Proceedings for the 2018 EUMETSAT Meteorological Satellite Conference, 17-21 September 2018, Tallinn, Estonia

HURRICANE-FORCE WIND OBSERVATIONS FROM SATELLITE

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Abstract

The challenges of satellite observations of ocean surface winds in storm are addressed here. One of the most outstanding problems in wind observations from space is for retrievals at very high winds, at storm (25 m/s) and hurricane force (greater than 33 m/s). The limited availability of in-situ observations at very high winds poses a challenge to the proper calibration of space-based retrievals. Most of the calibration now relies on measurements from the Stepped Frequency Microwave Radiometers (SFMRs) mounted on hurricane-penetrating aircrafts. The SFMRs observations themselves are verified using in-situ wind measurements from dropsondes descending through tropical storms. This paper describes how satellite winds from the L-band NASA radiometer SMAP, the US NAVY polarimetric radiometer WindSat, and the EUMETSAT scatterometer ASCAT processed at Remote Sensing Systems compare to SFMR measurements in tropical and extratropical storms. An additional source of validation in the tropics is the comparison of SMAP wind fields in Tropical Cyclones with Best Track data, in terms of storm size, intensity and rapid intensification. SMAP winds prove to be very reliable at hurricane-force winds, even in rain. Examples for some recent intense Tropical Cyclones in 2017-2018 are presented, as for hurricane Florence, super-typhoon Mangkhut. For extratropical storms, satellite winds are compared to anemometer winds from oil platforms off the coast of Norway.

SATELLITE WIND DATASETS

For the past two decades, scatterometers such as the NASA QuikSCAT (Lungu and Callahan, 2006; Katsaros et al., 2001, 2002; Liu et al., 2002 ; Chelton et al., 2006; Ricciardulli and Wentz, 2015) and the EUMETSAT ASCAT (Figa-Saldaña et al., 2002; Verspeek et al., 2010; Ricciardulli, 2016) provided a global view from space for Tropical Cyclone (TC) wind fields. These datasets greatly advanced the prediction capabilities for TC storm tracks and intensities (Von Ahn et al., 2006; Chang et al, 2009). These scatterometers are radars mounted on low-earth orbiting satellites, and measure the microwave signal backscattered from the ocean surface, which relates to the ocean surface roughness from which the wind speed and direction can be derived.

Classical radiometers, as the SSM/I or GMI, are also able to measure wind speeds from space, but not under rainy conditions, therefore their use for TC analysis is very limited. In 2003, a new polarimetric radiometer was introduced, the US NAVY WindSat (Geiser et al., 2004), which measures both wind speed and direction even in rain, using an all-weather algorithm (Meissner and Wentz, 2009). These scatterometers and radiometers are affected by reduced sensitivity at very high wind speeds (at and above category 2) and are less reliable under the intense rain typical of TCs.

More recently, a new type of radiometers such as the NASA SMAP (Entekhabi et al., 2010, 2014) and ESA SMOS (Mecklenburg et al, 2012) operating at very low frequency (L-band, 1.4 GHz) displayed excellent capabilities in observing hurricane-force wind speeds even in stormy conditions (Reul et al., 2012; 2016; Meissner et al. 2017; Reul et al. 2017, Fore et al. 2018). After validation, the wind speed retrievals from these sensors started to be processed in near-real time (NRT) for use in tropical cyclone forecasting.

Table 1 summarizes these missions, the instruments' features, their performance at storm/hurricane force wind speeds, and the data availability.

Sensor	Dataset	Resolu-tion	Mission dates	Performance in hurricanes	Processed at
SMAP (NASA L-band rad.)	Wind speed - daily 0.25° grid	40 km	2015-cur-rent	- Sensitivity up to 70 m/s (Cat. 5); - Minimally affected by rain - Lower resolution, loss of details	1. RSS (NRT 3hr; Final; TC fixes) 2. JPL (NRT)
ASCAT (EUMETSAT C-band scatt.)	Wind vector - swath data - daily 0.125° grid	25 km	2007-cur-rent	- Decreased sensitivity > Cat. 1 - Moderate wind speed bias in rain; - Good resolution, details of spatial structure	1. KNMI/EUMETSAT (NRT) 2. NOAA (NRT) 3. RSS (delayed, few days)
WindSat (US Navy MW polar-imetric rad.)	All-weather wind vector - daily 0.25° grid	30 km	2003-cur-rent	- C/X band. Trained up to 40 m/s - Good resolution - Some residual bias in intense rain - Next version (V8) will be retrained in rain at hurricane winds	1. RSS (almost NRT , 6-12 hr) 2. Navy (NRT, rain-free winds) 3. Similar algorithms for AMSR2 by IFREMER/Soslab + JAXA.
SMOS (ESA L-band rad.)	Wind speed - daily 0.25 grid	40 km	2010-cur-rent	Same as SMAP	1. IFREMER

Table 1: **List of satellite sensors for hurricane wind speed/direction observations described in this paper. The table provides information on the dataset grid features, the sensors' spatial resolution, the years of data availability, the advantages and shortcomings of performance in hurricanes, and the data processing centers. Data from SMAP, ASCAT, and WindSat used in this study are processed at Remote Sensing Systems, and they are available at www.remss.com.**

A major challenge for high wind measurements such as those experienced in Tropical Cyclones is the fact that some sensors like ASCAT and possibly WindSat display a reduced sensitivity at wind speeds above 35-40 m/s (Category 1 in the Saffir-Simpson scale for hurricanes). SMAP does not suffer this limitation. This can be easily seen in Fig. 1, which presents the wind fields in the North Tropical Atlantic as observed by SMAP, ASCAT and WindSat on September 12, 2018, with hurricane Florence heading towards the US coast. Both ASCAT and WindSat provided great details of the storm spatial structure, and wind direction, but their intensities are much lower (~40 m/s) than the intensity observed by SMAP (55 m/s), due to reduced sensitivity and impact of rain on the measurements. On the other hand, SMAP doesn't provide as great details on the spatial structure of the wind field due to the sensor's lower resolution, and the retrievals are noisier at lower wind speeds. Also visible in Fig. 1 is hurricane Helene in the Central Tropical Atlantic, with ASCAT able to detect the eye of the storm.

SMAP OBSERVATIONS IN TROPICAL CYCLONES

L-band radiometers, as SMAP and SMOS, measure the wind-induced emissivity averaged over the sensors' footprint (typically over 40 km); at storm/hurricane-force wind regimes the emissivity is mostly due to sea foam. As illustrated in Fig. 1, the L-band radiometers like SMAP are not significantly affected by precipitation and their signal linearly increases as a function of wind speed, retaining sensitivity even up to 70 m/s (Reul et al., 2012; Meissner et al., 2017, Fore et al., 2018). A necessary step before these observations can be used with confidence for TC forecasting, is the verification versus ground truth observations in storms. For this purpose, we considered in situ measurements from the Stepped Fre-quency Microwave Radiometers (SFMR; Uhlhorn and Black, 2003; Uhlhorn et al., 2007; Klotz and

Uhlhorn, 2014) onboard hurricane hunters' aircrafts. These data are publicly distributed by the NOAA Hurricane Research Division (www.aoml.noaa.gov/hrd/data_sub/).

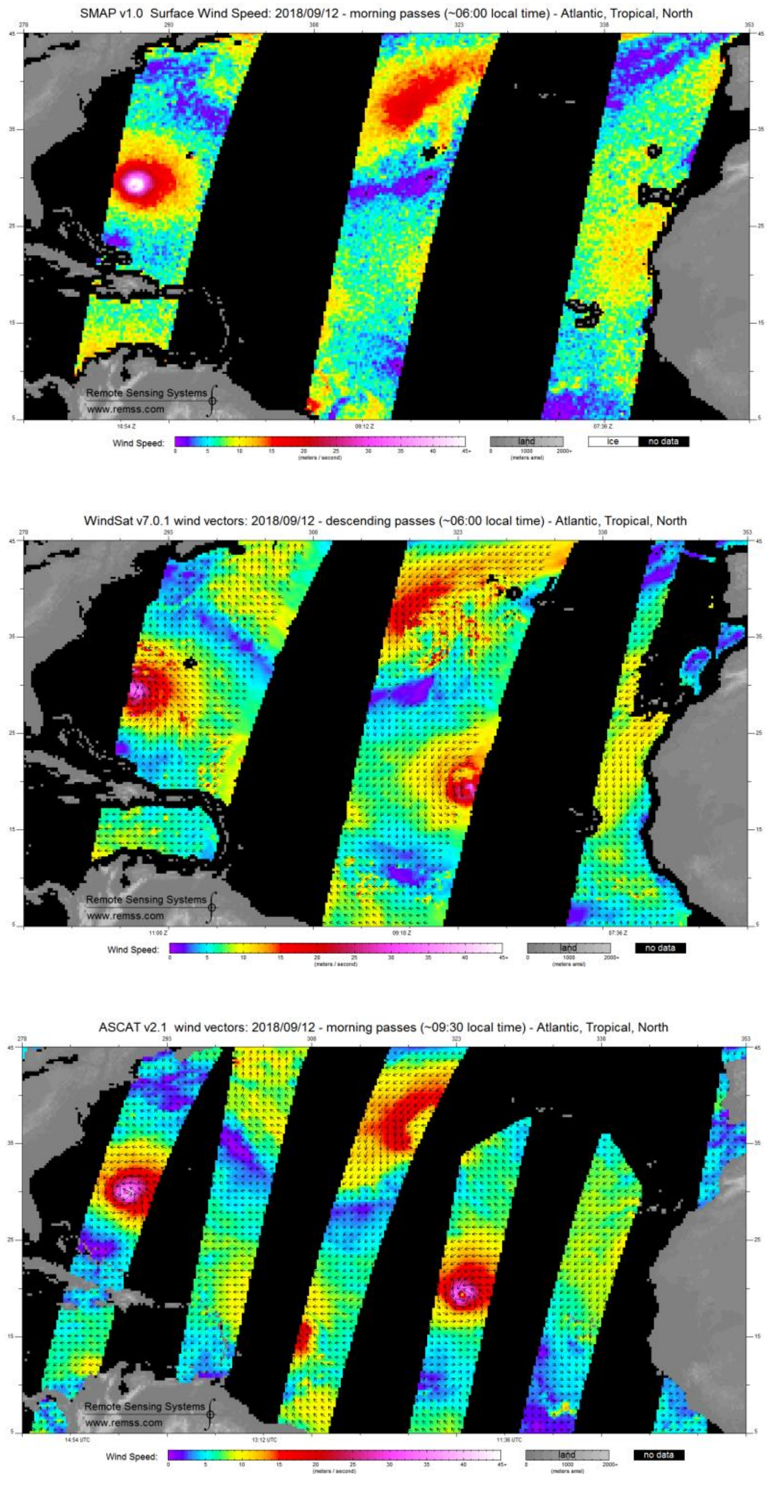

Figure 1: **Wind fields in the North Tropical Atlantic as observed by SMAP (top panel), WindSat (middle), and ASCAT (bottom), for September 12, 2018. Hurricane Florence is visible for all datasets as heading towards the US coast. Also visible in the ASCAT wind retrievals is hurricane Helene in the Central Atlantic.**

Fig. 2 illustrates the correlation between SMAP winds versus SFMR observations for several tropical storms in 2015/2016. The original SFMR observations are reported on flight tracks processed with a 10s running mean and at a spatial sampling of about 3km, but here are resampled over the satellite data grid (0.25 degree) to match SMAP resolution, as described in Meissner et al., 2017.

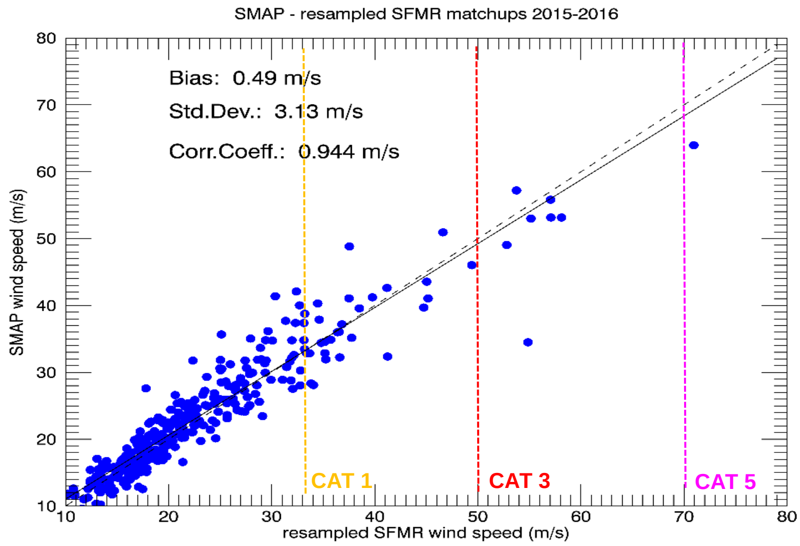

Figure 2: **Comparison of SMAP wind speeds with colocated SFMR wind speeds resampled at the SMAP resolution, for Tropical Cyclones in 2015-2016. The threshold wind speeds for Cat. 1, 3 and 5 as defined by the Saffir-Simpson hurricane scale are highlighted with the dashed vertical lines.**

Fig. 3 illustrates the SMAP wind field for two separate views of hurricane Florence, on September 12-13, 2018. The figure also displays the radii which define the regions affected by gale-, storm-, and hurricane-force winds (35, 50, and 64 kn, respectively). These parameters are important for marine advisories. They are determined in an automated analysis in a near-real-time (NRT) processing streams, and they are made available on www.remss.com/missions/smap within 2-3 hours. They are currently used in the Automated Tropical Cyclones Forecasting systems at US NAVY (Sampson and Schrader, 2000), and the Joint Typhoon Warning Center (JTWC).

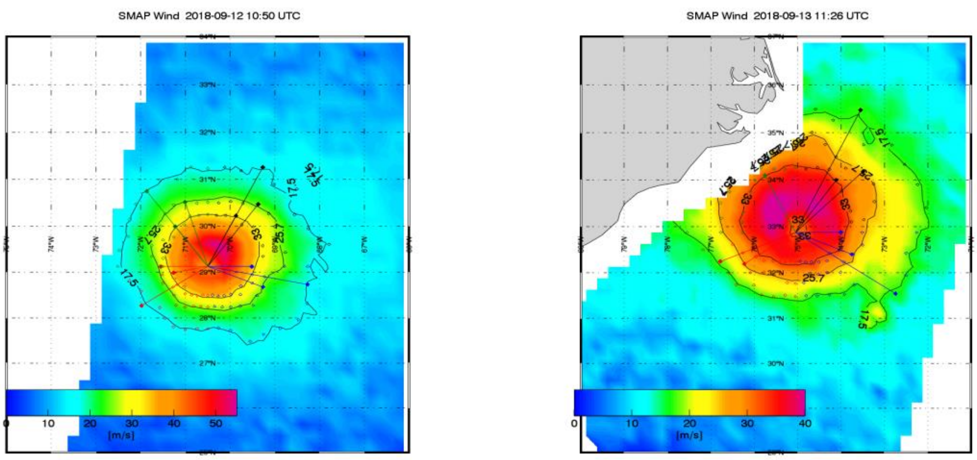

***Figure 3*: Wind field for hurricane Florence as observed by SMAP on September 12 and 13, 2018, just before landfall. Highlighted in the figures are the contours for gale force 35 kn (17.5 m/s), storm force 50 kn (25 m/s), and hurricane force 64 kn (33 m/s) winds. The maximum wind intensity observed at the SMAP resolution (averaged over a 40 km footprint) was 55 m/s on September 12 and 42 m/s on September 13, 2018. Actual maximum wind speed at finer spatial scales are typically higher by about 10% or more.**

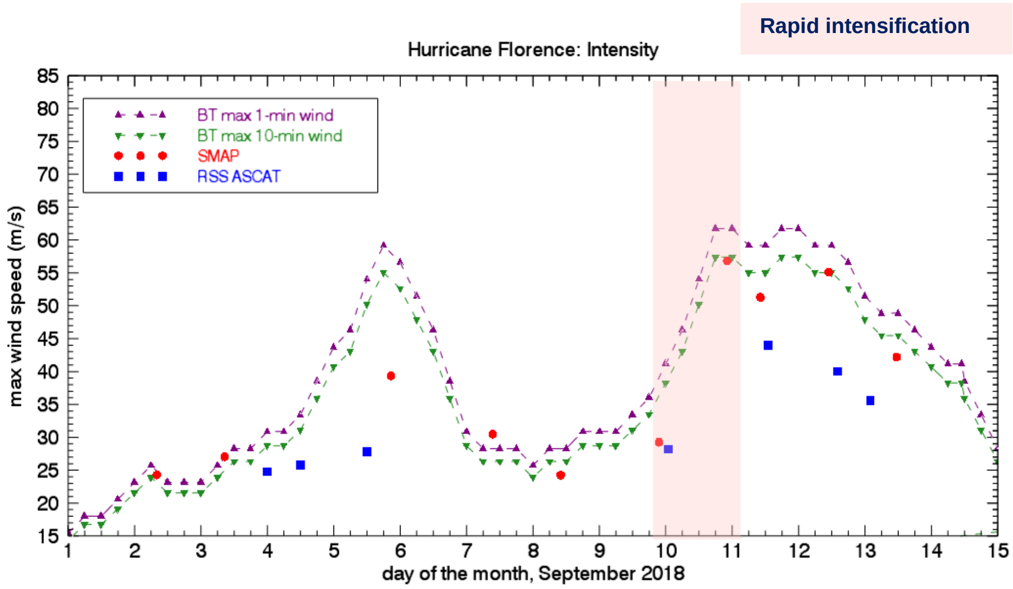

Figure 4: **Timeseries of maximum wind speeds for hurricane Florence in September 2018, as observed by SMAP (red) and ASCAT (blue) at their respective resolution, and compared to the wind speed as reported by the Best Track data from the JTWC storm warning. The best track data are typically reported as 1-minute sustained winds (purple dashed line). In the figure we also display the BT winds scaled down to represent 10-min sustained wind speeds (green dashed line), which provide a more meaningful comparison with observation at the satellite resolution of about 25-40 km.**

Fig. 4 displays the complete timeseries of the maximum wind speeds as observed by SMAP and ASCAT, together with by the Best Track (BT) data released by the JTWC. The BT data are typically reported as 1-minute sustained wind speeds. To be more comparable to the wind speeds observed at the average satellite footprint size (25-40 km), we have scaled the 1-min sustained winds to winds sustained over 10-minutes, by using a scale factor of 0.92 (Harper et al., 2010). The figure highlights the remarkable capability of SMAP observations to follow the variability of the intensity over the lifetime of the storm, and the ability to detect the Rapid Intensification phase on September 10. This capability from space-based observations is critical for forecasting the evolution and impact of the TCs, especially in remote locations, when no in-situ observations are available.

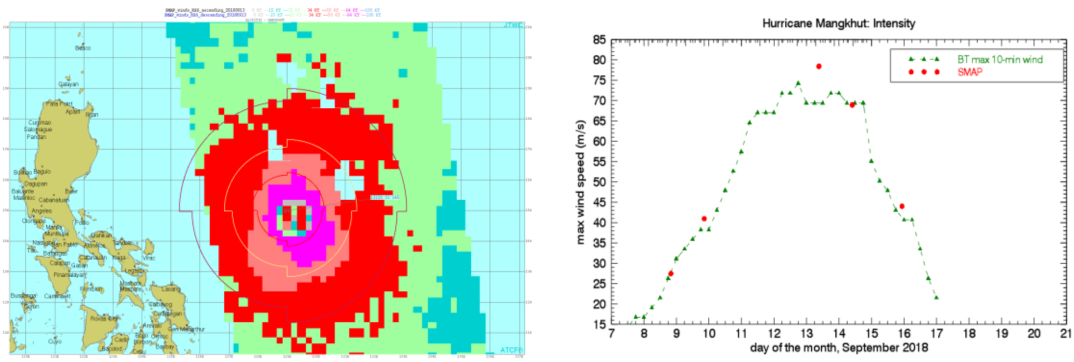

Figure 5: **Right: Regions of gale- (35 kn, red), storm- (50 kn, coral), and hurricane-force (64 kn, magenta) SMAP winds in the super-typhoon Mangkhut before landfall in the Philippines, on September 13, 2018 at 13 UTC. The circular sectors identify the radii estimates in each quadrant of these wind regimes. Left panel: Evolution of the maximum wind speed as observed at the SMAP resolution over the duration of the storm, compared to the BT winds scaled down to 10-minutes sustained winds for better comparison with satellite data. The storm reached Category 5 (super-typhoon).**

An additional metrics for validating the satellite wind observations in Tropical Cyclones is to verify that the estimates of the gale-, storm-, and hurricane-force wind radii are accurate. These parameters have a critical role in the marine advisories, which identify to the public regions unsafe for ship traffic. Figure 5 displays an example of how these radii are summarized in term of the four quadrants of each storm, in this case for the super-typhoon Mangkhut before landfall in the Philippines in September 2018. Figure 6 displays the temporal evolution for the radii estimates in the North-East quadrant at gale- (35 kn) and hurricane- (64 kn) force for hurricane Florence, as estimated from SMAP and ASCAT wind observations, and compared to the value reported in the BT data from the JTWC. Both SMAP and ASCAT provide reliable estimates of the wind radii and their evolution, compared to the Best Track data.

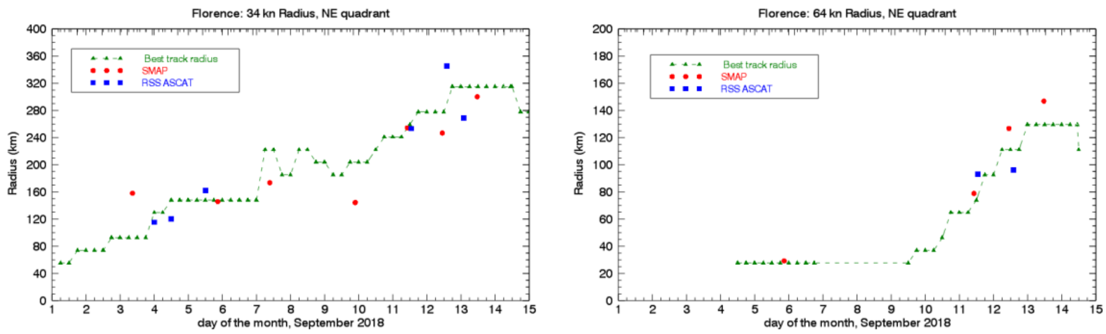

Figure 6: Temporal evolution of the NE quadrant 35 kn and 64 kn wind radii for hurricane Florence in September 2018, as estimated from SMAP (red) and ASCAT (blue) satellite wind observations and compared to values reported in the BT data (green line) from the JTWC. Notice as both SMAP and ASCAT consistently provide reasonable estimates of the regions affected by gale and hurricane-force winds.

VALIDATION OF EXTRATROPICAL STORM WINDS USING OIL PLATFORM ANEMOMETERS

We recently considered an additional source of validation of high winds given by anemometers mounted on oil platforms in the Norwegian Sea. The data we used for this analysis were acquired from the Norwegian Met Office. These included long term wind speed measurements from 10 different oil platform sites between the period of January 1999 to October 2016 in the North Sea between Norway and Britain. Platform winds typically at 50-100m, were converted to 10m winds using different assumptions for vertical profile.

The WindSat high winds are in good agreement with the platform winds, within a 10% uncertainty. In addition to WindSat, we repeated this type of analysis by comparing the 10m platform winds to the following satellite datasets processed at Remote Sensing Systems, for all colocations available within the period 1999-2016: QuikSCAT, ASCAT, AMSR-E, AMSR2, and SMAP; and to the following analysis winds: CCMP V2, ECMWF , and NCEP. Overall, all satellite datasets are in good agreement with the platform winds up to 28 m/s (Manaster et al., submitted in 2018), while the analysis winds underestimate high winds by about 10% (CCMP), to more than 20% (ECMWF) compared to the platform winds.

SUMMARY AND CONCLUSIONS

L-band radiometers (SMOS, SMAP) have proven to be an important and reliable tool for determining size and intensity of strong TC. Their advantage over the classical co-polarized scatterometers (ASCAT, QuikSCAT, RapidScat) and higher frequency radiometers (WindSat, AMSR, GMI, SSMI) is that the L-band wind signal does not saturate in high wind speeds and that thy are only minimally affected by precipitation. The main limitation of L-band radiometers is their coarse spatial resolution (40 km), which in many cases does not allow to resolve the inner structure of the TC.

Acknowledgements: This work was supported by the NASA SMAP Science Utilization Program SUS-MAP (Contract NNH17CA04C) and the NASA Ocean Vector Wind Science Team (Contract NNH14CM09C).

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