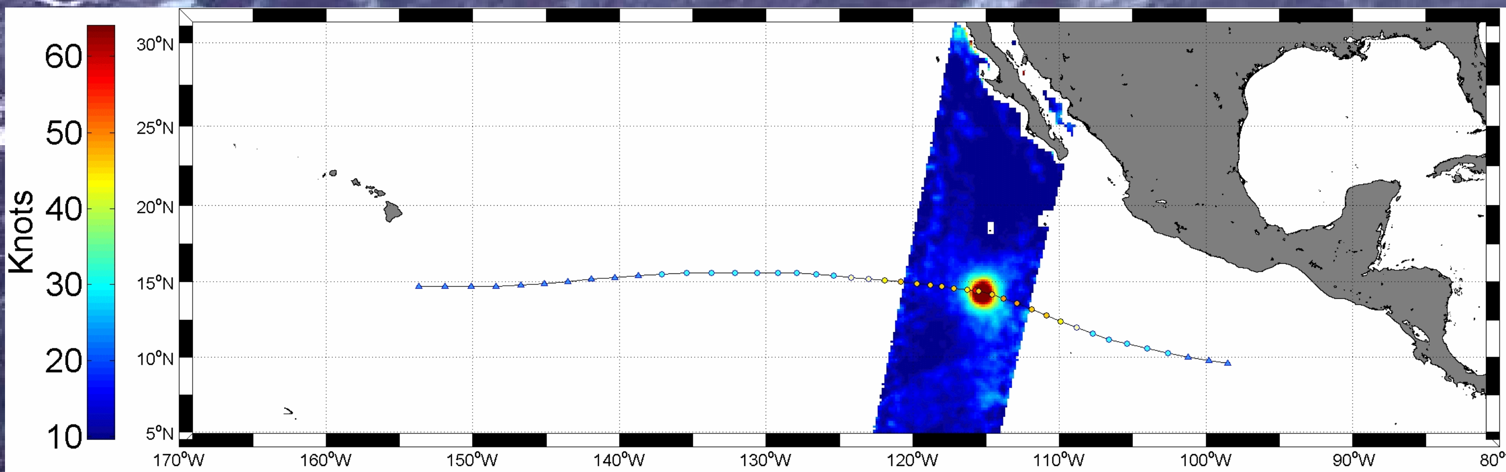
smos+ storms
support to science element

Severe Marine Weather Studies using SMOS L-Band Sensor Data and Multi-Sensor Synergies

N. Reul, E. Zabolotskikh, B. Chapron, Y. Quilfen, F. Collard, J. Cotton, P. Francis & V. Kudryavtsev



ESA-SOLAS-EGU
EO4OcAtm-2014

esa · Ifremer · SOLab Satellite Oceanography Laboratory · Met Office · oceandatalab making sense of the deep blue sea

Tropical cyclone & Extra-Tropical storm track prediction is steadily improving, while **storm intensity prediction has seen little progress** in the last quarter century.

⇒Important physics are not yet well understood and implemented in tropical cyclone forecast models.

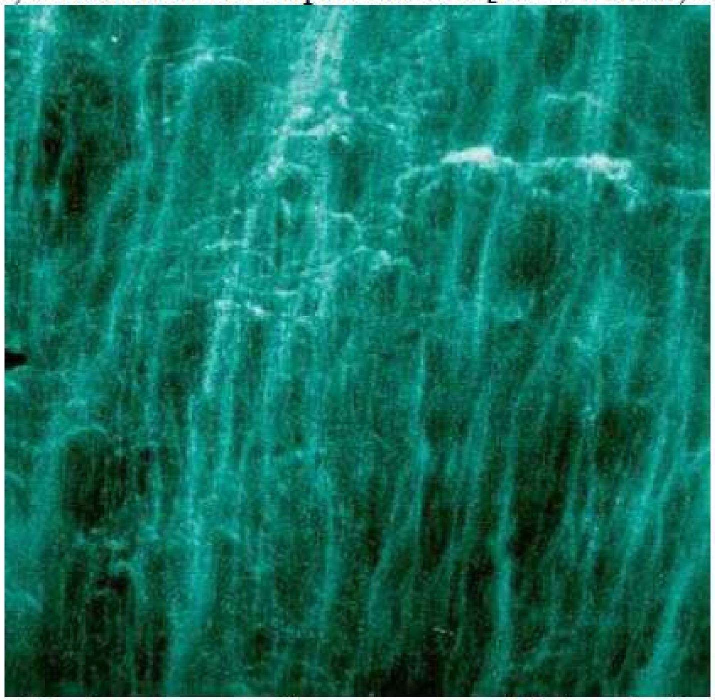
⇒Missing and unresolved physics, especially at the air-sea interface, are among the factors limiting storm predictions.

➢Detail Information on **surface winds under Tropical Cyclones** are key to better storm forecasting. However, their **measurements from Space with traditional onboard instruments** (radars, high-frequency radiometers) **is challenging** (rain contamination, lost of sensitivity at very high winds,..)

Focus here: study of low-microwave frequency radiometer capabilities & new inputs from L-band missions (SMOS, SMAP) for ocean surface remote sensing in extreme conditions

Ocean-Atmosphere Interface in very High Wind speed conditions

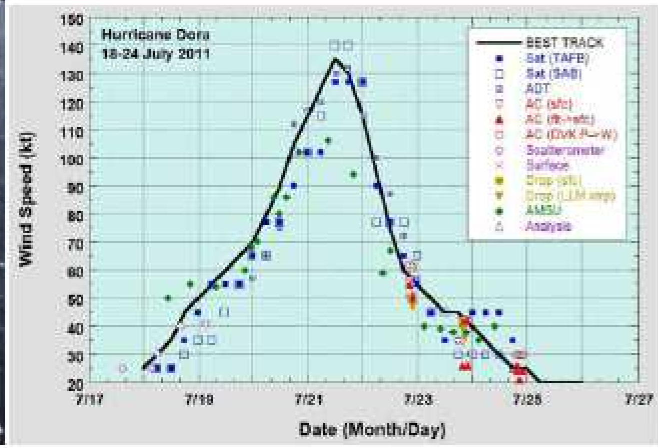
A breaking wave creates a patch of active foam at its crest – the white cap. As the wave moves on, the leading edge of the white cap follows the breaking crest but the trailing edge remains stationary and is slowly replaced by submerged bubbles in wind-aligned streaks. At very high wind speeds the white 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.

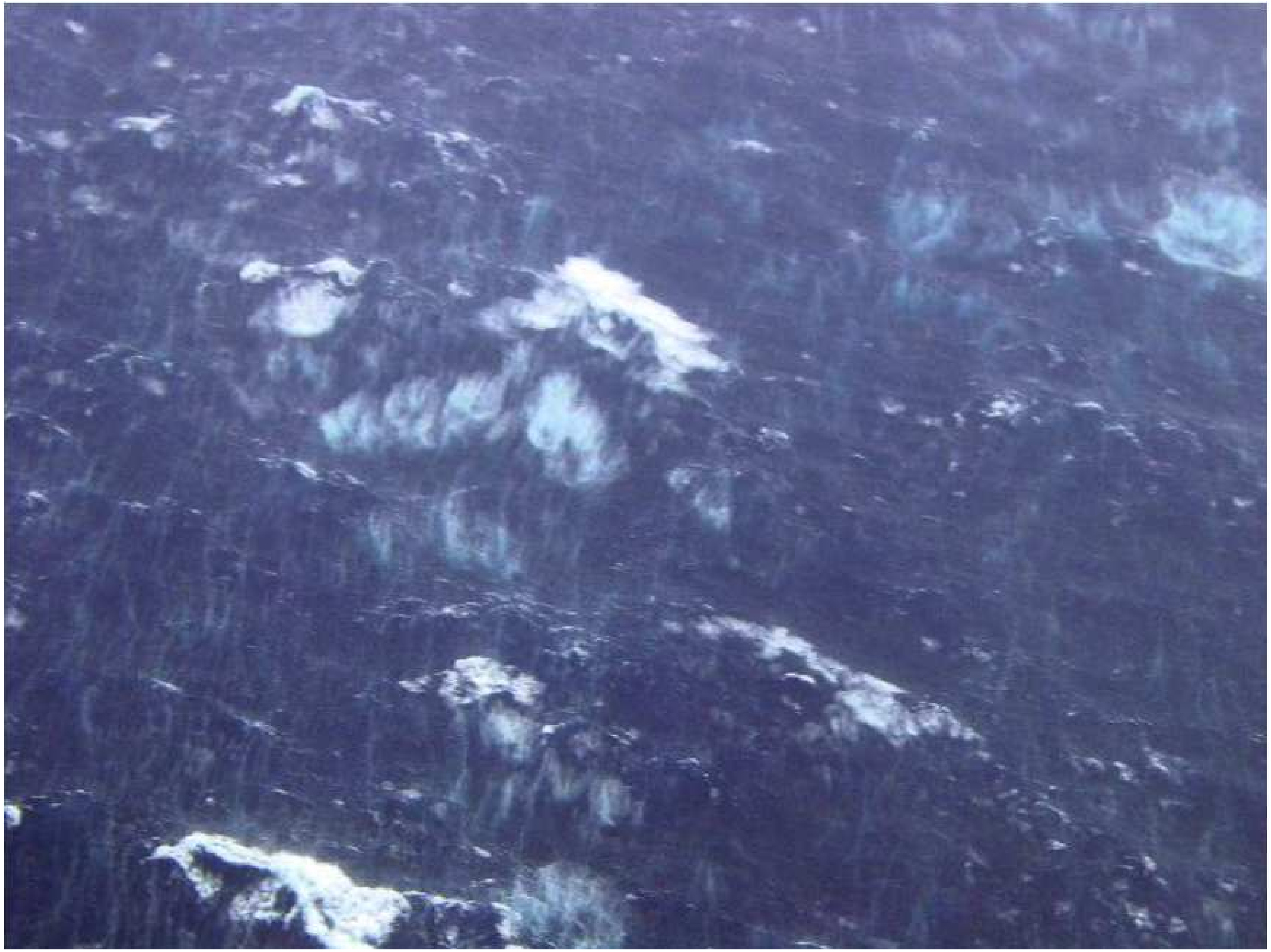
Sea surface as observed from 500 feet in Hurricane Belle.

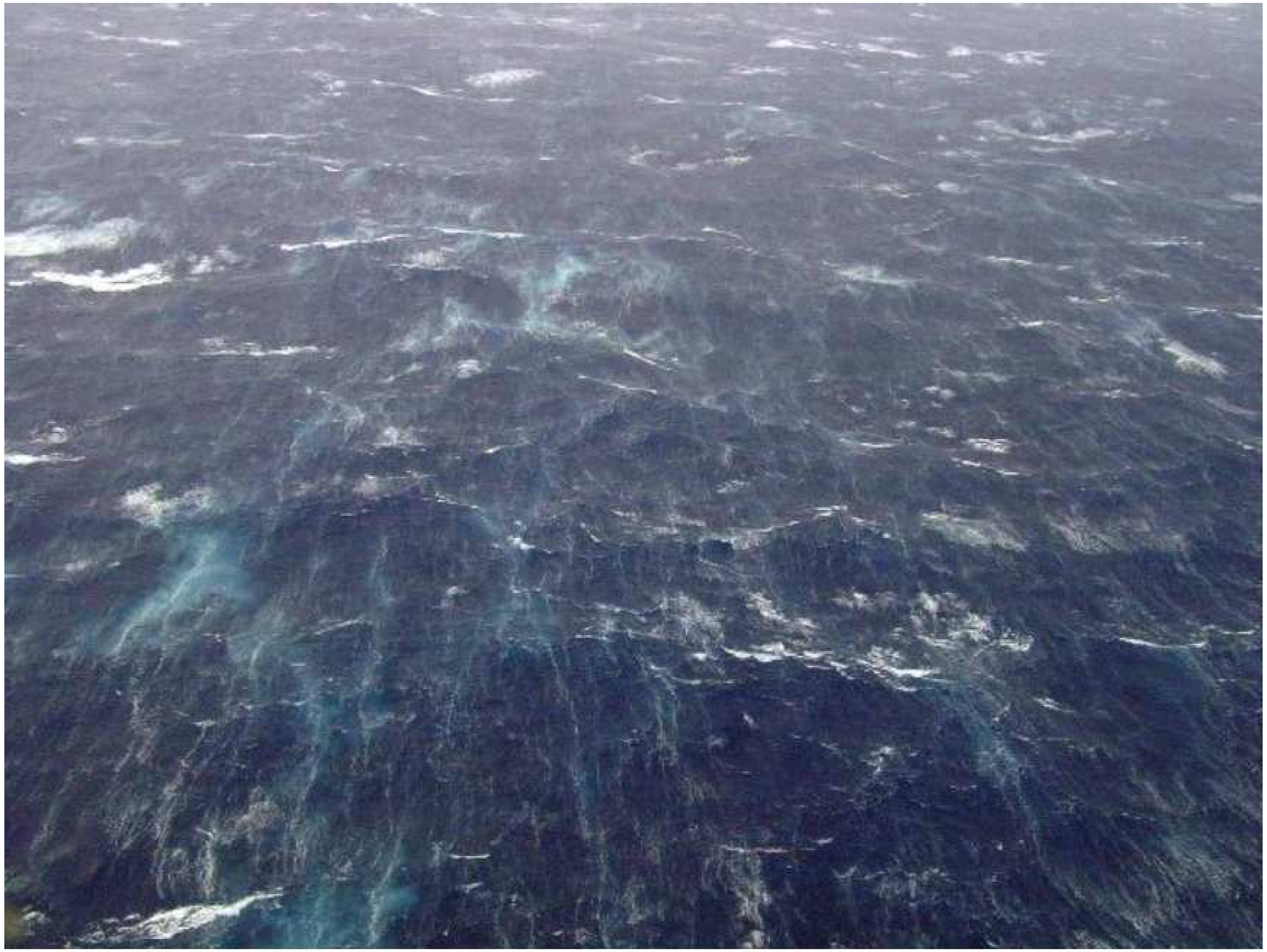
Image ID: fly00164, Flying With NOAA Collection
Photo Date: 1976 August 8



into Dora July 22, 2011 sfc winds=50-55 knts

Surface streaks in 65 kt winds during Hurricane Edouard, 14 Sep 2014 by Paul Chang

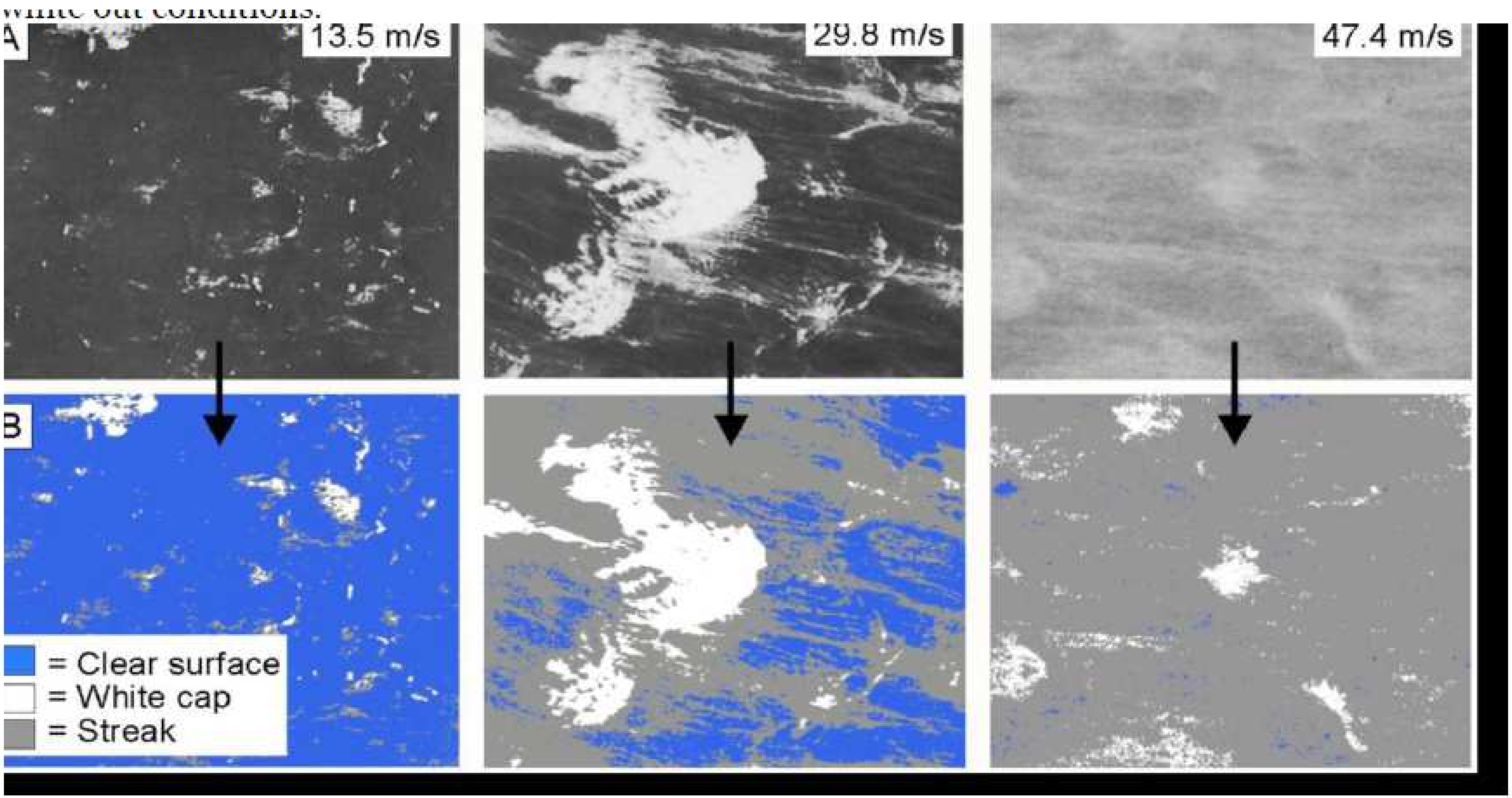




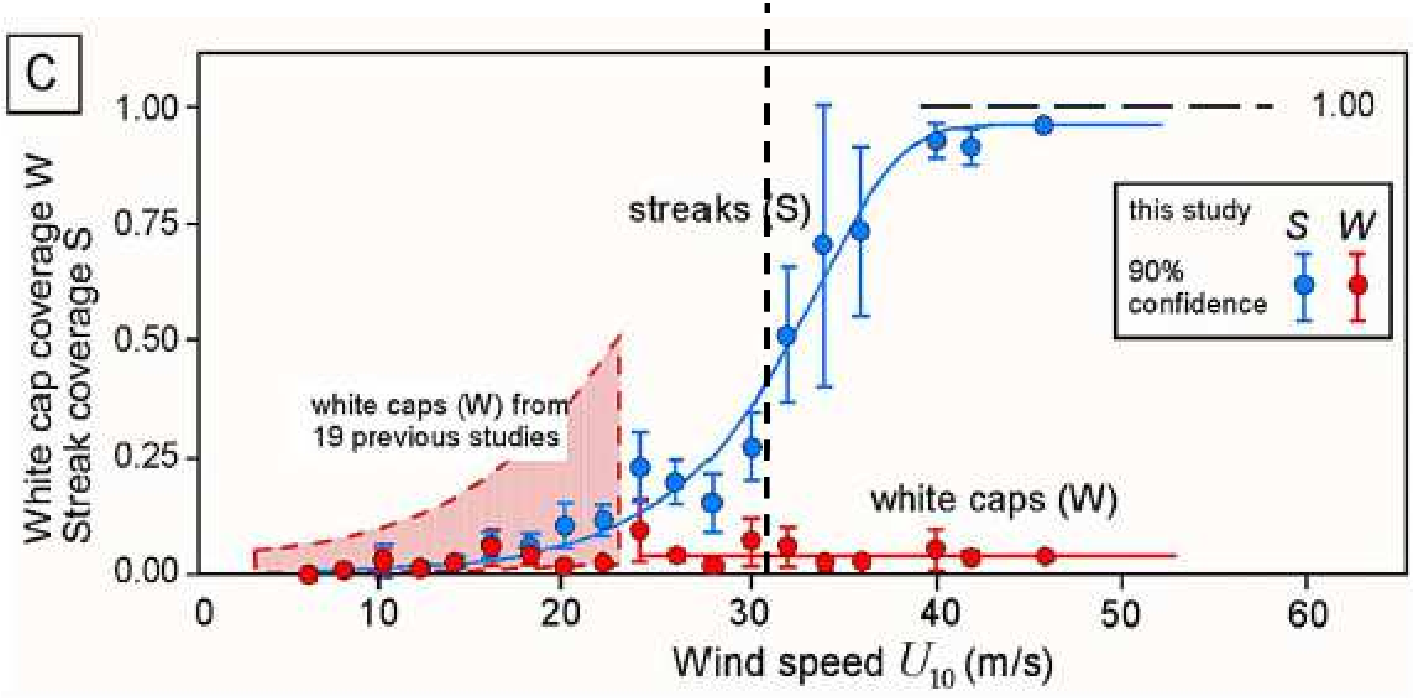

North Pacific storm waves as seen from the NOAA M/V *Noble Star*, Winter 1989.

Sea surface as seen from NOAA P-3 at 5000 feet during Hurricane Hugo. Seas were driven by over 100-knot winds and were 60-80 feet high. Image ID: fly00229, Flying With NOAA Collection

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



Separation of whitecap & streaks coverage



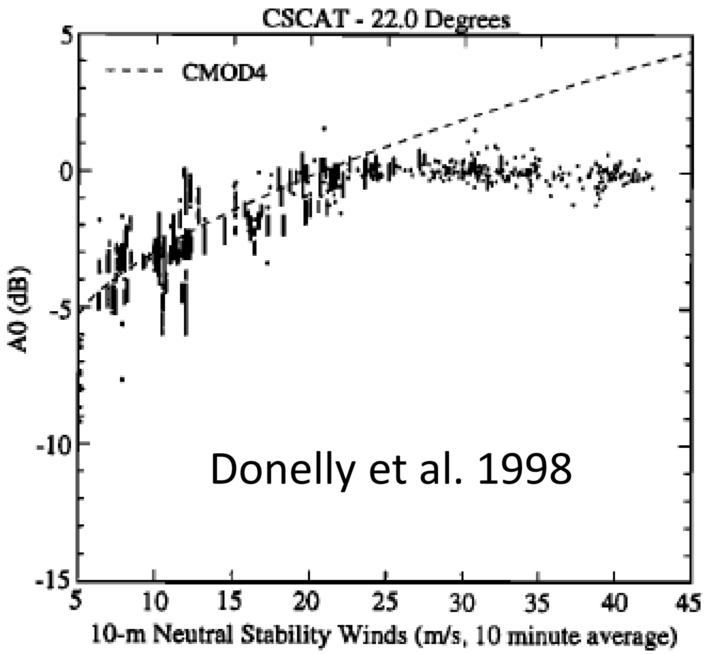
Holthuijsen et al. JGR 2012

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 %**

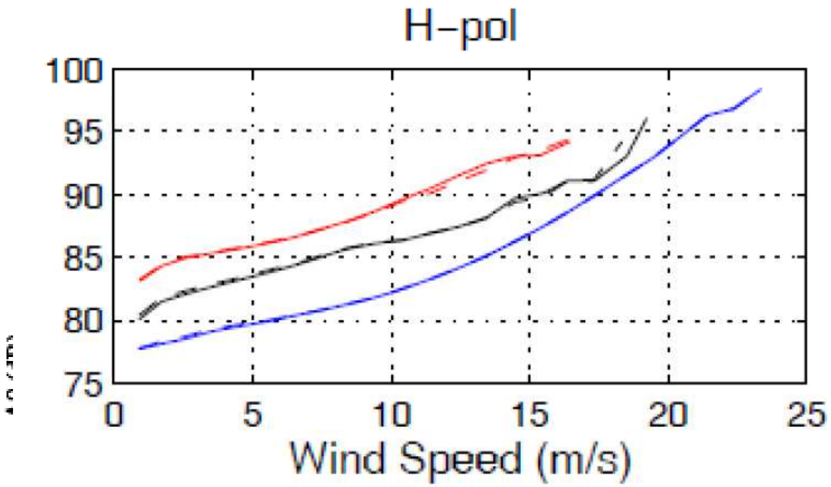
Sea Surface Observation Capabilities from Space in Extreme Wind Conditions

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



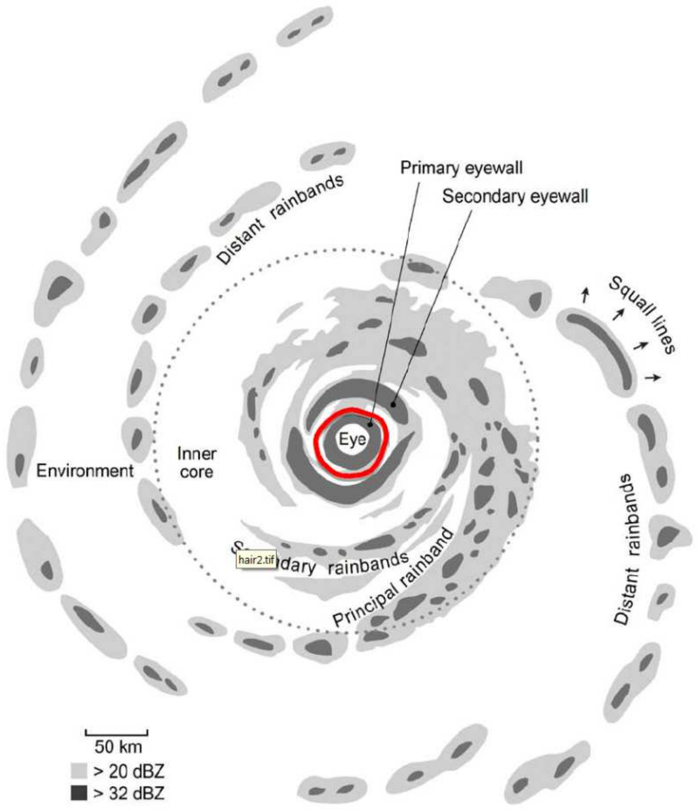
(a.)



Quilfen, Y., C. Prigent, B. Chapron, A. A. Mouche, and N. Houti (2007), **The potential of QuikSCAT and WindSat observations for the estimation of sea surface wind vector under severe weather conditions**, *J. Geophys. Res*

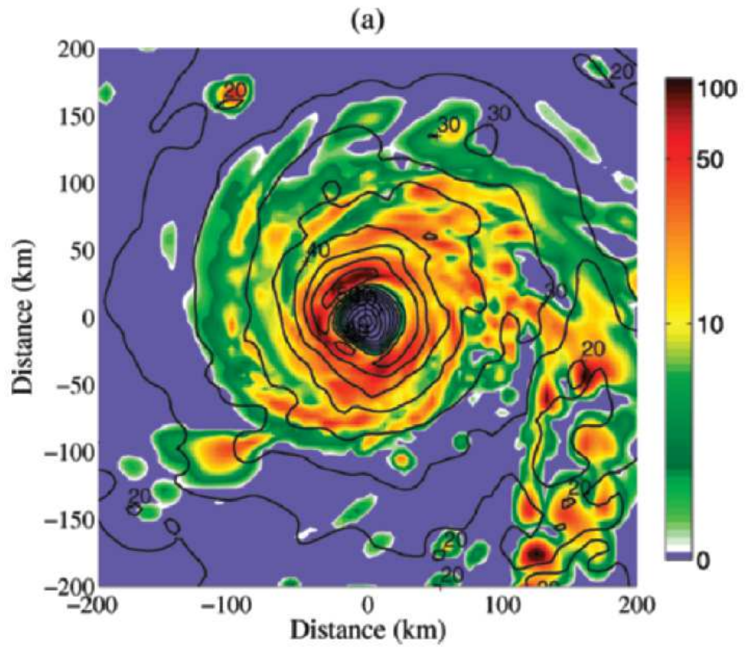
High winds in Hurricanes are very often associated with High rain rates

Rain Anatomy in a hurricane



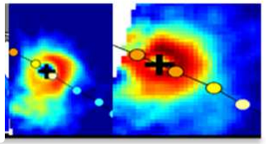
Houze 2010

Rain rate [mm/h]

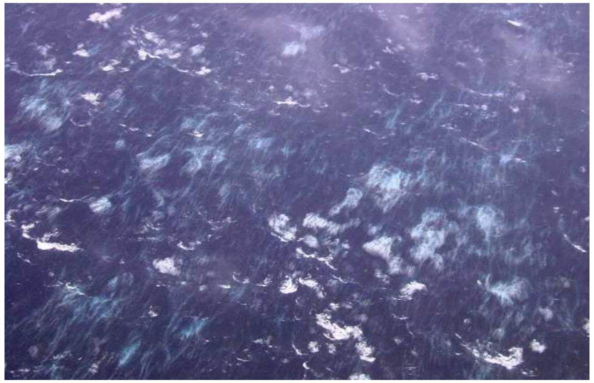


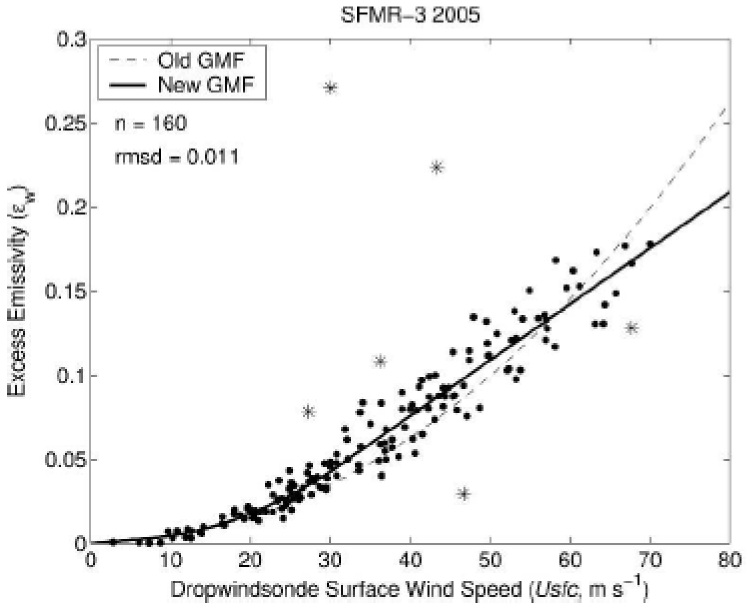
S.Shen and J. Tenerelli 2007

Wind speed retrieval in extreme winds : SFMR



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





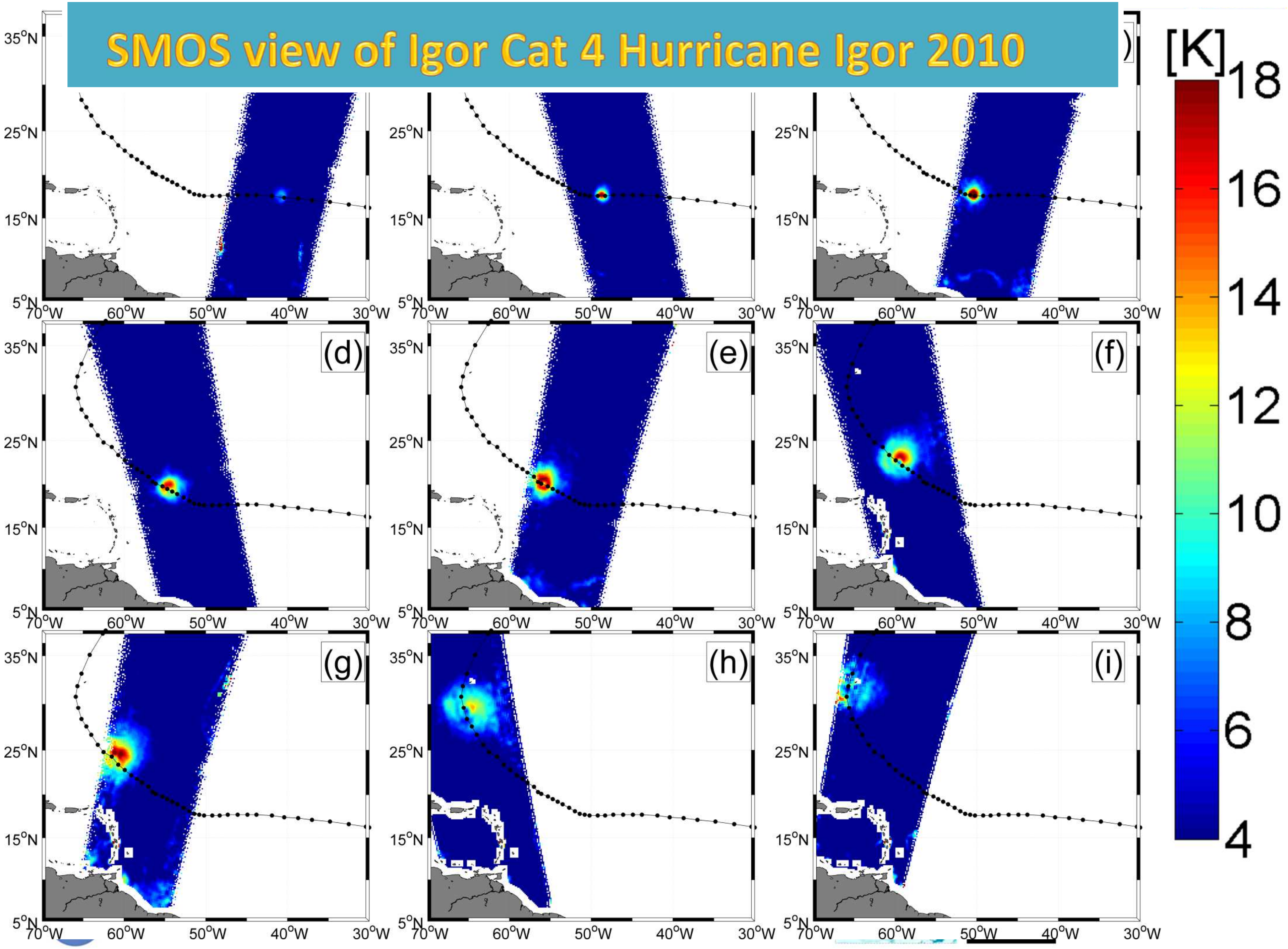
Hurricane hunter P-3

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

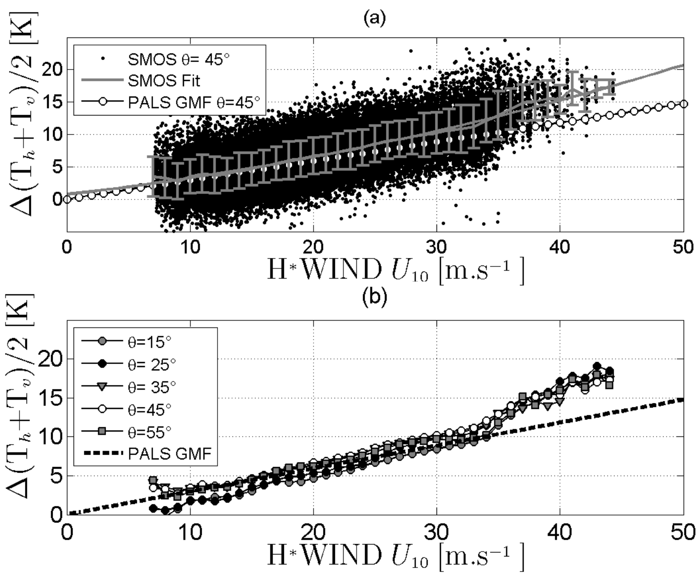
Principle of the Step Frequency Microwave Radiometer (SFMR) C-band:
=> Use mutli-frequency C-band channels to separate wind from rain effects
NOAA's primary airborn sensor for measuring Tropical Cyclone surface
wind speeds since 30 year (Ulhorn et al., 2003, 2007).

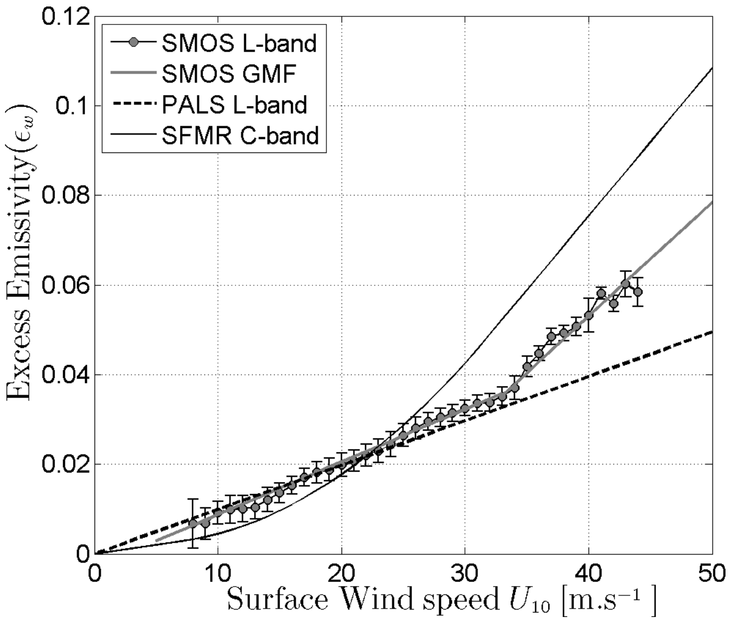
esa Ifremer S-O-Lab Satellite Oceanography Laboratory Met Office oceandatalab making sense of the deep blue sea

SMOS view of Igor Cat 4 Hurricane Igor 2010



Geophysical Model function: Tb=f(wind speed)





C-band

L-band:

0.7K/m/s for hurricanes

0.3 k/(m/s) below

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

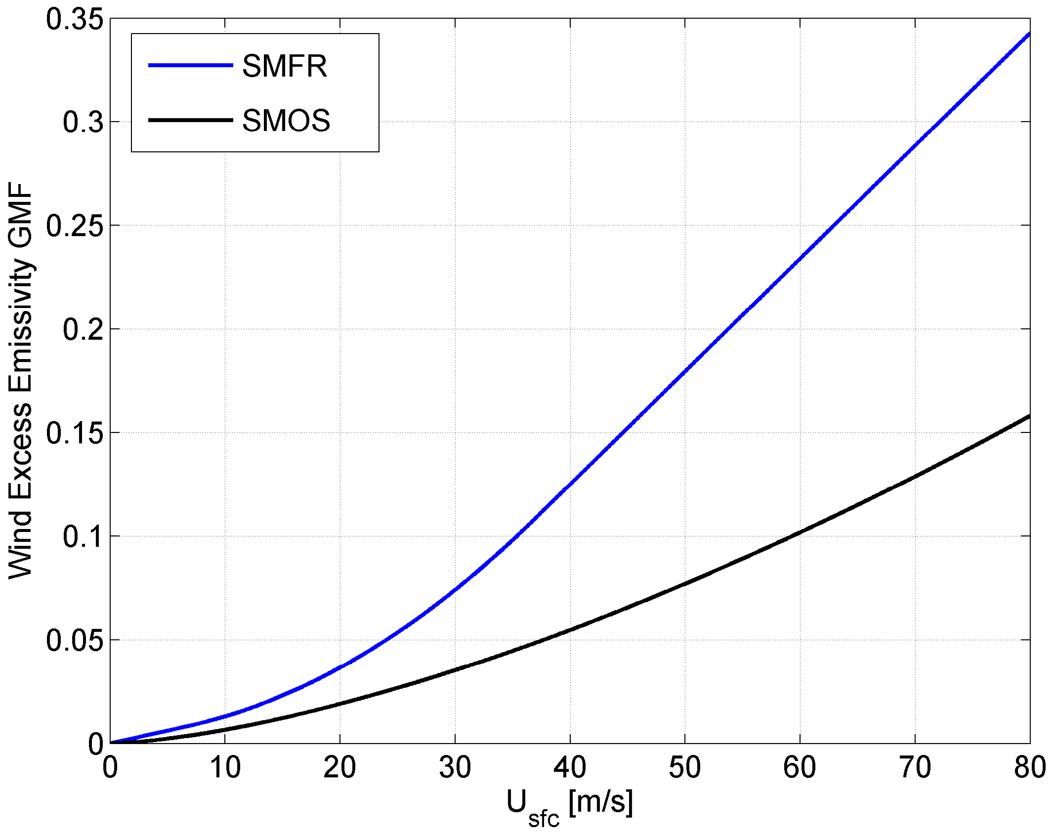
$$= 0.75\,U_{10}\text{-}14.5 \qquad U_{10} \ge 33\ \text{m.s}^{-1}$$

Development of a SMOS wind speed GMF based on Hwind products in IGOR hurricane

Bilinear L-band dependencies with surface wind speed

Reul et al., JGR, 2012

Wind Excess Emissivity at High winds



C-band (5 GHz):
~1K/m/s
Uhlhorn et al., 2014

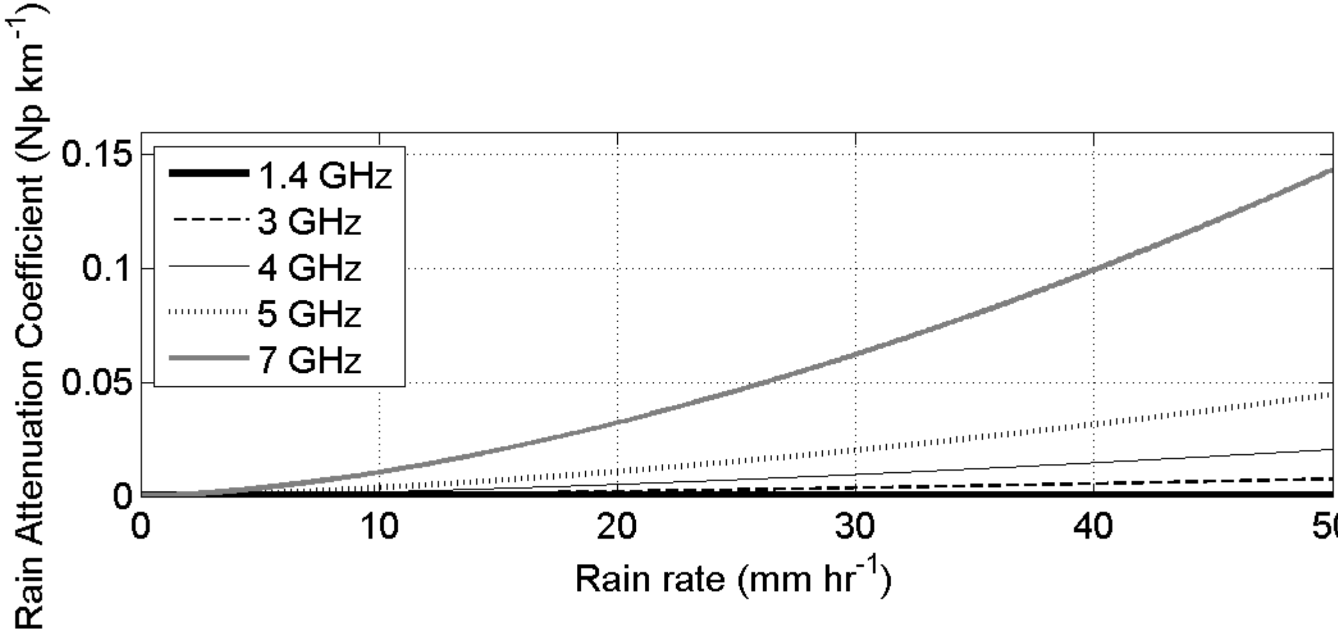
L-band (1.4 GHz):
0.35K/m/s
Reul et al., 2012

C-band TB~3 times more sensitive to wind speed than L-band

Rain attenuation at C & L-band

Because of the small ratio of raindrop size to the ~1 GHz electromagnetic wavelength (~20 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)



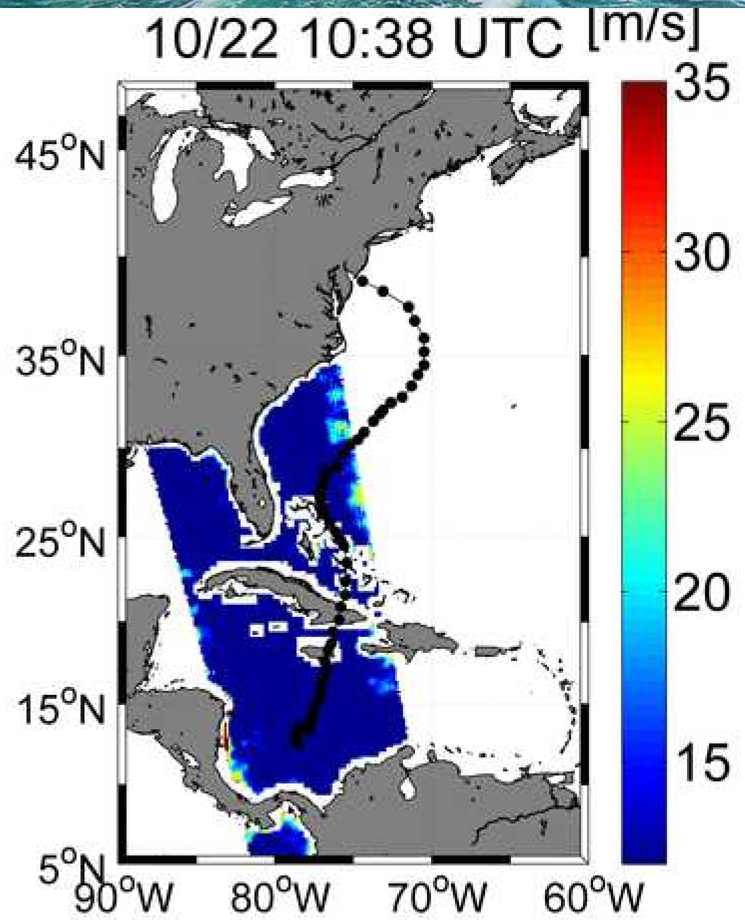
C-band: @7GHz

L-band: 1.4 GHz

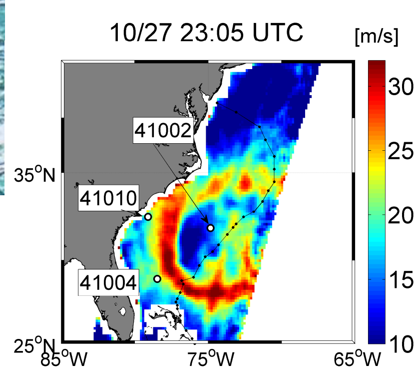
Rain impact Generally two order of magnitude smaller at L-band (1.4 GHz) than at C-band (5-7 GHz)

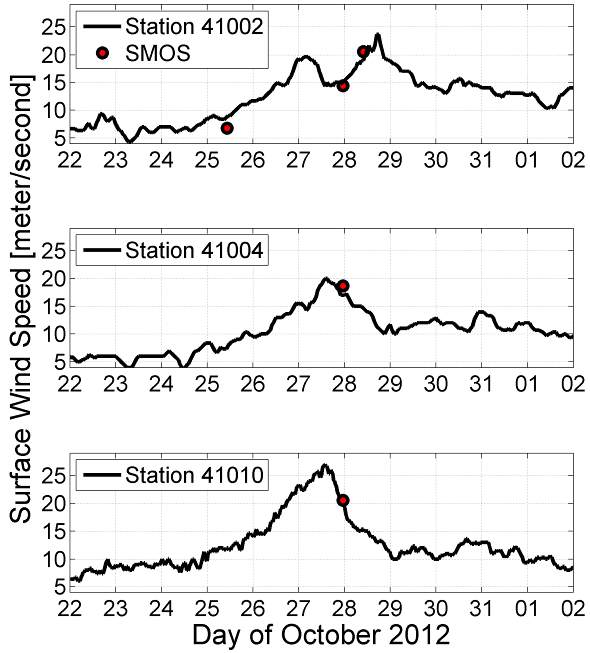
SuperStorm Sandy Viewed by SMOS

Hurricane Sandy Oct 2012



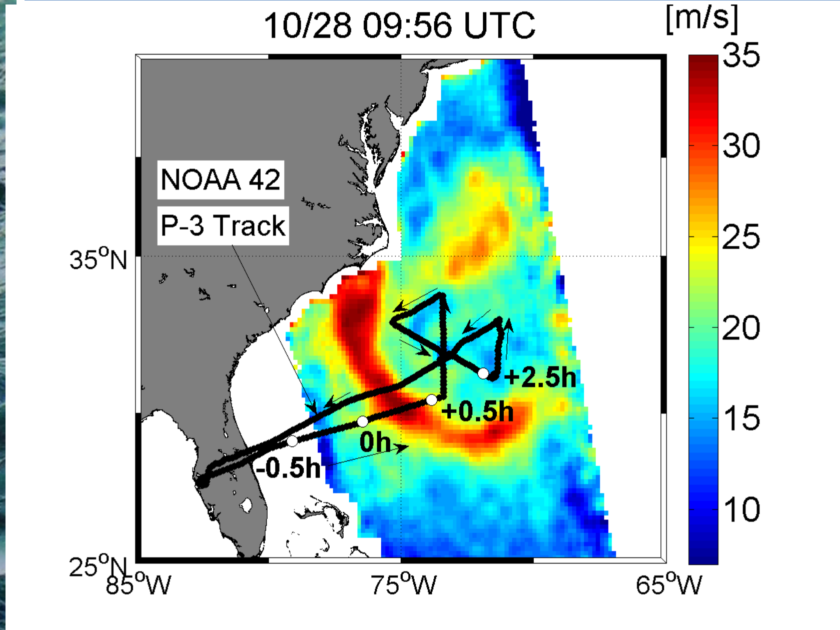
Validation with buoy data





Hurricane Sandy

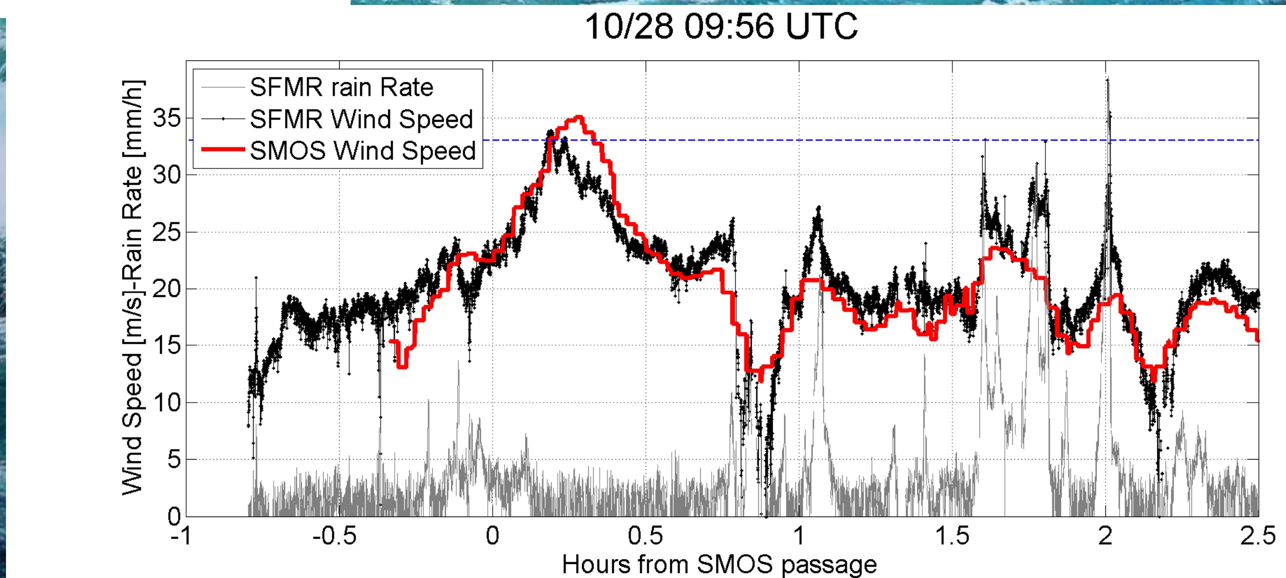
Validation with NOAA hurricane hunter Aircraft Data (C-band)SFMR



SMOS winds

Accuracy

~<3 m/s



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SMOS+STORM Evolution ESA-STSE project

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

Improve high wind speed retrieval algorithms (GMF, rain & wave impacts)

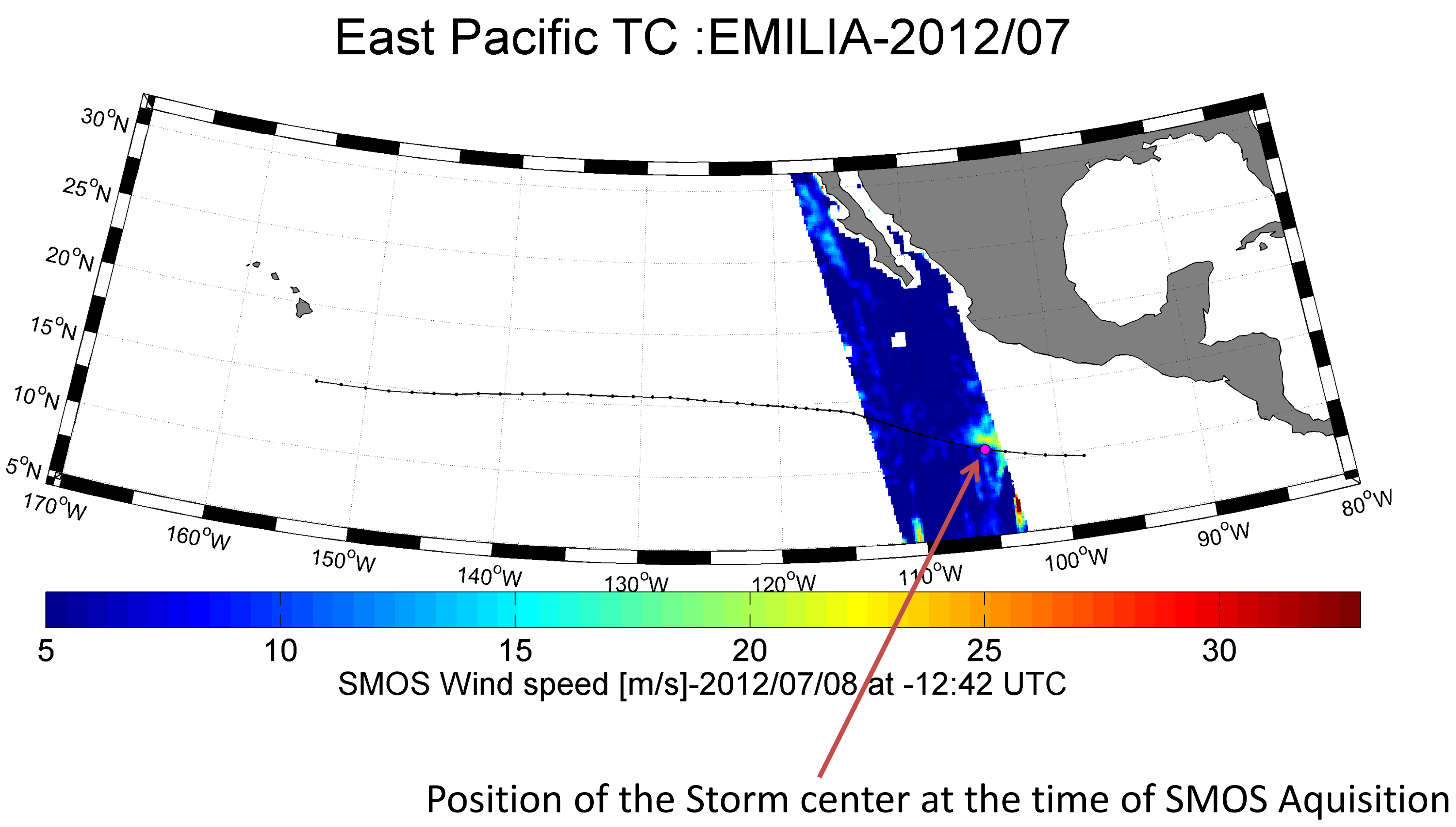
Produce a Global Tropical Cyclone & Extra-Tropical Cyclone storm catalogue from 2010 to now

Comparisons with NWP models & radiometer & scatterometer data

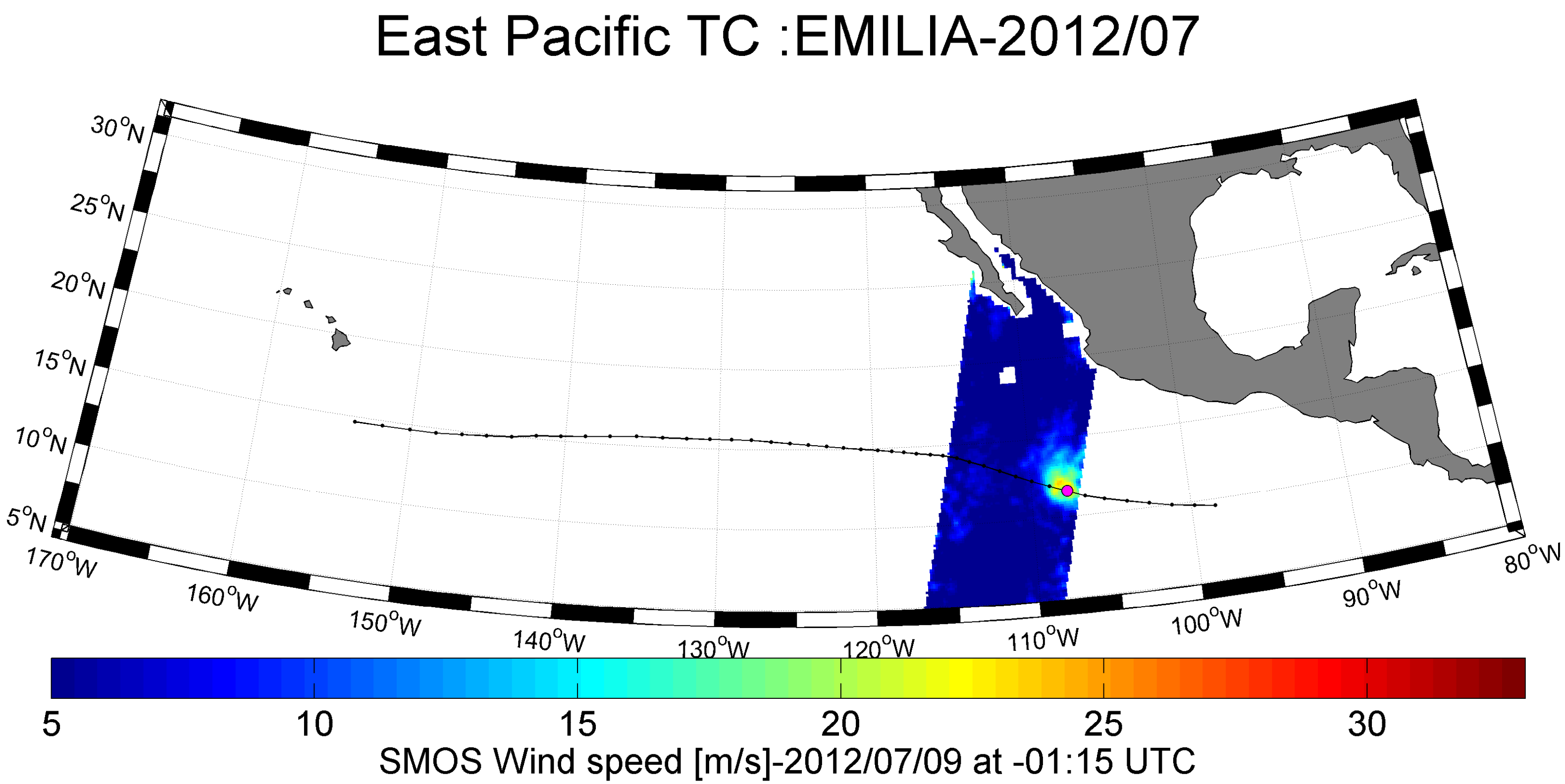
Combine with other observations : AMSR2, WindSat, SMAP, CYGNSS

Evaluate the impact of SMOS High Wind products assimilation on Metoffice forecast Errors: storm track & intensity forecasts

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



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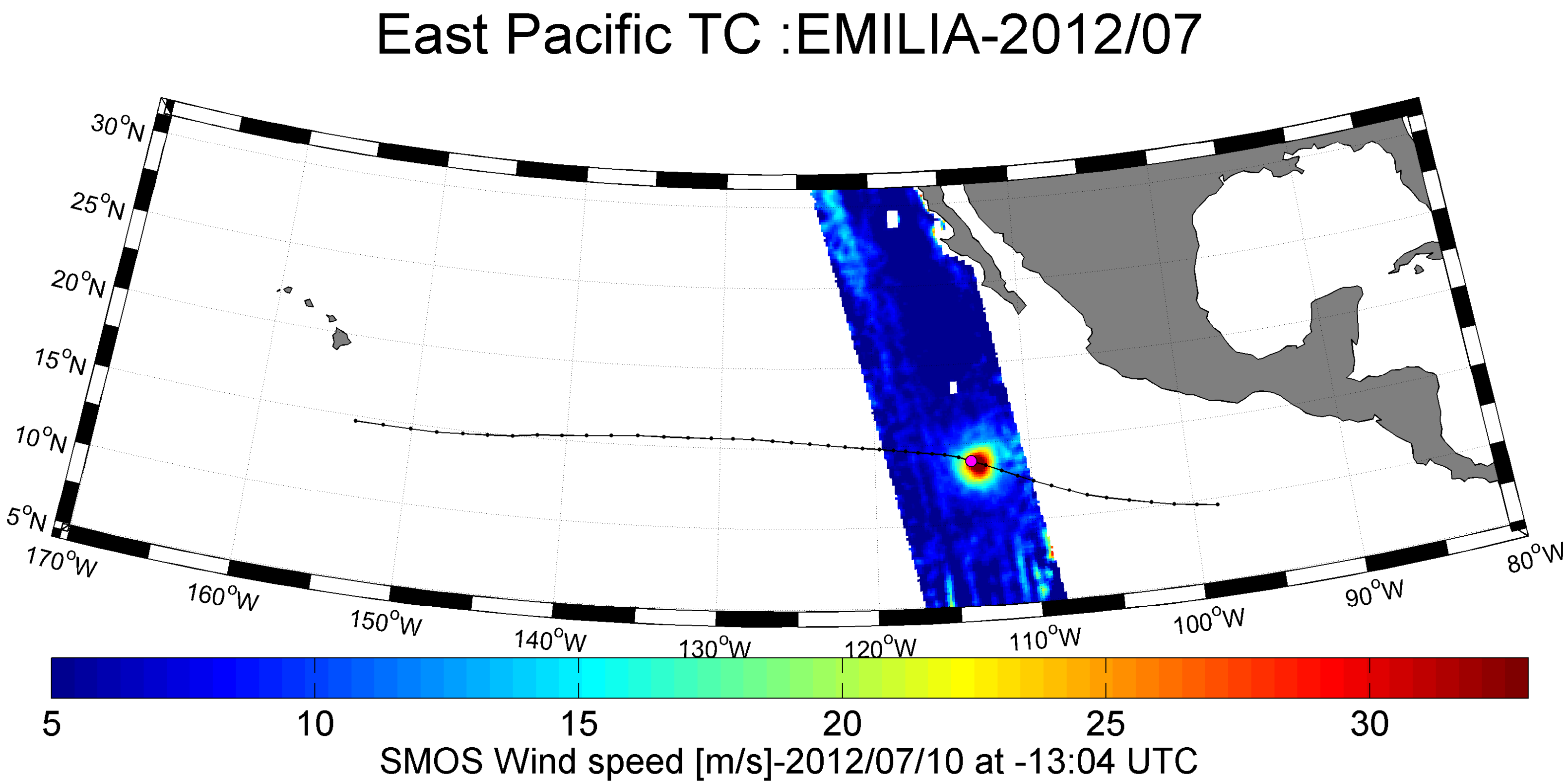
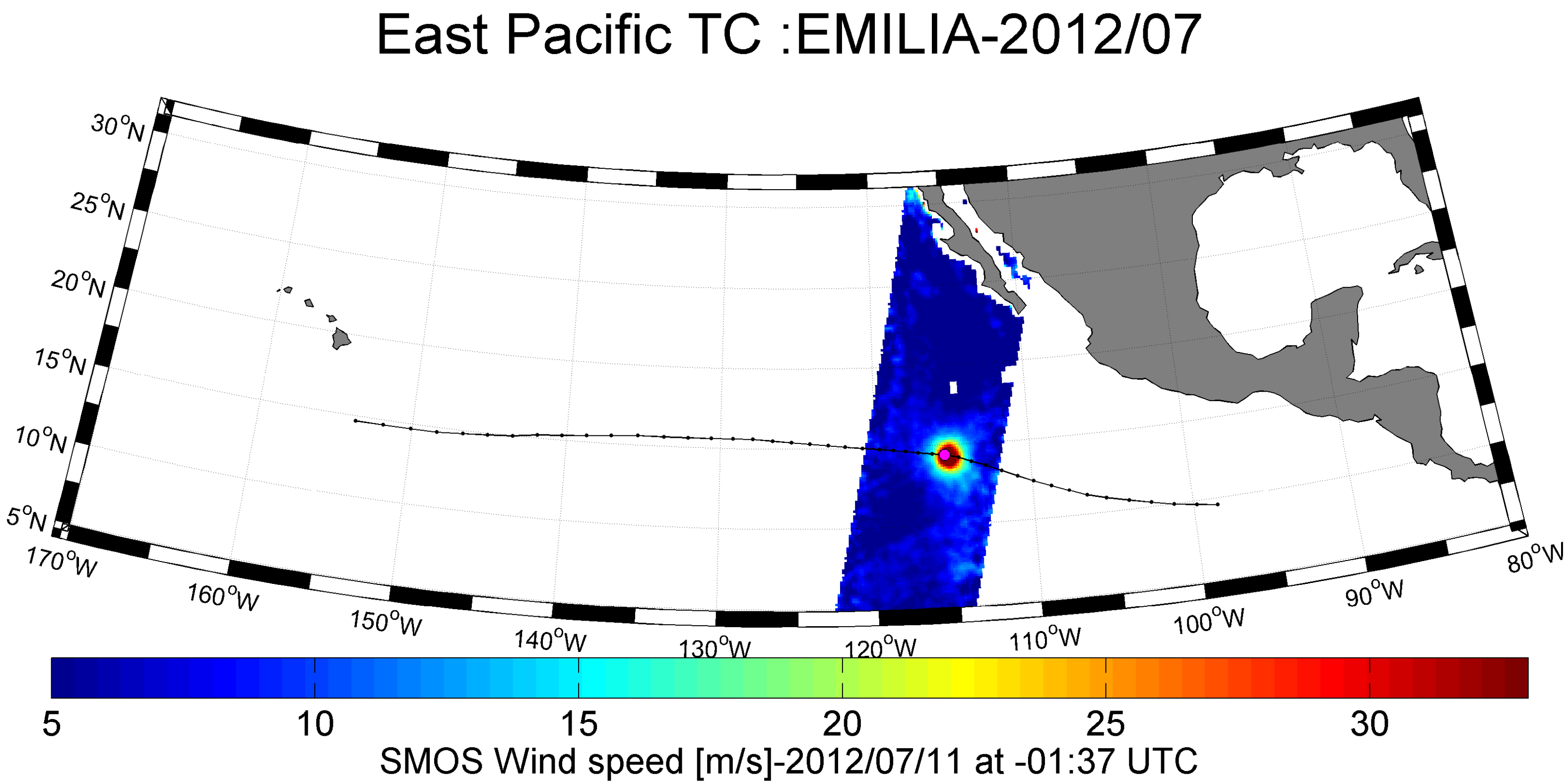
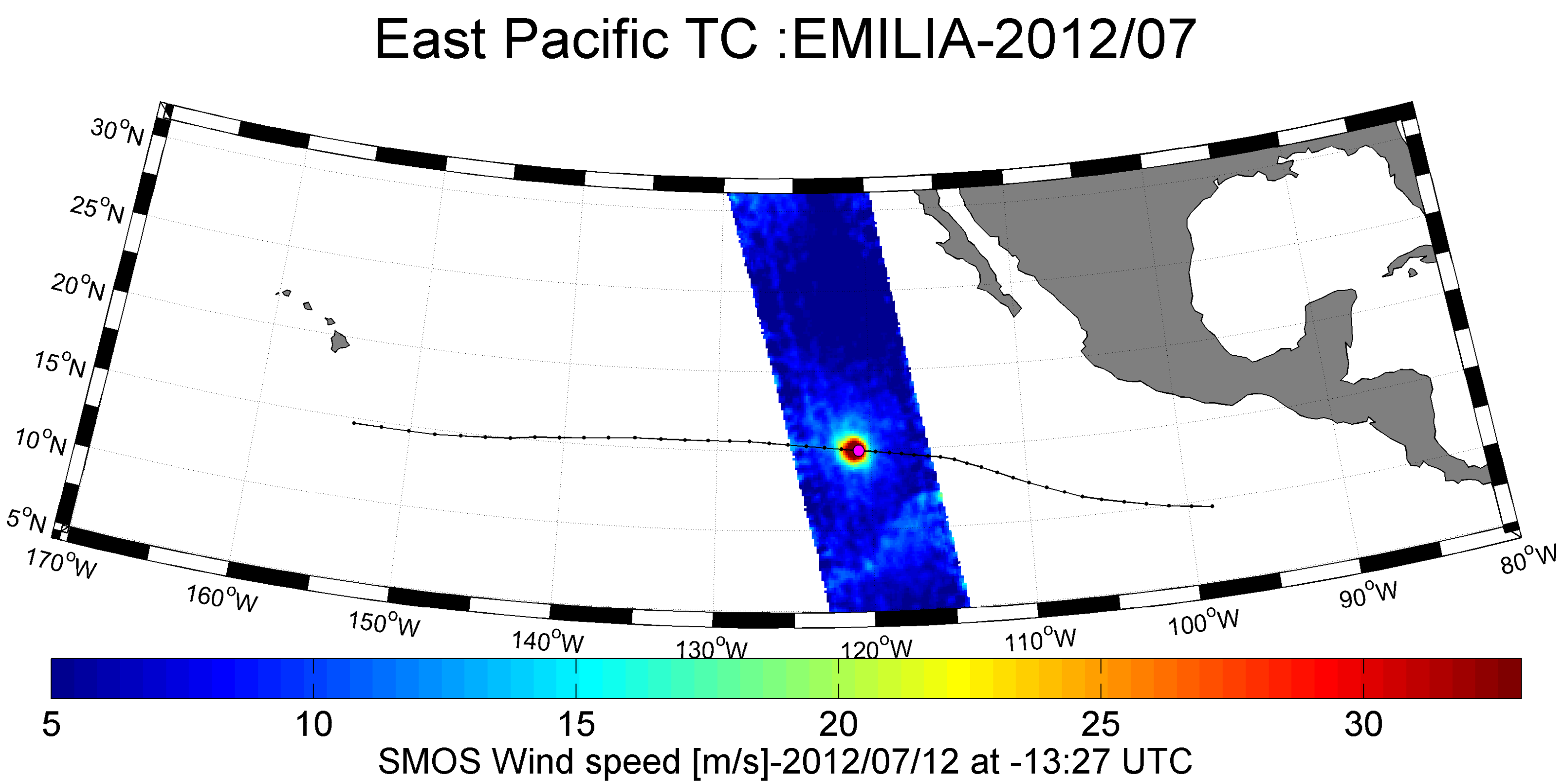


Tasks 2: Detect the useful TC & ETC events in SMOS data: Example of EMILIA



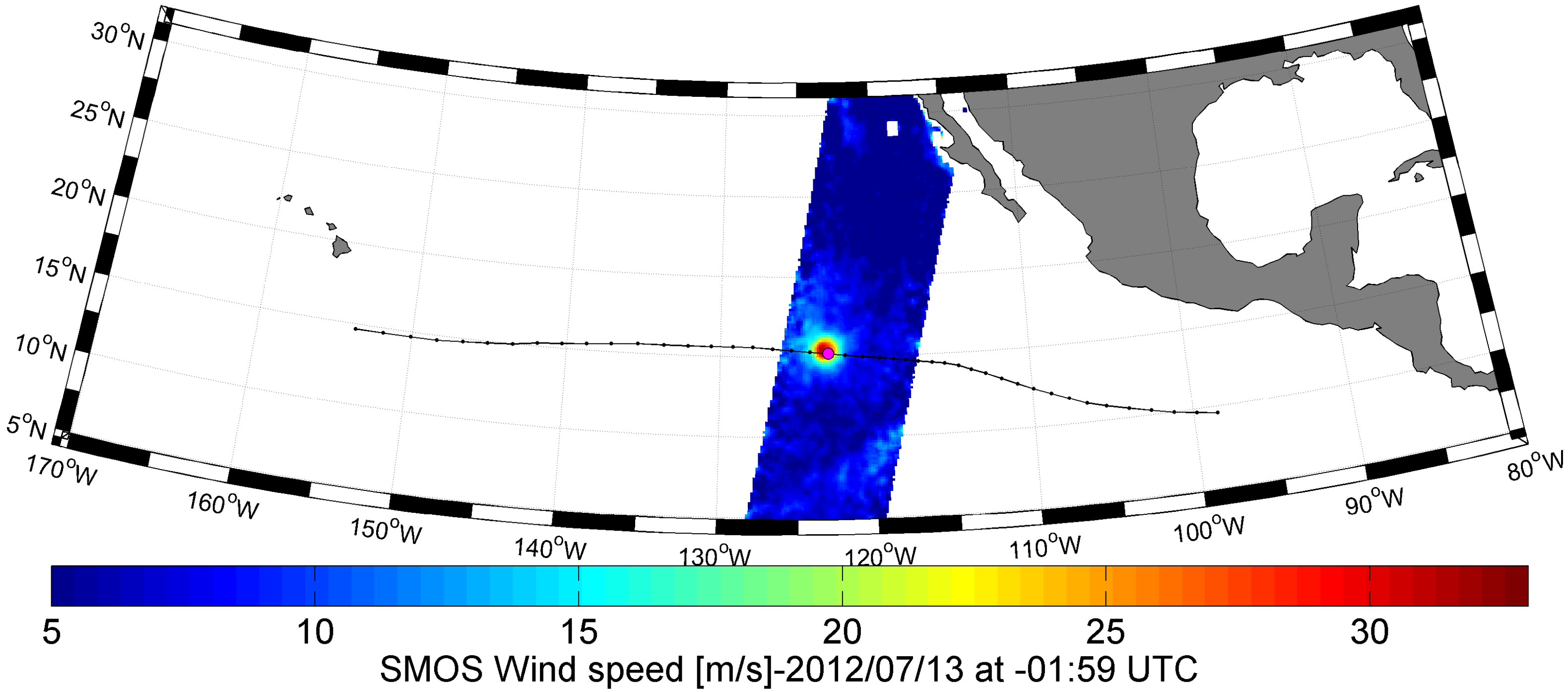
Tasks 2: Detect the useful TC & ETC events in SMOS data: Example of EMILIA



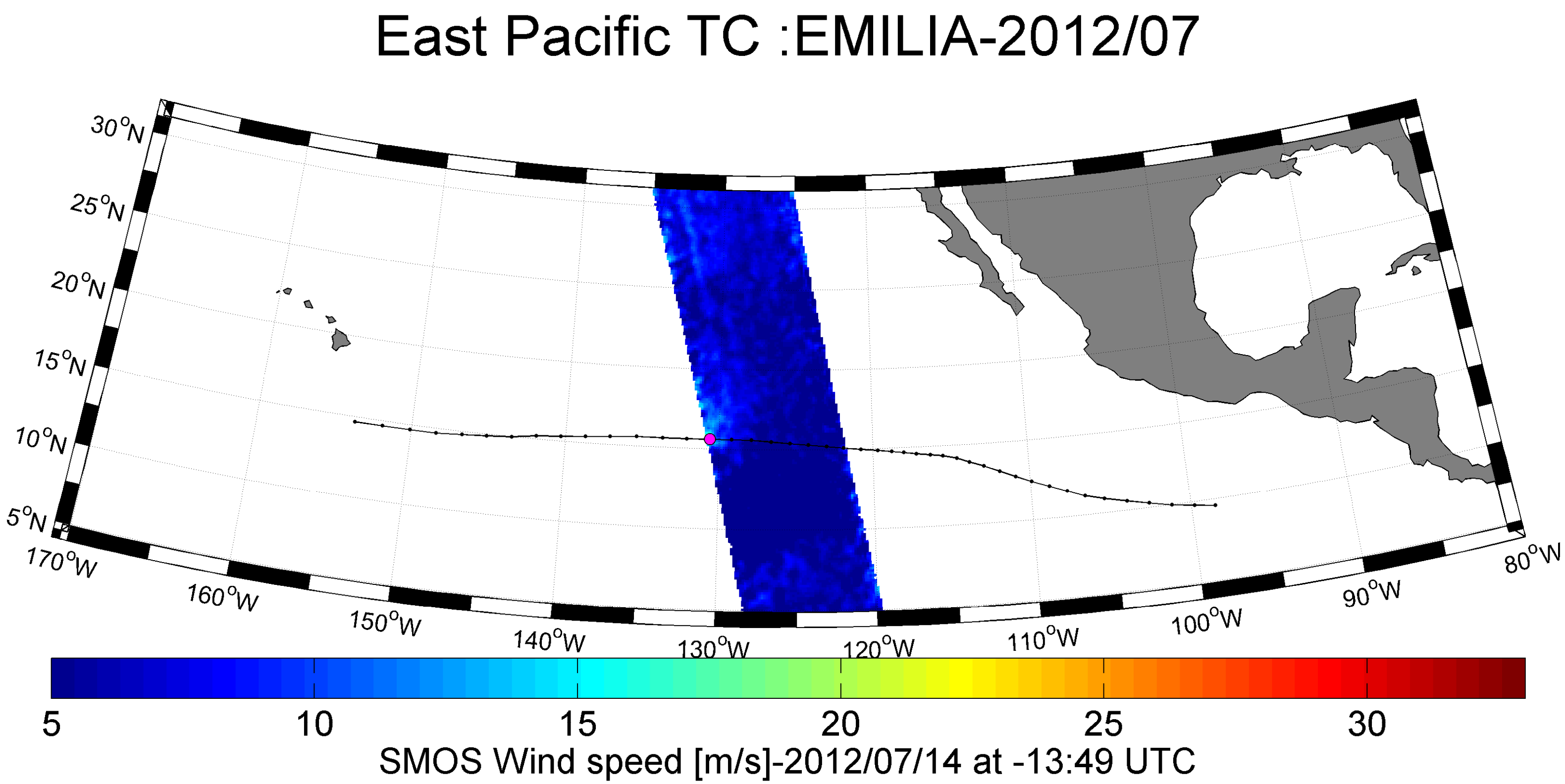
SMOS+STORM Evolution

Tasks 2: Detect the useful TC & ETC events in SMOS data: Example of EMILIA

East Pacific TC :EMILIA-2012/07



Tasks 2: Detect the useful TC & ETC events in SMOS data: Example of EMILIA



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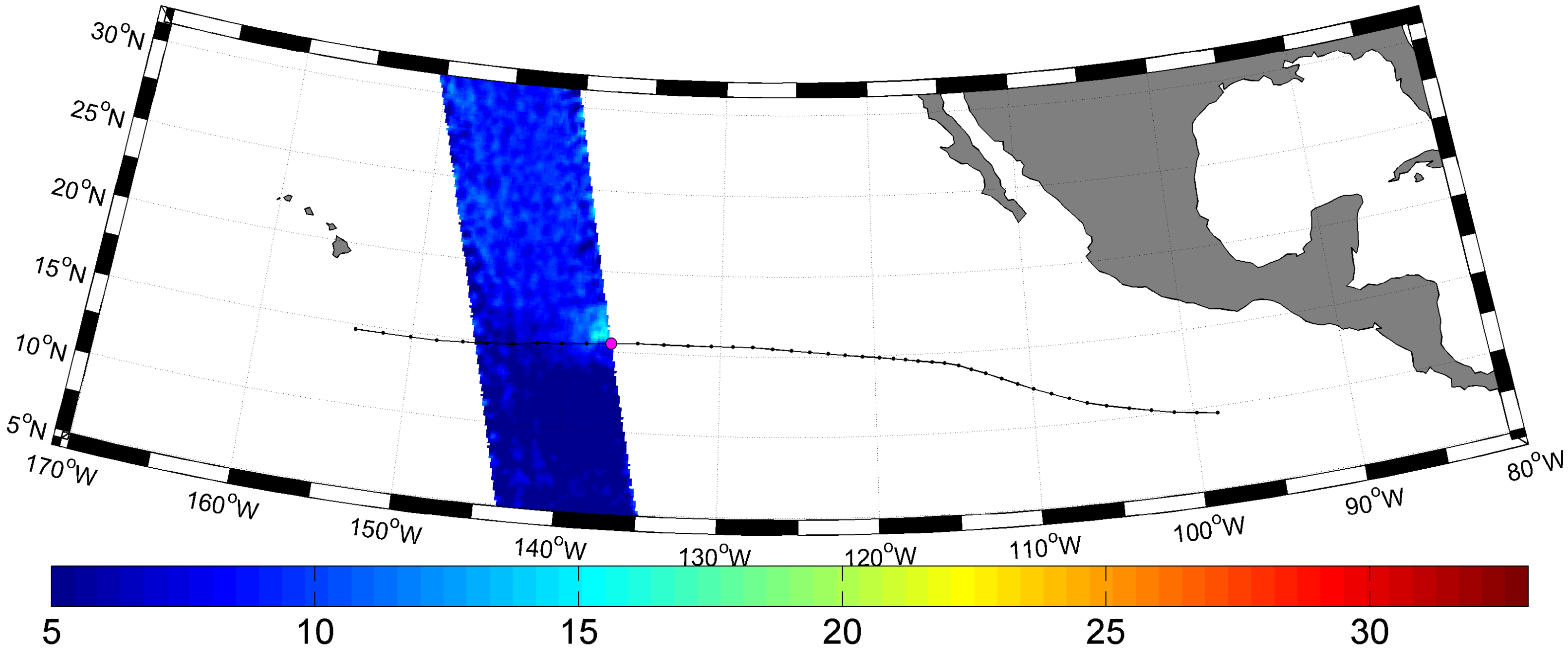
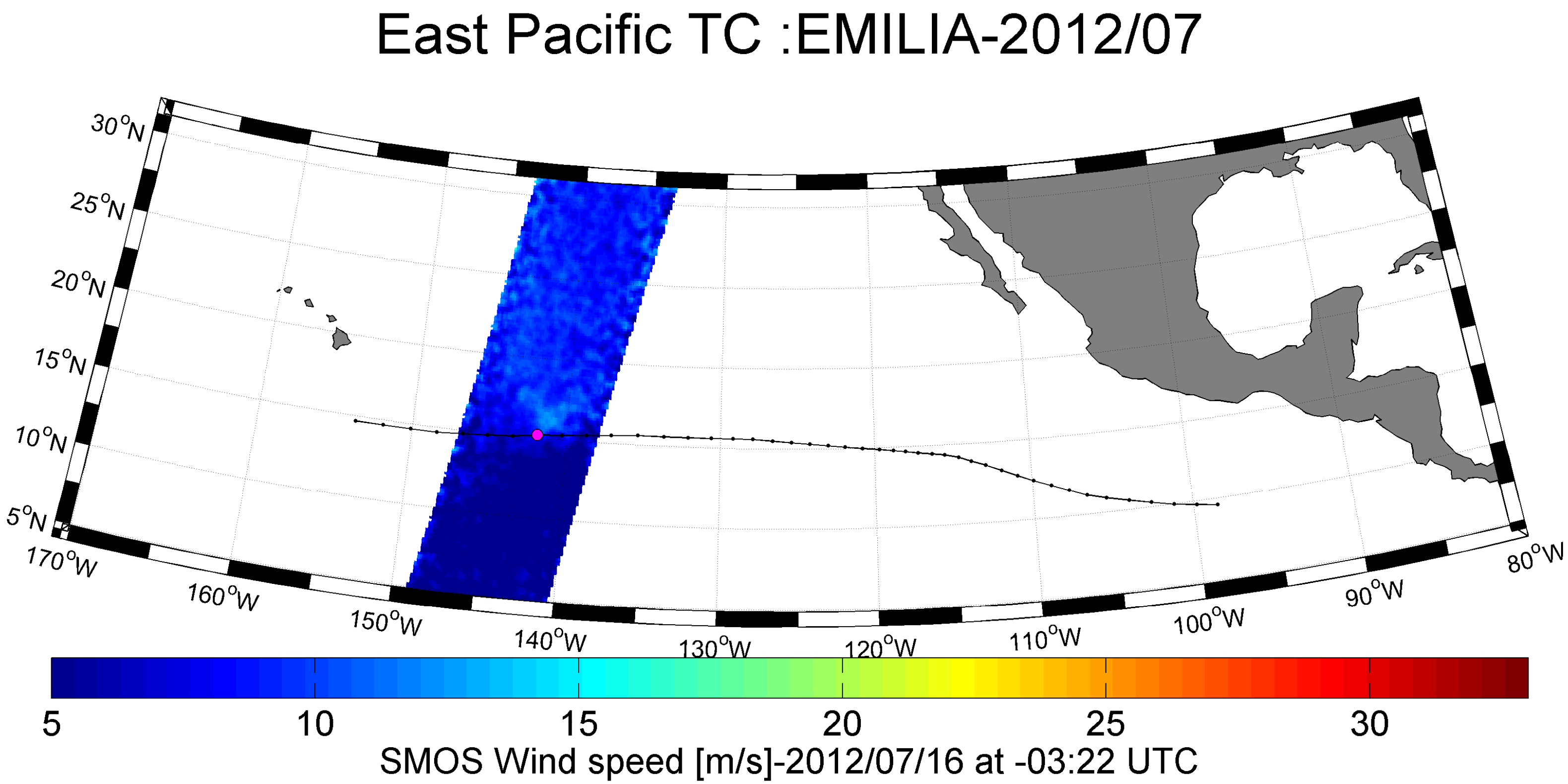
East Pacific TC :EMILIA-2012/07



SMOS Wind speed [m/s]-2012/07/15 at -14:50 UTC

Tasks 2: Detect the useful TC & ETC events in SMOS data: Example of EMILIA



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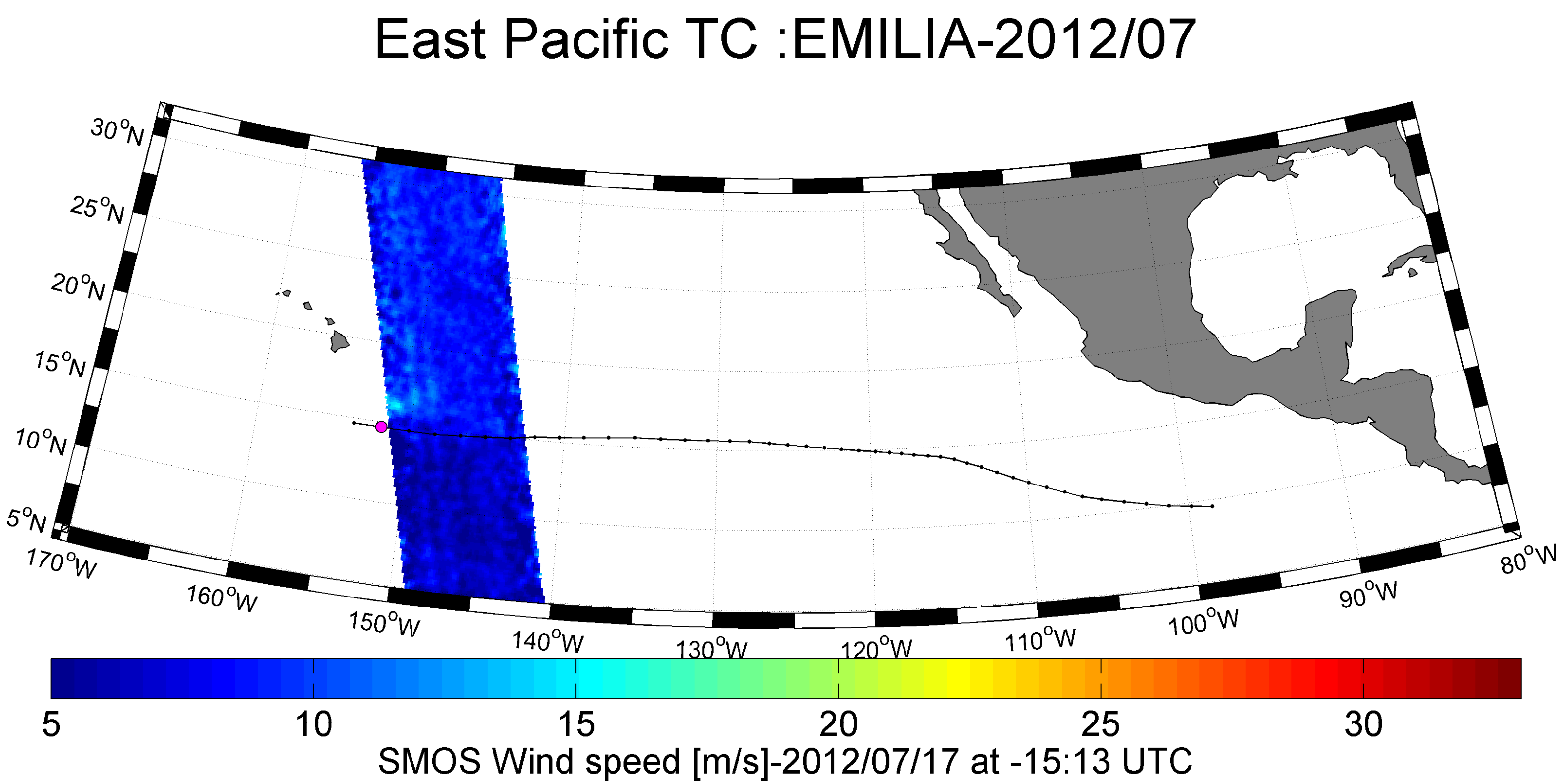

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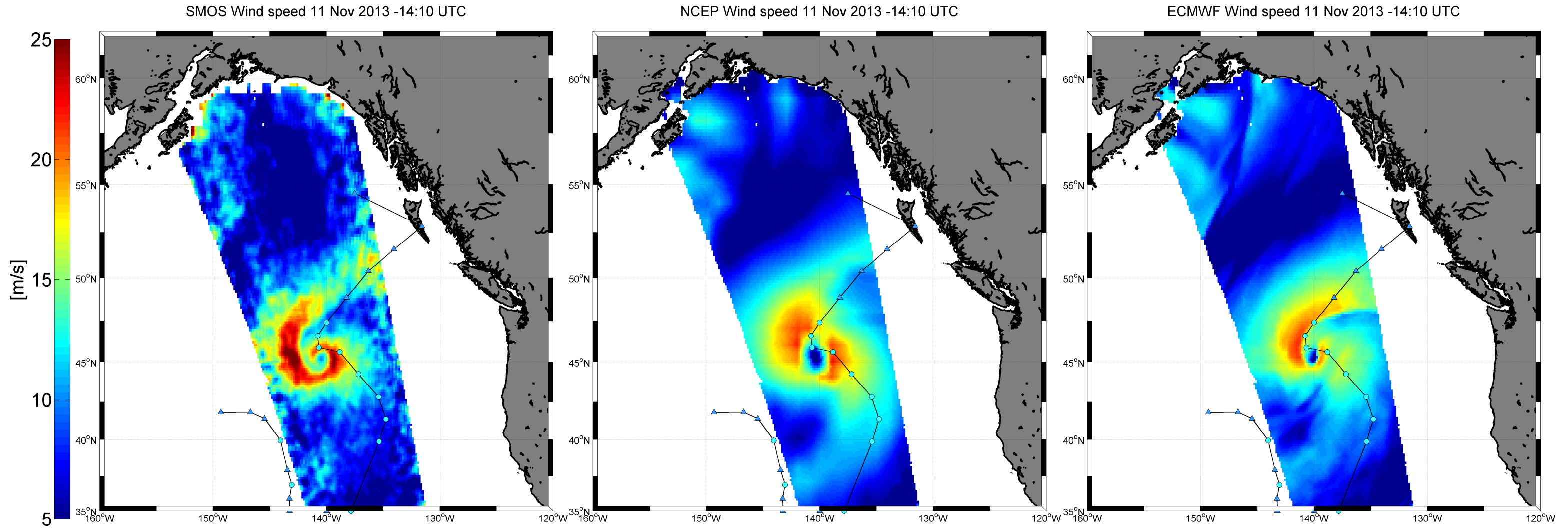
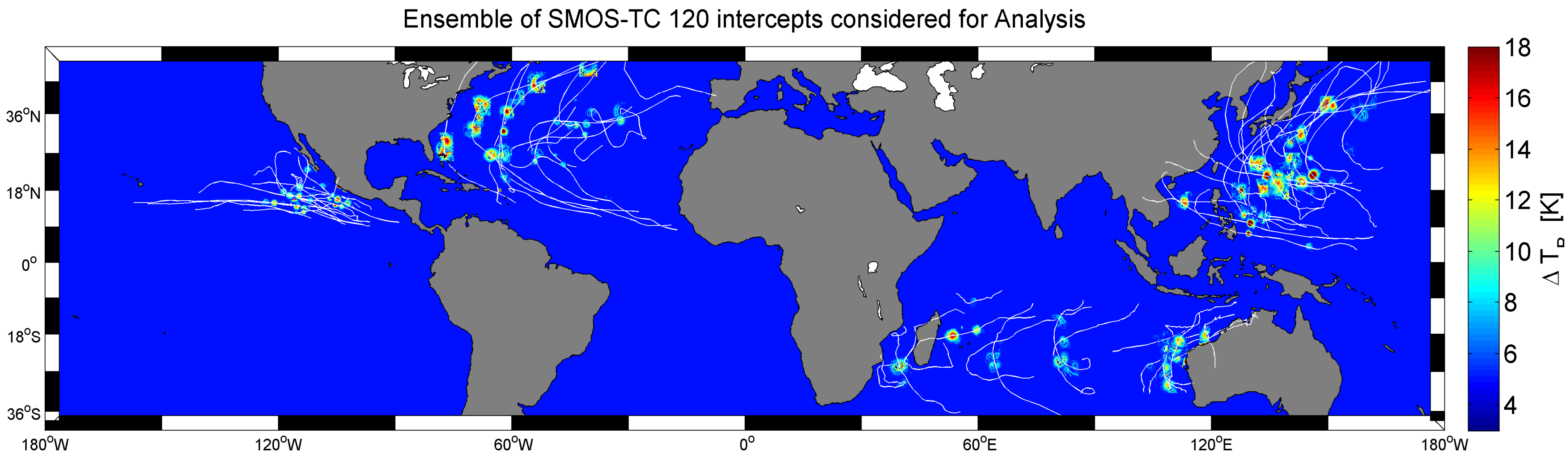
Monitoring Surface Winds with SMOS in Extra-Tropical Cyclones

SMOS NCEP ECMWF



SMOS systematically detects higher wind speeds & could help re-phasing the Storms structures in opereational weather forecast models

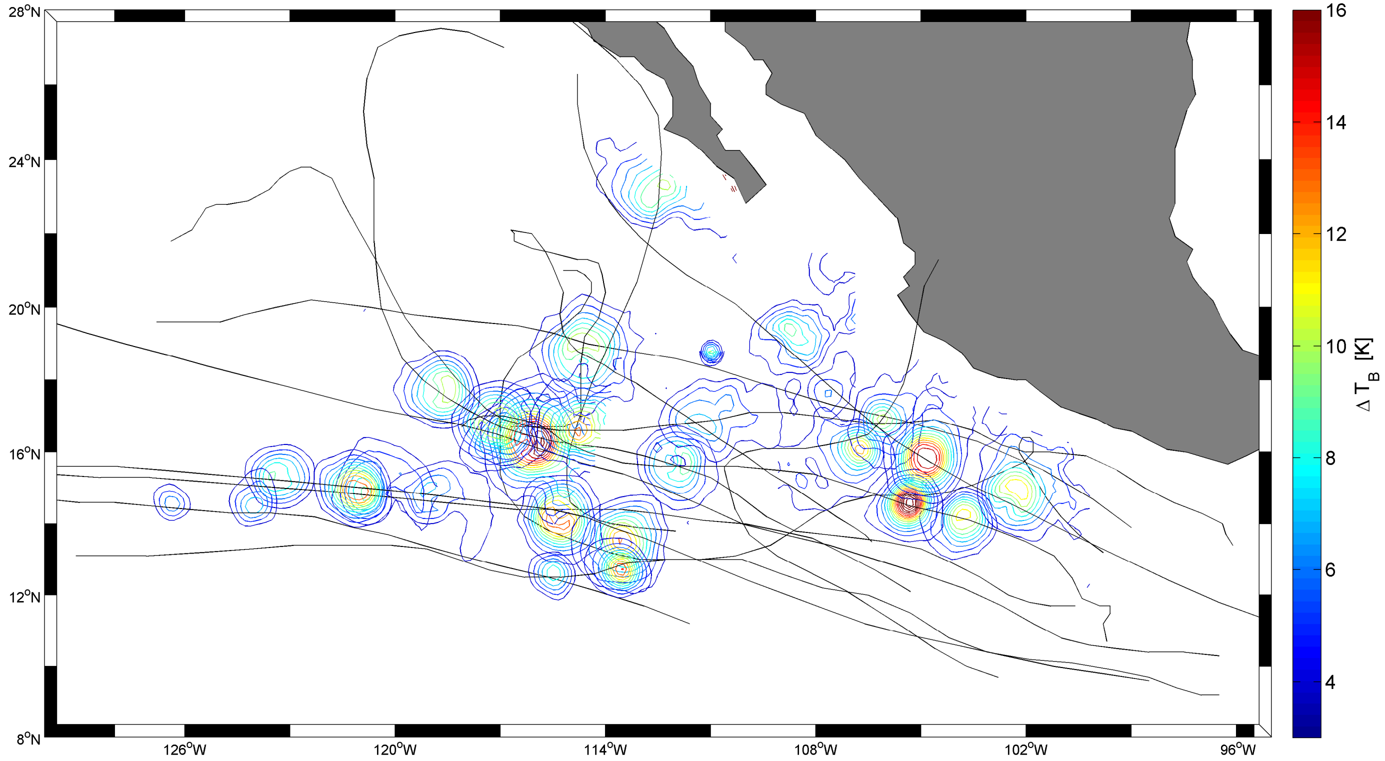
A view at the SMOS-STORM 2010-2014 TC database



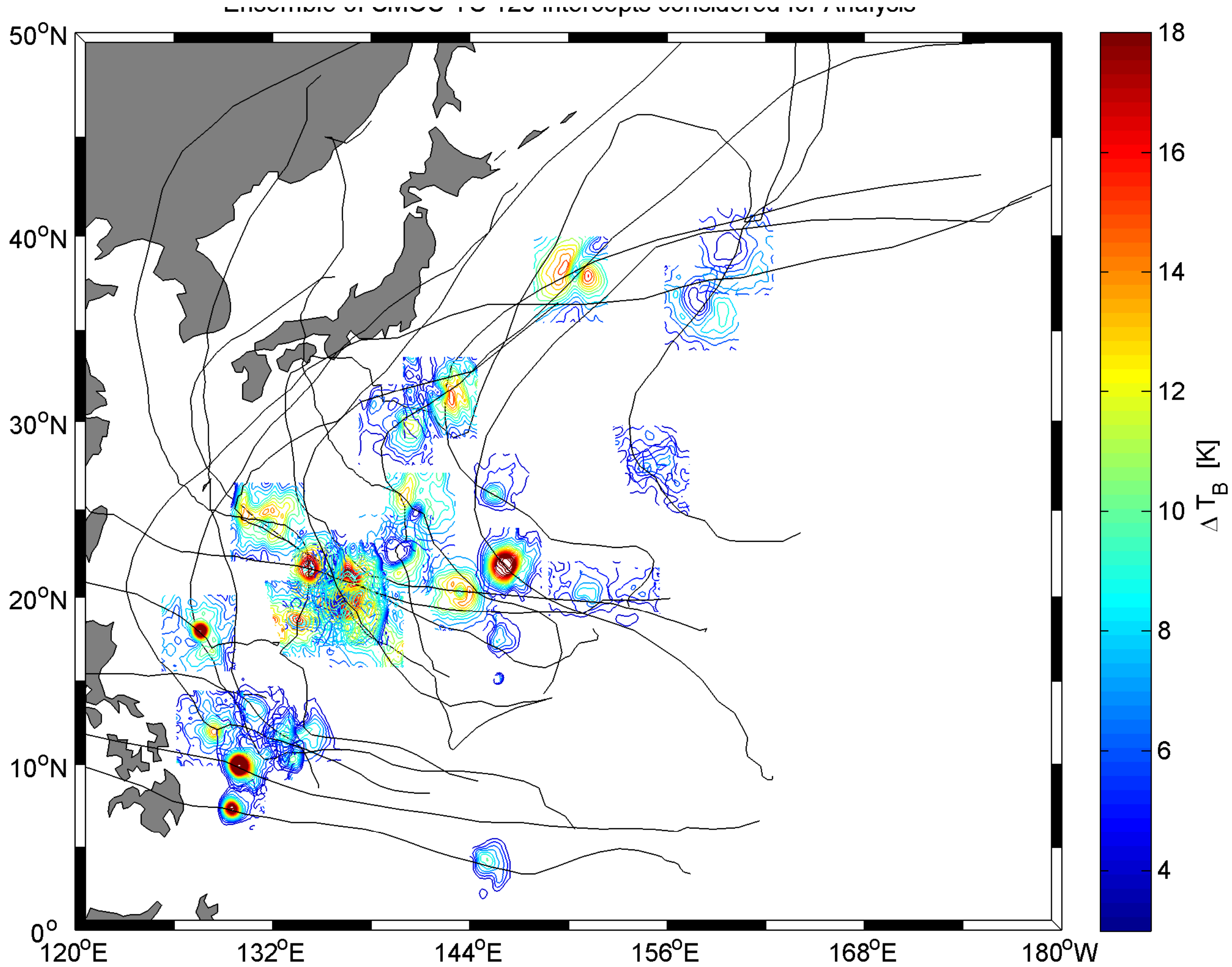
Here, only complete SMOS intercepts with TCs, free of Radio Frequency Interferences are selected

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

East Pacific SMOS intercepts with 2011-2013 TCs

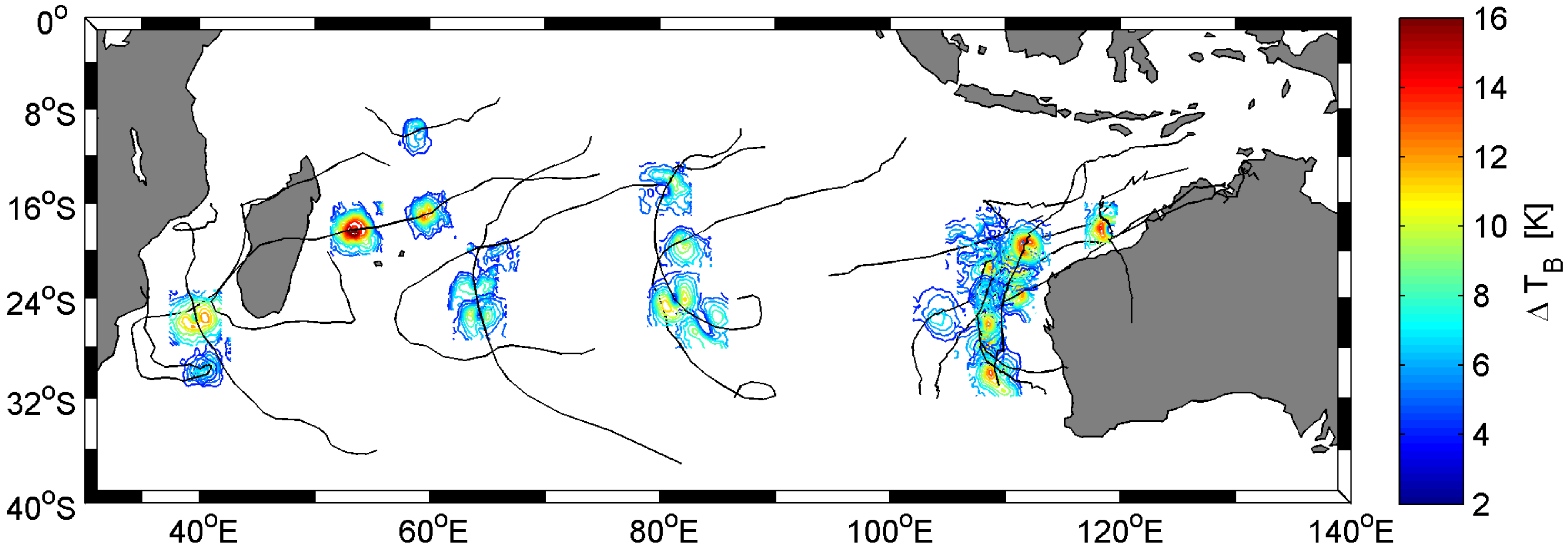


West Pacific SMOS intercepts with 2011-2013's TCs

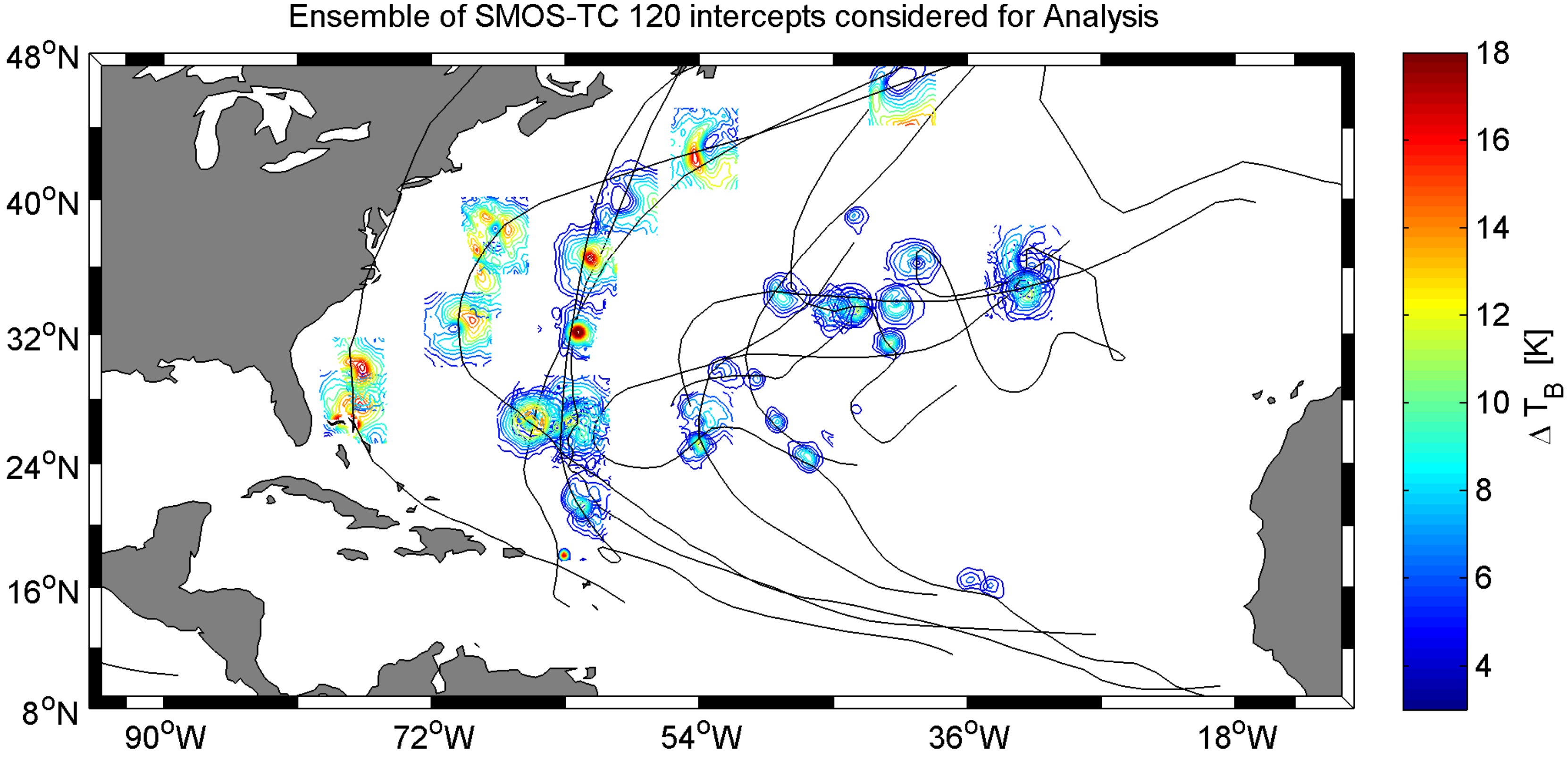


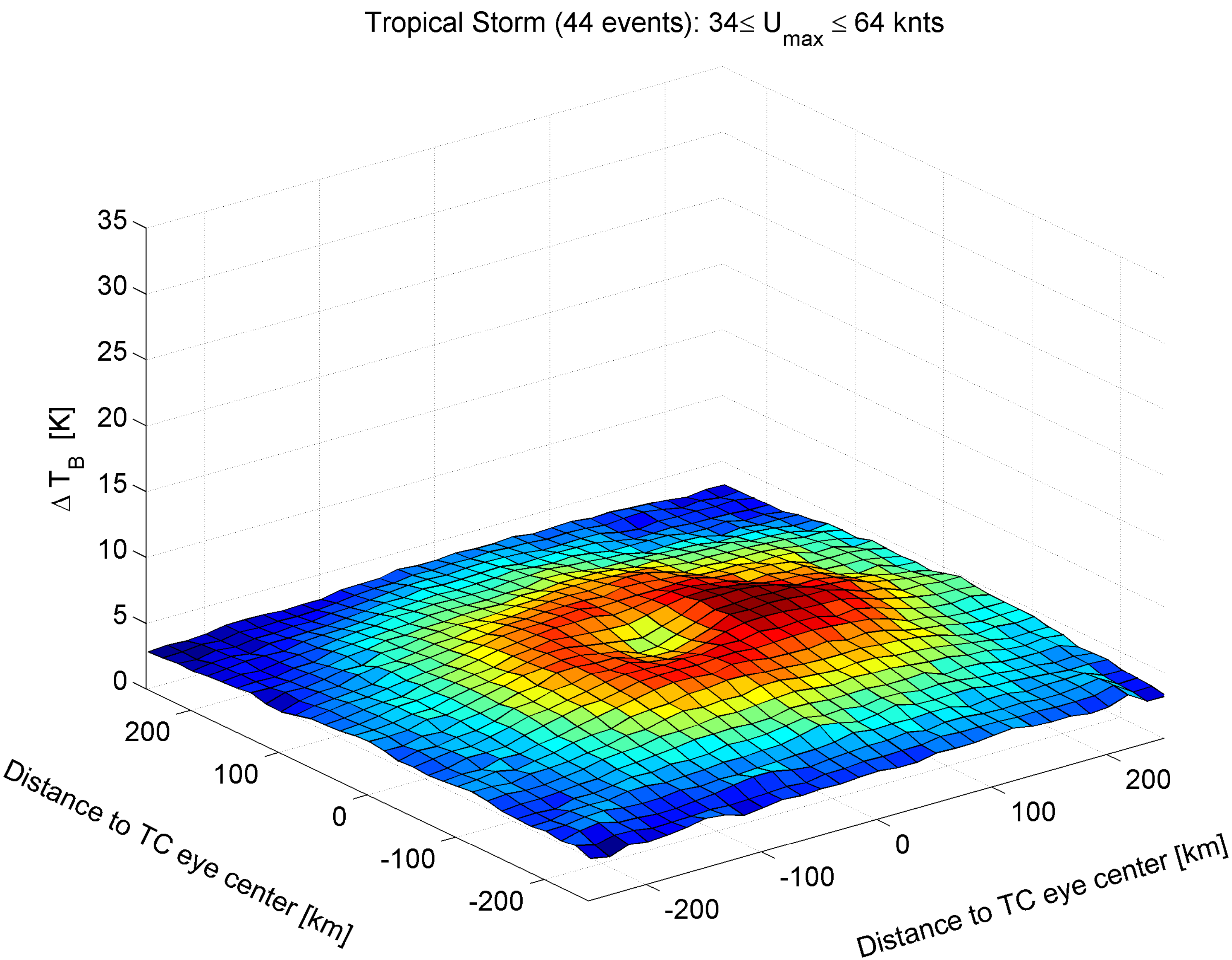
South Indian SMOS intercepts with 2011-2013's TCs

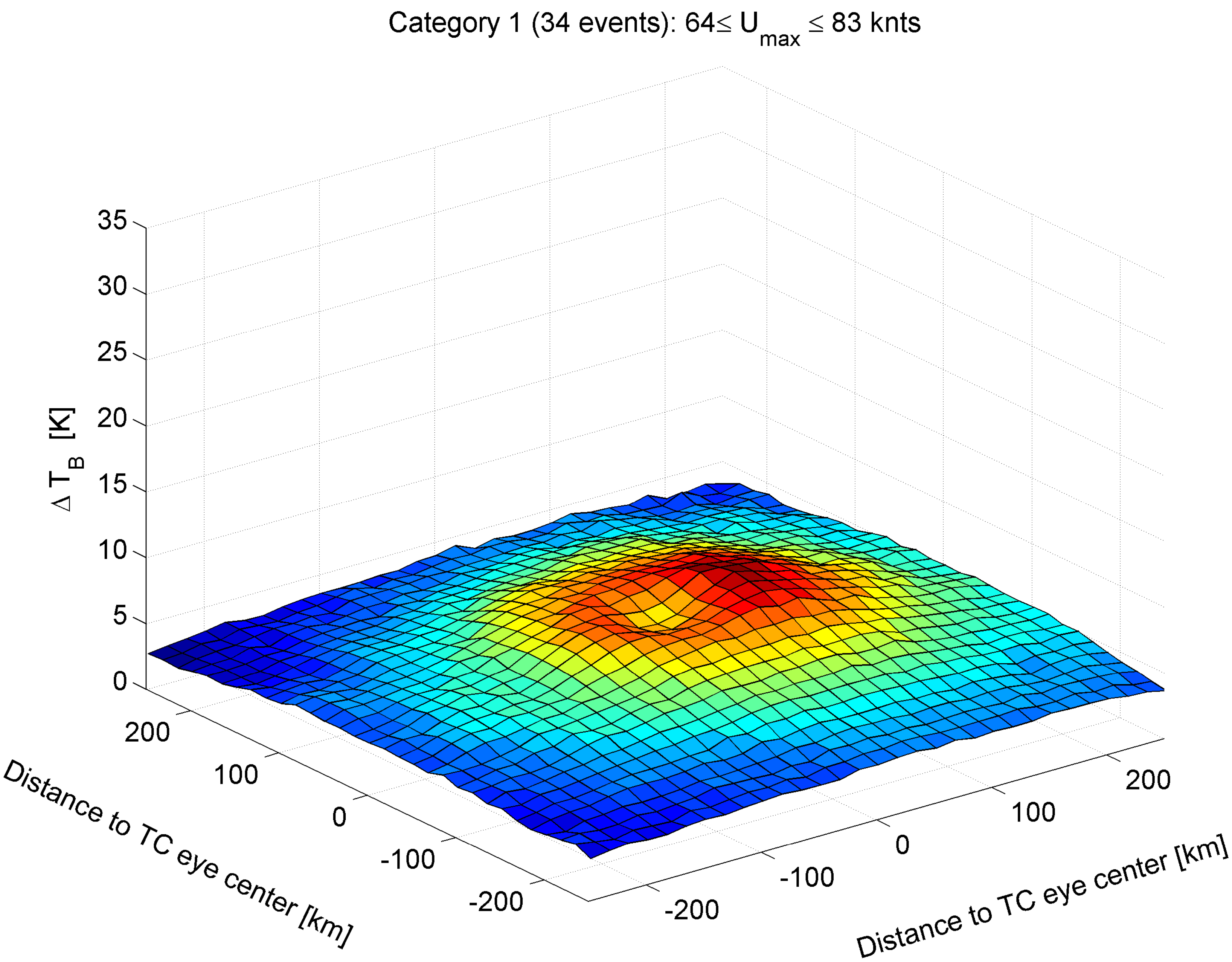
Ensemble of SMOS-TC 120 intercepts considered for Analysis



North Atlantic SMOS intercepts 2010-2014 TC

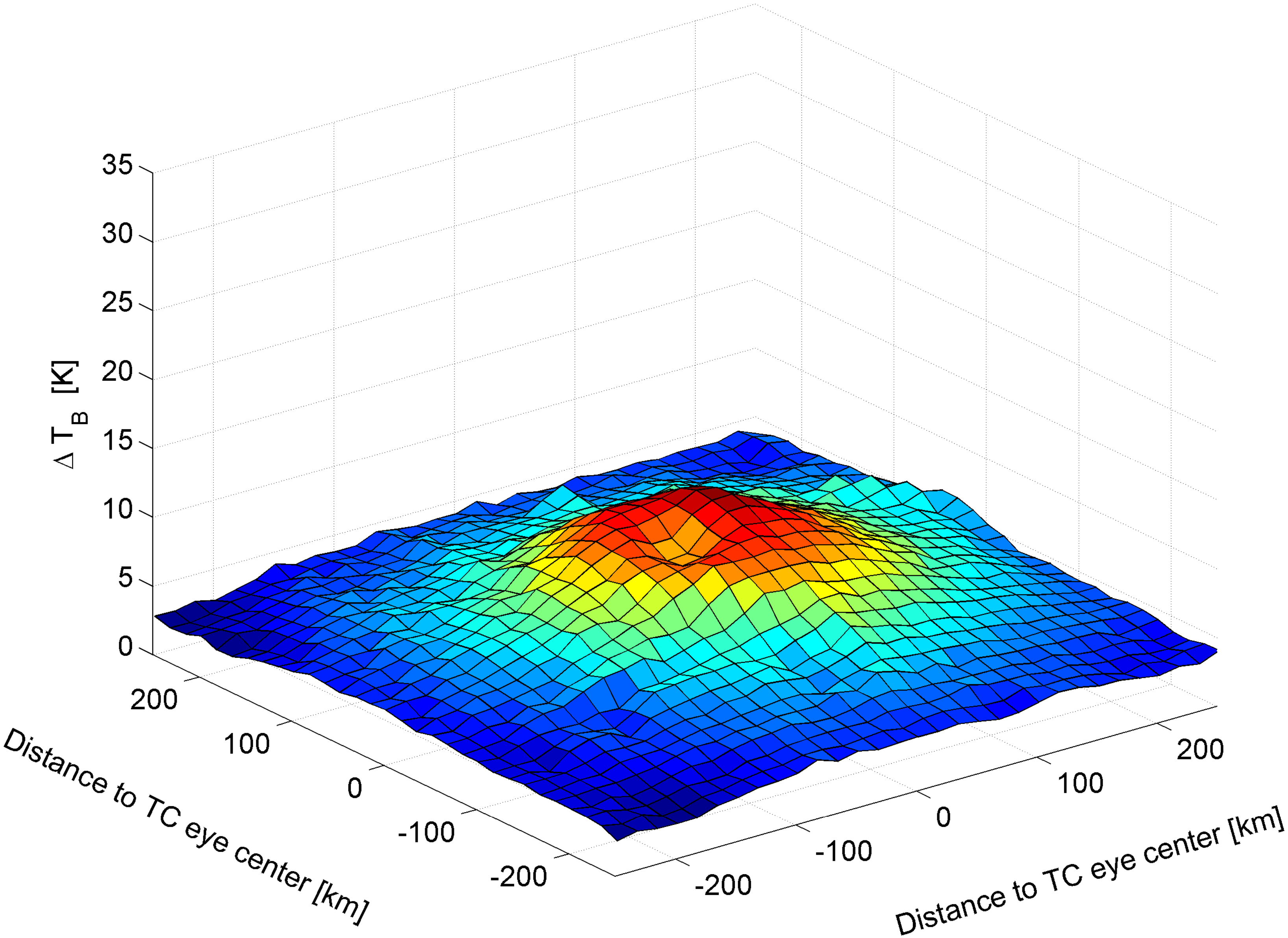


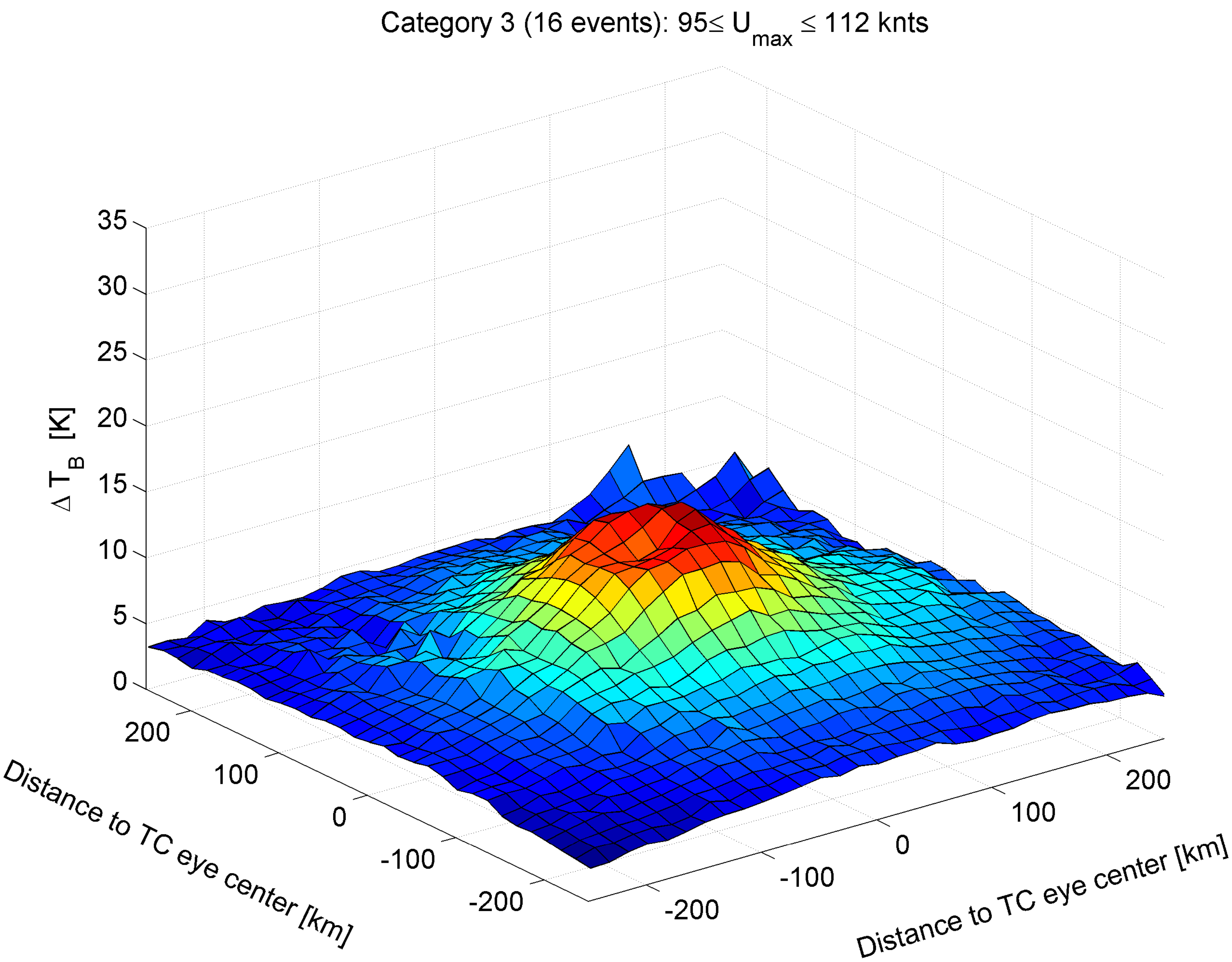

Tropical Storm (44 events): $34 \leq U_{max} \leq 64$ knts
ΔT_B [K]
35
30
25
20
15
10
5
0
200
100
0
-100
-200
Distance to TC eye center [km]
-200
-100
0
100
200
Distance to TC eye center [km]



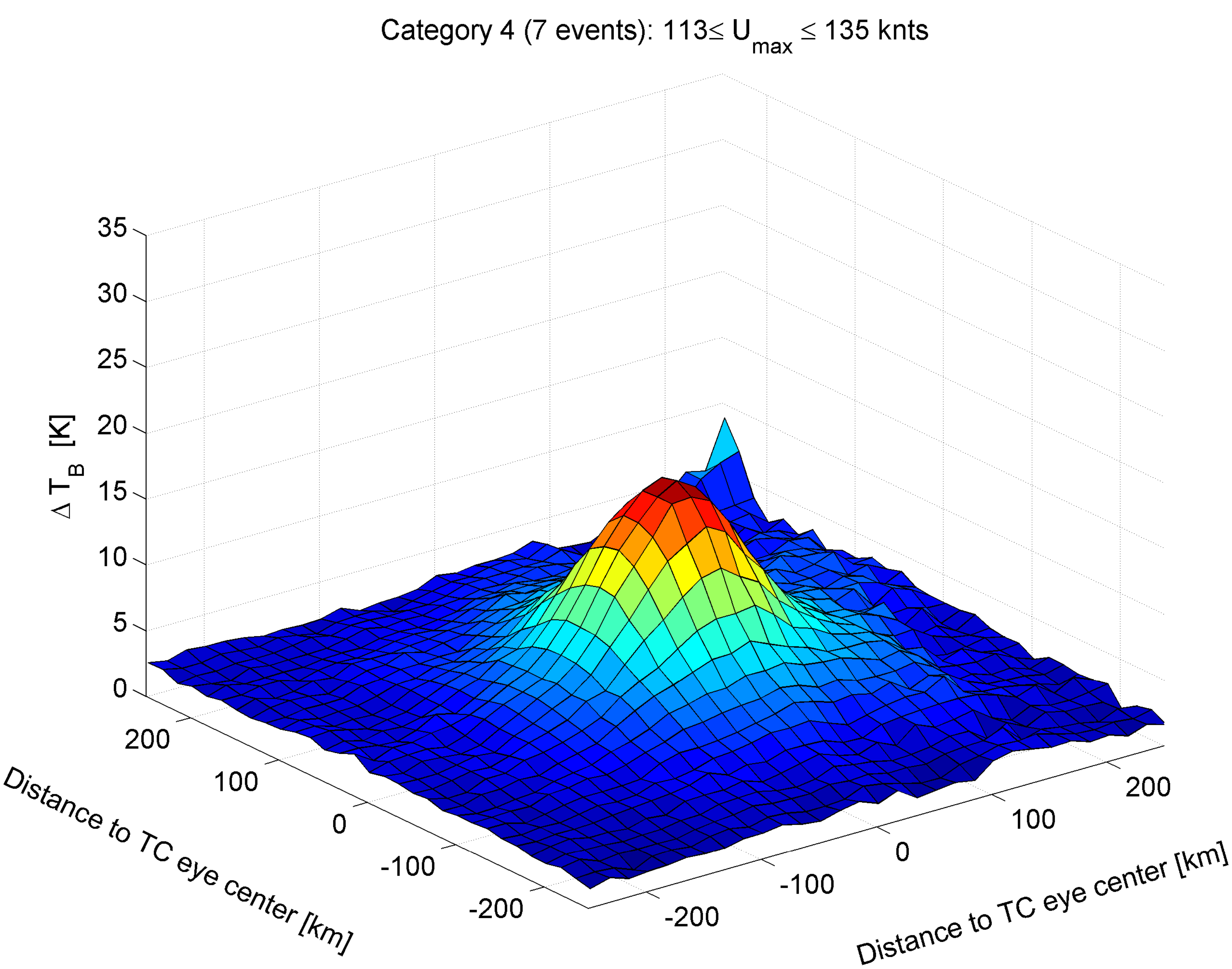
Category 1 (34 events): 64≤ U max ≤ 83 knts
35
30
25
20
15
10
5
0
ΔT B [K]
200
100
0
-100
-200
Distance to TC eye center [km]
-200
-100
0
100
200
Distance to TC eye center [km]

Category 2 (17 events): $84 \leq U_{max} \leq 95$ knts



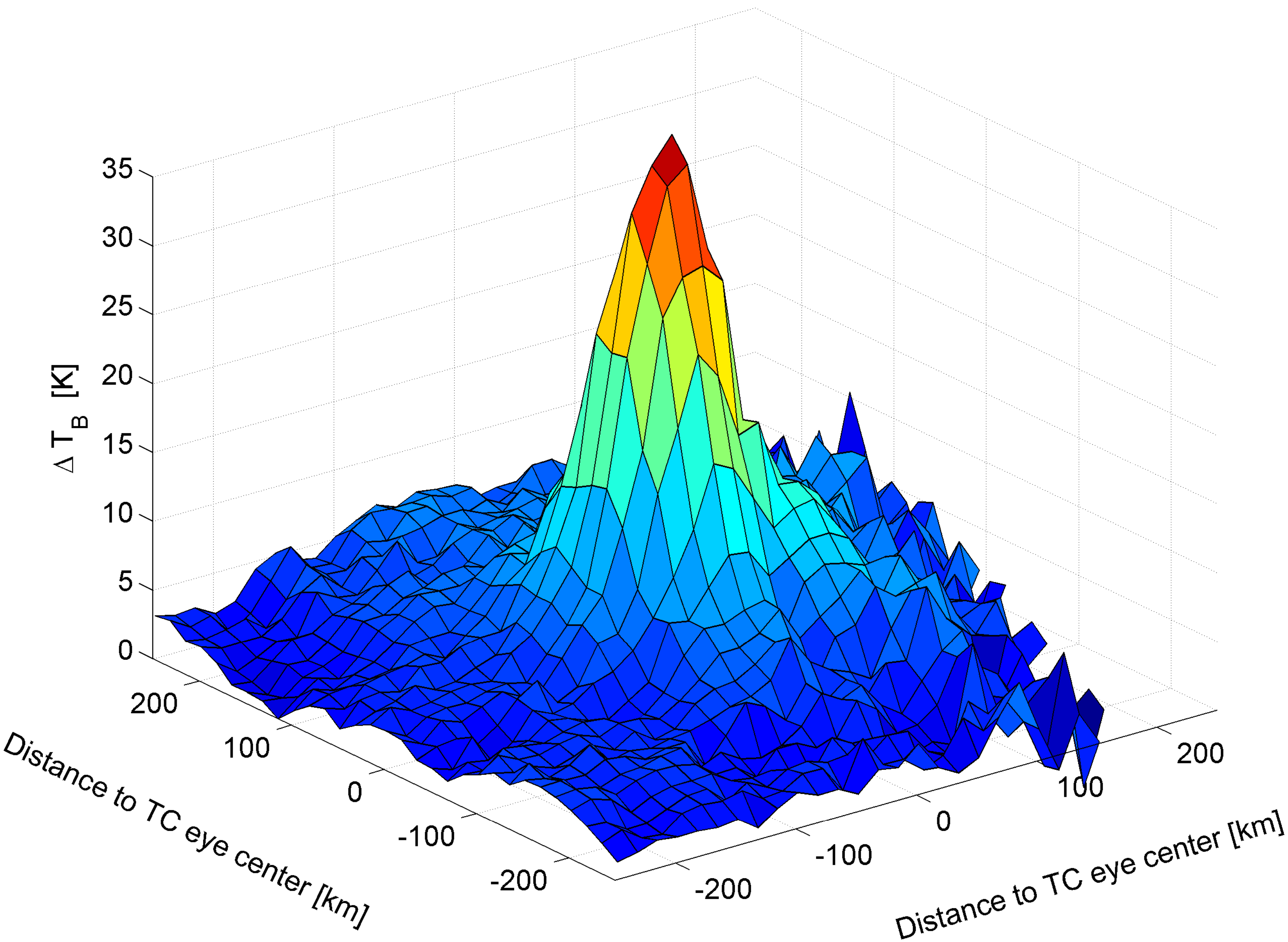


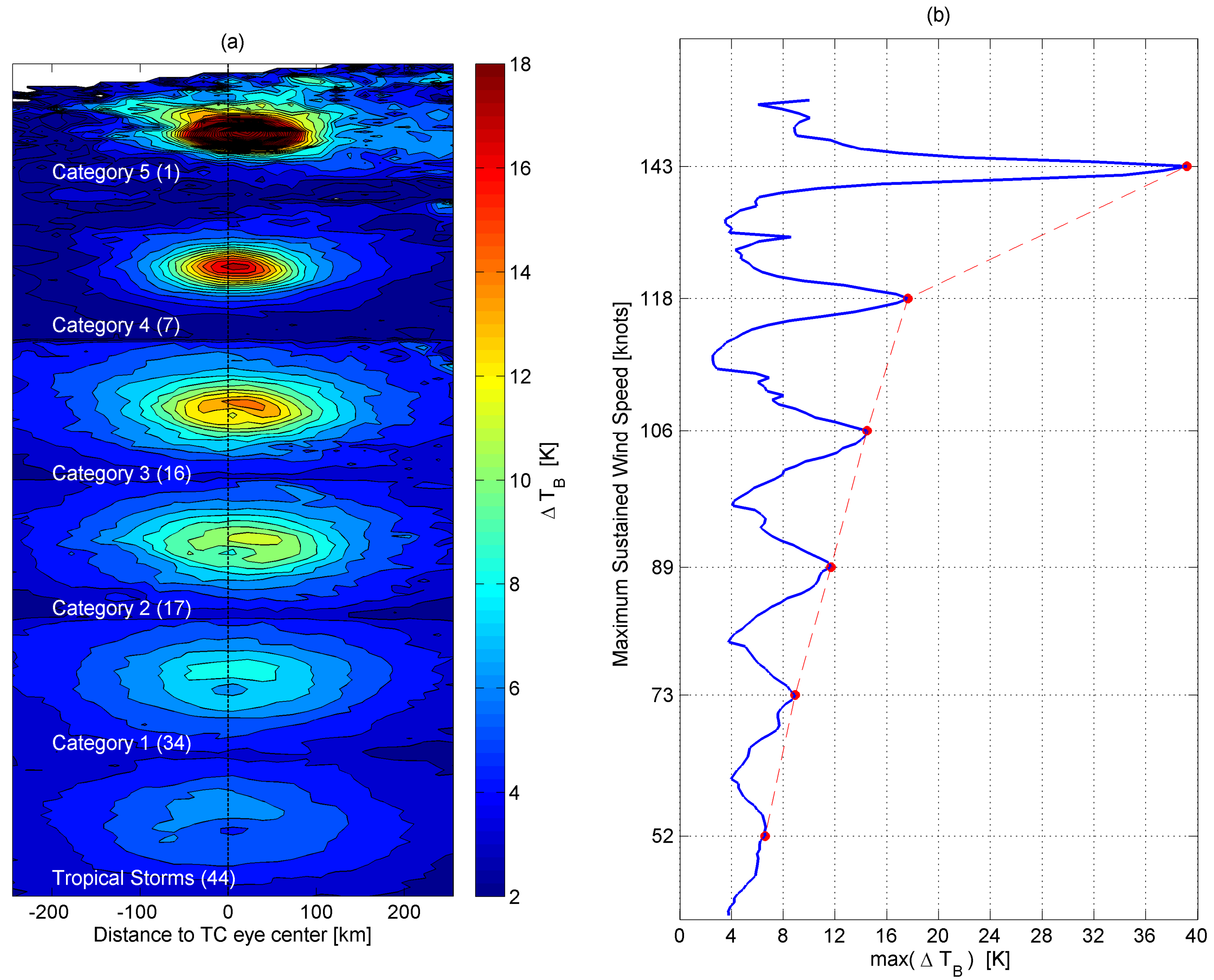
Category 3 (16 events): 95≤ U_{max} ≤ 112 knts
ΔT_B [K]
35
30
25
20
15
10
5
0
200
100
0
-100
-200
Distance to TC eye center [km]
-200
-100
0
100
200
Distance to TC eye center [km]

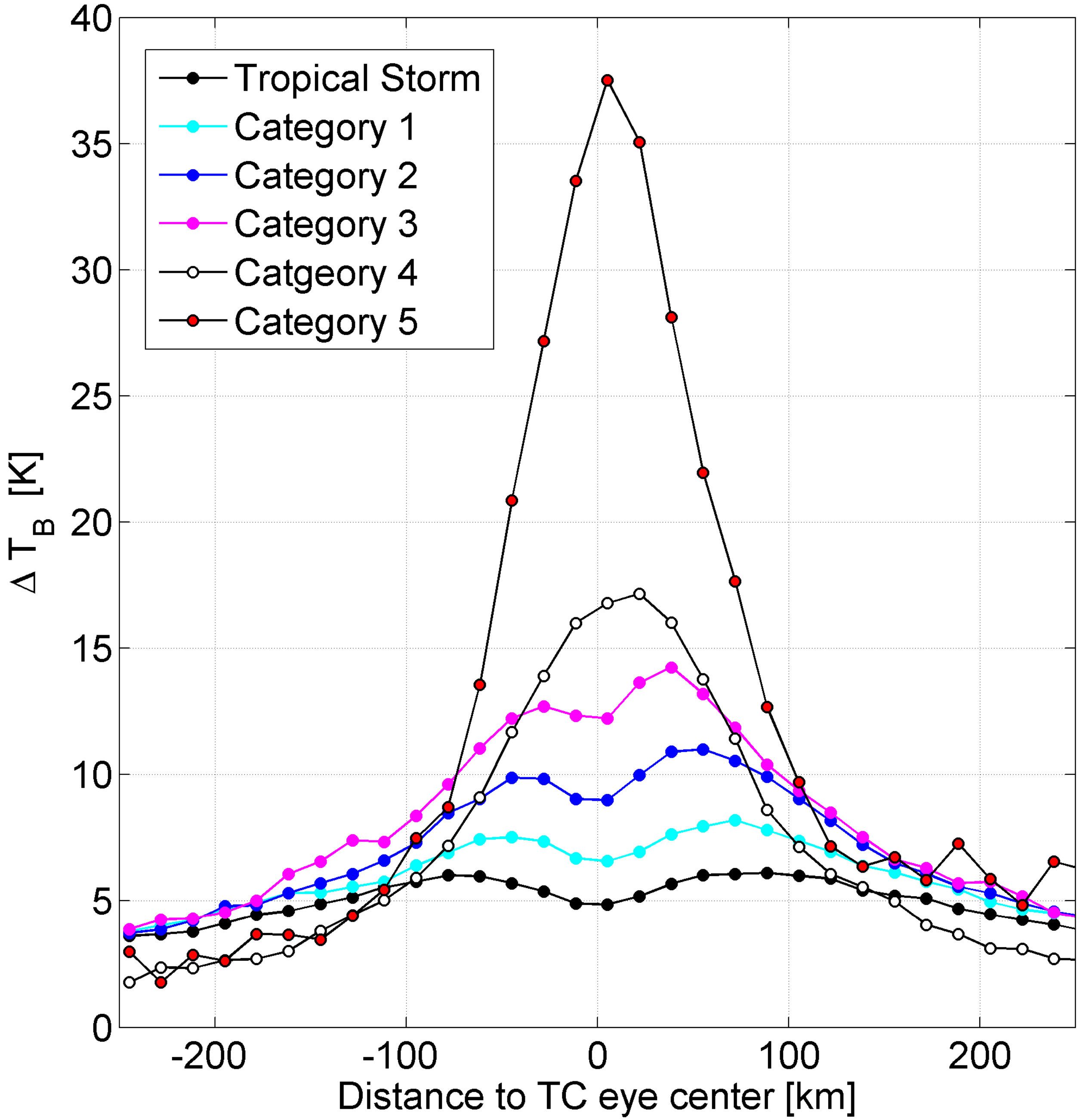


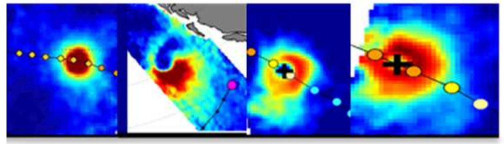
Category 4 (7 events): 113≤ U max ≤ 135 knts
35
30
25
20
15
10
5
0
Δ T B [K]
200
100
0
-100
-200
Distance to TC eye center [km]
-200
-100
0
100
200
Distance to TC eye center [km]

Category 5 (1 event): U_{max} ~ 140 knts



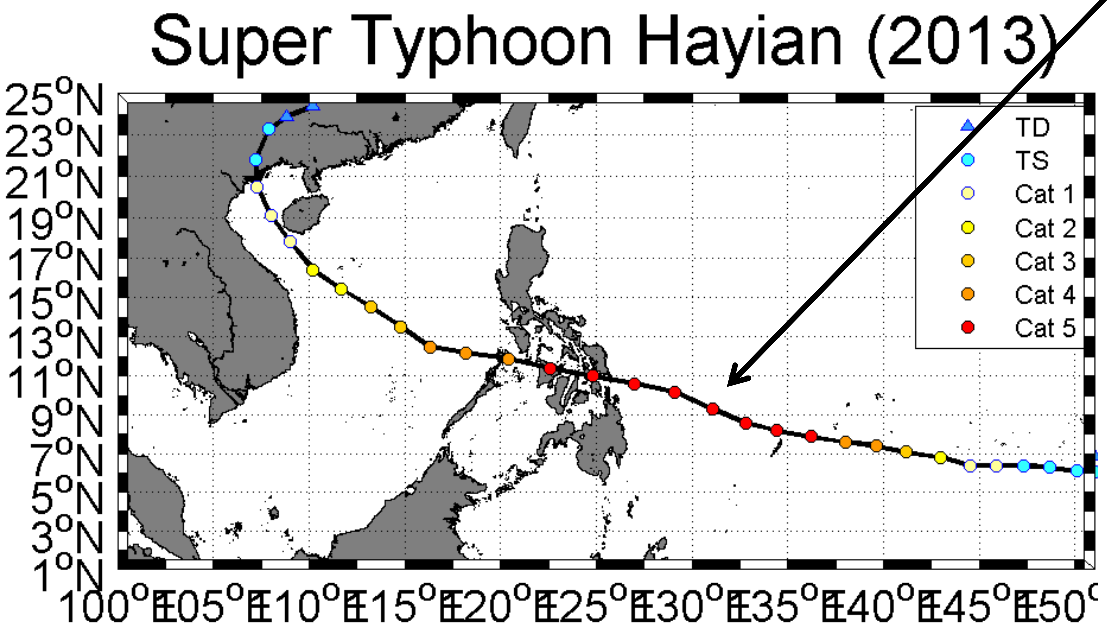

(a)
Category 5 (1)
Category 4 (7)
Category 3 (16)
Category 2 (17)
Category 1 (34)
Tropical Storms (44)
-200
-100
0
100
200
Distance to TC eye center [km]
18
16
14
12
10
8
6
4
2
Δ T_B [K]
(b)
Maximum Sustained Wind Speed [knots]
143
118
106
89
73
52
0
4
8
12
16
20
24
28
32
36
40
max(Δ T_B) [K]

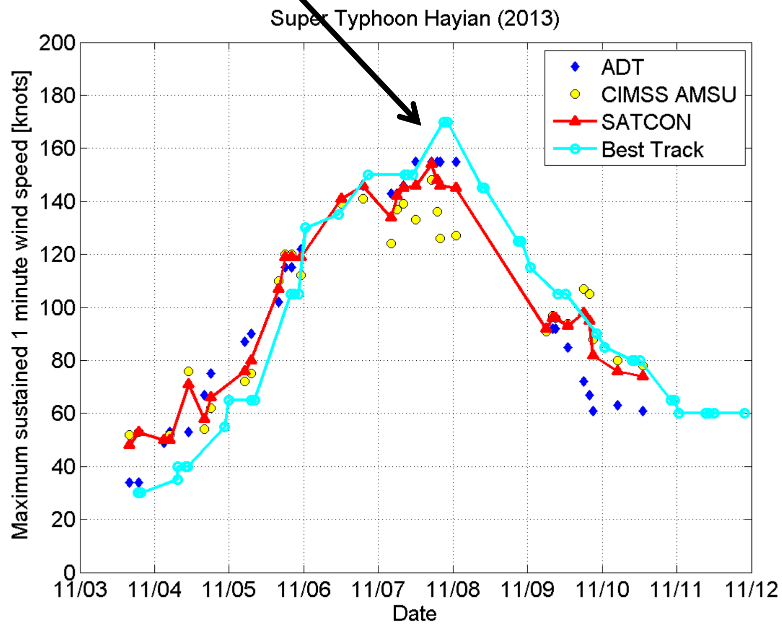




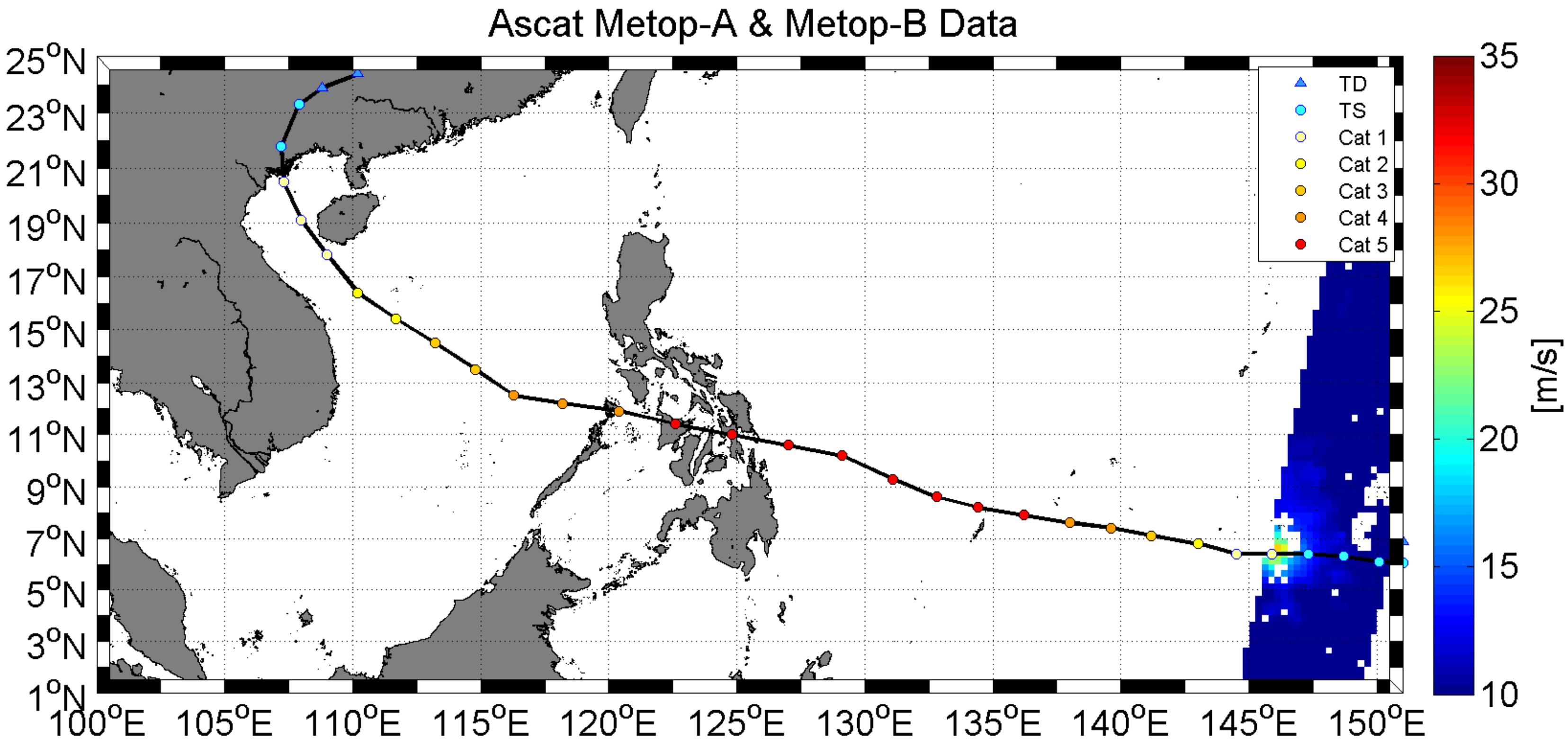
SMOS data
As a ‘clear’
Tropical storm intensity
meter

Super Typhoon
Maximum sustained Wind
Reaching ~150-170 knots





smos+ storms
support to science element



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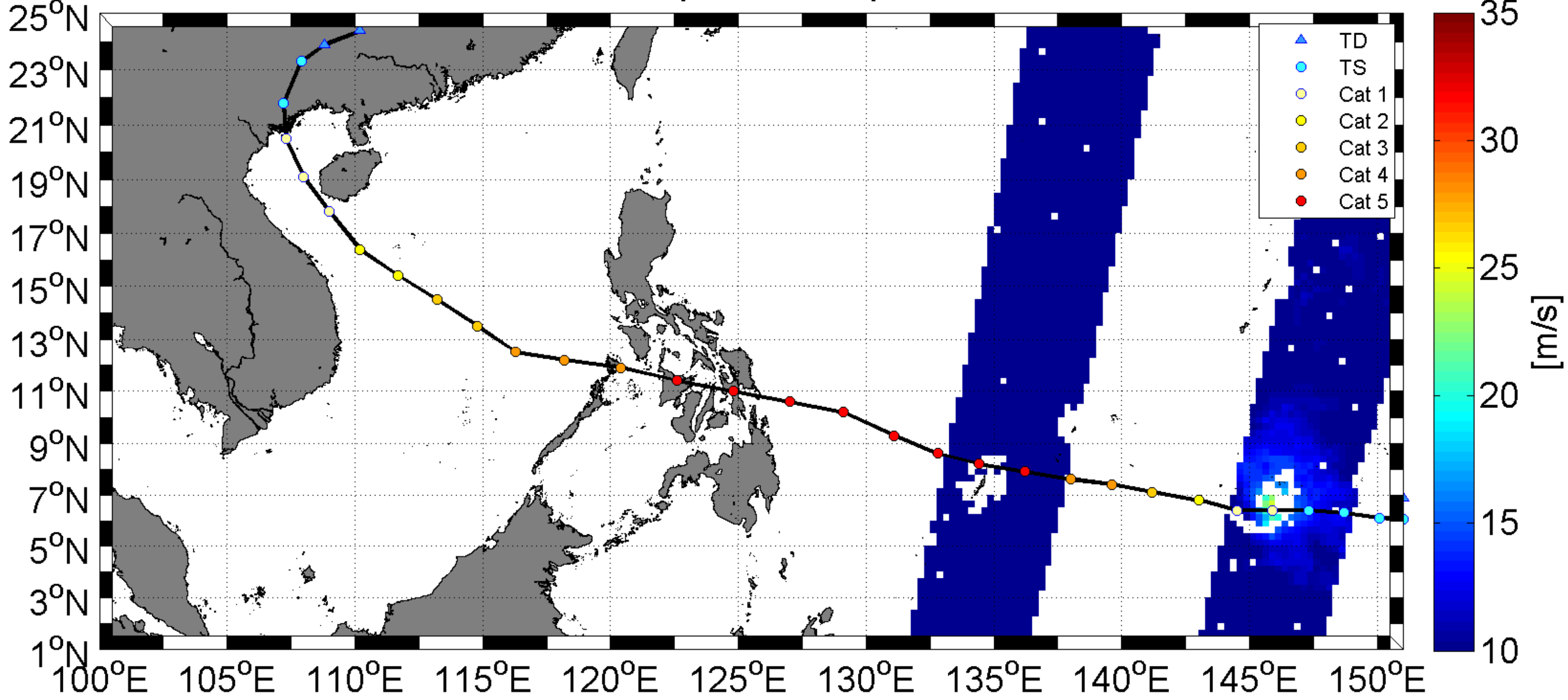
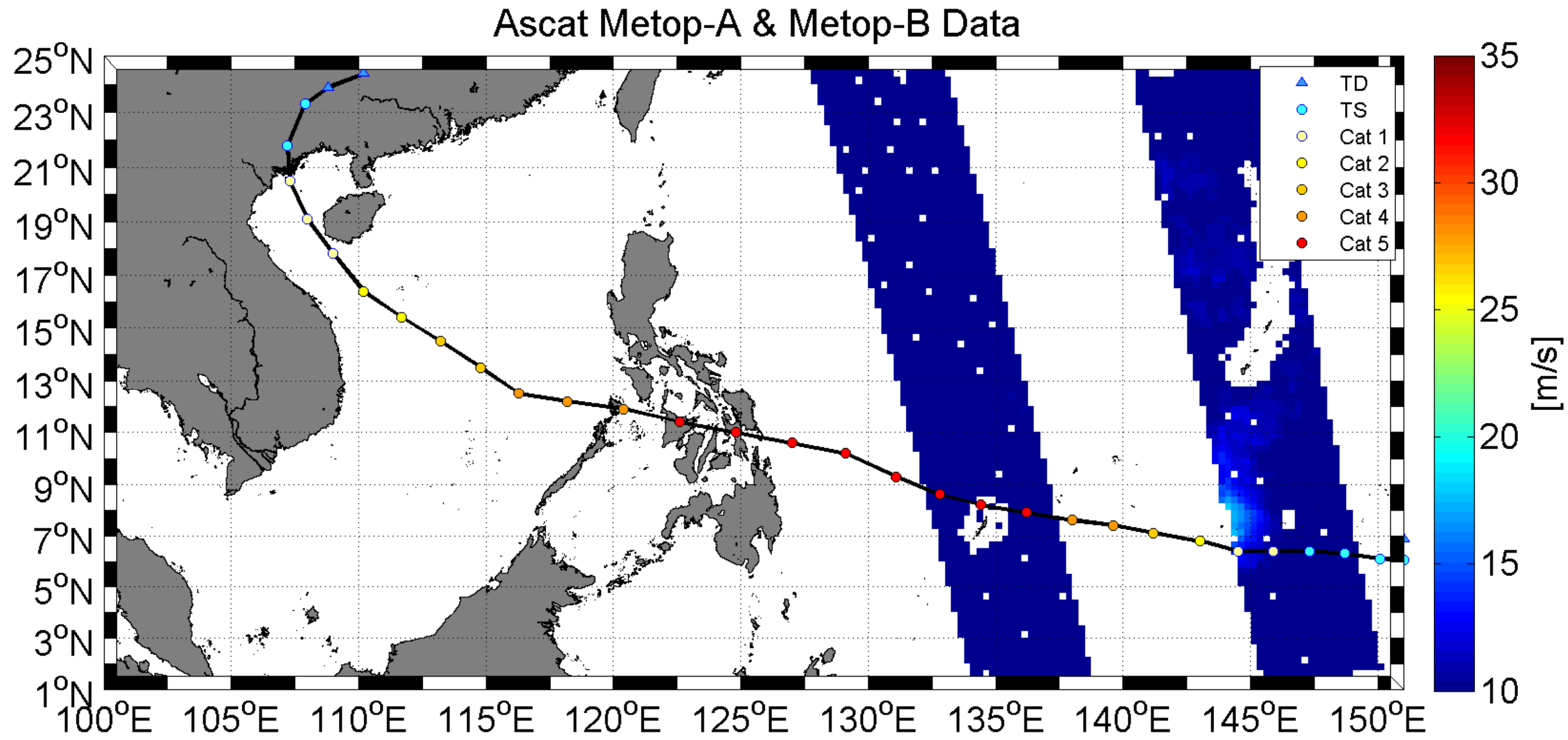
Ascat Metop-A & Metop-B Data

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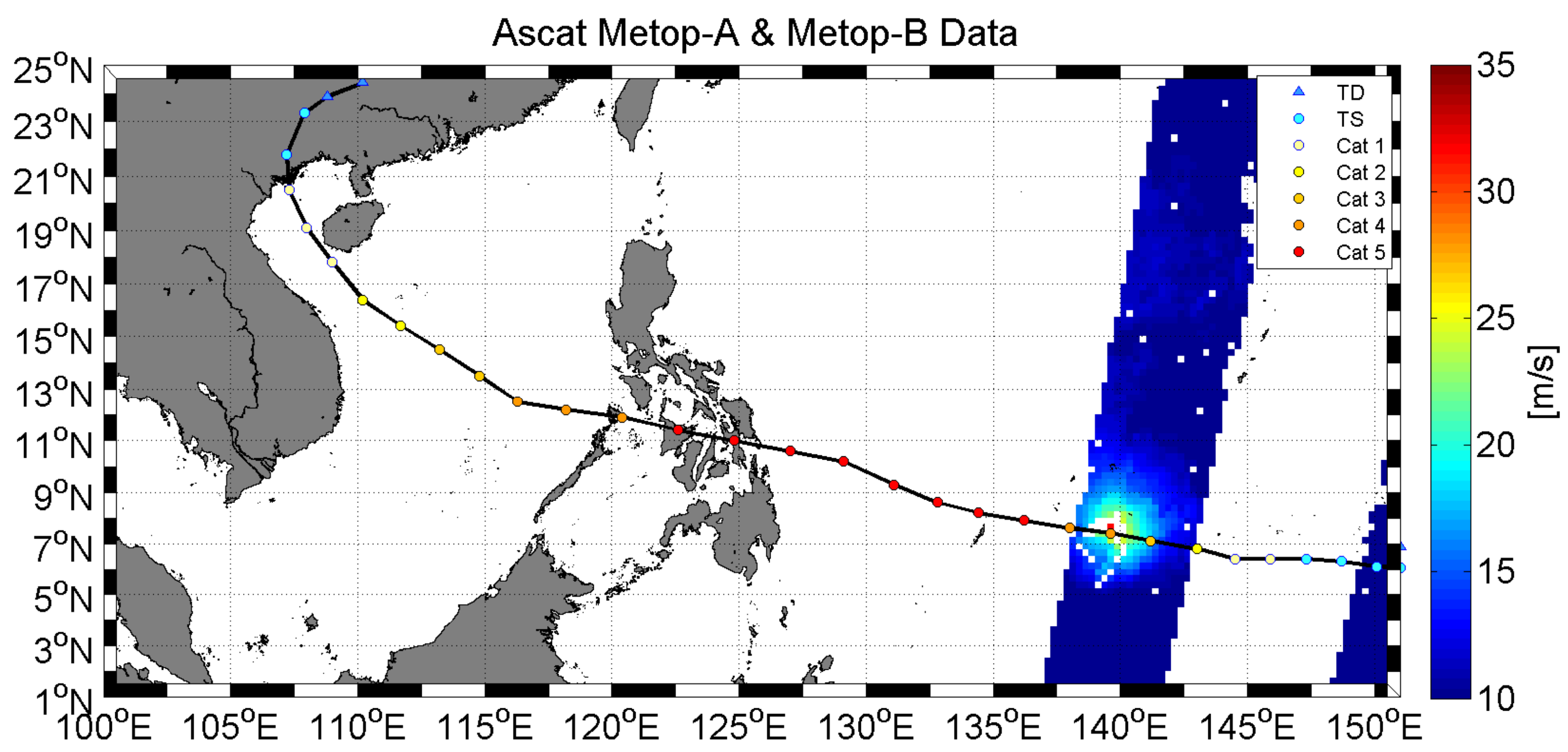
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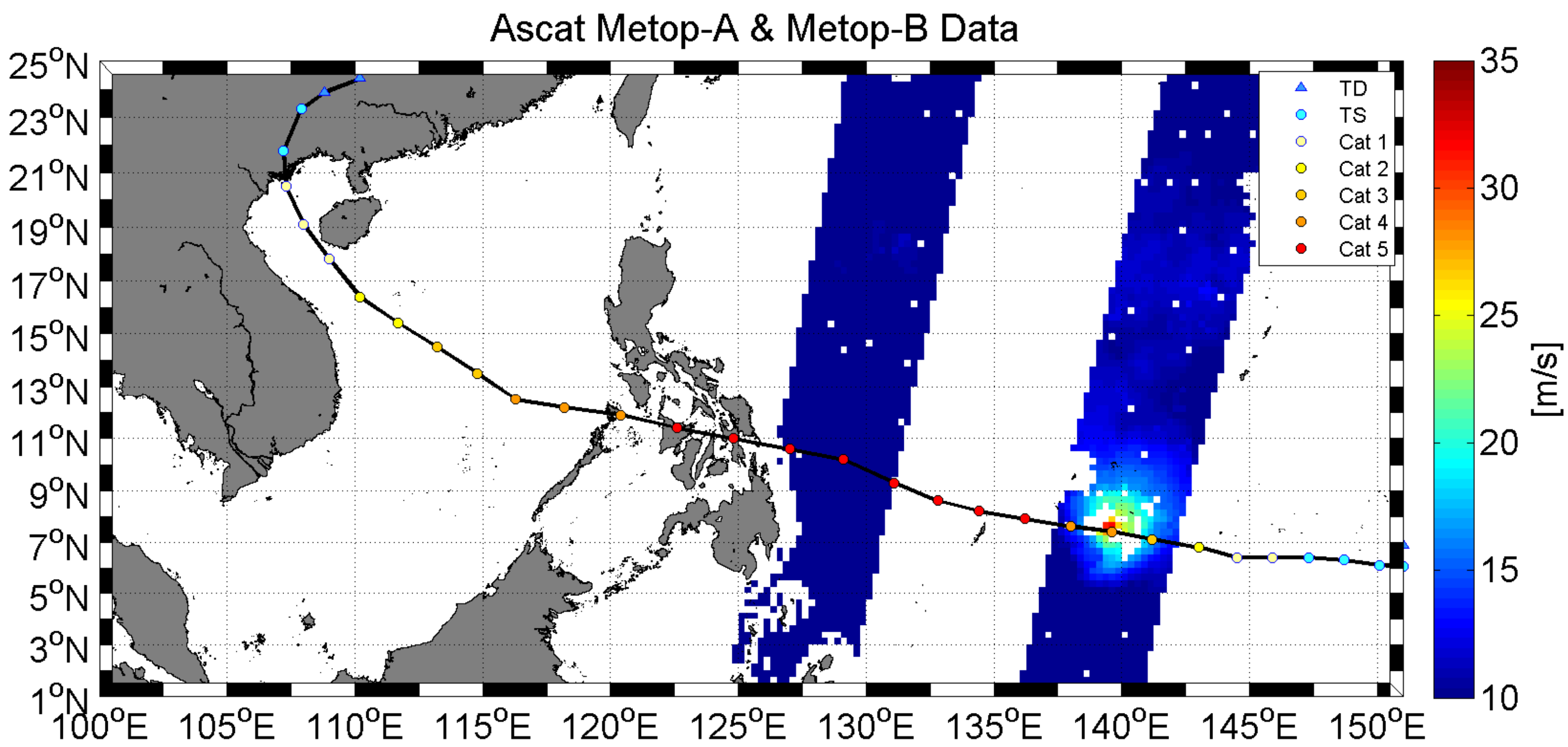
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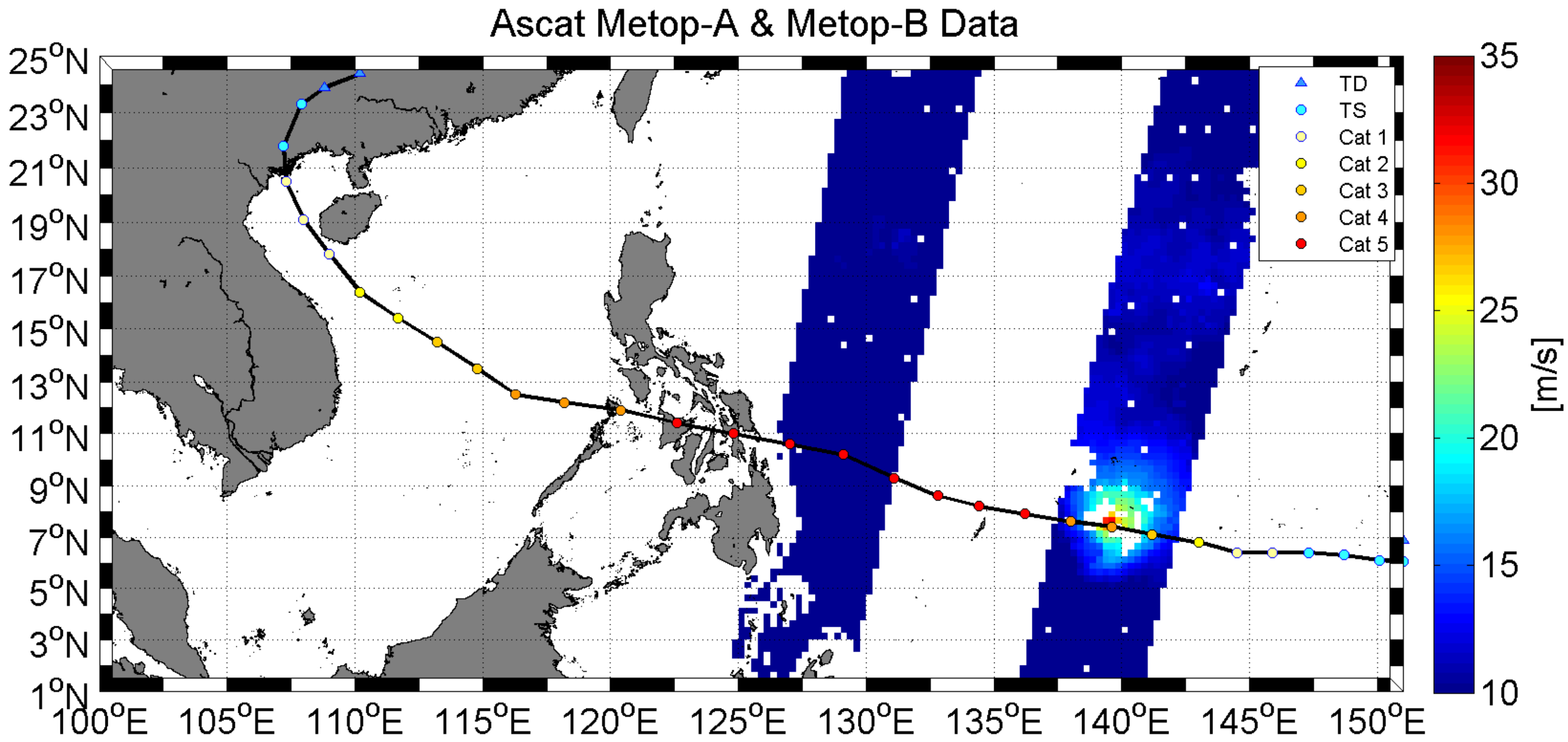
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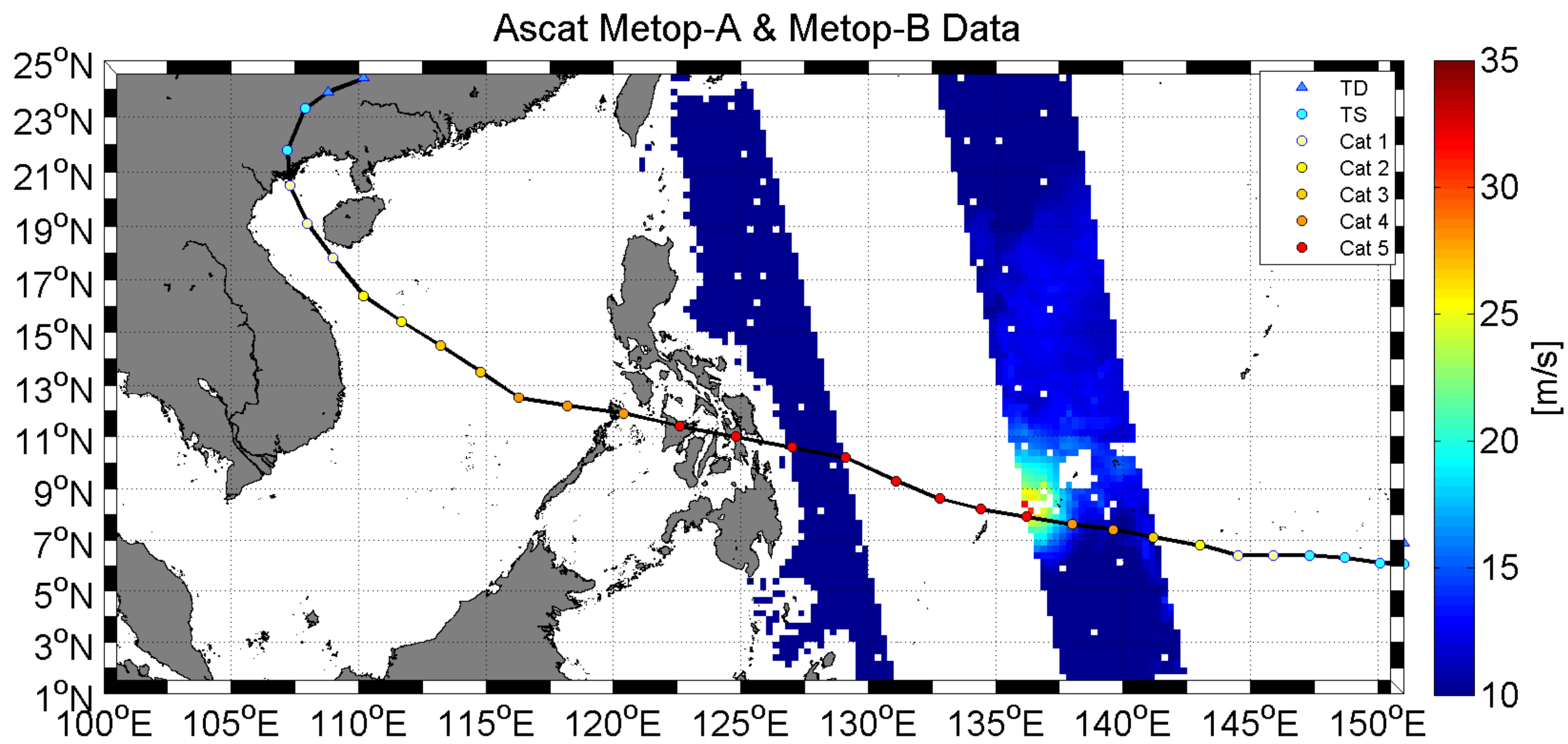
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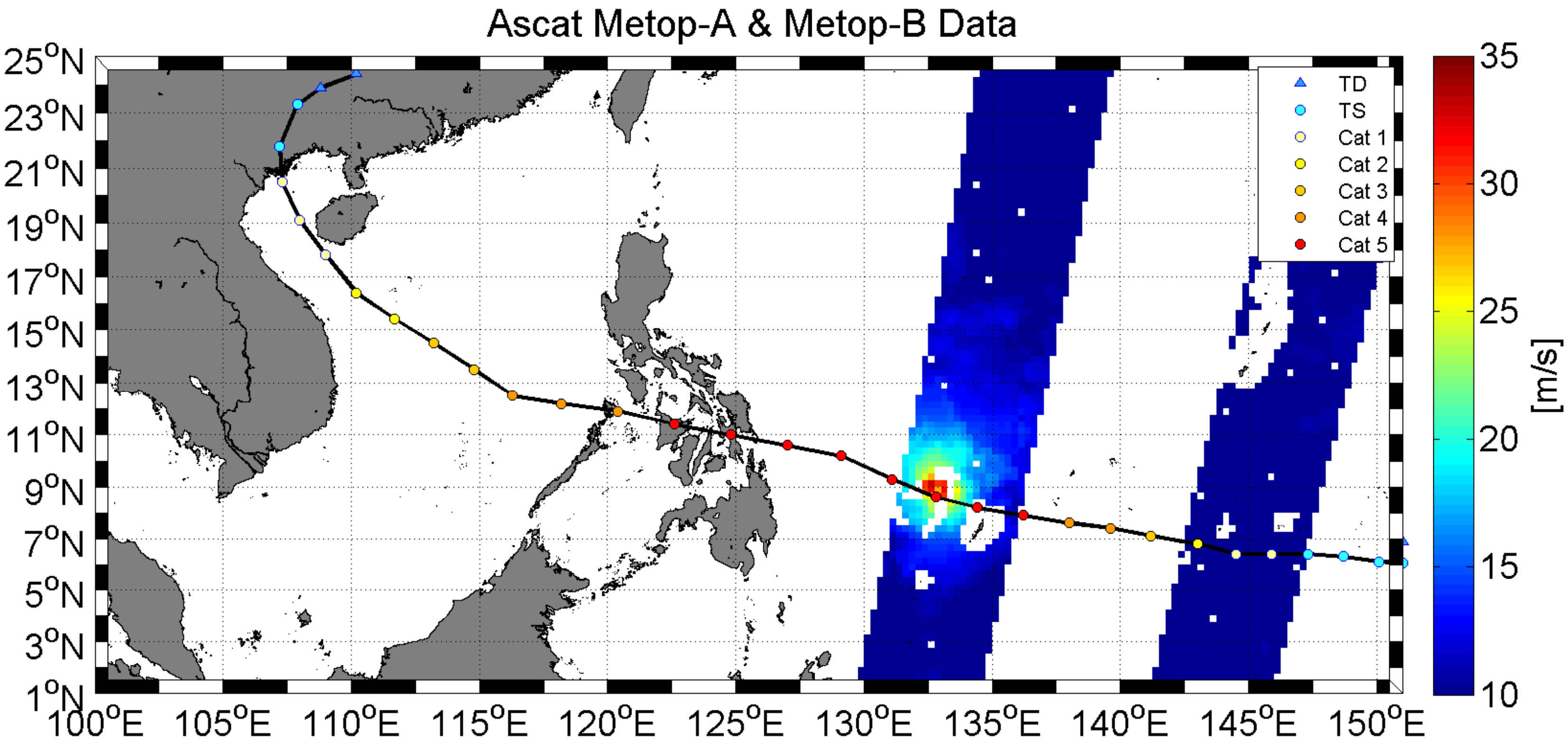
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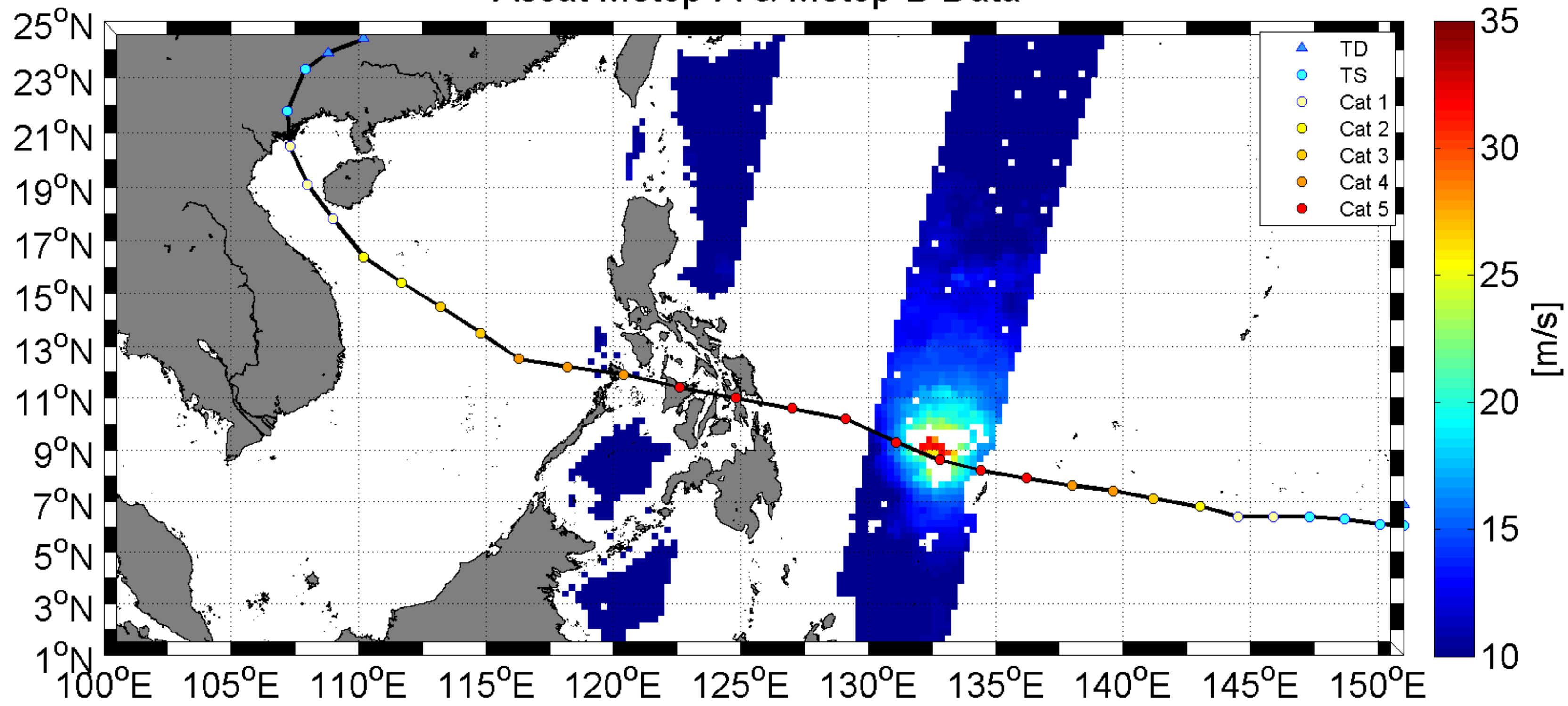

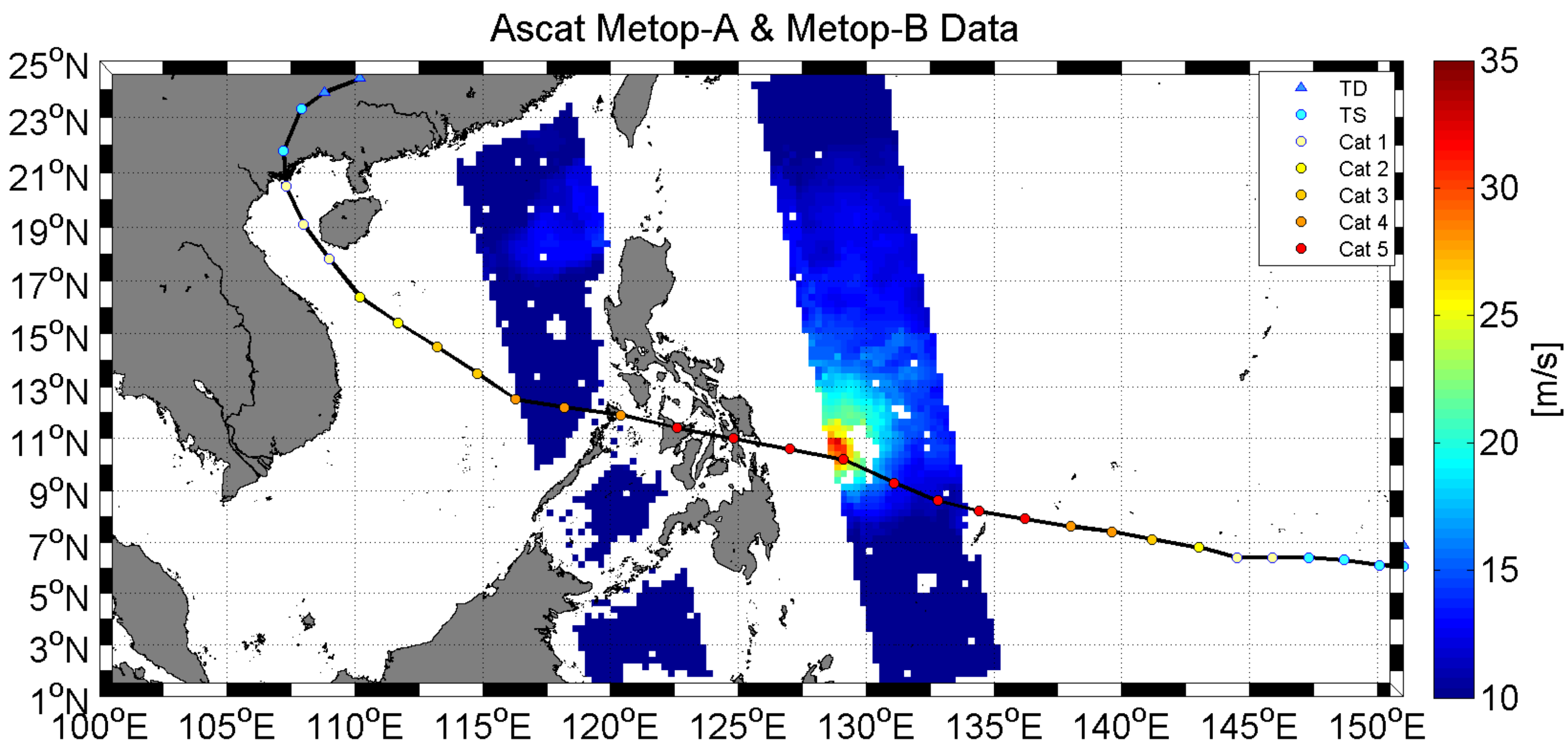
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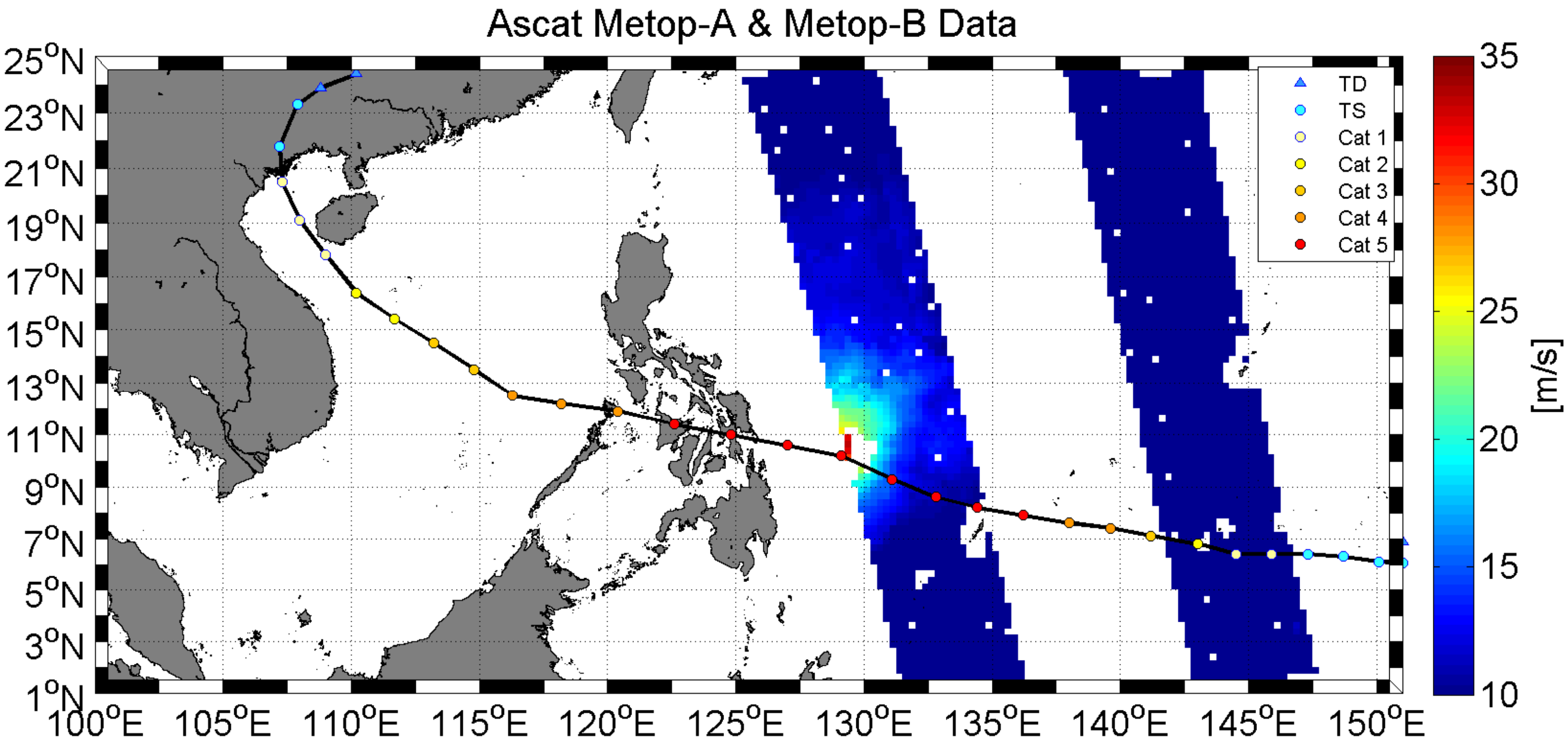
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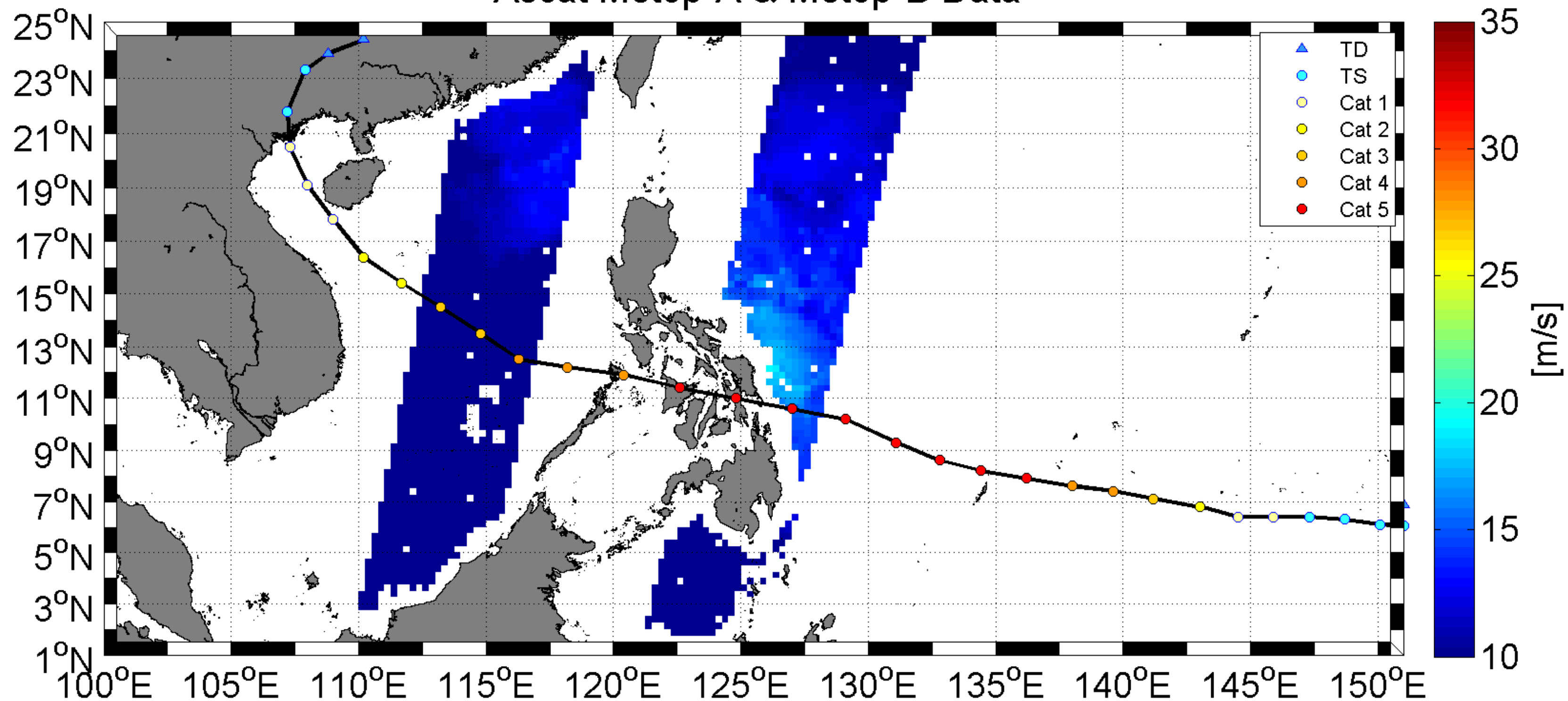

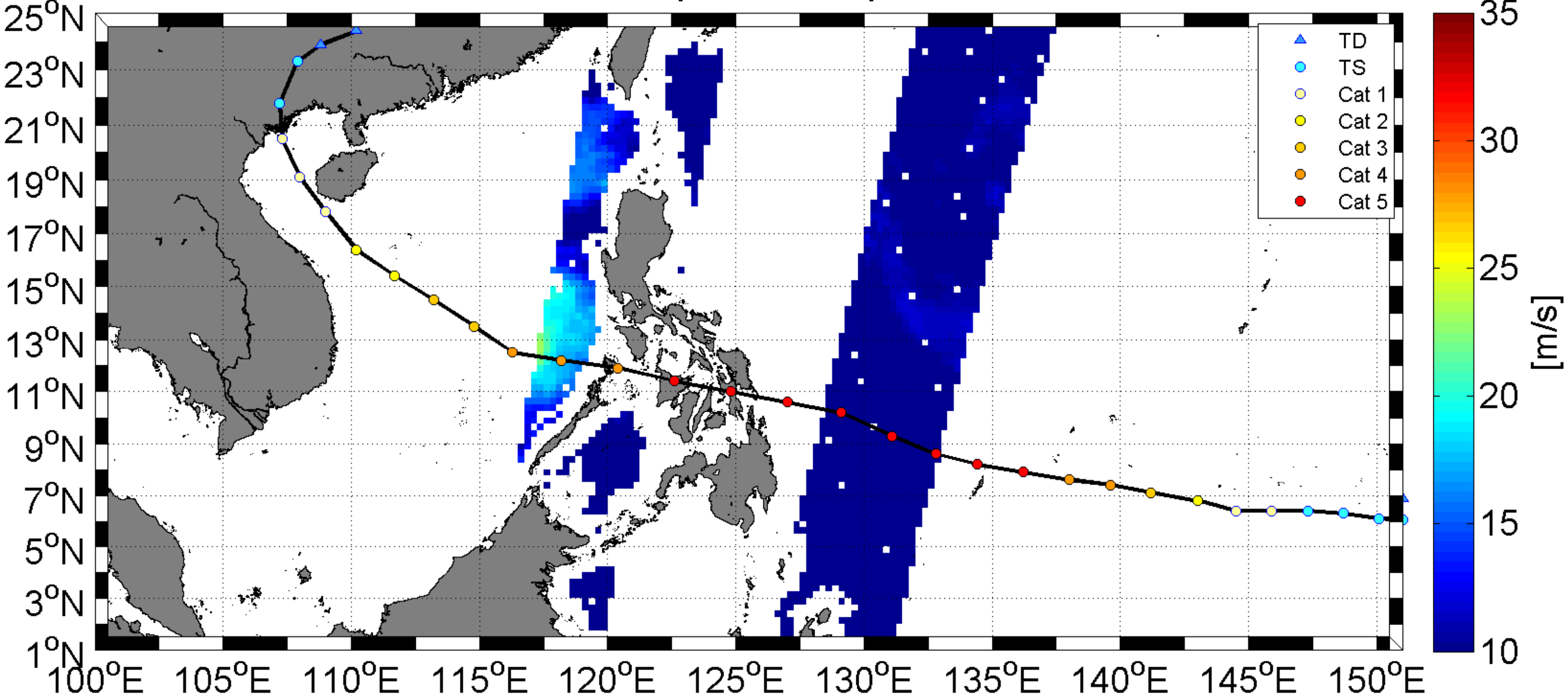
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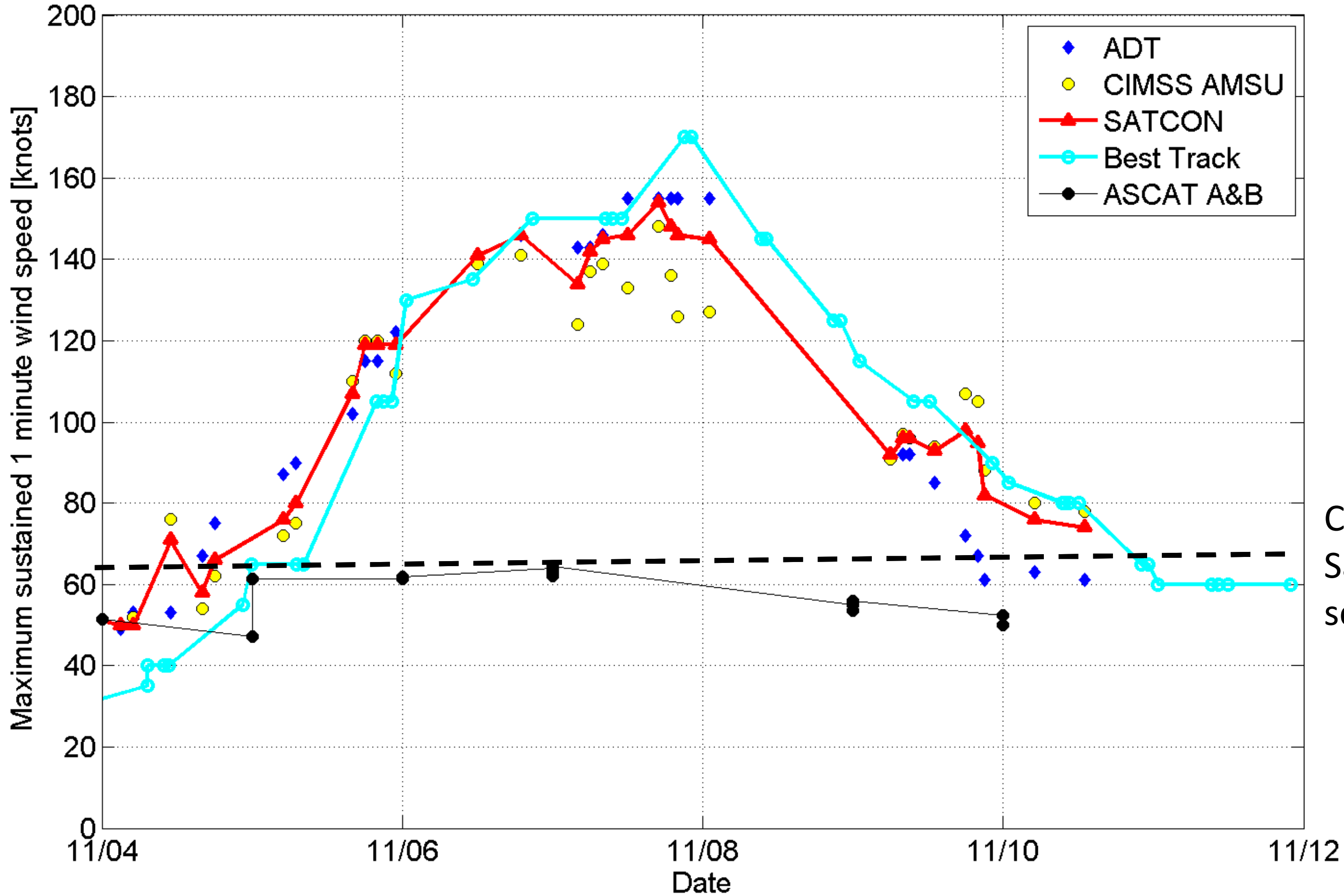
smos+ storms
support to science element



Cat 1 on Saffir-Simpson scale

Unability of the scatterometer to measure wind speeds above hurricane force (64 knots)

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Haiyan Super Typhoon Signature in SMOS data

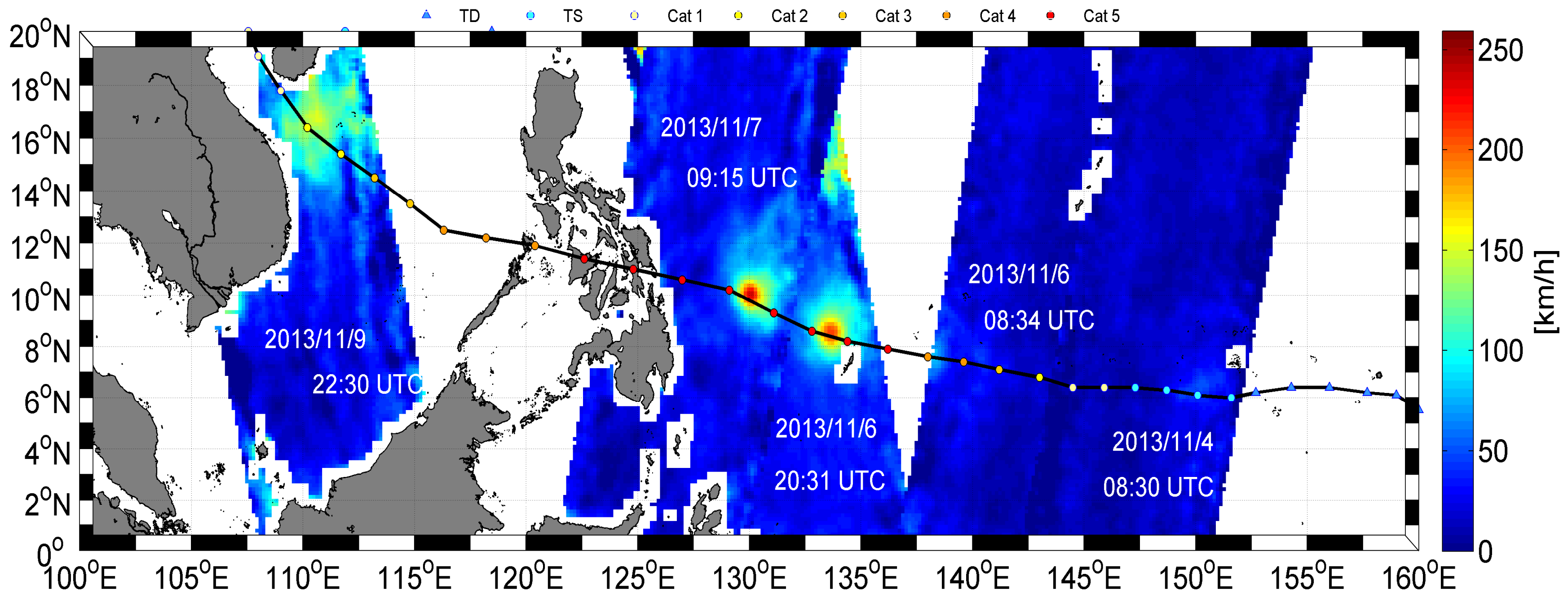
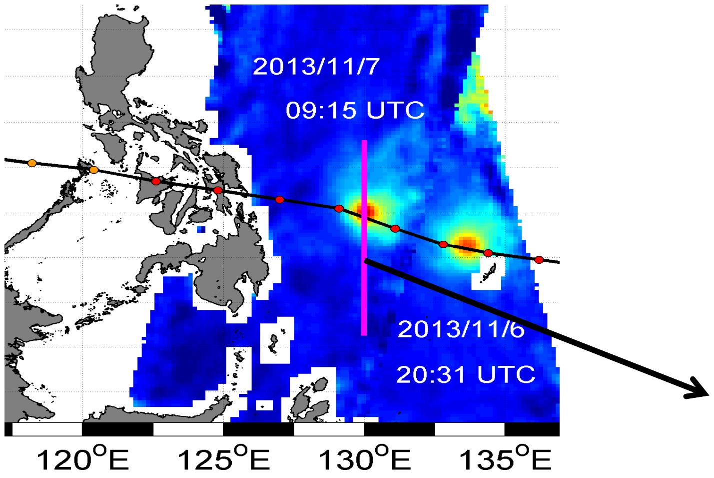
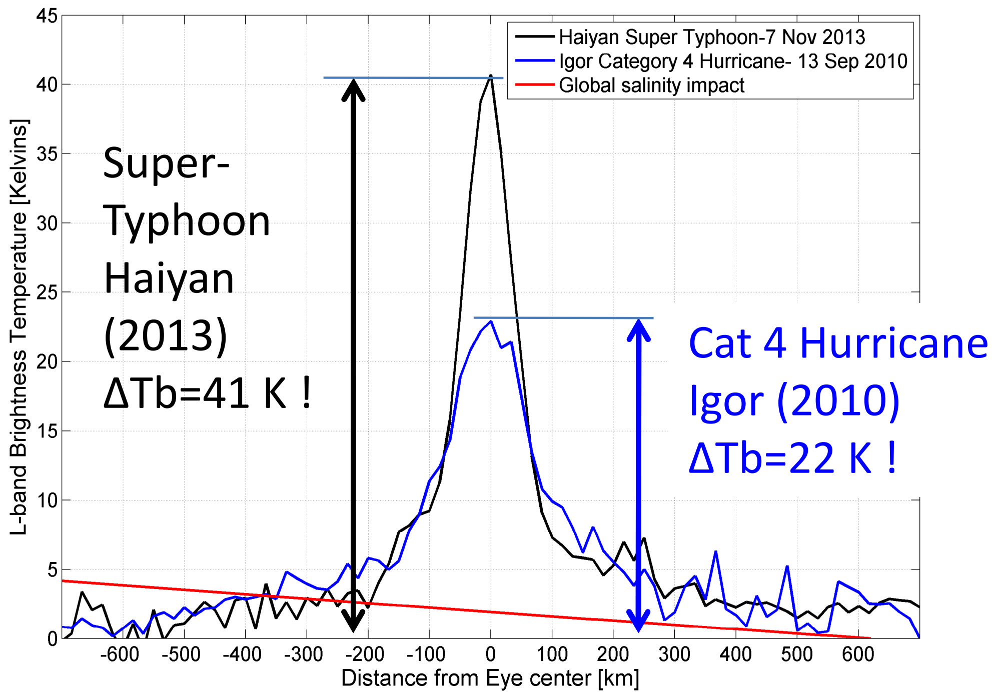


Figure 1: SMOS retrieved surface wind speed [km/h] along the eye track of super typhoon Haiyan from 4 to 9 Nov 2013.

Haiyan Super Typhoon Signature in SMOS data





Haiyan Typhoon in 2013:
The brightest natural source of L-band radiation ever measured over the oceans
=>an unprecedented natural extreme

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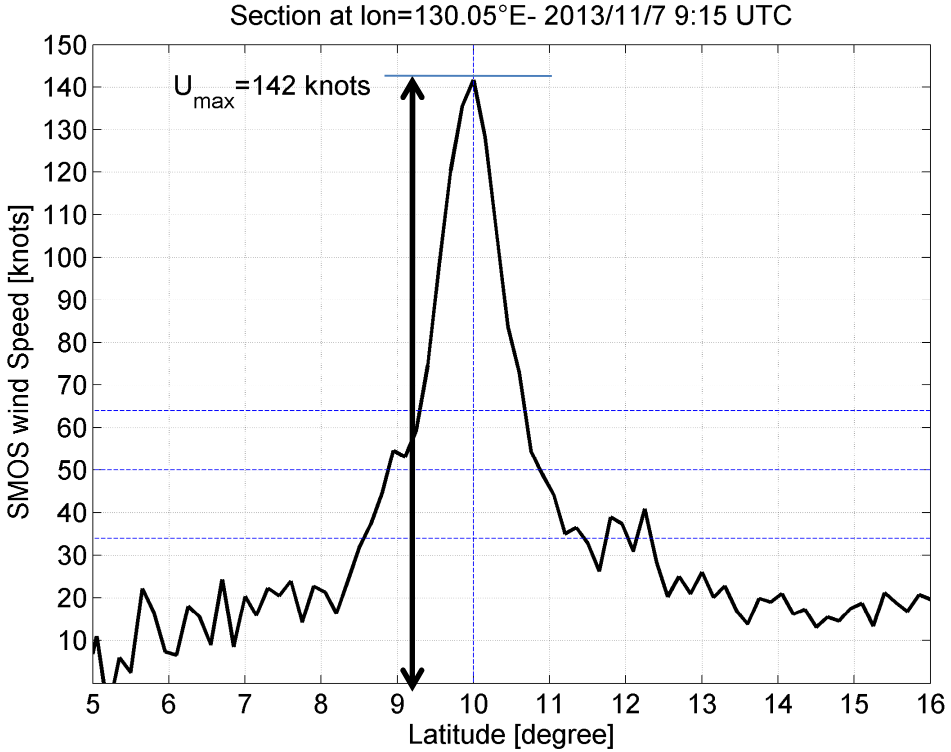
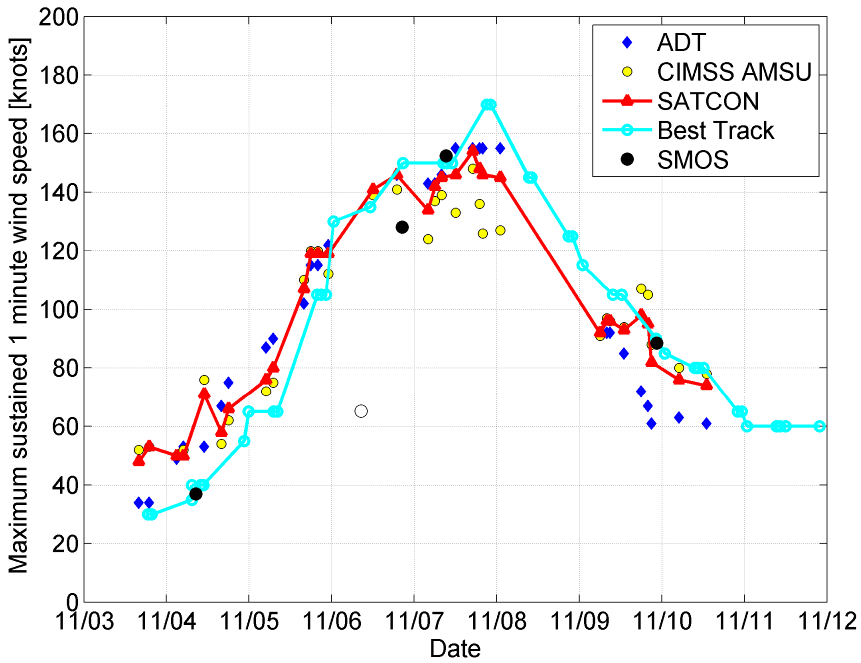
Haiyan Super Typhoon Signature in SMOS data



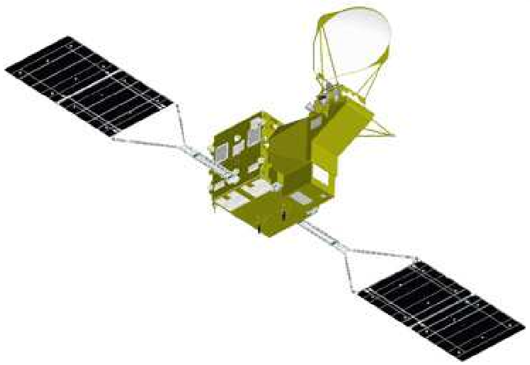
Surface wind speed deduced from the SMOS estimated excess brightness temperature.



Maximum sustained 1 minute wind speed estimated during Haiyan Typhoon. From SMOS data (black filled dots) compared to Advanced Dvorak Technique (ADT=blue diamond), CIMSS (yellow filled dots), SATCON (red) and Best Track from NHC (cyan).

Excellent agreement between SMOS max winds estimates and other traditional Top of the atmosphere estimates datasets (Dvorak, Best track,..)

Towards Merged SMOS-AMSR-2-SMAP High wind products



On 18 May 2012 Japan launched a new passive microwave instrument with the largest in the world diameter of antenna - Advanced Microwave Scanning Radiometer (AMSR2) onboard Global Change Observation Mission – Water satellite (GCOM-W1 "Shizuku")

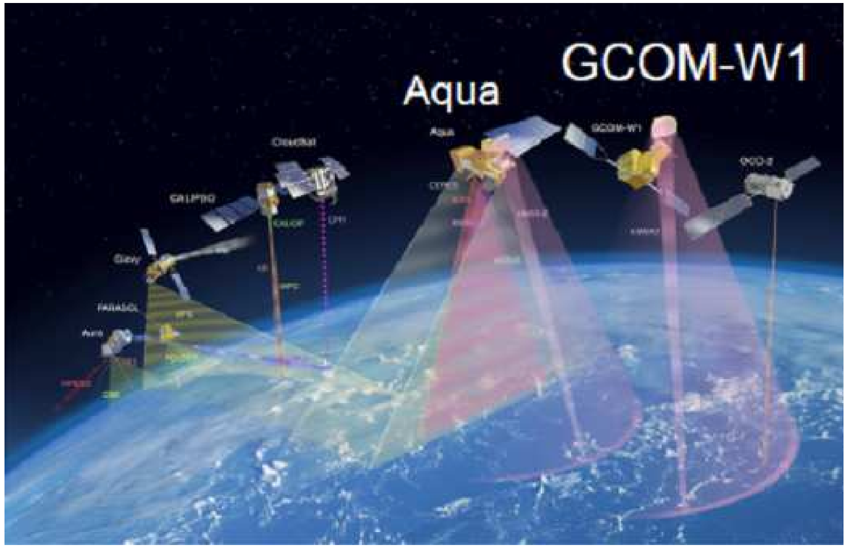
Additional channel

Better than AMSR-E

AMSR2 Channel Set

Center Freq. [GHz]	Band width [MHz]	Polarization	Beam width [deg] (Ground res. [km])	Sampling interval [km]
6.925 7.3	350	V & H	1.8 (35 x 61)	10
10.65	100		1.2 (24 x 41)	
18.7	200		0.65 (13 x 22)	
23.8	400		0.75 (15 x 26)	
36.5	1000		0.35 (7 x 12)	
89.0(A&B)	3000		0.15 (3 x 5)	5

Same as AMSR-E

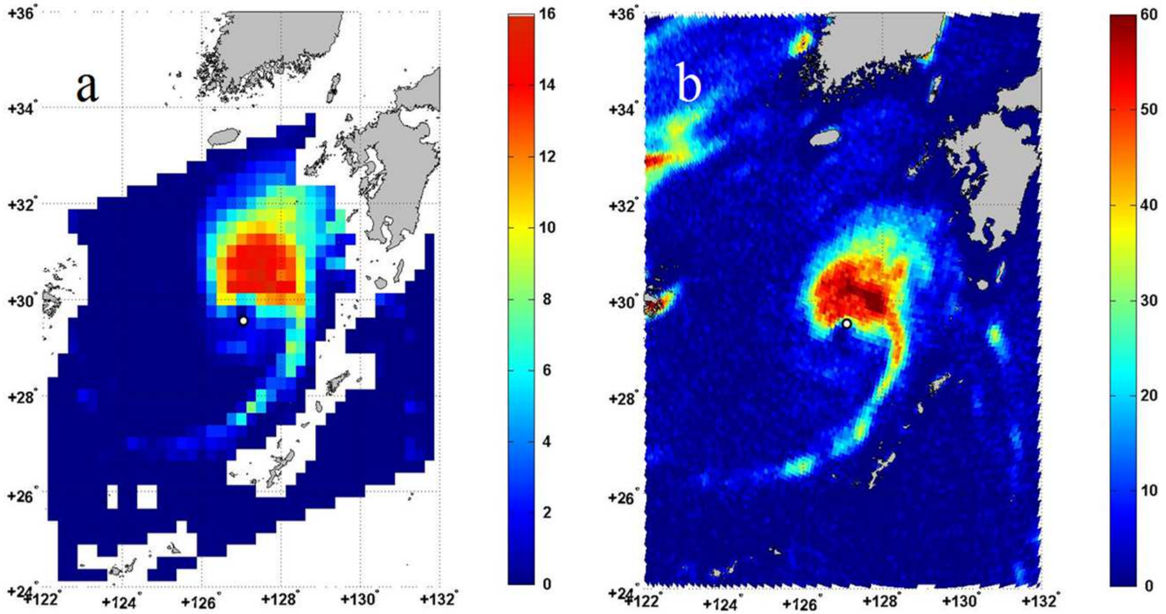


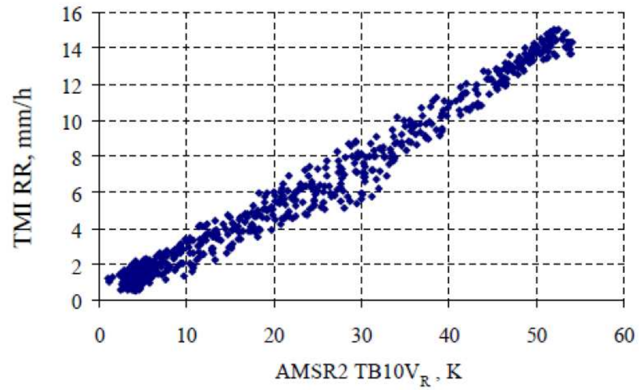
Potential accuracy for SWS retrievals is 1 m/s

AMSR2 all weather wind speed retrieval algorithms

Zabolotskikh E et al. GRL, 2014

Over most rainy atmospheres rain radiation at 10.65, 7.3, and 6.9 GHz can be parameterized in terms of $\Delta T_B{}^{V}{}_{7,6}$ and $\Delta T_B{}^{V}{}_{10,7}$. and related to rain rate (RR). After subtraction of the rain part from the total T_B rain-free SWS can be applied.

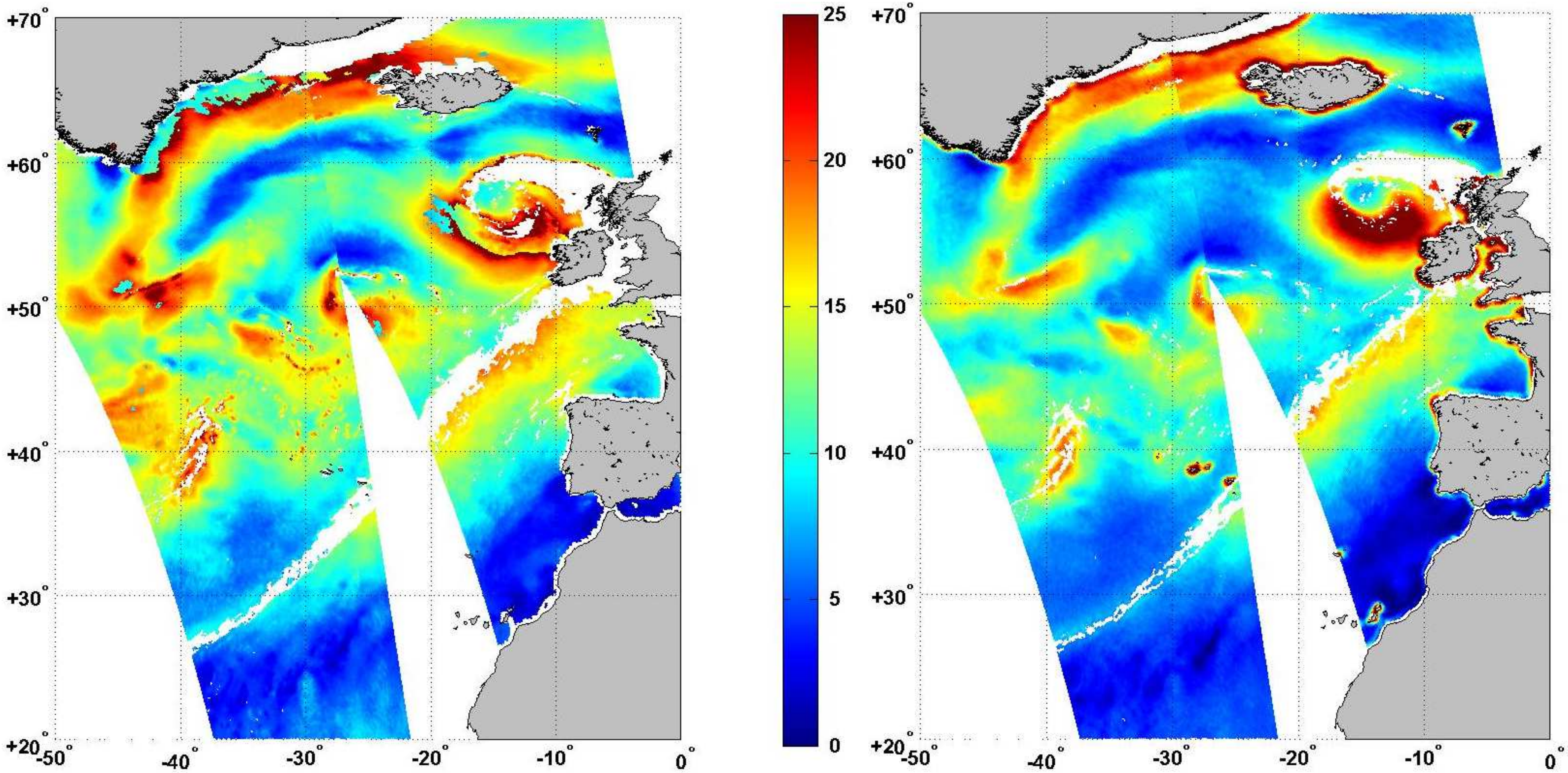




(a) TMI rain rate field (mm/h) for the typhoon Danas on 7 October 2013 (http://www.remss.com/) at ~ 18:36 UTC; (b). AMSR2 derived rain brightness temperature (K) at 10.65 GHz vertical polarization at ~ 17:14 UTC. White dots indicate the center of the typhoon at ~ 17:14 UTC

Towards Merged SMOS-AMSR-2-SMAP High wind products

Surface wind speed (SWS) in the extratropical cyclone 29 January 2013



AMSR2 JAXA standard product

AMSR2 new algorithm
Zabolotskikh E et al. GRL, 2014

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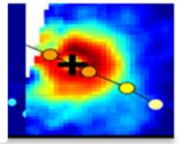
AMSR2 wind speed retrieval algorithm applied to Haiyan



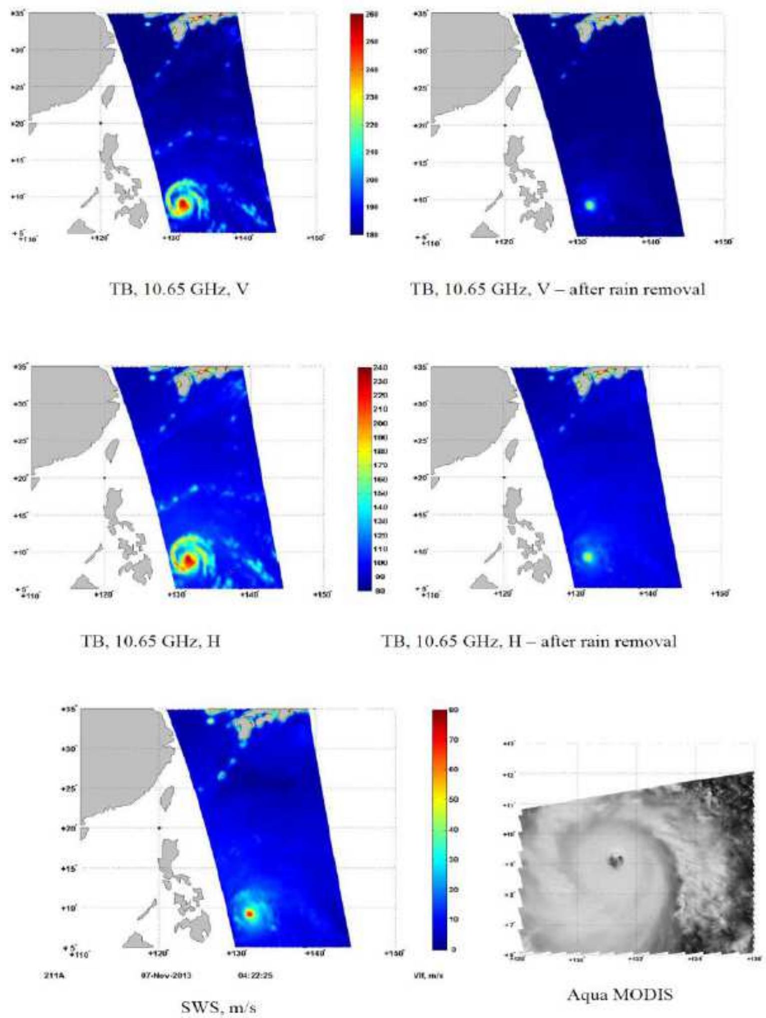
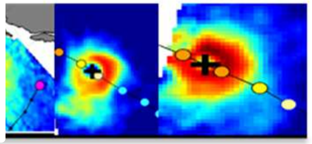
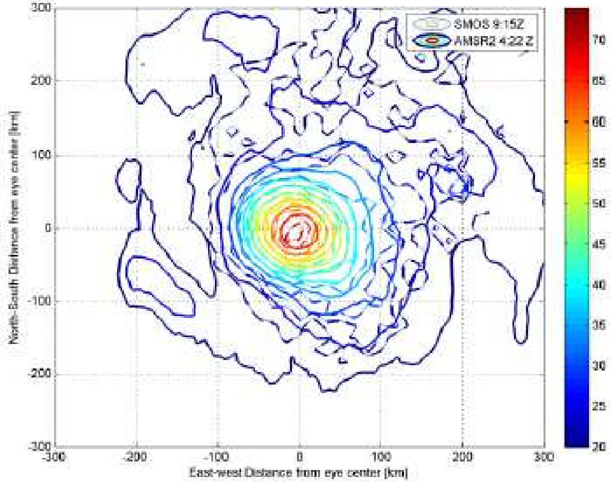


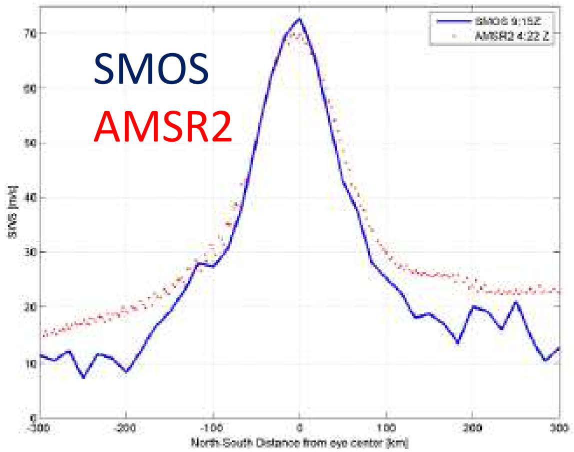
Figure 19: Rain effects removal algorithm applied to AMSR2 X-band Tb for an overpass of super Typhoon Haiyan as the surface wind speed reached maximum values of 150 knts on the 7 Nov 2013.

SMOS versus AMSR2 SWS in Haiyan





Very Coherent L (SMOS) & C (AMSR-2) SWS retrievals 5 hours appart



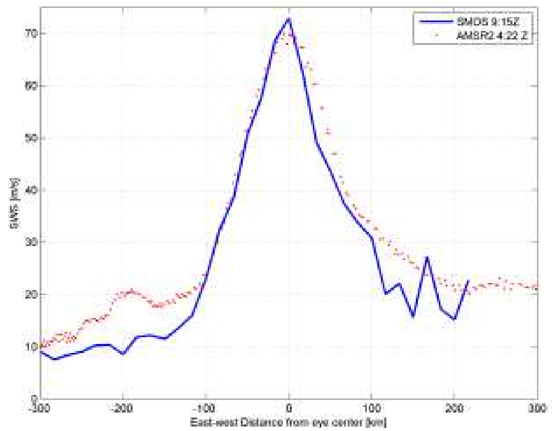


Figure 20: Top: *Superimposed contrours of SMOS (dashed) and AMSR2 (filled) surface wind speed fields estimated 5 hours apart as the sensors overpassed the super Typhoon Haiyan on the 7 Nov 2013. Bottom: North-South (left) and East-West (right) sections of the retrieved wind speed through the storm (blue=SMOS; red=AMSR2).*

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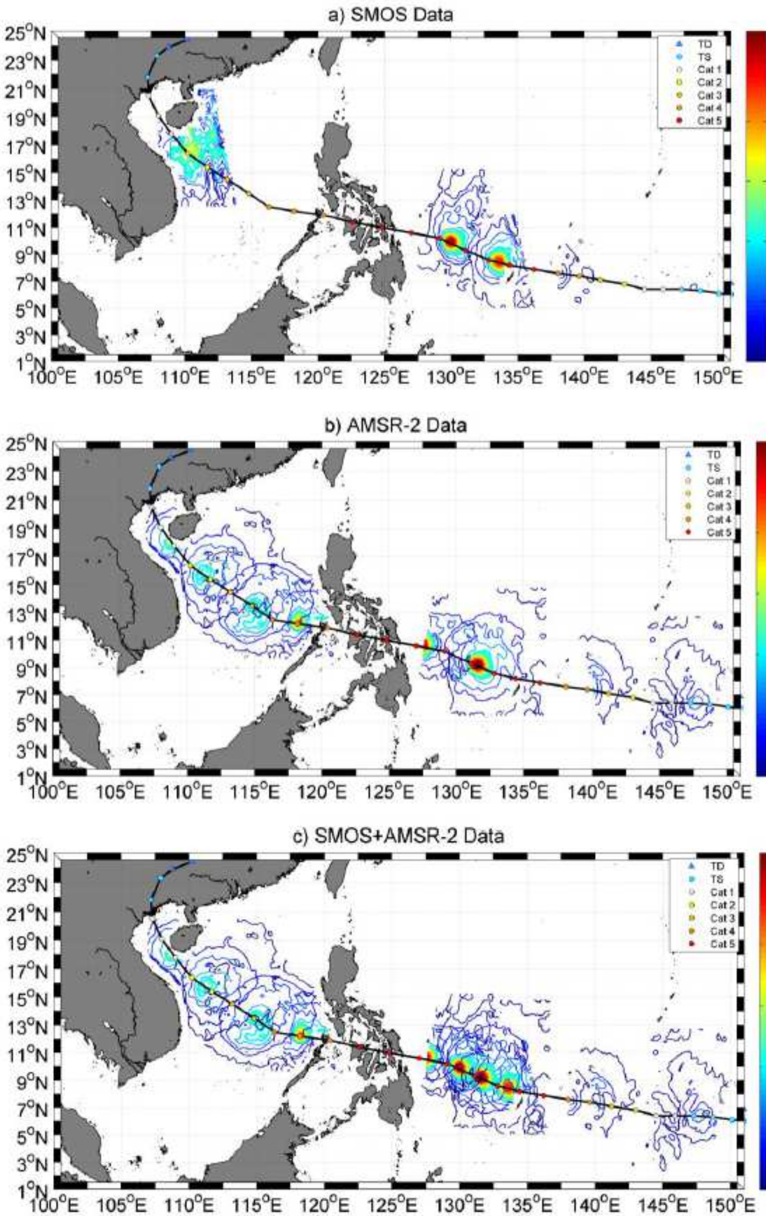
Towards Merged SMOS-AMSR-2-SMAP High wind products



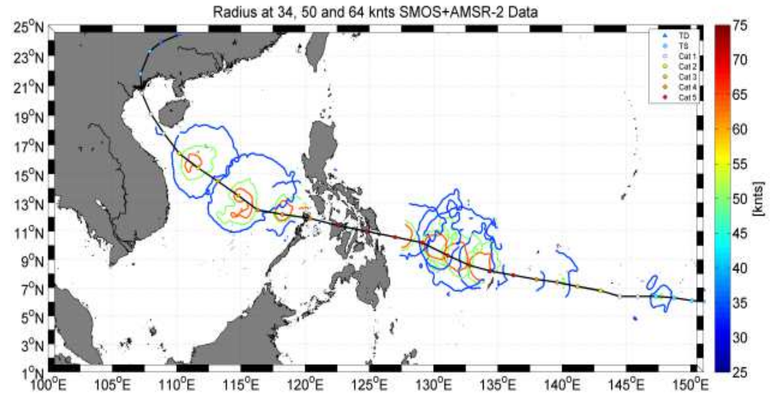


Figure 22: *Contours of the merged SMOS+AMSR2 retrieved winds over Haiyan at the threshold levels of 34 (blue), 50 (green) and 64 (orange) knots.*

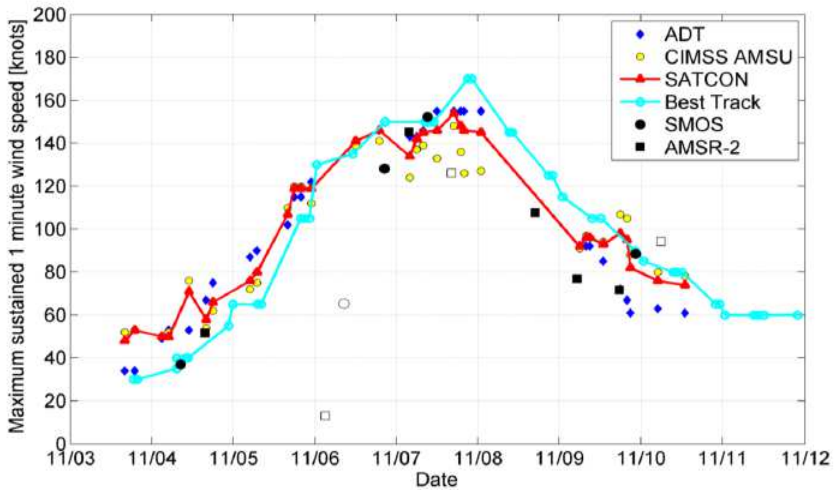


Figure 23: *Maximum sustained 1 minute wind speed estimated during Haiyan Typhoon. From SMOS data (black filled dots) and AMSR2 (black filled squares) compared to other top-of the atmosphere measurements. Note the empty circlesand squares correspond to the SMOS or AMSR2 measurements for which only a small portion of the cyclone signal was intercepted.*

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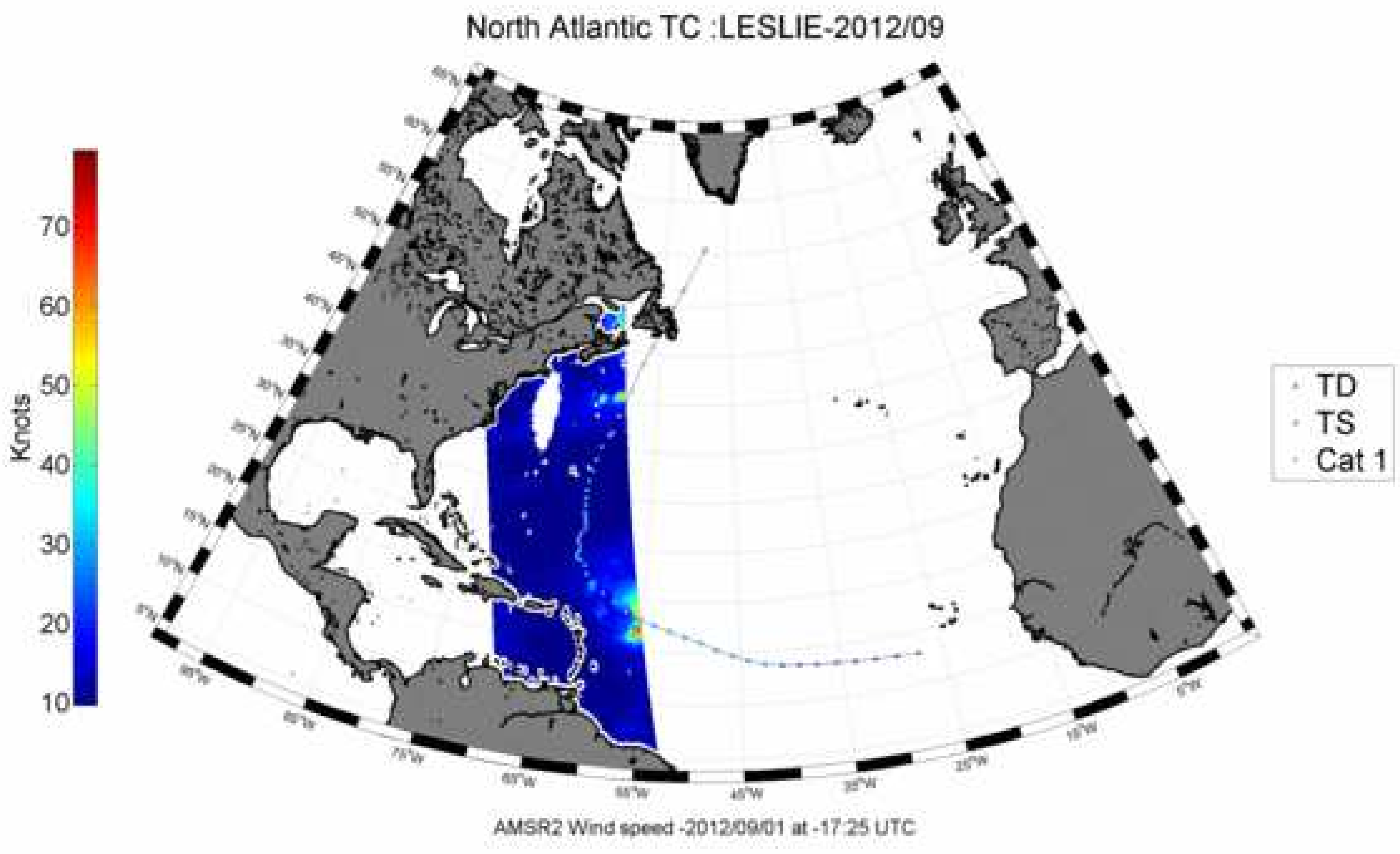
Towards Merged SMOS-AMSR2-SMAP High wind products



Summary

- We evidenced 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
- A complete storm database as been generated for the SMOS mission archive:

TC & ETC 2010-now

- We have shown that SMOS can allow to 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

Ascat can provide R34, sometimes R50, but not above R64 =>SMOS does

Perspectives

- Merged low-frequency radiometer observations in extremes : SMOS+AMSR-2+SMAP +…CYGNSS=> new opportunity to study air-sea interactions in extreme wind conditions: foam & whitecaps properties, ocean response to TC passage, drag coefficient..
- SMOS wind speed data assimilation experiments into UK Metoffice forecasts model will be performed to investigate the data impact on:

-storm track & intensity forecasts skills

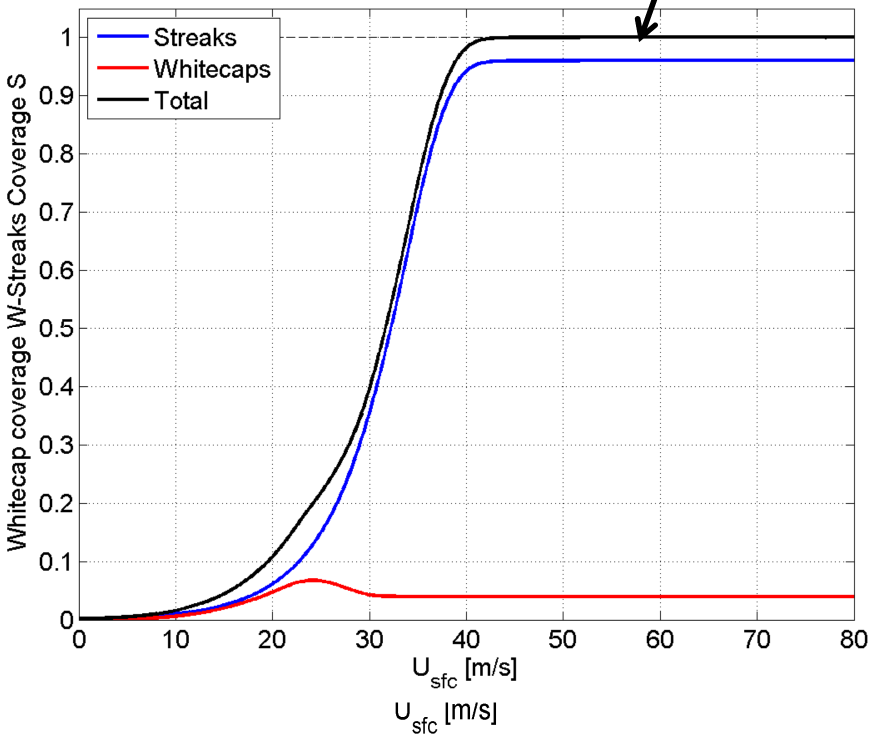
Foam Emissivity RT model (Anguelova & Gaiser, 2013)

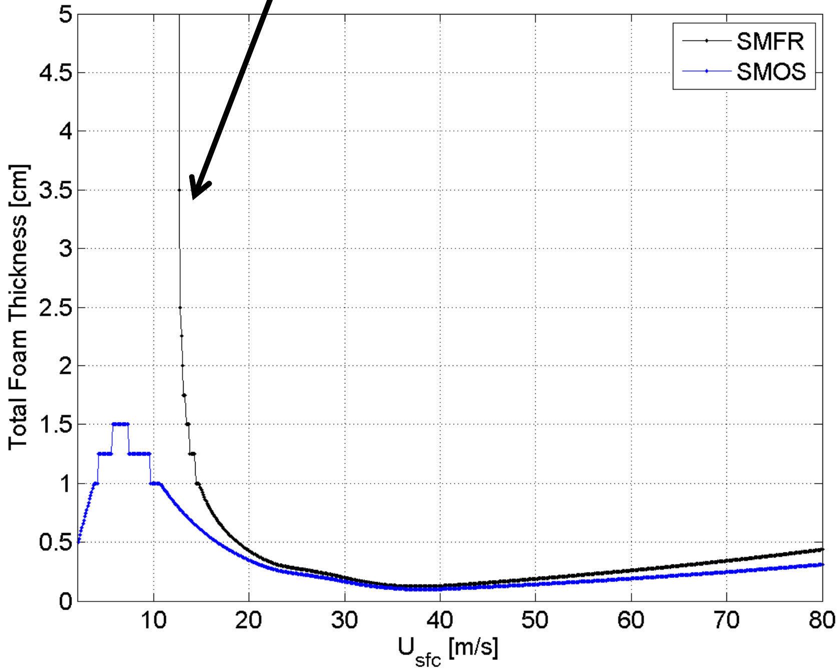
$$T_{Bf}(\theta,p,f,U) = \int F(U,\bar{\delta}) \cdot T_s \cdot e^{typ}_{Bf}(\theta,p,f,\bar{\delta})d\bar{\delta}$$

SMOS GMF (L-band)
SFMR GMF (C-band)

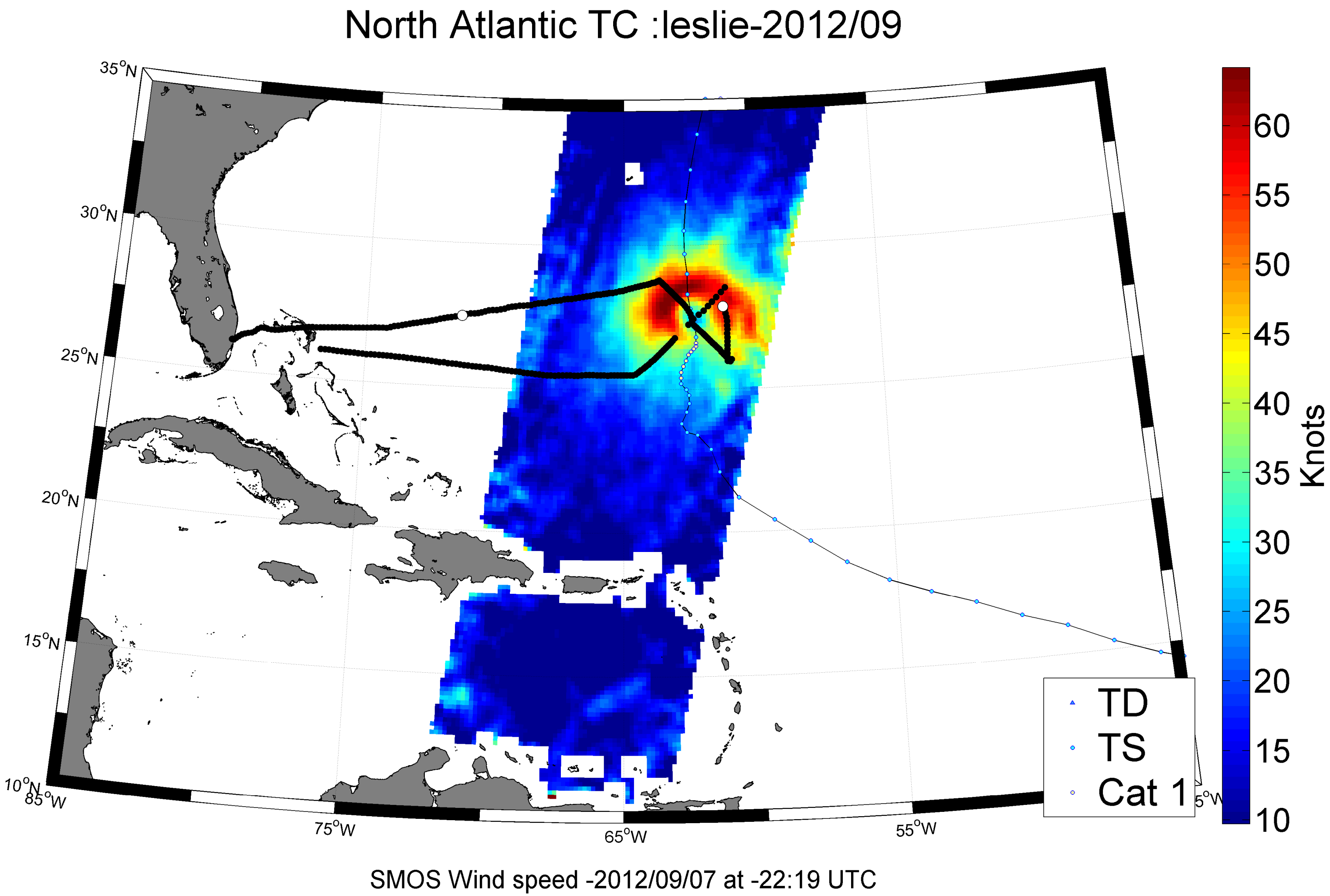
Holthuijsen et al. 2012

Foam thickness retrieval

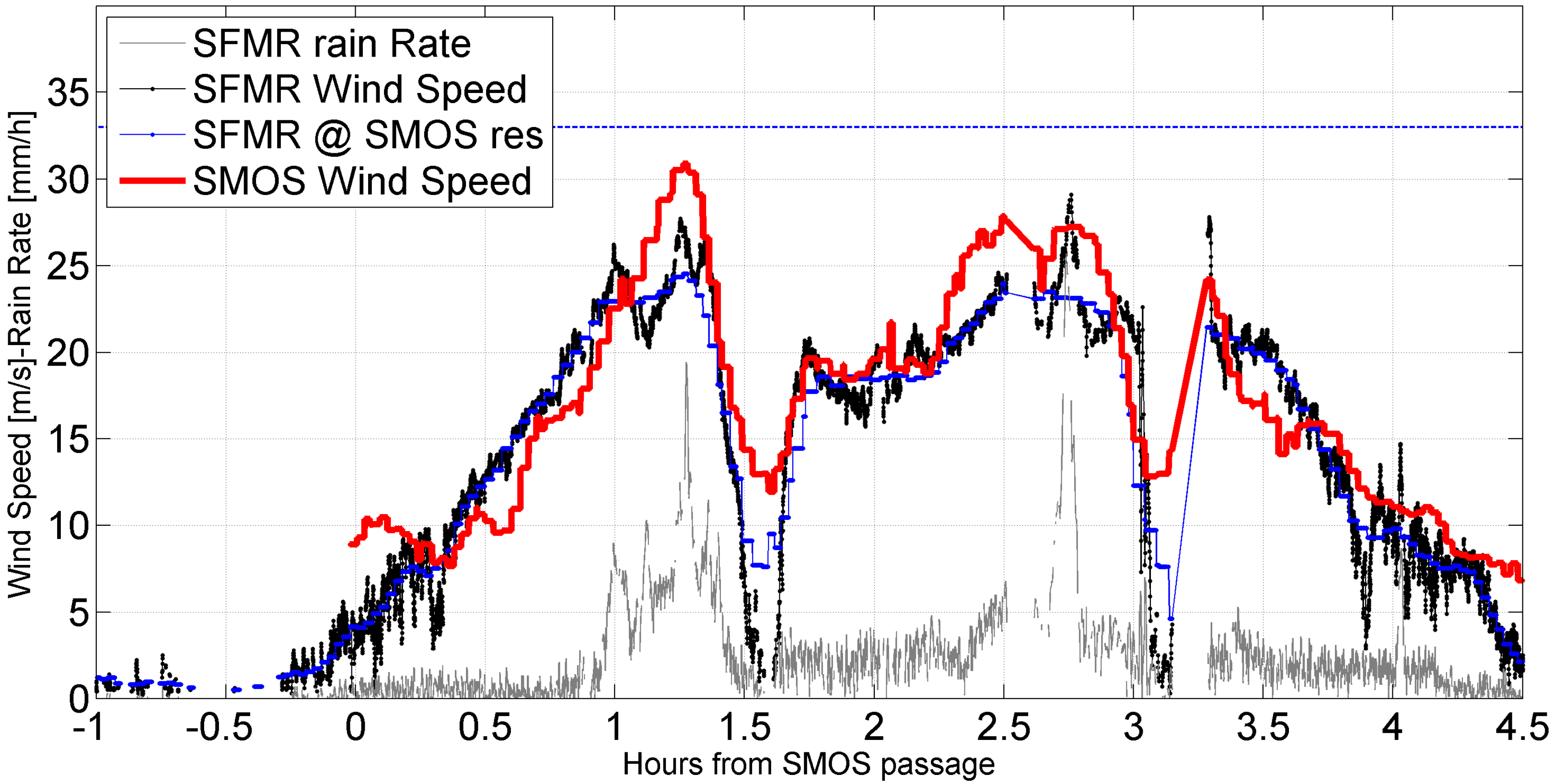


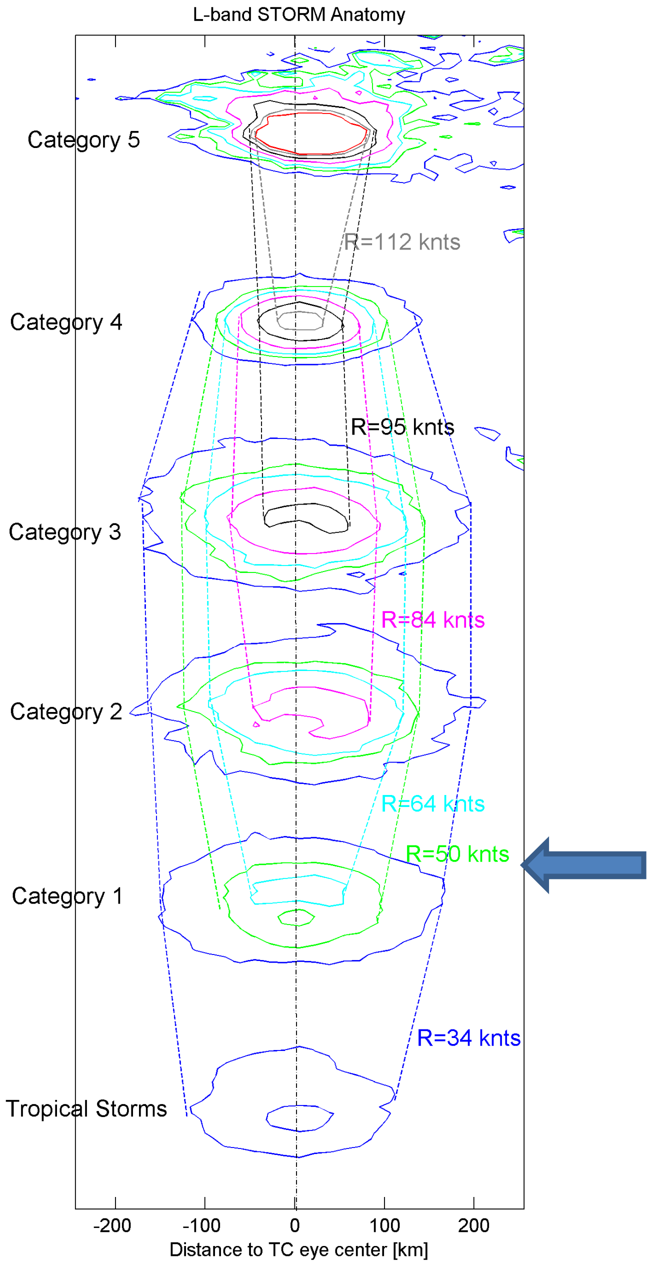


Validation: comparison with NOAA/Hurricane Research Division aircraft data



Hurricane Leslie 2012/9/7 22:19 UTC





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