

Total Suspended Matter (TSM) and maximum signal depth (Z90_max) for monitoring the evolution of sediment resuspension processes in shallow coastal environments

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ABSTRACT

Monitoring sediment fluxes patterns in coastal area, like dispersion, sedimentation and resuspension processes, is a relevant topic for scientists, decision makers and natural resources management. Time series analysis of Earth Observation (EO) data may contribute to the understanding and the monitoring of processes in sedimentary depositional marine environment, especially for shallow coastal areas. This research study show the ability of optical medium resolution imagery in interpreting the evolution of sediment resuspension from seafloor in coastal areas during intense wind forcings. Intense bora wind events in northern Adriatic Sea basin during winter season provoke considerable wave-generated resuspension of sediments, which cause variation in water column turbidity. Total Suspended Matter (TSM) product has been selected as proxy for qualitative and quantitative analysis of resuspended sediments. In addition, maximum signal depth (Z90_max), has been used to evaluate the evolution of sediment concentration in the water column.

STUDY AREA

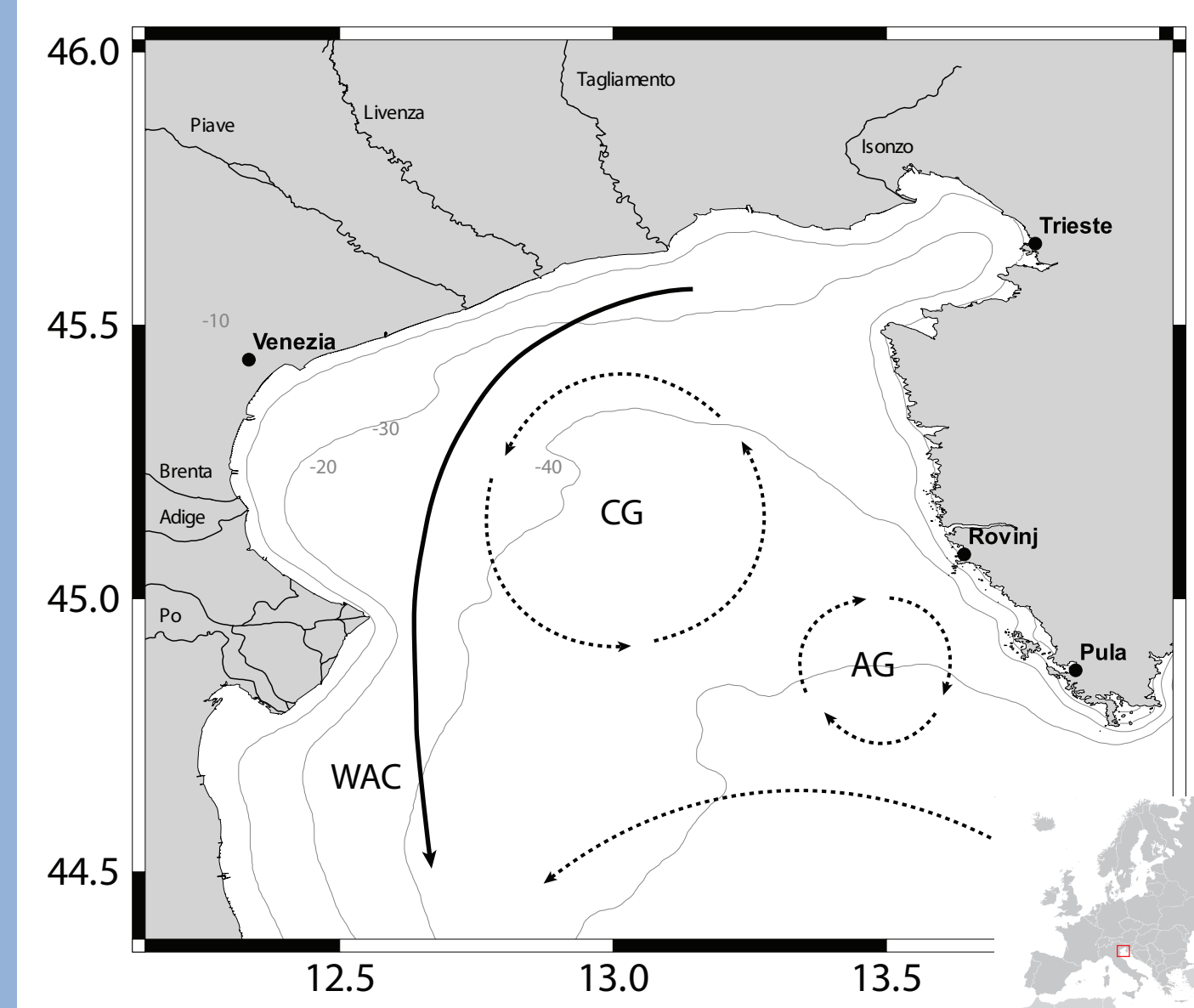


Figure 1 - Map of the northern Adriatic Sea. Main cities and rivers are shown on land side (gray area). Seaward, bathymetric contours are 10 m, surface circulation pattern during normal wind condition (solid arrow); Western Adriatic Current (WAC), surface circulation pattern during steady Bora wind condition (dashed arrows); Cyclonic Gyre (CG) and Anticyclonic Gyre (AG).

The Adriatic Sea is a shallow semi-enclosed shelf sea located between western and eastern parts of the Mediterranean Sea; it is about 800 Km long and 150 Km wide. Northern Adriatic Sea occupy the northern and shallower area (depth < 50 m) and has a gentle slope (about 0.02°). One of the major features is a coastal current along the western side of the basin, the Western Adriatic Current (WAC) in Fig. 1, driven by wind and thermohaline forcing (Poulain, 2001). Two distinct wind regimes, bora and sirocco, dominate conditions in the Adriatic and influence basin-wide circulation. sirocco is an upwelling favourable wind blowing from southeast with an available fetch of several hundreds of kilometers, thus particularly efficient in modulating the wave field (Orlic et al., 1994), while bora is a downwelling favourable wind blowing from east-northeast with a mean speed of 15 m s⁻¹, shows an evident interannual variability (Bignami et al., 2007) and can generate large waves with significant wave heights of 1 m, and period of 5 s (Cavaleri et al., 1997). Bignami et al. (2007) pointed out that the inhomogeneity in bora win spatial variability, like the dual-jet nature of the Trieste jet or the several kilometer structures in the Bakar and Senj jet region. Estimated wind fields at fine scale from SAR satellite (Fig. 2) allow the observation of morphology, wake patterns, the formation of the barrier jet on the western Adriatic coast and, where present, dual-jet structure of the bora wind (Signell et al., 2010), and have been successfully used to improve wave downscaling on shallow waters (Gutierrez et al., 2015).

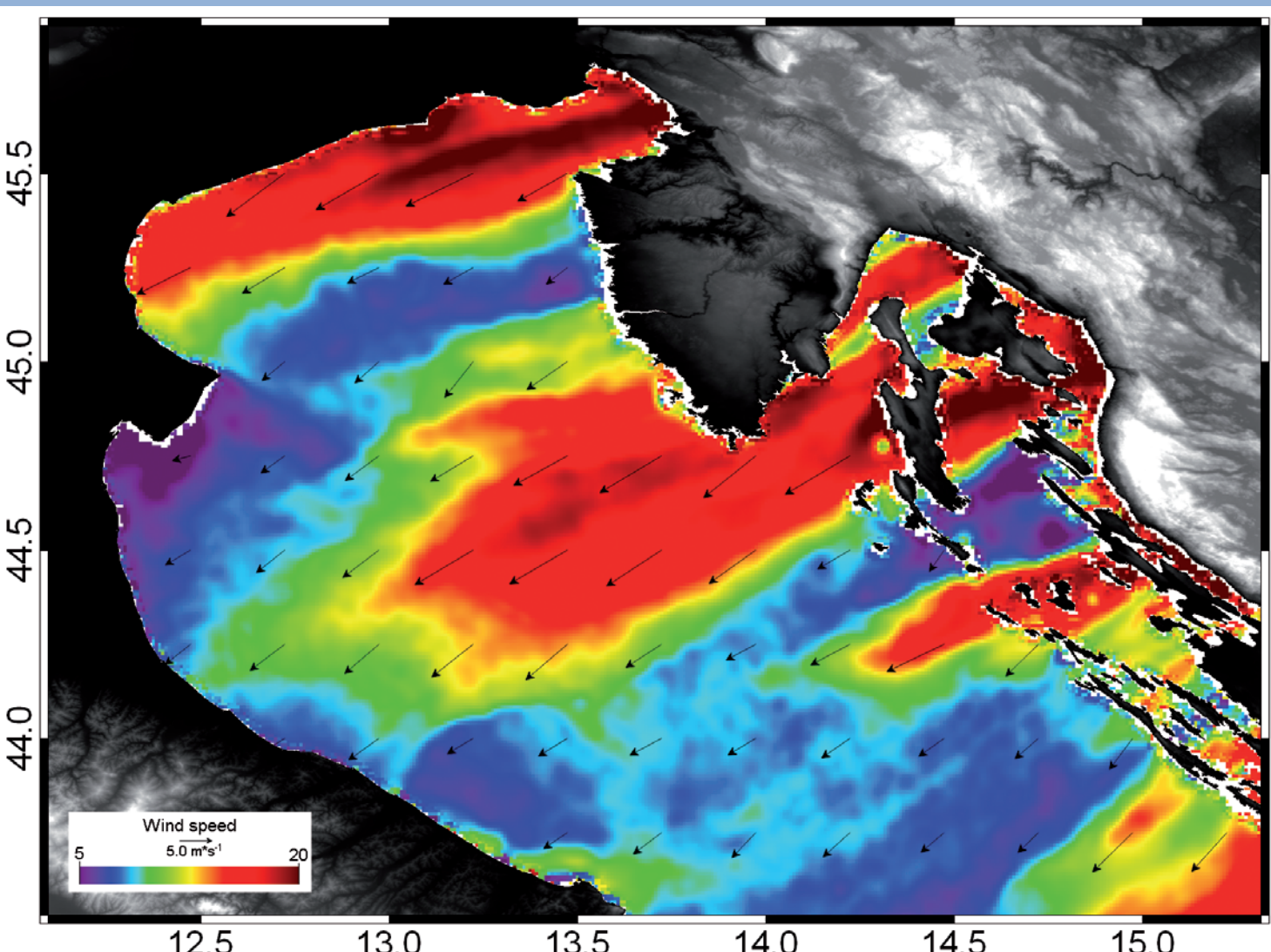


Figure 2 - Spatial representation of instantaneous wind field estimated during intense bora wind condition from ENVISAT ASAR WS image acquired on 02 February 2012 20:59:29 UTC.

MATERIALS AND METHODS

In situ measurements of wind speed and direction have been collected from CNR Acqua Alta platform (Fig. 1) for the period 1984-2012. Statistical analysis of wind forcing have been done in order to investigate inter- and intra-annual variability of wind conditions and number of intense wind stress cases. Number of days per year exhibiting maximum wind speed value exceeding the value of 15.43 m s⁻¹ (30 knots) has been reported. In addition, in situ measurements have been used to identify periods of steady wind regimes (lasting at least three days) and the availability of Envisat MERIS cloud free observations acquired during such periods. Envisat MERIS Level 1 Full Resolution Full Swath data (MER_FRS_1P) have been collected through the MERIS MERCI system and processed from L1b to L2 using CoastColour v2 processor and BEAM software. The generated L2 products have been binned to a L3 300 m regular grid, in order to perform time series analysis maintaining the spatial features detail. TSM product has been selected as proxy for qualitative and quantitative analysis of resuspended sediments. In addition, maximum signal depth (Z90_max), which indicates the water depth from which 90% of the reflected light comes from, was used to evaluate the evolution of sediment concentration in the water column. Earth Observation products were selected to: i) analyze superficial circulation patterns; ii) trace turbidity in the water column; iii) investigate the evolution of sediment resuspended and transported throughout the selected periods of intense wind regimes.

RESULTS

Wind forcing

- Sirocco wind regime has been found to be present throughout the year, bora wind has a marked seasonality, exhibiting intense steady wind conditions during winter period (wind speed higher than 10 m s⁻¹ on average) lasting up to two consecutive weeks;
- Inter-annual variability of intense wind regime for the period 1984-2012 reached its maximum in late '90, maximum number intense wind cases has been found in year 2003 and after that a constant decrease of number of observed cases has been noticed (Figure 3);
- Year 2012 recorded most intense steady wind period, accountable to bora wind regime, lasting two weeks in February with wind speed maxima exceeding 20 m s⁻¹;
- No cloud free observations availability have been found for the spatial representation sirocco wind regime, due to high cloud cover usually accompanying this wind regime, according to previous findings of Bignami et al. (2007).

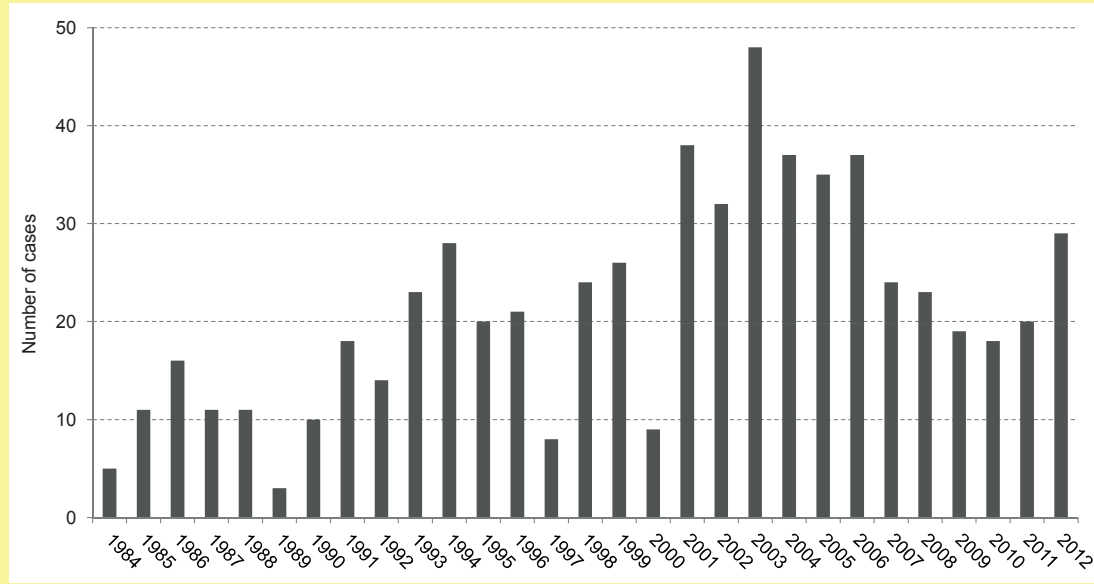


Figure 3 - Yearly number of cases of intense wind conditions (maximum daily wind speed exceeding the value of 15.43 m s⁻¹).

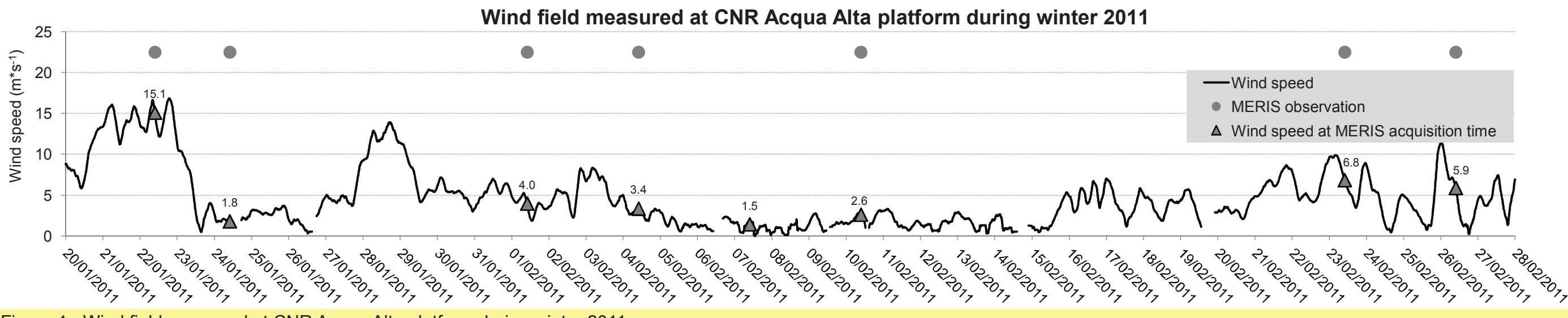


Figure 4 - Wind field measured at CNR Acqua Alta platform during winter 2011.

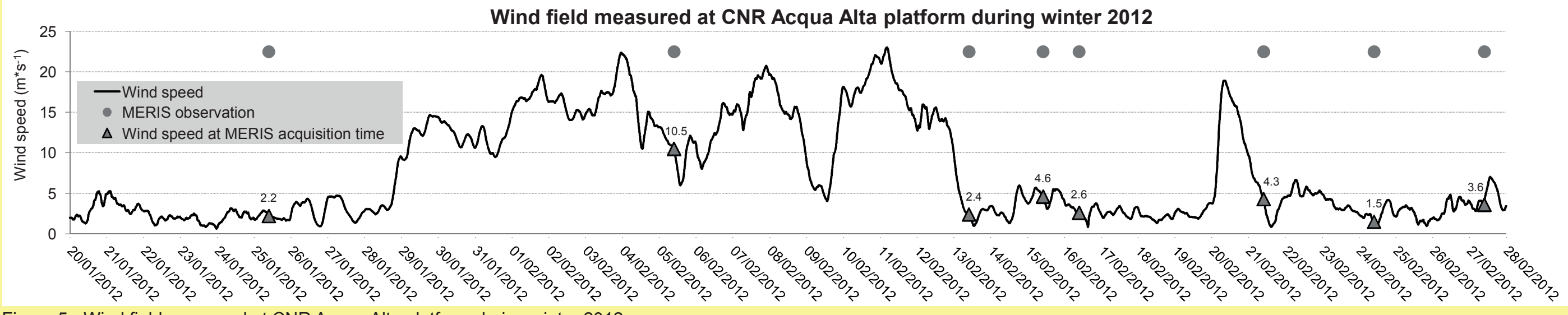


Figure 5 - Wind field measured at CNR Acqua Alta platform during winter 2012.

Sediment resuspension during intense wind stress

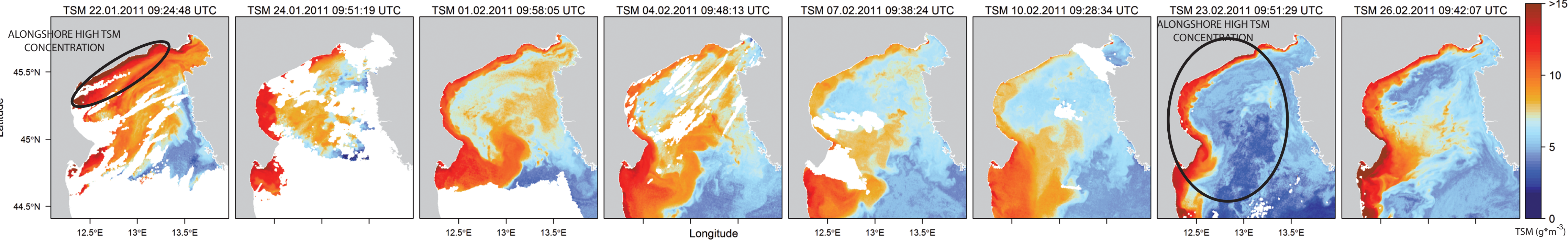


Figure 6 - Total Suspended Matter concentrations estimated from Envisat MERIS observations during winter 2011.

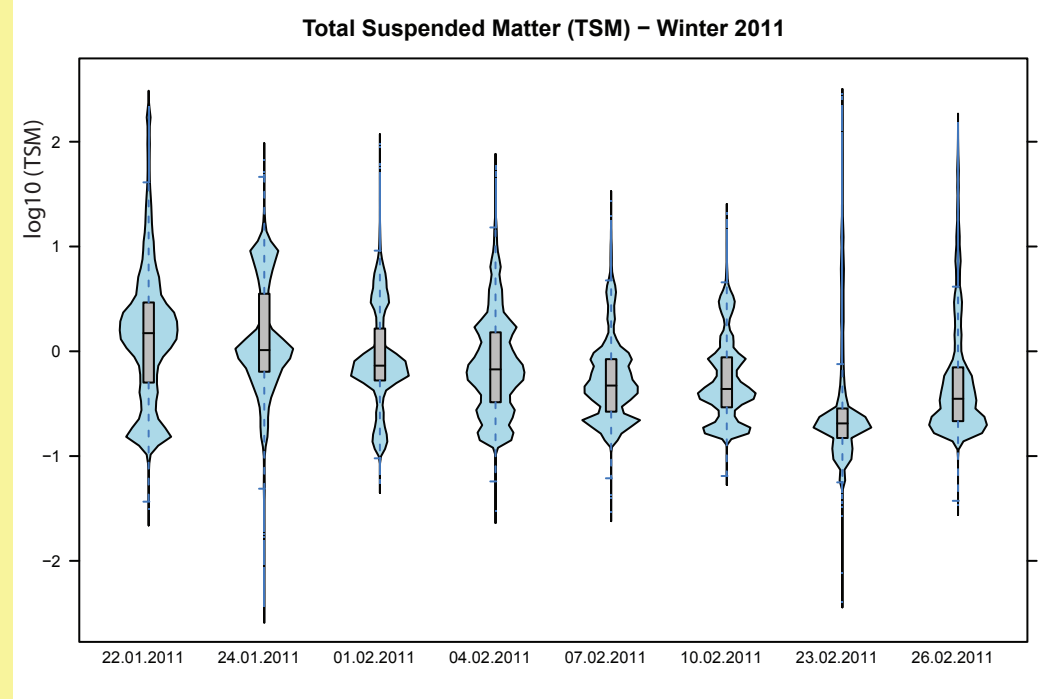


Figure 7 - Box whisker plots and kernel density distribution of TSM.

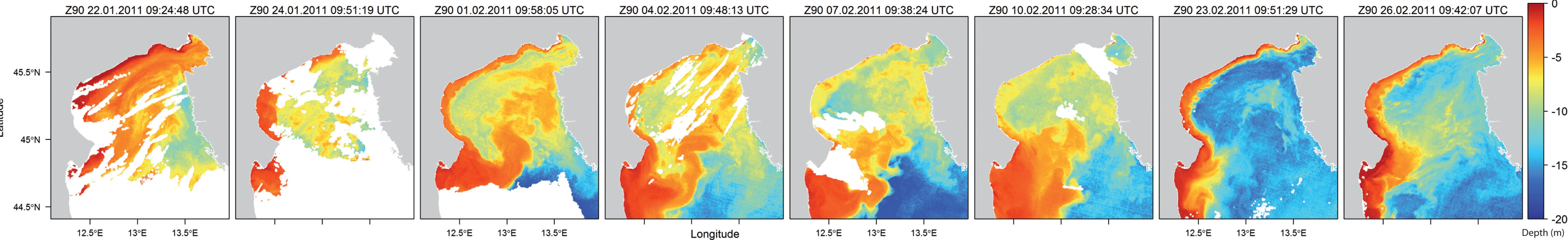


Figure 8 - Maximum signal depth estimated from Envisat MERIS observations during winter 2011.

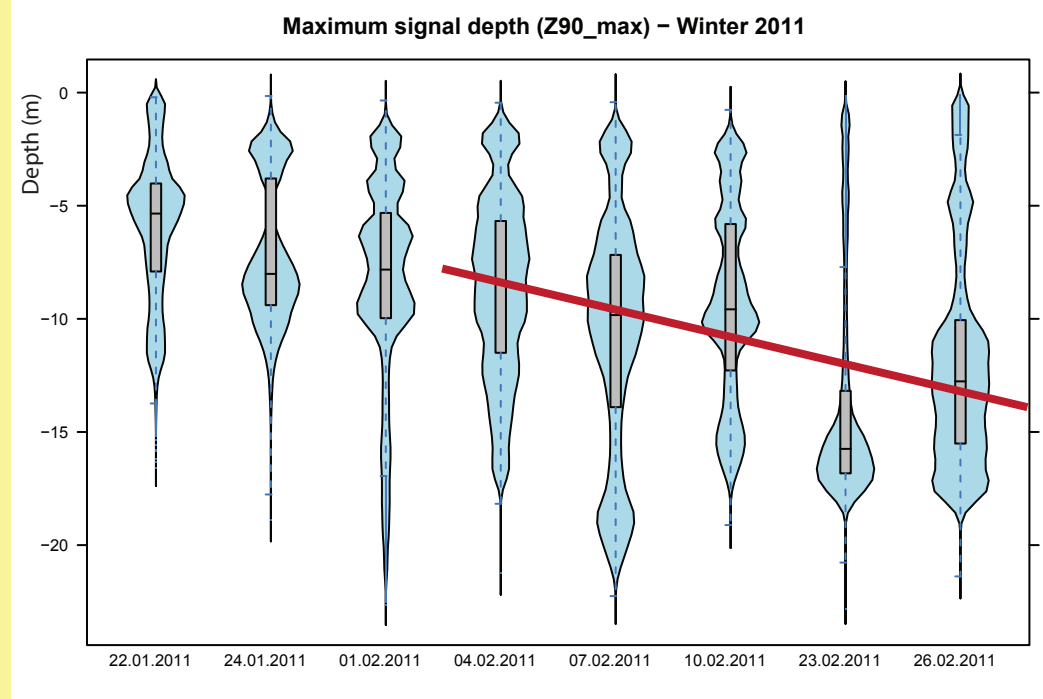


Figure 9 - Box whisker plots and kernel density distribution of Z90_max.

- During bora wind regime, intense wind stress produced favorable conditions for sediment resuspension, due to increased bottom shear stress, and transport, due to increased circulation velocity;
- Sediment is resuspended from seafloor at lower depths, generating an alongshore band, about 3 Km wide in the area northern Po delta, exhibiting very high TSM concentrations, that can reach 50 to 150 g m⁻³ with wind blowing at speeds higher than 10 m s⁻¹ (Figure 4, 5, 7 and 11);
- Resuspended sediment is then transported offshore due to the increased circulation velocity, in this area TSM concentration can exceed 5.0 g m⁻³
- Evidence of both the cyclonic gyre (Trieste), anticyclonic gyre (Rovinj) formation has been observed in MERIS dataset. Diameter of the observed cyclonic gyres has been spatially measured and found out to be about 50 Km wide (Figure 6 and 10; clearly visible gyre is represented in Figure 10, TSM from MERIS acquired on 13/02/2012);
- As consequence of modified circulation features, after some days of intense wind forcing all the basin show TSM concentration higher than 1.0 g m⁻³, atypical condition for an offshore area, that can last several weeks after the intense wind stress already weakened (figure 6 and 10);
- Suspended particles settle on the seafloor when fluid turbulence is not enough to keep the sediment moving. Maximum signal depth slowly return form values of -5 m to values of -15 to -10 m (Figure 9 and 13);
- Sediment settling lifetime is probably depending on the intensity and duration of the intense wind stress event and on the effects of dense water formation on thermohaline circulation, further investigation is needed to identify its lifetime (Figure 9 and 13);
- Maximum signal depth has be found to be highly correlated with TSM concentrations, because the amount of reflected light is strictly related to fine grained inorganic particles and material of organic origin that is suspended in the water column. This result suggests that it might be redundancy in quantitative estimation of EO products, probably inherited by the use of the same reflectance for the parameter estimation.

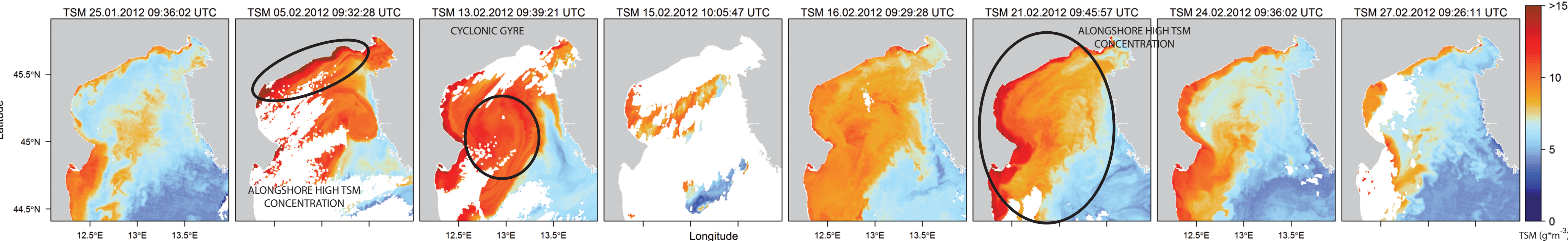


Figure 10 - Total Suspended Matter concentrations estimated from Envisat MERIS observations during winter 2012.

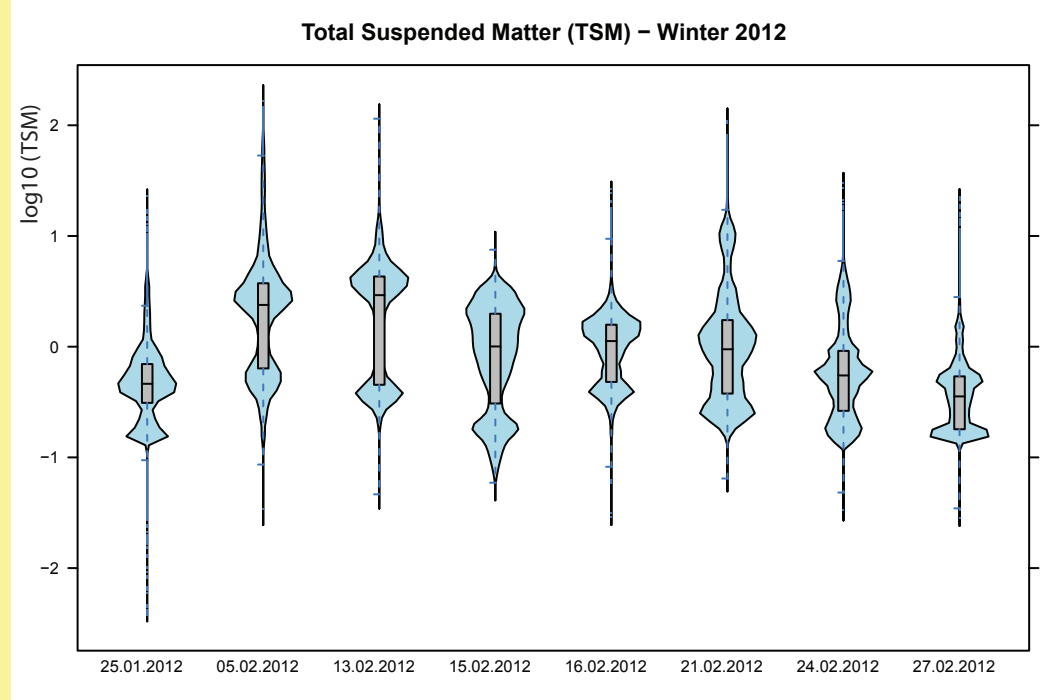


Figure 11 - Box whisker plots and kernel density distribution of TSM.

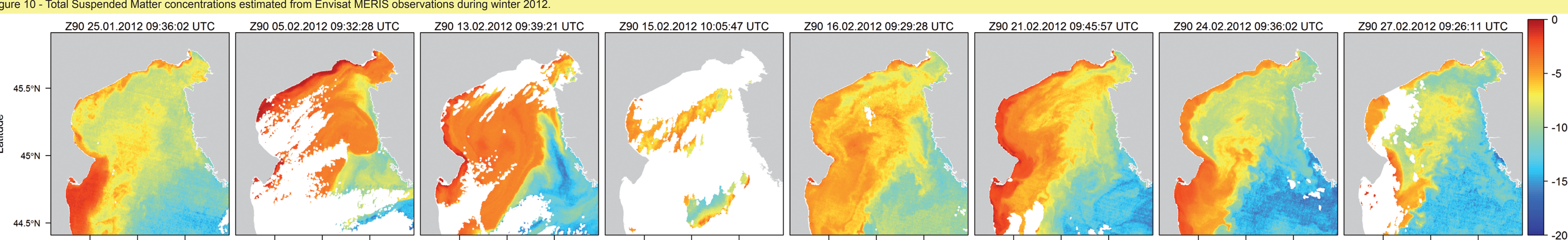


Figure 12 - Maximum signal depth estimated from Envisat MERIS observations during winter 2012.

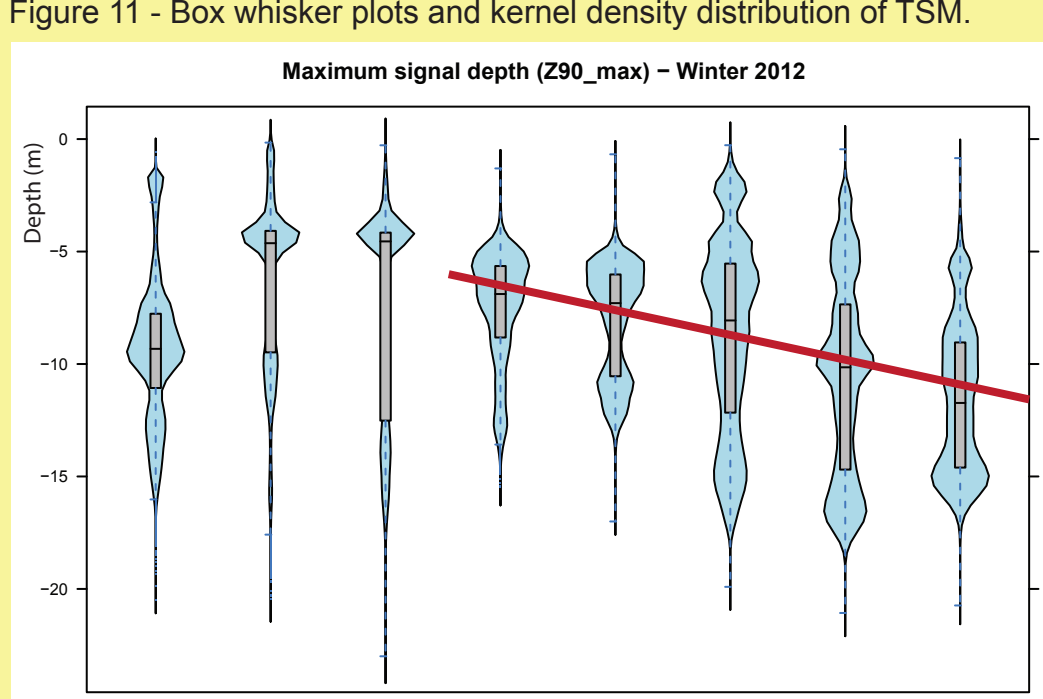


Figure 13 - Box whisker plots and kernel density distribution of Z90_max.

CONCLUSIONS

Outcome of this research study demonstrate how time series analysis of Earth Observation (EO) data may contribute to the understanding and the monitoring of processes in sedimentary depositional marine environment, especially for shallow coastal areas. Estimated TSM, derived from Envisat MERIS optical multispectral observations, has been identified as proxy for qualitative and quantitative analysis of resuspended sediments, and successfully used to interpret the evolution of sediment resuspension from seafloor in coastal areas during intense bora wind forcing. Spatialized maps of TSM concentration clearly showed the spatial and temporal variation of seawater turbidity and evidence of cyclonic gyre circulation, generated by steady bora wind during winter period. During intense bora wind forcing over the basin, lasting for many days, sediments are resuspended and circulation is altered with the formation of a double-gyre, which have the ability of transport and distribute sediments all over the northern portion of the basin. Maximum signal depth (Z90_max), was successfully used to evaluate the evolution of sediment concentration in the water column, particularly for the sediment settling process, even though it was highly correlated with TSM values. Therefore it has been recognized to be not only a proxy estimation of Secchi Disc Depth and a requirement to improve contribution of EO data assimilation in numerical modeling but also a relevant parameter to interpret the dynamics of sediment fluxes. ESA upcoming satellite Sentinel-3 will feature the OLCI sensor (Ocean and Land Color Instrument) to provide optical multispectral medium resolution imagery, with high spectral and temporal resolution (2-3 days). This research study demonstrated the capability of multiple EO products for monitoring the evolution of sediment resuspension processes in shallow coastal environment. New OLCI sensor will provide data to develop such prospective operational service for the monitoring of coastal and marine environments, ensuring continuity to MERIS, MODIS and SeaWiFS observations.

Acknowledgements
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