PICTURE OF THE MONTH

Encounter of Foehn Wind with an Atmospheric Eddy over the Black Sea as Observed by the Synthetic Aperture Radar Onboard *Envisat*

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ABSTRACT

Foehn wind blowing through the Kolkhida (Kolkheti) Lowland in the southwestern Caucasus (western Georgia) was observed on an *Envisat* synthetic aperture radar (SAR) image as it encountered an atmospheric cyclonic eddy over the Black Sea on 13 September 2010. This SAR image reveals unprecedented finescale features of the near-surface wind fields that cannot be resolved by other sensors. It shows, among others, the deflection of the foehn wind by the atmospheric eddy. Quantitative information on the near-surface wind field over the sea is extracted from the SAR image.

1. Introduction

At least since 1978, when the first spaceborne synthetic aperture radar (SAR) images became available from the American *Seasat* satellite, it has been known that SAR can sense finescale features of the near-surface wind field. But only in the last few years have robust algorithms been developed, which can be used operationally to retrieve near-surface wind fields from SAR images acquired of the ocean. The aim of this paper is to draw the attention of modelers to spaceborne SAR images, which are a useful resource for validating high-resolution mesoscale atmospheric models over the ocean. The SAR image presented in this paper shows the encounter of two local wind fields: a mesoscale atmospheric eddy and a foehn wind over the Black Sea. Furthermore, it shows the deflection of the foehn wind by the eddy.

The paper is organized as follows: In section 2 we present the SAR image and the SAR-derived wind field and in section 3 we present a quasi-simultaneously acquired cloud image, which also shows an eddy structure over the same area as the SAR image. Furthermore, in this section we discuss what might have caused the generation of the eddy. In section 4 we first present two more SAR images showing sea surface signatures of the foehn wind blowing over the Black Sea, which are unimpeded by ambient winds, and then we relate the SAR image to in situ measurements. Finally, in section 5 we focus on additional coastal wind fields visible on this SAR image, and in section 6 we present our conclusions.

2. The SAR image and the near-surface wind field

Figure 1 shows a SAR image that was acquired by the Advanced Synthetic Aperture Radar (ASAR) onboard the European *Envisat* satellite over the Black Sea and that captured sea surface signatures of an atmospheric cyclonic eddy with a foehn wind blowing from the east onto the sea. The image was acquired in the morning at...
0732 UTC (0932 local standard time) 13 September 2010 in the wide swath mode (WSM) at VV polarization (vertical polarization for transmission and vertical polarization for reception) and with a resolution of 150 m. The near-surface wind field retrieved from this SAR image is shown in Fig. 2. The pixels are here averaged over 500 m for more accurate estimates of the wind speed. The near-surface wind field (or more precisely, the wind stress) is indirectly measured by SAR via the sea surface roughness. The backscattered radar power (or normalized radar cross section) depends on the incidence angle, the near-surface wind speed, and the relative angle between the look direction of the SAR antenna and the wind direction (see, e.g., Valenzuela 1978). The wind field retrieved from SAR is referenced to a height of 10 m for a neutrally stable atmosphere. For inverting the SAR image intensity or backscattered radar power into wind speed, we have used the C-band Wind Scatterometer Model Function version 4 (CMOD4; Stoffelen and Anderson 1997), which was originally developed to retrieve near-surface wind fields from data of the wind scatterometer onboard the European Remote Sensing Satellites ERS-1 and ERS-2.

However, retrieving wind fields from SAR images is not as straightforward as from scatterometer data. While scatterometers measure the backscattered radar power from a resolution cell on the sea surface from (at least) three different azimuth directions, SARs only measure it from one azimuth direction, perpendicular to the satellite flight direction. Thus, in order to retrieve (two-dimensional) wind fields from SAR images, one has to get the wind direction from other sources than from backscattered radar power values (Monaldo et al. 2001, 2003; Horstmann and Koch 2005; Sikora et al. 2006; Alpers et al. 2009, 2010). This directional information can be obtained from 1) atmospheric models; 2) linear features visible on the SAR images, which are assumed to be aligned in wind direction; and 3) Doppler shifts induced by motions of the sea surface. Doppler shift information inherent in the SAR data has been tapped only recently for obtaining information on wind direction, and requires a special analysis of the complex SAR data. For details, the reader is referred to the papers by Chapron et al. (2005), Hansen et al. (2011), and Mouche et al. (2011). The Collecte Localisation Satellites (CLS) in France has recently implemented a wind retrieval algorithm that uses all three sources of information on wind direction. The wind field depicted in Fig. 2 was retrieved from the SAR image (Fig. 1) using this algorithm.

We show for comparison in Fig. 3 the surface wind field from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) model valid for 0900 UTC 13 September 2010. The GFS model developed by NCEP provides global wind fields every 3 h at a grid spacing of 0.5° in latitude and longitude. Figure 3 clearly shows a cyclonic wind pattern over the eastern section of the Black Sea, which is typical for a low pressure system. Comparing the wind fields depicted in Figs. 2 and 3, we see that the center of the cyclonic wind pattern visible in Fig. 3 is located slightly farther north than the position of the center of the cyclonic eddy visible in Fig. 2, which is probably due to the time difference of 1 h and 28 min between these two wind fields.

Apart from the fact that the NCEP model has a much coarser resolution than the SAR-derived wind field (order of 50 vs 1 km), there are significant differences between the two wind fields. The NCEP wind field does not show 1) the closed eddy structure in the wind field over the central eastern section of the Black Sea (the center marked “E” in Fig. 1), 2) the broad wind band adjacent to the southeast coast (marked “F” in Fig. 1) resulting from the foehn wind blowing from land onto the sea, and 3) the wind jet (marked “1” in Fig. 1) emanating from the central east coast and blowing toward the center of the eddy.
Other features that are not resolved by the SAR-derived wind field (Fig. 2), but are visible on the SAR image (Fig. 1) and marked by the numbers “2” to “5,” will be discussed in section 5.

3. The cyclonic eddy

The presence of an atmospheric cyclonic eddy over the eastern section of the Black Sea can also be inferred from a cloud image acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra satellite at 0830 UTC 13 September 2010 (see Fig. 4). The surface map of the Met Office valid at 0600 UTC 13 September 2010 depicted in Fig. 5 shows a small low pressure system over the eastern section of the Black Sea. The 1004-hPa isobar forms a semicircle with its center located over the eastern section of the Black Sea. This position closely corresponds to the center of the eddy visible on the SAR image (Fig. 1). The convergence lines in this chart (thick black lines crossing the isobars) indicate convergence of airflows at the ground. The 300-hPa pressure map valid at 0600 UTC 13 September 2010 (not reproduced here) shows positive vorticity advection over the eastern section of the Black Sea, which causes a lifting of air and thus a decrease in air pressure at the sea surface. Thus, warm air at low levels is spiraling into the low pressure center and is forced to rise. As it rises, it cools and forms clouds, which is confirmed by the MODIS image (Fig. 4). The advection of air into this low pressure region is very likely also the main reason for the generation of the high wind jet directed from the central east coast toward the center of the cyclonic eddy (marked 1 in Fig. 1). As noted before, this high wind speed jet is not predicted by the NCEP model. Furthermore, the broad band of high wind speed (marked 2 in Fig. 1) perpendicular to the foehn wind (see next section), is very likely also affected by this advection of air into the center of the eddy.
Given the fact that around the time of the SAR data acquisition no in situ meteorological data were available from ships or platforms or from coastal meteorological stations (even data from the radio sounding station at Tuapse, Krasnodar Krai, Russia, were not available for this period), we had to resort to meteorological maps to find explanations for the formation of the eddy.

For this purpose in Figs. 6 and 7 we show the ground weather maps of the Met Office valid at 0600 and 1800 UTC 12 September 2010, respectively, 25.5 and 13.5 h prior to the SAR data acquisition. They show a synoptic-scale low moving northward toward the Black Sea. It is very likely that the mesoscale eddy was formed by a boundary trough of the synoptic-scale low. When it moved over the Black Sea it encountered a high sea surface temperature (26°–27°C), which probably contributed to the formation of the eddy.

4. The foehn wind

Foehn winds are warm winds encountered on the lee side of mountain ridges due to the downward movement of airflow. They are associated with an increase in air temperature, reduction of relative humidity, and dispersal of lower layer clouds on the leeward side of the mountain range. Foehn is a common wind event on the northern side of the Alps from where the German word “foehn” originates. But foehn winds are encountered also in many other regions of the world. One of such regions is the Kolkhida or Kolkheti Lowland (also called Rioni River Valley) in the southwestern Caucasus (western Georgia; Gvozdetskiy 1958; Chogovadze 1982; Guniya et al. 2010). Here the foehn winds are often very strong, sometimes reaching speeds of 20–30 m s⁻¹. These high winds are a consequence of the specific orography of
this region (Burman 1969; Guniya et al. 2010). The Kolkhida Lowland is bordered to the north by the Greater Caucasus (3000–4000 m) and to the south by the Lesser Caucasus (2000 m). It has the form of a funnel having its narrowest cross section at the Likhi (Surami) Ridge (900–2500 m) and opening to the Black Sea on the west with a wide angle.

When the ambient wind over the Black Sea is low, the foehn emanating from the Kolkhida (Kolkheti) Lowland can blow in the direction of the axis of the valley onto the Black Sea and is not (or only very little) deflected by to the ambient wind. Two examples of Envisat ASAR images showing sea surface signatures of foehn winds blowing over the Black Sea unimpeded by ambient winds are depicted in Fig. 8. In the 9 September 2009 event (Fig. 8, left image) the wind over the Black Sea varied between 8 and 12 m s\(^{-1}\), while in the 12 September 2009 event (Fig. 8, right image) it varied between 7 and 9 m s\(^{-1}\) (not shown here).

During the times of the SAR data acquisitions on 9 and 12 September 2009 (Fig. 8), and on 13 September 2010 (Fig. 1) strong foehn winds were blowing through the Kolkhida Lowland as evidenced by meteorological
measurements carried out at the weather station in Kutaisi (42°16′N, 42°38′E; elevation of 116 m), Georgia, whose position is marked on the MODIS image depicted in Fig. 9. For the 13 September 2010 event (Fig. 1), the wind speed (top panel) and relative humidity (bottom panel) measured at Kutaisi between 0000 UTC 11 September and 2100 UTC 15 September 2010 are plotted in Fig. 10. These plots show two characteristics of foehn events: 1) an increase in wind speed and 2) a decrease in relative humidity after the onset of the foehn. A further feature of foehn events is that it is accompanied by an increase in air temperature and a decrease in pressure. This is also evidenced by the data of the Kutaisi weather station: before the onset of the foehn, at 0000 UTC 11 September, the air temperature was 20.0°C and at the peak of the foehn event, at 0000 UTC 13 September, it was 22.4°C. During the same time period, the pressure (at sea level) also decreased from 999.9 to 995.9 hPa. The wind speed and relative humidity plots (Fig. 10) show that the foehn started between 0900 and 1200 UTC 11 September and ended around 1200 UTC 13 September. Approximately 5 h before the SAR data acquisition, the wind reached its maximum speed of 27 m s⁻¹, with gusts up to 32 m s⁻¹.

Typically, foehn events are accompanied by the accumulation of the low-level clouds on the upwind side of a mountain ridge and by the absence of clouds on the downwind side. The MODIS image depicted in Fig. 9, which was acquired by the Terra satellite at 0745 UTC 12 September 2010 (i.e., approximately 24 h before the SAR data acquisition), shows these phenomena very clearly.

The times of the onset and decline of the foehn winds as measured by the meteorological station at Kutaisi are supported also by meteorological maps. The ground weather map depicted in Fig. 11, valid for 1200 UTC 11 September 2010, shows strong easterly winds in the region of the Likhi Ridge, thus fulfilling the condition for foehn formation. A further inspection of weather maps shows that strong winds started blowing around 0600 UTC 11 September 2010 and ended around 1200 UTC 13 September 2010, which is in agreement with the meteorological data collected at Kutaisi.
As pointed out by Chogovadze (1982), during strong foehn events, air is removed from the lower atmosphere toward the Black Sea and replaced by descending air from higher levels. Descending warm air from the Likhi Ridge flows through the Kolkhida Lowland to the Black Sea. As reported by Guniya et al. (2010), on its way westward, the airflow is strongly attenuated as a result of the interaction with the rough land surface and the widening of the cross section of the valley. The SAR-derived wind field depicted in Fig. 2 shows that at 0732 UTC the wind speed was around 12 m s\(^{-1}\) over the Black Sea. Assuming that the average speed of the air traveling from Kutaisi to the front of the wind band visible on the SAR image was 17 m s\(^{-1}\), then this air mass must have departed from Kutaisi 4 h before the time of the SAR data acquisition. At this time the wind speed at Kutaisi was close to its peak value of 23 m s\(^{-1}\) (Fig. 10). When the airflow associated with the foehn entered over the Black Sea, it interacted with the cyclonic eddy causing a deflecting of the foehn jet to the east against the eastern shore.

5. Other coastal wind fields visible on the SAR image

As pointed out in the introduction, the wind field derived from the SAR image (Fig. 2) reveals a wind jet (marked by 1 in Fig. 1) emanating from a valley on the central east coast of the Black Sea and blowing toward the center of the eddy, which is not predicted by the NCEP model. We conjecture that the existence of this jet is caused by the eddy, which draws air from land through the coastal valley onto the sea. A close inspection of the SAR image shows that also at other locations (marked 2, 3, 4, and 5 in Fig. 1), winds are blowing seaward from the coastal mountains. Such locations are found 1) at the east coast where a narrow wind jet directed perpendicular (seaward) to the front of the foehn wind band is
visible, and 2) at the south (Turkish) coast where one strong (eastward) and several weak westward wind jets are visible. It is very likely that these small seaward-directed wind jets are also generated by the eddy, which draws air from land through coastal valleys onto the sea. Note, however, that these wind fields are not resolved by the wind field map at 1-km resolution depicted in Fig. 2.

While we have inferred the wind direction of the small-scale wind jets marked 1, 2, 4, and 5 in Fig. 1 from the shape of the features (line structures) visible on the SAR image, we have been able to infer the directions of the winds in the region marked 3 from the Doppler shift map (not shown) of the same SAR scene. In this region a westerly wind blows head-on on an easterly wind from the mountains. Both winds are directed almost parallel and antiparallel to the look direction of the SAR antenna, which is the reason why their directions can easily be inferred from the Doppler shift map. The convergence line, where both wind systems meet (i.e., the wind front) is clearly visible as bright line in Fig. 12. Also visible are in this image are sea surface signatures of surface films, probably caused by mineral oil spilled from ships, which show up as black patches on SAR images. These surface films accumulate in regions of convergent surface current flow, induced by the wind, and damp the sea surface roughness.

6. Conclusions

In this paper we have presented a SAR image (Fig. 1) acquired over the eastern section of the Black Sea by Envisat ASAR in the WSM at a resolution of 150 m, and from which we have derived the near-surface wind field with a resolution of 1 km (pixel spacing: 500 m). Because of the long repeat cycles of polar orbiting satellites carrying SARs, and because of restrictions on electric power availability, spaceborne SAR images over a given sea area are available only at time intervals between typically 1 day in polar regions and several days at mid- and lower latitudes. Thus, if modelers want to use spaceborne SAR data acquired over the ocean to validate their mesoscale atmospheric model, they should first browse through the SAR archives of the space agencies for availability. If they find sea surface imprints of the desired atmospheric phenomenon on SAR images over the region of interest, they can order the precision-processed SAR images from the space agencies and derive high-resolution near-surface wind fields from them as shown in this paper.

Because of the large time separation between SAR data acquisitions, in general it is not possible to study the time evolution of a mesoscale atmospheric phenomenon over the ocean using spaceborne SAR images. Thus, in order to study time evolutions of mesoscale atmospheric phenomena, one has to combine spaceborne SAR images with other satellite data (e.g., cloud images) and/or in situ data (e.g., from meteorological stations).

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FIG. 12. Zoom of the SAR image depicted in Fig. 1 on the most eastern section of the SAR scene depicting showing sea surface signatures of the wind fronts and of surface films in more detail.


