smos+ storms

support to science element

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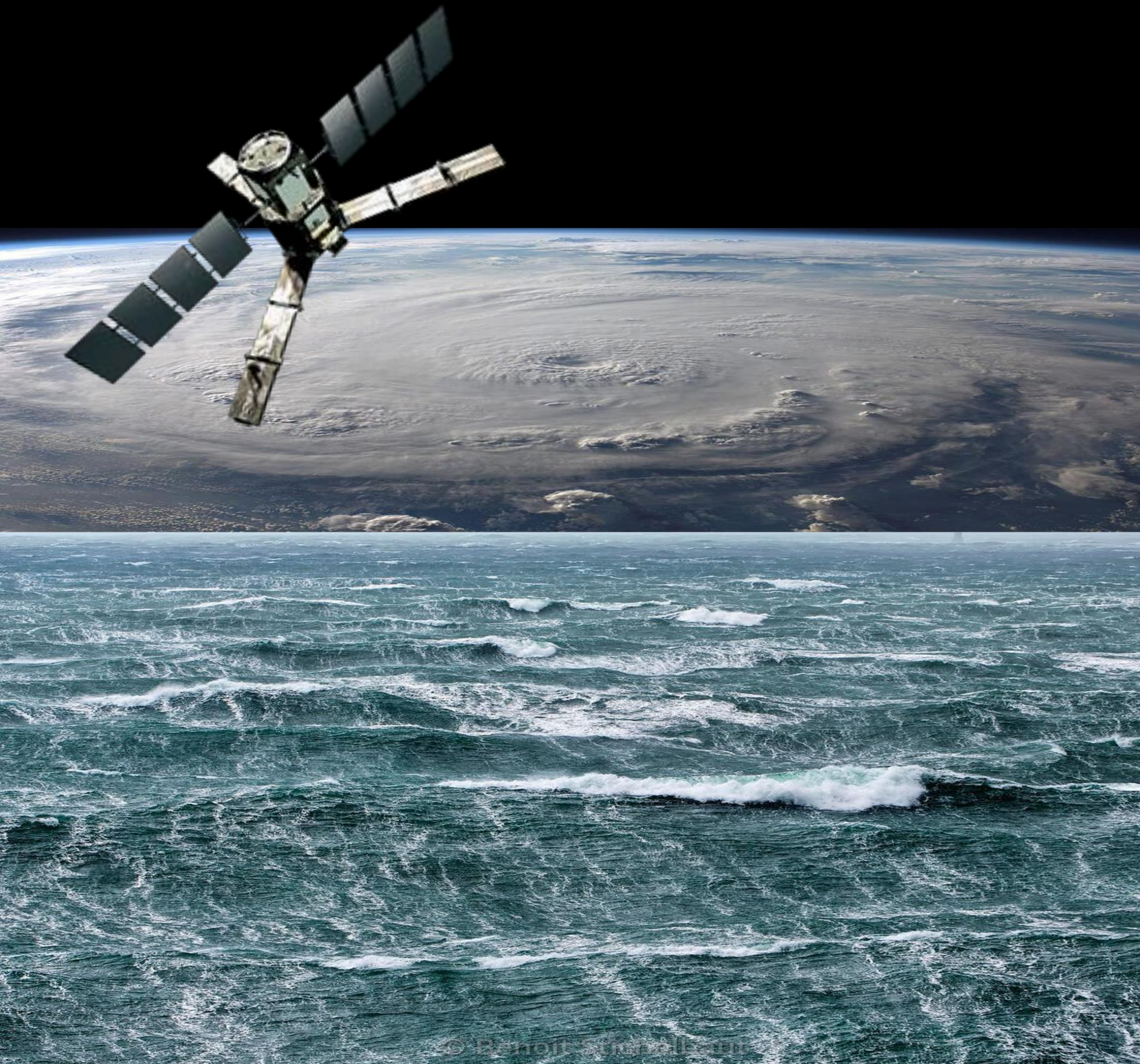
SMOS+STORM Evolution
Project Brochure



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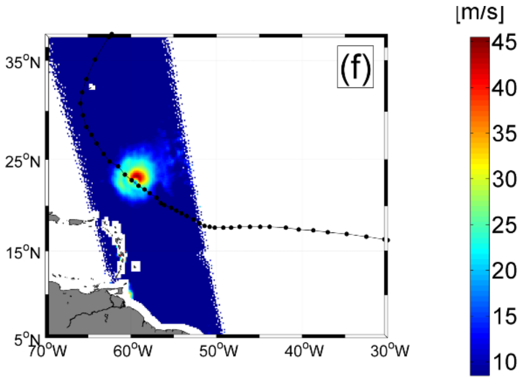
Inferring Sea Surface Wind Speed in Storms from radio-brightness Temperature contrasts measured at L-band

The European Space Agency Soil Moisture and Ocean Salinity (SMOS) mission provides multi-angular L-band (electromagnetic frequency of 1.4 GHz) brightness temperature images of the Earth. Because upwelling radiation at 1.4 GHz is significantly less affected by rain and atmospheric effects than at higher microwave frequencies, the SMOS measurements offer unique opportunities to complement existing ocean satellite high wind observations in tropical cyclones and severe weather that are often erroneous in such conditions. The physical basis for surface wind speed retrievals in extreme weather from passive microwave radiometers involves emission from a rough, foam-covered sea surface. The sea state within tropical cyclones and extra-tropical storms is complex (see picture above) and varies according to the storm sectors, but in the region where the wind speeds exceed tropical storm force (>17 m/s ~34 knots), breaking waves generate extensive foam patches and deep bubble layers. Foam patches are associated with high emissivity at microwave frequencies. The foam horizontal coverage and thickness extension as wind speed increases towards hurricane force and the associated emissivity increase are the basic principles for wind retrievals from radiometers. As first demonstrated in Reul et al., 2012 using SMOS data, this information can be used as a means of remotely measuring surface wind speeds in hurricanes from data acquired by orbiting L-band passive sensors.



Surface Wind speed (m/s) estimated from SMOS data during the passage of Category 4 hurricane IGOR in the tropical Atlantic in September 2010.

The SMOS+STORM Evolution project

The **main objective** of this project which started in April 2014 is **to exploit the identified capability of SMOS satellite Brightness Temperatures acquired at L-band to monitor surface wind speed and interfacial properties beneath Tropical Cyclones and severe Extra Tropical storms.**

The Specific Objectives of the project were to:

1) **Improve and consolidate our theoretical understanding of the L-band signal response** and physical properties that can be inferred over the ocean **during the passage of Tropical Cyclone (TC) and Extra-Tropical Cyclone (ETC) systems.**

2) **Consolidate, evolve, implement and validate the Geophysical Model Function (GMF) and retrieval algorithm for high wind speed conditions.**

3) **Systematically produce and validate L-band SMOS high wind speed products** with uncertainty estimates/flags for ETC and TC conditions **over the entire SMOS Mission archive**.

Team

The work has been conducted by a consortium between

L'Institut Français pour la Recherche et l'Exploitation de la MER, Laboratory of Oceanography from Space, France
Nicolas Reul (project leader), Bertrand Chapron, Y. Quifen, Alexis Mouche, Jean Francois Piolle
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The Satellite Imagery Applications Group of the UK Metoffice,

4) Develop, implement and validate **new blended multi-mission oceanic wind speed products** with uncertainty estimates incorporating SMOS+STORM Evolution L-Band measurements at high-wind speeds for TC and ETC events.

5) Generate **a global database of TC and ETC events** over the ocean surface and characterize each event **using diverse Earth Observation and other observations in synergy.**

6) Improve our understanding and parameterization of ocean-atmosphere coupling and mixed-layer dynamics for ETC and TC cases.

7) **Demonstrate the utility, performance and impact of SMOS+** STORM Evolution **products on TC and ETC prediction systems** in the context of maritime applications.

James Cotton & Peter Francis

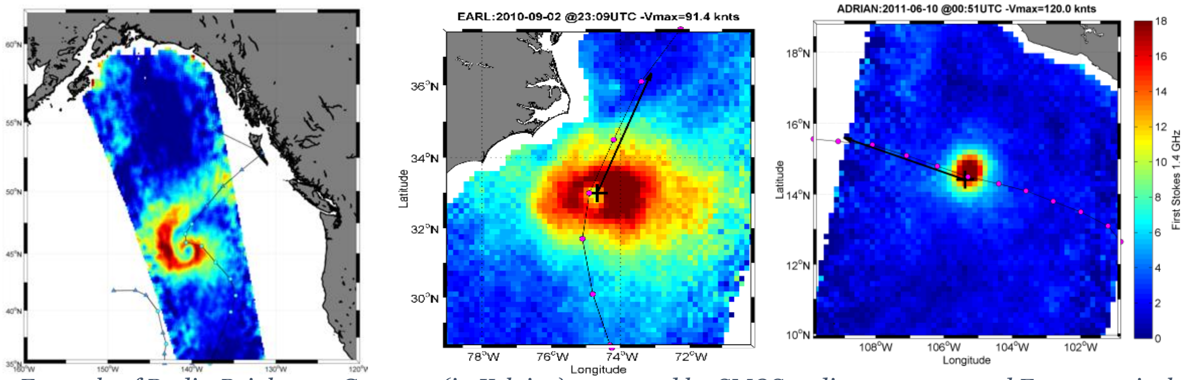
The French R&D company ***OceanDataLab***
Fabrice Collard, Jospeh Tenerelli

with external support from:

ЛАБОРАТОРИЯ СПУТНИКОВОЙ ОКЕАНОГРАФИИ

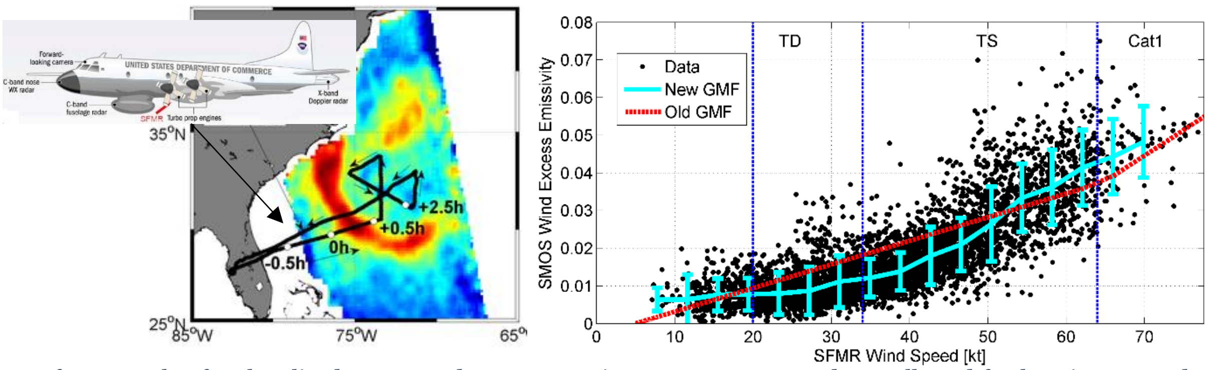
The ***Russian Satellite Oceanography Laboratory*** (**SOLab**).
ELisabetha Zabolotskikh & Vladimir Kudryavtsev

A new Geophysical Model Function and a refined retrieval Algorithm



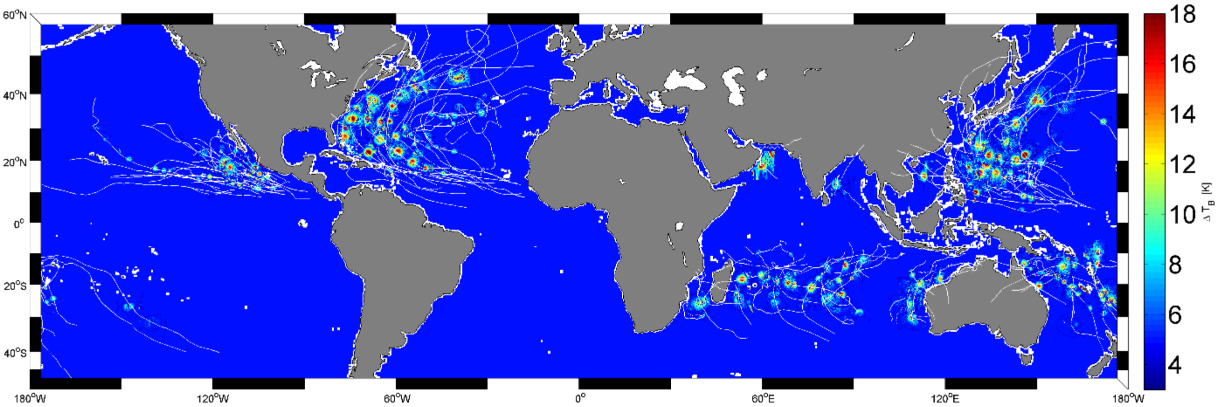
Example of Radio-Brightness Contrast (in Kelvins) measured by SMOS radiometer over and Extra-tropical Storms (left), a Category 2 (middle) and Category 4 hurricane (right) on the Saffir-Simpson scale.

A large ensemble of radio-brightness contrasts measured by SMOS in Tropical Cyclones have been collected over the first four years (2010-2014) of the mission operation and when feasible, compared to co-localized wind speed data inferred from the Step-Frequency Microwave Radiometer (SFMR) operated onboard NOAA hurricane hunter aircrafts. A new Geophysical Model Function was found (Reul et al., 2016) quadratically relating the L-band radio-brightness contrast to the surface wind. The wind speed retrieval algorithm from SMOS data has been refined to better correct/flag the retrieved wind modulus for error sources such as Radio Frequency Interference contaminations, land-sea contamination, sea surface salinity uncertainties, across- and along- track biases, sea-ice impact, ...



Left: Example of co-localized SMOS and NOAA Hurricane Hunter SFMR data collected for hurricane Sandy in 2012. Right: new GMF relating SMOS L-band radio-brightness contrasts and SFMR surface wind speed for an ensemble of TC in the North Atlantic and Gulf of Mexico (Reul et al., 2016).

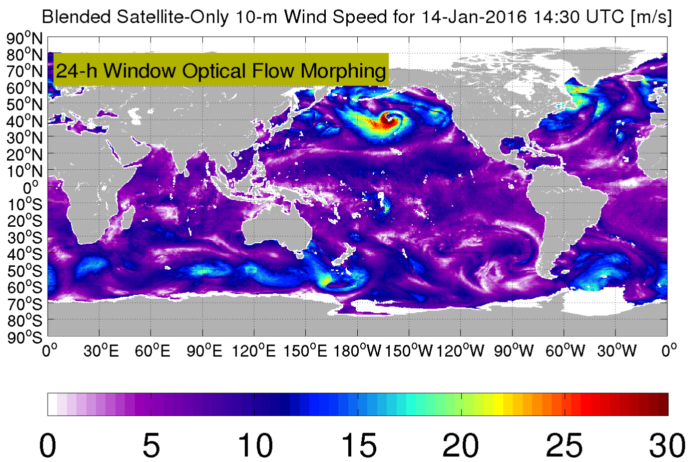
The SMOS-STORM Database



Ensemble of Tropical Cyclone intercepts with SMOS satellite Swath between mid-2010 and end 2015

Surface wind speed products have been systematically generated for both SMOS and SMAP sensors using the Reul et al, 2016 algorithm to cover all tropical cyclones intercepted by both instruments from mid-2010 to end 2016. This database has been complemented by the wind field derived from AMSR-2 TC intercepts using the algorithm of Zabolotskikh et al. (2013, 2014, 2015, and 2016) to cover all TC worldwide during the period from mid-2012 to end 2016. All SMOS, SMAP and AMSR2 wind data used in this study form the so-called “SMOS-STORM” project database. All swath data, a storm per storm catalog and user manuals were made freely available in Netcdf format at [http://www.smosstorm.org/.](http://www.smosstorm.org/)

Blending multiple-source wind data including SMOS, SMAP and AMSR-2 new products

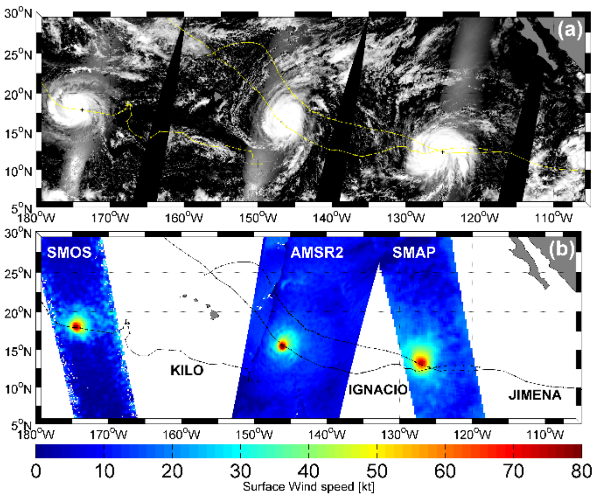


Left: Artistic views of the ESA SMOS (top), NASA SMAP (bottom left) and JAXA AMSR-2 (bottom right) satellite missions. Right: example of a global blended wind fields generated using SMOS, SMAP and AMSR-2 beyond others sources (ASCAT, SSM/I, WindSAT, ect...) and an optical flow morphing method.

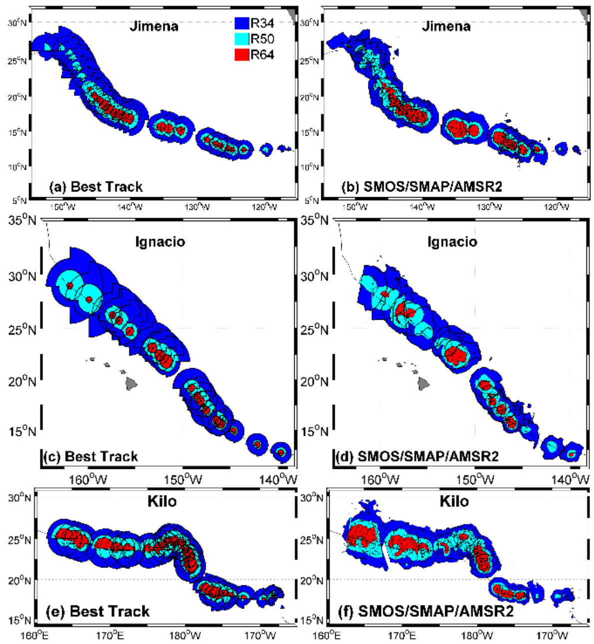
A novel approach applying an optical flow algorithm for combining non-synoptic satellite wind speeds to create synoptic wind maps is to propagate the satellite wind speeds in time using propagation fields derived from the evolution of the wind in some atmospheric model (such as ECMWF). The propagation fields are derived using the model wind speed fields. This is based on the assumption that storm structure evolution is continuous in time. We used L-band wind data from, SMOS and SMAP together with C-band (and other) measurements from AMSR-2 on GCOM-W1; METOP A/B, WindSat, SSMI F16/F17, GMI and RAPIDSCAT to create global maps of wind speed at some fixed time from satellite measurements distributed over many hours. We morphed all satellite swaths within a symmetric window (24 hours) about the desired analysis time to the analysis time to allow construction of complete global wind speed maps from available satellite data. We used 3-hourly ECMWF analysis and forecasts wind speed fields and derive the flow field using an optical flow algorithm applied to the wind speed.

Blend wind validation was performed using data that are not used in the morphing techniques. Results show that the method allows us to morph to distances of 600-650 km. In the vicinity of TC's there are challenges as the optical flow technique is not giving the same displacement compared to BESTRACK. For that reason, we are now using the BESTTRACK to estimate the deformation field in the TC vicinity.

Synergies SMOS, SMAP and AMSR-2: a new generation of Tropical Cyclone Size measurements from space



(a) NASA's Terra satellite visible imaging of Hurricanes Kilo (left), Ignacio (center), and Jimena (right) lined up across the Central and Eastern Pacific Ocean on August 29 at 22:25 UTC (b) Surface wind speed (in knots) retrieved from SMOS (29 August at 11:17 UTC) and SMAP (30 August 2015 at 2:15 UTC) radiometer data as their swathes intercepted hurricanes Kilo (left), Ignacio (middle) and Jimena (right), respectively. The three tropical cyclones were intercepted as they were developing into categories 3-4 on the Saffir-Simpson scale. Hurricane best tracks are indicated by yellow and black dotted curves in (a) and (b), respectively.

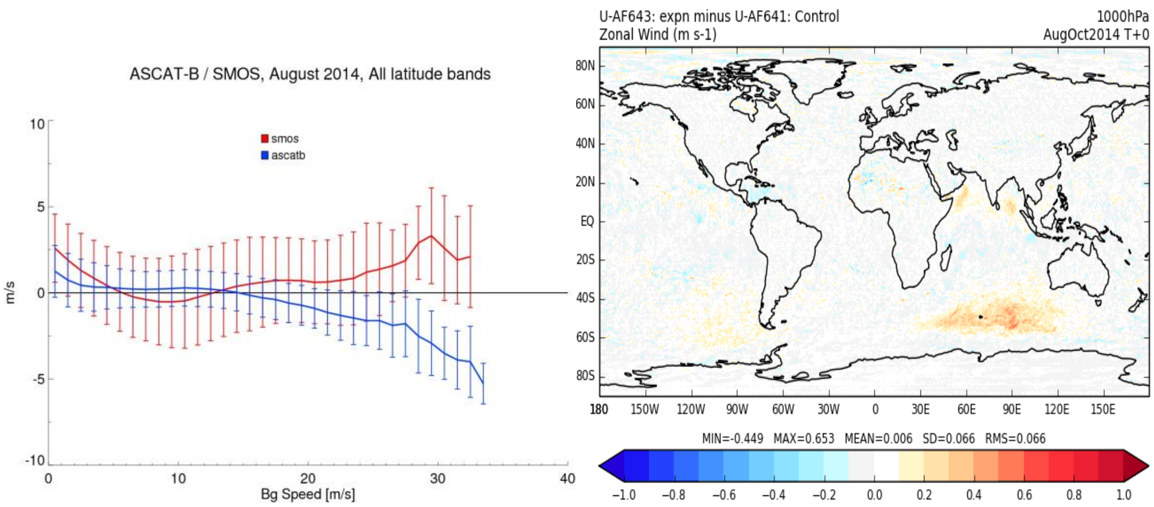


Wind radii estimates from the Best Track (left) and from the merged SMOS/SMAP/AMSR-2 surface wind data set (right) retrieved along the tracks of hurricane Jimena (a & b), Ignacio (c & d) and Kilo (e & f). All wind radii estimates are shown at every satellite intercepts with 34-, 50-, and 64-kt wind radii being displayed in blue, cyan, and red, respectively.

Wind radii estimates in Tropical Cyclones are crucial to help determine the TC wind structure for the production of effective warnings and to constrain initial conditions for a number of applications. As illustrated in Reul et al. (2017), data from these sensors collected over 2010-2015 are shown to provide reliable estimates of the gale-force (34-kt), damaging (50-kt), and destructive winds (64-kt), within the Best-track wind radii uncertainty. Combined, and further associated with other available observations, these measurements can now provide regular quantitative and complementary surface wind information of interest for operational TC forecasting operations.

Assimilation of SMOS L-band Wind Speeds: Impact on Met Office Global NWP and Tropical Cyclone Predictions

Ocean surface winds from scatterometers and microwave radiometers are routinely assimilated in Met Office numerical weather prediction (NWP) for wind speeds below 25 m/s. The new generation of L-band sensors such as ESA's Soil Moisture Ocean Salinity (SMOS) mission have the capability to provide complimentary information on the wind speed under high wind and rain conditions. In this study we evaluated the utility and impact of SMOS wind speeds within NWP. Observation minus background (O-B) departure statistics were used to investigate the SMOS error characteristics, evaluate the use of quality control flags, and develop a quality control method. Observation errors and spatial correlation distances were estimated using a statistical method. Observing system experiments were performed across several seasons to diagnose the impact of SMOS on NWP forecasts and analyses, including tropical cyclone (TC) predictions. The quality of SMOS retrievals appears reduced in the presence of sea ice contamination, strong river plumes, and RFI contamination. The quality flags show some skill in discriminating poor data but RFI remains a problem. SMOS wind retrievals have reduced sensitivity at low-moderate winds speeds, but above 15 m/s SMOS winds are faster than the model and differ considerably from ASCAT which has a large negative bias but lower variance. SMOS observation error correlations are small for distances greater than 50-km and diagnosed observation errors of 1.3 m/s are inflated to 2.25 m/s to ensure suitable weighting relative to ASCAT. We find that the assimilation of SMOS acts to strengthen the mid-latitude westerlies in the South Indian Ocean, as well as the Somali Jet. The number of SMOS observations assimilated is small at around 700 per 6-hour cycle, but some detriment is seen in the background fit to the scatterometer winds. The impact of SMOS on TC predictions is sensitive to the use of the TC pressure initialisation scheme which is confirmed to have a large beneficial impact on intensity. The assimilation of SMOS results in a small increase in intensity (+5% vorticity at T+0) leading to a reduction in pressure and wind errors (-0.4 mb, -0.8 knots at T+0), but cannot replicate the impact from the initialisation scheme. The impact on TC track errors is rather mixed. Changes in global forecast RMS scores are mostly neutral and any statistically significant impacts are sensitive to the use of TC initialisation. In the case of Hurricane Kilo, we find that when the storm radius is small SMOS is unable to resolve the storm structure and many observations are rejected by quality control. However when the storm radius is large and SMOS can resolve the eye, the analysed and short-range forecast central pressures are closer to best-track. The challenge in using wind speed excess emissivity from SMOS and other low resolution L-/C-band radiometers is to extract the useful information on intensity whilst preserving storm structure.



(Left): SMOS and ASCAT-B statistics as a function of model background wind speed. Mean O-B speed bias shown by the solid lines, with error bars representing +/- 1 standard deviation. Data from August 2014 after applying quality flag checks and background check ((SMOS only). ASCAT data are 25-km product from KNMI. Only bins containing more than 10 observations have been plotted. (Right)

An International workshop on measuring high wind speeds over the ocean

To present and discuss the findings of the SMOS+STORM project, ESA, Met Office and Ifremer co-organized a 3 days 'International Workshop on Measuring High Wind Speeds over the Ocean that was held at the Met Office headquarters in the cathedral city of Exeter (UK) on 15-17 November 2016. The workshop was open to scientists, forecasters and engineers with an interest in extreme wind speeds. It reviewed scientific progress made using L-band and C-band satellite microwave radiometers that are now producing innovative data products that estimate extreme wind speeds in tropical cyclone conditions. It also showcase examples from ESA SMOS, NASA SMAP and JAXA AMSR-2 (amongst others), highlighting retrieval approaches, characteristics of the data products, their strengths and shortfalls, and example applications. Applications involving data from Metop ASCAT, HY-2 and cross-polarised C-band SAR satellite and airborne radar data were as well presented and discussed. Validation approaches for high wind retrievals and results were presented and discussed while addressing the generic issue of spatial resolution and representation between different classes of instrument (scatterometer, altimeter, SAR imager and passive microwave radiometers).

The workshop also reviewed applications from Tropical Cyclone operation centres and assimilation approaches using satellite wind products, test results from Numerical Weather and wave Prediction models, tropical cyclone modelling/forecasting, the potential use of new microwave winds on hurricane forecasting benches, scientific applications, and the ocean response to extreme wind events. Finally, time was dedicated to explore the future generation of extreme wind measurements from space including the use of GNSS-R (e.gg NASA CYGNSS, TDS), cross-polarized scatterometry (RadarSat, Sentinel-1 A & B, airborne), and L-band and Cband microwave radiometers, and how they can be used in synergy. The proceeding of the workshop can be accessed here.

Scientific Roadmap

Near Real Time surface wind speed from SMOS

At the "International Workshop on Measuring High Wind Speeds over the Ocean" that was held at the UK MetOffice in Exeter (UK) on 15-17 November 2016, the user community has expressed its interest for a systematic data generation of the innovative L-Band measurements from passive sensors (e.g. SMOS, SMAP) in near real time for TC and ETC prediction and monitoring systems in the context of maritime applications and Numerical Weather Prediction operational centres activities. Results presented during the workshop highlighted the added value that L-Band observations could bring in the context of the available datasets.

Considering the above mentioned interest from users for L-band surface wind speed over ocean, a future step is to implement an operational service to provide, in near real time (NRT) within less than 5 hours from aquisition, surface wind speed over ocean derived from SMOS brightness temperature measurements.

Co-variation between active and passive sensors

Investigation on the relative sensitivity of active and passive EO sensors to the response of the ocean surface in storms shall be carried to better understand their complementarities. In particular, this could be done following :

1. Access and process all co-localized aircraft and active/passive satellite data for further analysis.

2. Assess the higher sensitivity of L-Band passive sensors with respect to active C-Band radar in co-polarization.

3. Evaluate the sensitivity difference between L-Band passive sensors and active C-Band radar in cross-polarization.

4. Assess the spatial resolution impact using Sentinel-1 data to compute NRCS at the resolution of the passive sensors and future MeTop scatterometer.

Project Publications:

Zabolotskikh et al (2014). GCOM-W1 AMSR2 and MetOp-A ASCAT wind speeds for the extratropical cyclones over the North Atlantic. *Remote Sensing Of Environment*, 147, 89-98. http://doi.org/10.1016/j.rse.2014.02.016

Reul et al (2014). Multisensor observations of the Amazon-Orinoco River plume interactions with hurricanes. *Journal of Geophysical Research-oceans*, 119(12), 8271-8295. http://doi.org/10.1002/2014JC010107

Zabolotskikh et al. (2015). New Possibilities for Geophysical Parameter Retrievals Opened by GCOM-W1 AMSR2. *IEEE journal of selected topics in applied earth observations and remote sensing*, 99, 1-14.: http://doi.org/10.1109/JSTARS.2015.2416514

Kudryavtsev et al. (2015). A simplified wave enhancement criterion for moving extreme events. *Journal of Geophysical Research-oceans*, 120(11), 7538-7558.: http://doi.org/10.1002/2015JC011284 ,

Reul et al. (2016). A revised L-band radio-brightness sensitivity to extreme winds under tropical cyclones: The 5 year SMOS-Storm database. *Remote Sensing of Environment*, 180, 274-291 http:/doi.org/10.1016/j.rse.2016.03.011

Mecklenburg S et al (2016). ESA's Soil Moisture and Ocean Salinity mission: From science to operational applications. *Remote Sensing Of Environment*, 180, 3-18. http://doi.org/10.1016/j.rse.2015.12.025

Zabolotskikh et al. (2016). Geophysical Model Function for the AMSR2 C-Band Wind Excess Emissivity at High Winds. *IEEE Geoscience and Remote Sensing Letters*, 13(1), 78-81. http://doi.org/10.1109/LGRS.2015.2497463

Yueh et al. (2016). SMAP L-Band Passive Microwave Observations of Ocean Surface Wind during Severe Storms. *IEEE Transactions On Geoscience And Remote Sensing*, 54(12), 7339-7350. http://doi.org/10.1109/TGRS.2016.2600239

Reul et al. (2017), A new generation of Tropical Cyclone Size measurements from space, *Bulletin of the American Meteorological Society*, http://doi.org/10.1175/BAMS-D-15-00291.1

Cotton et al. (2017), Assimilation of SMOS L-band Wind Speeds: Impact on Met Office Global NWP and Tropical Cyclone Predictions, in revision for *Quarterly Journal of the Royal Meteorological Society*.

Mouche et al. (2017) Combined Co- and Cross-Polarized SAR Measurements Under Extreme Wind Conditions. *IEEE Transactions on Geoscience and Remote Sensing*, http://doi.org/10.1109/TGRS.2017.2732508