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RADARSAT-1 SAR for Hurricane Watch

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Abstract

RADARSAT-1's ScanSAR wide (SCW) modes, with swath widths of 450 or 500 km and a spatial resolution of 100 m, can provide both near-synoptic scale and small-scale views of the imprint of mesoscale meteorological processes and features on the ocean surface's roughness. In the case of hurricanes, the images show wind speed and direction effects around the relatively calm eye, as well as regions of intense convection, rainfall, organized boundary layer phenomena such as boundary layer rolls, and storm-generated swell. Although initial observations were largely serendipitous, "Hurricane Watch" has routinely acquired SCW imagery of hurricanes during the 1999 and 2000 Atlantic Basin hurricane seasons (nominally August through October). The Canadian Space Agency's Disaster Watch Program and Background Mission Program submitted SCW imagery requests in support of this project. Disaster Watch made manual requests as late as 29 hours in advance of the pass time that were fewer in number but more accurate than those of the Background Mission. In this paper, we discuss some of the scheduling and swath coverage constraints, and show and discuss some of the striking images that were acquired. New insights to storm morphology, storm dynamics, and SAR ocean imaging have followed from these observations. Hurricane Watch will be repeated in 2001, with a particular emphasis on the study of organized boundary layer structures between rain bands. The wide spread extent of these structures was first revealed by RADARSAT-1 images.

Introduction

Synthetic aperture radar (SAR) images of the ocean's surface often show the imprints of marine atmospheric boundary layer processes that modulate the near surface wind field. Rougher areas corresponding to higher wind speeds appear bright in the images, while smoother areas corresponding to lower wind speeds appear relatively dark.

RADARSAT-1's ScanSAR Wide (SCW) modes, with swath widths of 450 or 500 km and a spatial resolution of 100 m, can provide both near-synoptic scale and small-scale views of the imprint of mesoscale meteorological processes on the ocean surface's roughness. A striking example is the case of hurricanes, for which the images can show wind speed and direction effects around the eye, intense convection and rainfall, boundary layer rolls, and storm-generated surface waves [Vachon *et al.*, 1999; Katsaros *et al.*, 2000; Friedman and Li, 2000; Clemente-Colón *et al.*, 2000].

We have been acquiring RADARSAT-1 SCW mode images of hurricanes through an organized effort for several years. In this paper, we present the RADARSAT-1 SAR "Hurricane Watch" project and discuss some of the implications of these unique SAR observations.

Hurricane Watch

Although initial RADARSAT-1 observations were largely serendipitous, "Hurricane Watch", a collaboration between the Canada Centre for Remote Sensing (CCRS), the Canadian Space Agency (CSA), and the National Oceanic and Atmospheric Administration (NOAA), routinely acquired RADARSAT-1 SCW imagery of hurricanes during the 1999 and 2000 Atlantic Basin hurricane seasons (usually August through October). The CSA's Disaster Watch and Background Mission Programs submitted SCW imagery requests in support of this project. Mission planners made manual submissions for Disaster Watch as late as 29 hours in advance of the pass time. These submissions were fewer in number but were generally more accurate than those of the

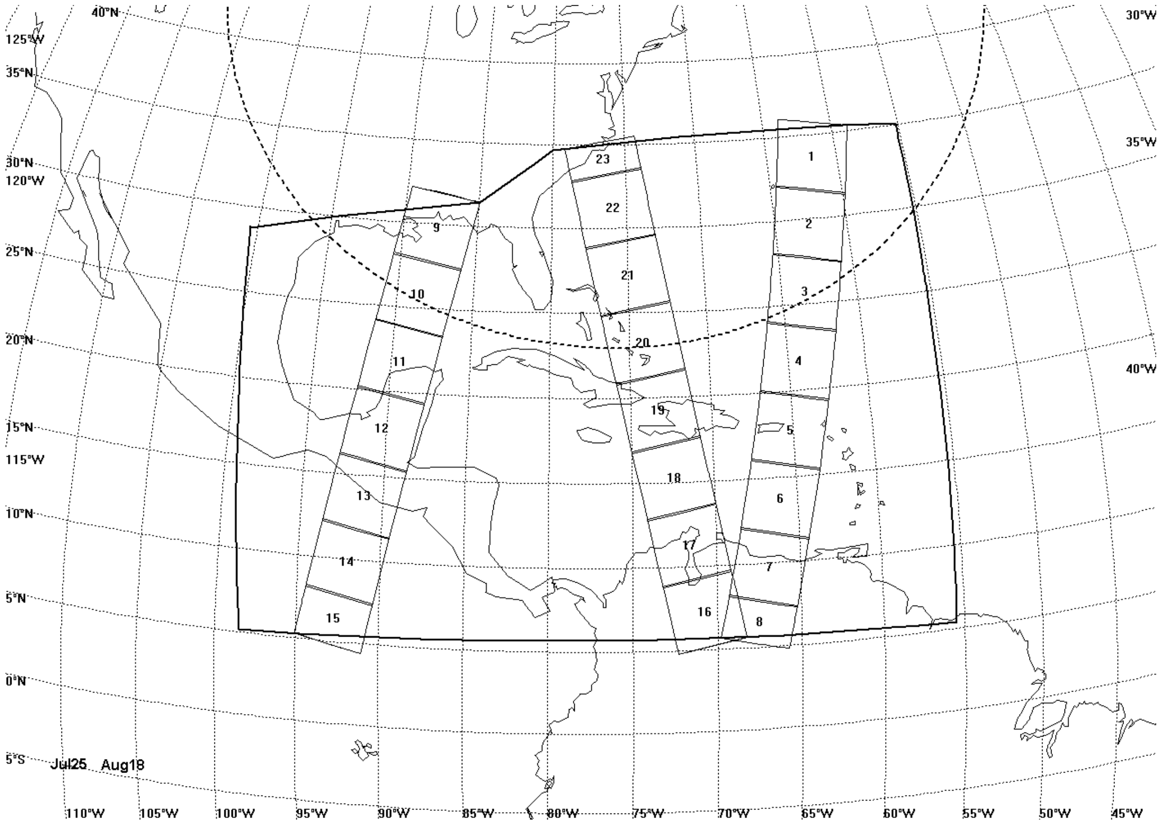

Figure 1: One day RADARSAT-1 ScanSAR wide mode coverage for the Hurricane Watch area of interest. The semicircular dashed line shows the coverage mask for the Gatineau Satellite Station located near Ottawa.

Table 1: Hurricane Watch Results

Year	Hurricane Watch Submissions	Eye Hits Over Ocean
1998	0	1
1999	33	4
2000	19	2

Background Mission. Meanhwile, NOAA's Hurricane Research Division (HRD) attempted to co-ordinate their P3 hurricane penetration flights with the RADARSAT-1 pass times, providing unique high wind speed validation opportunities as well as unique insights to hurricane processes.

For Hurricane Watch we have focussed on use of RADARSAT-1's SCW mode since it provides the most complete coverage over the area of interest. However, that coverage is still rather sparse, as illustrated by the one day SCW coverage shown in Fig. 1. Therefore, SAR images of hurricane eyes over the ocean are still rather rare, as summarized in Table 1, which is based upon our 3 years of hurricane observations. In practice, the RADARSAT-1 SAR acquisition planning is based upon hurricane track forecasts that are routinely available from the web (see, for example, http://www.nhc.noaa.gov/).

Implications

A. Boundary Layer Rolls

The presence of boundary layer rolls in hurricanes has been known from extensive coastal weather radar observations [Wurman and Winslow, 1998]. However, their large spatial extent in hurricanes was first revealed by RADARSAT-1 images. The image of Hurricane *Floyd* shown in Fig. 2 is characterized by a series of distinct striations that are aligned with the nominal wind direction. These striations are the well-known SAR image expression of the boundary layer roll processes. Boundary layer rolls can significantly modulate the air-sea fluxes. Hence, a better understanding of the evolution of these rolls as hurricanes develop could lead to more precise predictions of hurricane intensity change.

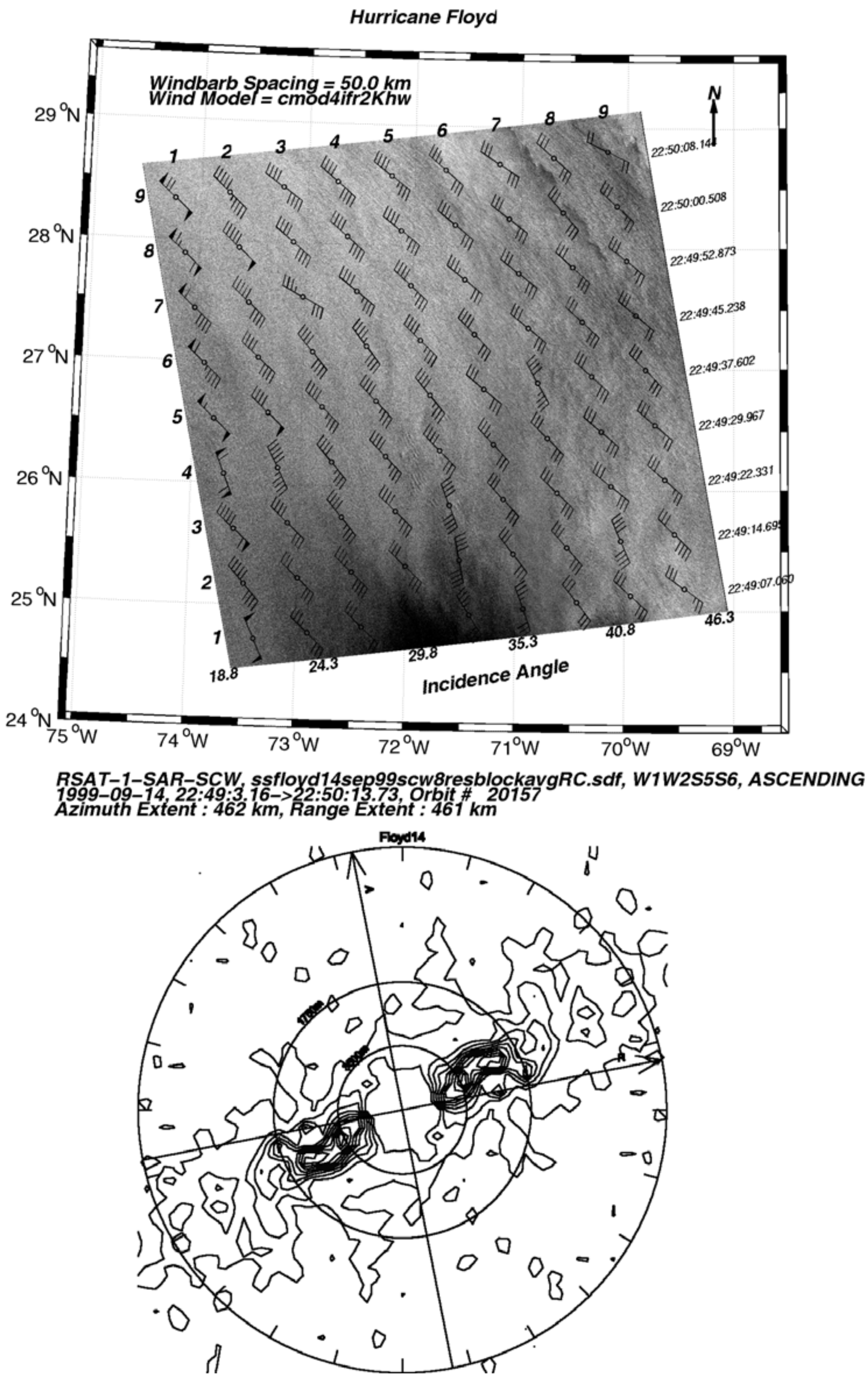

Figure 2: RADARSAT-1 SCW image of Hurricane Floyd on 14 Sept. 1999 covering 500 km from left-to-right (top). (the image is © CSA 1999) Note the striations across the image corresponding to boundary layer rolls. The corresponding image spectrum (bottom) indicates that the striations have a scale of 3.5 km.

B. Precipitation

Coastal Doppler radar has permitted the correlation of dark bands in SAR ocean images of hurricanes with heavy rainfall [Vachon *et al.*, 1999; Katsaros *et al.*, 2000; Friedman and Li, 2000; Clemente-Colón *et al.*, 2000]. Although the imaging mechanism is not well understood, other SAR studies suggest that turbulence generated in the upper few centimetres of water by the droplet impacts tends to damp the small scale roughness [Melsheimer *et al.*, 2001]. The droplet impacts can also produce roughness, depending on the duration and intensity of the rainfall. Also, under high rain rate conditions, rain volume attenuation can be a factor in lowering the observed radar backscatter. SAR images provide the potential for offshore precipitation observation (*e.g.* when hurricanes are beyond the range of coastal Doppler radar).

C. Eyewall Features

SAR images of hurricane eyes show interesting eyewall mesovortex features (see Fig. 3). For example, the image of Hurricane *Dennis* on 27 August 1999 (Fig. 3, row 1, column 2) shows a protrusion of higher backscatter curling into the eye from the north-east. This feature corresponds to a "super cell" that developed within the eyewall, which was also observed by a NOAA P3 research aircraft that circled upwind along the eyewall for about 1 hour shortly after the SAR pass. Analysis of the P3 Doppler radar and stepped-frequency microwave radiometer data [Black *et al.*, 2000] will help to define the wind field associated with this feature and will help to describe the processes causing the enhanced SAR return from well within the radius of maximum winds. Similar features were observed in Hurricane *Dennis* on other days and in other hurricanes; they may signal changes in storm structure and perhaps provide clues to intensity change, which is still one of the most difficult things to forecast for a tropical cyclone.

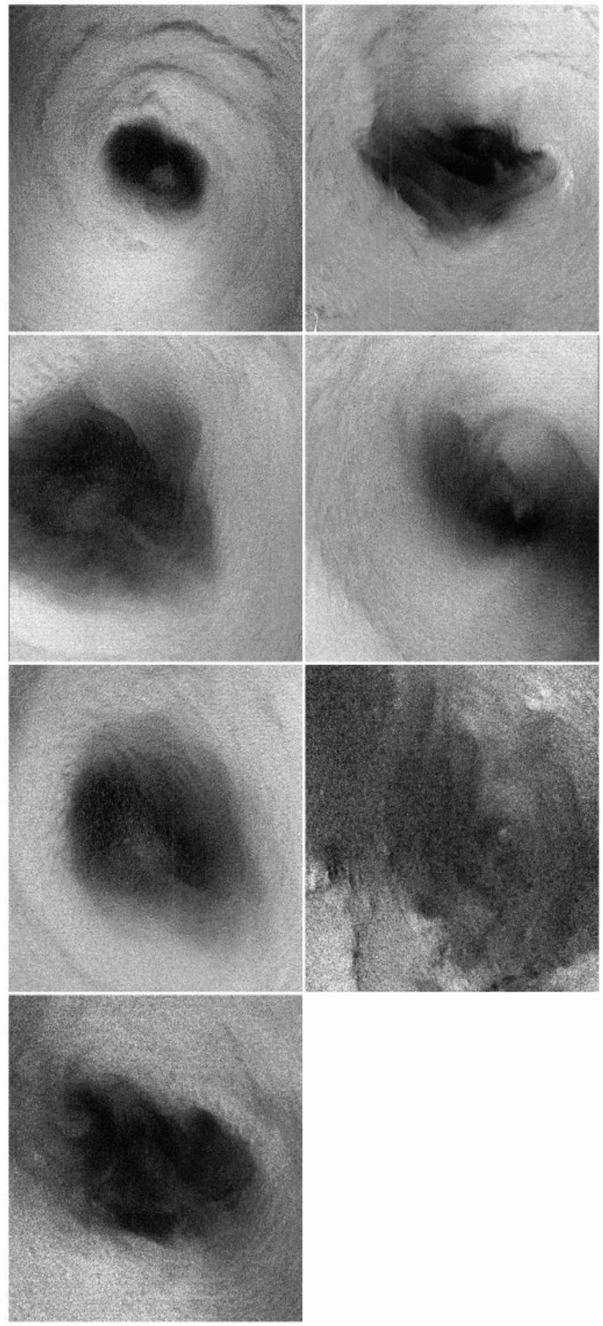

Figure 3: RADARSAT-1 ScanSAR Wide mode images of hurricane eyes: Danielle (upper-left, 31 Aug. 98); Dennis (upper-right, 27 Aug. 99); Dennis (29 Aug. 99); Dennis (31 Aug. 99); Floyd (15 Sept. 99); TS Alberto (17 Aug. 00); Florence (lower-left, 13 Sept. 00). Each subscene spans 100 km from left-to-right. (© CSA 1998, 1999, 2000)

D. Hurricane Wind Fields

In principle, it is possible to estimate the surface wind field from the radar brightness distribution in SAR images of the ocean surface. This requires a well-calibrated radar image and knowledge of the geometry (*i.e.* the incidence angle and the relative wind direction). The wind direction may be estimated (with a 180° direction ambiguity) from the orientation of the boundary layer rolls. The wind speed is then estimated from a scatterometry wind retrieval model. However, most models have problems with the high wind speeds associated with hurricanes. We have used a model

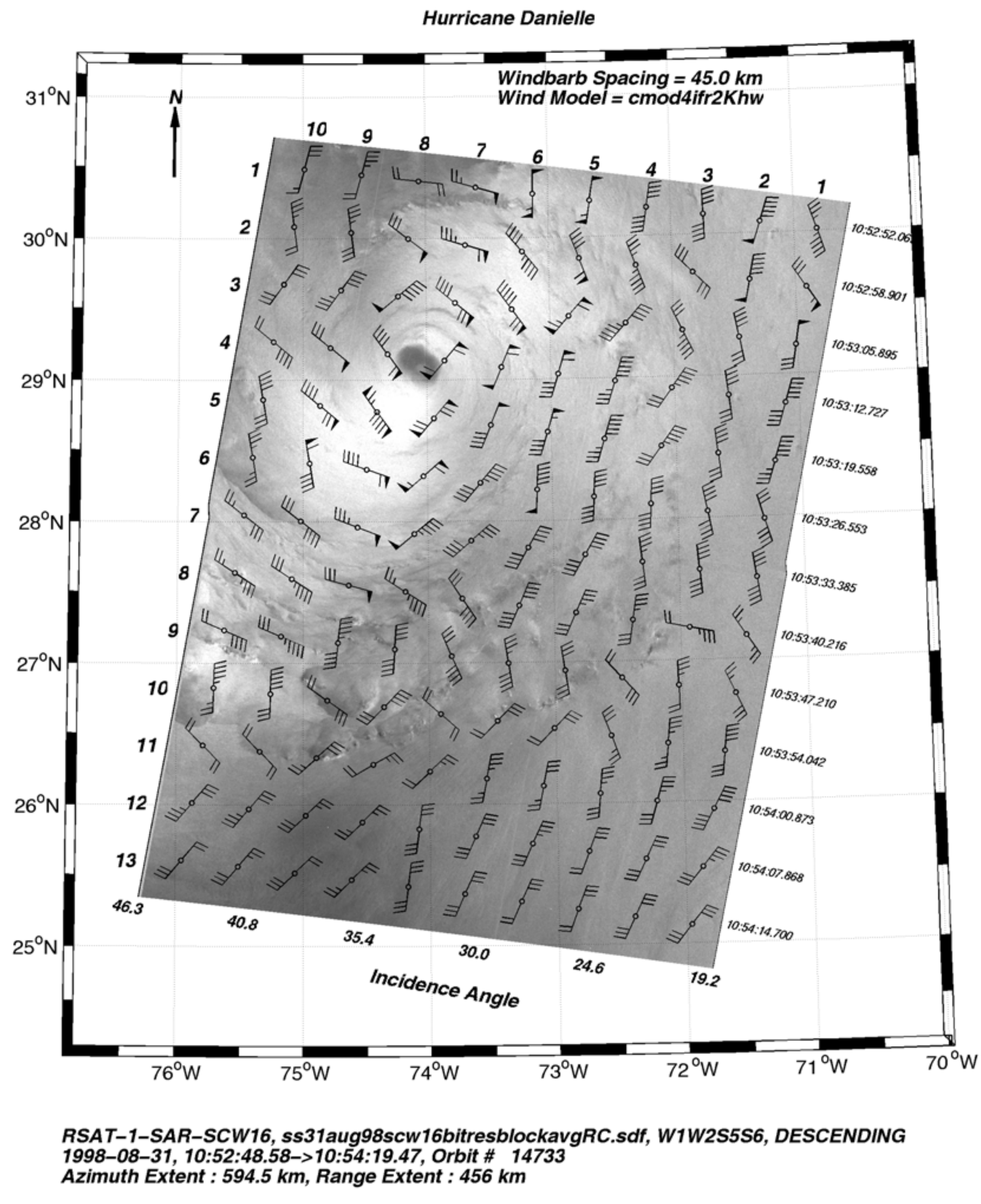

Figure 4: RADARSAT-1 ScanSAR Wide mode image of Hurricane Danielle overlain with a SAR-derived wind field with ambiguous wind direction solutions retained. Anomalous directions are associated with large-scale features not associated with boundary layer rolls. (the image is © CSA 1998)

with a modified high wind speed behaviour [Donnelly *et al.*, 1999] that tends to saturate for higher wind speeds. Example wind fields are shown in Fig. 2 (top) for Hurricane *Floyd* and in Fig. 4 for Hurricane *Danielle*. Validation of these high wind speed, SAR-derived wind fields is the subject of ongoing research.

E. Ocean Waves

The ability of SAR to image surface wave fields is dependent on the spatial resolution of the SAR, the height and length of the surface waves, and the platform range-to-velocity ratio, which is large for RADARSAT-1 and, therefore, not particularly favourable for ocean wave observation. Nevertheless, long waves generated by hurricane winds are often observed in the available RADARSAT-1 imagery. Although the waves are not imaged with high fidelity, they do provide evidence and measures of wave field in-homogeneity within these storms.

Plans

RADARSAT-1 ScanSAR wide mode images of hurricanes are providing new insights into storm morphology. Although repeat coverage is a problem, their "high" resolution provides kilometre scale observations of winds and wind shear, while their 500-km swath is nearly synoptic in scale. These images provide a sea surface view that is complementary to conventional cloud top observations. They provide the locations of the storm centre, the state of boundary layer evolution, zones of precipitation, the surface wind field, regions of precipitation and strong convection, and information on storm-generated waves.

Our research efforts in 2001 will focus on acquiring more supporting observations to further study the boundary layer rolls noted in the RADARSAT-1 data. We will attempt to acquire NOAA P3 aircraft measurements, including, GPS dropsondes, stepped frequency microwave radiometer, scanning radar altimeter, and gust probe data to measure surface fluxes near the times of RADARSAT-1 hurricane acquisitions.

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