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Observations of Bora Events over the Adriatic Sea and Black Sea by Spaceborne Synthetic Aperture Radar

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ABSTRACT

Bora events over the Adriatic Sea and Black Sea are investigated by using synthetic aperture radar (SAR) images acquired by the advanced SAR (ASAR) on board the European satellite *Envisat*. It is shown that the sea surface roughness patterns associated with bora events, which are captured by SAR, yield information on the finescale structure of the bora wind field that cannot be obtained by other spaceborne instruments. In particular, SAR is capable of resolving 1) bora-induced wind jets and wakes that are organized in bands normal to the coastline, 2) atmospheric gravity waves, and 3) boundaries between the bora wind fields and ambient wind fields. Quantitative information on the sea surface wind field is extracted from the *Envisat* ASAR images by inferring the wind direction from wind-induced streaks visible on SAR images and by using the C-band wind scatterometer model CMOD_IFR2 to convert normalized cross sections into wind speeds. It is argued that spaceborne SAR images acquired over the east coasts of the Adriatic Sea and the Black Sea are ideal means to validate and improve mesoscale atmospheric models simulating bora events.

1. Introduction

Bora winds are regional downslope winds, where cold air is pushed over a coastal mountain range due to the presence of a high pressure gradient or by the passage of a cold front over the mountain range. They are encountered in mountainous coastal regions where the mountain range is not too high (typically below 1000 m) such that the adiabatic warming of the descending cold air is small (Burman 1969; Yoshino 1976; more information is available online at http://www.weatheronline.co.uk/reports/wind/The-Bora.htm). In Europe, strong bora winds are encountered at 1) the east coast of the Adriatic Sea, where they are called Adriatic bora, and 2) the east coast of the Black Sea, where they are called Novorossiyskaya bora because they are encountered near the Russian town of Novorossiysk. Bora winds can attain speeds of more than 40 m s^{-1} and can be quite hazardous, especially for coastal ship traffic and harbor operations.

In this investigation we use synthetic aperture radar (SAR) images acquired by the advanced SAR (ASAR) on board the European *Envisat* satellite to study bora events at the east coasts of the Adriatic Sea and the Black Sea. The bora winds roughen the sea surface and thus leave a "fingerprint" on the sea surface, which is detectable by SAR. SAR images reveal finescale structures of bora wind fields (on scales of few hundred meters) that cannot be obtained by other spaceborne instruments. In particular, SAR is capable of resolving wind jets and wakes associated with bora events, which

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extend from the coast onto the sea and that often give rise to the generation of atmospheric gravity waves. In addition, quantitative information on the sea surface wind field can be extracted from the SAR images themselves (see, e.g., Horstmann and Koch 2005, and the literature quoted therein). Thus, spaceborne SAR turns out to be an ideal instrument for validating and improving mesoscale atmospheric models describing bora events.

Validations of such models have been carried out previously by using meteorological data collected from airplanes, which were flying transects through bora wind fields (Smith 1987). But an overall and instantaneous view of the bora wind field cannot be obtained in this way. However, spaceborne SAR can provide snapshots of the surface wind field because it can image a large sea area within seconds. In the case of the ASAR onboard the European *Envisat* satellite, the swath width varies between 100 and 450 km (depending on the operation mode) and is therefore often capable of capturing the entire bora wind field.

However, SAR yields only a two-dimensional view of the bora wind field and this only indirectly via the sea surface roughness pattern. A wind scatterometer model and wind directional information (from the SAR image itself or from a wind model) must be invoked to convert radar backscatter values into wind speeds, which are usually referenced to a height of 10 m and to a neutrally stratified atmospheric surface layer. In this study we calculate the sea surface wind field from the ASAR images by using the wind fields from SAR (WiSAR) tool (Horstmann and Koch 2005), which extracts wind directions from wind-induced streaks visible in the SAR image and wind speeds from the normalized radar cross section (NRCS) of the SAR data via the C-band wind scatterometer model CMOD_IFR2 (Quilfen et al. 1998).

2. Adriatic bora

The Adriatic bora or bura is a cold and dry northeasterly wind that blows from the eastern side of the Adriatic Sea (Dinaric Alps) onto the open sea and that is funneled through gaps or corridors in the coastal mountain range. The mountain range at the east coast of the Adriatic Sea is northwest–southeast oriented and its maximum width and height increase from northwest to southeast with peak heights ranging from 1000 to 1500 m in the north and from 1500 to 2000 m in the south. Along the northern (Croatian) coast the Dinaric Alps are narrowest with several prominent mountain gaps. Here the alongcoast variability of bora winds is most pronounced.

The Adriatic bora has been described in a scientific paper as early as 1866 by the Austrian meteorologist Prettner (Prettner 1866) as a dry and cold wind, which is greatly influenced by local orography and that can attain in gusts wind speeds of more than 40 m s^{-1}. The Adriatic bora occurs when the pressure is higher on the east (Croatian) side of the mountains and lower on the west (Mediterranean) side and when cold air has accumulated over Croatia. When the depth of the cold air pool has reached the height of the mountain passes, bora winds commence to blow. The dry bora winds usually clear the skies from clouds in the lee of the mountain range, while thick clouds associated with upslope air motion are found on the mountain crests. These clouds subsequently dissipate in the descending air on the lee side of the mountain range. Bora winds are most common during the cool season (November–March). The average duration of an Adriatic bora event, during which continuous gale-force winds are encountered, is about 12 h, but they sometimes last up to 2 days (Yoshino 1976).

The Adriatic bora has been extensively studied by using mesoscale atmospheric models (see, e.g., Klemp and Durran 1987). More recent studies have used the Comprehensive Meteorological Modeling System–Regional Atmospheric Modeling System (RAMS) developed by Pielke et al. (1992) (Gohm and Mayr 2005; Gohm et al. 2008), a limited-area model (Qian and Giraud 2000; Belusic and Klaic 2004), and a nested Eta Model (Tosic and Lazic 1998).

Bora events also have an effect of the water circulation, which has been studied extensively for the Adriatic Sea, both theoretically and experimentally (see, e.g., Orlic et al. 1994; Bergamasco and Gasic 1996; Pullen et al. 2003; Loglisci et al. 2004; Lee et al. 2005; Cushman-Roisin and Korotenko 2007). A recent collection of papers dealing with this topic can be found in the special Adriatic Sea issue of *J. Geophys. Res.* (2007, Vol. 112, C3). The strong horizontal wind shear associated with bora events induces a cyclonic oceanic gyre in the most northern part of the northern Adriatic basin and an anticyclonic oceanic gyre in the southern part. The sea surface signatures of these gyres are often visible on SAR images of the Adriatic Sea. However, in this paper we will not address this interesting topic.

a. The 14 January 2006 bora event

Figure 1a shows an *Envisat* ASAR image that was acquired at 2053 UTC 14 January 2006 during a bora event in the wide swath mode (WSM) over the northern part of the Adriatic Sea, and Fig. 1b shows the corresponding wind field retrieved by WiSAR (Horstmann and Koch 2005) from the ASAR data. Visible on the right-hand side are the Croatian coast and the Istria Peninsula and on the left-hand side the Italian coast. Several wind jets emanate from the Croatian coast,

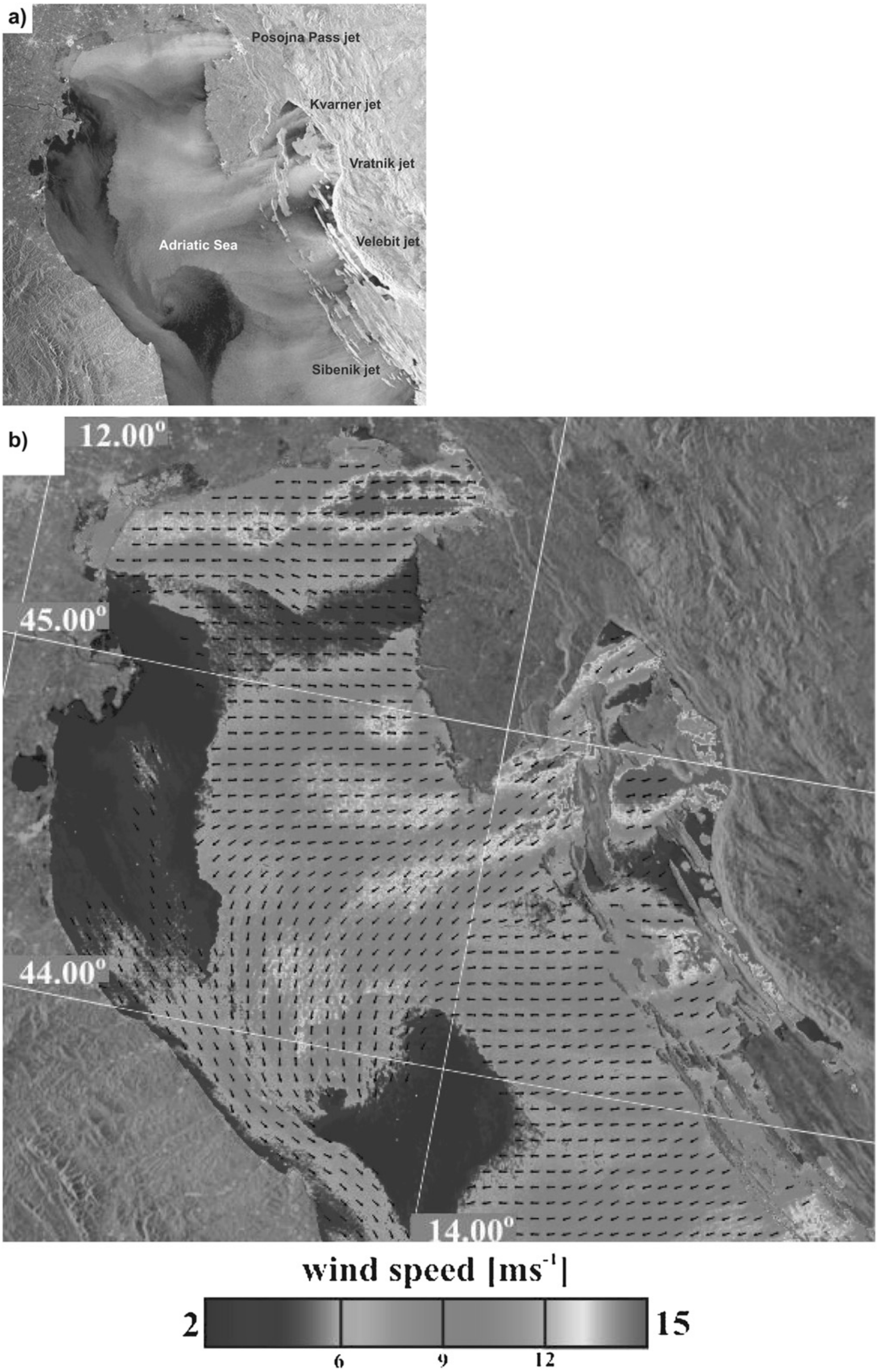

FIG. 1. (a) *Envisat* ASAR WSM image (image area: 290 km × 275 km) acquired at 2053 UTC 14 Jan 2006 over the northern section of the Adriatic Sea during a (weak) winter bora event. (b) Corresponding wind field retrieved by WiSAR from the ASAR data. The names of the wind jets associated with gaps in the mountain range are inserted. Note the cyclonic vortex in the lower section of the image, which has been generated by velocity shear in the bora wind field. (Courtesy of ESA.)

which correlate well with gaps in the mountain range and whose names are inserted in the ASAR image (Fig. 1a). Furthermore, another local wind field is visible on the ASAR image along the Italian coast. The bright band attached to the Italian coast could be interpreted as a sea surface signature of a katabatic wind field. Arguments in favor of this interpretation are 1) the time of the image acquisition, which is late in the evening (2153 local time), and 2) the absence of clouds in the northern region of the Adriatic Sea which gives rise to ''radiation weather'' [as evidenced by the Moderate Resolution Imaging Spectroradiometer (MODIS) image acquired on this day at 1100 local time (not reproduced here)]. However, a close inspection of the roughness band reveals that it contains wind streaks that point southward in a coast-parallel direction. This suggests that the roughness band adjacent to the Italian coast does not result from katabatic winds (at least not primarily), but rather from a local northerly coastal wind, which is probably driven by the Posojna Pass jet and that could be interpreted as a ''barrier jet.'' The dark lines emanating from the Italian coast and pointing into a southeasterly direction are most likely sea surface signatures of surface active material floating on the sea surface and are of anthropogenic origin (spilled into the sea from industrial and municipal plants, ships, etc.). Note that these dark lines have their origin always close to cities suggesting that they result from pollution.

However, the most noticeable feature visible on this ASAR image in the lower section (below the insert ''Adriatic Sea'') is the cyclonic vortex warping the downstream ends of the bora jets. The cyclonic vortex has been generated by horizontal velocity shear associated mainly with the Vratnik jet and the adjacent wake to the south. Through air–sea coupling it gives rise to a cyclonic gyre in the water, which causes upwelling of cold water. This can change the stability of the atmospheric surface layer from neutral to stable. In the latter case the radar backscatter is reduced, which is probably the reason why the cyclonic vortex appears on the ASAR image as a darkish patch. (For more information on the dependence on the radar backscatter on the stability of atmospheric surface layer caused by the air–sea temperature difference the reader is referred to the paper by Keller et al. 1989).

The wind field map (Fig. 1b) retrieved from this ASAR image shows three narrow wind jets with wind speeds around 15 m s^{-1} originating from westward directed airflow through the mountain gaps Posojna, Vratnik, and Velebit. In the darkish sea areas in the northern part of the Italian coast the wind speed is so low (below 3 m s^{-1}) that wind streaks are not well developed. Therefore WiSAR is unable to assign wind directions to these low wind speed areas. Another reason for the darkish sea areas is probably the presence of surface active material transported into the Adriatic Sea by the river Po. This surface active material floating on the sea surface suppresses surface ripple generation and thus leads to an underestimation of the wind speed in this area by WiSAR.

b. The 24 January 2006 bora event

Figure 2a shows an *Envisat* ASAR image that was acquired at 0920 UTC 24 January 2006 in the image mode (IM) over the northern section of the Adriatic Sea during a winter bora event, and Fig. 2b shows the corresponding wind field retrieved by WiSAR from the ASAR data. Since in this mode the swath width of the ASAR is 100 km, only a small section of the bora wind field is visible; in this case, only the wind jets generated by the airflow through the Velebit Pass and the Sibenik Pass. These wind jets have wind speeds of up to 25 m s^{-1}. Also, the wind field map derived from Quick Scatterometer (QuikSCAT) data that were acquired 3 h and 56 min earlier (not reproduced here) shows that in the area imaged by ASAR a northeasterly wind of 25 m s^{-1} was blowing. However, the QuikSCAT-derived wind fields have a resolution of 25 km (Liu et al. 1998) and thus cannot resolve the details of the wind fields that ASAR can resolve. This area was also imaged in the visible band by the Medium Resolution Imaging Spectrometer (MERIS; available online at http://envisat.esa.int/instruments/meris/) on board the *Envisat* satellite at the same time as the ASAR image was acquired (see Fig. 3). This optical image shows a cloud-free area as well as a cloud-covered area over the mountain range of the northern section of the Croatian coast. These are typical phenomena associated with bora events that are well known to the local people (Yoshino 1976). Note also the weak sea surface signatures of atmospheric gravity waves on the ASAR image (Fig. 2a) and the very strong cloud signatures of these waves over the Italian peninsula on the MERIS image (Fig. 2b).

c. The 23 January 2008 bora event

Figure 4a shows an *Envisat* ASAR image that was acquired at 0908 UTC 23 January 2008 during a winter bora event in the WSM over the Adriatic Sea, and Fig. 4b shows the corresponding wind field retrieved by WiSAR from the ASAR data. Visible on this ASAR image are several wind jets, similarly to the ASAR image of 14 January 2006 (Fig. 1). On this day the bora winds were stronger (wind speed in gusts up to 25 m s^{-1}) than on 14 January 2006 (wind speeds in gusts up to 15 m s^{-1}) and there was no local wind present at the Italian coast with which the bora winds could interact. Prominent features visible on this ASAR image are the sea

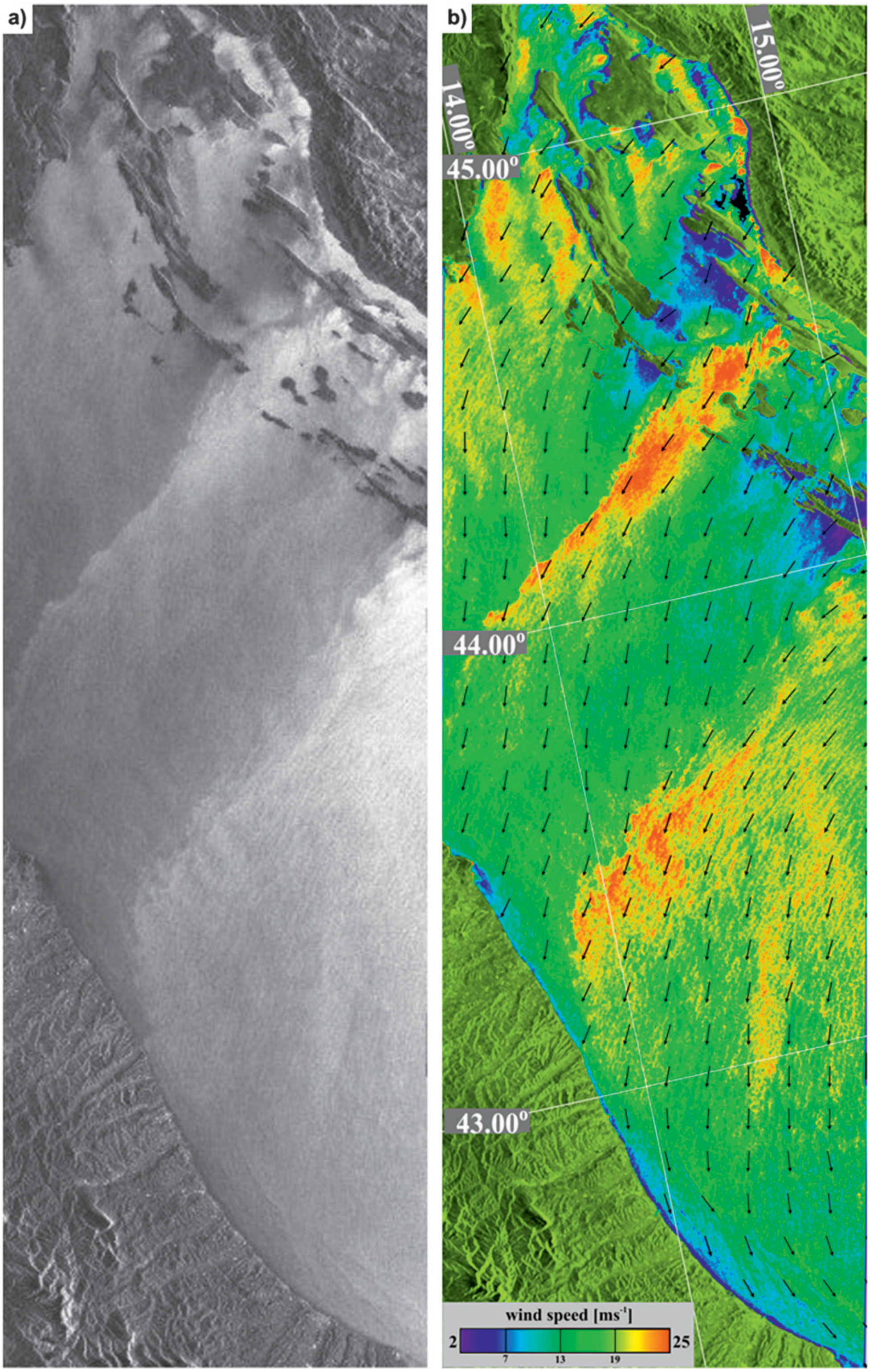

FIG. 2. (a) *Envisat* ASAR IM image (image area: 100 km × 305 km) acquired at 0920 UTC 24 Jan 2006 over the Adriatic Sea. (b) Corresponding wind field retrieved by WiSAR from the ASAR data. Note the strong wind of 25 m s^{-1} south of the Istria Peninsula, which is funneled through the Velebit Channel. Here the Adriatic bora winds are usually strongest. Farther south the wind blows through the Sibenik Pass. (Courtesy of ESA.)

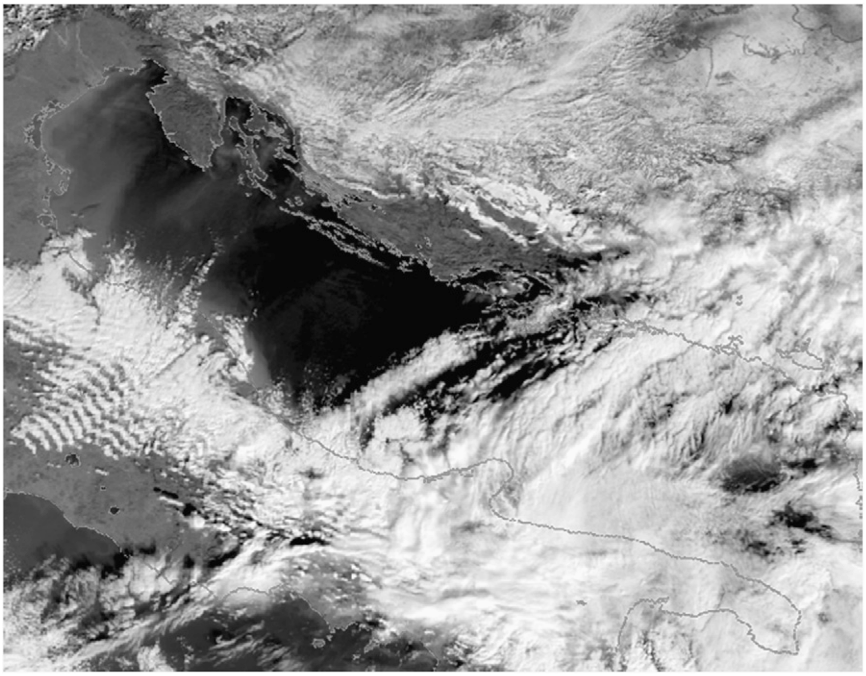

FIG. 3. MERIS image of the Adriatic Sea and its surroundings acquired simultaneous to the ASAR image depicted in Fig. 2a (0920 UTC 24 Jan 2006). Note that the bora has cleared the skies from clouds in the northern section of the Adriatic Sea and over the Croatian coast and that atmospheric gravity waves are visible in the cloud pattern.

surface signatures of atmospheric gravity waves at various locations, in particular in the Vratnik jet. Here the sea surface wind fluctuations associated with the atmospheric gravity waves range from about 13 to 18 m s^{-1}.

The same area was also imaged in the visible band by MODIS on board the *Terra* satellite (see Fig. 5; more information available online at http://modis.gsfc.nasa.gov/). This image shows atmospheric gravity wave patterns in the clouds in the northern section where the clouds are not as dense as in the southern section. Partial cloud coverage is a prerequisite for the visibility of the atmospheric gravity waves in cloud images. The wavelengths of these wave patterns visible on the ASAR and MODIS images are about the same: 10 km. Note that also on this day, as on 24 January 2006 (Fig. 3), the bora had cleared the skies from clouds over the Croatian coast.

The radiosonde data from Zadar, the nearest station at the Croatian coast, which were acquired at 1200 UTC 23 January 2008, show a very stable lower layer and a strong inversion at a height of approximately 1500 m (not reproduced here). This constitutes a favorable condition for atmospheric gravity waves to be trapped in the lower atmosphere such that they touch down onto the sea surface where they leave a fingerprint that is detectable by SAR.

3. Adriatic bora

Bora winds are also often encountered at the east coast of the Black Sea between the Russian towns of Anapa and Tuapse (Fig. 6a). The strongest winds occur usually in the area around the Russian town of Novorossiysk. This is the reason why they are sometimes called Novorossiysk boras or Novorossiyskaya boras (Gusev 1959; Burman 1969). On the average, bora winds are encountered on 30–40 days yr^{-1}. In this region, wind events are called boras only when the wind speed exceeds 15 m s^{-1}. Boras occur in 74% of all cases in the cold season (September–March) and in 26% of all cases in the warm season (April–August). In 78% of all cases their duration is 1–3 days, seldom 4–9 days, and quite seldom (1% of the cases) up to 10 days and more. Their average duration is 2.4 days (Gusev 1959).

In winter, the Novorossiysk boras are generated either by a high pressure difference between a low pressure area residing over the North Caucasus and a low pressure area over the eastern Black Sea or by a cold front passing over the east coast of the Black Sea. They are generated by a strong northeasterly wind that pushes cold air from the east against the Varada Ridge (600 m) and forces it to flow through mountain gaps onto the sea, in particular through the Markhotskiy Pass

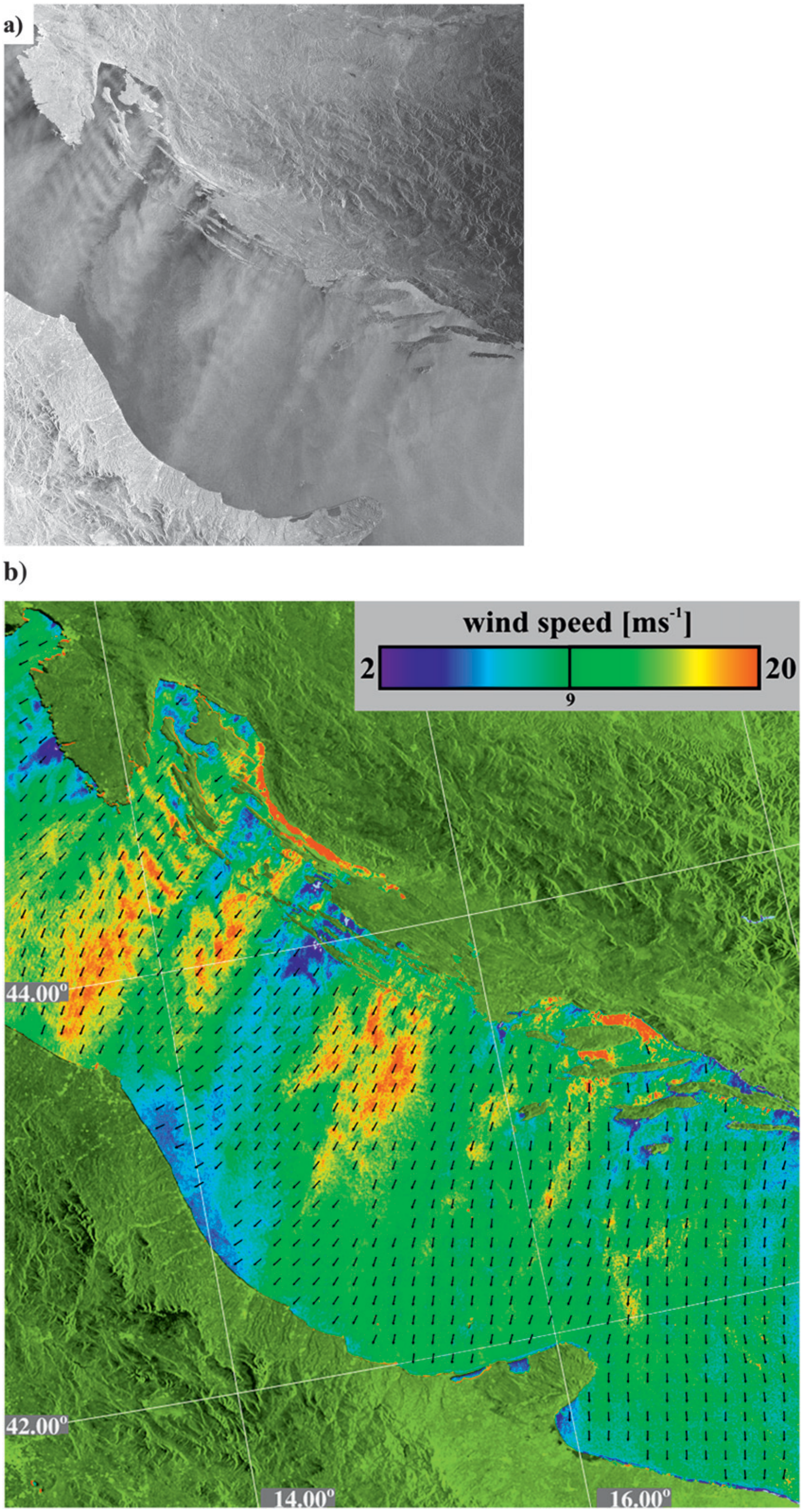

FIG. 4. (a) *Envisat* ASAR WSM image (imaged area: 400 km × 410 km) acquired at 0908 UTC 23 Jan 2008 over the Adriatic Sea during a weak winter bora event. (b) Corresponding wind field retrieved by WiSAR from the ASAR data. Pronounced sea surface signatures of atmospheric gravity waves are visible in the Vratnik jet. (Courtesy of ESA.)

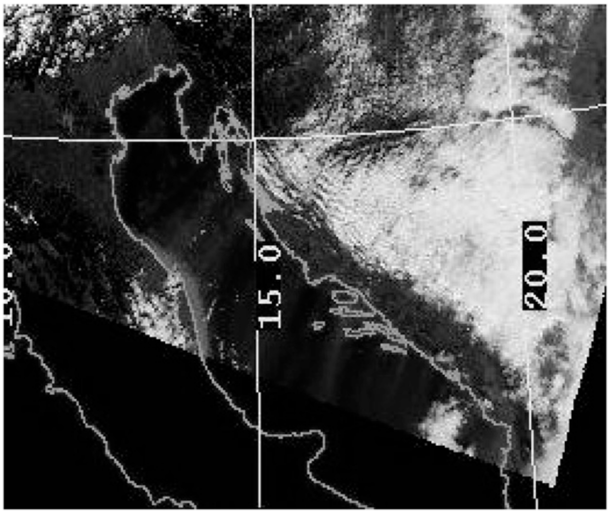

FIG. 5. MODIS *Terra* color composite image of the Adriatic Sea and its surroundings acquired at 1030 UTC 24 Jan 2008. Note that the bora has cleared the skies from clouds in the northern section of the Adriatic Sea and over the Croatian coast. Note the wave pattern in the clouds over Croatia caused by atmospheric gravity waves. Also on this day, as on 24 Jan 2006 (Fig. 3), the bora has cleared the skies from clouds over the Croatian coast.

(435 m) near Novorossiysk. Most often bora events occur in the coastal area around Novorossiysk, but they can also occur in other coastal areas farther south. In summer, the boras are generated either by a cold front passing over the coast from northwest or by differential cooling of air over the mountains and the sea. In the latter case, the boras are weak and are called katabatic boras (for more details see section 3b). During bora events the wind speed at Novorossiysk often reaches values of 30–40 m s^{-1}. The highest wind speed ever measured at the Markhotskiy Pass was 50 m s^{-1}. Sometimes bora events in the Novorossiysk area are catastrophic, causing sinking of ships and damage to houses. The last destructive strong bora event occurred in December 2001, when the area around Novorossiysk was declared a zone of natural disaster.

In the following we present three *Envisat* ASAR images on which sea surface signatures of bora events over the Black Sea are visible.

a. The 21 December 2006 bora event

Figure 6a shows an *Envisat* ASAR image acquired in the WSM at 0736 UTC 21 December 2006, and Fig. 6b shows the corresponding wind field retrieved by WiSAR from the ASAR data. It shows several wind jets emanating from the east coast of the Black Sea and a cyclonic atmospheric vortex (gyre) farther down the coast (toward the southeast). A northeasterly wind blows through the mountain gaps onto the sea, but only in those areas where the coastal mountains are not too high. To the southeast the airflow is blocked by the higher mountains (height about 1500 m). On the sea this leads to the generation of positive vorticity at the transition zone and thus to the formation of a cyclonic vortex.

From the analysis of the synoptic weather data we infer that this bora event was caused by the passage of a cold front. The data from the weather station at Novorossiysk show that between 20 and 23 December the air temperature dropped from 8° to −10°C. At the time of the ASAR data acquisition on 21 December the air temperature was −2°C and the gusty wind had speeds of up to 16 m s^{-1}. On the following day the wind speed reached 24 m s^{-1}. Furthermore, between 21 and to 23 December 2006 the relative humidity dropped from 80% to 40%, causing clear skies at the coast.

b. The 7 June 2007 bora event

Figure 7a shows a section of an *Envisat* ASAR image acquired at 1914 UTC (2214 local time) 7 June 2007 in the WSM, and Fig. 7b shows the corresponding wind field retrieved by WiSAR from the ASAR data. The imaged area of 115 km × 90 km is located just south of Novorossiysk (see also Fig. 6a). It shows sea surface signatures of several wind jets associated with a katabatic bora event. On this day radiation weather prevailed, which is also supported by the MODIS image acquired on this day at 0750 UTC (not reproduced here) showing mostly clear skies at the east coast of the Black Sea. Thus, a large amount of cool air could flow from behind the mountain range down through mountain gaps onto the sea.

A characteristic feature of katabatic boras is that strong winds are encountered only in the northern section of the east coast of the Black Sea (Novorossiysk area) close to the shore line and only late in the evening and at night. During daytime, moderate winds prevail. The wind field map derived from QuikSCAT data acquired at 1706 UTC (2006 local time) 7 June 2007 (not reproduced here) shows in the Novorossiysk area winds of only 10 m s^{-1}. However, the wind field derived from the ASAR image shows winds in this area of around 15 m s^{-1}. Thus, this example demonstrates again the advantage of SAR for revealing finescale structures features of bora wind fields, in particular, in the vicinity of coastlines.

Note the high wind speed bands parallel to the coastline visible on the wind field map depicted in Fig. 7b. They could be sea surface signatures of trapped atmospheric gravity waves, of borelike structures, or of mountain-wave-induced rotors as described by Doyle and Durran (2002). But since additional information is

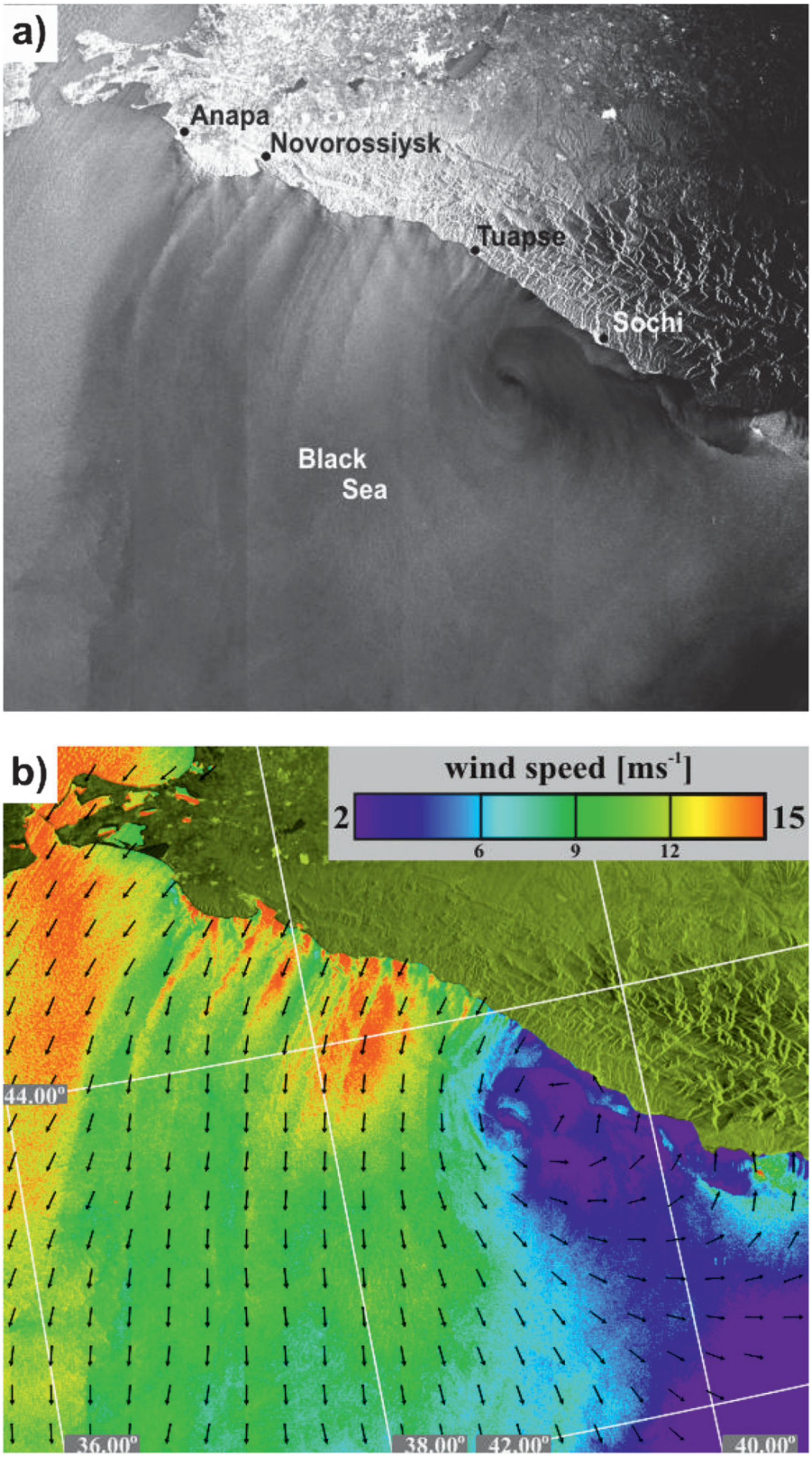

FIG. 6. (a) *Envisat* ASAR WSM image (image area: 400 km × 350 km) acquired at 0736 UTC 21 Dec 2006 during a winter bora event over the east coast of the Black Sea. (b) Corresponding wind field retrieved by WiSAR from the ASAR data. Note that south of Tuapse the airflow from northeast is blocked by the high mountains. This leads to the generation of positive vorticity at the transition zone and therefore to the formation of a cyclonic vortex. (Courtesy of ESA.)

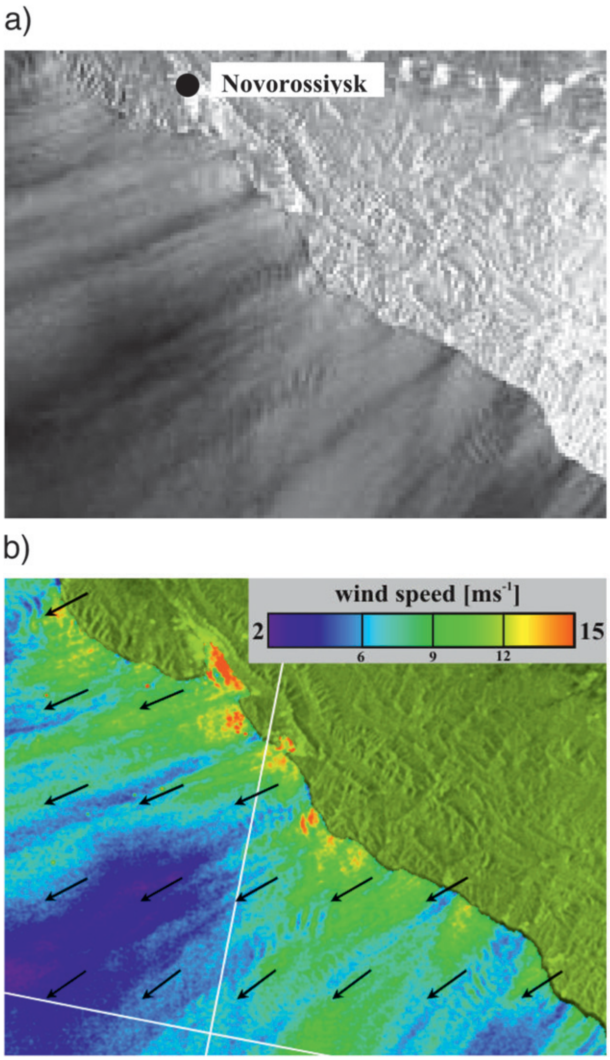

FIG. 7. (a) Section of an *Envisat* ASAR WSM image (image area: 115 km × 90 km) acquired at 1914 UTC 7 Jun 2007 during a summer katabatic bora event over the east coast of the Black Sea. (b) Corresponding wind field retrieved by WiSAR from the ASAR data. Note the weak sea surface manifestations of quasi-linear atmospheric gravity waves in the areas between the jets and the high wind speed areas near the coast. (Courtesy of ESA.)

missing, we cannot determine the physical nature of this phenomenon. Similar banded high wind speed bands are also visible at the same locations in the wind field map of 2 May 2006 depicted in Fig. 8b. Note also the weak sea surface signatures of quasi-linear atmospheric gravity waves in the areas between the jets.

c. *The 2 May 2006 bora event*

Figure 8a shows an *Envisat* ASAR image acquired at 1919 UTC 2 May 2006 in the Alternating Polarization Mode (swath width: 100 km) during a summer bora

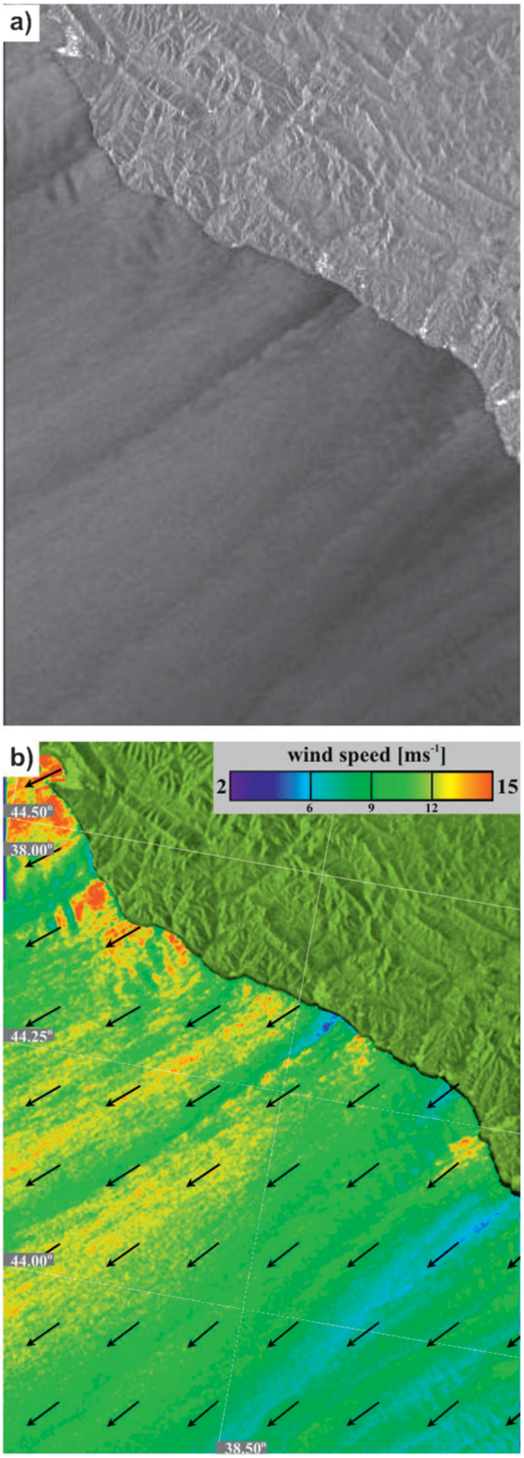

FIG. 8. (a) *Envisat* ASAR APP image (image area: 100 km × 140 km) acquired at 1919 UTC 2 May 2006 during a summer bora event at the east coast of the Black Sea between Novorossiysk and Tuapse showing sea surface manifestations of several wind jets and wakes. (b) Corresponding wind field retrieved by WiSAR from the ASAR data. Note the high wind speed areas in the upper left-hand section of the image that are located in the same areas as in the ASAR image of 7 Jun 2007 depicted in Fig. 7. (Courtesy of ESA.)

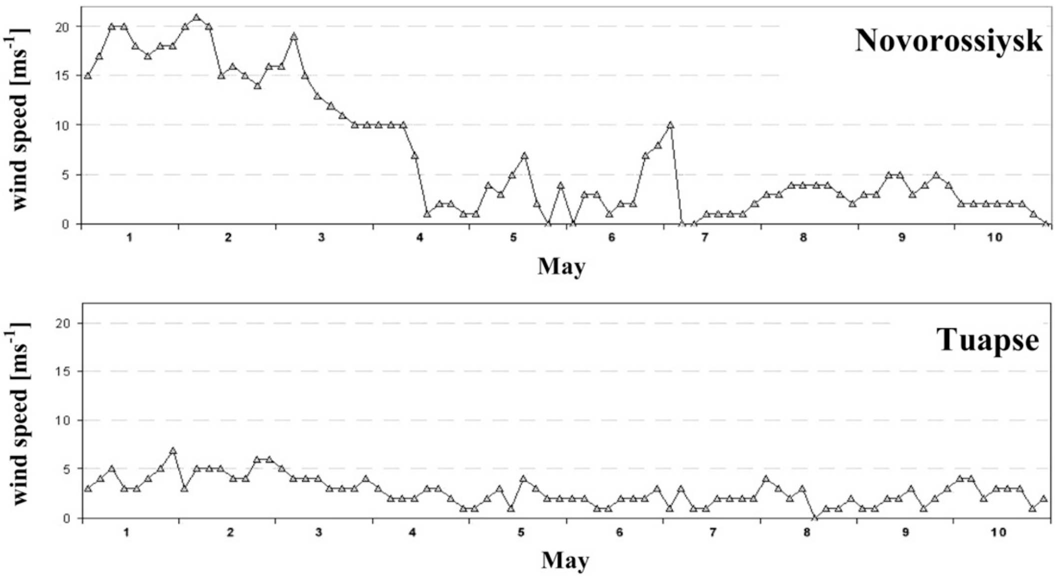

FIG. 9. Wind speed measured at the meteorological stations at (top) Novorossiysk and (bottom) Tuapse, plotted as a function of time. The horizontal axis spans the period from 1 to 10 May 2006 and the vertical axis spans the wind speed range from 0 to 20 m s^{-1}.

event at the east coast of the Black Sea between the Russian towns of Novorossiysk and Tuapse, and Fig. 8b shows the corresponding wind field maps retrieved by WiSAR from the ASAR data. Several sea surface signatures of wind jets are visible, which are separated by narrow wakes (areas of reduced image intensity and thus of reduced wind speed). Note again high wind speed areas adjacent to the coast visible in the upper section of the image. They are located in the same areas as the coast-parallel high wind speed bands visible in the wind field map of 7 June 2007 depicted in Fig. 7b.

Farther to the south, periodic features are visible between two wind jets. They seem not to be sea surface signatures of atmospheric gravity waves, but rather of instability waves generated by strong horizontal wind shear at the interface between a jet and a wake. The wind field map derived from QuikSCAT data at 1700 UTC 2 May (not reproduced here) shows in the northern section of the east coast wind speeds around 10 m s^{-1}. This low value of the wind speed would not qualify this event to be a Black Sea bora event. However, the in situ measured wind data from the meteorological station at Novorossiysk (Fig. 9, top) show that on 2 May wind speeds of up to 20 m s^{-1} occurred. These data further show that between 1 and 3 May the wind speed was always above 15 m s^{-1}. On the other hand, the wind data from the meteorological station at Tuapse (Fig. 9, bottom) show that in the whole period from 1 to 10 May the wind speed was always below 7 m s^{-1}. This clearly demonstrates that the bora was confined to the region north of Tuapse. Farther south the coastal mountains are too high for the cool air to be pushed over the mountain range. This topographic peculiarity is the reason why during bora events atmospheric cyclonic vortices are often generated over the sea.

4. Conclusions

Boras are local coastal wind phenomena that have a great impact on the local weather as well as on the winds in coastal areas. The best known areas, where such phenomena occur in Europe are the east coast of the Adriatic Sea and the east coast of the Black Sea. We have presented six SAR images acquired by the European *Envisat* satellite over these areas (three over the Adriatic Sea and three over the Black Sea) and have shown that these SAR images reveal details of the wind field over the sea that cannot be obtained by other means. In addition, quantitative information on the sea surface wind field has been extracted from these SAR images. In particular, bands of high wind speed have been detected near the coastline on two SAR images acquired over the Black Sea. These high wind speed areas have a banded structure and could be sea surface signatures of trapped atmospheric gravity waves or of wave-induced rotors as described by Doyle and Durran (2002). We conclude that the information contained in spaceborne SAR images acquired over coastal sea areas are of great value for validating and improving numerical bora models.

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