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OBSERVATION OF LOCAL WIND FIELDS AND CYCLONIC ATMOSPHERIC EDDIES OVER THE EASTERN BLACK SEA USING ENVISAT SYNTHETIC APERTURE RADAR IMAGES

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Offshore blowing winds at the east of the Black Sea are often strongly variable in space and time due to the interaction with mountainous coastline. In particular, near the Russian town of Novorossiysk the winds can be quite strong (above 15 ms^{-1}), in which case they are called bora winds. We have analyzed several wind events, including bora events, by using synthetic aperture radar (SAR) images acquired in 2008 by the Advanced Synthetic Aperture Radar (ASAR) onboard the European Envisat satellite. In addition, we have also used Quikscat and MODIS data as well as meteorological data from the weather station at Novorossiysk and radio sounding data from the weather station at Tuapse. It is shown that the sea surface roughness patterns associated with these wind events captured by SAR yields information on the spatial extent and the fine-scale structure of these local wind fields, which cannot be obtained by other instruments. In particular, SAR is capable of resolving: 1) wind jets, wakes, and atmospheric eddies generated by the interaction of easterly winds with the coastal topography, 2) boundaries between the local and ambient wind fields, and 3) atmospheric gravity waves. Quantitative information on the near-surface wind field is derived from the SAR images by using the CMOD4 wind scatterometer model for converting radar backscatter values into wind speeds. These fine-resolution wind fields extracted from SAR images can be used to validate and improve mesoscale atmospheric models.

Key words: coastal wind fields, Novorossiyskaya bora, atmospheric eddies, atmospheric gravity waves, Envisat, synthetic aperture radar, Black Sea

INTRODUCTION

The Black Sea is bordered to the east by a coastal mountain range of variable height having several gaps through which airflow from the northeast can be funneled onto the sea. When the offshore northeasterly coastal winds are strengthened by atmospheric forcing, like the passage of an atmospheric front, and when they have speeds above 15 ms^{-1}, they are called boras. This term has been adopted in analogy to the strong winds, which are often encountered at the east coast of the Adriatic Sea and which are also called boras (Prettner, 1866; Yoshino, 1979; Smith, 1987; Gohm, Mayr, 2005; Askari et al., 2003; Belušić et al., 2006; Dorman et al., 2007; Cushman-Roisin, Korotenko, 2007; Signell et al., 2009). Since these strong winds are mainly countered in the coastal areas near Novorossiysk (44.7° N, 37.8° E), they are also termed Novorossiyskaya boras (Новороссийская бора, 1959; Бурман, 1969). These winds can attain speeds of more than 30 ms^{-1} and can be quite hazardous, especially for coastal ship traffic and harbor operations (Новороссийская бора,1959; Бурман, 1969; Иванов, 2008).

Bora winds are local down-slope 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 600 m) such that the adiabatic warming of the descending cold air is small (Prettner, 1866; Klemp and Durran 1987; Gohm and Mayr, 2005), in contrast to Föhn and Chinook winds where adiabatic warming is significant.

In this paper we investigate several high wind events, which occurred between September and December 2008 at the east coast of the Black Sea. However, not all of them were bora events since the wind speed was not always above 15 ms^{-1}. But all events were associated with pronounced wind jets and wind wakes over the sea which resulted from the interaction of the airflow from the northeast with the coastal mountain range. In particular, the blocking of the airflow by the high mountains south of Tuapse (44.1° N, 39.1° E) often caused the generation of a small-scale/meso-scale cyclonic atmospheric eddy over the south eastern section of the Black Sea. Readers can find additional information on the generation of local atmospheric cyclones over the sea, sometimes called orographic cyclones, in (Герман, 1985). When the wind is sufficiently strong and when it persists over a sufficiently long period (typically several days), then a cyclonic oceanic eddy is generated at the east coast of the Black Sea southeast of Tuapse. We shall show that this is confirmed by model calculations carried out by the US Navy Coastal Ocean Model (NCOM) (available online: http://www7320.nrlssc.navy.mil/global_ncom/ blacksea.html).

In this investigation we use primarily synthetic aperture radar (SAR) images acquired by the Advanced Synthetic Aperture Radar (ASAR) onboard the European Envisat satellite (launched in 2002) over the eastern part of the Black Sea for study the near-surface wind fields associated with these events. Near-surface wind fields are extracted from SAR images via the measurement of the small-scale sea surface roughness. The stronger the wind, the higher is the sea surface roughness and thus the higher is the radar backscattering. SAR measures the backscattered radar power or normalized radar cross section (NRCS), which is a function of radar parameters and wind speed and wind direction (Valenzuela, 1978). An empirical relationship, called CMOD4 model (C-band Scatterometer MODel, Version 4), has been developed to relate NRSC values measured by a C-band radar over the sea to near-surface wind speed and wind direction. The SAR onboard the Envisat satellite operates at frequency of 5.3 GHz and thus is a C-band radar. The CMOD4 model was originally developed for the C-band wind scatterometer onboard the European Remote Sensing satellites ERS-1 and ERS-2 (Stoffelen, Anderson, 1997), but now it is also widely applied to the Envisat ASAR.

Since the NRCS values of the sea surface depend on the wind speed and direction, but SAR measures only one NRCS value per resolution cell, one has to get wind direction information from another source to retrieving two-dimensional near-surface wind fields from SAR images. This information can be obtained from numerical atmospheric models or from the SAR image itself. On SAR images often linear features can be delineated which are indicative for the direction of the near-surface wind. Such linear features include sea surface signatures of wind streaks and wind shadows behind islands and coastal mountains (Horstmann et al., 1998; Monaldo et al., 2001; Monaldo et al., 2003; Horstmann and Koch, 2005, Alpers et al., 2009). Both methods are used in this paper. When taking the wind direction from an atmospheric model, we use in this paper the NCEP model (Model of the National Center for Environmental Prediction, USA). NCEP provides global wind fields at a grid spacing of 0.5° every three hours. When inferring the wind direction from SAR images, we primarily use the direction of the wind jets. The near-surface wind fields extracted from SAR images presented in this paper have a resolution of 500 m.

In this paper we present six SAR images acquired in 2008 by the ASAR onboard the European Envisat satellite showing pronounced sea surface signatures of wind events off the east coast of the Black Sea, which led to the generation of cyclonic atmospheric eddies south of Tuapse. In order to strengthen our interpretation of these SAR images we have also used data from the scatterometer onboard the Quikscat satellite (Liu et al., 1998) and from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra satellite as well as meteorological data from weather stations located at the east coast of the Black Sea.

THE DECEMBER 12, 2008 EVENT

A high wind speed period with wind speeds between 10 to 20 ms^{-1} lasting for about 5 days was encountered at the northeast coast of the Black Sea between December 12 and 17, 2008. With a time separation of 3 days and 7 min, two ASAR images were acquired during this period. At the time of the first ASAR data acquisition the wind speed was only 10 ms^{-1}, but at the time of the second ASAR data acquisition the wind speed was 20 ms^{-1}.

In Fig. 1*a* an Envisat ASAR image is depicted, which was acquired in the Wide Swath Mode (WSM) at VV-polarization on December 12, 2008 at 19:02 UTC over the east coast of the Black Sea. It shows in the north eastern and south eastern section of the Black Sea areas of increased wind speed (areas of increased image brightness) and between them an area of low wind speed (area of low image brightness). Note also the tongues of increased image brightness emanating from the coast in the central eastern and southern sections of the coastline, which are sea surface manifestations of katabatic winds. They are often encountered in coastal areas bordered by high mountains late in the evening, at night, and early in the morning (Alpers et al., 1998). A prerequisite for their occurrence is that the air can cool off during these times, which requires the absence of low-level clouds over the coastal mountains. This was indeed the case on December 12, 2008 as revealed by the MODIS cloud image acquired on December 12, 2008 at 08:30 UTC (not reproduced here). The time of the ASAR data acquisition (22:02 MSK (Moscow Time = UTC+3 h)) falls into the time period where katabatic winds can exist.

In Fig. 1*b* the near-surface wind field is depicted which was retrieved from the ASAR image by using the wind direction from the NCEP model. This plot shows that the dark area visible in the ASAR image is associated with a cyclonic atmospheric eddy. Note the low winds in the center of the eddy.

THE DECEMBER 15, 2008 EVENT

In Fig. 2*a* an Envisat ASAR WSM image is depicted, which was acquired at HH polarization on De-

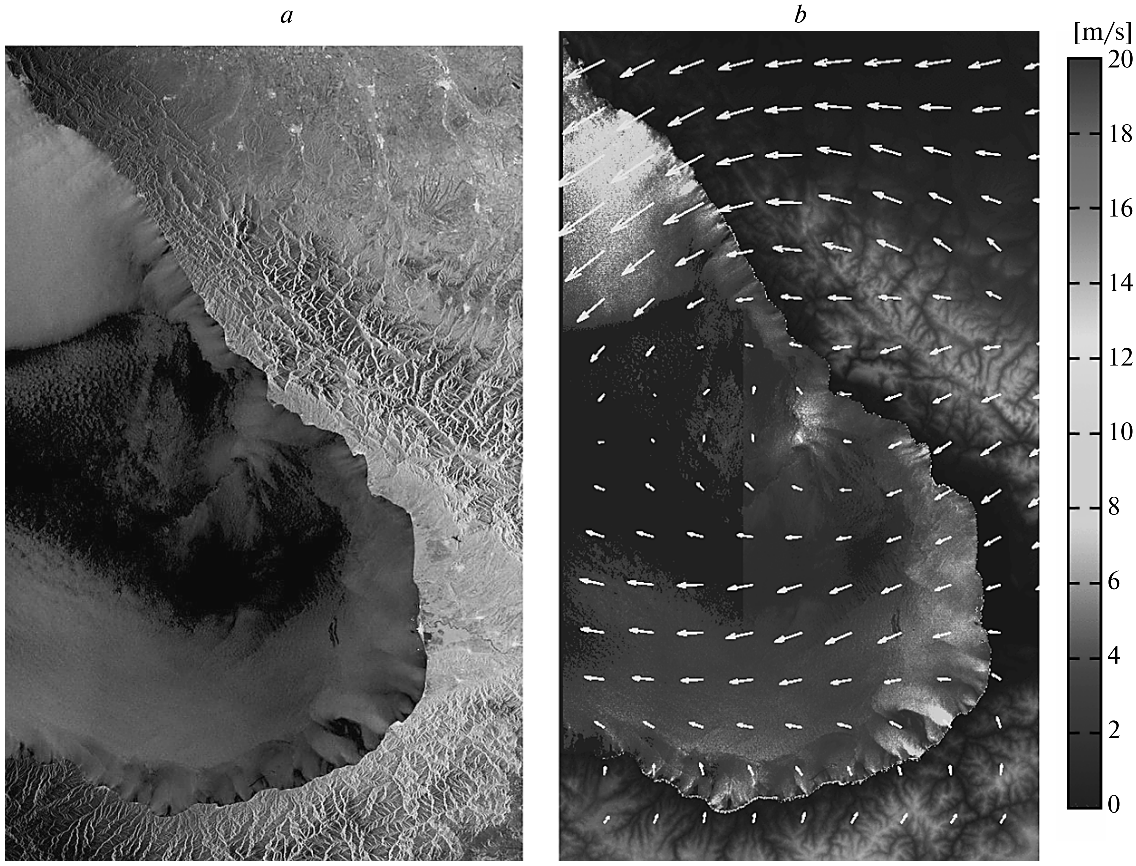

Fig. 1. *a* – Envisat ASAR WSM image (VV-polarization) acquired on December 12, 2008 at 19:02 UTC over the east coast of the Black Sea. The imaged area is 400 × 660 km. © ESA; *b* – near-surface wind field retrieved from the ASAR image by using the wind direction from the NCEP model.

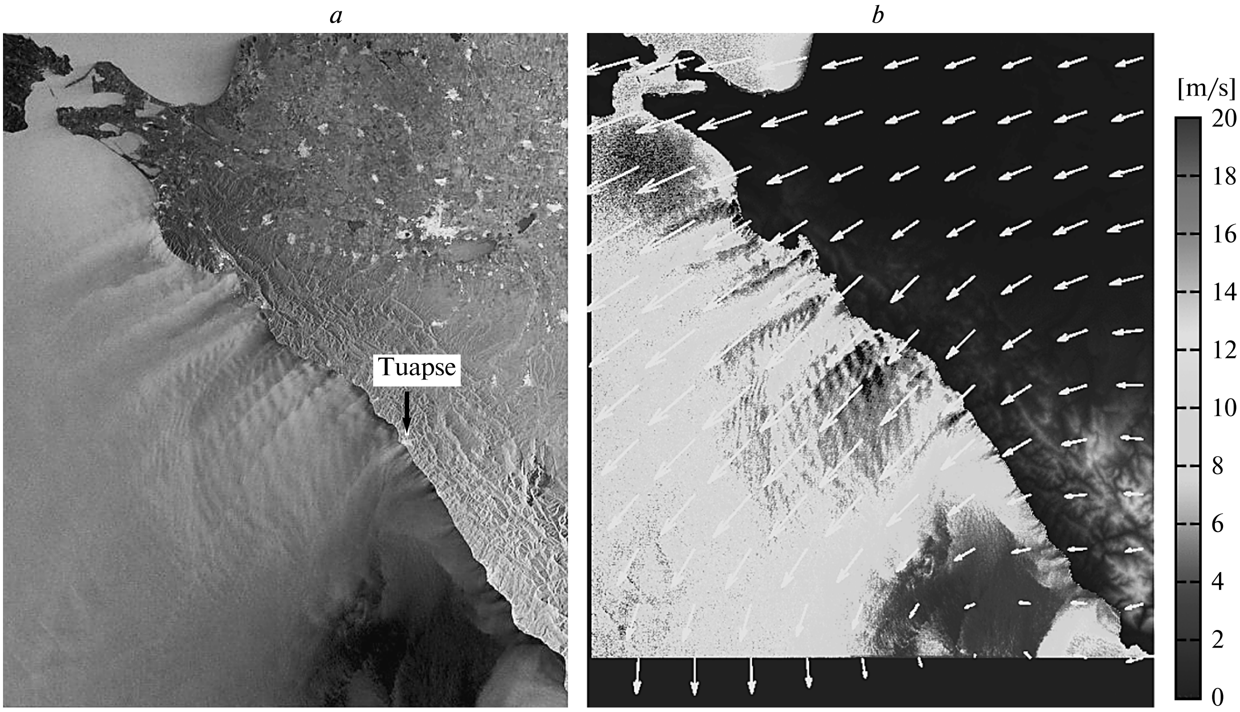

Fig. 2. *a* – Envisat ASAR WSM image (HH-polarization) acquired on December 15, 2008 at 19:10 UTC during a bora event over the east coast of the Black Sea. The imaged area is 400 × 480 km. © ESA; *b* – near-surface wind field retrieved from the ASAR image by using the wind direction from the NCEP model.

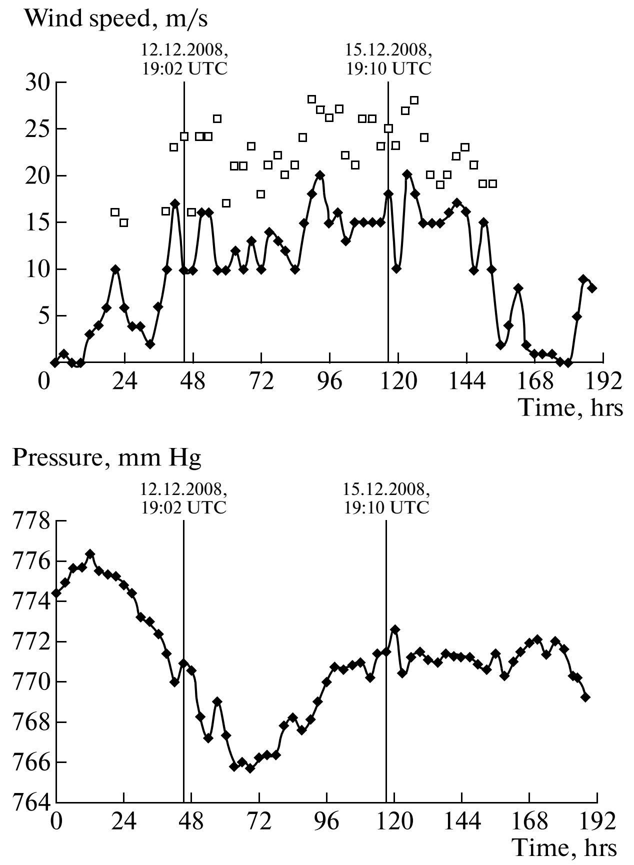

Fig. 3. Time series of wind speed (upper plot) and atmospheric pressure (lower plot) measured by the weather station at Novorossiysk on December 11, 2008 (00:00 MSK) to December 18, 2008 (21:00 MSK). The squares in the upper plot above the line show wind speed associated with wind gusts. The vertical lines denote the times of the ASAR data acquisitions. Note that the onset of the high wind speed period coincides with the drop in atmospheric pressure.

cember 15, 2008 at 19:10 UTC over the east coast of the Black Sea. On this day the wind speed was much higher than on December 12, 2008. Visible are sea surface signatures of strong wind jets. Also sea surface manifestations of atmospheric gravity waves and katabatic winds are visible.

In Fig. 2*b* the near-surface wind field is depicted which was retrieved from the ASAR image by using the wind direction from the NCEP model. It shows that the wind jets have speeds of up to 20 ms^{-1} and that the dark area in the ASAR image is associated with the center of a cyclonic atmospheric eddy.

Fig. 3 shows the time series of wind speed (upper plot) and the atmospheric pressure (lower plot) measured by the weather station at Novorossiysk from December 11, 2008 (00:00 MSK) to December 18, 2008 (21:00 MSK). The squares in the wind plot above the line show the wind speed associated with wind gusts. The vertical lines indicate the times of the ASAR data

Fig. 4. MODIS Terra color composite image of the east coast of the Black Sea and its surroundings acquired on December 15, 2008 at 09:00 UTC showing weak signatures of wind jets in the sea surface roughness pattern and signatures of atmospheric gravity waves in the cloud pattern. © NASA GSFC.

acquisitions. Note that the onset of this high wind speed event coincides also in this case with the drop in atmospheric pressure, which implies that this bora event was of the frontal type (Бурман, 1969).

In Fig. 4*a* MODIS Terra colour composite image of the east coast of the Black Sea and its surroundings is depicted, which was acquired on December 15, 2008 at 09:00 UTC. It shows signatures of wind jets in the roughness pattern of the sea surface and manifestations of atmospheric gravity waves in the cloud pattern over land as well as over the sea. An increase of the sea surface roughness gives rise in this case to an increase in image brightness because the imaged area lies outside of the sun glitter area (Mitnik et al., 2000; Jackson, 2007).

A set of the near-surface wind fields retrieved from Quikscat data acquired between December 14 and 16, 2008 is depicted in Fig. 5. Note that the wind speeds measured by Quikscat over the sea area near Novorossyisk are consistent with the wind speeds measured by the weather station at Novorossiysk.These plots show the persistence of a cyclonic wind pattern (cyclonic eddy) in the south eastern section of the Black Sea over three days.

The surface current field calculated by the NCOM model for December 16, 2008 at 00:00 UTC is depicted in Fig. 6. It shows a tongue of increased surface currents stretching from the east coast of the Black Sea between Novorossiysk and Tuapse onto the sea. This

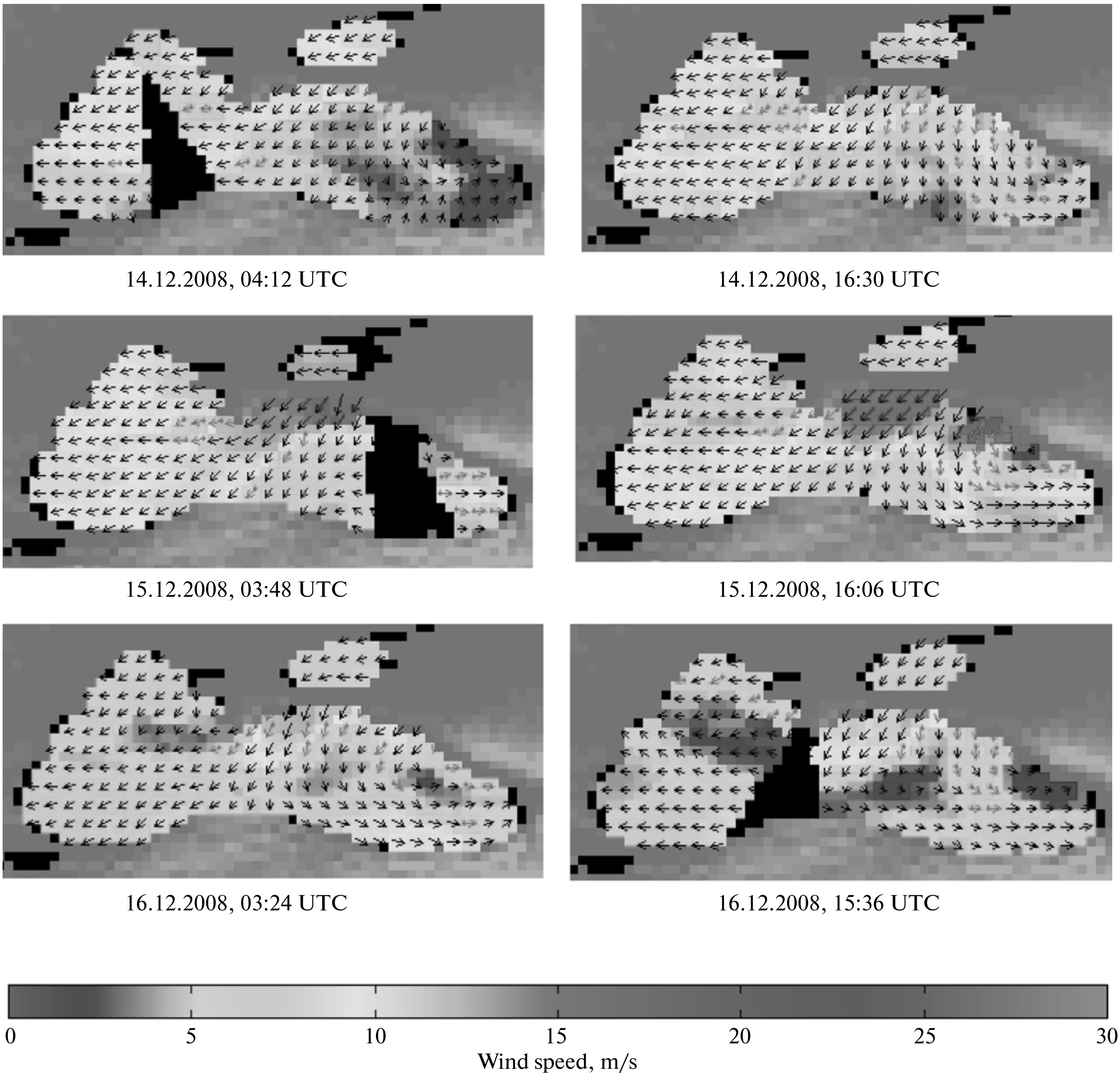

Fig. 5. Sea surface wind maps derived from Quikscat data acquired between December 14 and 16, 2008. It shows the persistence of cyclonic wind pattern in the south eastern section of the Black Sea. © Remote Sensing Systems.

tongue of increased surface current velocity is obviously induced by the wind jets encountered between Novorossiysk and Tuapse. In addition, also a weak cyclonic surface current pattern is visible south of Tuapse, which very likely is linked to the presence of the cyclonic atmospheric eddy in this area.

Since the ASAR image acquired on December 15, 2008 (Fig. 2*a*) shows sea surface signatures of atmospheric gravity waves, we now check whether the state of the atmosphere was such to support trapped atmospheric gravity waves in the lower atmosphere. Fig. 7 shows the skew T-diagram of temperature (right curve) and dew point temperature profiles (left curve) derived from radiosonde data acquired by the weather station at Tuapse on December 15, 2008 at 12:00 UTC. This diagram shows a strong temperature inversion located at a height of 826 m, which acts as vertical boundary of the waveguide for the atmospheric gravity waves. This vertical boundary prevents the atmospheric gravity waves from propagating into higher levels (Cheng, Alpers, 2010).

THE SEPTEMBER 26 AND 27, 2008 EVENTS

A period with wind speeds around 15 ms^{-1} lasting for about 48 hours was encountered at the north east

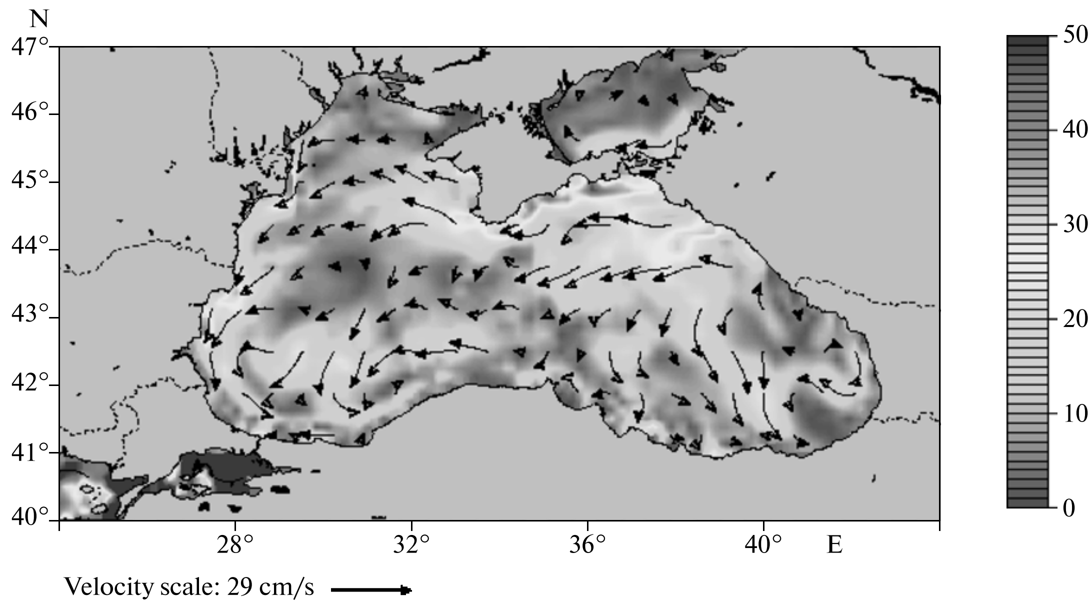

Fig. 6. Surface current field calculated from the NCOM model for December 16, 2008 at 00:00 UTC. Note the area of increased westward surface current off the east coast of the Black Sea between Novorossiysk and Tuapse and the weak cyclonic surface current pattern in the south eastern section of the Black Sea.

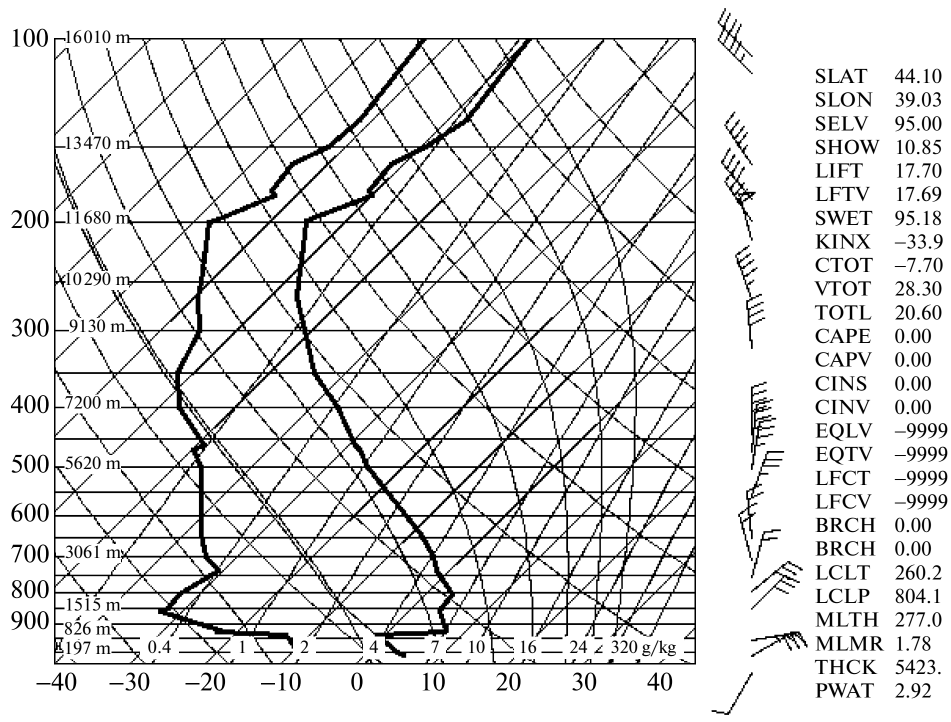

Fig. 7. Skew T diagram of temperature (right curve) and dew point temperature profiles (left curve) measured by a radiosonde launched at Tuapse on December 15, 2008 at 12:00 UTC. Note the strong temperature inversion located at a height of 826 m. © University of Wyoming.

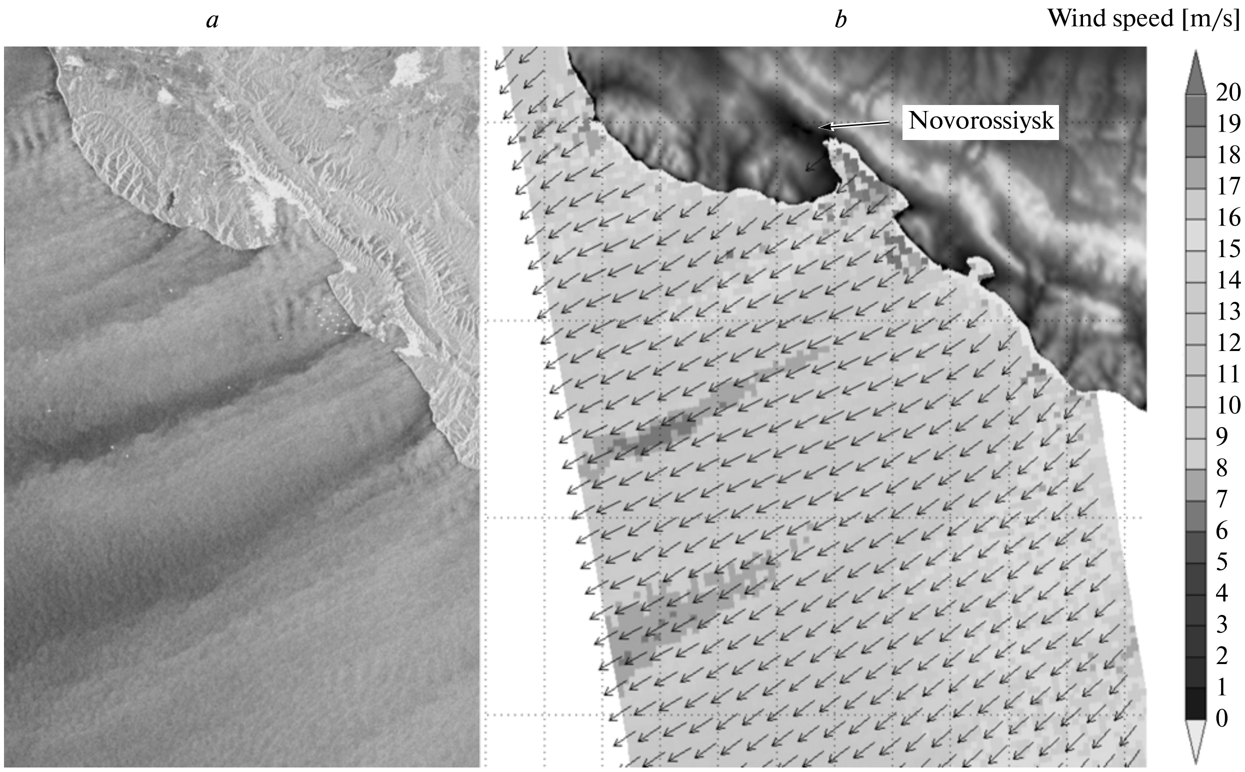

Fig. 8. *a* – Envisat ASAR APM image (VV-polarization) acquired on September 26, 2008 at 19:24 UTC over the east coast of the Black Sea. The imaged area is 100 × 150 km. © ESA; *b* – near-surface wind field retrieved from the ASAR image by using the wind direction retrieved from the direction of the wind jets visible on the ASAR image (courtesy Division of Radar Applications of CLS).

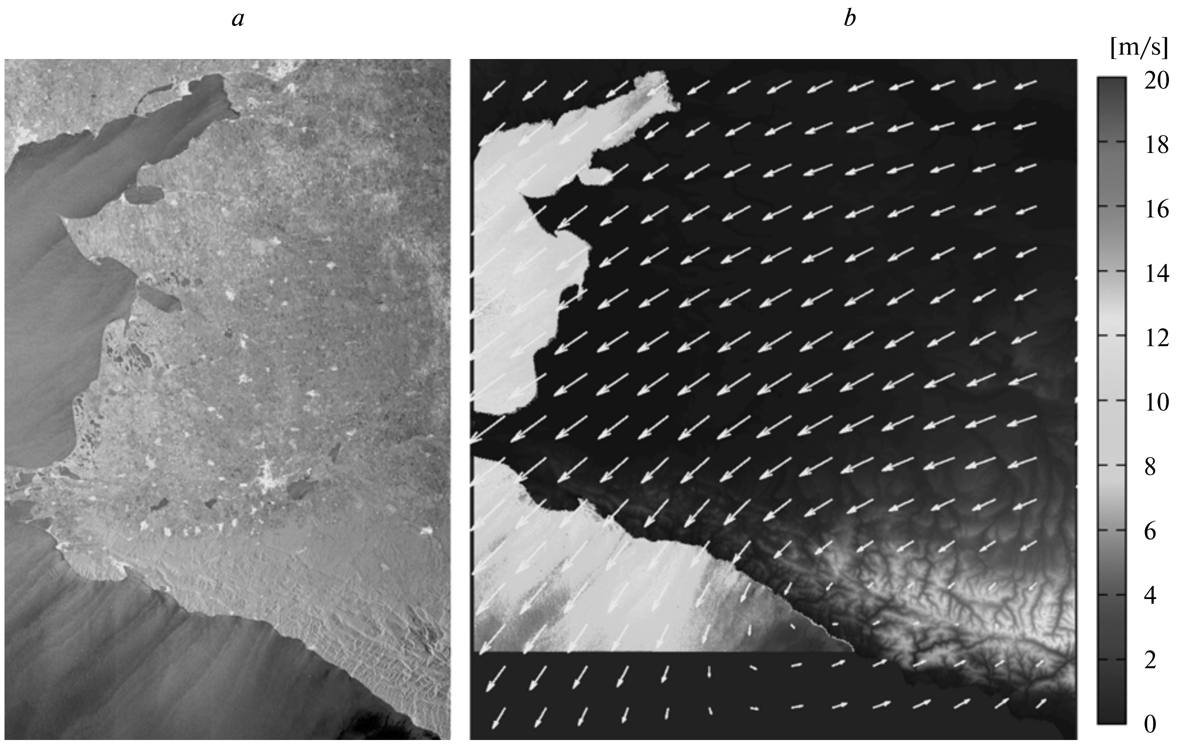

Fig. 9. *a* – Envisat ASAR WSM image (VV-polarization) acquired on September 27, 2008 at 07:33 UTC during a bora event over the east coast of the Black Sea. The imaged area is 400 × 615 km. © ESA; *b* – near-surface wind field retrieved from the ASAR image by using the wind direction from the NCEP model.

coast of the Black Sea between September 26 and 28, 2008. Thus this event can be called a Novorossiyskaya bora. Two ASAR images were acquired during this period with a time separation of 12 h and 9 min.

In Fig. 8*a* an Envisat ASAR image is depicted which was acquired in the Alternating Polarization Mode (APM) on September 26, 2008 at 19:24 UTC over the east coast of the Black Sea. Here only the ASAR image is shown which was acquired at VV-polarization (transmission and reception both in vertical polarization). In Fig. 8*b* the near-surface wind field is depicted which was retrieved from the ASAR image by using the wind direction inferred from the direction of the wind jets visible on the ASAR image. Note the sea surface signatures of several wind jets, in particular the two strong ones south of Novorossiysk, whose widths vary between 15 and 30 km. Visible are also sea surface signatures of two pronounced wind wakes (dark bands between the bright bands associated with wind jets). The boundaries are areas of strong wind shear, where instabilities develop which give rise to wavy sea surface patterns at the interface. Note further the wave patterns on the ASAR image, in particular the one near Novorossiysk and the other one north of Novorossiysk. They are sea surface signatures of atmospheric gravity waves generated by the interaction of airflow from the northeast with the mountain range.

In Fig. 9*a* an Envisat ASAR WSM image is depicted, which was acquired on September 27, 2008 at 07:33 UTC, i.e., 12 hours and 9 min later than the first ASAR image (Fig. 8*a*). In Fig. 9*b*, on the right, the near-surface wind field is depicted, which was retrieved from the ASAR image by using the wind direction calculated by the NCEP model. On this ASAR image also sea surface signatures of several pronounced wind jets and wakes are visible. Of particular interest is the dark area visible at the lower right-hand corner of the ASAR image. It is a low-wind speed area caused by shadowing of the airflow from the east by the high mountain range (higher than 1000 m) southeast of Tuapse. This leads, together with the high wind speed area farther north, to a wind shear zone generating positive vorticity that gives rise to a cyclonic atmospheric eddy. This is confirmed by the wind field depicted in Fig. 9*b* where the wind direction is given by the NCEP model.

Fig. 10 shows the time series of wind speed (upper plot) and atmospheric pressure (lower plot) measured by the weather station at Novorossiysk from September 21, 2008 (00:01 MSK) to September 28, 2008 (22:00 MSK). The squares in the upper plot show above the line the wind speeds associated with wind gusts. The vertical lines denote the times of the ASAR data acquisitions. We see from this plot that the high wind speed period lasted only 40 hours, where the wind speed fluctuated around 15 ms^{-1}. Thus this event was only marginally a Novorossiyskaya bora. It was a bora of the frontal type because also here, like in the

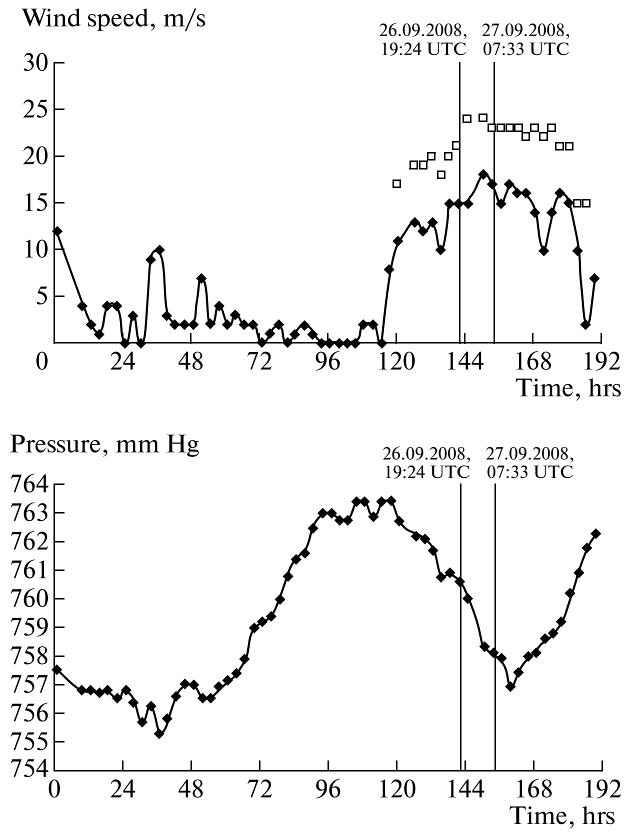

Fig. 10. Time series of wind speed (upper plot) and atmospheric pressure (lower plot) measured by the weather station in Novorossiysk from 00:01 MSK (UTC+4 hours) on September 21, 2008 to 22:00 MSK on September 28, 2008. The squares in upper plot above the line show wind speed associated with wind gusts. The vertical lines denote the times of the ASAR data acquisitions. Note that the onset of the high wind speed period, which in this case is a bora, coincides with the drop in atmospheric pressure.

previous event, the onset of the high wind speed period coincided with the drop in atmospheric pressure

A MODIS Terra colour composite image of the east coast of the Black Sea and its surroundings, which was acquired on December 15, 2008 at 09:00 UTC (not reproduced here), shows a cloud-free area over the northern section of the Black Sea and a cloud-free band inland of the coastline. This is a well-known phenomenon observed during bora events at the east coast of the Adriatic Sea and the Black Sea. Cloud images acquired by the MODIS sensor showing this phenomenon can be found in (Иванов, 2008; Alpers et al., 2007).

If the offshore wind is strong enough and blows over a sufficiently long period, then there is an oceanic response causing a variation in the surface current field.

In Fig. 11 the surface current field calculated by the NCOM model for September 28, 2008 at 00:00 UTC, i.e., at a time close to the end of the high wind speed period, is depicted. It shows a tongue of high velocity

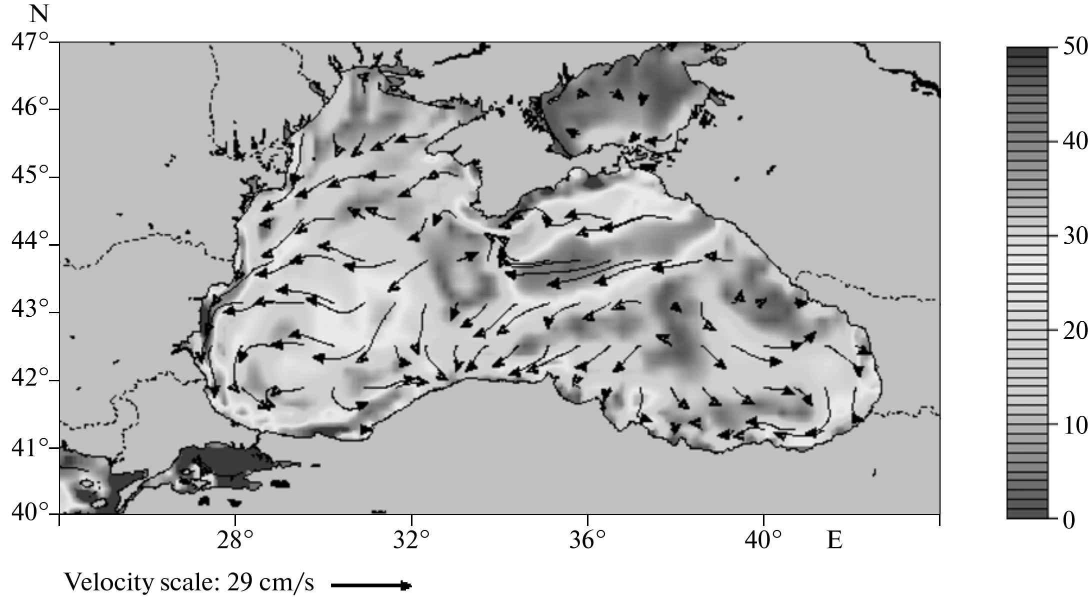

Fig. 11. Surface current field calculated from the NCOM model for 00:00 UTC on September 28, 2008. Note the tongue of high surface currents stretching from the east coast of the Black Sea (north of Tuapse) onto the sea and the weak cyclonic surface current pattern in the south-eastern section of the Black Sea.

surface currents, which stretches from the east coast of the Black Sea between Novorossiysk and Tuapse onto the sea. This high surface current area is obviously induced by the strong wind jets encountered between Novorossiysk and Tuapse as visible on the ASAR images depicted in Fig. 8*a* and 9*a*. The induced surface current on the order of 0.30 ms^{-1} is about 2% of the wind speed (~15 ms^{-1}), in agreement with typical measurements of Ekman wind driven current. In addition, also a weak cyclonic surface current pattern south of Tuapse is visible on this current map, which very likely is linked to the presence of the cyclonic atmospheric eddy in this area.

THE OCTOBER 25, 2008 EVENT

In Fig. 12*a* an Envisat ASAR WSM image (VV-polarization) is depicted which was acquired on October 25, 2008 at 19:12 UTC over the east coast of the Black Sea. In Fig. 12*b* the near-surface wind field retrieved from the ASAR image by using the wind direction from the NCEP model is shown. It shows several wind jets north of Tuapse with wind speeds between 10 and 13 ms^{-1}. Thus, due to the relatively low wind speed, this event cannot be associated with a bora event. Also visible on this image is a pronounced cyclonic atmospheric eddy south of Tuapse. Noteworthy is the dark area in the center of the eddy, which looks like the "eye of a hurricane" on the ASAR image. In this area the wind speed is very low.

A MODIS Terra thermal image of the east coast of the Black Sea and its surroundings acquired on October 25, 2008 at 19:35 UTC, i.e. only 23 min after the ASAR data acquisition (not reproduced here), shows that the area of the cyclonic atmospheric eddy was almost cloud-free. Such phenomenon was observed also in other MODIS images acquired over atmospheric cyclonic eddies (Ivanov et al., 2007; Alpers et al., 2007).

THE DECEMBER 28, 2008 EVENT

In Fig. 13*a* an Envisat ASAR image is depicted which was acquired in the Image Mode (IM) at VV-polarization on December 28, 2008 at 07:42 UTC over the east coast of the Black Sea. In Fig. 13*b* the near-surface wind field retrieved from the ASAR image by using the wind direction from the NCEP model is shown. In this case the wind speed was everywhere well below 15 ms^{-1} such that this event cannot be associated with a bora event. The ASAR image shows a cyclonic atmospheric eddy with a diameter of only 30 km. Note also here the dark patch in the center of the eddy indicates that here the wind speed is very low. The near-surface wind field retrieved from Quikscat data acquired on December 28, 2008 at 03:12 UTC (not reproduced here) shows also a small-scale cyclonic atmospheric eddy at the same location, but with much less detail than the SAR-derived wind field.

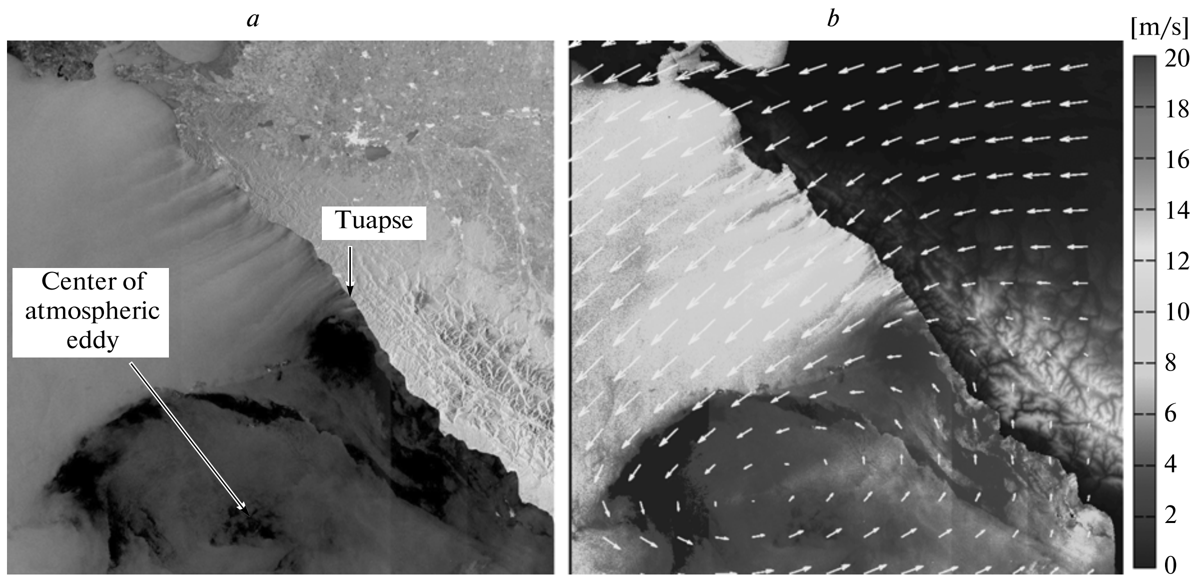

Fig. 12. *a* – Envisat ASAR WSM image (VV-polarization) acquired on October 25, 2008 at 19:12 UTC over the east coast of the Black Sea. The imaged area is 400 × 400 km. © ESA; *b* – near-surface wind field retrieved from the ASAR image by using the wind direction from the NCEP model.

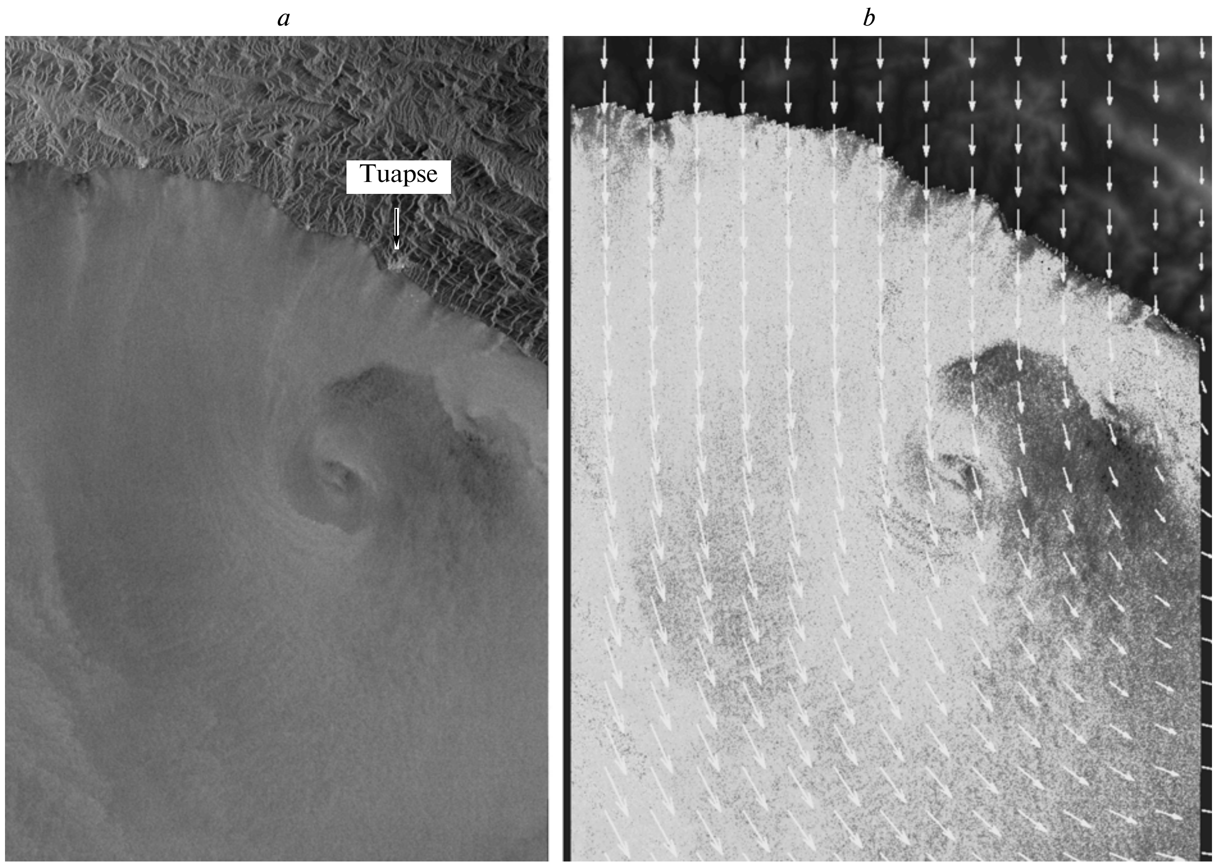

Fig. 13. *a* – Envisat ASAR IMM image (VV-polarization) acquired on December 28, 2008 at 07:42 UTC over the east coast of the Black Sea. The imaged area is 100 × 185 km. © ESA; *b* – near-surface wind field retrieved from the ASAR image by using the wind direction from the NCEP model.

RESULTS AND DISCUSSION

Findings of this study can be briefly summarized as follows:

1) At the northeast coast of the Black Sea strong northeasterly winds are frequently encountered in autumn, winter and spring. They are generated by boras and cyclones and often have speeds above 20 ms^{-1}. On the sea surface, these winds emanating from the coastal mountains give rise to banded patterns resulting from wind jets and wind-shadowed areas. Depending on the strength and duration of these wind events, the jets often remains distinct over more than 100 km. The detailed spatial structure of these surface wind fields cannot be captured by in situ (contact) measurements, but this is possible by using spaceborne SAR. The high resolution SAR images do not only yield detailed information on the structure of the wind fields, but also quantitative information about the near-surface wind fields with a resolution of typically 250–1000 m. This is a much finer resolution than can be achieved by other remote sensing instruments including spaceborne scatterometers, like Quikscat or ASCAT, which have resolution of about 25 km;

2) On SAR images not only wind jets, wakes, atmospheric eddies, and boundaries between local and ambient wind fields can be delineated, but also wind gusts, which are pulsations in the wind jets. If we assume that the pulsations are caused by atmospheric gravity waves propagating opposite to the mean wind direction and that they are stationary in an earth-fixed reference frame, then the period of the bora gusts can be estimated by measuring their wavelengths on the SAR image (typically several kilometers) and by assuming the wind speed is equal to the phase speed (Иванов, 2008; Signell et al., 2009). Typical periods derived from SAR images are 2–4 min (Petkovček, 1987), which agree quite well with periods measured by stationary anemometers;

3) Evidently SAR images can also be used to discriminate between the different wind field types (and even bora types) by investigating the spatial extent and the signatures of the wind jets. Contrary to the wind jets generated by orographic, frontal and monsoon type boras (Иванов, 2008; Alpers et al., 2009), which often extend up to 150 km from the coast, the ones generated by katabatic boras only extend to few tens km from the coast (Бурман, 1969; Alpers et al.,1998);

4) SAR-derived wind data can also be used as input for ocean models simulating wind induced oceanic circulation in coastal areas. As pointed out in (Комплексные исследования..., 2002), strong wind events, which occur most frequently in the period from September to May, strongly affect the stability, intensity and circulation pattern of the Main Black Sea Current;

5) The high resolution wind fields derived from spaceborne SAR images are more useful than any other in-situ or remotely sensed data for validating high resolution atmospheric models. Such comparison of model data with SAR data (in this case with data from Radarsat) have been carried out recently for Adriatic boras by Signell et al., 2009. In their paper they compared SAR-retrieved wind fields with model-derived wind fields from the COAMPS model (developed by the Naval Research Laboratory; 4 km resolution) and the LAMI model (Limited Area Model Italy; 7 km resolution). They showed that these numerical models are able to simulate the spatial structure of the wind fields visible on the SAR images, but they showed also that the models have deficiencies in their ability to represent the fine-scale structure within the wind jets and the transitions between wind jets and low wind speed bands;

6) Of particular interest are local (orographic) cyclones, which are often encountered in the NE section of the Black Sea and which leave fingerprints on the sea surface visible on SAR images. These cyclones are generated by the interaction of the northeasterly wind with the variable topography of the coastal mountains. The northeasterly wind blows through mountain gaps onto the sea, but is blocked at higher sections of the mountain range further south. This generates a cyclonic vorticity in the transition zone which leads to the formation of a cyclonic vortex in the atmosphere. Local cyclones over the NE Black Sea were studied already in the 1960–70s (see, e.g., Герман, 1985), but at that time very little data was available to study this phenomenon. Today, spaceborne SAR data can be used to study these local cyclones in much more detail.

CONCLUSION

Six SAR images acquired by the ASAR onboard the European Envisat satellite over the east coast of the Black Sea have been analyzed. All of them were acquired during high wind speed events between September and December 2008. At two events the wind speed was well above 15 ms^{-1} qualifying them as bora events (Novorossiyskaya boras). Visible are on all these SAR images pronounced sea surface signatures of wind jets and wind wakes generated by the interaction of the airflow from the northeast with the coastal mountains at the east coast of the Black Sea. On two of the SAR images also pronounced sea surface signatures of atmospheric gravity waves are visible. From these SAR images near-surface wind fields have been derived by using the CMOD4 wind scatterometer model for converting radar backscatter values into wind speeds and by taking the wind direction from the NCEP atmospheric model (in 5 cases) or by inferring the direction from linear features visible on the SAR image (in one case). The wind fields derived from SAR data have a resolution between 250 m and 1 km. Although the SAR onboard the Envisat satellite has a resolution of 25 m, spatial averaging is required for obtaining the near-surface wind field with a sufficient accuracy. Thus SAR provides much more detailed information on near-surface wind fields than scatterometers, which have resolutions of typically 25 km (This is the resolution of the Quikscat scatterometer). In particular, SAR can resolve fine-scale structures of coastal wind fields, like (1) the distribution of katabatic wind tongues along coastlines (Fig. 1 and 2), (2) waves generated by shear instabilities at the interface between a wind jet and a wind wake (Fig. 8), (3) small-scale eddies (Fig. 13), and (4) atmospheric gravity waves (Fig. 2 and 8). Five of the six SAR images presented in this paper (Fig. 1, 2, 9, 12, and 13) show blocking of airflow from the northeast by the high mountain range south of Tuapse leading to the generation of cyclonic atmospheric eddies in the south eastern section of the Black Sea. If the wind is strong enough and if it persists over a sufficiently long time, then it induces an oceanic response leading to a variation in the surface current field. Examples of such oceanic responses are shown in Fig. 6 and 11. We believe that with this paper we have demonstrated that spaceborne SAR imagery acquired over coastal areas is an excellent means to study coastal near-surface wind fields. Furthermore, we propose to use such SAR imagery to validate and improve meso-scale atmospheric models for describing Novorossiyskaya boras.

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Наблюдение поля ветра и циклонических вихрей в атмосфере в восточной части Черного моря с помощью радиолокатора с синтезированной апертурой ИСЗ Envisat

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Вариации скорости ветра в восточной части Черного моря могут достигать больших значений во времени и пространстве из-за влияния прибрежной топографии. В районе г. Новороссийск, например, северо-восточные ветры достигают ураганной силы (более 15 м/с), что в большинстве случаев связано с новороссийской борой. В настоящей статье проведен анализ ряда радиолокационных изображений (РЛИ), полученных в 2008 г. радиолокатором с синтезированной апертурой (РСА) на ИСЗ Envisat, на которых отобразились характерные поверхностные проявления. Помимо этого, для анализа привлекались данные скаттерометра Quikscat, а также данные метеостанции г. Новороссийск и радиозондирований в г. Туапсе. В результате обработки и анализа радиолокационных данных показано, что поверхностные проявления, наблюдаемые на РЛИ, связаны с зонами усиления ветра и дают уникальную информацию о пространственной неоднородности и тонкой структуре поля ветра над морем. Мониторинг подобных явлений, а также оперативный контроль возможен только с помощью космической радиолокации. В частности, РСА позволяет получить уникальную информацию: 1) о ветровых полосах, струях, атмосферных вихрях и подобных структурах, образованных в результате взаимодействия ветра с прибрежной топографией, 2) о границах между зонами с различной скоростью ветра, 3) о гравитационных волнах в атмосфере. Количественная информация о скорости и направлении ветра у поверхности моря может быть получена с помощью скаттерометрической модели CMOD4 путем преобразования величин интенсивности рассеяния в значения скорости ветра. Наконец, подобные радиолокационные данные и картины поля ветра высокого разрешения, полученные из РЛИ, могут быть использованы для валидации мезомасштабных моделей атмосферы.

Ключевые слова: поле ветра, Новороссийская бора, атмосферные циклонические вихри, атмосферные гравитационные волны, Envisat, радиолокационные изображения, Черное море