BORA IN THE ADRIATIC SEA AND BLACK SEA IMAGED BY THE ENVISAT 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 Synthetic Aperture Radar (ASAR) onboard the European Envisat satellite. These images show pronounced elongated patterns of increased sea surface roughness caused by bora winds. The comparison of the SAR images with wind fields derived from Quikscat data confirms that in all cases a strong northeasterly wind was blowing from the mountains onto the sea. It is shown that the SAR images reveal details of the spatial extent of the bora wind fields over the sea which cannot be obtained by other instruments. Furtheremore, also quantitative information on the wind field is extracted from the SAR images by using a wind scatterometer model.

KEY WORDS: bora, SAR, wind fields, Adriatic Sea, Black Sea

1. Introduction

Bora (Italian: bora, Greek: boreas – northward wind) is a strong cold wind blowing in coastal areas downhill onto the sea [Shelkovnikov, 1985]. Usually the cold air flows downhill over mountain ridges and is guided by the coastal topography. Boras are encountered in mountainous coastal regions where the mountains are not too high (typically below 1000 m) such that the adiabatic warming of the descending cold air is small. Well known coastal areas with boras are the Adriatic coast of Croatia, the east coast of the Black Sea near Novorossiisk, and the coasts of Lake Baikal, Novaya Zemlya, and Greenland.

Meteorological data associated with bora events are routinely collected at coastal stations, but the spatial extent of the bora wind field over the sea is largely unknown. In this paper we present two examples of bora events over the Adriatic Sea and two examples over the Black Sea which were imaged by the Advanced Synthetic Aperture Radar onboard the European Envisat satellite. On these synthetic aperture radar images sea surface roughness variations caused by bora events are visible. Thus information on the extent of the bora wind field can be obtained from them. But also quantitative information on wind speed and direction can be extracted from these images by using a wind scatterometer model (see, e. g., Horstmann et al., 2000, Ivanov et al., 2004) which originally was developed for retrieving wind speed and direction from C band scatterometer data (Stoffelen and Anderson, 1997).

2. Adriatic Sea Bora

The Adriatic bora or bura is a cold and dry north-easterly wind. It blows from the the eastern side of the Adriatic Sea towards the open sea and brings bright weather to the coast. It starts abruptly and blows in squalls toward the sea. It is funneled through corridors in the coastal mountain range. Fig.1 shows a map of the Adriatic region where the boras are encountered and Fig. 2 shows a sketch of the main corridors through which the bora winds blow onto the sea. The winds are strongest in the Velebit Channel and in the Gulf of Trieste. In summer, the bora blows as a local wind and lasts only a few days. In winter, it may blow for six to fourteen days and can be quite strong (with wind speeds up to 40 m/s).

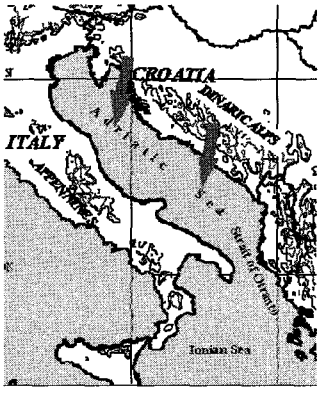

Fig.1. Map of the Adriatic Sea and its surroundings. The arrows denote the direction into which the bora winds are blowing.

In the following we present two Envisat ASAR images on which sea surface mainfestations of boras over the Adriatic Sea are visible and compare them with Quikscat data. Quikscat is a mirowave scatterometer which flies on an American satellite and which measures the wind field over the ocean with a resolution of 25 km (Liu et al., 1998).

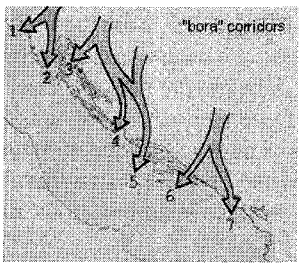

Fig.2. Bora corridors at the eastern Adriatic coast: (1) Golf of Trieste, (2) Kvarner, (3) Velebit Channel, (4) Sibenik, (5) Split - Makarska, (6) Peljesac and (7) Dubrovnik.

2.1 The 14 February 2005 bora event

Fig.3 shows an Envisat ASAR image which was acquired on 14 February 2005 at 16:21 UTC in the Gobal Mode (GM) over the Adriatic Sea during a winter bora event. The swath width of the ASAR in the Global Mode is 400 km which makes it possible to view the full spatial extent of the bora wind field over the Adriatic Sea. The wind pattern consits of several wind jets which reach to the Italian coast. These patterns correspond well with the corridors depicted in Fig.2. For comparison, the wind field derived from Quikscat data acquired 9 minutes earlier is depicted in Fig.4. The wind field map shows that at the coast of Croatia the bora winds were blowing from a northeasterly direction with speeds of around 15 m/s.

Fig.3. Envisat ASAR image acquired on 14 February 2005 at 16:21 UTC in the Gobal Mode (GM) over the Adriatic Sea during a winter bora event. Visible is on the right the Croatian Coast and on the left the Italian coast. Six pronounced wind patches (patches of increased image intensity) are visible. They correlate well with the corridors shown in Fig.2. © ESA

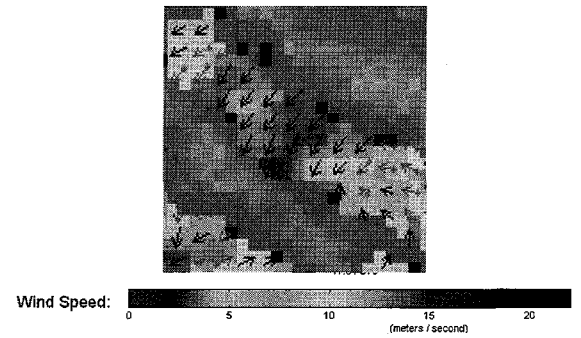

Fig.4. Ocean surface wind field map of the Adriatic Sea derived from Quikscat data acquired on 14 February 2005 at 16:12 UTC.

2.2 The 24 January 2006 bora event

Fig.5 shows an Envisat ASAR image which was acquired on 24 January 2006 at 09:20 UTC in the image mode (IM) over the northern section of the Adriatic Sea during a winter bora event. The swath width of the ASAR is in this mode only 100 km. Thus only a small section of the bora wind field is visible, in this case only the wind jets associated with the Velebit Channel and the Sibenik corridor. For comparison, the wind field derived from Quikscat data, which were acquired 3 hours and 56 minutes earlier, is depicted in Fig.6. The wind field map shows that in the area which was imaged by ASAR , a

Fig.5. Envisat ASAR image acquired on 24 January 2006 at 09:20 UTC in the image mode (IM) over the northern part of the Adriatic Sea during a winter bora event. Visible is on the right the Croatian Coast, on the upper left the Istra Peninsula, and on the lower left the Italian coast. © ESA

northeasterly wind of 25 m/s was blowing. The same area was also imaged in the visible band by the Medium Resolution Imaging Spectrometer (MERIS) (http://envisat.esa.int/instruments/meris) onboard the Envisat satellite at the same time the ASAR image was

acquired, see Fig. 7. It shows a cloud-free area in the northern section of the Adriatic Sea. This is agreement

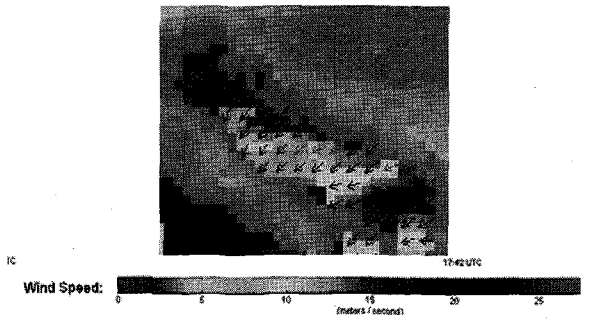

Fig.6. Ocean surface wind field map of the Adriatic Sea derived from Quikscat data acquired on 24 January 2006 at 05:24 UTC. Note the strong winds of 25 m/s south of the Istria Peninsula which are funneled though the Velebit Channel. Here the Adriatic bora winds are usually strongest.

Fig.7. MERIS image of the Adriatic Sea and its surroundings acquired at the same time (24 January 2006 at 09:20 UTC). at which the ASAR image was acquired, Note that the bora has cleared the skies from clouds in the northerrn section of the Adriatic Sea.

with visible observations that boras bring clear weather to the coast.

3. Black Sea bora

Bora winds are often encountered at the east coast of the Black Sea around Novorossiisk, between Anapa and Gelenjik. In the literature these boras are sometimes called Novorossiisk boras. They occur in in 74% of all cases in the cold season (from September to March) and in 26% of all cases in the warm season (April to August). Bora events are defined as events during which the wind speed exceeds 15 m/s. In 78% of all cases their duration is 1–3 days, seldom 4 to 9 days, and quite seldom up to 10 days and more (1%). Their average duration is 2.4 days (Guseva, 1959, Shlygin, 1987).

In winter, they are generated when a high pressure area is present over the North Caucasus and a low pressure area over the eastern Black Sea. The resulting strong northeasterly wind pushes cold air from the North Caucasus against the Varada Ridge (600 m) and forces it through the Markhotskii Pass (435 m) from where it flows down the mountain slopes towards the sea. In summer, the boras are generated when a cold front passses the coast from northwest which also forces cold air to flow down the mountain slopes.

At Novorossiisk, the wind speed during bora events often reaches values of up to 30-40 m/s. The highest value measured at the Markhotskii Pass was 50 m/s. On the average, bora winds are encountered on 30 to 40 days per year, but most often they are encountered in November and December. Sometimes bora events in the Novorossisk area are catastrophic events causing sinking of ships and damage on houses. The last strong bora occurred in December 2001, when the area around Novorossisk was declared a zone of natural disaster.

In the following we present two Envisat ASAR images on which sea surface mainfestations of boras over the Black Sea are visible.

3.1 The 21 August 2005 bora event

Fig.6 shows an Envisat ASAR image which was acquired on 21 August 2005 at 7:43 UTC in the Wide Swath Mode (WS) during a summer bora event. It shows pronounced streaks in the NE-SW direction, which are sea surface imprints of inhomogeneties in the wind field. They are caused by the interaction of the wind with the

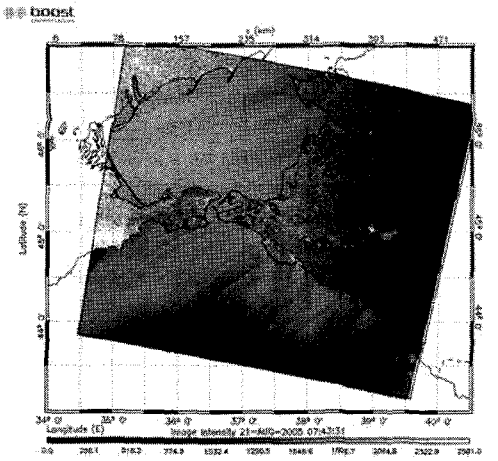

Fig.6. Envisat ASAR image acquired on 21 August 2005 at 7:43 UTC in the Wide Swath Mode (WS) during a summer bora event. Visible is in the upper part the Sea of Asov and in the lower part the northern section of the Black Sea. Note the streaks in the wind field which result from the interaction of the northeasterly wind with coastal topography. © ESA

coastal topography and are aligned in wind direction. With this information on wind direction provided by the SAR image, it is possible to retrieve the wind field from the SAR image intensity distribution. To achieve this, one has first to convert the SAR image intensity field into a Normalized Radar Cross Section (NRCS) field and then apply a wind scatterometer model, e. g. , the CMOD 4 model (Stoffelen and Andersen, 1997) to invert NRCS values into wind speeds. Fig.7 shows the result of such an inversion, which was carried out using the software

package SARTool developed by Boost Technologies. The wind speed in the high wind speed areas at the coast is between 10 and 13 m/s, which is agreement with the wind speed obtained from Quikscat data '(Fig.8),

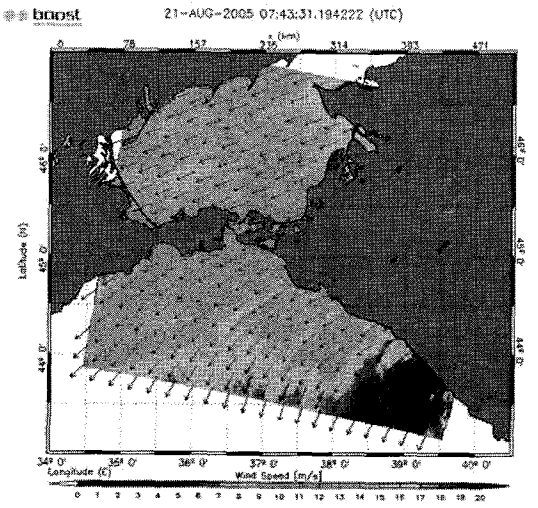

Fig.7. Ocean surface wind field derived from the Envisat ASAR image of 21 August 2005 (Fig.6) by using the CMOD 4 wind scatterometer model (Courtesy Vincent Kerbaol, Boost Technologies).

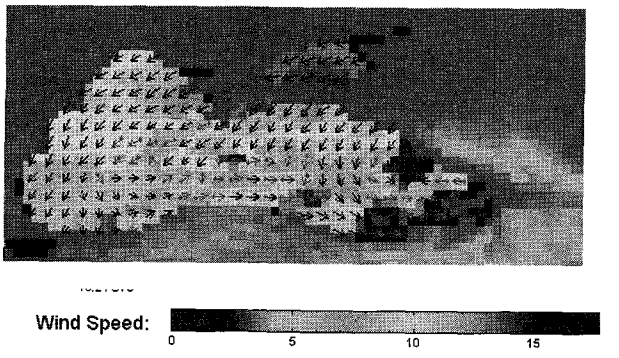

Fig.8 Ocean surface wind field map of the Black Sea and the Sea of Asov derived from Quikscat data acquired on 21 August 2005 at 02:48 UTC.

3.2 The 2 May 2006 bora event

Fig. 9 shows an Envisat ASAR image which was acquired on 2 May 2006 at 19:19 UTC in the Alternating Polarisation Mode (APP) during a summer bora event at the east coast of the Black Sea between Novorossiisk and Tuapse. It shows again pronounced streaks in the NE-SW direction, which are sea surface imprints of inhomogeneties in the wind field. Note the wave-like features in the upper section of the image (2) which are sea surface manifestations of atmospheric gravity waves or lee waves generated by the interaction of the wind with the coastal mountains. The wind field map derived from Quikscat data depicted in Fig.10 shows in the northern section of the east coast of the Black Sea only wind speeds around 10 m/s, which would not qualify this event to be a bora event. However, the *in-situ measurements carried out at the meteorological station in* Novorossiisk (Fig. 10, upper panel) show on 2 May wind speeds of up to 20 m/s. The meteorological records show further that from 30 April at 00 UTC to 3 May at 03 UTC the wind speed was always above 15 m/s. Note that at Tuapse (Fig. 10, lower panel) the wind speed was on this day always below 7 m/s. This shows that the bora was confined to the region north of Tuapse.

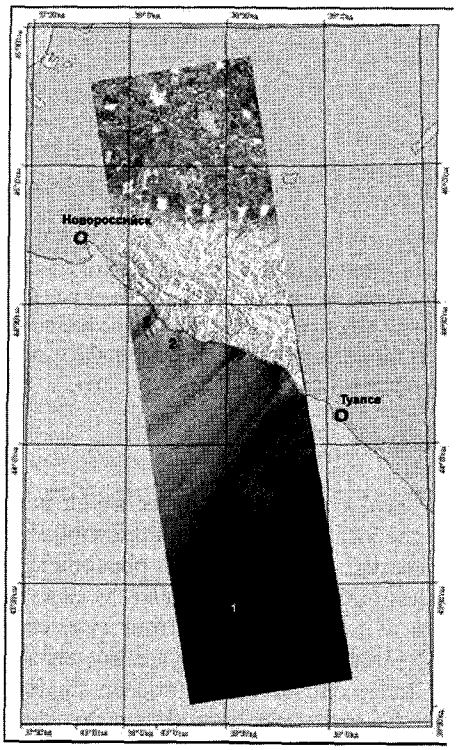

Fig.9. ASAR image acquired on 2 May 2006 at 19:19 UTC in the Alternating Polarisation Mode (APP) during a summer bora event at the east coast of the Black Sea between Novorossiisk and Tuapse at the east coast of the Black. Note the streaks in the wind field which result from the interaction of the northeasterly wind with coastal topography. The black patch in the upper section of the image (1) results very likely from an oil spill. In the northern section sea surface manifestations of atmospheric gravity waves or lee waves (2) are visible. © ESA

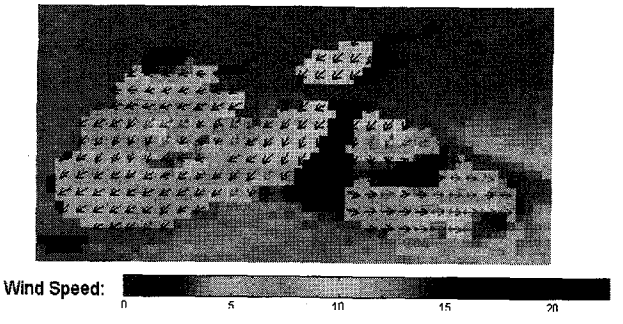

Fig.10. Ocean surface wind field map of the Black Sea and the Sea of Asov derived from Quikscat data acquired on 5 May 2006 at 17.00 UTC.

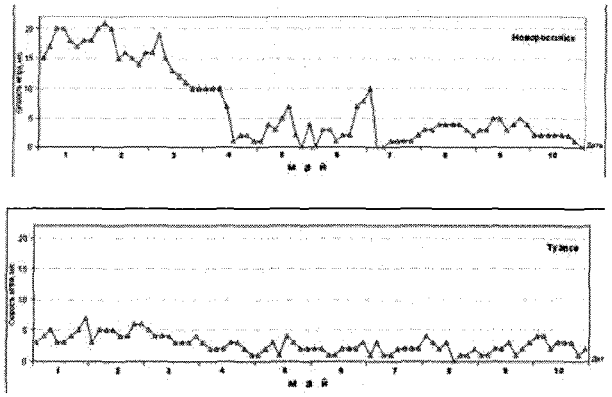

Fig.11 Wind speed measured at the meteorological stations at Novorossiisk (upper panel) and Tuapse (lower panel). Plotted is the wind speed as a function of time. On the horizontal axis the time range is from 1 to 10 May 2006 and on the vertical axis the wind speed range is from 0 to 20 m/s.

4. Conclusions

Boras are local coastal phenomena which have a great impact on the local weather and on the wind fields at sea. The best known areas where such phenomena occur are the east coast of the Adriatic Sea and the east coast of the Black Sea. We have presented four synthetic aperture radar (SAR) images acquired by the Advanced Synthetic Aperture Radar onboard the European Envisat satellite over these sea areas and have shown that these images reveal details of the wind field over the sea that cannot be obtained by other means. We therefore recommend to take advantage of the information contained in spaceborne SAR images when carrying out studies on bora events. E.g., such images are well suited for validating numerical models on such events.

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5. Acknowledgements

We thank ESA for supporting this research .