High-resolution wind fields from ERS SAR

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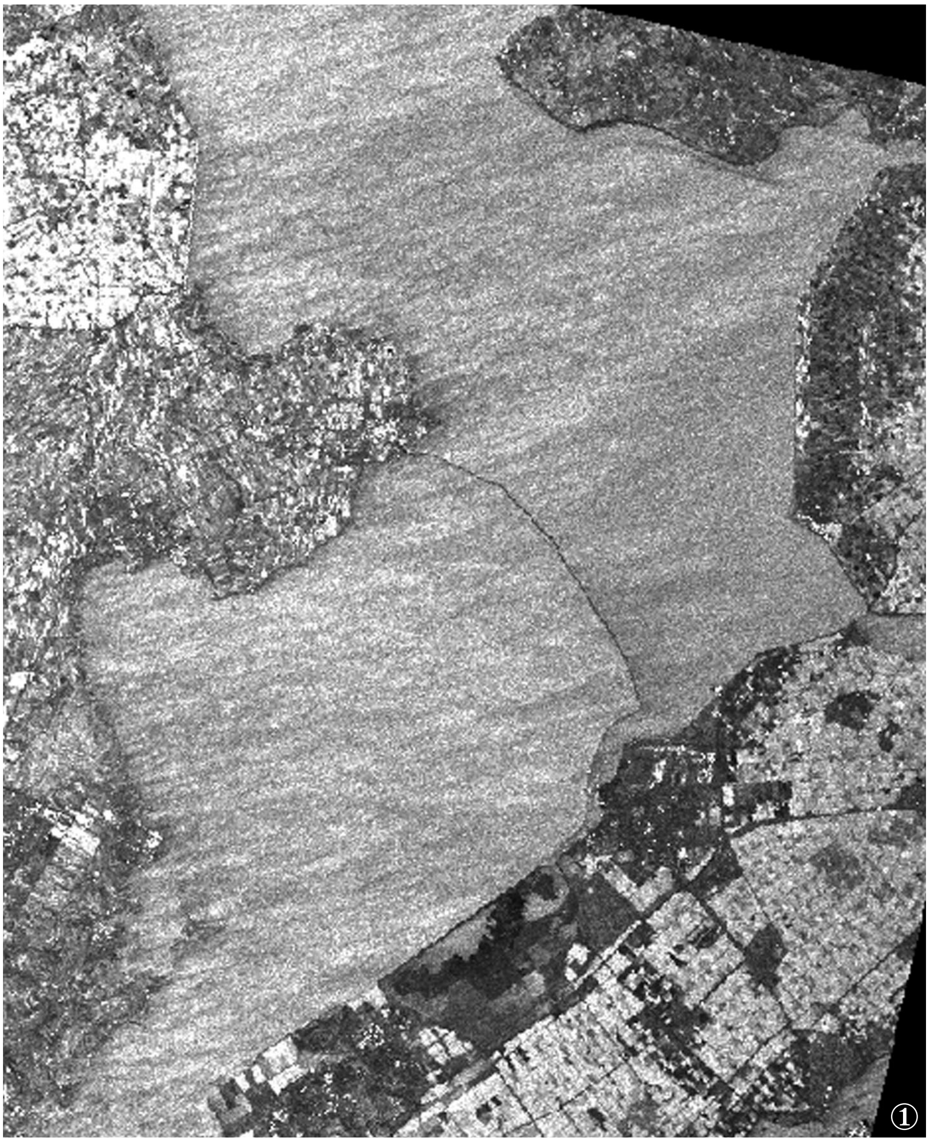
Studies of wind and wave climate in estuaries and lakes suffer from a lack of in-situ measurements. Using the high-resolution images acquired by spaceborne SARs, this gap may be filled. Examples of wind fields retrieved from ERS SAR images of the Dutch IJsselmeer and coastal waters show the potential of this technique.

Introduction
It is well known that the radar cross-section measured over the oceans with radars in the centimetre range can be related to wind speed. For moderate incidence angles, the electromagnetic radar waves reflect off wind ripples on the ocean surface via the Bragg mechanism. This mechanism becomes more effective when increased short waves are present, hence the dependence on wind speed. As these short wind waves are, to a certain extent, aligned with wind direction, the backscatter also depends on the angle between wind direction and the viewing direction of the radar.



Using ERS-1/2 scatterometer measurements, an empirical relationship has been derived between the wind over the ocean and the resulting radar backscatter [*Stoffelen & Anderson* 1993]. This relationship, known as CMOD4, is subsequently used to derive wind vectors from radar cross-section measurements made by the scatterometer. By combining observations made under three separate angles, both the wind speed and direction can be obtained from the scatterometer measurements.

The SARs carried by the ERS-1/2 satellites use the same radar frequency (C-band) and polarisation (VV) as do the scatterometers on these same satellites. Hence, it might be expected that the CMOD4 relationship between wind and radar backscatter also holds true for the SAR. Given the fine spatial resolution of the SAR instruments, this opens the way for the retrieval of very high-resolution wind fields.

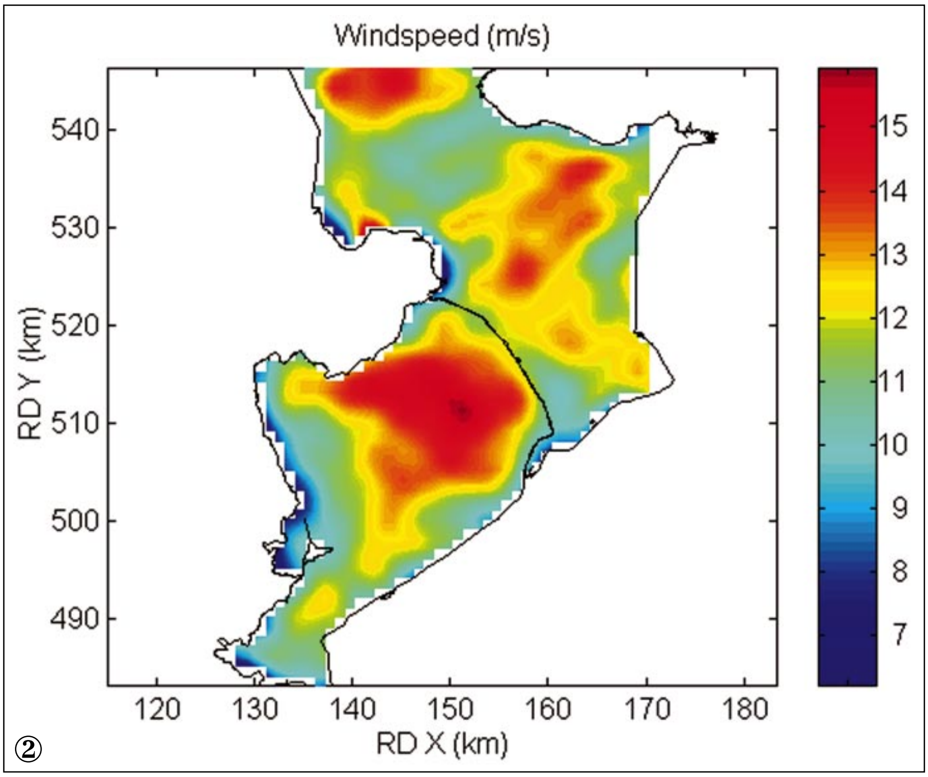
ERS-1 SAR PRI image of the IJsselmeer, The Netherlands, recorded on 16 February 1995.

The retrieval of wind fields from SAR is particularly relevant for the Envisat mission, which lacks a scatterometer to measure wind. In the present study we focus on a different application: the effects of a land-sea transition on the atmospheric boundary layer. Several images acquired from the Dutch coastal waters were analysed, and used to drive a numerical wave model.

The method
The retrieval of the wind field from a SAR image is split into two parts. First, the wind direction is determined from wind-rows, which are often visible on the SAR image. Following *Faller* [1964] we assume that these wind streaks are aligned at an angle of 15° (rotated clockwise on the Northern Hemisphere) to the wind. In cases where no wind streaks were visible, the wind direction was taken from *in-situ* measurements.

In the second stage, the radar backscatter measured by the SAR is related to the wind speed, given the wind direction from the wind streaks or *in-situ* measurements. As discussed elsewhere in this issue, the SAR measurements of the ERS satellites suffer from a saturation in the AD-converter. This can result in an underestimation of the radar backscatter by as much as 6 dB for ERS-1. Hence, before they were processed, the SAR images were corrected for this power loss using the procedure proposed by Laur et al. [1996]. Subsequently, the radar backscatter was spatially averaged to a grid of 1 x 1 km, after masking out the radar return from pixels over land.

Given the incidence angle and the wind direction, the wind speed can now be determined from the radar backscatter. This could be done by constructing a table of the radar backscatter as a function of wind speed, and to use this table to find the wind speed that corresponds to a particular backscatter. However, since the radar backscatter also depends on the wind direction and the incidence angle, a large set of look-up tables would be required: one for each different combination of wind direction and incidence angle that is encountered in the image. As this would be very inefficient, a different approach is followed.

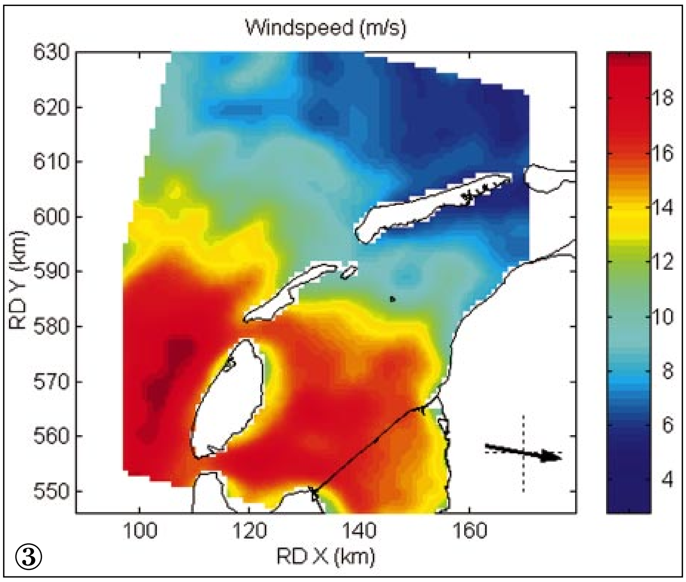


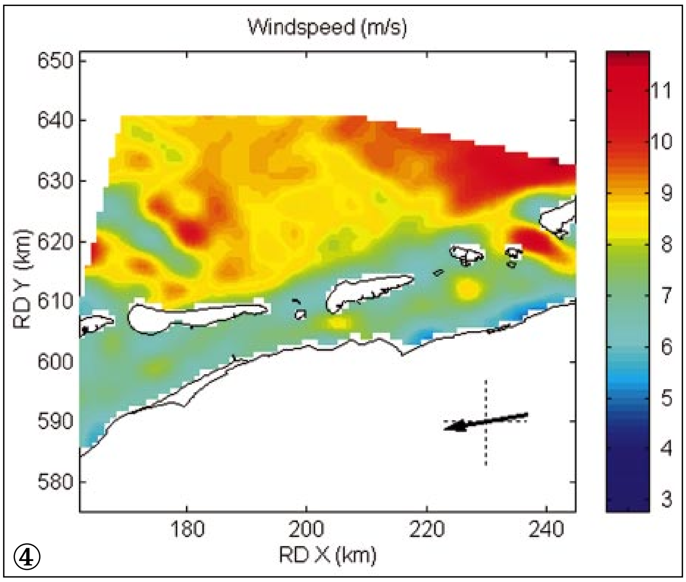
Wind speed distribution over the IJsselmeer derived from the SAR image shown in the previous figure. The wind speed in indicated in m/s.

In this approach the wind speed is represented as a two-dimensional Fourier series in space. The Fourier coefficients are found by minimising a cost function that expresses the difference between the observed and the calculated radar backscatter. This can be done very efficiently since the gradient of this cost function also takes the shape of Fourier transform. A more detailed account of the procedure followed here can be found in *Mastenbroek et al.* [1997].

Wind over Lake IJssel, the Waddensea and the North Sea
Figure 1 shows the (calibrated) SAR image recorded by ERS-1 on 16 February 1995 at 10:35 GMT. The image shows a large part of Lake IJssel in The Netherlands. The wind streaks in the image are all aligned within a few degrees, their main direction being 255°. The wind direction measured at 5 different locations along shore of the lake varied between 243 and 246°. This difference of about 10° is in reasonable agreement with the value of 15° found by *Faller* [1964].

To calculate the wind field, it was represented by 10 spectral components in each direction, which correspond to a spatial resolution of 6 km. The wind field obtained from the SAR image (Fig. 2) shows that the wind speed on the upwind side of the lake is about 8 m/s, increasing to about 14 m/s in the middle. Wind measurements on land indicate a wind speed of 8 to 10 m/s on the upwind side of the lake, and 14 m/s on the downwind side. This example shows that the wind over the lake is affected by the presence of land for a distance of about 20 km. To assess the importance of this phenomenon for wave climate studies, the wind field was fed into a numerical wave model. Compared to conventional calculations, when a spatially homogeneous wind field is used, the wave height and period changed up to 20% [*Vogelzang et al.* 1997], which was considered to be significant.





Wind speed distribution derived from an ERS-1 SAR image acquired on 12 August 1994. The image covers the Western part of the Dutch Waddensea.

Distribution of the wind speed in the eastern part of the Waddensea on 13 May 1994.

Two further examples are shown in Figures 3 and 4. The first shows the wind field on 12 August 1994 for an area to the northeast of The Netherlands. The wind streaks in the image indicate a wind direction of 280°. The image shows a quite non-homogeneous distribution of the wind speed: almost no wind in the north, and a 16 to 18 m/s wind in the south (of the image). This spatial variability is consistent with *in-situ* wind speed records. At the time that the SAR image was recorded, the wind speed measured on Terschelling (second island from the south) was 8 to 10 m/s, which increased to 16 m/s a few hours later.

The backscatter from the sea surface is not only governed by the local wind speed. Several other phenomena, such as the presence of slicks, breaking waves, and current gradients also affect the radar cross-section. Obviously this limits the possibilities to interpret the measured radar cross-section solely in terms of wind. This is illustrated in Figure 4, which shows wind distribution in a part of the Waddensea to the north of The Netherlands on 13 May 1994. The interaction between waves and a strong tidal current caused a large radar backscatter in the area between the two eastern-most islands. However, in the straightforward scheme applied here, this backscatter maximum is interpreted as a local maximum in wind speed. More comprehensive schemes will have to account for ancillary effects like this in order to benefit from the potential of the SAR to produce high-resolution wind fields.

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