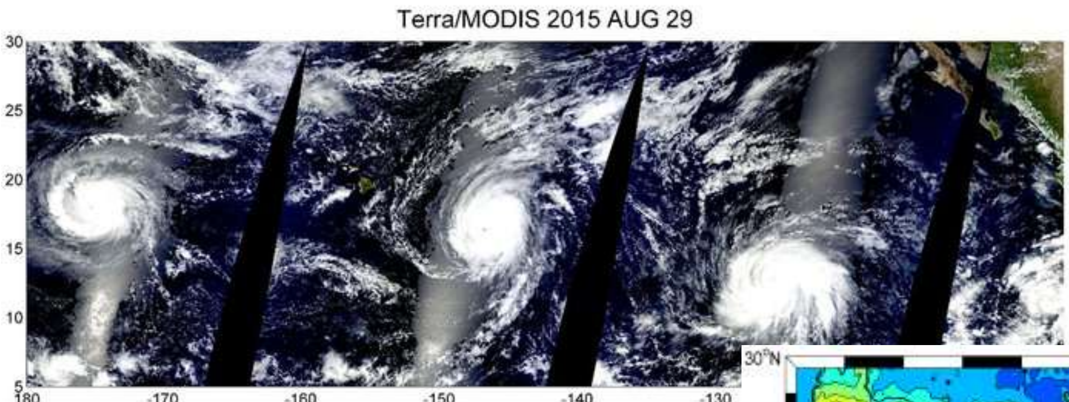
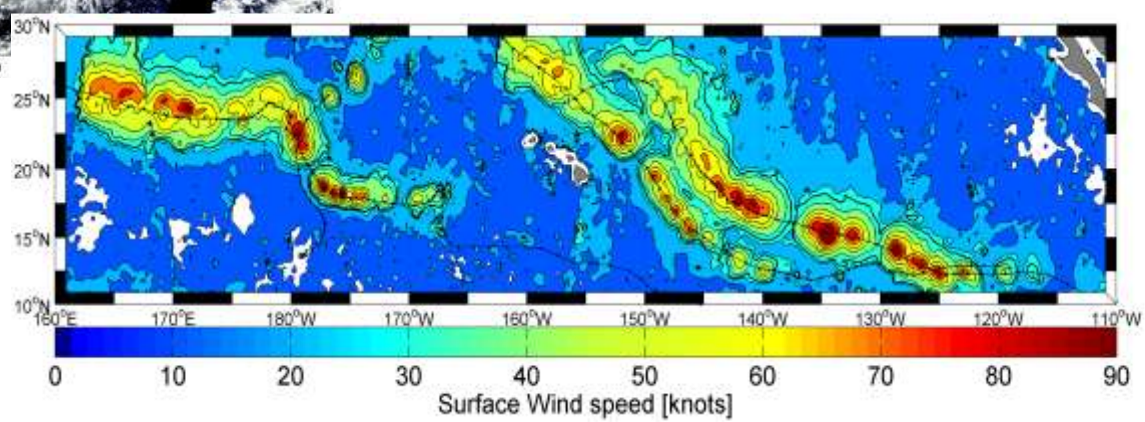
Air-Sea Gas Flux Conference
Ifremer Brest 6-9 sep 2016

A new generation of extreme wind speed measurements from space borne L- and C-band passive radiometers

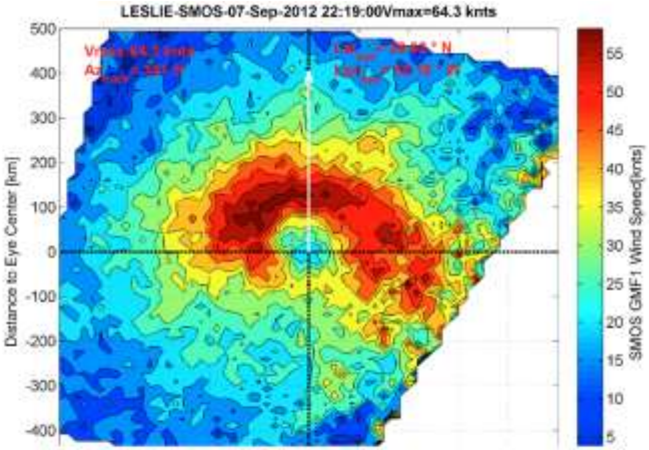
N Reul, E. Zabolotskikh, B. Chapron,A.Mouche, F. Collard, J. Cotton,
P. Francis, V. Kudryavtsev, J. Tenerelli and C. Donlon





Overview

- Introduction
- L-Band passive microwave emissions
- ESA SMOS+ STORM project
- Examples of TC
- SMOS+STORM database
- Revised GFM
- Multi-satellite synergy
- Summary and Conclusions



The ocean surface in high/extreme wind speeds – a simplified view…

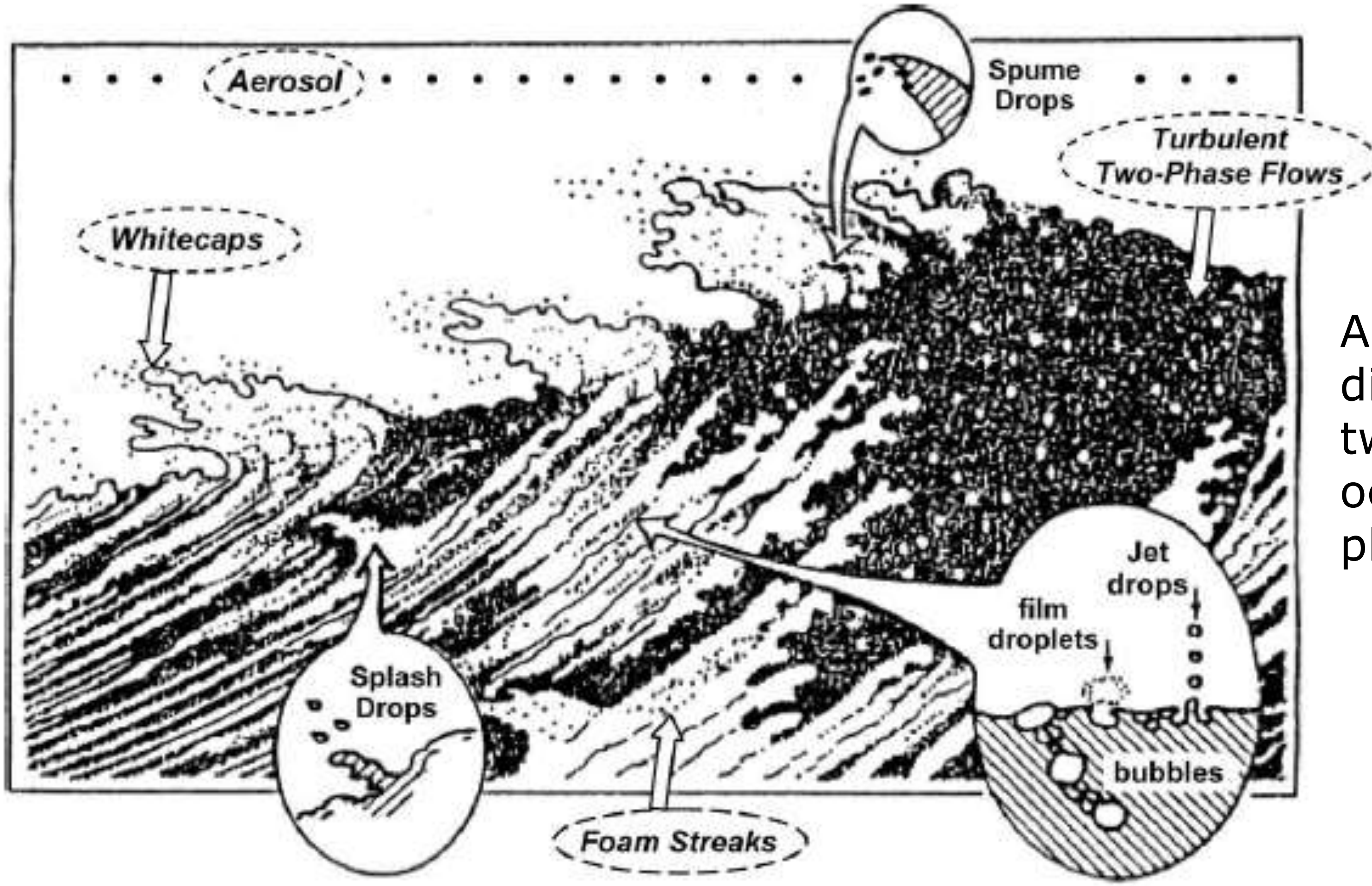
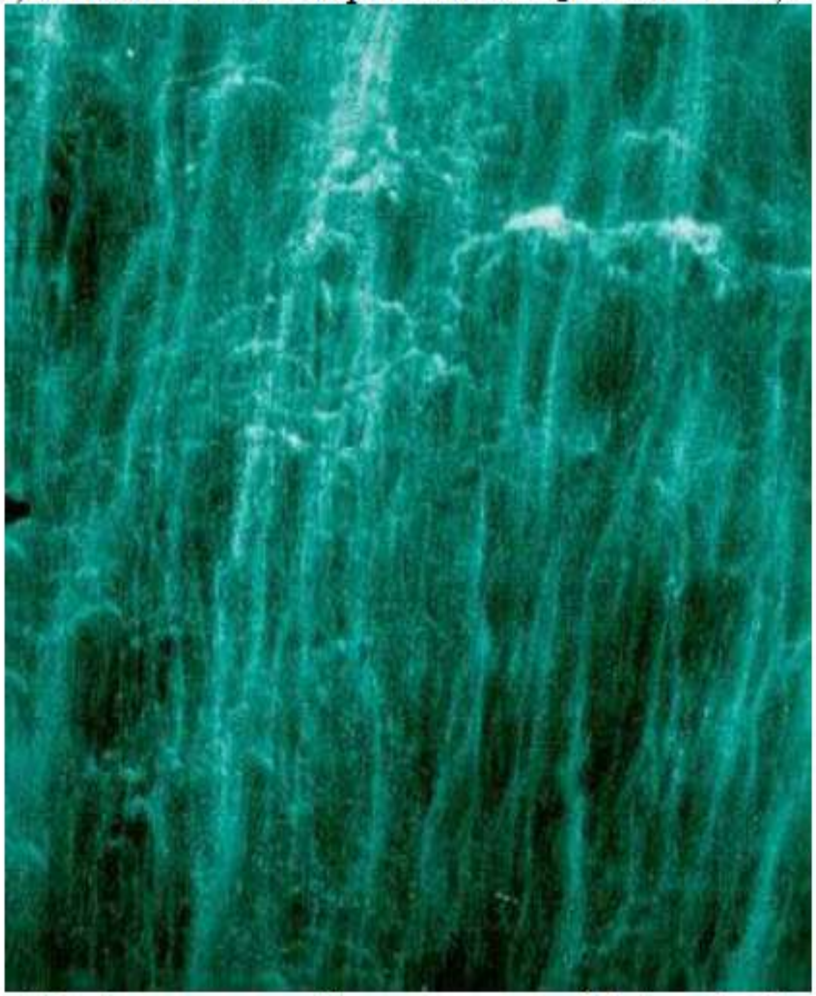


Fig. 1. Classifications of oceanic dispersed media for remote sensing.

A complex distribution of two-phase oceanic phenomena

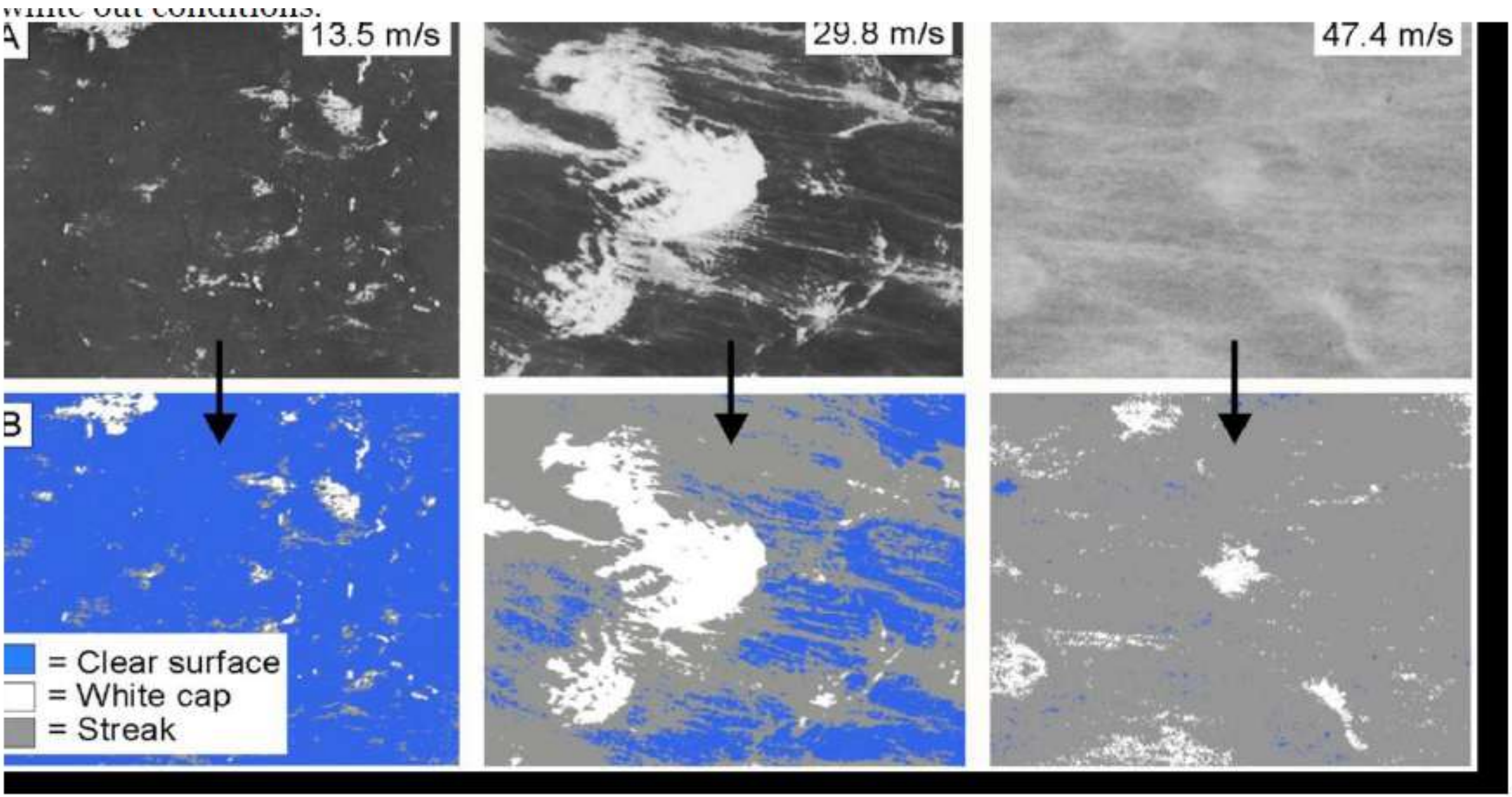
A breaking wave creates a patch of active foam at its crest – the white cap. As the wave moves on, the leading edge of the white cap follows the breaking crest but the trailing edge remains stationary and is slowly replaced by submerged bubbles in wind-aligned streaks. At very high wind speeds the white cap is blown off the crest in a layer of spray droplets. Under such conditions, the ocean-atmosphere interface is a foam, spray, bubble emulsion layer, which acts as a slip layer for the wind, rather than as a liquid surface [Powell et al., 2003; Emanuel, 2003].



At very high wind speeds this layer covers the waves as a high-velocity white sheet, resulting in white out conditions.

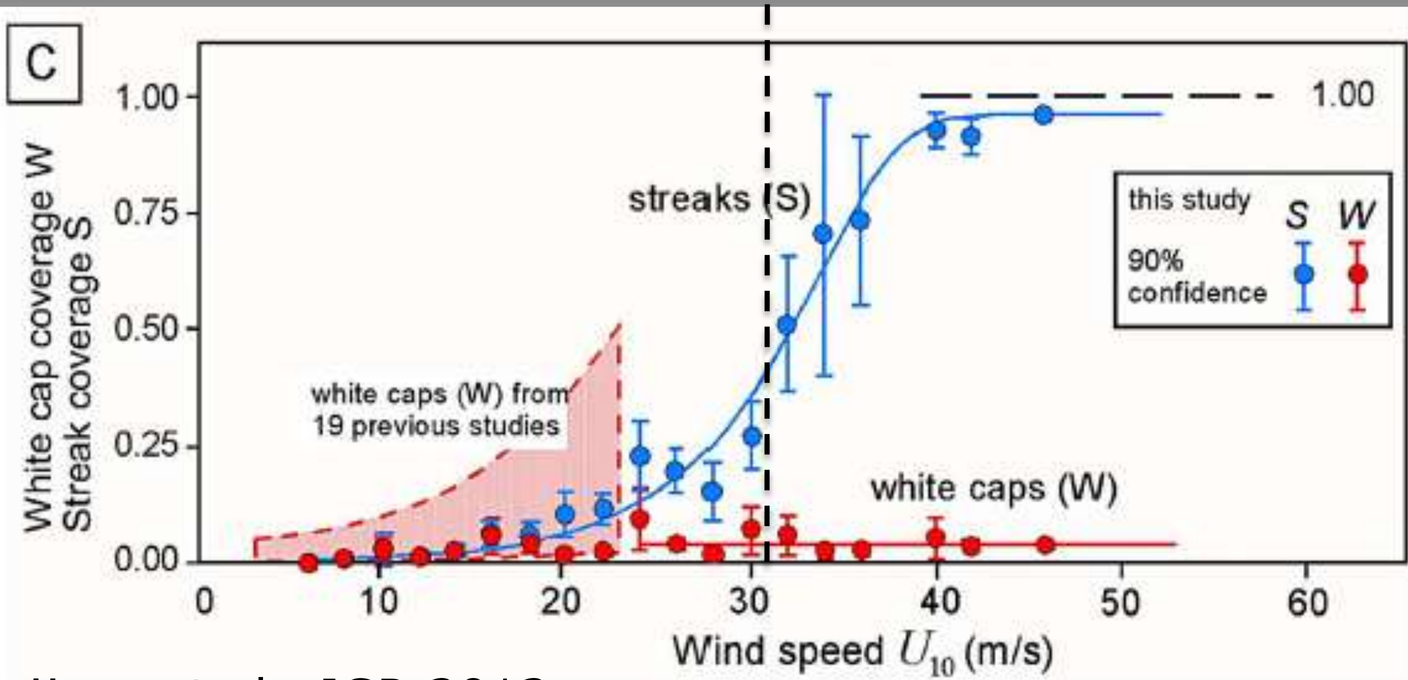
Whitecaps and foam streaks

Holthuijsen et al. 2012 investigated these processes using aerial reconnaissance films and GPS drop sondes in hurricanes



Separation of whitecap & streak coverage

Ocean surface “whitening”



Holthuijsen et al. JGR 2012

- **Most of the increased surface whitening at & above hurricane force (>33 m/s)** is principally induced by an **increase in foam streak coverage**

- **Whitecap coverage is found ~constant above Hurricane force ~4 %**

The sensitivity of L-band emissivity to surface ocean foam: FROG Campaign



Empirical measurements made before the launch of SMOS to assess the impact of ocean foam on the L-band signal

This resulted in the developement of a theoretical foam emissivity model showing that the growth of foam-layer thickness plays an important role in the Tb increase at high wind

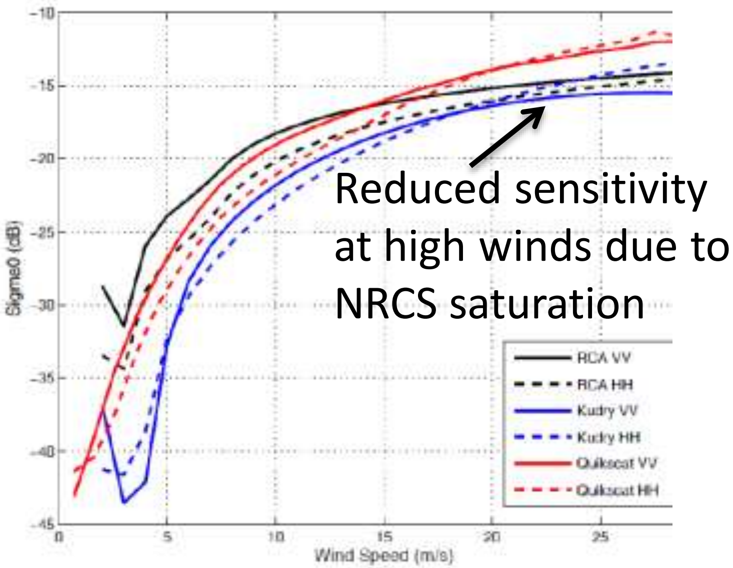
N.Reul and B. Chapron, "A model of sea-foam thickness distribution for passive microwave remote sensing applications", J. Geophys. Res., 108 (C10), Oct, 2003.

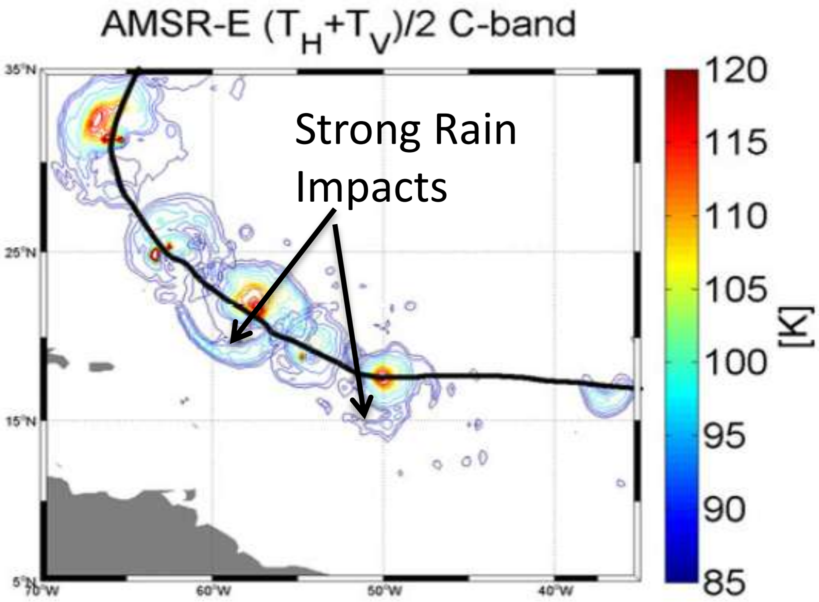
A.Camps, et al, *"The Emissivity Of Foam-Covered Water Surface at L-Band: Theoretical Modeling And Experimental Results From The Frog 2003 Field Experiment", IEEE TGRS*, vol 43, No 5, pp 925-937, 2005.

Limitations of satellite microwave at high winds

- Active microwave backscatter signal saturates under hurricane force winds and is heavily affected in the presence of high rain rates;

- Contrarily to scatterometer signal, radiometric signal does not saturate with high winds. Moreover, the sensitivity of microwave brightness temperature tends even to increase for the winds above 15 m/s

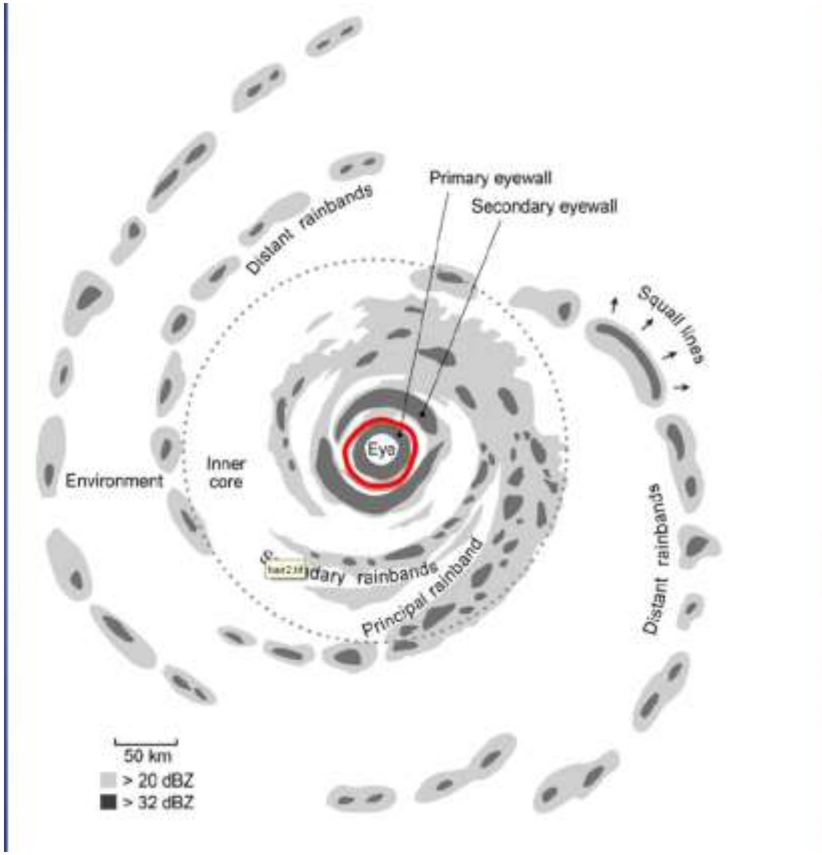




conditions, *J. Geophys. Res*

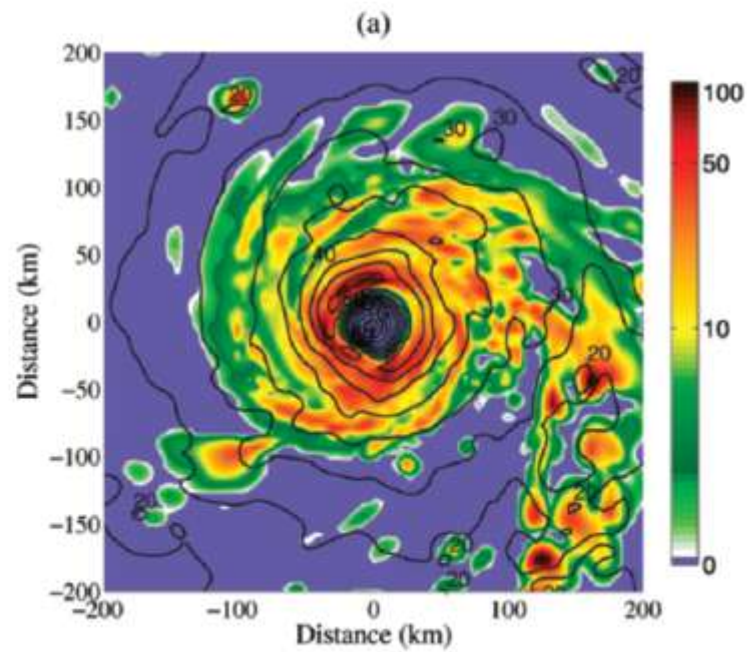
High winds in Hurricanes are very often associated with High rain rates

Rain Anatomy in a hurricane



Houze 2010

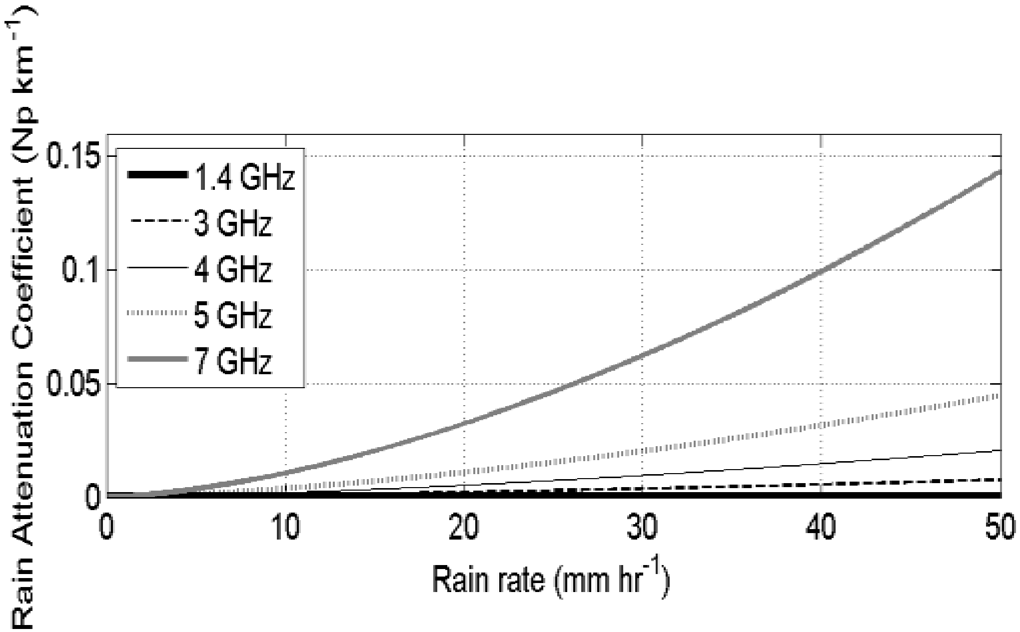
Rain rate [mm/h]



S.Shen and J. Tenerelli 2007

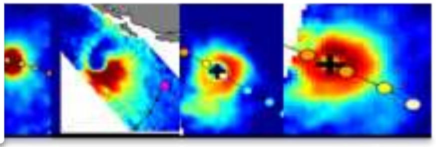
Rain attenuation at C and L-bands

- 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.
- Rain impact at 1.4 GHz can be approximated entirely by absorption and emission (Rayleigh scattering approximation valid)

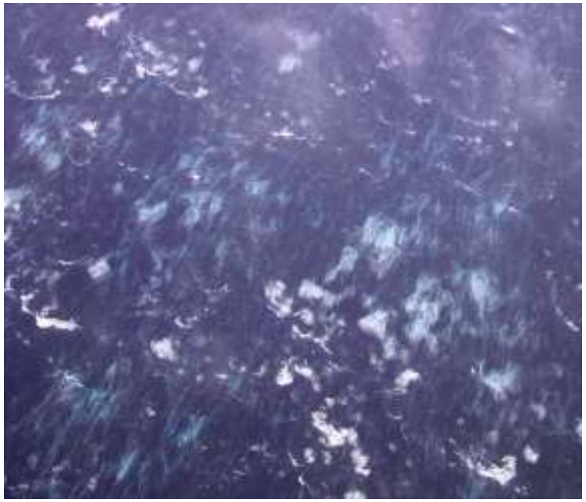


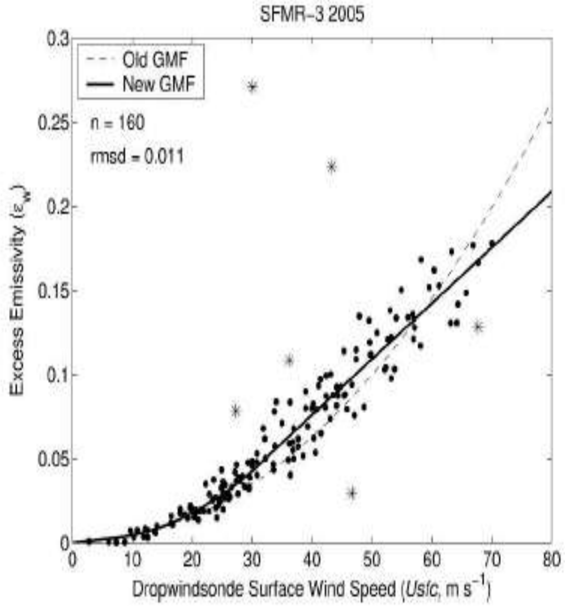
Rain attenuation
A factor 100 less
At L band than at 7 Ghz

Generally two order of magnitude smaller at L-band (1.4 GHz) than at C-band (5-7 GHz)



Increase of the microwave ocean emissivity with wind speed ⇔ surface foam change impacts





Hurricane hunter P-3

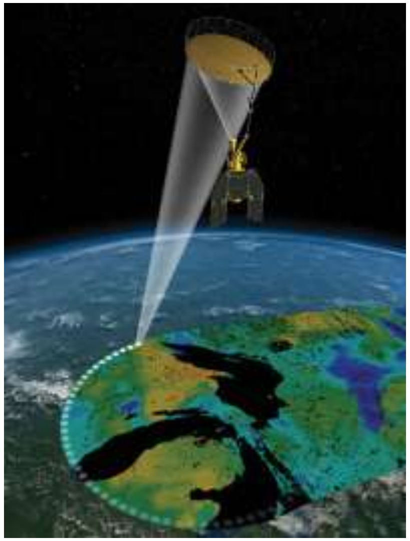
This information can be used to retrieve the surface wind speed in Hurricanes:

- Principle of **the Step Frequency Microwave Radiometer** (SFMR) C-band: => Use mutli-frequency C-band channels to separate wind from rain effects
- **NOAA's primary airborn sensor for measuring Tropical Cyclone surface wind speeds since 30 year** (Ulhorn et al., 2003, 2007).

Three Low-frequency Microwave radiometers enhancing High Wind Speed ocean Surface monitoring capabilities

SMOS-ESA

Interferometric Radiometer
Frequency: 1.4 GHz L-band
Spatial Resolution: ~43 kms
Swath Width: ~1000 kms
Revisit time Equator: ~3 days
Incidence angles: 10°-60°
Fully polarimetric
Launched Nov 2009



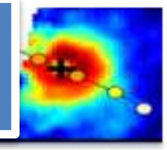
SMAP-NASA

Real Aperture Radiometer
Frequency: 1.4 GHz L-band
Spatial Resolution: ~30 kms
Swath Width: ~1000 kms
Revisit time Equator: ~3 days
Incidence angle: 40°
Fully polarimetric
Launched Jan 2015

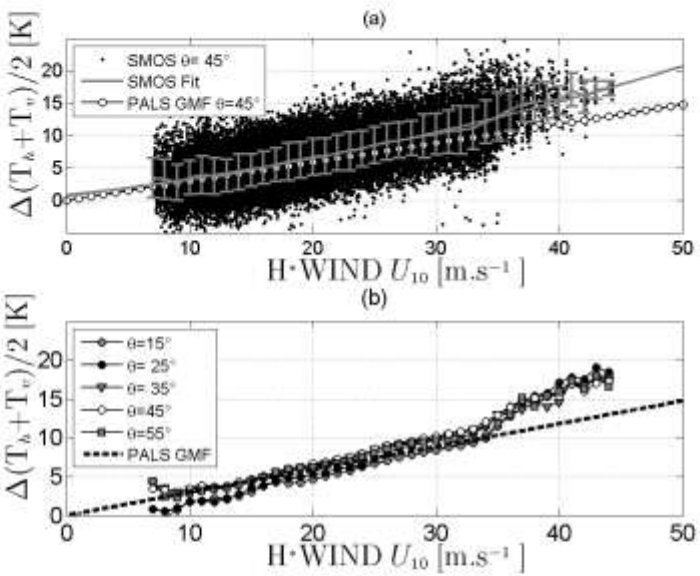
AMSR-2-JAXA

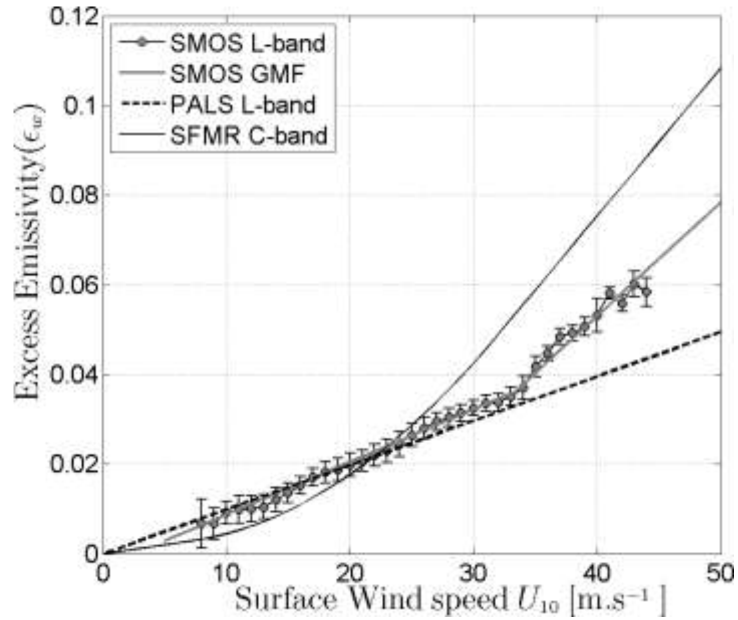
Real Aperture Radiometer
Multi Frequency including 6.9 and 7.3 GHz C-band
Spatial Resolution: ~30 kms
Swath Width: ~1450 kms
Revisit time Equator: ~3 days
Incidence angle: 50°
Linear polarizations
Launched may 2012

Geophysical Model function: Tb=f(wind speed)



Mean incidence angle Stokes “surface roughness and foam-induced” brightness temperature residual: ΔI = ΔTH + ΔTV.





C-band

L-band:

0.7K/m/s for hurricanes

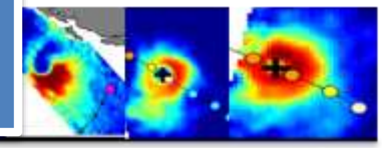
0.3 k/(m/s) below

$$\Delta I = \frac{\Delta(T_H+T_V)}{2} = 0.35\, U_{10} - 1.3 \qquad U_{10} \leq 33\ \mathrm{m.s^{-1}}$$

$$= 0.75\, U_{10} - 14.5 \qquad U_{10} \geq 33\ \mathrm{m.s^{-1}}$$

- **Version-1 SMOS wind speed GMF based on Hwind products in IGOR hurricane**
- **Bilinear L-band dependencies with surface wind speed**

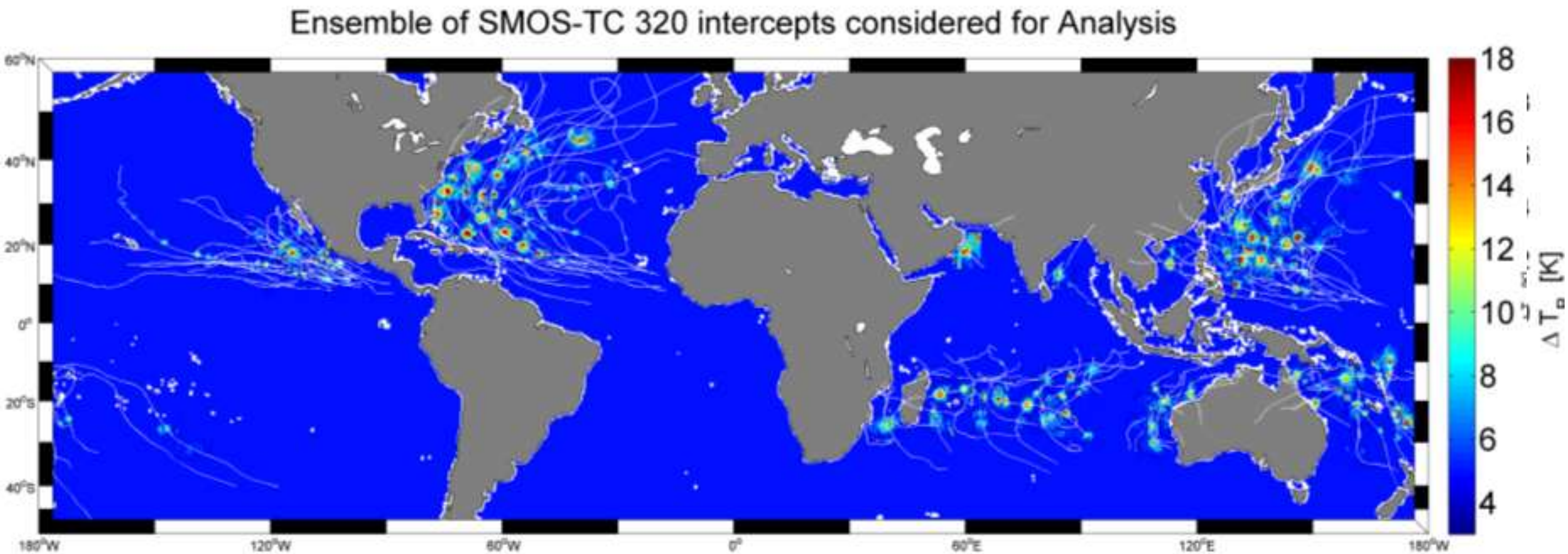
Reul Nicolas, Tenerelli Joseph, chapron B, Vandemark Doug, Quilfen Y, Kerr Yann (2012). SMOS satellite L-band radiometer: A new capability for ocean surface remote sensing in hurricanes. *Journal Of Geophysical Research-oceans*, 117



Collaboration IFREMER & Met Office- (2 years: KO Apr 2014)

- ❑Improve high wind speed retrieval algorithms (GMF, rain & wave impacts)
- ❑Produce a Global Tropical Cyclone & Extra-Tropical Cyclone storm catalogue & database from 2010 to now
- ❑Comparisons with NWP models & radiometer & scatterometer data
- ❑Combine with other observations : AMSR2, WindSat, SMAP, CYGNSS
- ❑Evaluate the impact of SMOS High Wind products assimilation on Metoffice forecast Errors: storm track & intensity forecasts

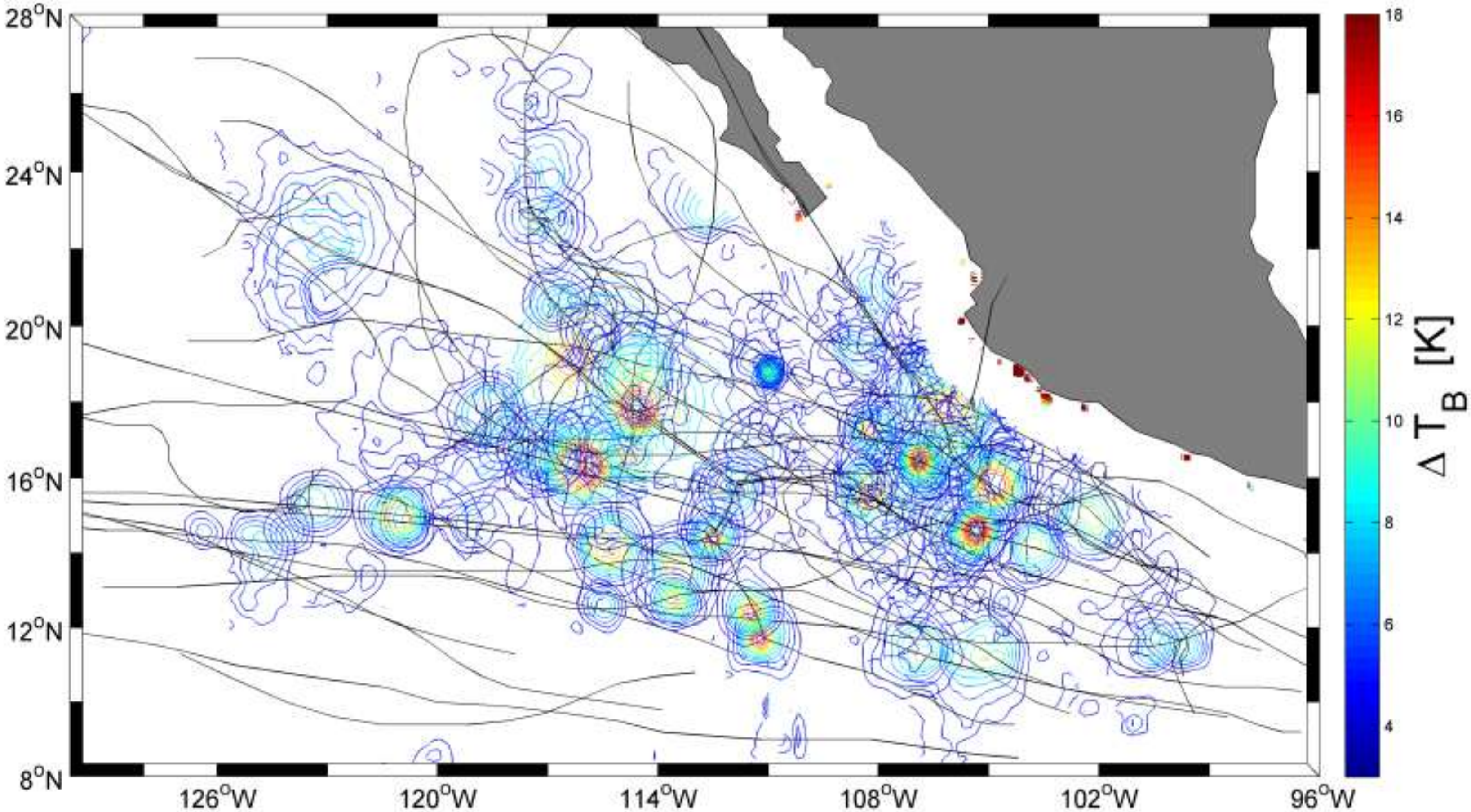
A view at the SMOS-STORM 2010-2015 TC database



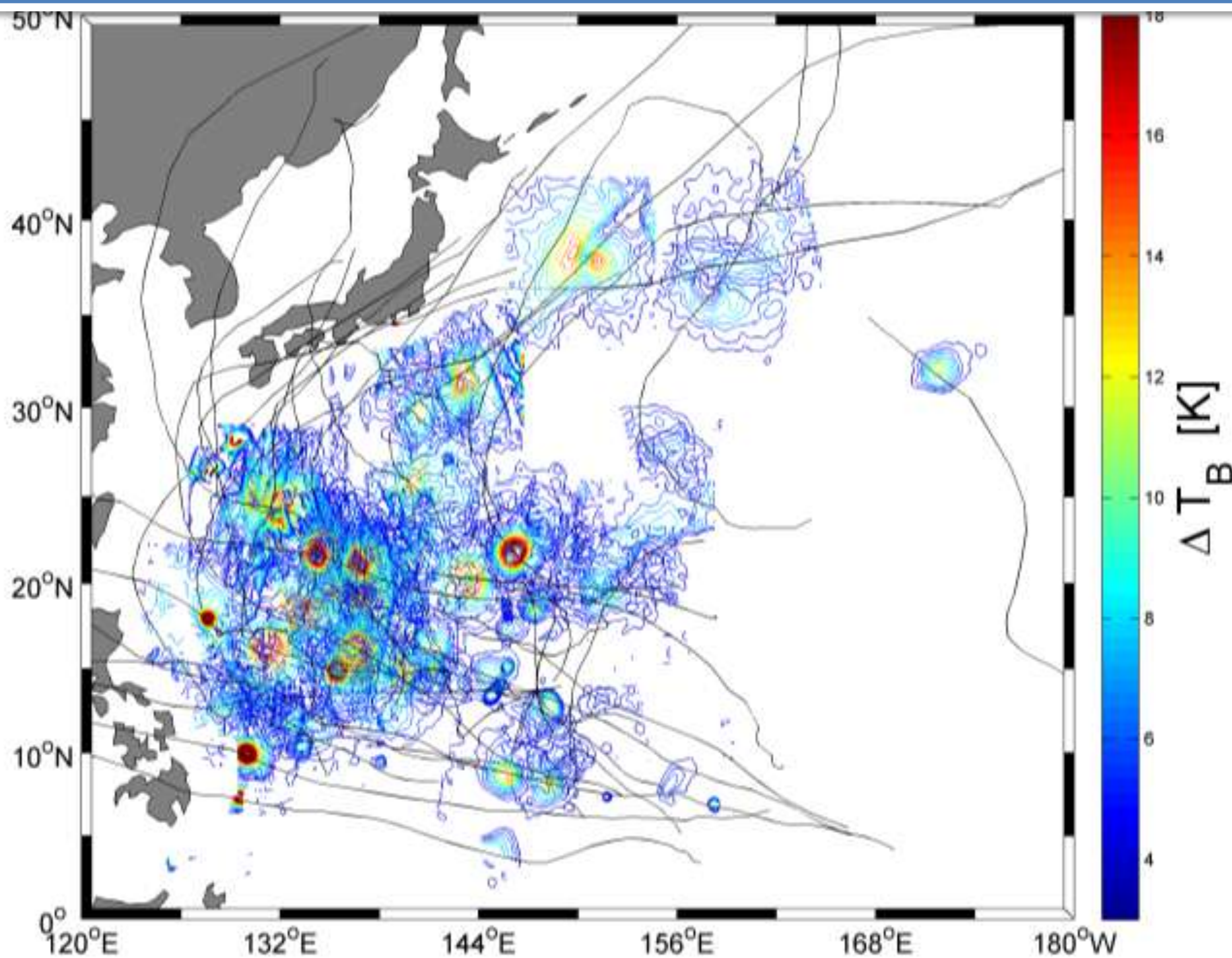
A subset of 320 SMOS swath intercepts with TCs over 2010-2015, free of Radio Frequency Interferences and with pixel distances >150 km from coasts are selected

Data available at **http://www.smosstorm.org/**

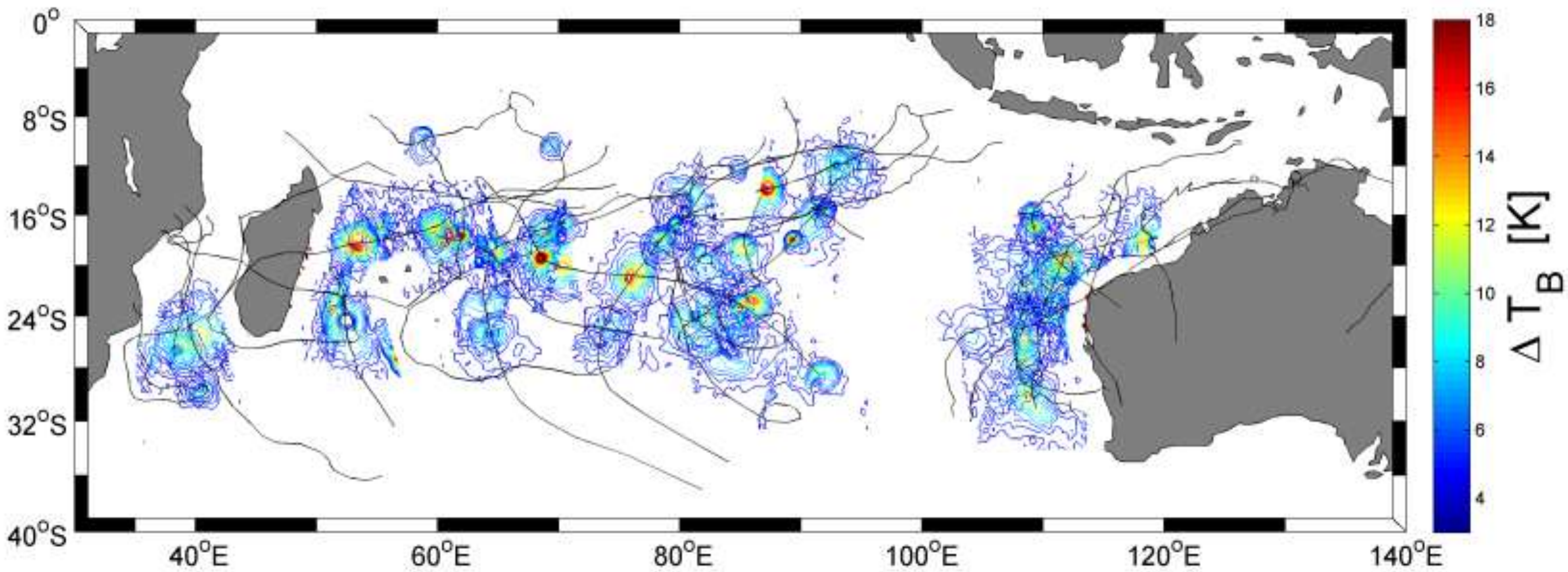
East Pacific SMOS intercepts with 2010-2014 TCs



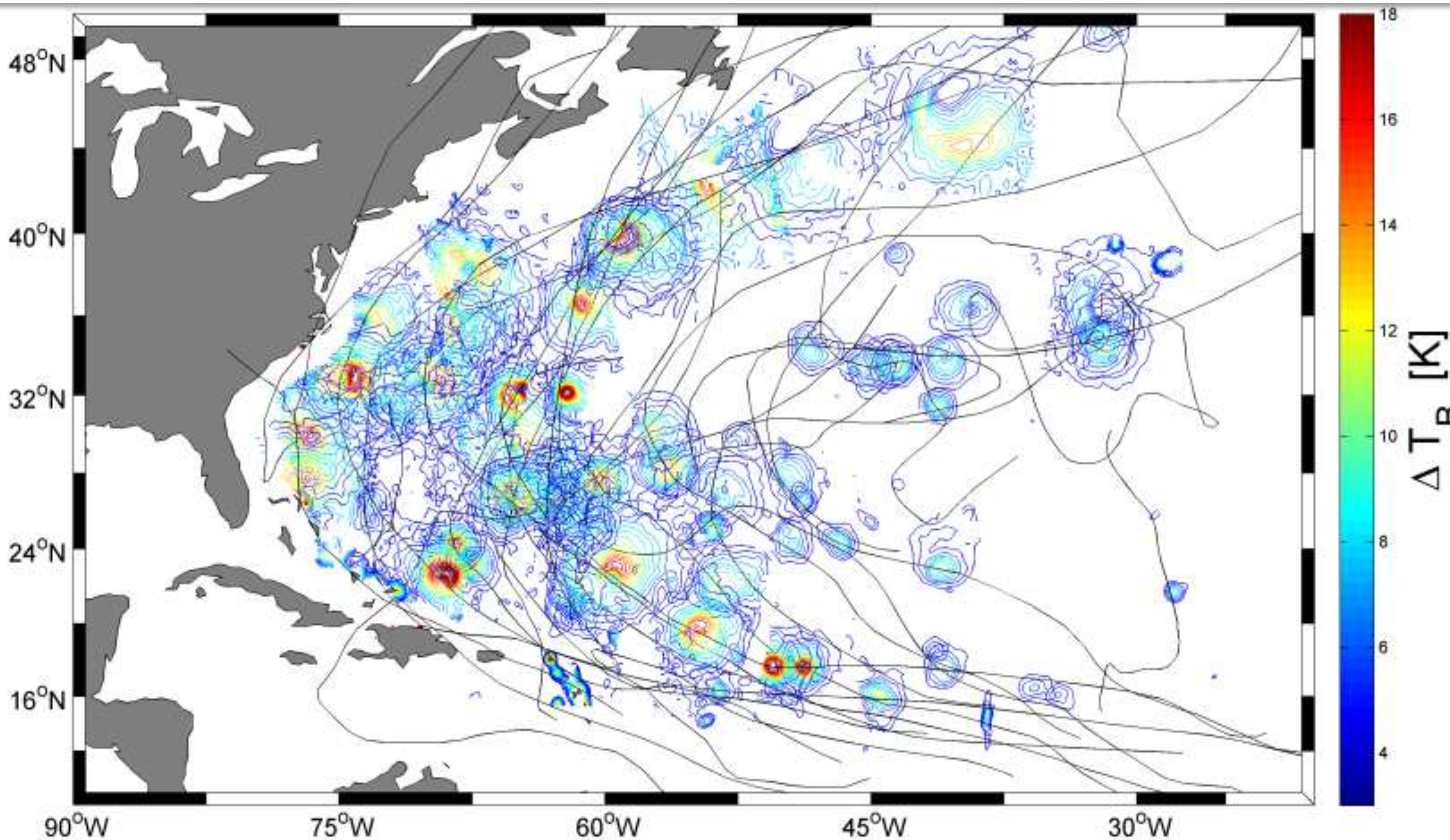
West Pacific SMOS intercepts with 2010-2014's TCs

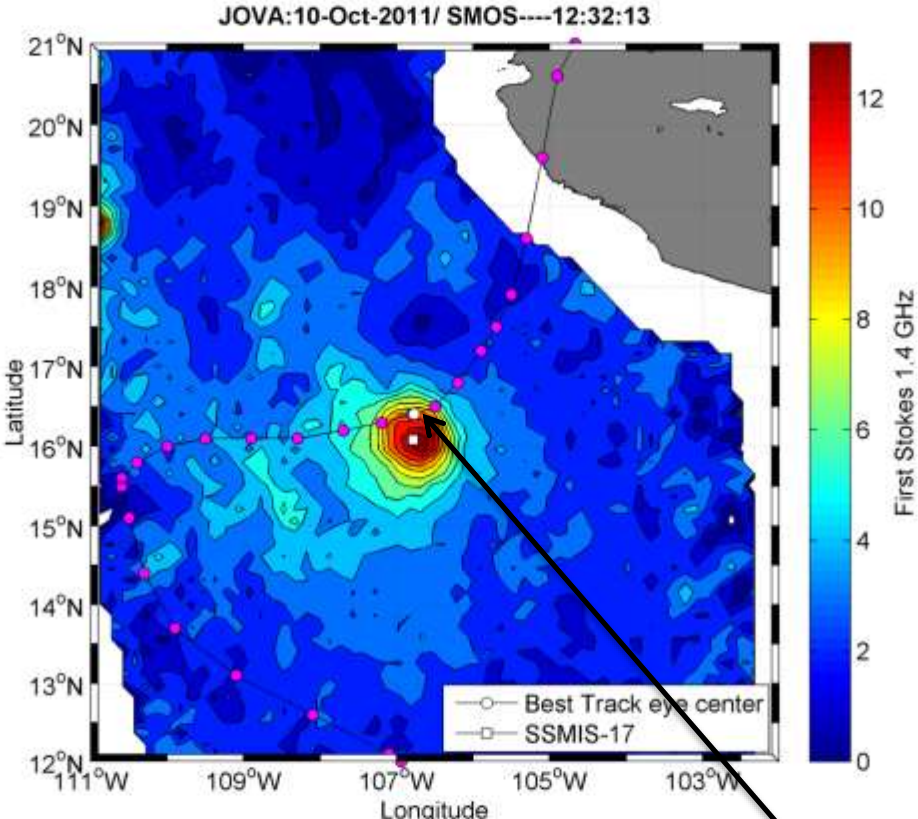


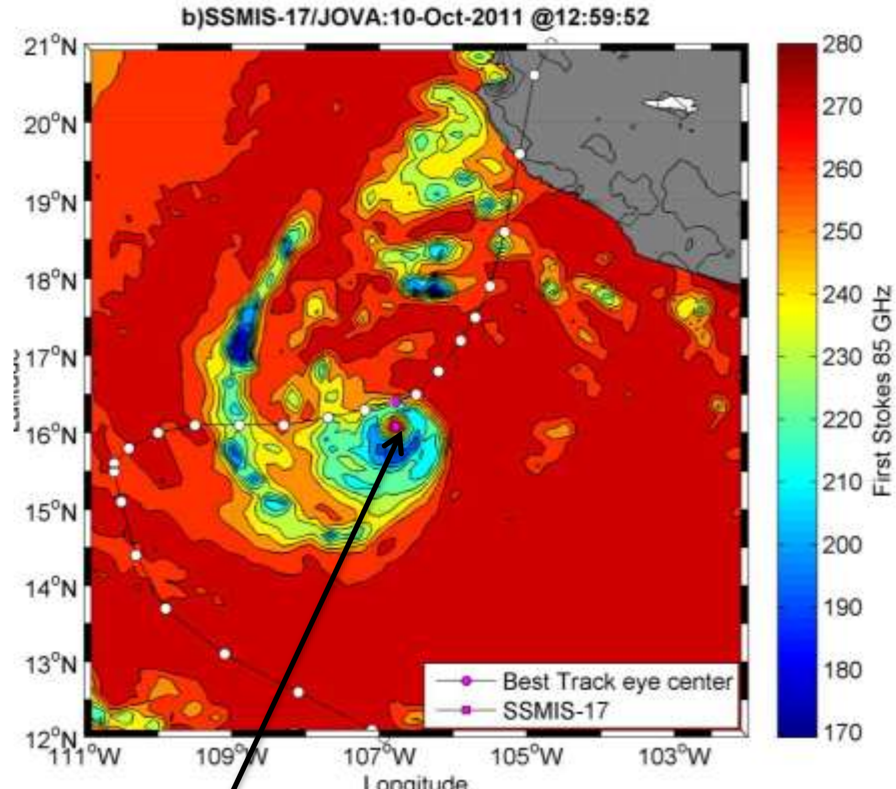
South Indian SMOS intercepts with 2010-2014's TCs



North Atlantic SMOS intercepts 2010-2014 TC



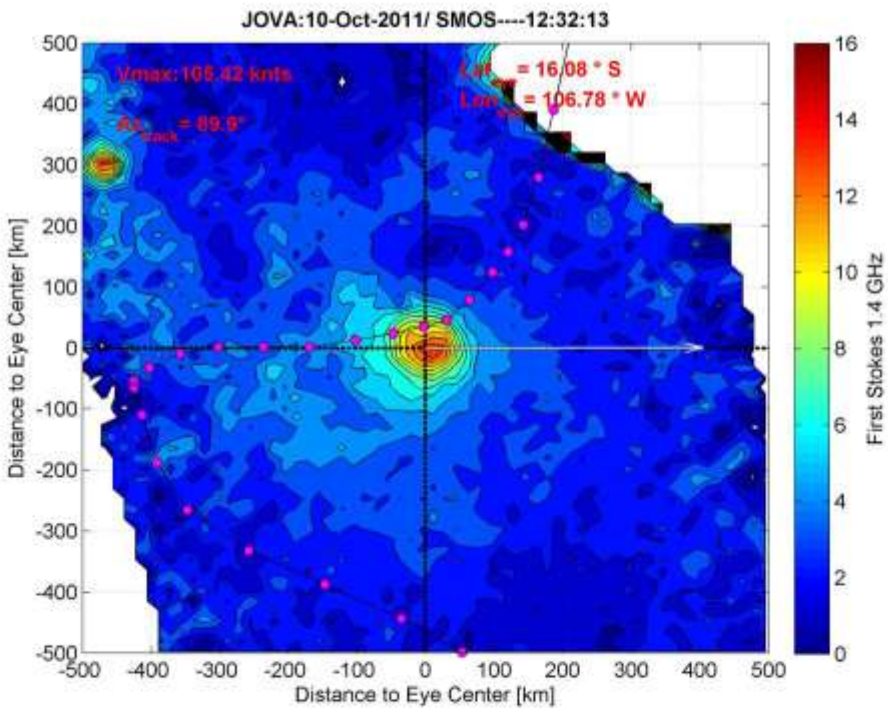


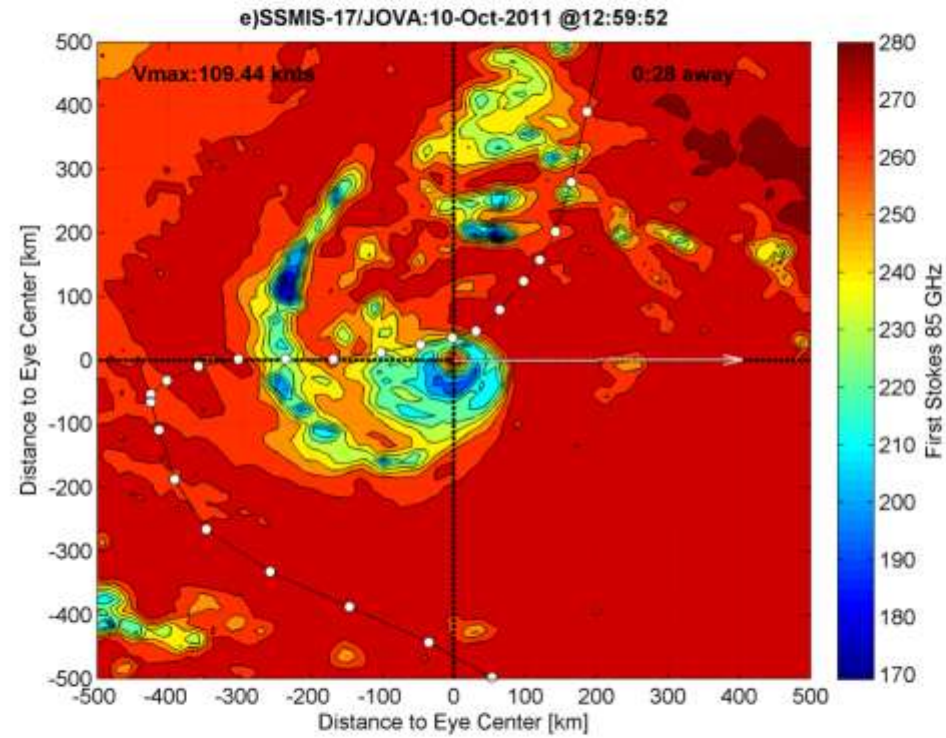


Best track eye position

actual eye position

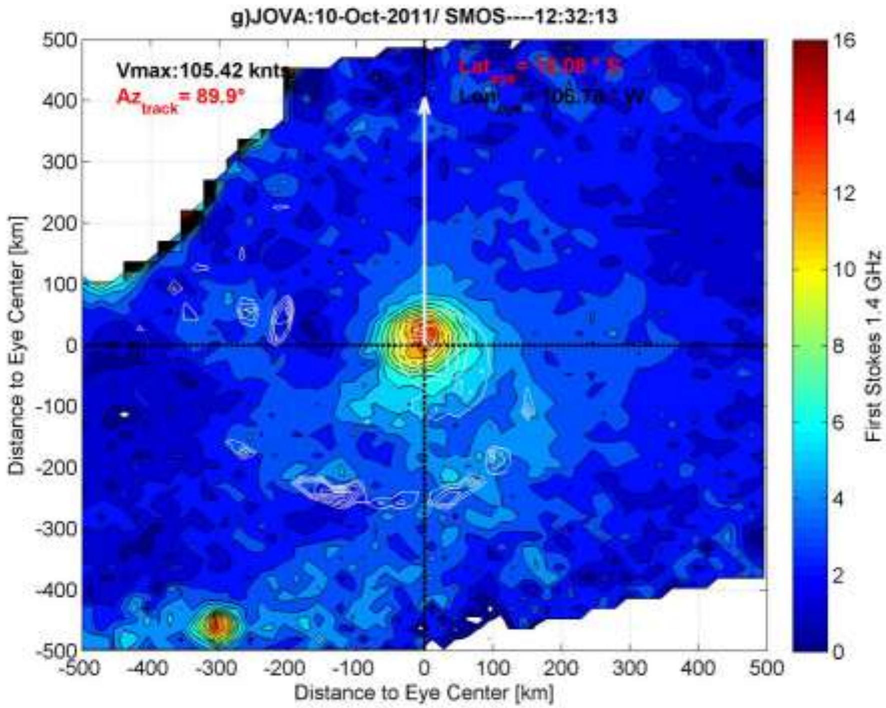
TC eye position is adjusted using 85 GHz datasets

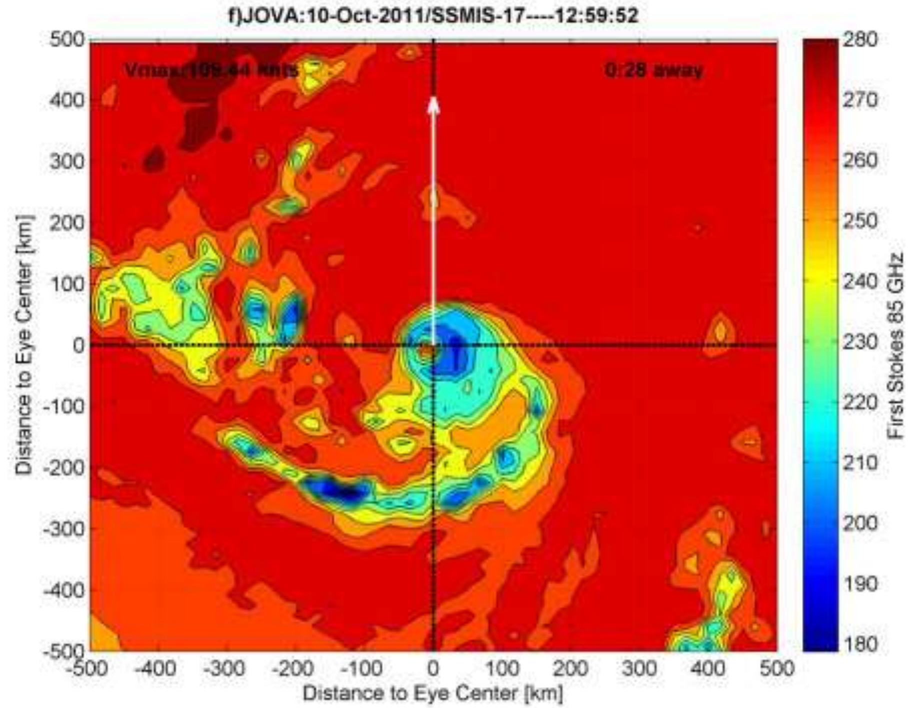




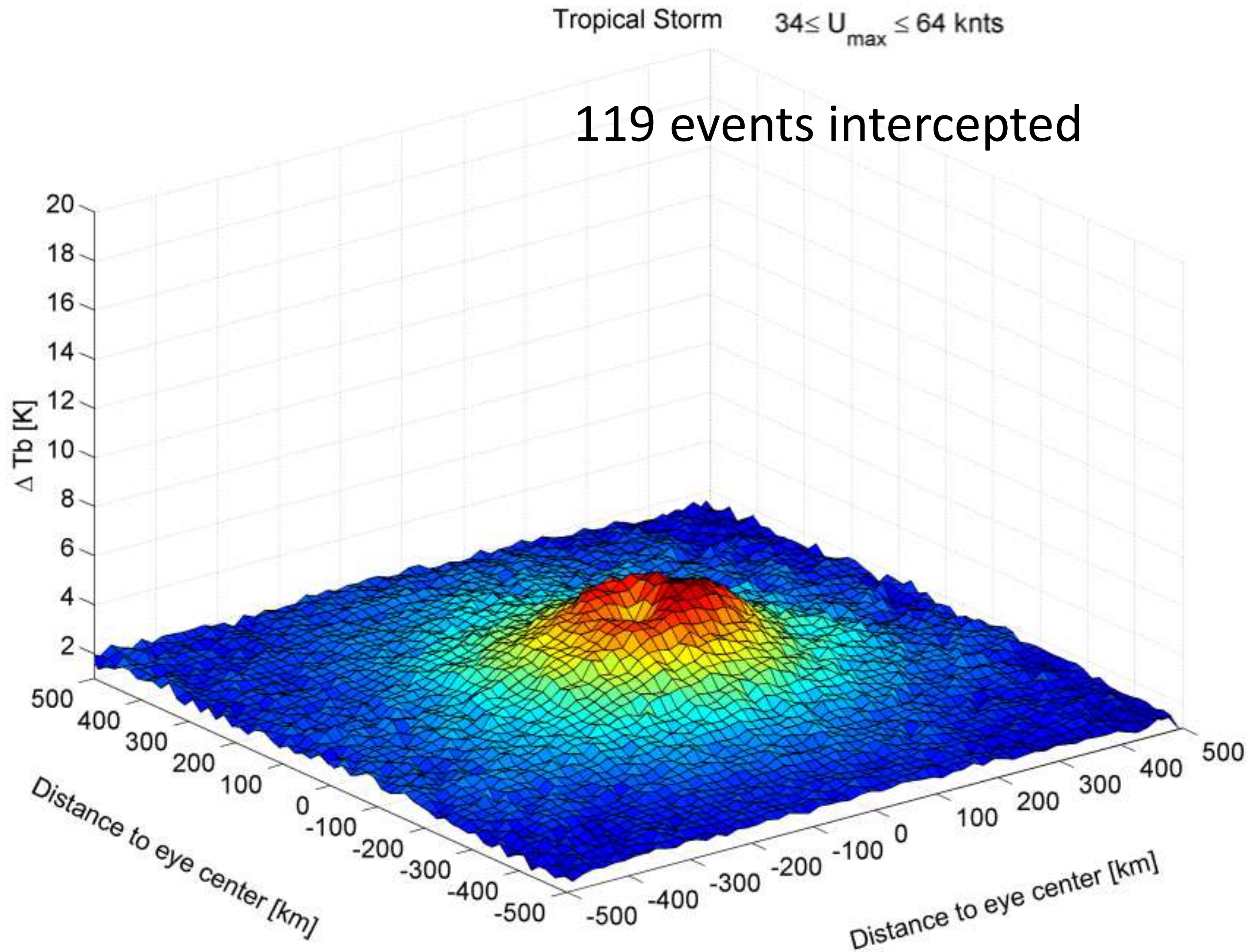
- SMOS Tb is then recentered on a TC eye-centered frame
- Storm propagation direction is evaluated

smos+ storms
support to science element



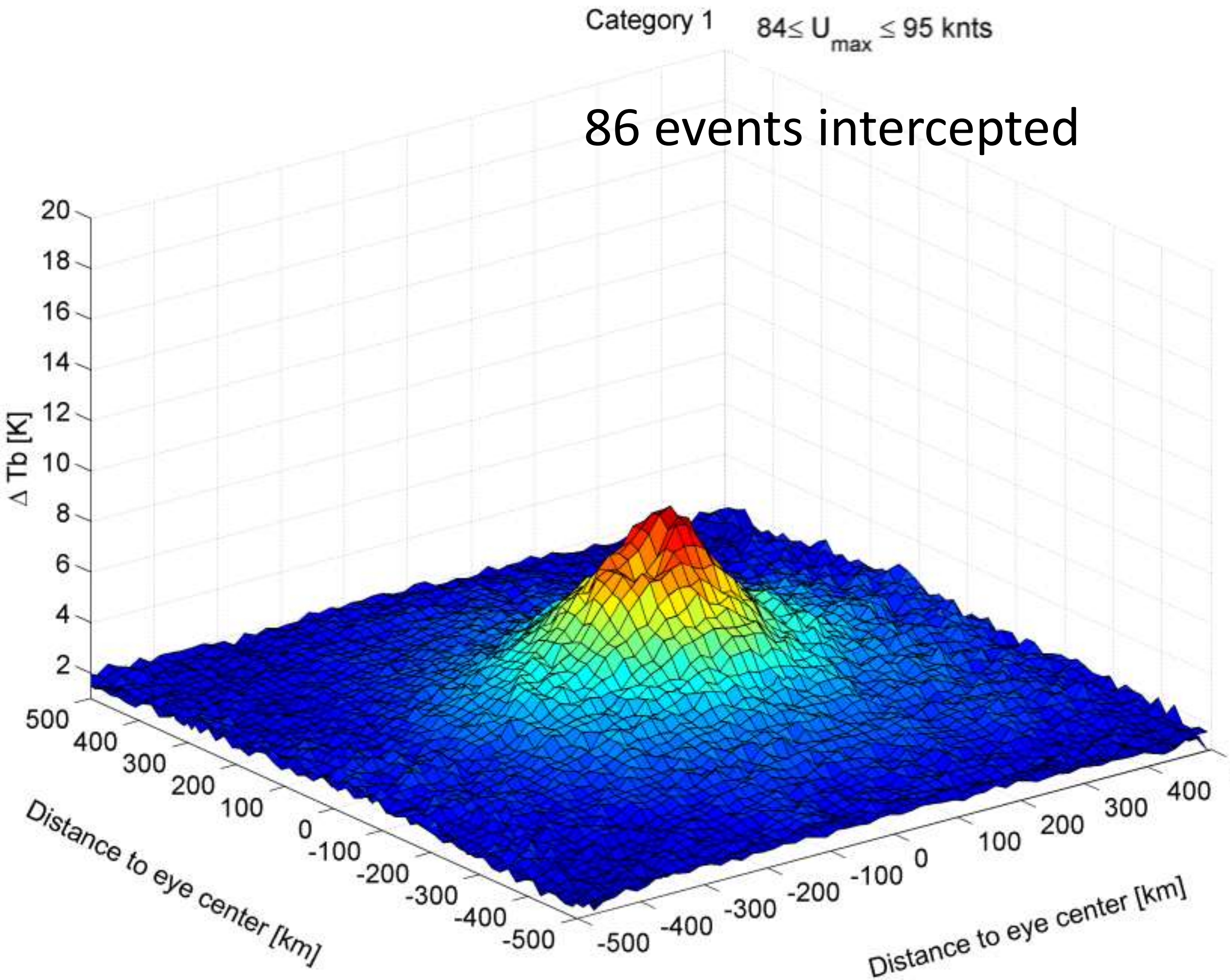


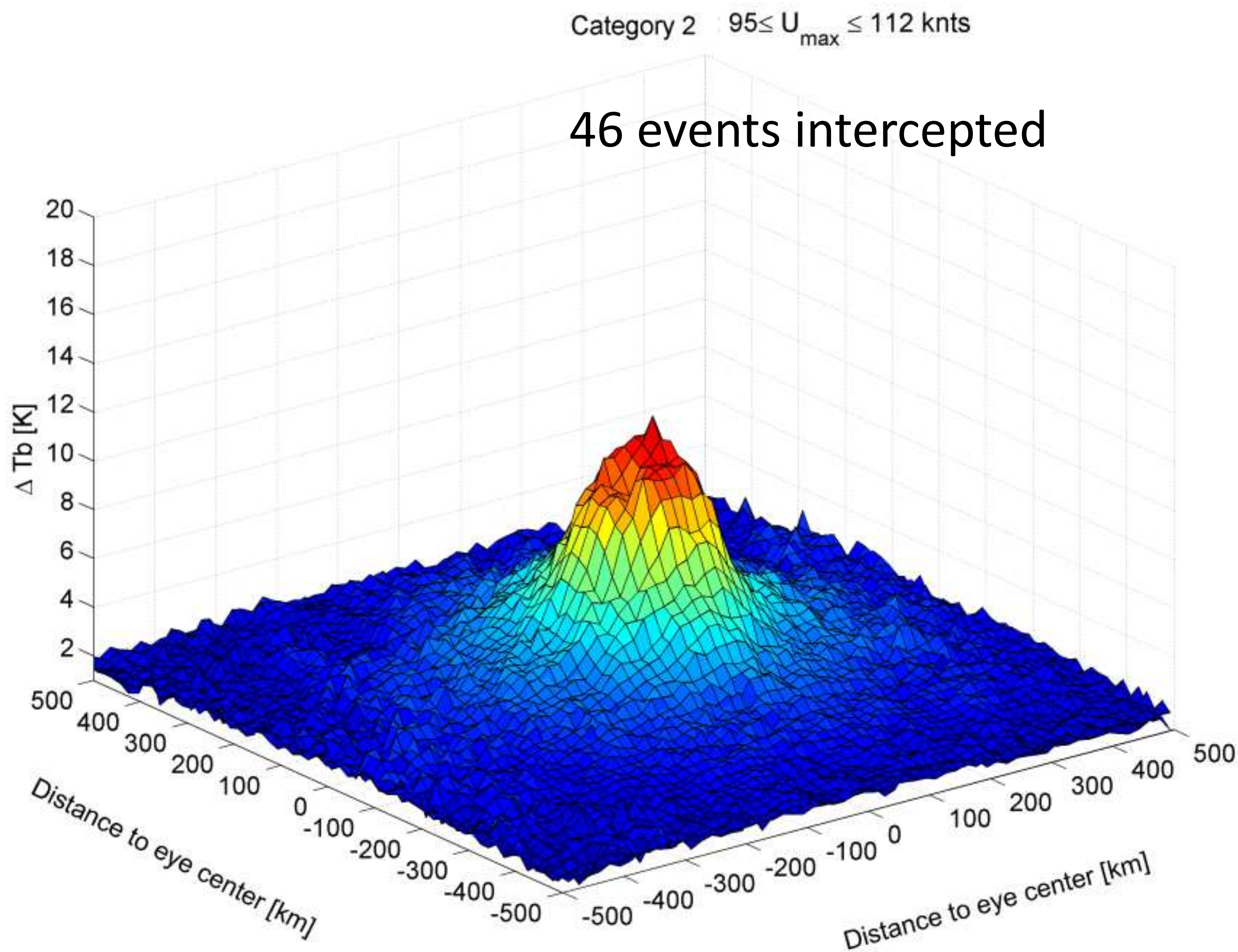
SMOS Tb is rotated to a fixed ”North up” propagation direction for further averaging of Tb



Tropical Storm
34≤ U max ≤ 64 knts
119 events intercepted
Δ Tb [K]
20
18
16
14
12
10
8
6
4
2
500
400
300
200
100
0
-100
-200
-300
-400
-500
Distance to eye center [km]
-500
-400
-300
-200
-100
0
100
200
300
400
500
Distance to eye center [km]

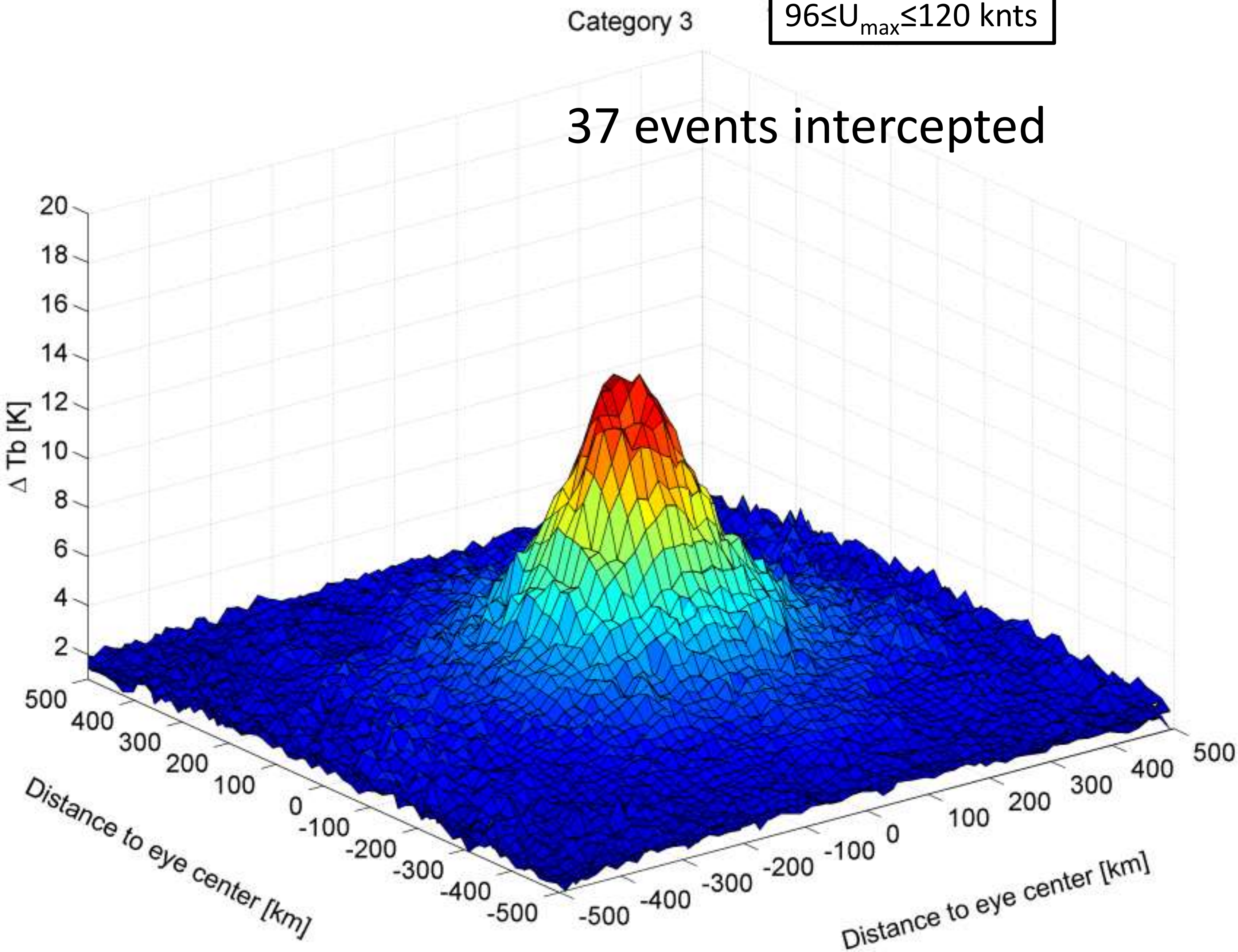
86 events intercepted

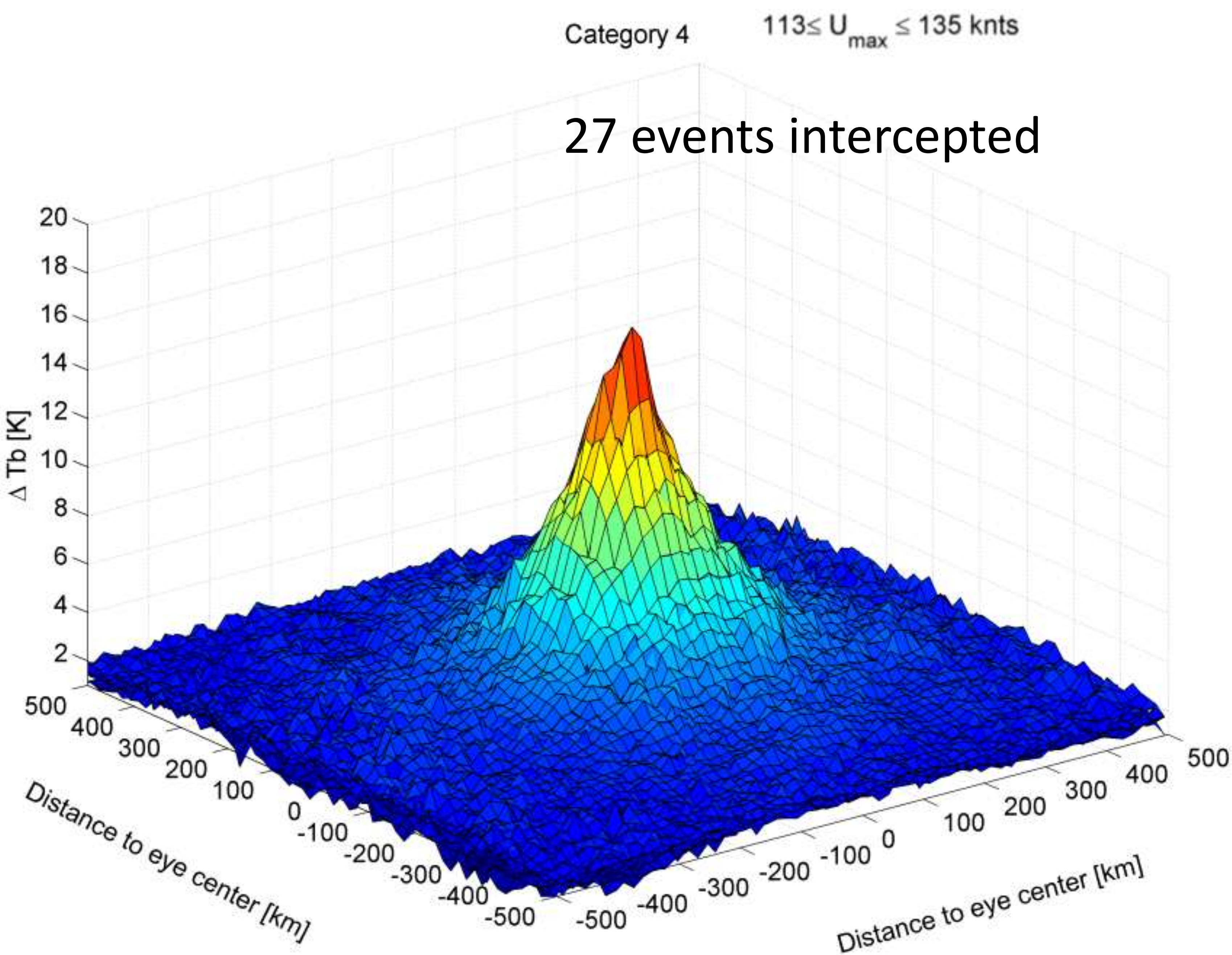


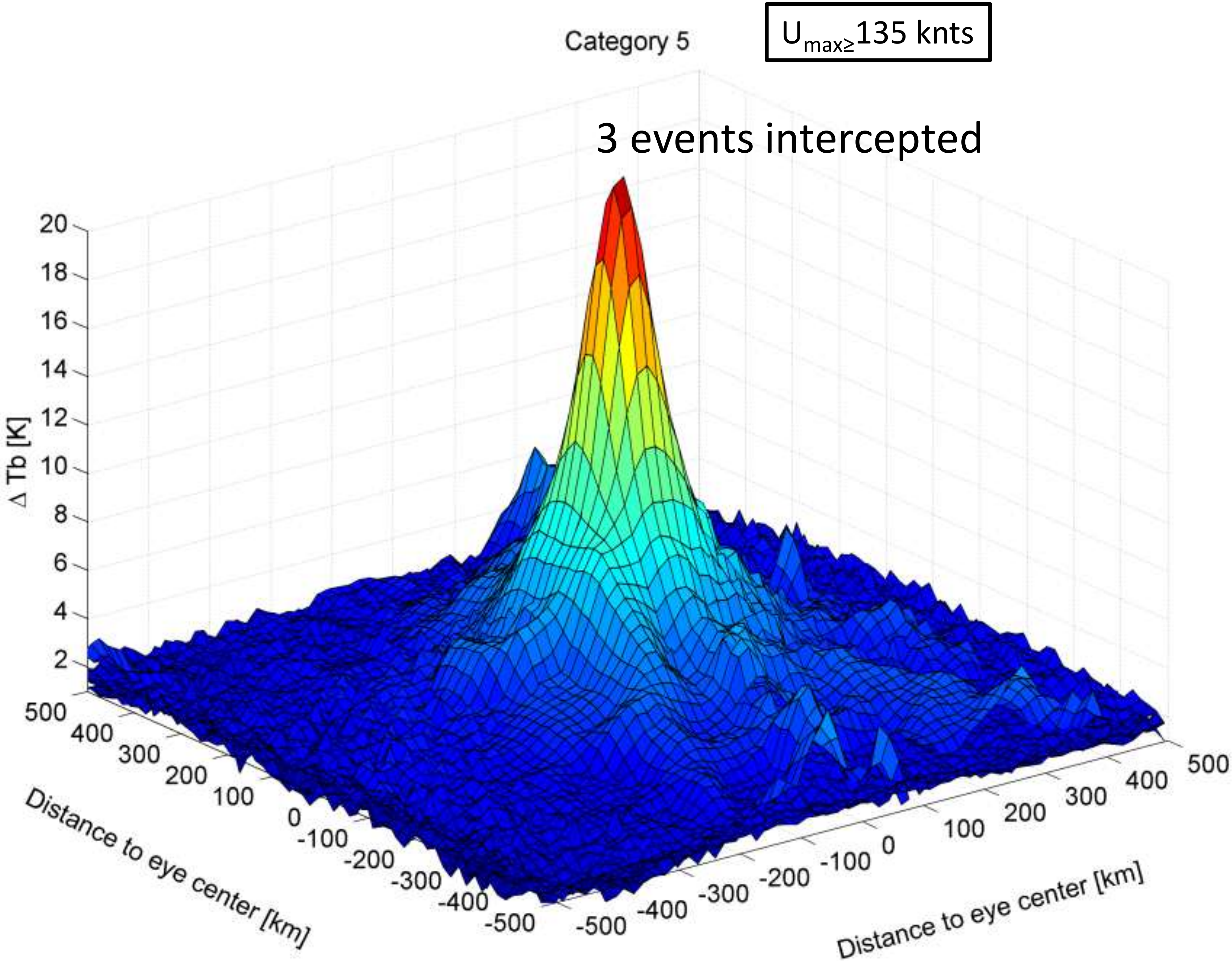

Category 2 95≤ U_{max} ≤ 112 knts
46 events intercepted
Δ Tb [K]
20
18
16
14
12
10
8
6
4
2
500
400
300
200
100
0
-100
-200
-300
-400
-500
Distance to eye center [km]
-500
-400
-300
-200
-100
0
100
200
300
400
500
Distance to eye center [km]

$96 \leq U_{max} \leq 120$ knts

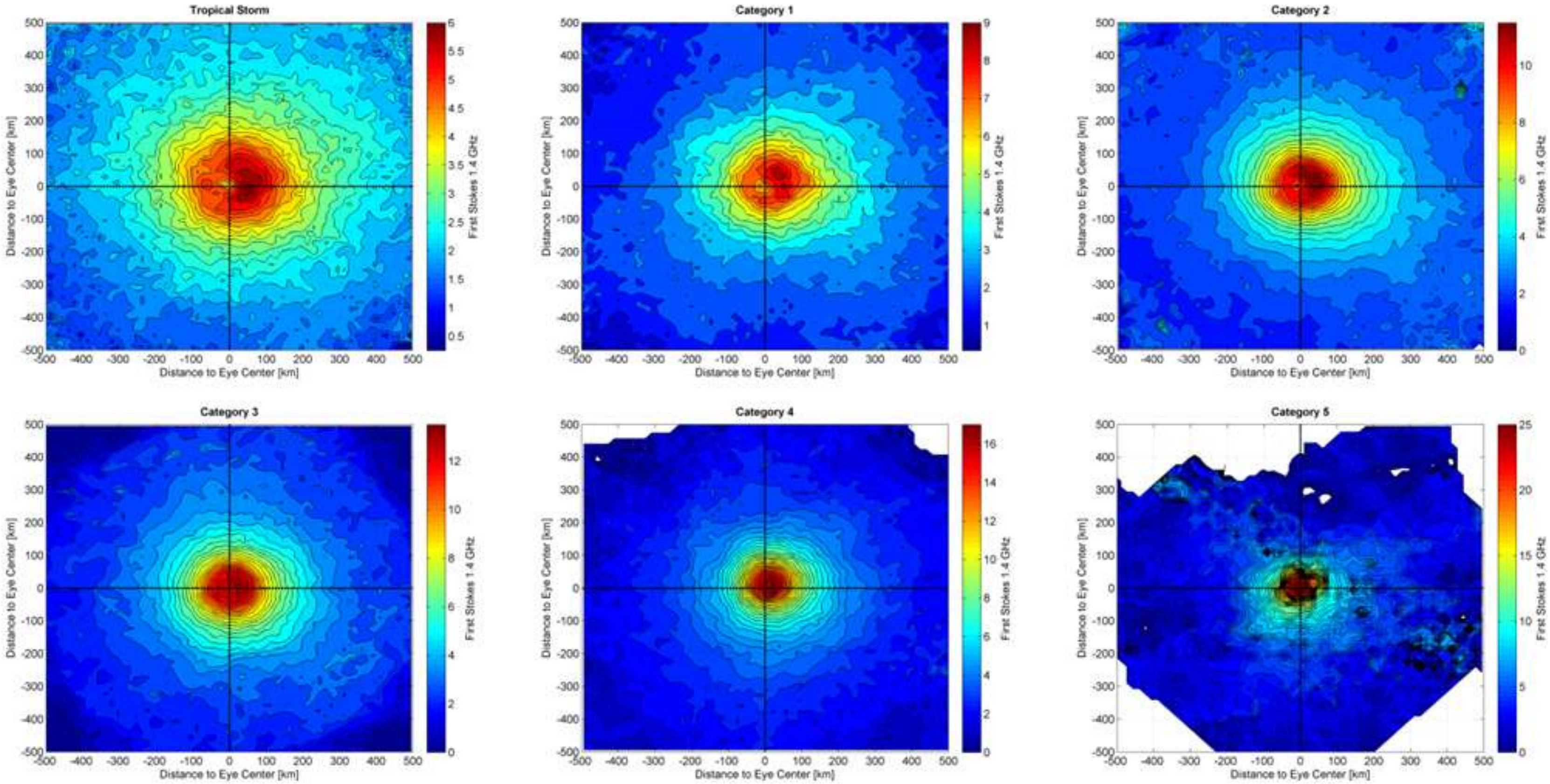
37 events intercepted



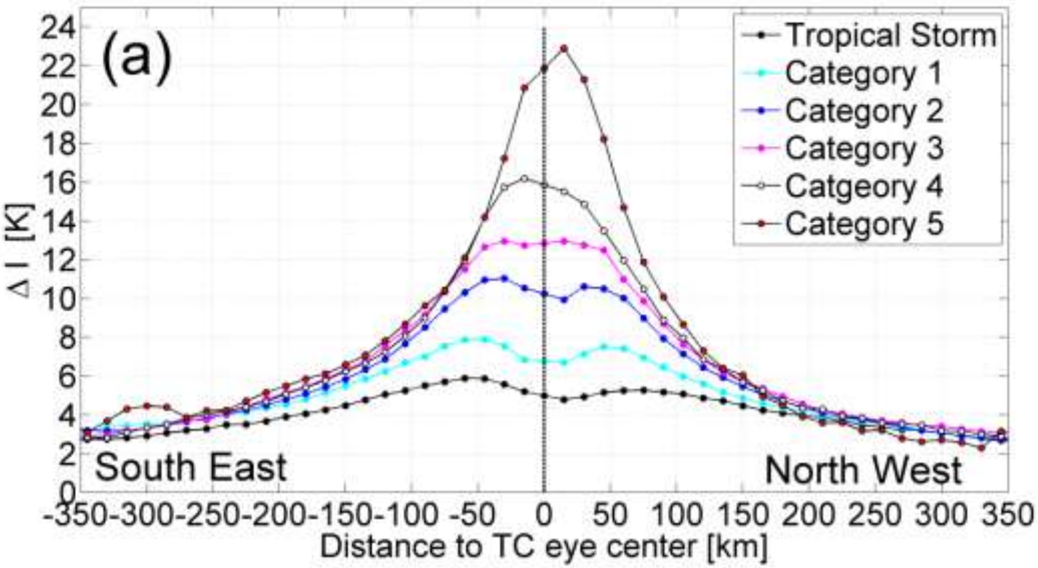

Category 4
113≤ U max ≤ 135 knts
27 events intercepted
Δ Tb [K]
20
18
16
14
12
10
8
6
4
2
500
400
300
200
100
0
-100
-200
-300
-400
-500
Distance to eye center [km]
-500
-400
-300
-200
-100
0
100
200
300
400
500
Distance to eye center [km]

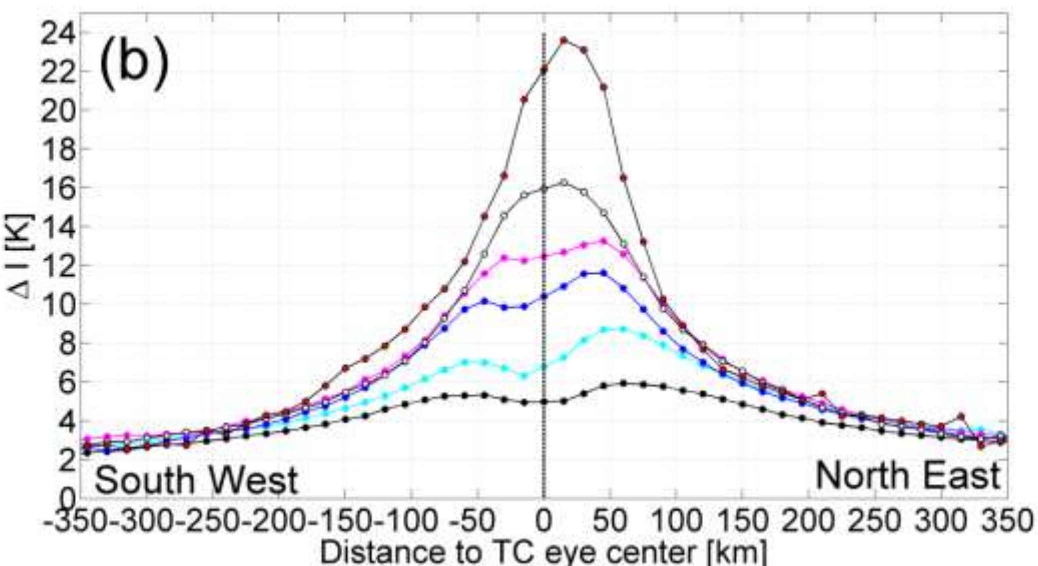

Category 5
$U_{max\geq}$135 knts
3 events intercepted
Δ Tb [K]
20
18
16
14
12
10
8
6
4
2
500
400
300
200
100
0
-100
-200
-300
-400
-500
Distance to eye center [km]
-500
-400
-300
-200
-100
0
100
200
300
400
500
Distance to eye center [km]

Average L-band Tb contrasts as function of storm Intensity & sectors



Systematic right-hand sectors asymetries in Tb as expected in
wind & waves distribution in TCs (extended fetch=>Young, 2003; MacAfee and Bowyer, 2005

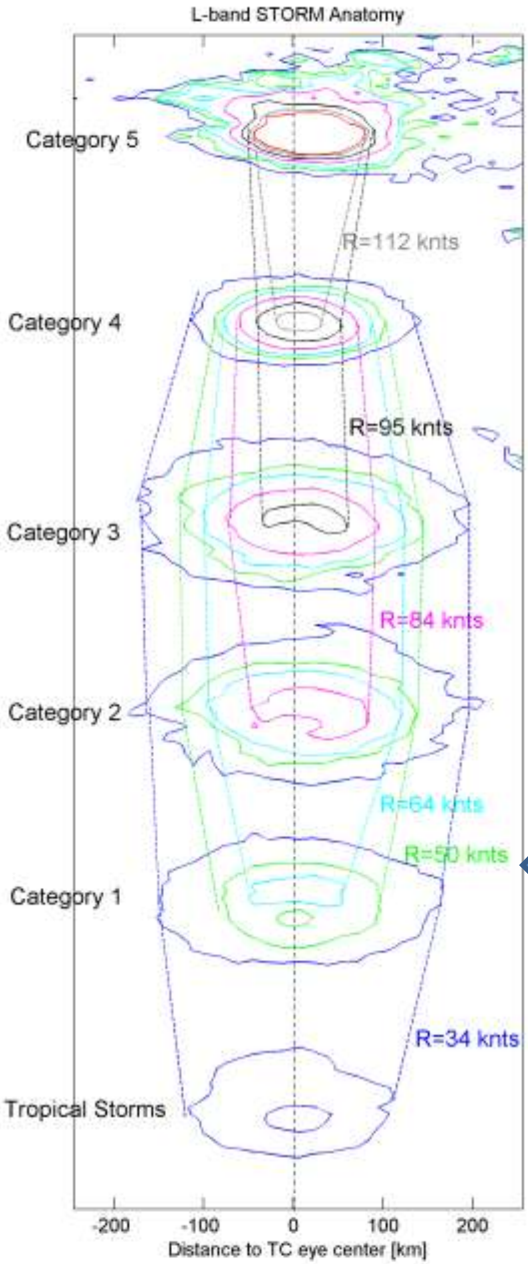




SMOS surface Tb data reveal a clear average growth of amplitude with storm intensity

=> Can be used as a Tropical cyclone intensity meter

SMOS shows sector distribution asymetries with max in RHS Storm quadrants (east)



SMOS STORM SHAKER

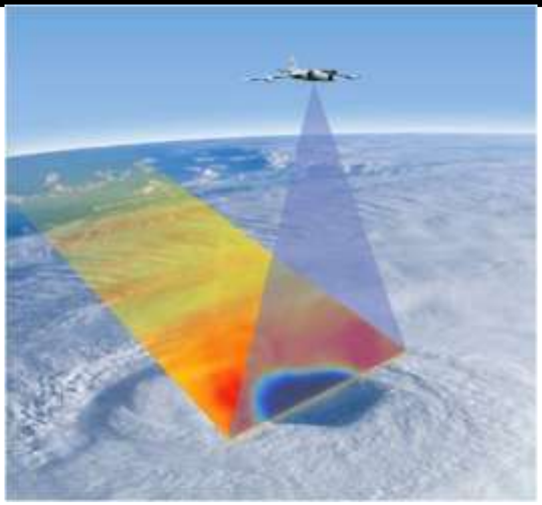
New 'average ' structural
Information on
tropical cyclones
in terms of radius of high winds

General limits of orbiting scatterometer
Wind speed monitoring capabilities

Derivation of a revised Geophysical Model Function U=f(Tb) using co-located SFMR wind speed data

64 - SFMR flights were co-localized with SMOS-STORM Tb database over 2010-2014

NOAA Hurricane hunter P-3



SFMR data from NOAA:

-C-band Tbs

-retrieved surface wind speed (6 km res)

-retrieved rain rate

-SSS along track (climato)

-SST along track (IR data)

SMOS data:

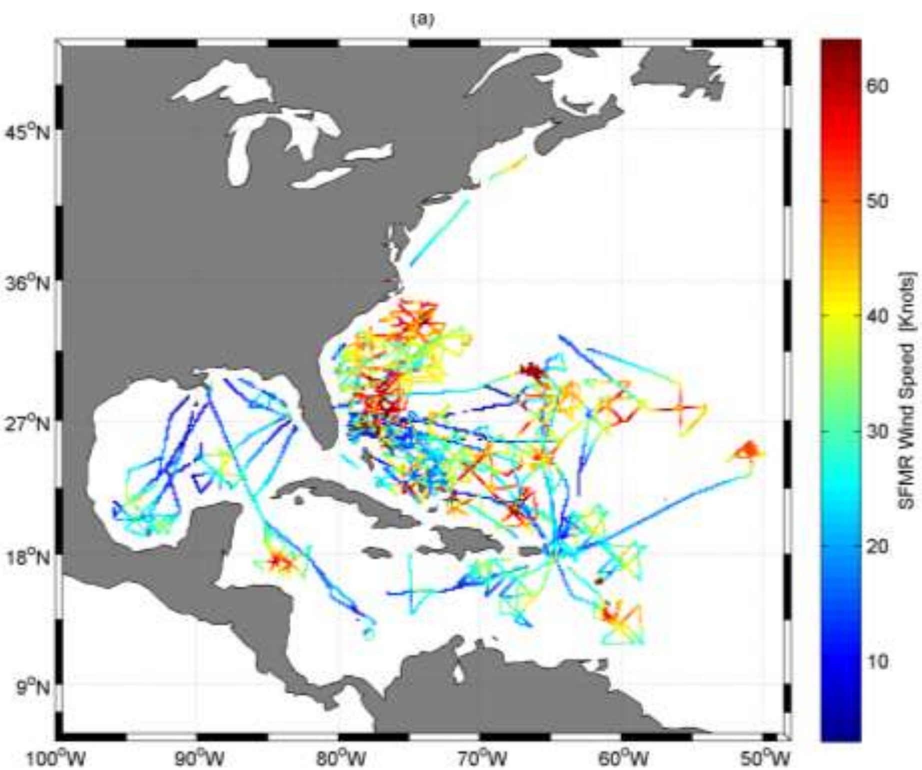
-Multi-incidence Tbs

-retrieved wind speed from SMOS 1st GMF

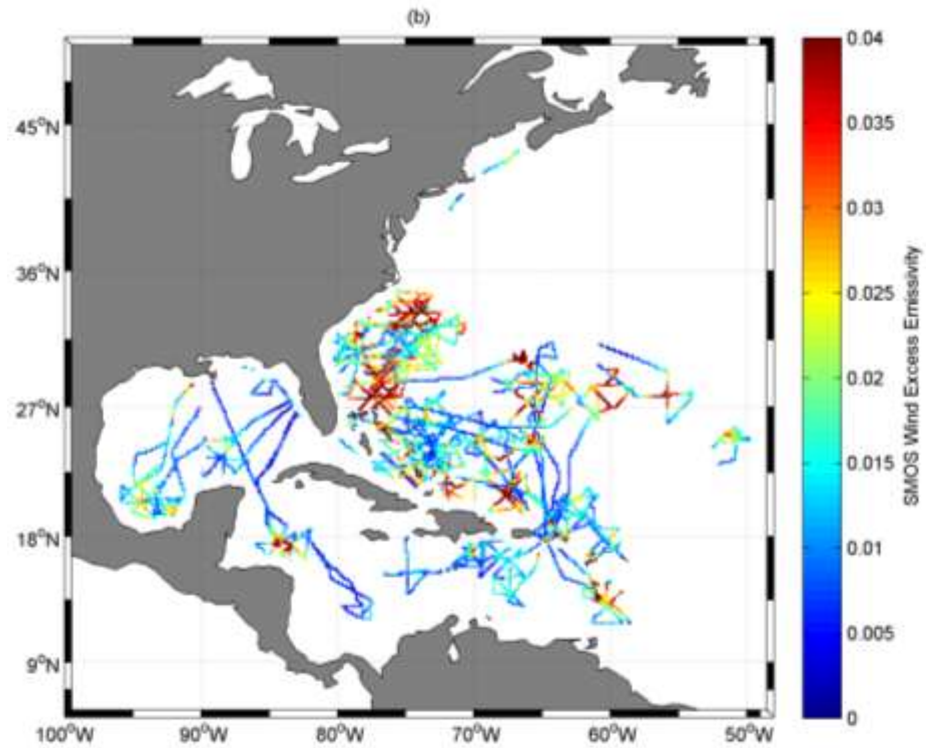
-SST ostia

-SSS from SMOS data composite of L3 during the week preceeding each storms

Derivation of a revised GMF: comparisons with SFMR and NOOA/NHC H*WIND analyses

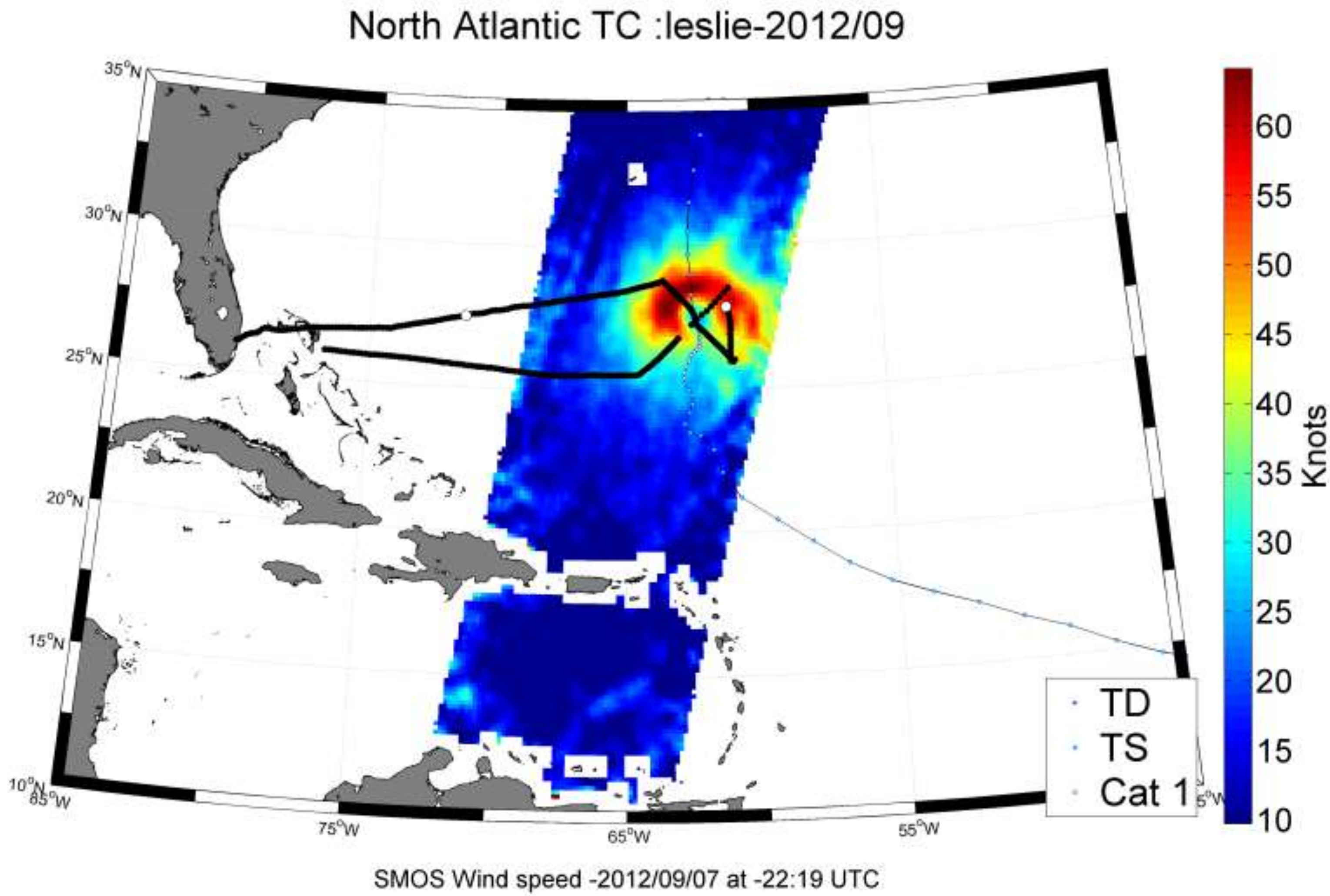


Ensemble of SFMR tracks & Wind Speed [knots]

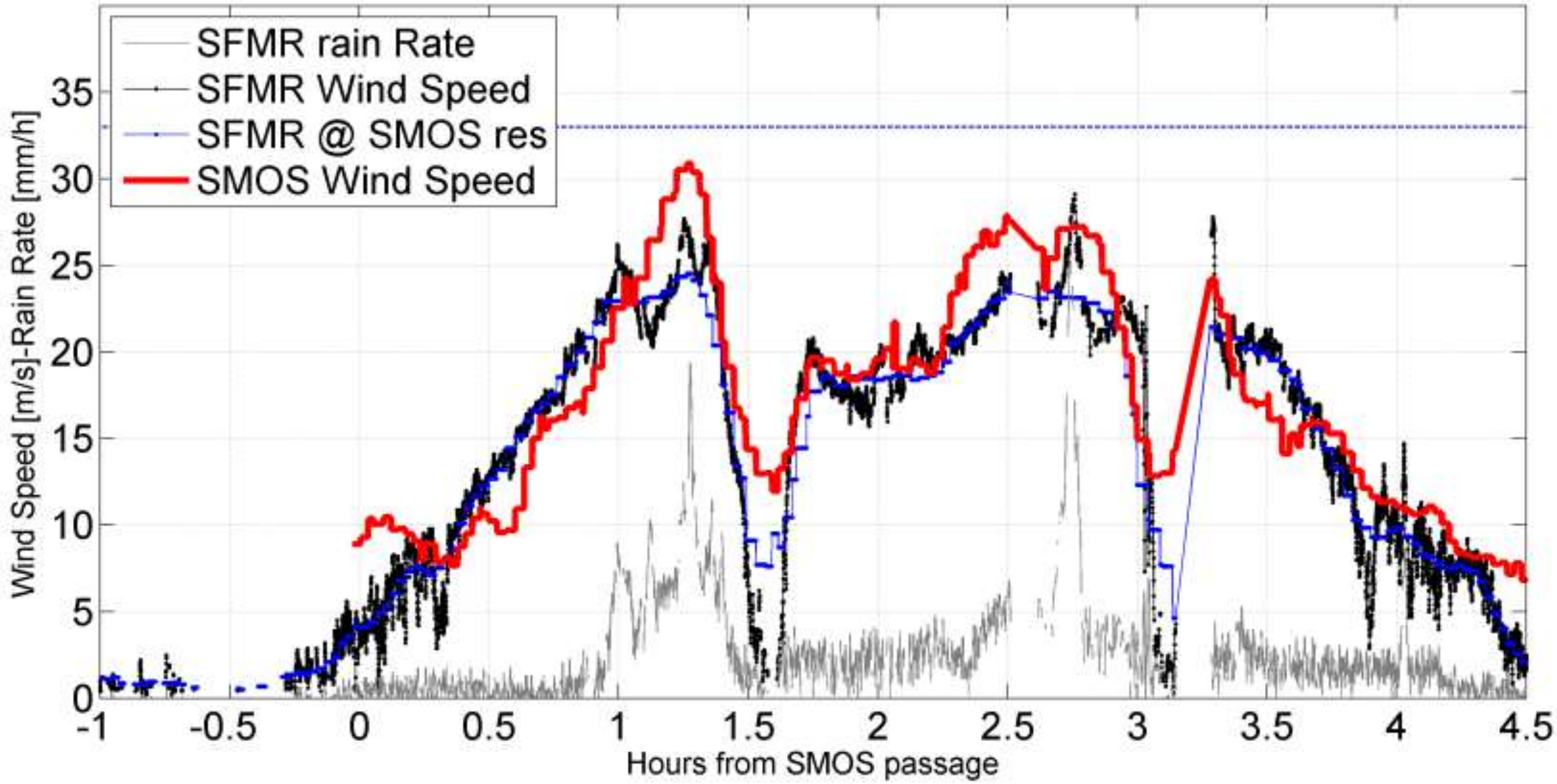


Co-localized SMOS wind Excess Emissivity
Δtime (SMOS-SFMR) < 1/2 hour

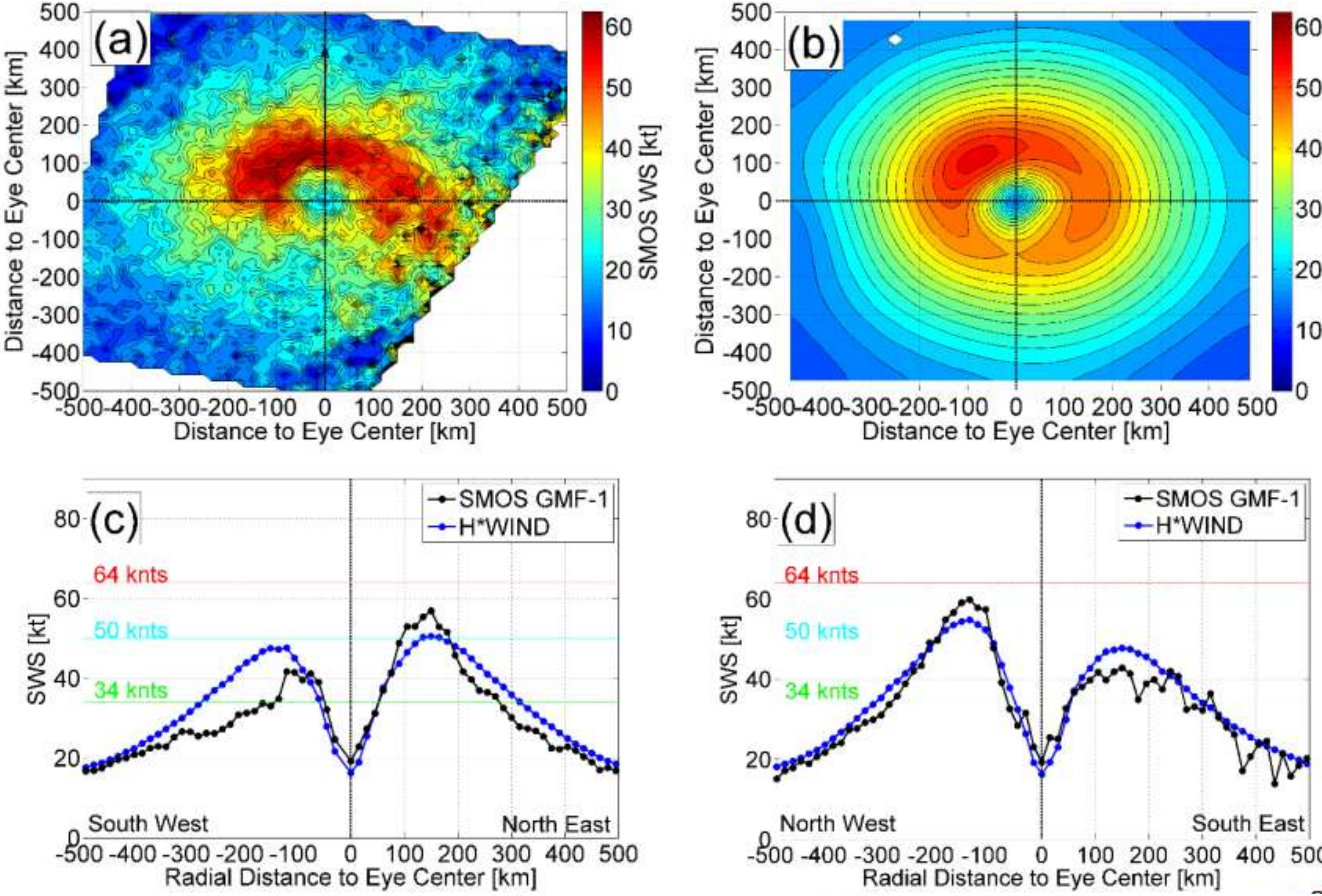
Validation: comparison with NOAA/Hurricane Research Division aircraft data : in moderately strong winds (TS &Cat 1)



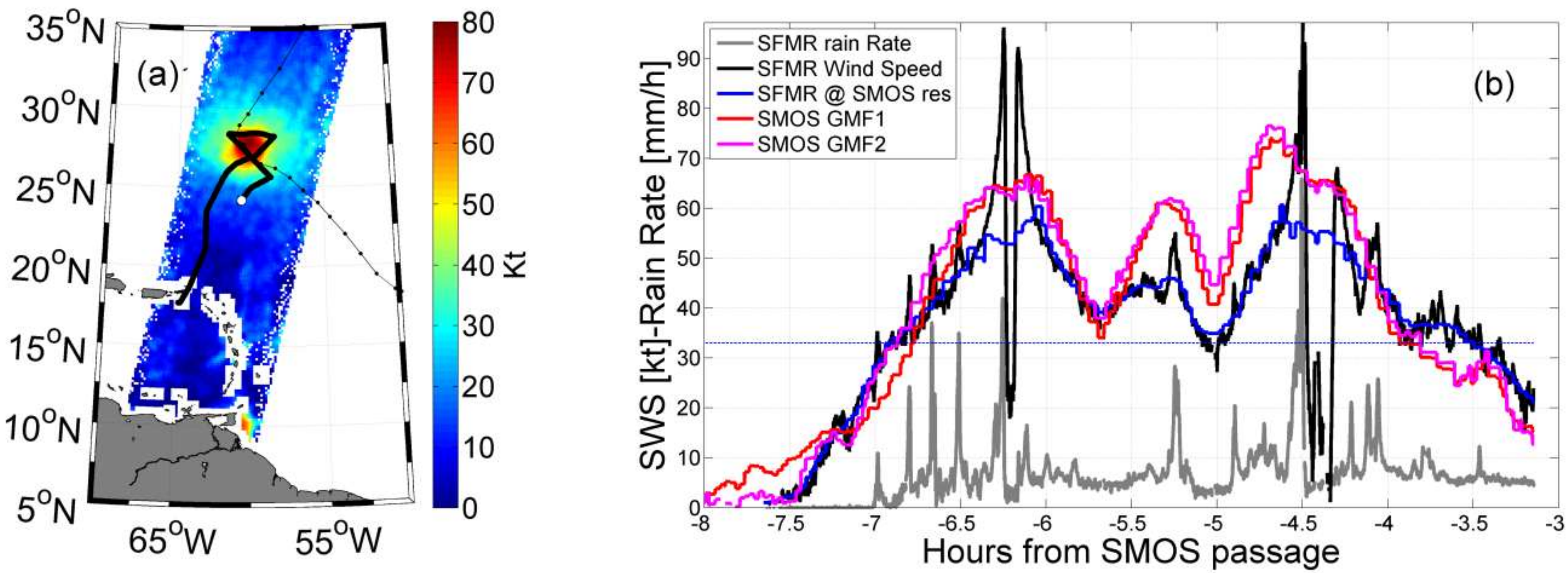
Hurricane Leslie 2012/9/7 22:19 UTC



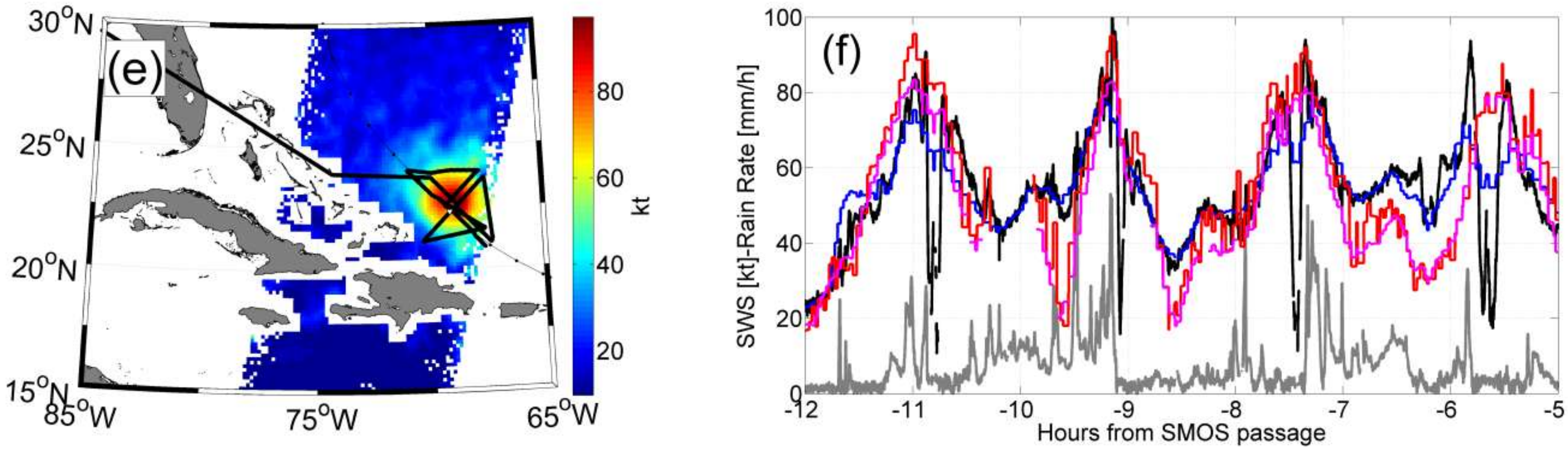
Good agreement

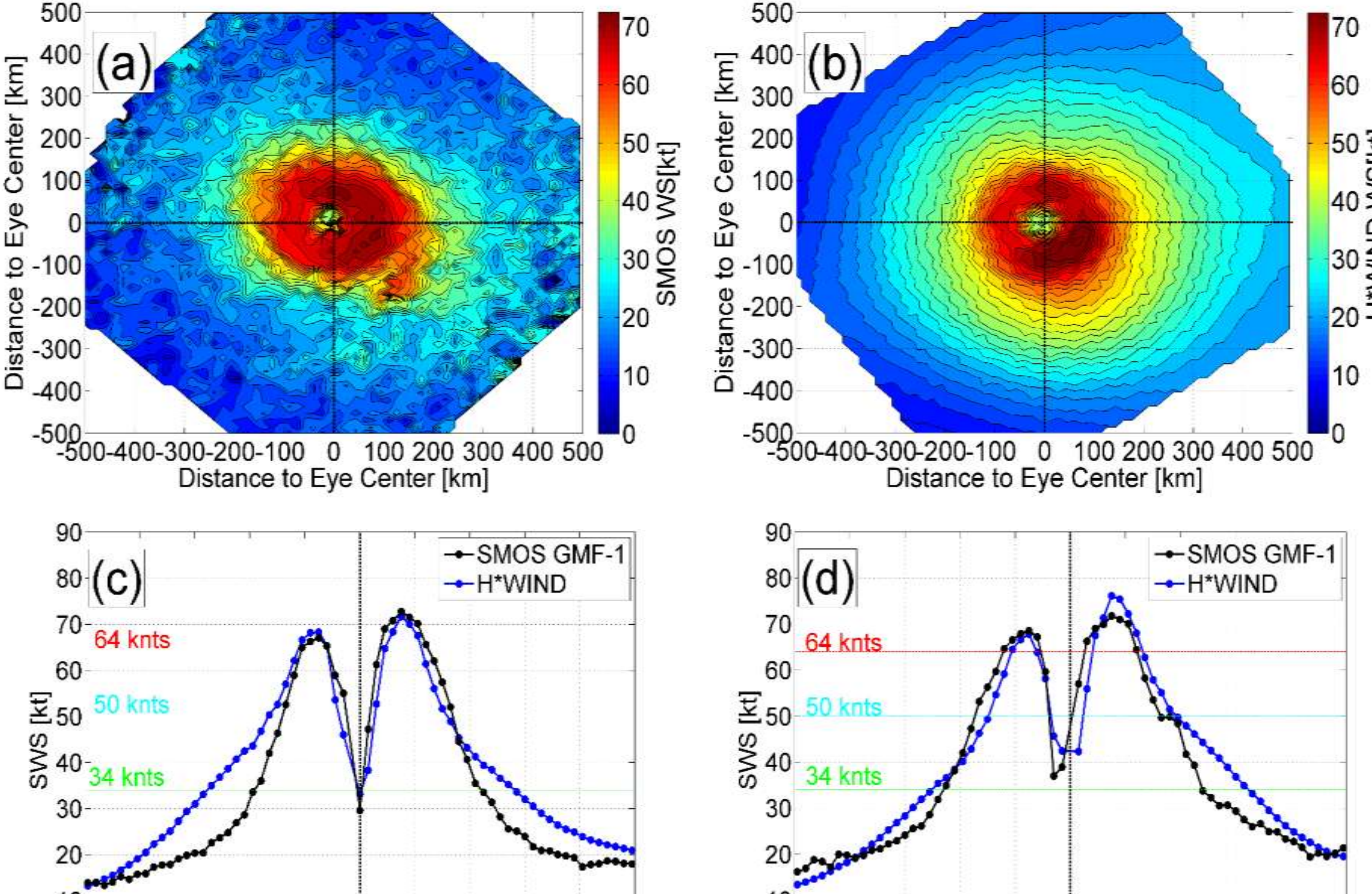

(a)
Distance to Eye Center [km]
SMOS WS [kt]
(b)
H*WIND WS[kt]
(c)
SMOS GMF-1
H*WIND
64 knts
50 knts
34 knts
SWS [kt]
South West
North East
Radial Distance to Eye Center [km]
(d)
North West
South East

hurricane Daniele the 28 August 2010

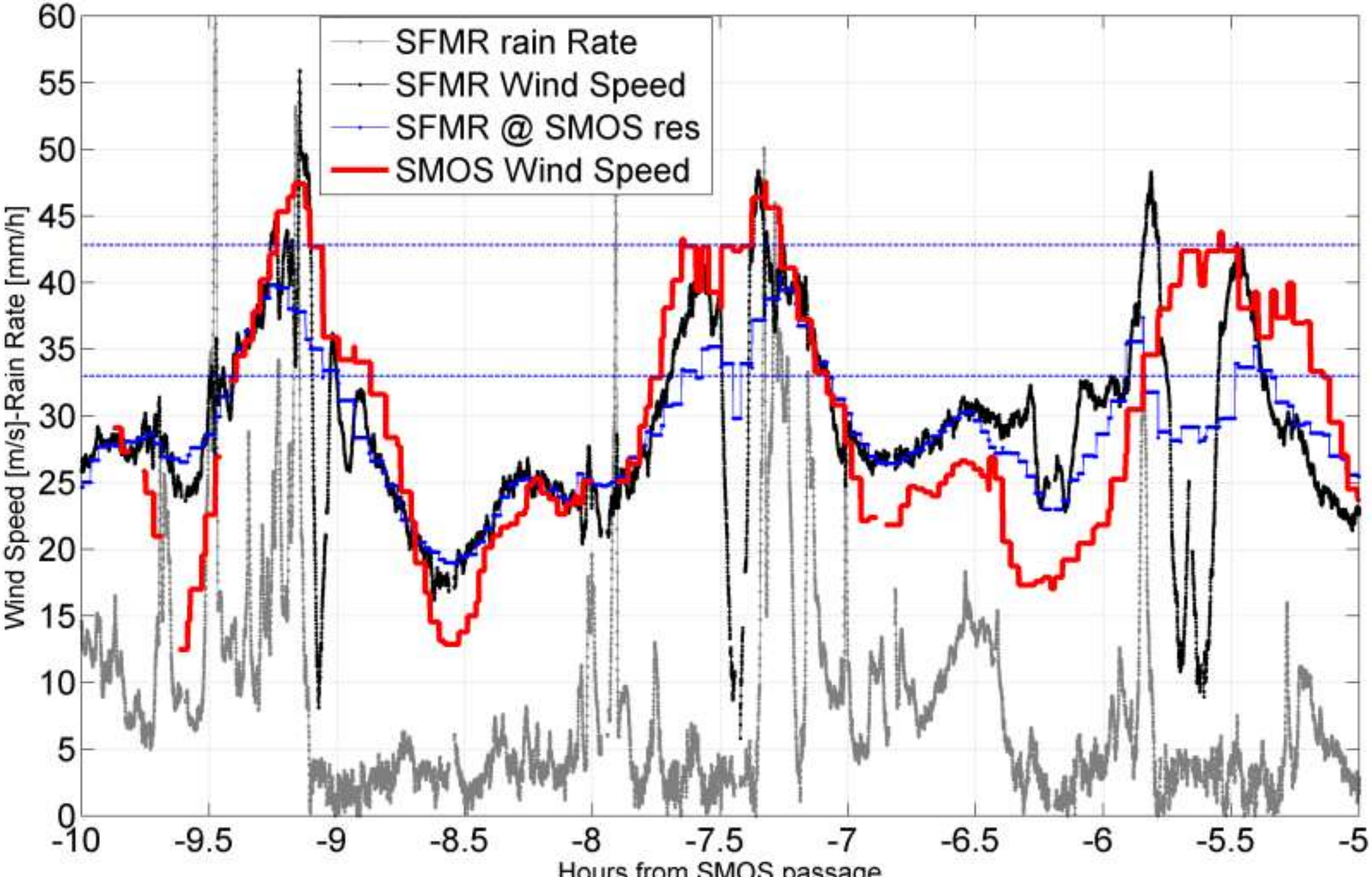


hurricane Earl on 31 August 2010

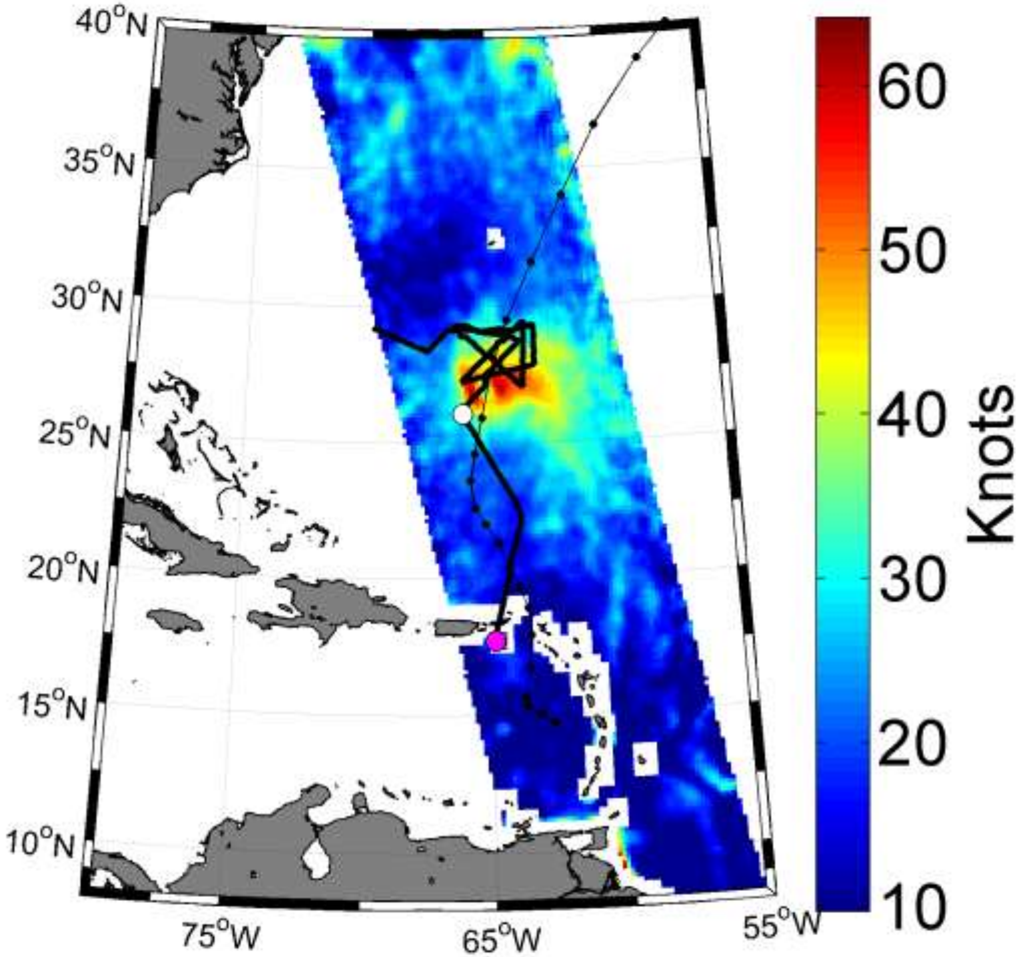




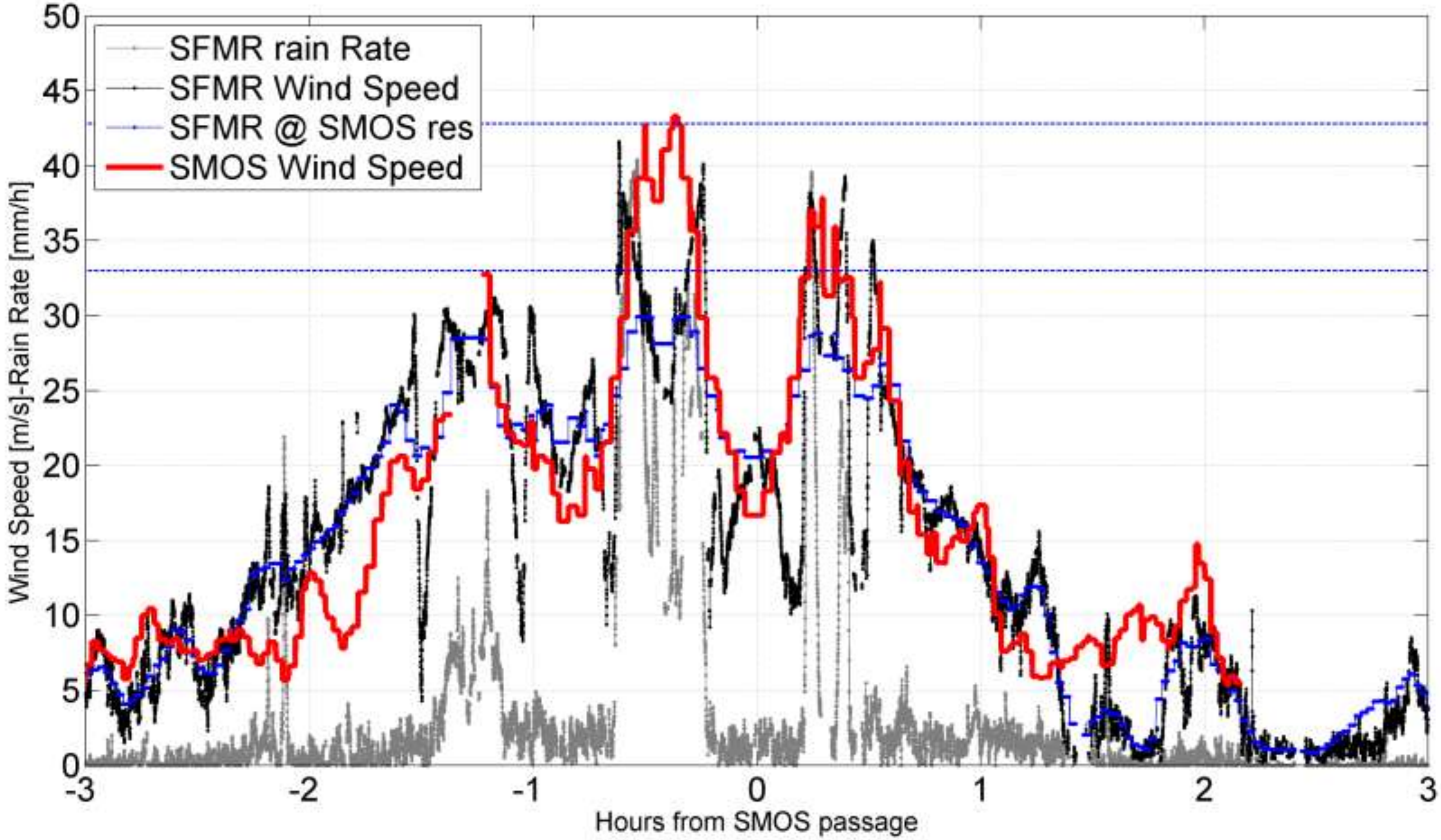
(a)
(b)
(c)
(d)
Distance to Eye Center [km]
SMOS WS[kt]
H*WIND WS[kt]
SMOS GMF-1
H*WIND
64 knts
50 knts
34 knts
SWS [kt]


SFMR rain Rate
SFMR Wind Speed
SFMR @ SMOS res
SMOS Wind Speed
Wind Speed [m/s]-Rain Rate [mm/h]
Hours from SMOS passage
60
55
50
45
40
35
30
25
20
15
10
5
0
-10
-9.5
-9
-8.5
-8
-7.5
-7
-6.5
-6
-5.5
-5

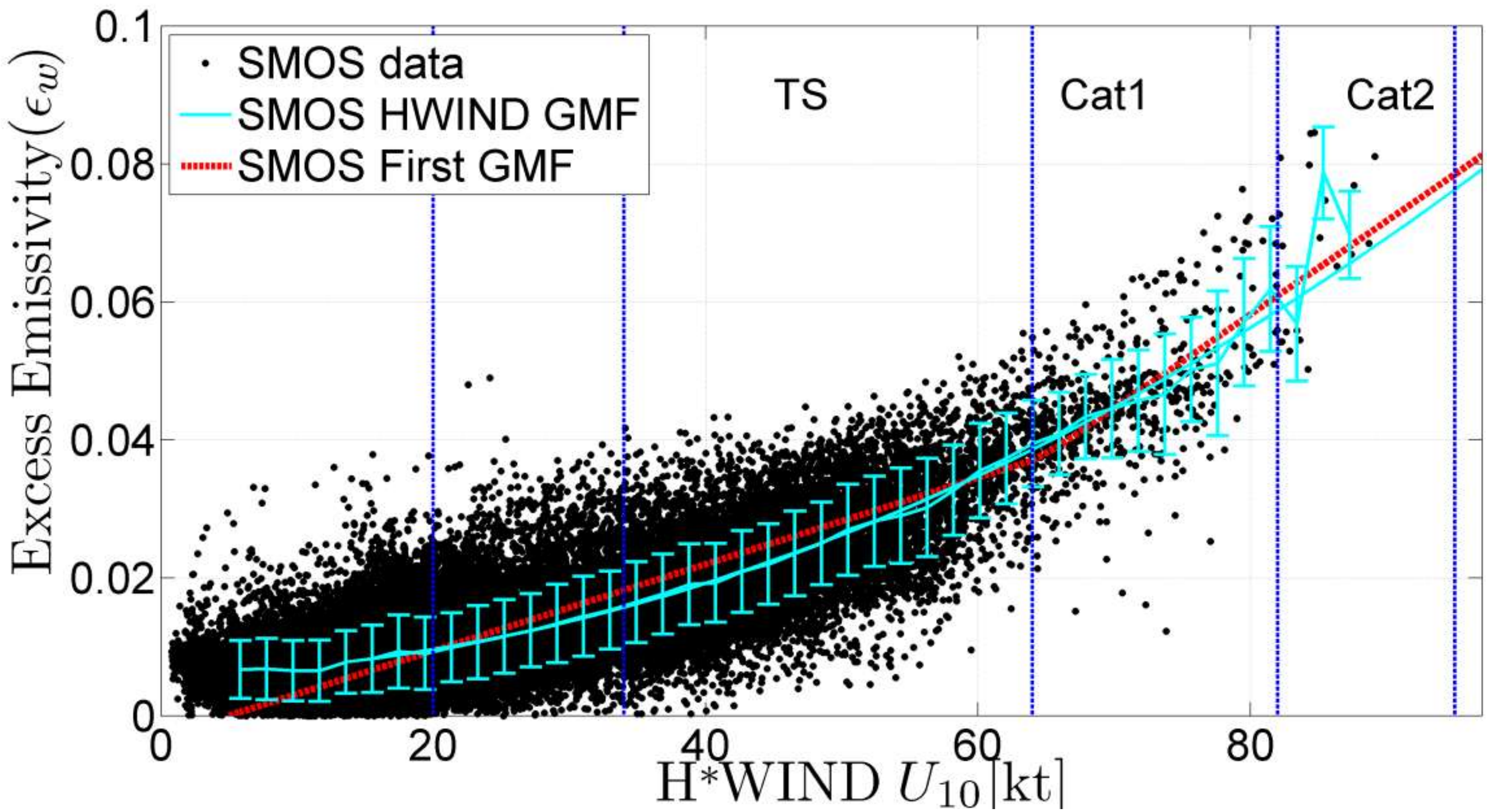
North Atlantic TC :RAFAEL-2012/10



SMOS Wind speed -2012/10/16 at -09:30 UTC


SFMR rain Rate
SFMR Wind Speed
SFMR @ SMOS res
SMOS Wind Speed
Wind Speed [m/s]-Rain Rate [mm/h]
Hours from SMOS passage
50
45
40
35
30
25
20
15
10
5
0
-3
-2
-1
0
1
2
3

New GMF



Reul Nicolas, Chapron Bertrand, Zabolotskikh E., Donlon C., Quilfen Yves, Guimbard Sebastien, Piolle Jean-Francois (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.

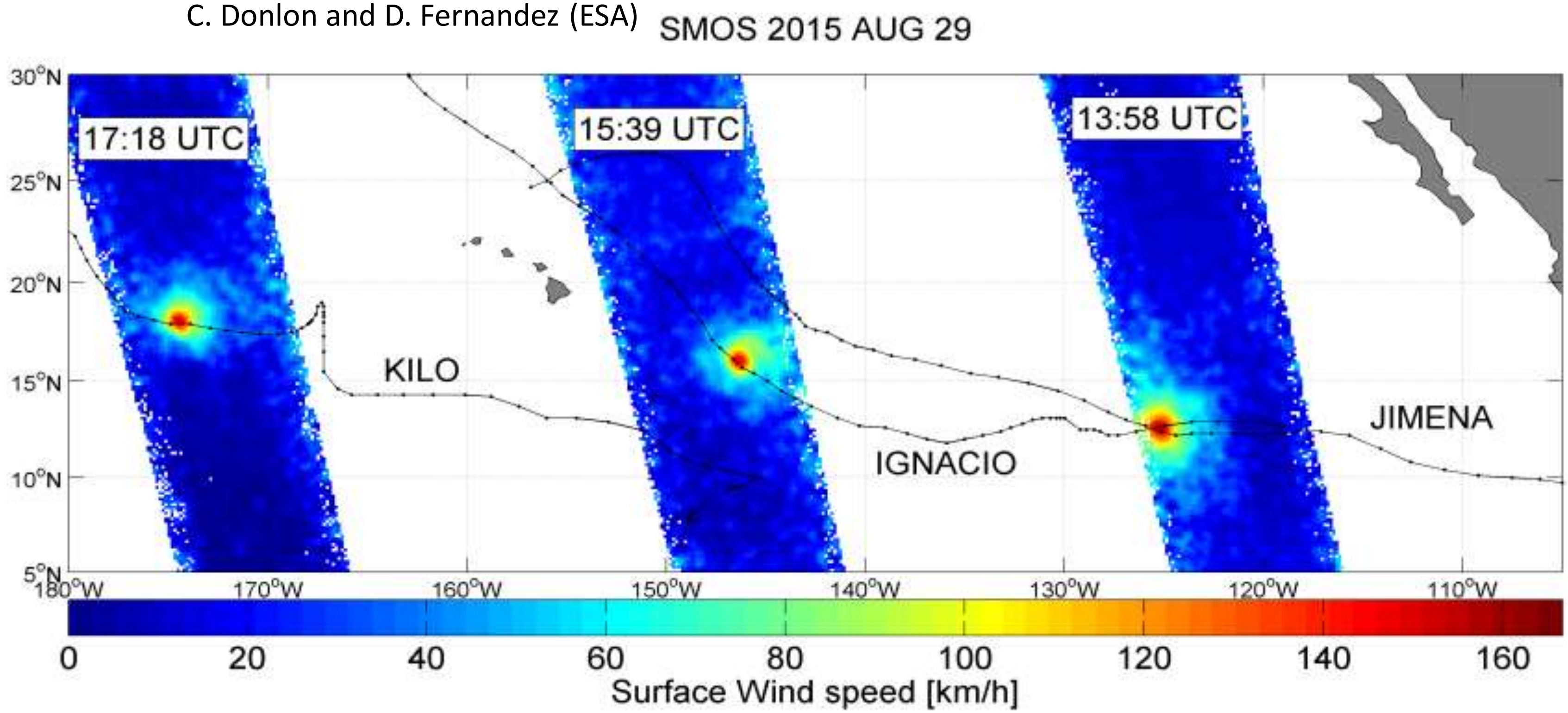
Signatures of 3 co-evolving 2015 major Hurricanes from 22 Aug to 9 Sep in the East and Central tropical Pacific as seen from SMOS, SMAP and AMSR-2 observations (beyond others)

A work in progress….by SMOS-STORM's ESA/STSE study teams:

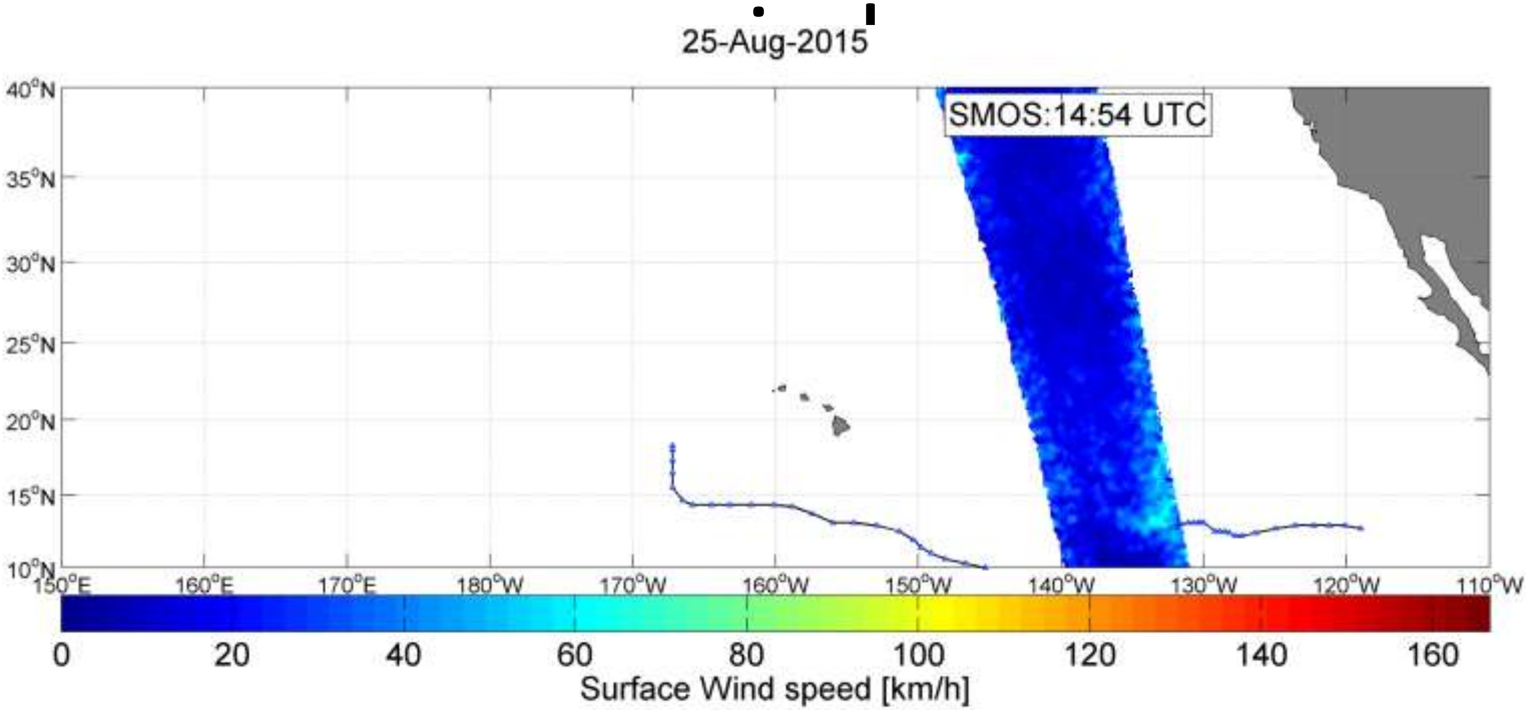
N. Reul, B.Chapron, A. Mouche, S. Guimbard, J-F Piolle & F. Paul(Ifremer)

J. Tenerelli and F. Collard (ODL), E. Zabolotskihk, P. Golubkin and V. Kudryavtsev (SOLAB)

C. Donlon and D. Fernandez (ESA)

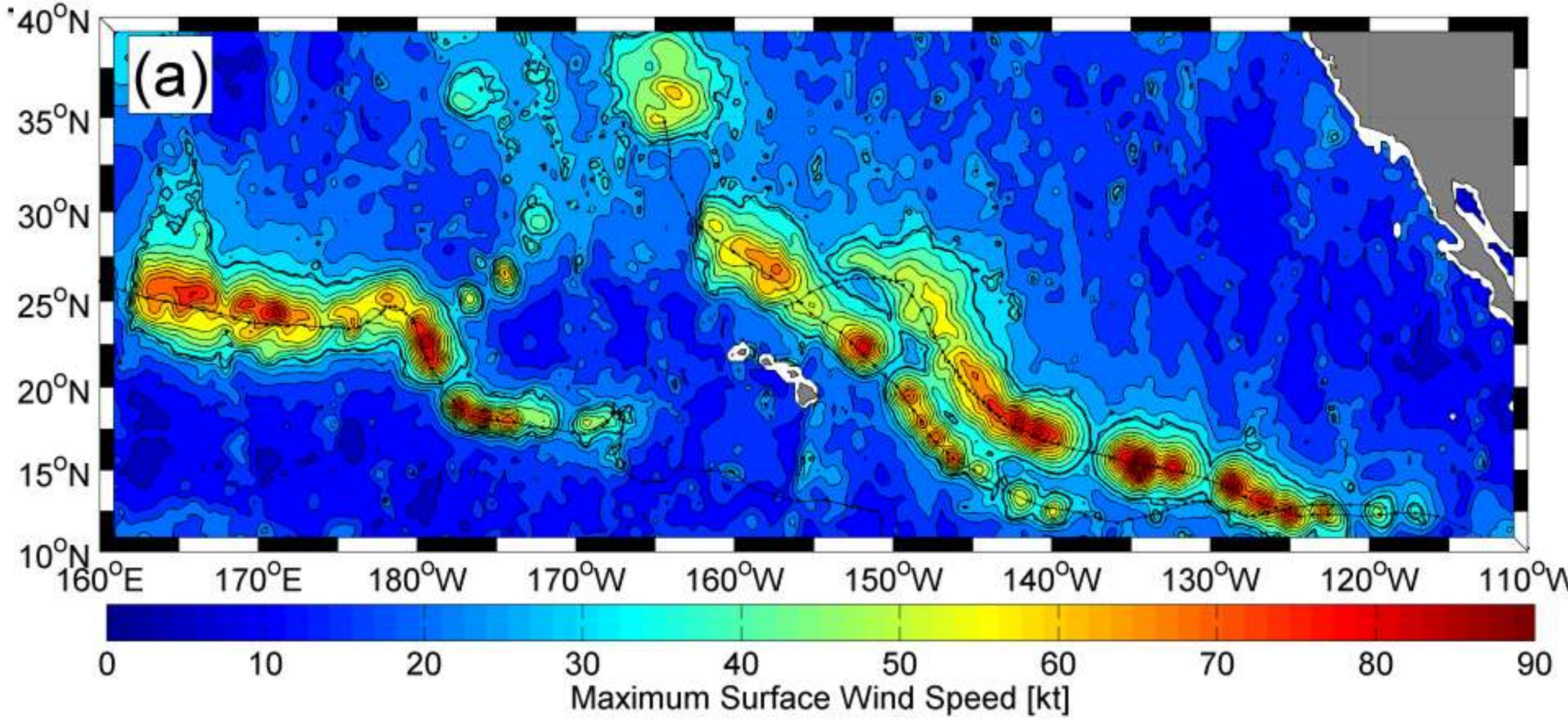


Time laps of SMOS-SMAP-AMSR-2

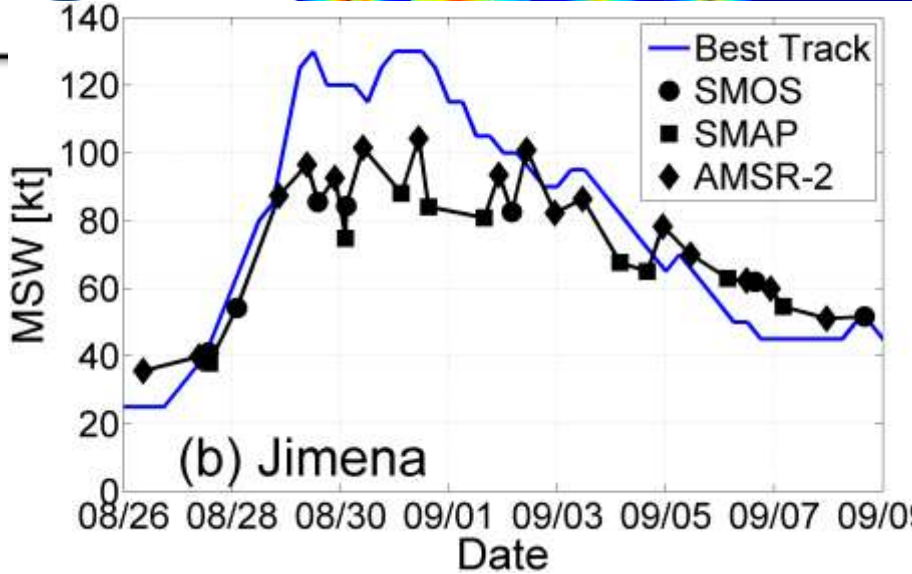


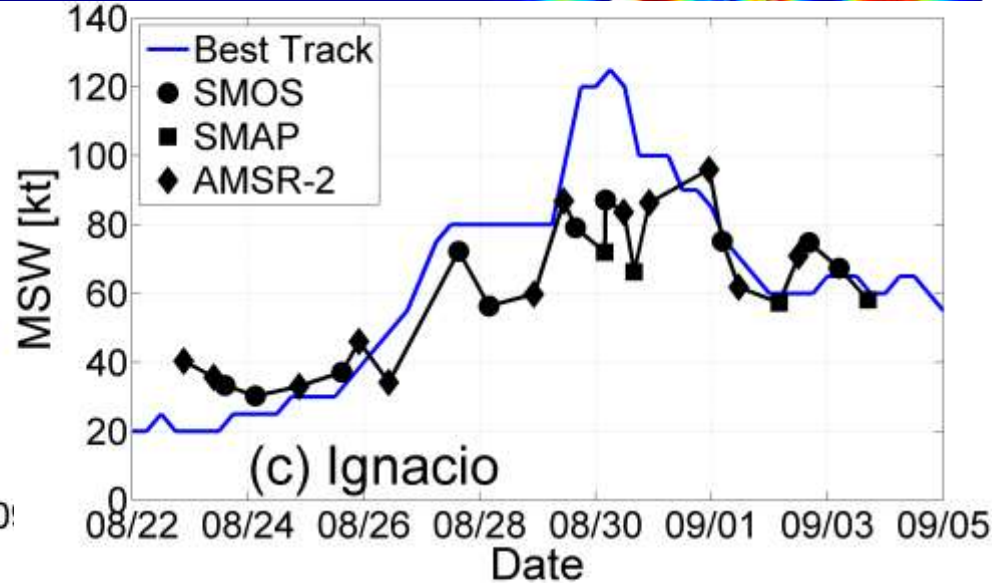
A time-series mosaic of surface wind speed measurements from 25 Aug to 8 Sep 2015 over Hurricanes Kilo, Ignacio and Jimena is shown in this animation. Data from three satellite microwave radiometer missions: the ESA L-band SMOS mission, the recently launched NASA L-band SMAP mission and JAXA C-band AMSR-2 mission are combined before your eyes to reveal the track of each Hurricane and the maximum surface wind speed.

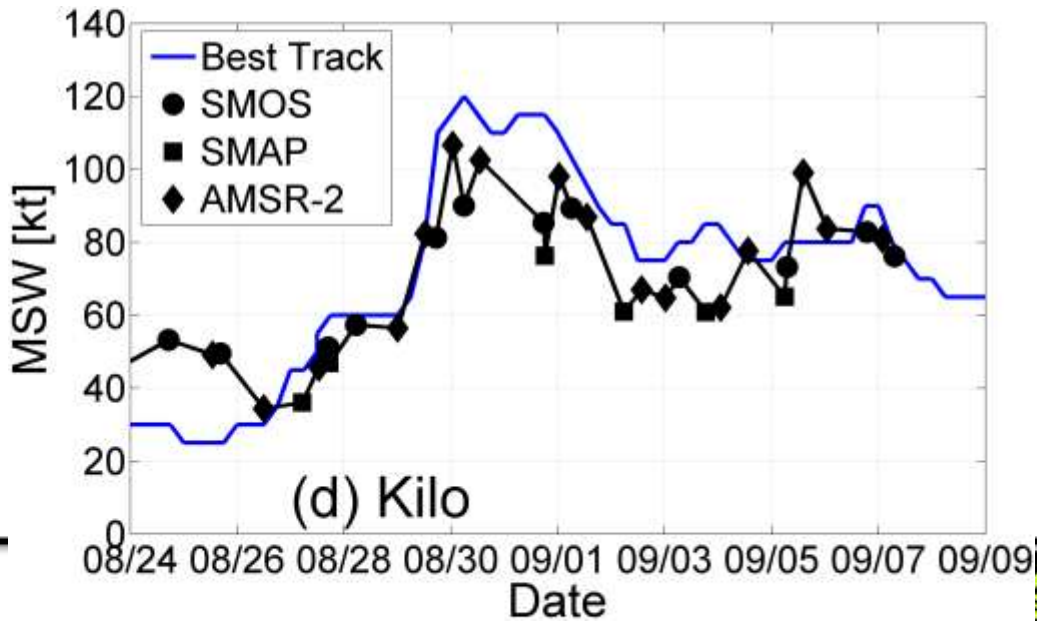
32, 26 and 35 intercepts of Jimena, Ignacio and Kilo respectively



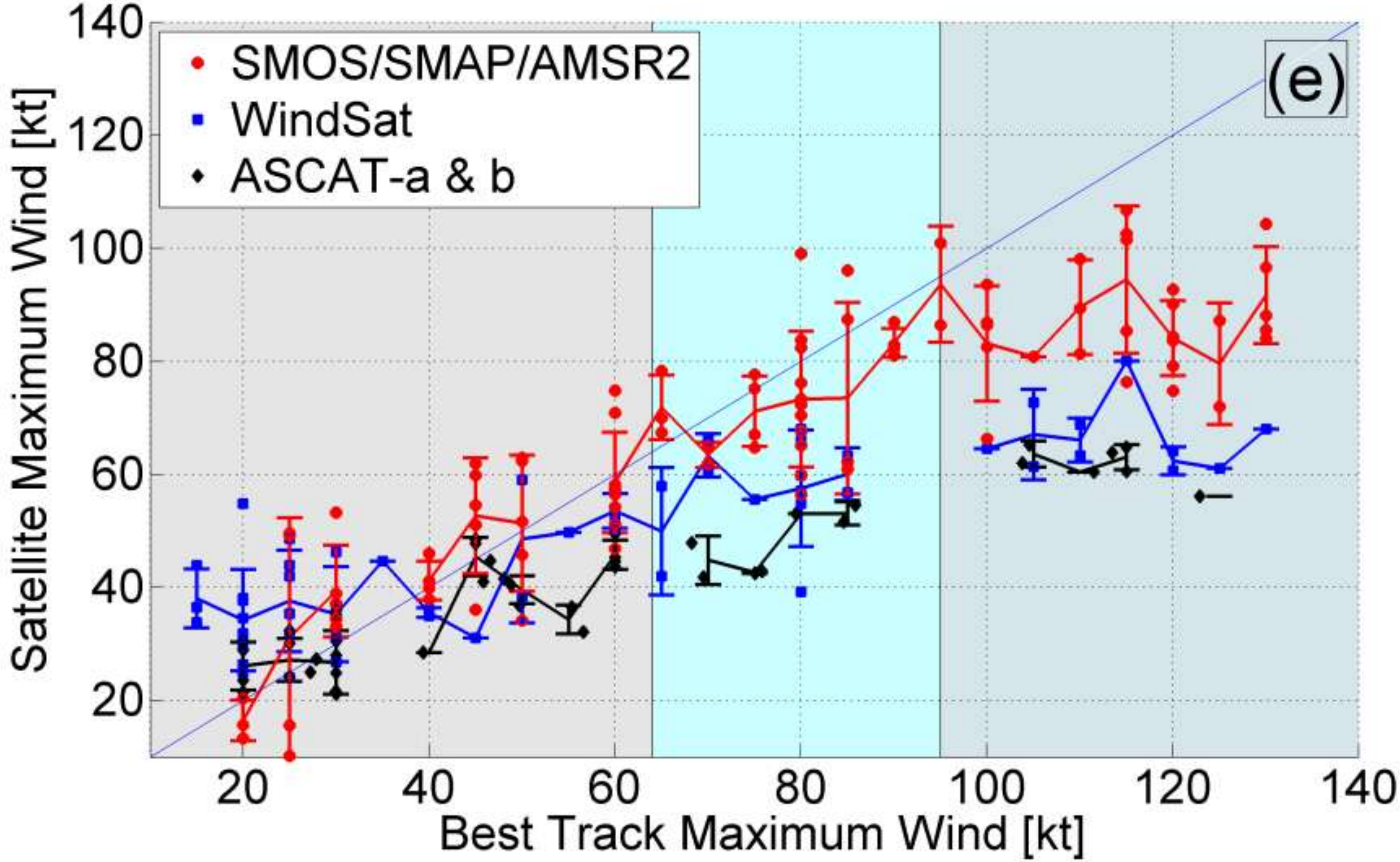
Caption: Contours of the domains showing the maxima of surface winds obtained from the combined multiple observations of SMOS, SMAP and AMSR-2 sensors from 22 Aug to 9 Sep 2015 showing the high wind trails over Hurricanes Kilo and Loke (left), Ignacio (center), Jimena (right).


Best Track
SMOS
SMAP
AMSR-2
MSW [kt]
Date
(b) Jimena
08/26 08/28 08/30 09/01 09/03 09/05 09/07


Best Track
SMOS
SMAP
AMSR-2
MSW [kt]
Date
(c) Ignacio
08/22 08/24 08/26 08/28 08/30 09/01 09/03 09/05


Best Track
SMOS
SMAP
AMSR-2
MSW [kt]
Date
(d) Kilo
08/24 08/26 08/28 08/30 09/01 09/03 09/05 09/07 09/09

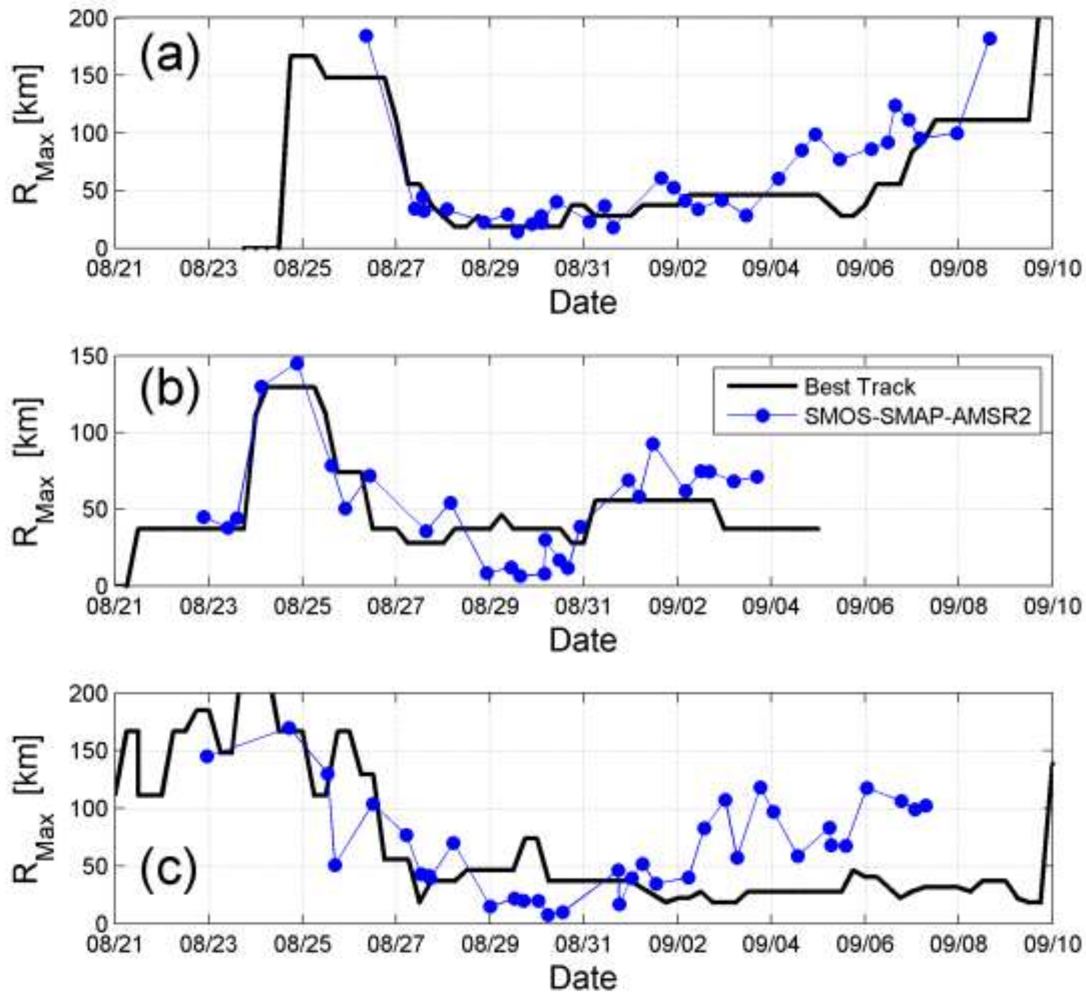
Met Office



Gain of Wind Speed Sensing capability from Hurricane Cat 1 (64 kt) to Category 2 (95 kts)
Saturation above ~100 kts due to spatial resolution

Radius of Maximum Winds:

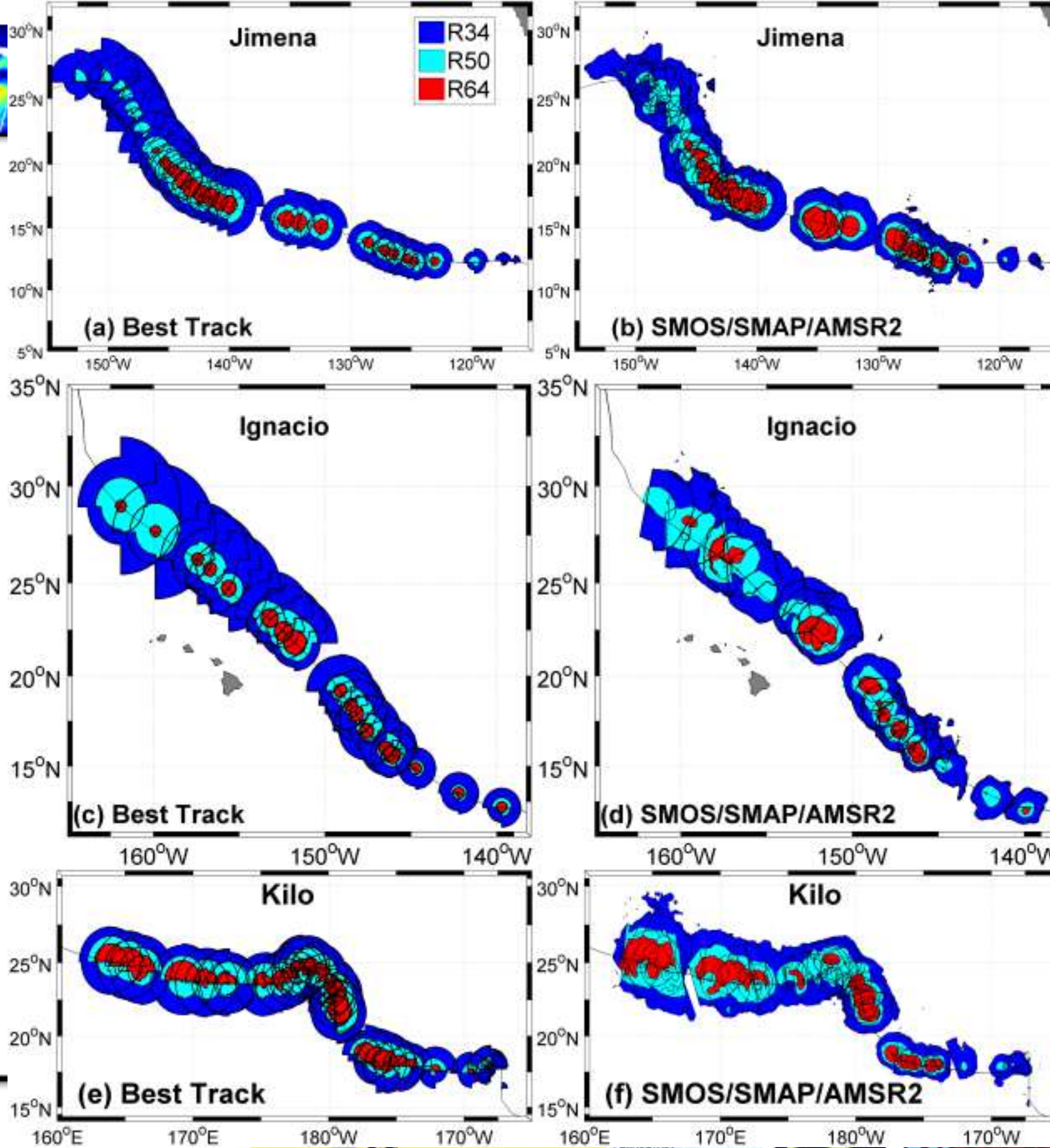
A key TC structural parameter
well retrieved



smos+ storms
support to science element

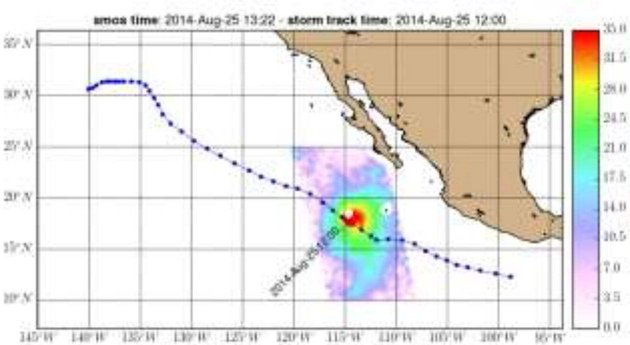
34-, 50-, and 64-kt wind radii being displayed in blue, cyan, and red, Winds:

Other key TC structural parameters
well retrieved
By SMOS, SMAP
And AMSR-2



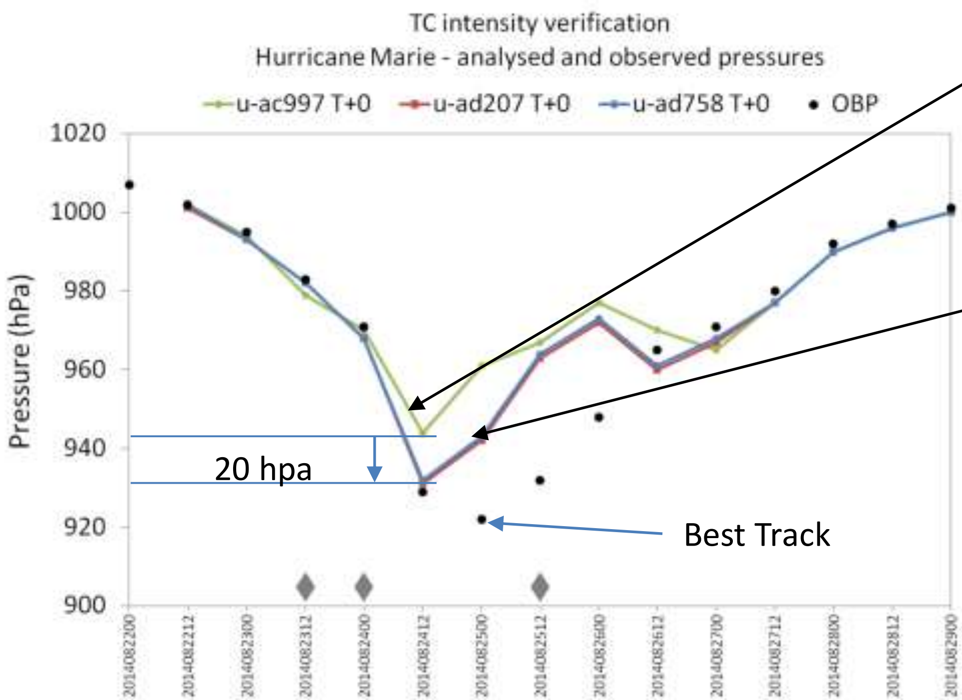
esa
Ifremer
Met Office

Marie (2014) - SMOS



- Initial experiments have been conducted at the Met Office to examine the impact of assimilating SMOS wind speeds on NWP analyses and forecasts of tropical storms
- Hurricane Marie (2014) located in the East Pacific was chosen as an initial NWP case study since it was a very intense storm (MSW of 160 mph and minimum pressure of 918 hPa=Cat 5) and there were several SMOS intercepts around peak intensity. A series of short assimilation experiments were performed from 19-31 August 2014, covering the main lifecycle of Marie. A control experiment was run in order to provide a reference and this incorporated all model and observational upgrades made to the global model since 2014.
- The set of observations assimilated included all conventional and satellite observations, with ocean surface wind vectors observations assimilated from ASCAT on Metop-A/B and WindSat.
- A set of trial experiments was run to include the addition of SMOS wind speeds above a minimum wind speed threshold of 15 m/s. After quality control, e.g. to remove possible RFI contamination, the SMOS observations were thinned to a distance of 80-km to mitigate the impact of spatial error correlations (since the assimilation assumes errors to be uncorrelated). The initialization and forecasts of Hurricane Marie's intensity and track were validated for each of the experiments using BT data. Here we present results from two trial experiments, using assumed observation errors for SMOS of 2.25 m/s and 2.5 m/s.

- As shown next slide, initial results from assimilating SMOS only to improve TC intensity in NWP are promising and further experiments are in-progress, considering longer periods



Observed and analysed central pressure estimates for Hurricane Marie at 12-hour intervals from 22 – 29 August 2014. The green line is from the control experiment and the red and blue lines are experiments assimilating SMOS with observation errors of 2.25 m/s and 2.5 m/s respectively. Best Track pressures are shown by the black dots and SMOS intercept times are shown by the grey diamonds.

Control experiment:
the central pressure was found to be too weak in the analysis and at short lead times, but slightly too strong at longer range. Maximum winds were similarly too weak in the analysis and short-range forecasts.

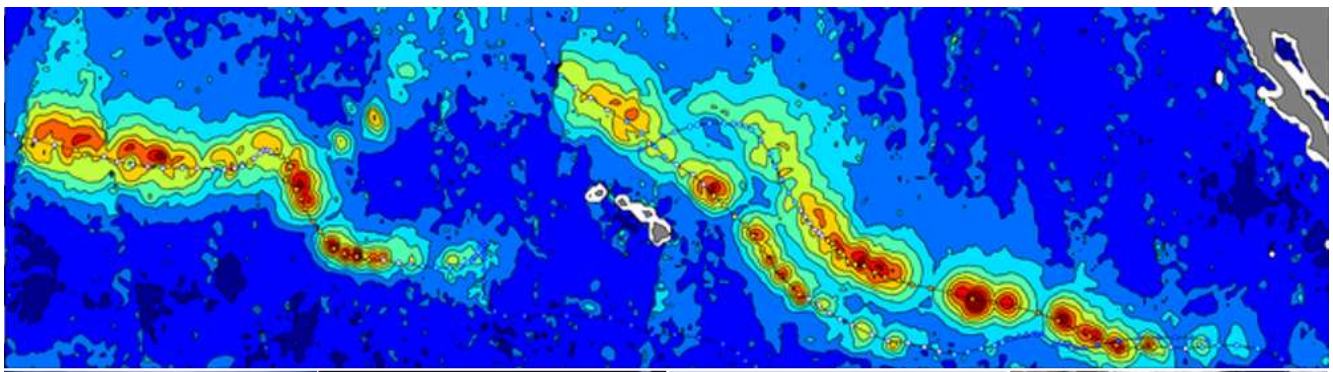
Experiments assimilating SMOS that Absolute wind errors and pressure errors at T+0 were reduced by around 3.0 mb and 3.0 knots respectively, with small improvements also seen at short lead times

SMOS experiments produce a more intense storm and **central pressure errors are reduced by ~20 hPa at peak intensity.** Note that although SMOS does not intercept the storm in the cycles on 12Z/24 August and 00Z/25 August, the **analysed pressure error is still reduced because of the improved background state** carrying forward the information from assimilating SMOS in previous cycles.
TC track errors for Marie are improved by 5% at T+0 but forecast tracks are either neutral or worse.

INTERNATIONAL WORKSHOP ON MEASURING HIGH WIND SPEEDS OVER THE OCEAN

UK Met Office Exceter
15-17 November 2016

http://www.metoffice.gov.uk/conference/ocean-winds-workshop



Summary and Conclusions

- A clear SMOS brightness temperature signal (ΔT_B) 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.up to 50 m/s
- SMOS can retrieve important structural surface wind features within hurricanes such as the radius of wind speed larger than 34, 50 and 64 knots. These are Key parameters to monitor tropical cyclone intensification
- An extensive database of Storms has been developed for TC and ETC storms for 2009-2016 and is available to the community
- SMOS wind speed data assimilation experiments at the UK Metoffice will be performed in the next months to investigate the data impact on storm track & intensity forecasts skills