

Pros and cons:
- Up to four wind solutions (rank-1 most often the correct one)
- Broad swath (1,800 km)
- Affected by rain
- Problems regarding wind direction:
  - azimuth diversity not good in centre of swath
  - outer 200 km only sensed by one beam.
Dependency of the backscatter on... Wind speed
Dependency of the backscatter on... Wind direction

- Asymmetry Upwind – Downwind (particularly small)
- Asymmetry Upwind – Crosswind

Using multiple observations from different azimuth angles improves the accuracy of the derived wind direction.
Dependency of the backscatter on... Wind direction

Backscatter response depends on the relative angle between the pulse and capillary wave direction (wind direction)

C-band SCAT geometry
How can we relate backscatter to wind speed and direction?

Measurements sensitive to the **ocean-surface roughness** due to capillary gravity waves generated by local wind conditions (**surface stress**)

- The relationship is determined empirically
  - Ideally collocate with **surface stress** observations
  - In practice with buoy and 10m model winds

\[
\sigma_0 = GMF(U_{10N}, \phi, \theta, p, \lambda)
\]

- \(U_{10N}\): equivalent neutral wind speed
- \(\phi\): wind direction w.r.t. beam pointing
- \(\theta\): incidence angle
- \(p\): radar beam polarization
- \(\lambda\): microwave wavelength

**Geophysical model functions (GMF) families**
- C-band: **CMOD** (currently CMOD5.N)
- Ku-band: NSCAT, QSCAT
Wind Direction Ambiguity removal

✓ Measurements affected by noise
✓ Each wind vector cell has usually two possible solutions for wind direction and speed.
✓ The correct solution is determined by using NWP forecasts and wind field spatial patterns.
Operational usage of scatterometer winds at ECMWF

Currently testing: Oceansat-3 (Oct ‘18), HY-2B (Nov ‘18)

Reanalysis usage of Scatterometer winds
## Scatterometer assimilation strategy

<table>
<thead>
<tr>
<th></th>
<th>C-band</th>
<th>Ku-Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>25 km</td>
<td>50 km</td>
</tr>
<tr>
<td>( \sigma_0 ) bias correction</td>
<td>( \checkmark )</td>
<td>-</td>
</tr>
<tr>
<td>Wind Inversion</td>
<td>ECMWF</td>
<td>KNMI</td>
</tr>
<tr>
<td>Wind Speed bias correction</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>QC – Sea Ice check</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>Rain flag check</td>
<td>-</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>Thinning</td>
<td>100 km</td>
<td>-</td>
</tr>
<tr>
<td>Maximum wind speed assimilated</td>
<td>35 m/s</td>
<td>25 m/s</td>
</tr>
<tr>
<td>Assigned observation error</td>
<td>1.5 m/s</td>
<td>2 m/s</td>
</tr>
<tr>
<td>4D-Var</td>
<td>2 solutions</td>
<td>1 solution</td>
</tr>
<tr>
<td>Assimilated as 10m eq. neutral wind (U&amp;V)</td>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
</tbody>
</table>
TC QC issues

TC KILO – 2015090812   ASCAT-A Observations

Less observations due to:
- Thinning
- VarQC
Observation weight: VarQC & Huber Norm

Comparing Observation weights:
Gaussian + flat (VarQC): more weight in the middle of the distribution
Huber Norm: more weight on the edges (to data with large departure)
TC QC issues

TC KILO – 2015090812  ASCAT-A Observations

Less observations due to:
- Thinning
- VarQC
Background Departure

ASCAT-A Wind speed O-B

Wind speed bias in the Tropics: also due to Ocean Current?

Mean ocean currents from OCEAN5 from 20181101 to 20190129
ASCAT sees a calm ocean and underestimates the atmospheric wind speed.

ASCAT sees a rough ocean and overestimates the atmospheric wind speed.
Coupled Data Assimilation (CDA)

In the **coupled assimilation** the SST shows a clear and immediate impact on SST of the storm winds mixing the ocean (cold wake) and the storm’s arrival in the Caribbean damping the usual pronounced diurnal cycle in the SST.

Irma/Jose with ocean – atmosphere DA coupling
Coupled Data Assimilation (CDA)

What is the role of ASCAT (and JASON) in the coupled data assimilation during Irma and Jose?

In CDA ASCAT gives SST information below Tropical Cyclones.

Quantifying heat exchange between the storm and ocean surface is an important factor in predicting the intensification / de-intensification of Tropical Cyclones.

ASCAT sees through the cloud and rain (IR/MW cannot) and informs the coupled analysis of the surface roughening below the storm, in turn influencing the ocean mixing and thus the SST!
Impact of scatterometer winds ...on the ocean parameters

Coupled Data Assimilation (CDA)

Focus on a specific weather event:
- TC Phailin
- Bay of Bengal
- formed on the 4th October 2013
- Argo probe with high-frequency measurements

Temperature measurements at 40-meter depth

Impact of scatterometer surface wind data in the ECMWF coupled assimilation system
P. Laloyaux, J-N Thépaut and D. Dee. MWR, 2016
Impact of scatterometer winds ...on the ocean parameters

TC Phailin

Wind measurements from scatterometers (ascending pass, 11 October 2013)

Ocean temperature analysis at 40-meter depth (scatterometer data are assimilated)

Coupled analysis with Scatterometer winds is closer to the observations with a stronger cold wake
Impact of Scatterometer on Ocean Temperature

NO SCATT - SCATT / Sea Surface Temperature / Jan-Jun 2014

No SCATT – SCATT

NO SCATT - SCATT / Ocean Potential Temperature Equatorial Section / Jan-Jun 2014
Impact of Scatterometer on Ocean Salinity

NO SCATT - SCATT / Sea Surface Salinity / Jan-Jun 2014

NO SCATT - SCATT / Ocean Salinity Equatorial Section / Jan-Jun 2014

No SCATT – SCATT
Scatterometer Concluding remarks

Scatterometer observations widely used in NWP
✓ Ocean wind vectors
✓ Positive impact on analysis and the forecast
✓ Global scale and extreme events
✓ Impact on Atmospheric, Ocean and Wave model

ECMWF has a long experience with scatterometry
✓ Available continuously from 1991 onwards:
✓ GMF development
✓ Monitoring, validation, assimilation, re-calibration

On-going efforts to improve usage and impact
✓ Improve QC
✓ Adapt observation errors, thinning, super-obbing
✓ Include dependency from other geophysical quantities (i.e. Ocean Currents)
✓ Assessment in coupled system

Use in the Reanalysis
✓ ERS1/2 and QuikSCAT in ERA-Interim
✓ ASCAT-B and ASCAT-A reprocessed products used in ERA5
 ✓ Radar altimeter is a nadir looking instrument.

 ✓ Specular reflection.

 ✓ Electromagnetic wave bands used in altimeters:
   - Primary:
     • Ku-band (~ 2.5 cm) – ERS-1/2, Envisat, Jason-1/2/3, Sentinel-3
     • Ka-band (~ 0.8 cm) – SARAL/AltiKa (only example)
   - Secondary:
     • C-band (~ 5.5 cm) – Jason-1/2/3, Topex, Sentinel-3
     • S-band (~ 9.0 cm) – Envisat

 ✓ Main parameters measured by an altimeter:
   - Significant wave height (*wave model*)
   - Wind speed (*used for verification*)
   - Sea surface height (*ocean model*)
How Altimeter Works

Height = $\Delta t / 2 \times c$

emitted signal

returned signal

flat surface

rough surface

power

time
Significant Wave Height (SWH)

- SWH is the mean height of highest 1/3 of the surface ocean waves
- Higher SWH → smaller slope of waveform leading edge
- Errors are mainly due to waveform retracking (algorithm) and instrument characterisation.
Surface wind speed

- Backscatter is related to water surface Mean Square Slope (MSS)
- MSS can be related to wind speed
- Stronger wind $\rightarrow$ higher MSS $\rightarrow$ smaller backscatter
- Errors are mainly due to algorithm assumptions, waveform retracking (algorithm), unaccounted-for attenuation & backscatter.
✓ Time delay → sea surface height

✓ Radar signal attenuation due to the atmosphere is caused by:
  - Water vapour impact: ~ 10’s cm.
  - Dry air impact: ~ 2.0 m

Correction made using radiometer and model data
Operational Assimilation of SWH (wave model)

Assimilation method for SWH data:

- ✓ Data are subjected to a quality control process (inc. super-obbing).
- ✓ Bias correction is applied.
- ✓ Simple optimum interpolation (OI) scheme on SWH.
- ✓ The SWH analysis increments ➔ wave spectrum adjustments…

Sentinel-3A/B (Q2, 2020), CFOSAT (~Q1, 2021), Sentinel-6 (~Q4, 2021).
Altimeter SWH data available from five satellites – nice synergy!
Plot shows random error reduction of SWH compared to model only.

All the five altimeter instruments listed below

- Cryosat-2 (CS2)+
- SARAL AltiKa (SA)+
- Jason-2 (J2)
- Sentinel-3A&B
- Sentinel-3A
- Sentinel-3B
Impact of one additional altimeter on the SWH analysis

[CS & J2] - [J2 only]
Altimeter data in the Ocean Model

The altimeter measures the range which can be used to determine Sea Surface Height (SSH)

SLA = Sea Level Anomaly

Assimilated in the ocean model

From sea level observation it is possible to infer information on the vertical density structure in the ocean
Sea surface height observations from satellite (i.e. AVISO L3 along track SLA data) are assimilated in ECMWF ocean reanalysis (ORAS4, ORAP5 and ORAS5) system using NEMOVAR.

Satellite data includes observations from ERS-1/2, Envisat, Jason-2/3 and Topex/Poseidon, Altika, HY-2A, Cryosat-2 (Sentinel-3 in the future).

The SLA along track data has very high spatial resolution → Features in the data which the model can not represent.

This can be dealt with in different ways:

- Inflate the observation error to account for non representativeness of the “real” world in the assimilation system
- Construction of “superobs” by averaging
- Thinning
Before the assimilation, a thinning or supersembling scheme is normally implemented to avoid over sampling of the satellite observations.
Impact of SLA assimilation

The figure illustrates the impact of assimilating altimeter SLA data, with time correlation compared to altimeter SL products. The graphs depict depth profiles of potential temperature with varying RMSE for different models and assimilation methods.

- **CNTL**: Baseline model
- **NEMOVAR TS**: Model with additional TS assimilation
- **ORAS4 (TS+Alti)**: Model incorporating TS and altimeter data

The graphs show improvements in RMSE with the incorporation of altimeter data, highlighting the effectiveness of SLA assimilation in enhancing model accuracy.

**Key Points**:
- Reduction in RMSE at various depths
- Enhanced correlation with altimeter SL products
- Comparison of models with and without altimeter assimilation
ECMWF has a long experience with altimetry in the wave model

✓ Available continuously from 1993 onwards:
  - ERS1/2, Envisat, Jason1/2, Cryosat, Saral…
  - Now with new missions: Jason-3, Sentinel-3,…

Altimeter wind and wave data are used for:

✓ Data assimilation
✓ Error estimation
✓ Use in reanalyses (assimilation and validation)
✓ Long term assessments & climate studies
✓ Monitoring of model performance (inc. model resolution) & Assessment of model changes

Altimeter sea level anomaly:

✓ Use for assimilation and validation
✓ Significant impact for surface and sub-surface ocean
✓ Importance for reanalysis and climate studies
✓ Uncertainty from the ensemble members potentially used for model error
SMOS (Soil Moisture and Ocean Salinity) was launched in November 2009.

The SMOS synthetic antenna consists of 69 radiometer elements operating at L-band (frequency ~1.4 GHz, $\lambda=21$ cm) and distributed along three equally spaced arms, resulting in a planar Y-shaped structure.

In aperture synthesis radiometers, a TB image is formed through Fourier synthesis from the cross correlations between simultaneous signals obtained from pairs of antenna elements.

Multi-angular images of the brightness temperature are obtained over a large swath width (1200 km), with a spatial resolution varying within the swath from 30 km to about 80 km, and with a revisit time of less than 3 days.
SMOS wind data

- L-band is less affected by rain, spray and atmospheric effects than higher mw frequencies (C-band, Ku-band)

- There is no saturation at high wind speed like for radars

- Sea foam, generated by breaking waves which mainly depends on surface wind strength and sea state development, increases the microwave ocean emissivity
Most of the increased surface whitening at & above hurricane force (>33 m/s) is principally induced by the increased streaks coverage.

Whitecap coverage is found ~constant above Hurricane force ~4  [Holthuijsen et al. JGR 2012]
Because of the small ratio of raindrop size to the SMOS electromagnetic wavelength (~21 cm), scattering by rain is almost negligible at L-band, even at the high rain rates experienced in hurricanes.
Increase of the microwave ocean emissivity with wind speed ↔ surface foam change impacts

This information can be used to retrieve the surface wind speed in Hurricanes:

Principle of **the Step Frequency Microwave Radiometer** (SFMR)

C-band: => Use multi-frequency C-band channels to separate wind from rain effects

**NOAA’s primary airborne sensor for measuring Tropical Cyclone surface wind speeds since 30 year** (Ulhorn et al., 2003, 2007).
Detect the useful TC & ETC events in SMOS data: Example of EMILIA

East Pacific TC: EMILIA-2012/07

Position of the Storm center at the time of SMOS Acquisition
Tasks 2: Detect the useful TC & ETC events in SMOS data: Example of EMILIA
Tasks 2: Detect the useful TC & ETC events in SMOS data: Example of EMILIA

East Pacific TC: EMILIA-2012/07

SMOS Wind speed [m/s]-2012/07/11 at -01:37 UTC
Tasks 2: Detect the useful TC & ETC events in SMOS data: Example of EMILIA

East Pacific TC: EMILIA-2012/07

SMOS Wind speed [m/s] - 2012/07/12 at 13:27 UTC
Tasks 2: Detect the useful TC & ETC events in SMOS data: Example of EMILIA
A subset of 320 SMOS swath intercepts with TCs over 2010-2015, free of Radio Frequency Interferences and with pixel distances >150 km from the coast are selected.


[https://smos-storm.oceandatalab.com](https://smos-storm.oceandatalab.com)
The SMOS brightness temperature signal ($\Delta T_B$) is clearly associated with the passage of Tropical Cyclones

- Correlations between L-band Tb increase with TC intensity from Cat 1 to Cat 5 was demonstrated

- L-band observations provide a first non-atmosphere corrupted view of the ocean surface in extreme conditions=> wind speed retrieval with ~5m/s accuracy

- A complete storm database as been generated for the SMOS mission archive: TC & ETC 2010-now available at [http://www.smosstorm.org/](http://www.smosstorm.org/)
Thank you for your attention
Any questions?