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Combined use of SAR and scatterometer for the study of the atmospheric boundary layer(*)

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Summary. — The paper illustrates a possible way of combining SAR images over the sea with scatterometer derived wind fields, to study the spatial characteristics of the marine atmospheric boundary layer (MABL). Both instruments are active microwave radars, relying upon the same physical mechanisms of electromagnetic wave-sea surface interaction. Sensing the sea surface with different spatial resolutions, they make possible to investigate the horizontal and vertical structure of the MABL from the mesoscale (< 100 km) down to the intermediate (< 10 km) and small (< 2 km) scales. An example of the multi-scale description of the MABL is provided analysing overlapping SAR image and scatterometer wind field in the Mediterranean Sea. Environmental conditions of this case study were characterised by moderate wind (8 to 10 m s^{-1}) and unstable air-sea conditions. The radar backscatter modulations exhibited by the SAR image reveal the presence of large-scale atmospheric variations, orographic wind distortions and wind rolls. The majority of the large-scale modulations of radar backscatter are obviously related to the wind speed; some other large-scale feature, which does not seem directly related to the wind, could be explained by the weak Ekman vertical velocity, derived from the scatterometer wind field. The analyses of the wind rolls have been performed through the bi-dimensional spectrum of the SAR image, which shows a two-scale orthogonal wave system with wavelengths of 7 km and 1.5 km. The paper points out the importance of other parameters, such as the sea and air temperatures, in the interpretation of the SAR images and in the full exploitation of the scatterometer winds.

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1. – Introduction

The advent of satellite remote sensing has permitted to study the horizontal properties of the marine atmospheric boundary layer (MABL) over the sea at different scales, measuring the degree of development of the high-frequency sea waves ($f > 5$ Hz, $\lambda < 10$ cm) which are, in some extent, in equilibrium with the wind. Thus, from a measure of the sea surface roughness, it is possible to get information on the strength and spatial structure of the wind field.

The microwave radar backscatter is a measure of the sea surface roughness. From satellite, it is provided by the scatterometer, the Synthetic Aperture Radar (SAR) and the altimeter, all radars operating in the microwaves range. The scatterometer and the SAR operate through the same mechanism of electromagnetic waves-sea surface roughness interaction, providing respectively a ≈ 25 km by 25 km resolution wind field over ≈ 500 km wide swaths, and maps of radar backscatter from the sea surface at spatial resolution $O(10$ m) over ≈ 100 km wide swaths.

Apart few sites in the open sea (from platforms, buoys or ships), at present the scatterometer wind fields represent the major source of experimental data available over the oceans. Besides their use for global scale studies (data assimilation into global atmospheric models, climatology and so on [1]), they may be very important in the study of the mesoscale (< 100 km) features of the MABL, especially in the semi-enclosed or regional seas [2, 3]. On the other hand, the SAR images represent a unique tool, in meteorology, to investigate the small-scale (< 10 km) horizontal structure of the MABL, under convective, low wind [4-8, 3] and high winds [9-12] conditions, as well as to study the organised structures of the wind field in the regions of vortex formation [13, 14]. Furthermore, SAR may be used to retrieve the wind field with a spatial resolution of $O(1)$ km [15-19].

This paper is aimed to show the different views of the MABL provided by the two sensors through the analysis of overlapping and almost coincident in time scatterometer wind field and SAR images in the central Mediterranean Sea. Section **2** briefly describes the principles of radar backscatter from the sea at off nadir incidence angles, while the environmental conditions during the satellites pass are presented in sect. **3**. The following section **4** describes some of the possibilities offered by the scatterometer and the SAR in the study of the horizontal and vertical structure of the MABL. Section **5** ends the paper with the conclusions.

2. – Scatterometer and SAR: principles

Both scatterometer and SAR operate at off nadir angles $\theta \approx> 20°$ (θ is the angle between the radar look direction and the vertical). In this incidence angle range, the radar backscatter σ_0 is proportional to a power of the wind speed U, *i.e.*

$$\sigma_0 \propto U^\gamma \,. \tag{1}$$

The exponent γ depends, among others, on the radar incidence angle θ: at C-band (5.4 GHz) it ranges roughly from 0.5 at $\theta = 15°$ to 1.5 at $\theta = 65°$ [22].

The mechanism involved in the electromagnetic waves-sea surface roughness interaction is known as Bragg interference [20], which links the radar wave number k_r to the

Fig. 1. – The SAR frames selected for this study, with the scatterometer wind field superimposed. The numbers identify the image frame.

sea roughness wave number k_w through θ, *i.e.*

$$k_\mathrm{w} = 2k_\mathrm{r} \sin\theta\,. \tag{2}$$

According to eq. (2), at fixed θ, the radar backscatter is produced only by the sea roughness of wave number k_w: the radar selects, from the wave spectrum, only a particular narrow frequency band of waves.

Despite some work has been done [21], a reliable physical model relating σ_0 to the full wave spectrum and wind speed does not exist yet, due to the difficulty to model the electromagnetic waves interaction with the sea surface (Bragg scattering is an approximation), to describe the sea surface (non-linearities as the breaking) and to model the sea roughness generation by the wind. The actual models retrieving the wind from the radar backscatter are of parametric form [22].

Fig. 2. – The SAR image, composed by three frames, expressed in σ_0 backscatter coefficient. Left panel: original image. Right panel: with the incidence angle dependence removed. Compression rate: 40. Pixel size: 500 m.

3. – The case study

The data used in this paper were provided by two different satellites: the Japanese ADEOS-I (ADvanced Earth Observation Satellite) [23] which operated the American NASA NSCAT (Nasa SCATterometer) at Ku-band (13.955 GHz, VV and HH polarisations) and the European Remote Sensing Satellite ERS-2 [24], still providing, among others, SAR images at C-band (5.3 GHz, VV polarisation).

Figure 1 shows the selected episode of overlapping NSCAT wind field and ERS-2 SAR images of the 22 of May 1997, south of Sicily, east of Tunisia.

The scatterometer pass time was 10:05 GMT, while the SAR swathed the area at 09:51 GMT, during orbit 10912. Three SAR frames, the 2871, 2889 and 2907 are considered in this work.

The wind was stronger in the most northern frame (2871), where it reached 10 m s^{-1}.

Proceeding southwards, the speed decreased, to reach 7 m s^{-1} in the frame 2907 and the direction changed clockwise from South-East to South.

The SAR image, composed by the three frames of fig. 1, is shown in fig. 2, left panel, expressed in terms of the normalised radar cross-section σ_0. The horizontal black strips are artifact in the data. The image has been obtained compressing the original data of a pixel resolution of 12.5 m by 12.5 m by a factor of 40.

The unbalance of intensity from the right to the left side of the image is due to the different incidence angles, typically from $\theta = 19.5°$ (on the right side) to $\theta = 26.6°$. This effect has been removed by subtracting a one-dimensional surface fitting to the original image (fig. 2, right panel). The relative spatial uniformity of the wind direction across the two northern frames makes the radar backscatter features independent of the angle between the wind direction and the radar line of sight.

This image exhibits several interesting structures: mesoscale (≈ 50 km) modulations of σ_0 visible as black (for instance at pixel range $x = 70 : 150$ and $y = 200 : 250$, or along the southwestward diagonal of the upper part of the image) and white ($x = 100, 500 \leq y \leq 600$, for example) areas, wave-like structures of ≈ 10 km of wavelength (upper left corner, $0 \leq x \leq 100$, $500 \leq y \leq 600$), long wake filaments at the lee side of the two islands (Linosa and Lampedusa), as the wind was blowing south-eastwards. While the wave-like modulations of the radar backscatter reveal the spatial structure of the MABL at small scale, it is of interest to evaluate if the large-scale modulations of σ_0 are related to the spatial variations of the wind field.

4. – Different views of the atmospheric boundary layer

Figure 3, left panel, shows the SAR image with the scatterometer wind field and the wind speed contours superimposed. There is a large-scale correspondence, as it should be, between the radar backscatter and wind speed patterns: areas of higher wind speed correspond to areas of higher radar backscatter. However, the high backscatter area in the bottom right corner of the image ($x = 150 : 200$, $y = 0 : 200$) does not appear to have a similar pattern of the wind speed, which is spatially homogeneous here.

This imperfect correspondence rises the question: in what extent SAR and scatterometer detect the same phenomena at different spatial scales on the sea surface?

The relationship between meso and small-scale atmospheric structure is a new topic, which may be faced using the data from these two sensors. It addresses to questions like the relationship between the small-scale convection and the wind stress curl, or like the structure of the large- and small-scale orographic winds. Here it is only possible to look for similarities and discordances, leaving for future a more detailed study on this topic using more appropriated examples.

Performing a spatial average of the radar backscatter over ≈ 50 km by 50 km, the scatterometer cannot obviously reveal the small-scale variability of the wind, but it may be influenced by it. Neither it can account for the air-sea temperature difference, since such dependence is not taken into account in the wind retrieval scatterometer algorithms.

On the other hand, the radar backscatter, hence the SAR signature, does not depend uniquely on the wind, but also on other scalar parameters like sea and air temperatures, water density and so on [25]. The air-sea temperature difference plays an important role in the sea roughness generation because it influences the strength of the wind stress and thus the high-frequency wave generation. There is not a definite law linking ΔT to σ_0, even if experimental evidences [25] indicate a decrease of σ_0 as the stability increases, and a constant value at unstable conditions. Under stable conditions, a rate of of ≈ 1 dB

Fig. 3. – Left panel: SAR image and scatterometer wind field. Solid lines: contours of wind speed in m s^{-1}. Right panel: SAR image and scatterometer derived Ekman vertical velocity w_{Ek} field in cm s^{-1}. Solid lines: atmospheric upwelling. Dashed lines: atmospheric subsidence. Compression rate: 40. Pixel size: 500 m.

degree^{-1} at moderate wind speed $\approx$ 8–9 m s^{-1}would be expected. In this case study, the atmospheric conditions were unstable ($\Delta T < 0$), and thus it is not expected to find the structure of backscatter related to ΔT.

Using SAR and scatterometer data one should bear in mind their different characteristics. The scatterometer provides neutral stability winds, derived from the radar backscatter through the parametric algorithms, while SAR a plain radar backscatter map of the sea surface. From the former the meso scale structure of the wind and wind stress can be derived (using also other geophysical information); the SAR, instead, requires appropriate processing to retrieve geophysical information, which may be related to the

Fig. 4. – Top panel: portion of the image of fig. 2 ($x = 1 : 200$, $y = 320 : 520$). Compression rate: 10. Pixel size: 125 m. Bottom left panel: blow up of the central part (16 km by 16 km) of the above figure to put in evidence the wind rolls. Bottom right panel: its bi-dimensional spectrum.

wind but also to the other parameters mentioned above and to the oceanographic features.

A step towards the integration of the two data sets may be obtained computing, from the scatterometer data, the wind stress τ and the Ekman vertical velocity $w_{\mathrm{Ek}} = \frac{1}{\rho f}\mathrm{rot}\tau$, where f is the Coriolis parameter and ρ the air density, which accounts for the air-sea temperature difference as well as for the spatial structure of the wind stress. The wind stress τ has been computed using the sea surface temperature provided by the AVHRR (Advanced Very High Resolution Radiometer) NOAA (National Oceanic Atmospheric Administration) satellite and the analysis air temperature fields by the ECMWF (European Center Medium Weather Forecast), Reading, U.K., through a boundary layer model. Figure 3, right panel, reports the Ekman vertical velocity field, in cm s^{-1} (solid lines: atmospheric upwelling, dashed lines: atmospheric subsidence), overlapping the SAR image. Some broad correspondence may be found between areas of higher backscatter and atmospheric upwelling, but the w_{Ek} field is very weak here, and other cases should be studied before claiming for a relationship between the two fields. It suffices to remind here that the spatial variability of the vertical motion of the air derived from the scatterometer winds is important to study the heat and moisture vertical transport, the cloud formation or dissipation, as well as the permanent and transient ocean circulation [26].

Underneath the mesoscale structure exhibited by the wind speed and w_{Ek} fields, there exists a smaller-scale variability which may depend on the air-sea temperature difference, on orographic effects and on the local meteorological conditions, and which may be studied only through the SAR images.

Consider, for example, a portion of the original image reported in the top panel of fig. 4, consisting of a 96 km by 16 km area, with a pixel resolution of 125 m, which corresponds to the stripe $x = 1 : 200$, $y = 320 : 520$ of fig. 2. Large wave-like structures are clearly visible on the top left corner, with wavefronts orthogonal to the wind direction, as well as a series of fine strips, known as wind rolls [27, 28]. They are better visible in the bottom left panel of fig. 4, which consists of a blow up of the central part of the above image (16 km by 16 km).

The corresponding bi-dimensional spectrum as a function of the wavenumber k is reported in the bottom right panel of fig. 4. It shows the structure of the long wavelength modulation of backscatter ($k \approx 1.5 \cdot 10^4 \mathrm{m}^{-1}$, $\lambda \approx 7$ km), roughly at $135° \pm 180°$, as well as that of the wind rolls ($k = 7 \cdot 10^4$, $\lambda \approx 1.5$ km) at $60° \pm 180°$. Probably the two systems are connected each other, in the sense that the organised wind rolls are modulated along the wind direction, as other experimental *in situ* data seem to suggest.

The definition of the spatial properties of the wind rolls permits, according to the model by [29, 27], to estimate the convective layer depth z_i, roughly half of the rolls wavelength, and thus to have information about the vertical structure of the atmospheric boundary layer at small spatial scales.

5. – Conclusions

The paper has shown some of the possible information about the MABL which can be derived from using scatterometer derived wind fields and SAR images, *i.e.* the horizontal and vertical structures of the MABL at different spatial resolutions, from the mesoscale (< 100 km) to the intermediate (< 10 km) and small (< 2 km) scales.

The study of the relationship among the phenomena at different scales represents one of the most attractive topics for future investigations. The study of the MABL cannot prescind from the knowledge of complementary parameters, which require additional data from satellite (sea surface temperature) and from the atmospheric models (air temperature and humidity). In fact, both the interpretation of SAR signature, which depends on the wind as well as on the above scalars, and the full utilisation of the scatterometer winds, which describe only the wind structure at neutral conditions, can take advantage of a more precise characterisation of the environmental conditions.

The symbiotic use of SAR and scatterometer may be important to study in greater detail the mesoscale processes inferred from the analysis of the scatterometer wind and wind stress fields, as under atmospheric convection, in stormy regimes with the presence of wind rolls and when strong gradients in wind speed and direction, as across atmospheric fronts, are present. Moreover, SAR may be used to extend the study of the MABL close to coasts, where scatterometer data are missing (actually, scatterometer cannot sense the wind closer than 25 km to the coast).

Finally, the interpretation of the SAR images may take advantage of the scatterometer winds when oceanographic and meteorological structures are present in the same image and their separation difficult.

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